Integrated Reactor Building/Containment Design of a Simplified Boiling Water Reactor (SBWR) Plant

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INTRODUCTION

The majority of containments designed for light water reactors utilize forced containment cooling systems and rely upon active systems to bring containment pressures and temperatures down after a postulated Loss of Coolant Accident (LOCA). Studies have been conducted by General Electric, Bechtel and M.I.T. and Foster Wheeler supported by EPRI, U.S. DOE and JAPC at various times towards the development of advanced light water reactor concepts for possible application in the 1990's. The SBWR, a 600 MWe boiling water reactor, uses a Passive Containment Cooling System (PCCS) which removes heat across the containment boundary by natural convection and evaporation. Use of this and other improvements allow the elimination of safety grade diesel generators, reactor core cooling pumps, heat removal pumps, etc., thus simplifying the plant design and reducing plant cost. Due to the use of passive containment cooling, the SBWR containment structure will be subjected to internal pressures and higher temperatures for a longer period of time than most of the existing containment designs.

The containment for the SBWR is a reinforced concrete structure with a steel liner plate for leaktightness. Gravity is relied upon for reactor core cooling and containment cooling therefore, the suppression pool and refill pools are located at high elevations. The containment is integrated with the reactor building which provides lateral stability.

The main objective of the integrated reactor building/containment design study described herein was to demonstrate the structural design feasibility of the containment for the pressure and temperature responses associated with the PCCS adopted for the SBWR. The design was evaluated for severe accident conditions and ultimate pressure capability.

GENERAL DESCRIPTION OF THE CONTAINMENT AND REACTOR BUILDING

The analysis and design of the SBWR containment is based on the configuration shown in Figure 1. The structure consists of three concentric cylinders on a common basemat with interconnected partition slabs at various elevations. The structure is primarily reinforced concrete construction except for the upper-drywell wall, which is composite steel and concrete construction consisting of two steel cylindrical plates interconnected with radial vertical stiffener plates. The upper drywell wall contains embedded vent pipes connecting the upper drywell to the wetwell.

The drywell top slab supports the reactor well and fuel pools. Fuel pool girders on the drywell top slab provide support to resist containment accident pressure loads. The suppression pool contains a group of PCCS pipe modules for heat removal. Each pipe module is anchored in the suppression pool ceiling slab and is connected to the refill pool above.

DESIGN CRITERIA

The containment structure is designed in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Div. 2, Subsection CC, 1986 edition including the 1988 addenda. The design is based on a peak horizontal ground acceleration of 0.3g (SSE) with a response spectra per the US NRC Regulatory Guide 1.60. The seismic analysis for this feasibility study was based on a fixed base, lumped mass analysis without considering soil structure interaction or embedment effects.

The containment temperature and pressure conditions for normal, testing, LOCA, and severe accident conditions considered in the design study are shown in Table 1. Hydrodynamic loads have not been considered since they are not postulated to be coincident with the peak pressure/temperature which occurs 72 hours after the LOCA or the postulated severe accident conditions. Temperatures greater than 150F are postulated to last a longer period of time after a LOCA or postulated severe accident conditions in the SBWR. Degradation of material properties is expected and therefore temperature dependent material properties are considered in the analysis and design.

High temperature concrete properties based on Reference 1 were used. The design compressive strength of 4000 psi (f_c') concrete was assumed to reduce to 2500 psi at a temperature of 400F.

The reinforcing steel (ASTM A615 Grade 60) with a yield strength of 60 ksi at room temperature was assumed to reduce to a yield strength of 50 ksi at 400F. Similarly, structural steel plates and the containment liner plate (SA516 Grade 70) with a yield strength of 38.0 ksi at room temperature was assumed to reduce to a yield strength of 32.6 ksi at 400F.

ANALYSIS AND DESIGN

The reactor building and containment are analyzed as an idealized axisymmetric integral structure. The FINEL computer program (Reference 3) was used to perform the analysis and design. FINEL was selected for its cost effectiveness and its capability to include non-linear behavior due to cracking of concrete and yielding of reinforcing steel. FINEL also takes into account temperature dependent material properties.

Figure 2 shows the FINEL finite element model which includes foundation soil, concrete, reinforcing steel, the containment steel liner plate, and the composite concrete and steel wall separating the drywell from the wetwell. The region of the containment top slab and fuel pool girders are not axisymmetric and therefore could not be accurately represented in this model. They were analyzed separately.

