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REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 1.90

INSERVICE INSPECTION OF PRESTRESSED CONCRETE CONTAINMENT STRUCTURES WITH GROUTED TENDONS†

A. INTRODUCTION

General Design Criterion 53, "Provisions for Containment Testing and Inspection," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," requires, in part, that the containment be designed to permit (1) appropriate periodic inspection of all important areas and (2) an appropriate surveillance program. This guide describes bases acceptable to the NRC staff for developing an appropriate surveillance program for prestressed concrete containment structures with grouted tendons. The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position

B. DISCUSSION

Inservice inspection of prestressed concrete containment structures with grouted tendons is needed to verify at specific intervals that the safety margins provided in the design of containment structures have not been reduced as a result of operating and environmental conditions. Grouting of tendons to protect them against corrosion is a proven technology in other types of structures. However, there is as yet no real experience to adequately define the long-term characteristics of containment structures with grouted tendons. The major concern in containment structures with grouted tendons is the possibility that widespread corrosion of the tendon steel may occur and remain undetected. The major factors influencing the occurrence of corrosion are (1) the susceptibility of the tendon steel to corrosion, (2) the degree of exposure of the tendon steel to a deleterious environment, (3) the extent of temperature variations, and (4) the quality of the grout and its installation. Following the recommendations of Regulatory Guide 1.107, "Qualifications for Cement Grouting for Prestressing Tendons in Containment Structures," could significantly reduce the danger of widespread corrosion. However, the mechanism of corrosion in all conditions and situations is not fully understood. Because many parameters can influence the development of corrosion or stress corrosion, there is always an area of uncertainty with regard to the corrosion of tendon steel, and it is necessary to monitor the structure in a manner that would reveal the existence of widespread corrosion.

This guide outlines the recommendations for inservice inspection of containments having grouted tendons of sizes up to an ultimate strength of approximately 1300 tons (11,000 kN) and consisting either of parallel wires or of one or several strands. The detailed recommendations of the guide are not directly applicable to grouted tendon containments having bar tendons. However, the inservice inspection program for grouted tendon containments with bar tendons may be developed using the principles in this guide and will be reviewed by the NRC staff on a case-by-case basis. This guide does not address the inservice inspection of prestressing foundation anchors. If they are used, the inservice inspection program will be reviewed by the NRC staff on a case-by-case basis. Inservice inspection of the containment liner and penetrations is also not addressed in this guide.

The simplest means of monitoring these prestressed concrete structures would be to ascertain the amount of prestress at certain strategically located sections in the structure. However, it is generally felt that available instrumentation for concrete, i.e., strain gages, stress meters, and strain meters, is not reliable enough to provide such information. When

* The substantial number of changes in this revision has made it impractical to indicate the changes with lines in the margin.

† For the purpose of this guide, a tendon is defined as a tensioned steel element consisting of wires, strands, or bars anchored at each end to an end anchorage assembly.

instrumentation that either can be recalibrated or replaced in case of a malfunction or is proven to be sufficiently reliable is developed, monitoring the prestress level would be a desirable means of assessing the continuing integrity of prestressed concrete structures with grouted tendons.

Another means of monitoring the functionality of the containment structure would be to subject it to a pressure test and measure its behavior under pressure. Industry comments indicate that an inservice inspection program based on the test of overall functionality is preferable.

This regulatory guide provides two acceptable alternative methods of inspecting containment structures with grouted tendons: (1) an inservice inspection program based on monitoring the prestress level by means of instrumentation, and (2) an inservice inspection program based on pressure-testing the containment structure.

The detailed inspection program outlined in this guide is applicable to a sphere-torus dome containment having cylindrical walls about 130 feet (40 m) in diameter and an overall height of about 200 feet (61 m) with three groups of tendons, i.e., hoop, vertical, and dome. For the purpose of this guide, such a containment is termed the "reference containment." The recommendations in the guide may be used for similar containments with cylindrical walls up to 140 feet (43 m) in diameter and an overall height up to 210 feet (64 m).

For containments that differ from the reference containment or are under a controlled environment, the inservice inspection program may be developed using the concepts evolved in this guide and the guidelines in Appendix A.

The inservice inspection program recommended in this guide consists of:

1. Force monitoring of ungrouted test tendons;
2. Monitoring performance of grouted tendons by
    a. Monitoring of prestress level, or
    b. Monitoring of deformation under pressure; and
3. Visual examination.

