

# ANALYSIS AND TESTING OF PRESTRESSED CONCRETE NUCLEAR CONTAINMENT STRUCTURES

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## ABSTRACT

This paper presents a brief discussion of the analysis and testing methods developed by Bechtel for the engineering of the first generation of prestressed concrete nuclear containment structures which are currently in various stages of design and construction. The discussion considers the overall response of the structure and the response of its components that require special consideration such as large penetrations, the liner system and tendon anchorage zones. Some pertinent results of the analysis, including two-dimensional and three-dimensional numerical solutions, are presented in graphical form. Results of the full-scale structural tests in the field are presented in several plots that show also the corresponding response of the structures as predicted by analysis.

## I. INTRODUCTION

The initial phase of engineering the prestressed concrete containment consisted of performing a study to investigate the feasibility of its design and construction. This study indicated that prestressed concrete containment was technically and economically feasible, but that methods of predicting its behavior with a higher level of accuracy would have to be developed. This requirement was dictated, of course, by the extreme importance attached to the reliability and safety of a nuclear reactor facility and the stringent requirements of the regulatory agencies for approval of both the design and the completed structures.

Accordingly, a major effort was devoted in the subsequent phases of the program to establishing criteria for design, construction, and inspection; developing improved analytical methods for detailed design; and planning and conducting test programs in the laboratory and in the field to verify the theoretical analysis.

## 2. FUNCTION

The function of the containment structure is to prevent release to the atmosphere of unacceptable doses of radioactive fission products during operation and during a postulated credible accident associated with the nuclear reactor system it contains. This system consists of the pressurized water reactor, steam generators, reactor coolant loops and portions of the auxiliary and engineered safeguards system.

The containment structure also provides biological shielding during both normal operation and accident conditions.

## 3. DESCRIPTION OF THE STRUCTURE

The containment structure consists of a vertical cylinder with a convex dome and a basically flat bottom slab. Both the dome and the cylinder are constructed of prestressed concrete, while the bottom slab is constructed of reinforced concrete. A carbon steel liner extends over the entire internal surface of the structure and is anchored to the concrete at close intervals. The structure has a large equipment hatch, personnel access doors and many smaller penetrations for electrical conduits, piping and other systems. Figure 1 shows the general configuration of the structure.

The construction procedure, after completing the base slab, consists of erecting the liner in vertical segments, followed by placement of the reinforcement, tendon conduits and concrete. The structure is then post-tensioned after the concrete has cured. The steel liner is used as the inside form during concrete pour and also provides support during construction for placement of piping and other components.

Prestressing of the cylindrical wall is achieved by a post-tensioning system consisting of vertical and circumferential tendons. A continuous access gallery is provided beneath the base slab for installation of vertical tendons.

For sphere-torus domes prestressing is achieved by a three-way pattern of tendons that are anchored, at both ends, at the ring girder. In a hemispherical dome the tendons extend to the bottom of the cylindrical wall.

In addition to post-tensioning, the containment structure employs a substantial amount of reinforcing steel, particularly in areas where localized stresses occur such as around the equipment hatch, personnel access door, tendon anchorage zones, at the junction of the cylinder and bottom slab, and in the ring girder.

## 4. DESIGN CRITERIA

The containment structure is designed to maintain the required leak integrity and to have a predictable response. The loads considered in its design are:

- o Pressure, temperature transients and other forces such as internal missiles, associated with the "Design Basis Accident".

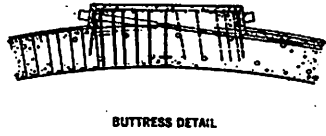
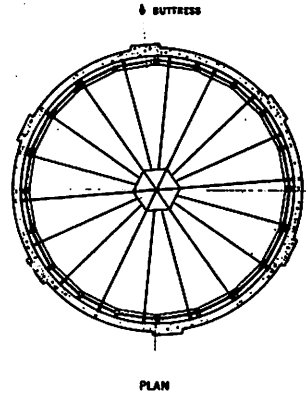
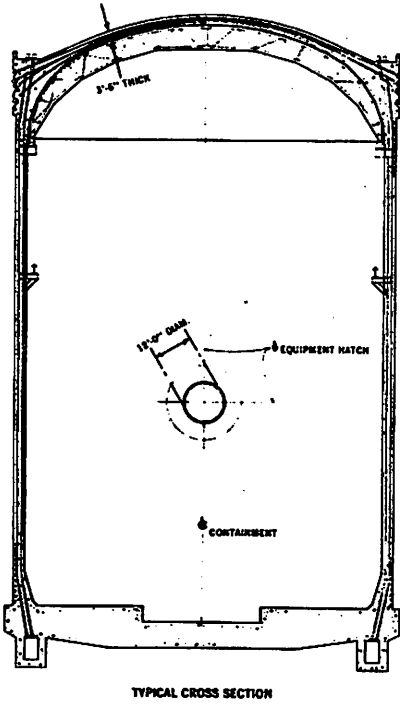


Figure 1

The Containment Structure

- o Other design loads which include: dead load, live load, temperature, earthquake, wind, tornado forces and associated missiles, hydrostatic pressure, external pressure and prestressing forces.