The FINEL model consists of a total of 998 nodal points and 1757 elements. There are 891 elements with unidirectional stiffness representing rebar with remaining 866 isotropic elements representing steel, concrete, and the soil.

The thermal distribution analysis to determine the temperature gradients through the walls and floors for LOCA and severe accident conditions was performed using the computer program ME643 (Reference 4).

FINEL gives the results in terms of section resultant forces, stresses and strains in various structural elements due to loads and loading combinations involving axisymmetric loads. The stresses and strains for loading combinations involving non-axisymmetric loads, such as seismic loads, were determined using the CECAP computer program (Reference 5). The analysis and design of the drywell top slab and the supporting fuel pool girders were based on hand calculations. The calculations were performed to determine the ultimate capacity of the containment.

The design required rebar density was determined to be highest in the suppression pool outer wall. The reinforcement consisted of 2-#18@1^{o} (0.62%) on each face in the meridional direction and 2-#18@8" (1.27%) on each face in the hoop direction.

DESIGN EVALUATION FOR SEVERE ACCIDENT/ULTIMATE PRESSURE CAPACITY

A severe accident peak pressure of 110 psig was specified in the design criteria associated with the thermal condition at 72 hours after the postulated accident.

The highest stresses were found in the suppression pool outer wall with meridional and hoop rebar in the outer face being 50.6 ksi and 44.2 ksi, respectively due to the 110 psig severe accident pressure. Stresses in the rebar on the inner face of the wall are quite low; -4.8 ksi and 10.2 ksi in the meridional and hoop directions, respectively. As the internal containment pressure is increased above 110 psig, the outer curtain rebar starts yielding and the inner rebar starts picking up more and more load. At a pressure of 220 psig (i.e., 4 X design pressure), the stresses in the inner curtain of the rebar increase to 8.2 ksi and 39.4 ksi in the meridional and hoop rebar, respectively. The hoop stresses in the liner change from -13.0 ksi (compression) to +20.0 ksi (tension) as pressure is increased from 110 psig to 220 psig. Figure 2 shows the plots of the radial displacements. The displacements at mid-height on the outer wall increase from 1.42 to 2.367 inches as pressure is increased from 110 psig to 220 psig. The liner strain reaches approximately 0.005 in/in at 220 psig pressure, which is still within the code allowable limits. The drywell top slab was found to have a much lower ultimate pressure capacity. The top slab, edge beam, and the fuel pool girders can carry the accident pressure of 110 psig, but soon reach their shear strength capacity as the containment internal pressure is increased.

CONCLUSIONS

The following conclusions are drawn based on this analysis and design study of the SBWR integrated reactor building/containment structure:

o Containment design based on ASME Section III Division 2, is feasible for the SBWR integrated configuration with the postulated pressure/temperature loading conditions. The results of the analysis indicate that the effect of high temperature on the material properties does not appear to have a significant influence on the ultimate capacity of the containment.

o The containment, as designed for LOCA conditions, can withstand a severe accident pressure of 110 psig together with associated temperatures, without yielding of the reinforcing steel.

o The cylindrical portions and floor slabs of the containment, other than the drywell top slab and the fuel pool girders, can withstand pressures up to 220 psig, i.e., 4 times the design pressure, with reinforcing steel yielding in the outer curtains of the wetwell wall. The highest strains in the liner plate were calculated to be about 5 times the yield strain in the portion of the wetwell wall near the drywell top slab. Since the drywell top slab and the fuel pool girders are non-axisymmetric and cannot be modeled adequately using the FINEL program, the estimated liner strains need to be further refined based on a more detailed analytical model of this region.

- o The drywell top slab and fuel pool girder assembly has an ultimate pressure capacity of about 120 psig and is limited by the shear capacity of the fuel pool girders.

- o Modifications to the present design should be made to increase the pressure load resistance capability of the drywell top slab and the fuel pool girders. Such modification would improve the uniformity of structural strength, resulting in a well-balanced design.

