5B Design Program for
Reactor Building

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APPENDIX 5B

DESIGN PROGRAM FOR REACTOR BUILDING

1. GENERAL

1.1 QUALIFICATIONS OF BECHTEL AND CONSULTANTS

Bechtel Corporation has a large staff of technically qualified engineers with experience in designing complex structures of high integrity. Bechtel participated in the early development of nuclear power plants; designed the first hardened ballistic missile facilities; was first to design and construct isocrackers for the refinery industry; and has designed and built ammonia plants in which the vessels operate at pressure exceeding 10,000 psi. In addition, Bechtel is engaged in designing and building thin arch dams, powerhouses and other large complex concrete structures in many locations in the world. Through broad, continuous exposure to all types of nuclear power plants and their structures, Bechtel has developed a thorough understanding of the design problems associated with the development of such plants.

For some time Bechtel has recognized the inherent advantages of using prestressed concrete for nuclear pressure vessels. Consequently, in-house feasibility and design studies of prestressed concrete reactor vessels and secondary containment vessels were undertaken. These studies included a thorough investigation of design techniques, available hardware, acceptable methods of construction and the application of a computerized stress analysis program. A specific study of a secondary containment vessel included the formulation of design criteria, detailed investigation of the problems associated with the liner plate, preliminary design of large openings in the shell, alternate methods of protecting the tendons from corrosion and anchorage details. Some of the engineers that carried out these studies are assigned to this project, and the remainder will be available for consultation and technical support.

Bechtel's demonstrated performance in large facility design and in the analysis and construction involving pressure containment in steel and concrete structures is of direct application to the Reactor Building.

The detailed design of this containment will be carried out by a Project Group with supplementary technical support furnished by the following staff specialists in the San Francisco offices:

Mr. D.R. Johnson of the Metallurgical and Welding Department, under the direction of Mr. G.B. Grable, will be assigned to follow the entire project. He will advise the design group and review all related designs and techniques and assist in the preparation of specifications and quality control and testing procedures.

Mr. D.E. Graham has a broad background in concrete technology and will participate in the preparation of concrete specifications, placement procedures and field quality control and testing programs.

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In addition to the project personnel and staff specialists, the following independent consultants were retained in the development of the design program for the Turkey Point and Palisades Plants. No significant changes in design concept, basic criteria, or technical specifications are contemplated for this project. Careful attention will be given to all site-adaptive and environmental factors and to the requirements of the particular PWR nuclear steam supply system selected for this station. This is not expected to result in any fundamental changes in the design parameters. However, wherever it should prove to be prudent, we again intend to utilize the assistance of these consultants to the full extent necessary.

T. Y. Lin, Kulka, Yang and Associates - Prestressed Concrete Consultant
G. W. Housner - Seismic and Structural Consultant
Edward L. Wilson - Shell Analysis Consultant

1.2 SIMILAR PRESTRESSED STRUCTURES

The following discussion and representative list of prestressed structures is given to indicate the proven adaptability of prestressing for pressure vessels of various requirements.

1.2.1 GENERAL VESSELS AND SHELLS

A large number of wire wound prestressed concrete water storage tanks have been built in this country in the past 20 years. More recently, a number of tanks and shells have been built using circular tendons terminating at buttresses. Some of these are listed in Table 5B-1.

1.2.2 SECONDARY REACTOR CONTAINMENT VESSELS

The El 4 Reactor Containment (Brennilis, France) is a leakproof enclosure in the form of a cylinder about 157.5 feet high and 151 feet inside diameter. The bottom is a flat slab 4 feet, 7 inches thick and the spherical dome has an inside radius of 115 feet. The overall height is therefore about 185 feet. It is designed for the following conditions:

Interal pressure - 8.1 psig
Temperature - 176° F (Hypothetical maximal accident temperature of 320° F)

The walls of the enclosure were designed so they will not crack at any pressure less than or equal to three times the nominal pressure or approximately 25 psig. The vessel is lined with 500 microns of coal-tar paint to maintain leak tightness. The cylinder is prestressed by vertical tendons and horizontal tendons. The horizontal tendons cover 90° segments and are anchored in vertical buttresses. The dome tendons are oriented in three groups, 120° apart. They follow the curvature of the dome and are anchored in the outside face of the ring girder at the edge of the dome. The tendons in the base slab consist of two groups oriented at 90°. They are anchored at the outside edges of the slab.