These loads, grouped in several load combinations that represent normal and remotely probable conditions, are used to design the structures for the following phases of its construction and operation: prior to prestressing, at transfer of prestress, under sustained prestress, under normal conditions, under design accident conditions, and under extreme environmental conditions.

The analysis of the prestressed and reinforced concrete portions of the containment generally complies with the American Concrete Institute (ACI) requirements as modified to render them more compatible with the predicted response and intended function. These modifications concern the allowable levels of membrane compression, membrane tension, shear and localized stress concentration for concrete, and allowable levels of tension for prestressing and reinforcing steel.

The analysis of covers for hatches and other penetrations in the liner conforms to the requirements of Section III, of the American Society of Mechanical Engineers (ASME) Pressure Vessel Code. However, the liner as a whole is not subject to these requirements. Tensile strain levels and strain capacity of the liner are the most pertinent criteria in its design.

## 5. METHODS OF ANALYSIS

The preliminary analysis of the containment is based on established shell and flexure design equations. However, because of the composite nature of the containment material and the complexity of its geometry and loading conditions, computerized numerical techniques - principally two-dimensional axisymmetric finite element programs - are used for the final design. In this method, a mathematical model is constructed of the physical structure by representing it as a collection of interconnected elements whose geometry is defined by a spatial grid of nodal points. The displacement field within each element is assumed to have a known mathematical form which requires only a set of linear algebraic equations to describe its behavior. Thus, the mathematical model is generated by forming the structural stiffness matrix relating forces at the nodal points to nodal displacements.

The presence of several materials with various properties, such as reinforcing steel, concrete, and a liner, is accounted for by adjusting the material properties at the appropriate elements. Concrete cracking is accounted for in a similar manner; however, the solution is iterative and often becomes quite tedious. External forces can be applied as concentrated loads at the nodal points, line loads at the periphery of the elements, or

uniform loads at the elements surface. The output of the program generally consists of nodal point forces and corresponding displacements and element or nodal stresses and strains in the specified or principal directions.

To determine the response of the major structural components (i. e. , dome, cylindrical shell and foundation) an axisymmetric analysis is made. The presence of penetrations, buttresses and other non-axisymmetric structural elements are ignored in this analysis since their effect is local and contributes negligibly to the overall response. The structure in the vicinity of these elements is analyzed separately by using two - or three-dimensional programs as appropriate.

Figures 2a, b, c and d show theoretically predicted strain profiles at a typical section of the containment structure for the prestress and internal pressure loading conditions.

## 6. SPECIAL CONSIDERATIONS

Major components of the containment structure that require special consideration in their analysis are: large penetrations such as the equipment hatch, the liner system and prestressing anchorage zones.

Equipment Hatch - There is very little published information that is directly applicable to the detailed design of the containment structure in the vicinity of a large opening. In fact, problems associated with penetrations in steel pressure vessels which have been in use for decades, are continuously under study. The design of the containment around large penetrations is made more complex because of: a) the presence of stiffening members; b) temperature stress distribution across the thickness of the wall and c) the undefined nature of stress concentration in concrete materials. The analysis is further complicated by the proximity of the opening in some instances to other discontinuities and by the arrangement of prestressed tendons and reinforcing steel around the opening.

Savin derived a mathematical solution for determining the stress concentration around circular holes in plates. However, he assumed elastic and isotropic conditions and a small hole compared to the size of the plate. Eringen, Naghdi and Thiel derived a solution which assumed a uniform thickness shell of homogenous and elastic material, but did not take temperature stresses into consideration. This solution was used initially to obtain the preliminary stress distribution for the design of the earlier containment structures discussed here. Also, two-dimensional finite element programs were used to obtain detailed stress distribution. These analyses gave adequate results; subsequently, more refined three-dimensional programs, particularly SAP, were implemented for this analysis.