1. FORCE MONITORING OF UNGROUTED TEST TENDONS

Some tendons (otherwise identical) are left ungrouted and are protected from corrosion with grease. The changes observed in these tendons are not intended to represent the changes due to environmental or physical effects (with respect to corrosion) in the grouted tendons. Instead, these test tendons will be used as reference tendons to evaluate the extent of concrete creep and shrinkage and relaxation of the tendon steel.

The measurement of forces in ungrouted test tendons would provide a quantitative means of verifying the design assumptions regarding the volumetric changes in concrete and the relaxation of prestressing steel. If some lift-off readings (or load cell readings) indicate values lower than the expected low values, checks should be made to determine if such values are due to corrosion of wires of ungrouted tendons or to underestimation of prestressing losses. The plant need not be shut down or maintained in a shutdown condition during such an evaluation period. These tendons may also serve as an investigative tool for assessing the structural condition after certain incidents that could affect the containment.

2. MONITORING ALTERNATIVES FOR GROUTED TENDONS

a. Monitoring of Prestress Level (Alternative A)

After the application of prestress, the prestressing force in a tendon decreases owing to the interaction of such factors as:

(1) Stress relaxation of the prestressing steel;

(2) Volumetric changes in concrete;

(3) Differential thermal expansion or contraction between the tendon, grout, and concrete; and

(4) Possible reduction in cross section of the wires due to corrosion, including possible fracture of the wires.

In this alternative, the prestress level is monitored at certain strategically located sections in the containment. Thus it is a sampling procedure in which degradation in the vicinity of the instrumented section will be detected by evaluation of the instrumentation readings. However, if corrosion occurs at locations away from the instrumented sections, it would have to produce gross degradation before the instrumentation readings would be affected.

The prestressing force imparted to the structure by a grouted tendon system could be monitored by an appropriate combination of the following methods:

(1) Monitoring the tensile strains in the wires of a tendon;

(2) Evaluating the prestress level at a section in the structure from readings of appropriately located strain gages or strain or stress meters at the section (see Refs. 1 through 7).

Method (1) above is useful for direct monitoring of prestressing force in a tendon. However, the installation of the instrumentation required for this method needs careful attention during installation and grouting of the tendons. Moreover, strain gages installed on the prestressing wires of a tendon will not detect the loss of force due to relaxation of prestressing steel. Allowance for this can be based on relaxation data for the prestressing steel used.

Evaluation of strain gage and stress meter readings requires a full understanding of what makes up the readings, e.g., elastic, creep, and thermal strain or stress components. Strain gage readings will consist of elastic strains corresponding to the prestressing stress in concrete and strains due to creep and shrinkage of concrete. Strains from creep and shrinkage of concrete can vary between 1.5 and 2.5 times the elastic strains in concrete. However, there are methods that can be used to isolate these effects. Three such methods are:

(1) Calculate average creep and shrinkage strains from the time-dependent losses measured on the ungrouted tendons.

(2) Use stress meters at sections where strain gages are used.

(3) Use special strain meters that respond only to volumetric and temperature changes in concrete (Ref. 7).

A sufficient number of temperature sensors installed at the sections where instrumentation is located can be useful in isolating the thermal effects. It is recognized that the raw instrumentation readings can be deceptive, and adjustments may be necessary to account for the calibration constants and temperature effects. The interpretation and evaluation of the results will be simplified if the instrumentation is provided at sections away from structural discontinuities. The applicant should provide sufficient redundancy in the instrumentation to permit the evaluation of anomalous readings and the isolation of a malfunctioning gage. One such combination would be two strain gages and one stress meter at each face of a section.

After appropriate use has been made of the methods and instruments available, an average stress and an average prestressing force at a section can be evaluated. Even though the predicted prestressing force corresponding to a specific time may include adequate consideration for creep of concrete and relaxation of prestressing steel, the chance that the value based on measurements will compare well with the predicted value is small. Hence it is recommended that an applicant establish a band of acceptable prestress level similar to that illustrated in Figure 1. It is also recommended that the bandwidth not exceed 8% of the initial prestressing force at a section after considering the loss due to elastic shortening, anchorage takeup, and friction. The 8% bandwidth would amount to between 40% and 70% of the total time-dependent losses.