1.2.3 REACTOR PRESSURE VESSELS

Significant data for the most recent European prestressed reactor pressure vessels are listed in Table 5B-2.

2. DESIGN BASES

2.1 GENERAL

The Reactor Building will be designed by the working stress method and checked against the design loading combinations indicated in paragraph 2.2 Appendix 5A "Structural Design Bases". The design and the checking will be done in accordance with the following supplementary design bases.

2.1.1 PRESTRESSED CONCRETE

Sufficient prestressing will be provided in the cylindrical and dome portions of the building to eliminate membrane tensile stress (tensile stress across the entire wall thickness) and to limit flexural tensile stresses to the allowable values stated in the ACI Code 318-63 for the design load conditions. Bonded unprestressed reinforcing will be used wherever flexural tension is permitted.

Deviations in allowable concrete stresses for the design loading conditions in the working stress method will be permitted if the yield capacity criteria are fully satisfied.

Membrane tensile stresses will be permitted in developing the yield capacity of the structure for the factored loads in accordance with the structural design bases of Appendix 5A. Membrane tensile cracking will not be permitted in developing the yield capacity of the structure.

Flexural tensile stress cracking will be permitted but will be controlled by bonded unprestressed reinforcing steel. Flexural crack depth will be limited to permit the shear loads to be carried by the uncracked portion of the concrete cross section.

2.1.2 REINFORCED CONCRETE

No special design bases are required for the design and checking of the base slab. It will act primarily in bending rather than membrane stress. This condition is covered by the ACI Code 318-63.

2.2 LOADING CASES

The Reactor Building will be designed for the following specific loading cases.

1. D+F+L
2. D+F+L+W (or E)
3. D+F+L+P+T+W (or E)

Where -

D = Dead Load
L = Appropriate Live Load
F = Appropriate Prestressing Load (Varies With Time Between Initial and Final Prestress Loads)
P = Design Pressure
W = Wind Load
E = Seismic Load
T = Thermal Loads Based on a Temperature Corresponding to a Pressure P

2.2.1 DESIGN LOADS

The following design loads will be used in the structural design:

Maximum Design Pressure - ~~55~~ 29 Psig
Test Pressure - ~~63.3~~ [illegible] Psig
Live Loads - Applicable Loads Such as Roof Loads, Pipe Forces and the Reactor Service Crane
External Pressure - 2.5 Psig
Maximum Design Temperature - ~~281 F~~ 236
Wind Load - In Accordance with ASCE Paper No. 3269, "Wind Forces on Structure" Using the Fastest Mile of Wind Equals 95 Mph at 30 Feet
Seismic Ground Accelerations - 0.05g Horizontal and Vertical

The thermal loads on the Reactor Building walls and their variation with time will be determined from transient temperature gradients developed from the pressure time curve in Section 14 of the Preliminary SAR. It will be assumed that a 2 mil gap exists between the liner plate and the concrete for transmission of heat. This assumption will produce conservative heat loads within the structure.

The seismic loads are to be determined by the methods outlined in Appendix 5A.

3. DESIGN ANALYSIS

3.1 GENERAL

The Reactor Building analysis will be performed by the finite element method developed by E. L. Wilson under sponsorship of National Science Foundation Research Grant G18986. (Ref. 1) This program has been further developed to apply the axisymmetrical vessels. Such a method of analysis is normally used only for thick-walled structures where conventional shell analysis yields inaccurate results. Good correlation has been demonstrated between the finite element analysis method and the test results for thick wall model vessels. (Ref. 2)

Based on Bechtel's recent design study of prestressed concrete containment vessels, it has been substantiated that the main areas for design analysis are:

1. The restraints at the top and bottom of the cylinder.
2. The restraints at the edge of the spherical sector dome.
3. The stresses around the large penetrations.