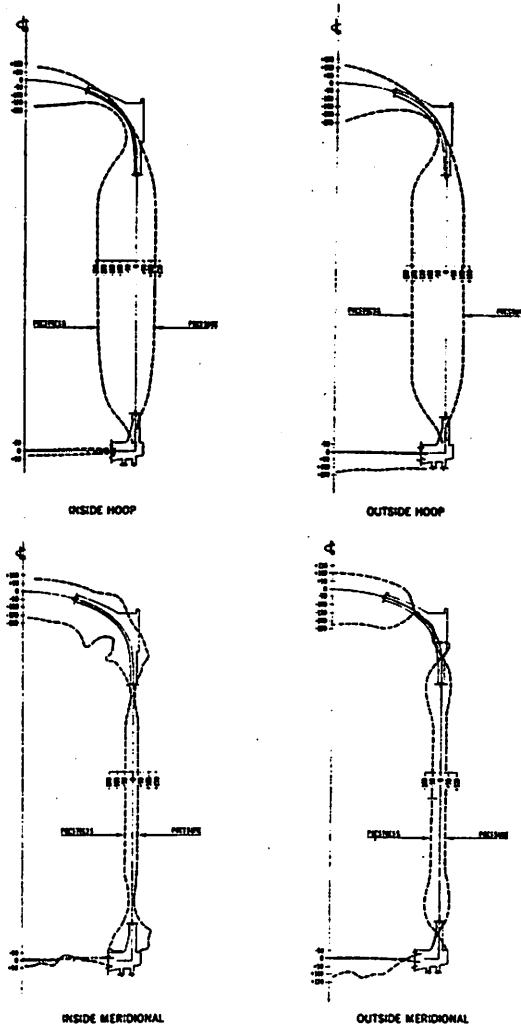


Figure 2

Strain Profiles

Implementation of the SAP finite element program enabled the three-dimensional geometry to be accurately modeled with solid elements. This program was extensively checked out by comparing solutions for an unstiffened penetration with those obtained by different techniques. In addition, since each element could only be assigned a constant temperature, a technique was devised which enabled accurate stress determinations for non-linear temperature distributions. The problems of geometric and kinematic compatibility of the model structure interface were treated by varying the extent of the model and the type of boundary conditions (i. e., displacement or stress).

Figures 3, 4, 5 and 6, respectively, show the cross section of a typical equipment hatch, corresponding finite element model and some of the moment curves in the vicinity of the equipment hatch.

**Liner System** - The containment liner has an apparent resemblance to a pressure vessel because of its configuration and pressure containment function. However, it differs significantly from a pressure vessel in the manner of support and loading.

The containment liner system is designed to withstand strains caused by: dead load, prestressing, creep and shrinkage, internal pressure, temperature gradients, earthquakes, wind, tornadoes, hydrostatic pressure and vacuum.

Of these loads, temperature gradients during accident conditions cause, by far, the largest amount of strain. For instance, a thermal gradient of  $280^{\circ}$  F inside the containment and  $0^{\circ}$  F outside causes compressive strains at the mid-height of the cylinder in excess of  $1700\mu\epsilon$  both in circumferential and longitudinal directions. Prestressing, including the effects of creep and shrinkage, causes the next highest strain, which may exceed  $300\mu\epsilon$ .

The failure modes which establish the basis for determining the required design capacity of each component of the liner system are: tensile cracking of the liner plate or the weld and major distortion of the liner that may be caused by buckling or inward bending and associated anchorage failure.

Generally, the liner is designed to preclude buckling in the elastic range. Consequently, the analysis becomes concerned with determining the unbalanced forces caused by the propagation of an initial inward curvature of liner panels and maintaining tensile strains within the allowable range. In addition, the liner is designed to act as a concrete form. In determining the thickness of the liner, consideration is given to making it as thin as possible to reduce its effect on the magnitude of the prestressing force and to reduce the load at liner discontinuities. On the other