Alternative A is based on the use of instrumentation. Many of these instruments have to be built into the structure in such a manner that they can be neither replaced nor recalibrated. It is quite likely that such built-in instrumentation may not remain reliably operable throughout the life of the structure. Recognizing such a possibility, the guide provides for an alternative of pressure testing (Alternative B) when the data obtained from instrumentation readings are found to be questionable.

b. Monitoring of Deformation Under Pressure (Alternative B)

Testing the containment under pressure and evaluating its elastic response has been proposed as a means of assessing the integrity of the containment. The elastic response under pressure testing is primarily a function of the stiffness of the structure. Any significant decrease in the stiffness of the structure due to loss of prestress would be the result of cracking of the structure. Because of the insensitive and indirect relationship between the prestressing force and the elastic response of the structure, such a method cannot be used to establish the existing prestress level at various sections. However, comparison of the condition and deformation of the structure during the ISI (Inservice Inspection) pressure testing with those during the ISIT (Initial Structural Integrity Testing) pressure testing could provide a basis for evaluating the functionality of the structure. This method has been accepted* previously by the NRC staff on the condition that the containment be designed conservatively so that there will be no cracking (or only slight cracking at the discontinuities) under the peak test pressure. Section III, Division 2, of the ASME Code (Ref. 8) allows a 33-1/3% increase in the allowable stress in tensile reinforcement under a test condition. The NRC staff has accepted this allowance on the assumption that it is only a one-time loading (i.e., during the ISIT). However, if such testing is to be performed a number of times during the life of the containment structure, it is prudent not to use this allowance in order to avoid or minimize gradual propagation of cracking during subsequent pressure tests.

The locations for measuring the deformations under pressure should be based on the recommendations of this guide. For a meaningful comparison of the deformations, it is recommended that the locations where the deformations are to be recorded have deformations larger than 0.06 inch (1.5mm) under the calculated peak containment internal pressure associated with the design basis accident and that these

* Three Mile Island Nuclear Power Station Unit 2 and Forked River Nuclear Power Station.