4. The elastic behavior of the base slab.
5. The stresses due to transient temperature gradients in the liner plate and concrete.
6. Stresses within the ring girder.

The use of prestressing will prevent the cylinderical portion and dome of the vessel from developing any significant cracks at the design or test conditions. This continuity of the structure will ensure the predictability of the behavior of the vessel at locations such as the ring girder, openings and the cylinder to base slab joint.

3.2 ANALYSIS

The use of a finite element analysis will permit an accurate determination of the stress pattern at all discontinuities. The analysis method has been demonstrated on the following types of structures:

1. Arch dams (including a portion of the foundation).
2. Thick-walled prestressed concrete vessels.
3. Spacecraft heat shields.
4. Rocket Nozzles.

The computer program used in the analysis will handle the following inputs:

1. Seven different materials.
2. Nonlinear stress strain curves for each material.
3. Any shape transient temperature curves.
4. Any shape axisymmetrical loading.

The program outputs will be:

1. The direct stress and shear stress for each element.
2. The principal stresses and their directions for each element.
3. The deflections for each element.

An auxiliary computer program will plot stress curves based on the above analysis program outputs.

The finite element grid of the vessel base slab will be extended down into the foundation material to take into consideration the elastic nature of the foundation material and its effect upon the behavior of the base slab.

3.3 PRESTRESS LOSSES

In accordance with the ACI Code 318-63, the design will make allowances for the following prestress losses:

1. Seating of anchorage.
2. Elastic shortening of concrete
3. Creep of concrete.
4. Shrinkage of concrete
5. Relaxation of steel stress.
6. Frictional loss due to intended or unintended curvature in the tendons.

All of the above losses can be predicted within safe limits. The environment of the prestress system and concrete is not appreciably different in this case from that found in numerous bridge and building applications.

Considerable research (Ref. 3) has been done to evaluate the above items and is available to designers in assigning the allowances. Building code authorities consider it acceptable practice to develop permanent designs based on these allowances.

3.4 LINER PLATE

The liner plate will be designed to retain its integrity under design pressure and temperature conditions. The design will consider the thermal expansion forces, vessel restraint forces, pressure forces and the buckling stability of the liner plate.

3.5 BUILDING BEHAVIOR

The behavior of the building will be predicted and then monitored during the pressure tests. The use of prestressing will permit good control of the building deflections. Additional prestressing and concrete will be used at the large openings for the equipment hatch and for the personnel access if required in order to minimize differential deflections and strains of the shell at the openings relative to the main shell. Refer to Figure 5-3. Surface strains will be measured at selected discontinuities during the pressure test to substantiate the design predictions.

4. REACTOR BUILDING

4.1 GENERAL

The general configuration and dimensions of the Reactor Building are shown in Figure 1-9 through 1-14. The structure is a concrete vertical right cylinder with a flat base slab and a shallow domed roof, A ¼-inch thick welded steel liner is attached to the inside face of the concrete shell to insure a high degree of leak tightness.

3ft 4 3'3"

The ~~3-foo~~t, ~~6~~-inch thick cylinderical wall and ~~3-foo~~t thick dome are prestressed post-tensioned. The 8-foot, 6-inch thick concrete base slab is conventionally reinforced. Representative details are shown in Fig. 5-1.

4.2 PRESTRESSING

The configuration of the tendons in the dome (Figure 5-1) is based on a three-way tendon system consisting of three groups of tendons oriented at 120° with respect to each other. A large concrete ring girder is provided at the intersection of the dome and walls in order to develop sufficient horizontal restraint for the dome when subjected to the internal design pressure. The cylinder wall is provided with a system of vertical and horizontal tendons. Hoop tendons are placed in a 120° system in which three tendons form a complete ring. Six buttresses are used as anchorages with the tendons staggered so that a complete ring is formed from any one buttress.