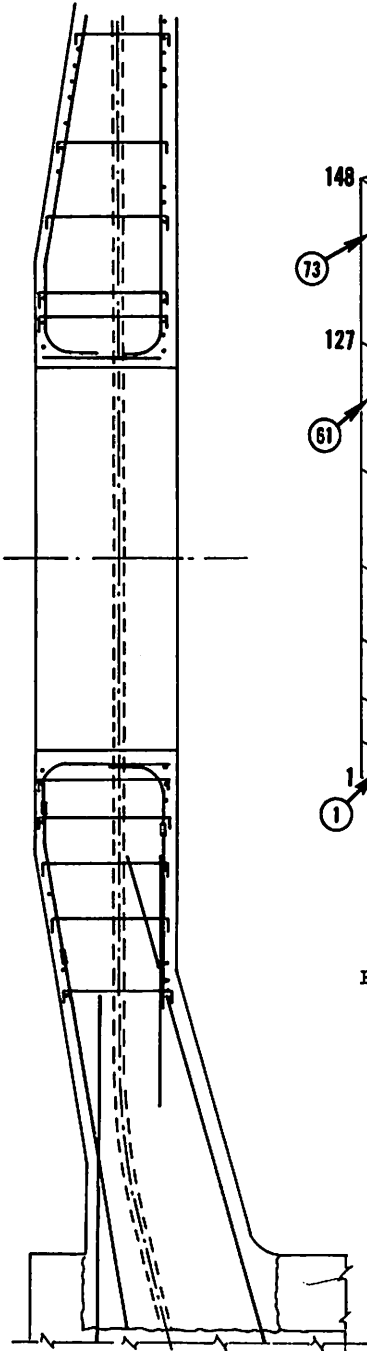


Figure 3

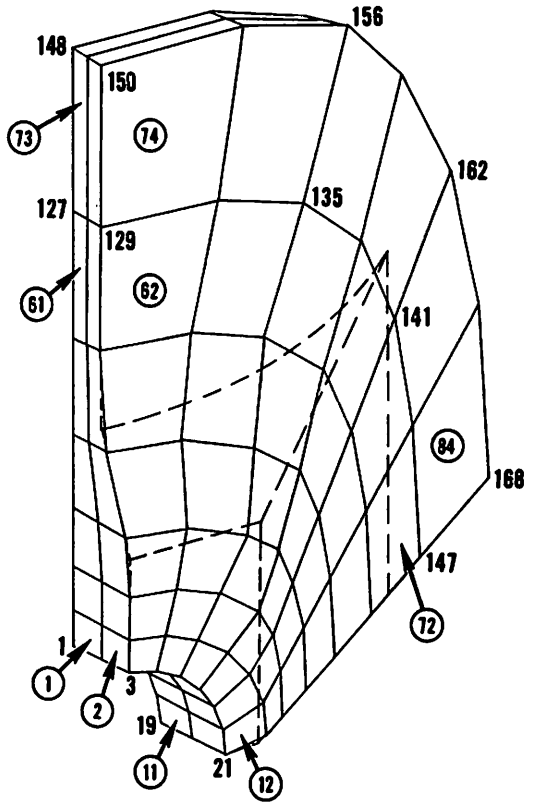


Figure 4

Finite Element Model

Equipment Hatch Cross Section

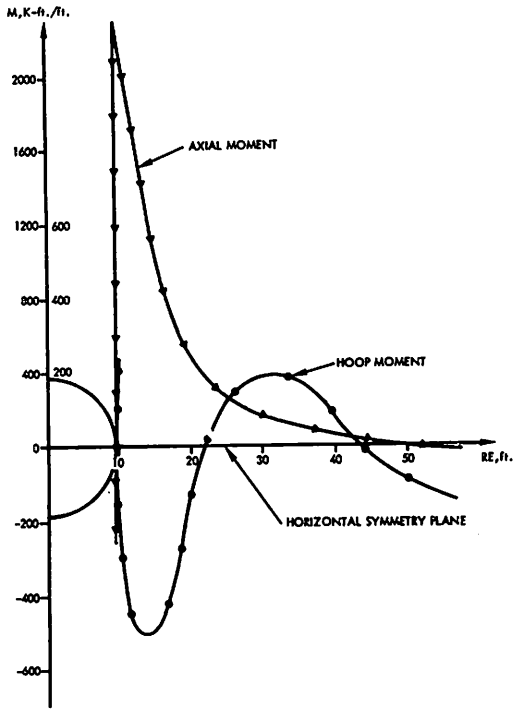


Figure 5 Moment Profiles at Horizontal Axis of Equipment Hatch

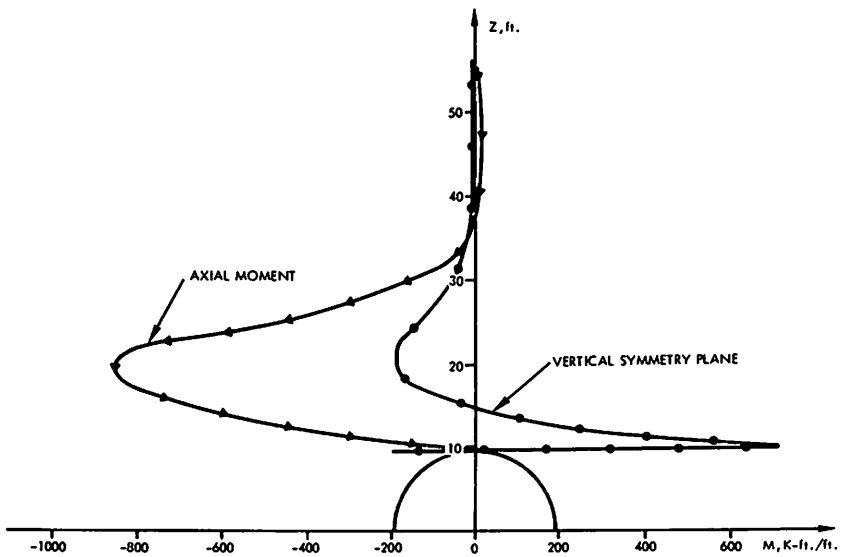


Figure 6 Moment Profiles at Vertical Axis of Equipment Hatch

hand it is made thick enough to produce a good quality weld. So far, a 1/4 inch thick liner has been used for all containment structures discussed here. The choice of carbon steel was dictated by the requirements of good weldability and high ductility so that local bending or yielding could occur without developing cracks in the liner.

Prestressing Anchorage Zones - Special considerations in the analysis of anchorage zones are concerned mainly with localized stresses in the concrete in the vicinity of the bearing plate which transfer the tendon prestressing force to the supporting structure. Detailed stress distribution in this area is obtained by numerical analysis. Figures 7 and 8 show, respectively, examples of isostress plots for minimum and maximum compressive stress, and maximum tensile stress at a typical horizontal segment of the buttress. These maximum stresses are usually caused by the combined effect of internal pressure and prestressing force. However, it should be noted that because of the large discrepancy between various theoretical solutions, also between the results of analysis and corresponding tests, a conservative amount of reinforcing steel is provided in these areas.

## 7. PROPORTIONING

Proportioning of the major components of the containment structure consists of determining the thickness of concrete, amount and location of prestressing tendons, amount and location of reinforcing steel and determining the thickness and anchorage details of the liner.

The base slab thickness is controlled by the maximum bending moment at the center of the slab or by the maximum vertical shear forces at the junction of the bottom slab and the cylinder. These critical moments and shears are generally caused by load combinations that include design accident pressure and associated temperature.

The cylindrical wall thickness is controlled by the average prestressing membrane force in the circumferential direction or by shielding requirements. In most cases, both of these factors require a wall thickness of about 3'-6". In some cases, the thickness is increased to about 3'-9" to satisfy strength requirements.

Shear reinforcement, in the radial direction relative to the axis of the cylinder, is required near the junction of the cylinder and the bottom slab and is generally controlled by seismic or accident pressure and associated temperature loads. Tensile reinforcement is provided at the outside face, both vertically and horizontally, to resist temperature stresses and to control cracking. Also, tensile reinforcement is provided in the vertical direction near the bottom and top ends of the cylinder.