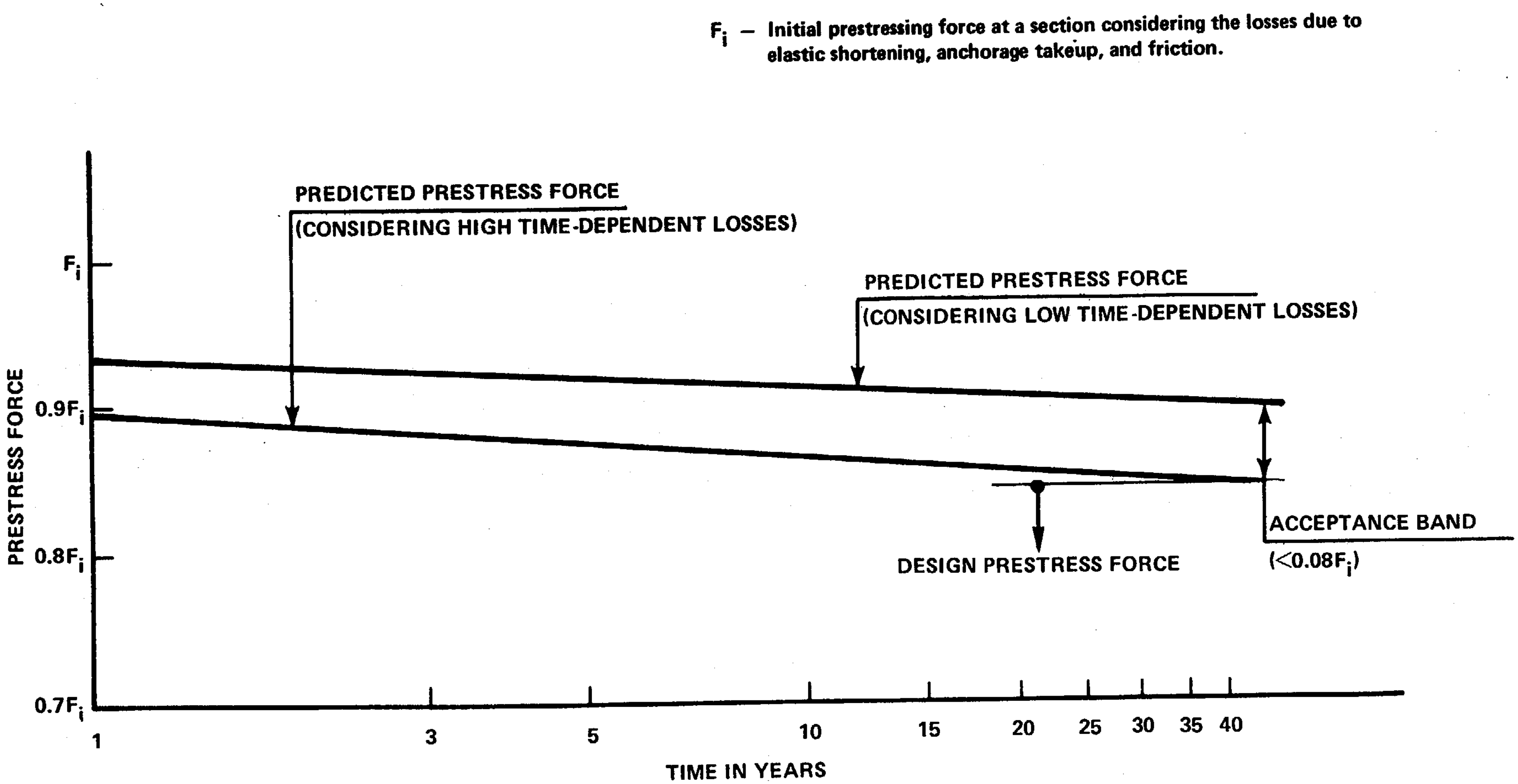


Figure 1. Typical Band of Acceptable Prestress Level

locations be approximately the same during the ISIT and the subsequent ISIs. This will require these locations to be away from the areas of structural discontinuities. Thus the number of locations for measurement of deformations in typical cylinder and dome areas will be in excess of those recommended in Regulatory Guide 1.18, "Structural Acceptance Test for Concrete Primary Reactor Containments."

If an analysis of the effects of such parameters as normal losses in prestressing force, increase in modulus of elasticity of concrete with age, and differences in temperatures during various pressure tests indicates that they could affect the deformations of the selected points, these parameters should be considered in comparing the deformations during various pressure tests.

3. VISUAL EXAMINATION

Visual examination of structurally critical areas consisting of the areas of structural discontinuities and the areas of heavy stress concentration is recommended. Reference 9 provides excellent guidance for reporting the condition of concrete and should be used whenever applicable for reporting the condition of examined areas.

There are numerous examples of the use of pulse velocity technique to obtain information concerning the general quality level of concrete. Based on experience and experimental data (Refs. 10, 11, 12), a pulse velocity of 14,000 ft/sec (4300 m/sec) or higher indicates a good to excellent quality of concrete. For normal weight concrete, a pulse velocity of 11,000 ft/sec (3400 m/sec) or lower indicates concrete of questionable quality. Thus the technique can be used as part of the inspection of concrete containments when the visual examination reveals a high density of wide (>0.01 in. or 0.25 mm) cracks or otherwise heavy degradation. The detailed procedure and limitations of the techniques are described in Reference 13.

C. REGULATORY POSITION

1. GENERAL

1. All prestressed concrete containment structures with grouted tendons should be subjected to an inservice inspection (ISI) program. The specific guidelines provided herein are for the reference containment described in Section B.

2. For containments that differ from the reference containment, the program described herein should serve as the basis for developing a comparable inservice inspection program. Guidelines for the development of such a program are given in Appendix A to this guide.

3. The inservice inspection program should consist of:

a. Force monitoring of ungrouted test tendons;

b. Periodic reading of instrumentation for determining prestress level (Alternative A) or deformations under pressure (Alternative B) at preestablished sections; and

c. Visual examination.

4. The inservice inspection should be performed at approximately 1, 3, and 5 years after the initial structural integrity test and every 5 years thereafter. However, when an applicant chooses pressure testing (Alternative B) as a part of the inspection, the frequency of inspections should be as indicated in Figure 2.

5. Alternative B may be substituted for Alternative A by the applicant if, at some time during the life of the structure, the inspection based on Alternative A does not provide satisfactory data. The details of such a substitution will be reviewed by the NRC staff on a case-by-case basis.

6. If the containment base mat is prestressed, its proposed inspection program will be evaluated by the NRC staff on a case-by-case basis.