Provisions are made to monitor stress development in representative tendons located in critical sections of the structures during the proof test.

4.3 POST TENSIONING SYSTEMS

There are a number of post-tensioning systems suited to containment vessels available in this country. The ultimate capacity of the wire or strand systems presently considered suitable for this containment varies from 494 kips to 987 kips. Listed below are pertinent features of some of these post-tensioning systems:

Manufacturer	Freyssinet	*Prescon Ryerson	Stress Steel (SEEE)
Designation	Wire Strand	Wires	Wire Strand
Ultimate Capacity	494 Kips	987 Kips	792 Kips
Design Capacity	296 Kips	592 Kips	468 Kips
End Anchorage	Open End, Male and Female Cone	Buttonhead	Swaged, Threaded Collar and Nut

*Prescon and Ryerson both market the Swiss BBRV systems.

All three of the above systems have been used in foreign prestressed concrete reactor vessels as well as domestic conventional structures. The design will permit the use of any system that meets the specified requirements.

The 12-0.5" Freyssinet system was used in the French containment vessel at Brennilis. A larger Freyssinet system of 12-0.6" seven-wire strands is being used for the prestressed reactor vessel at Wylfa, England.

Stress Steel is the U.S. licensee for the SEEE 19-0.5" strand system. The 0.5" strands are the same as used in the Freyssinet systems. The SEEE strand was used as the prestressing for the French EDF-3 and EDF-4 reactor vessels.

The tendons will be encased in rigid steel conduit. Corrosion protection will be provided by grease injected into the conduit under 100 psi pressure. Greasing has the advantage of slightly reducing the friction losses. Also, stress concentrations in the concrete are not transferred to the tendons because the tendons are not bonded to the concrete. Failure of any tendon during the test will be readily apparent by movement of the anchorage. Loss of the tendon would not impair the strength of the structure. It was estimated from the study vessel that three adjacent tendons could be lost without seriously impairing the strength of the structure. End anchorages will be given a protective coating and then covered with cast-in-place concrete after the initial testing and acceptance of the vessel.

The steel strand will conform to "Specifications for Uncoated Seven-Wire Stress-Relieved Strand for Prestressed Concrete," ASTM A-416 with a minimum ultimate strength of 250,000 psi or seven-wire 270 K strands with minimum ultimate strength of 270,000 psi. The minimum yield strength for all strands will not be less than 85% of the specified minimum breaking strength.

The prestressing wire used in the tendon will conform to "Specifications for Uncoated Stress-Relieved Wire for Prestressed Concrete," ASTM A-421.

Anchorages will develop 100% of guaranteed minimum ultimate strength of tendons.

4.4 REINFORCING STEEL

The principal reinforcing steel in the base slab will conform to "Specifications for Deformed Billet Steel Bars for Concrete Reinforcement With 60,000 psi Minimum Yield Strength," ASTM A-432.

Mild steel reinforcing conforming to "Specifications for Billet-Steel Bars for Concrete Reinforcement," ASTM A-15, deformed bars with bend and elongation properties of intermediate grade will be used in the cylinder wall, the domed roof and around the openings to control shrinkage and tensile cracks.

4.5 CONCRETE

All concrete work will be in accordance with ACI 301-66 "Specifications for Structural Concrete for Buildings" and ACI 318-63 "Building Code Requirements for Reinforced Concrete." The concrete for the Reactor Building walls and dome will have a minimum compressive strength of 5000 psi @ 28 days and the base slab ~~4000 psi~~ 5000 psi @ 90 days.

Portland Cement will conform to "Specifications for Portland Cement, "ASTM C-150, Type II, low heat cement.

Concrete aggregates will conform to "Specifications for Concrete Aggregates," ASTM C-33.

Maximum practical size aggregate, a low slump of 2 to 3 inches and additives will be used to minimize shrinkage and creep. Calcium chloride or an admixture containing calcium chloride will not be used.