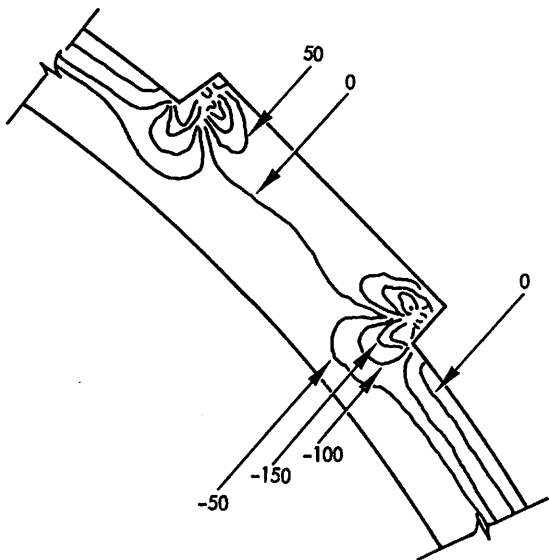


Figure 7

Iso-Stress Plots at Anchorage Zone Showing Maximum Tensile Stresses

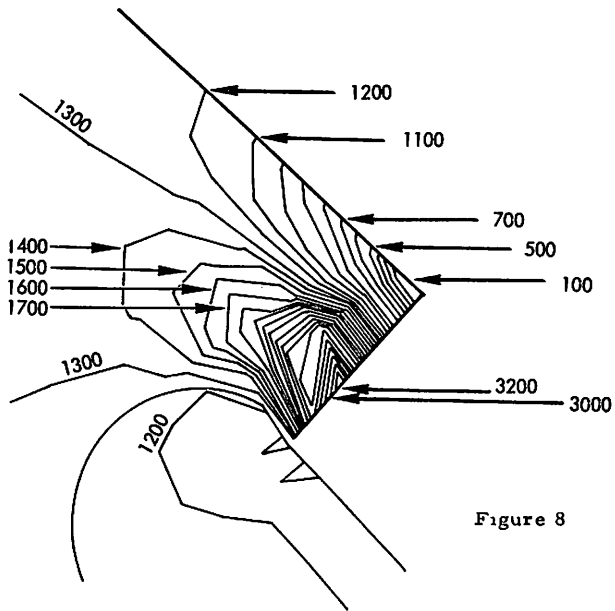


Figure 8

Iso-Stress Plots at Anchorage Zone Showing Maximum Compressive Stresses

This reinforcement is controlled generally by load combinations that include accident pressure and temperature or seismic loads.

The thickness of the dome is controlled by the average prestressing membrane force, which in the spherical portion is equal in both the circumferential and meridional directions. Shielding requirements at the dome are appreciably less significant than at the lower part of the cylinder. Also, the effects of seismic acceleration are negligible.

The reinforcing steel in the dome, away from discontinuities such as the ring girder, consists of a two-way layer near the outside face to resist thermal stresses and to control cracks.

In the case of the sphere-torus shaped dome a ring girder is necessary to resist discontinuity moments and shears and to provide anchorage for the dome tendons and the vertical tendons of the cylinder. In the case of the hemispherical dome, the transition is smooth except for minor discontinuity moments and shears caused by the relatively small but abrupt change in thickness at the junction of the cylinder and the dome. The selection of the dome configuration is controlled mainly by clearance requirements. The sphere-torus configuration is usually economical when the crane or other equipment requires that the spring line be close to the top of the structure; otherwise the hemispherical dome is more economical.

The amount of prestressing tendons in the cylinder and the dome is controlled basically by the magnitude of the minimum membrane prestressing force required to maintain the dome and cylinder in a general state of compression when subjected to the design accident. Allowances are made in the analysis for estimated concrete creep, tendon relaxation, earthquake overturning moment and stiffness of the steel liner.

## 8. STRUCTURAL TESTS

The structural test program associated with the design of the containment consisted of field tests of the full-scale structure to verify its integrity and several experimental analysis tests performed in the laboratory and the field to supplement the design effort. The most pertinent of the latter tests concern stress distribution at tendon anchorage zones, strain vs. load response of the liner and tests to verify the performance of the prestressing system.

The field test program consisted of taking strains, displacements and temperature measurements at a large number of points in the structure. These measurements were obtained during construction, prestressing and during the proof pressure test. Test devices used included strain gages, load cells, Carlson meters, displacement transducers, an optical system, thermocouples, a 500-channel automatic-scan data acquisition system and a 100-channel digital strain indicator.

A large number of strain gages was placed on reinforcing bars and on both sides of the liner. Several load cells were placed between the bearing plate and anchorage system of selected tendons. Carlson meters were placed in the concrete to measure temperature and strains. Displacement transducers were used to measure displacement of the inner face of the containment wall and a transit was used to measure displacements of the outside face. Thermocouples were embedded in the concrete near the outside and inside surfaces of the structure. The data acquisition system scanned and recorded test measurements at prescribed and close intervals during post-tensioning and during the proof pressure test.

The performance of the various types of test devices was verified respectively by calibration tests and other tests that simulated severe field conditions. Subsequently, the accuracy of the strain measurements was evident from the stable and consistent plots of strain time history profiles plotted for gages after installation in the structure.

Representative results of the test program are illustrated in Figures 9 through 14. Figures 9 and 10 show the response of the structure during and after prestressing. Figure 11 shows temperature and strain measurements over a period of approximately two years. Figure 12 shows the response during the pressure test. Figures 13 and 14 show profiles of test data and the corresponding values predicted earlier by analysis.

Comparison of these measurements with data obtained by analysis confirmed the expected structural behavior during the test and consequently verified that the design methods used were sufficient to proportion and specify the structure for its intended purpose.