2. UNGROUTED TEST TENDONS

1. The following ungrouted test tendons should be installed in a representative manner:

a. Three vertical tendons,

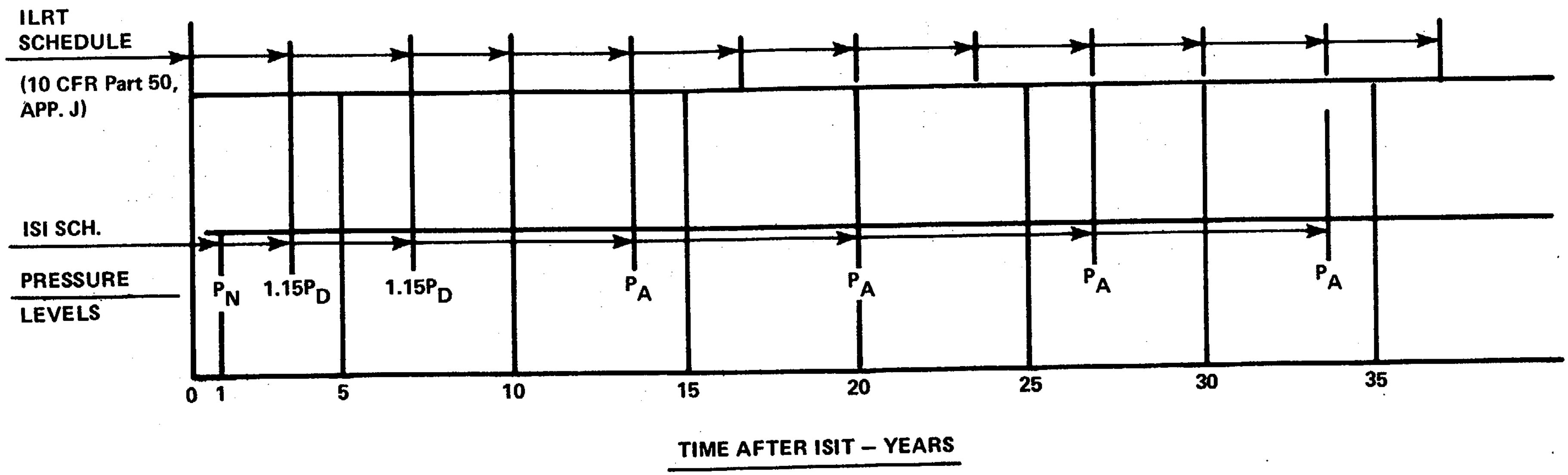
b. Three hoop tendons, and

c. Three dome tendons for the design utilizing three 60° families of tendons.

2. The ungrouted test tendons need not be in addition to the design requirements.

3. The ungrouted test tendons and their anchorage hardware should be identical to the grouted tendons and their hardware.

4. The ungrouted test tendons should be subjected to force measurement by lift-off testing or load cells to assess the effects of concrete shrinkage and creep and relaxation of the tendon steel. These data should be evaluated in conjunction with the overall structural condition of the containment evident from the other examinations.



KEY

P_N – Normal Operating Pressure or Zero

P_D – Containment Design Pressure

P_A – Calculated Peak Internal Pressure Associated with the Design Basis Accident

ILRT – Integrated Leak Rate Testing

ISIT – Initial Structural Integrity Testing

ISI – Inservice Inspection

Figure 2. Schedule for Inservice Inspections (Alternative B)

3. MONITORING ALTERNATIVES FOR GROUTED TENDONS

3.1 Instrumentation for Monitoring the Prestress Level (Alternative A)

3.1.1 Installation

1. The prestressed cylindrical wall and dome should be instrumented. This instrumentation may be either embedded in the concrete or inserted into the structure so that it can be maintained or replaced. Instrument types, locations, and quantities should be selected to provide the best representation of prestress level in the structure. A sufficient number of temperature sensors should be installed to isolate and evaluate the effects of variations in temperature gradients on the instrument readings and observations. Redundancy of the embedded instrumentation should be based on a conservative estimate of the probability of malfunction of the instrumentation to be installed.

2. The instrumentation in the concrete should be arranged and distributed in such a manner as to permit evaluation of the prestressing levels and should be located:

a. At six horizontal planes to measure the hoop prestressing levels;

b. Along three vertical tendons to measure vertical prestress levels;

c. Along three dome tendons for the design using three families of 60° tendons.