4.6 LINER PLATE

The Reactor Building will be lined with ¼-inch thick welded steel plate conforming to ASTM A-36 to provide for a low leakage vessel. Minimum elongation of an A-36, 8-inch steel specimen at ultimate is 17.5% at room temperature.

The liner plate will have vertical anchors embedded in the concrete at an approximate spacing of 15-inches on center. See Fig. 5-1.

4.7 BUILDING PENETRATIONS

A reinforced concrete collar will be provided for handling of stresses at the equipment hatch. The additional concrete in the collar around the opening will reduce the concrete stresses to approximately equal those in the cylinder. Representative details of the collar are shown in Fig. 5-3.

Mild steel reinforcing will be provided around the piping and electrical penetrations. The location of these penetrations will be coordinated with the spacing of the tendons to minimize tendon deflections and stress concentrations.

5. INSPECTION AND TESTING

5.1 INSPECTION PROGRAM DURING CONSTRUCTION

5.1.1 GENERAL

Specifications and working drawings for materials and installation will be of such scope and detail to assure that the quality of work will be commensurate with the desired integrity of the reactor building.

5.1.2 CONCRETE

The testing of concrete will be the responsibility of Duke's Construction Department, (for its experience record, see Section 5.6.1.1.1 of main body of report). A full program of ASTM or ACI tests of aggregate, cement, mixes, and resulting strengths will be conducted. A full time inspector, who has had wide experience in concrete work, will continuously check the batching and placing of concrete.

5.1.3 PRESTRESS REINFORCING

Mill test reports will be obtained for the prestress wire. These reports will be certified statements from the mill showing that the material has the specified composition and properties. Field inspection will ensure that there are no visible mechanical or metallurgical notches or pits on the tendon material. A length of ~~strand or~~ wire from each reel will be tested to failure. Stress-strain curves will be plotted and the yield and tensile strengths verified. In addition, five assemblies will be made up with tendons and anchorages as they would be for final installation and they will be tested to failure. The anchorages will demonstrate the ability to develop at least the guaranteed minimum ultimate strength of the tendon material. All conduits for prestress tendons will be checked in place for integrity, alignment and position in the forms. The stress in the tendon will be determined by measuring the tendon elongation during jacking and also by either checking the jack pressure on a recently calibrated gauge or by the use of a recently calibrated load cell. The cause of any discrepancy which exceeds 5% will be ascertained and corrected.

5.1.4 REINFORCING STEEL

Mill test results will be obtained from the reinforcing steel supplier for each heat of steel to show proof that the reinforcing steel has the specified composition, strength and ductility.

The concrete inspector will check the condition and placement of the bars in the forms. Splicing of large bars where required will be by welding or approved mechanical splices such as Cadweld. Welding of reinforcing steel, if required, will be performed by qualified welders. Wherever the integrity of the containment is dependent upon such welding, the welds will be inspected by an appropriate nondestructive method.

5.1.5 LINER PLATE

Mill test results will be obtained for the liner plate material. The plate will be visually checked for thickness, possible laminations and pitting. Welding procedures and qualification of welders will be in accordance with ASME Boiler and Pressure Vessel Code, Section IX. Ten percent of all welds will be inspected by an appropriate nondestructive method.

5.1.6 PENETRATION ASSEMBLIES

Penetration material, welding, testing and inspection will conform to the requirements of ASME Boiler and Pressure Vessel Code, Section III.

5.2 QUALIFICATIONS AND AUTHORITY OF INSPECTORS

Qualified field supervisory personnel and inspectors will be assigned to the project to carry out the work in accordance with the specifications and drawings. Project design personnel will make frequent visits to the jobsite to coordinate the construction with the design. Inspectors will be experienced and thoroughly familiar with the type of work to be inspected, particularly in the field of prestressed concrete. The inspector will perform such examinations as are necessary to satisfy himself that the standards set forth in the applicable codes and specifications have been met.

Where work does not satisfy the standards, he will have the authority to stop work until the necessary alterations are made.

5.3 INSTRUMENTATION FOR COLLECTING DATA DURING TESTING

Refer to Appendix 5F, Reactor Building Instrumentation.