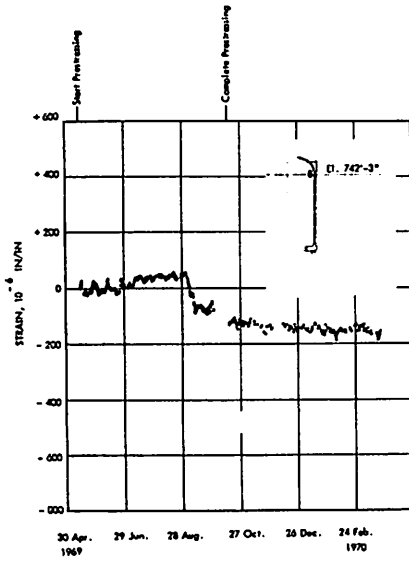


Figure 9  
Measured Strain at Elevation 742'-3"

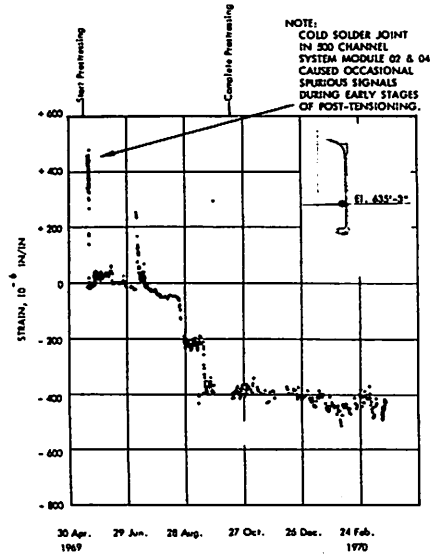


Figure 10  
Measured Strain at Elevation 635'-3"