3. Sections through the structure should be selected at a minimum of four locations in each horizontal plane, three locations along each vertical tendon, and two locations along each dome tendon (see Figure 3). At these sections, the prestress level should be monitored by (a) a combination of stress meters or strain gages in concrete or on rebar at a minimum of two points through the section or (b) strain gages directly on tendon wires with a minimum of 3% of the tendon wires instrumented.

3.1.2 Characteristics

1. Instrumentation provided for the determination of concrete prestress level should be capable of effective use over the life span of the containment structure within specified operational limits under the following conditions, unless otherwise defined by the designer and approved by the NRC staff:

a. Humidity: 0% to 100%;

b. Temperature: 0°F (-18°C) to 200°F (93°C); and

c. Cyclic loading: 500 cycles of 600 psi (4.2 MPa) stress variation in compression.

2. The instruments should be protected against adverse effects of the expected environment in which they will be located, e.g., electrolytic attack, including the effects of stray electric currents of a magnitude that may be encountered at the particular site and structure. They should be protected against temperature extremes to which they may be exposed while the containment is under construction.

3. The sensitivity of strain gages should be specified; the drift or stability under the conditions in 1 and 2 above should be accounted for in the specified limits, or the gages should be subject to recalibration in service.

4. The stress meters should be able to measure compressive stresses up to 2500 psi (17.2 MPa).

3.1.3 Monitoring Instrumentation Operability

After the installation of the instrumentation, all embedded strain gages and stress meters should be read every two months until the initial structural integrity test (ISIT) is performed. The response of the instrumentation during prestressing and pressure testing (ISIT) should be used to confirm their operability. After the ISIT, the monitoring of the instrumentation should be continued every two months to confirm operability of the instrumentation until the first inservice inspection. The monitoring frequency may be reduced to once every six months thereafter unless local conditions or special circumstances dictate more frequent readouts. The operability of the instrumentation should also be confirmed during subsequent pressure tests. If anomalous readings are obtained, the reason for such readings should be determined. If it is determined that they result from defective gages, the basis for such a determination should be justified.

3.2 Monitoring Deformation Under Pressure (Alternative B)

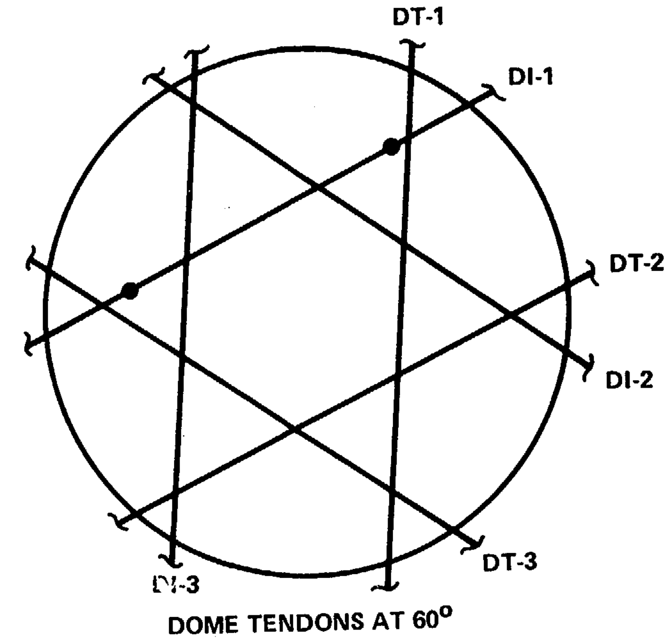
When it is planned to use this alternative as a part of the total inservice inspection program, it is recommended that the design of the containment structure include the following considerations:

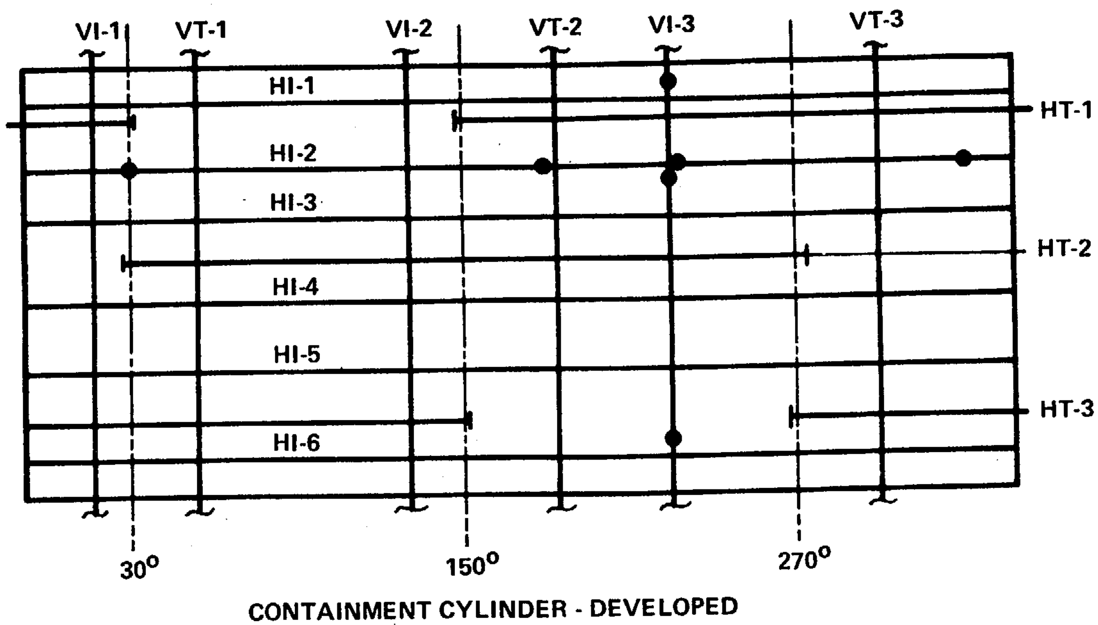
1. Membrane compression should be maintained under the peak pressure expected during the ISI tests.

2. The maximum stress in the tensile reinforcing under the peak pressure expected during the ISI test should not exceed one-half the yield strength of the reinforcing steel ($0.5f_y$).

3.2.1 Pressurization

1. During the first inspection, the containment structure need not be pressurized.





KEY

HT, VT, DT - HOOP, Vertical, Dome Ungrouted Test Tendons.

HI - Horizontal Planes to be Selected for Instrumentation.

VI & DI - Vertical & Dome Tendons to be Identified for Instrumentation.

Four Sections Along HI Planes, Three Sections Along VI Tendons, Two Sections Along DI Tendons to be Selected for Monitoring Prestress Level.

●- Shows Selection of Sections Along One Horizontal Plane, One Vertical Tendon, and One Dome Tendon.

Figure 3. Containment Diagram Showing Typical Locations of Test Tendons and Instrumentation

2. During the second and third inspections, the containment structure should be subjected to a maximum internal pressure of 1.15 times the containment design pressure.

3. During the fourth and subsequent inspections, the containment structure should be subjected to a maximum internal pressure equal to the calculated peak internal pressure associated with the postulated design basis accident.

3.2.2 Instrumentation and Deformations

1. Instrumentation similar to that used during the ISIT should be installed prior to the pressure testing for measurement of overall deformations at the selected points.

2. The limit of accuracy of readings of the instruments to be used should be specified by means of an error band so that a meaningful comparison of deformations measured during the ISIT and ISI can be made.

3. The points to be instrumented for the measurement of radial displacements should be determined in six horizontal planes in the cylindrical portion of the shell, with a minimum of four points in each plane (see Figure 3).

4. The points to be instrumented for the measurement of vertical (or radial) displacements should be determined as follows:

a. At the top of the cylinder relative to the base, at a minimum of four approximately equally spaced azimuths.

b. At the apex of the dome and one intermediate point between the apex and the springline, on at least three equally spaced azimuths.

5. The intermediate pressure levels at which the deformations at the selected points are to be measured should correspond to those for the ISIT.

4. VISUAL EXAMINATION

4.1 Structurally Critical Areas

A visual examination should be performed on the following exposed structurally critical areas:

1. Areas at structural discontinuities (e.g., junction of dome and cylindrical wall or wall and base mat).

2. Areas around large penetrations (e.g., equipment hatch and air locks) or a cluster of small penetrations.

3. Local areas around penetrations that transfer high loads to the containment structure (e.g., around high-energy fluid system lines).

4. Other areas where heavy loads are transferred to the containment structure (crane supports, etc.).

A visual examination of structurally critical areas should be scheduled during all pressure tests while the containment is at its maximum test pressure, even if visual examinations of these areas have been conducted at other times.