Strain gauges will be installed at strategic points in or on the Reactor Building to continuously monitor stress development during the pressure proof test. Other methods of measuring and recording stresses and strains will be investigated for use in conjunction with strain gauges.

The actual position and coverage of the instruments will be determined during the final design. The stress in a representative number of tendons, the stress in the liner plate, and the compression or cracking of the concrete will be measured and compared with values predicted from the final structural analysis.

Particularly, stresses and strains at critical sections, such as at the ring girder, cylinder base, and at large penetrations will be measured.

After the location of the strain measuring instruments has been determined, the expected stresses and strains will be calculated from the structural analysis of the vessel for each instrument with respect to its position and orientation. An acceptance tolerance will be placed on the values according to the sensitivity of the instrument and accuracy of analytical prediction.

Although the prestressed concrete system will be designed for no tension on the net section, there will be some cracking due to bending in combination with axial loads. This cracking will be due to tensile stresses permitted by the ACI code. The crack pattern will be predicted at major points of discontinuity such as at the access penetrations and criteria established prior to testing for comparison with the observed conditions.

TABLE 5B-1

GENERAL VESSELS AND SHELLS

	Capacity in Gallons	Dimensions	Year Completed
St. Louis Planetarium Dome Ring Girder St. Louis, Missouri		160' Dia	1961
Missile Silo Dome Ring Girder Ellsworth Air Force Base		108' Dia	1961
Clearwater Storage Reservoir Lakewood, Colorado	1,900,000	127' Dia 21' High	1961
Cate Reservoir Pico Rivera, California	1,250,000		1958
Brighton Water Tank Brighton, Colorado	1,000,000		1957
South Adams County Reservoir Derby, Colorado	1,000,000		1955
Elevated Water Storage Tank Conical Tank Supported on Cylinderical Tower Orebro, Sweden	2,400,000	150' Dia 160' From Grade to Water Surface	1958

TABLE 5B-2

PRESTRESSED CONCRETE VESSELS FOR GAS-COOLED REACTORS

Name	EDF3	EDF4	Oldbury	Wylfa
Country	France	France	England	England
Reactor Thermal Power (Mw)	1560	1560	834	1875
Part Enclosed in Vessel	Core	Primary System	Primary System	Primary System
Completion Date of Vessel	1965	1966	1965	1967
Coolant Pressure (Atm)	30	30	27	28.3
Coolant Temperature (^{o}C)	240 - 410	225 - 400	245 - 410	247 - 414
Boiler Location	Outside Vessel	Below Core	Around Core	Around Core
Outside Vessel Shape	Parallel Piped	Right Hexagonal Prism	Cylindrical	5 Concentric Right Cylinders, 16 Vertical Ribs
Outside Dimensions (Ft)	90 x 90, 104 High	93 (Top), 101 (Bot), 160 High	90, 104 High	117 Minimum
Inside Dimensions (Ft)	Dia. 62, Ht69	Dia. 62, Ht. 119	Dia. 77, Ht. 60	Diameter 96
Prestressing Tendons	8720	5146	3520 Helical Cables (Alt) + Horiz. System	Two Vertical Systems & External Hoop Tendons
Cable Protection	Cement Grouting	Cement Grouting	Ungrouted	Ungrouted
Maximum Concrete Temperature (^{o}F)	167	158 Avg, 176 Max	131 - 140 (Floor)	95 Avg, 113 Max

REFERENCES

1. Structural Analysis of Axisymmetric Solids, Wilson, E.L., AIAA Journal, Volume 3, No. 12, December 1965.

2. The Use of Models in Prestressed Concrete Reactor Vessel Design, Marsh, R.O. and Rockenhauser, W., ASCE Structural Engineering Conference Preprint 306, January 31 - February 4, 1966.

3. State of the Art of Prestressed Concrete Pressure Vessels in Nuclear Power Reactors, A Critical Review of the Literature, The Franklin Institute, ORNL-TM-812.