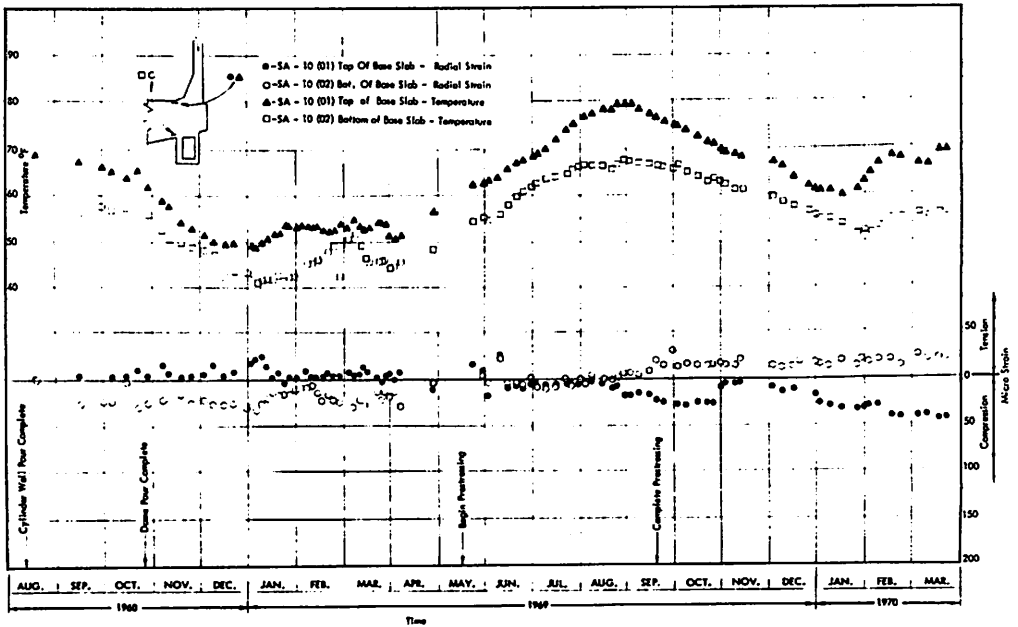


Figure 11 Measured Temperatures and Strains at Base Slab During Construction



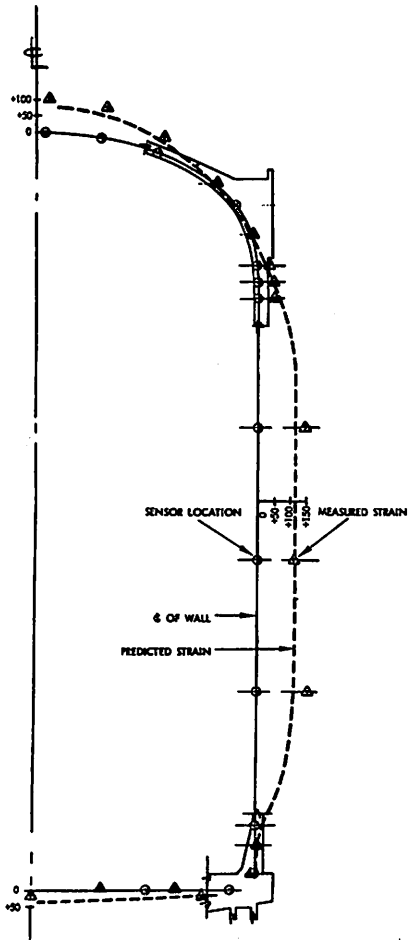


FIG. I3

Measured and Predicted Inside Hoop Strains  
Due to 1.15 Internal Design Pressure

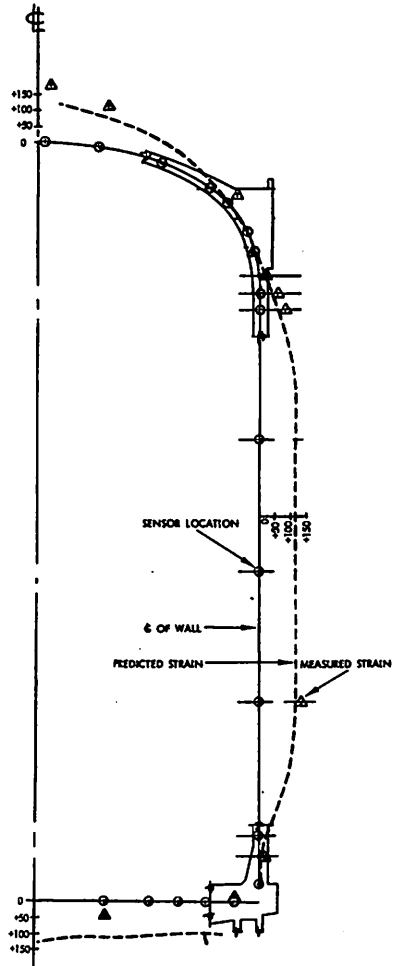


FIG. I4

Measured and Predicted Outside Hoop Strains  
Due to 1.15 Internal Design Pressure

DISCUSSION

P. KASSOVIC, France

**Q** Did you pay any attention to circumferential, daily and seasonal variation of temperature ?

R. S. BEKOWICH, U. S. A.

**A** Yes we did. Temperature variations were measured during post tensioning and during the proof pressure test. These values were correlated to strain measurements at a large number of locations on the structure. As a result it was possible to evaluate the effect of daily and seasonal variation in temperature.

N. N. KULKARNI, India

**Q** How does liner behave during progressive stressing ? How is it taken care of in the design ?

R. S. BEKOWICH, U. S. A.

**A** The liner is subjected to the strain occurring in the concrete which is generally a compressive strain except in some localized areas where bending is predominant. The most significant strain in the liner results from temperature associated with the "Design Basis Accident"; liner strain during prestressing is appreciably lower. The liner is designed to preclude buckling and to maintain elastic response during prestressing and during normal operating conditions.

W. F. MÜLLER, Germany

**Q** In which manner did you attach your liner ?

R. S. BEKOWICH, U. S. A.

The liner is attached to the concrete by an array of stiffeners welded to the liner and spaced at close intervals. During construction the liner acts as the inner form. Accordingly the concrete is poured directly around the stiffeners.

**Q** M. S. RAO, India

1. Was a steel liner considered absolutely necessary ? Could you not have considered alternative liners like Vinyl paints ? Have any experiments been conducted on leakage through concrete ? At what pressures is a steel liner considered necessary ?
2. It was mentioned that tendons were taken from the one end of the cylindrical shell then

over the hemispherical shell to the other end of the cylindrical shell. Does this not increase the frictional losses in the cables ? Could you terminate the cables at the junction of the cylindrical and hemispherical shells ?

**A**

R. S. BEKOWICH, U. S. A.

1. We have considered alternate liners. However, I am personally not aware of any alternate liners that provide the required leak integrity with the desired level of confidence and that are economically feasible. I don't know the pressure level above which a steel liner is considered necessary.
2. The disadvantage of increase in frictional loss is outweighed by the desirable features of reducing moments and shears at the junction of the dome and the cylinder and reducing construction costs.

Terminating the tendons at the junction of the dome and the cylinder would require a ring girder for anchoring the tendons which would increase construction costs.