4.2 Anchorage Assemblies

Exposed portions of the tendon anchorage assembly hardware or the permanent protection thereon (whether it be concrete, grout, or steel cap) should be visually examined by sampling in the following manner:

1. A minimum of six dome tendons, two located in each 60° group (three families of tendons) and randomly distributed to provide representative sampling,

2. A minimum of five vertical tendons, randomly but representatively distributed,

3. A minimum of ten hoop tendons, randomly but representatively distributed.

For each succeeding examination, the tendon anchorage areas to be examined should be selected on a random but representative basis so that the sample group will change each time.

The inservice inspection program should define the defects the inspector should look for during visual examination of the exposed anchor hardware and protection medium and should establish the corresponding limits and tolerances. Special attention should be given to the concrete supporting the anchor assemblies, and any crack patterns at these points should be observed and analyzed.

5. REPORTABLE CONDITIONS

5.1 Inspection Using Alternative A

If the average prestress force along any tendon falls below the acceptable band (see Figure 1), the condition should be considered as reportable.

If the prestress force determined at any section falls below the design prestress force, the condition should be considered as reportable.

5.2 Inspection Using Alternative B

If the deformation measured under the maximum test pressure at any location is found to have increased by more than 5% of that measured during the ISIT under the same pressure, the condition should be considered as reportable.

5.3 Reportable Conditions for Visual Examinations

If the crack patterns observed at the structurally critical areas indicate a significant decrease in the spacing or an increase in the widths of cracks compared to those observed during the ISIT at zero pressure after depressurization, the condition should be considered as reportable.

If the visual examination of the anchor hardware indicates obvious movements or degradation of the anchor hardware, the condition should be considered as reportable.

If the anchor hardware is covered by permanent protection and the visual examination reveals a degradation (e.g., extensive cracks or corrosion stains) that could bring into question the integrity and effectiveness of the protection medium, the condition should be considered as reportable.

5.4 Reportable Conditions for Ungrouted Test Tendons

When the force monitoring (by liftoff or load cell) of ungrouted test tendons indicates a prestress force below the acceptable band (see Figure 1), the condition should be considered as reportable.

6. REPORTING TO THE COMMISSION

The reportable conditions of Regulatory Position C.5 could be indicative of a possible abnormal degradation of the containment structure (a boundary designed to contain radioactive materials). Any such condition should be reported to the Commission.*

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used in the evaluation of submittals in connection with construction permit applications docketed after October 1, 1977.

If an applicant wishes to use this regulatory guide in developing submittals for applications docketed on or before October 1, 1977, the pertinent portions of the application will be evaluated on the basis of this guide.

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* The report to the Commission should be made in accordance with the recommended reporting program of Regulatory Guide 1.16, "Reporting of Operating Information—Appendix A Technical Specifications."

APPENDIX A

GUIDELINES FOR DEVELOPING THE INSERVICE INSPECTION PROGRAM FOR CONTAINMENTS (OTHER THAN REFERENCE CONTAINMENT DISCUSSED IN THE GUIDE) WITH GROUTED TENDONS

Ungrouted Tendons

Three ungrouted tendons should be provided in each group of tendons (e.g.,vertical, hoop, dome, inverted U).

Instrumentation (Alternative A)

The following criteria should be used to determine the number of sections (N) to be monitored for each group of tendons:

$$N = \frac{\text{Actual Area Prestressed by a Group of Tendons}}{\text{K x Area Monitored by a Set of Instruments at a Section (determined as SxL)}}$$

where

S = spacing of tendons in feet (meters)

L = length of a tendon monitored by a set of instruments- may be considered as 12 ft (3.66m)

and K is determined as follows:

For containments under uncontrolled environment and having continuous tendon curvature,

$K \leq 100$

For containments under uncontrolled environment and having essentially straight tendons,

$K \leq 160$

For containments under controlled environment and having either straight or curved tendons.

$K \leq 200$

Monitoring Deformations Under Pressure (Alternative B)

The number of locations (N) to be selected for measuring the deformations under pressure should be determined as follows:

For radial deformations of cylinder,

$$N = \frac{\text{Surface Area of Cylinder in square feet (square meters)}}{2700\ (250)}$$

but not less than 12.

For vertical deformations of cylinder,

N = 4

For radial or vertical deformations of dome,

$$N = \frac{\text{Surface Area of Dome in square feet (square meters)}}{2700\ (250)}$$

but not less than 4

APPENDIX B

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