ACKNOWLEDGEMENT

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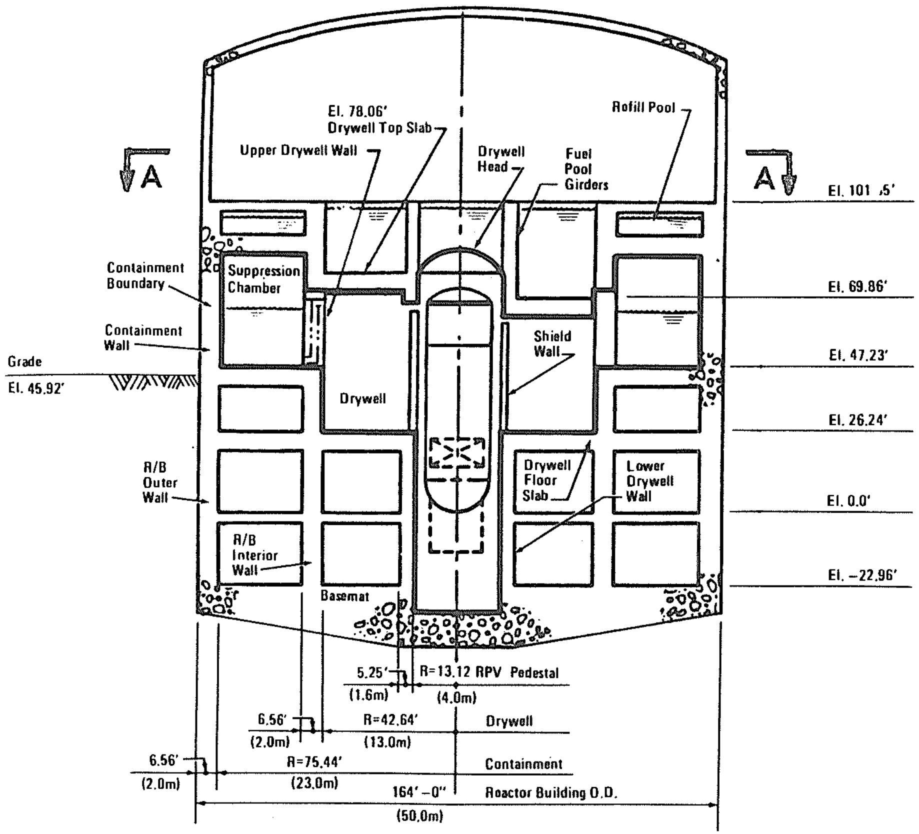
3. FINEL "Finite Element Program for Cracking Analysis: User/Theoretical Manual" Bechtel Power Corporation, San Francisco, 1986

4. ME643 "Thermal and Stress Analysis Program: Users/Theoretical Manual" Bechtel Power Corporation, San Francisco, 1987

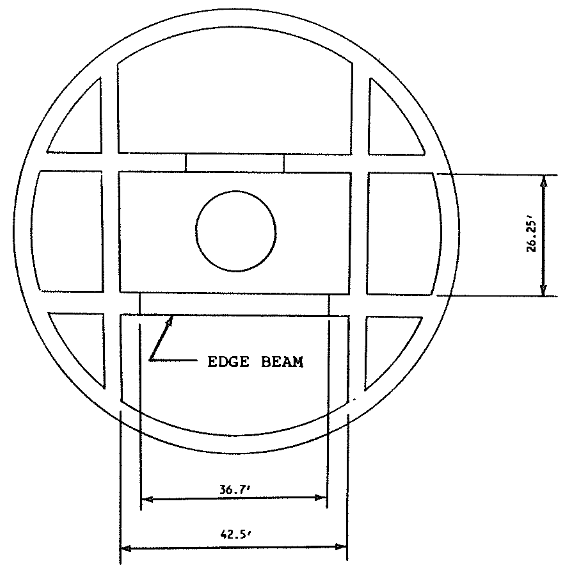
5. CECAP "Concrete Element Cracking Analysis Program: Users/Theoretical Manual" Bechtel Power Corporation, San Francisco, 1988

TABLE 1

Condition	Pressure (psid)		Temperature (^oF) (See Figure 1)					
	Drywell	Wetwell	Drywell	Wetwell	T_R	T_E	T_S	T_{RP}
Test	63.3	63.3	60	60	60	60	60	60
Operating			135	80	80	40	60	80
LOCA (at 72 hrs)	55	55	303	260	80	40	60	215
Severe Accident (at 72 hrs)	110	110	320	320	80	40	60	215



ELEVATION VIEW



SECTION A-A

FIGURE 1
REACTOR BUILDING / CONTAINMENT
ARRANGEMENT

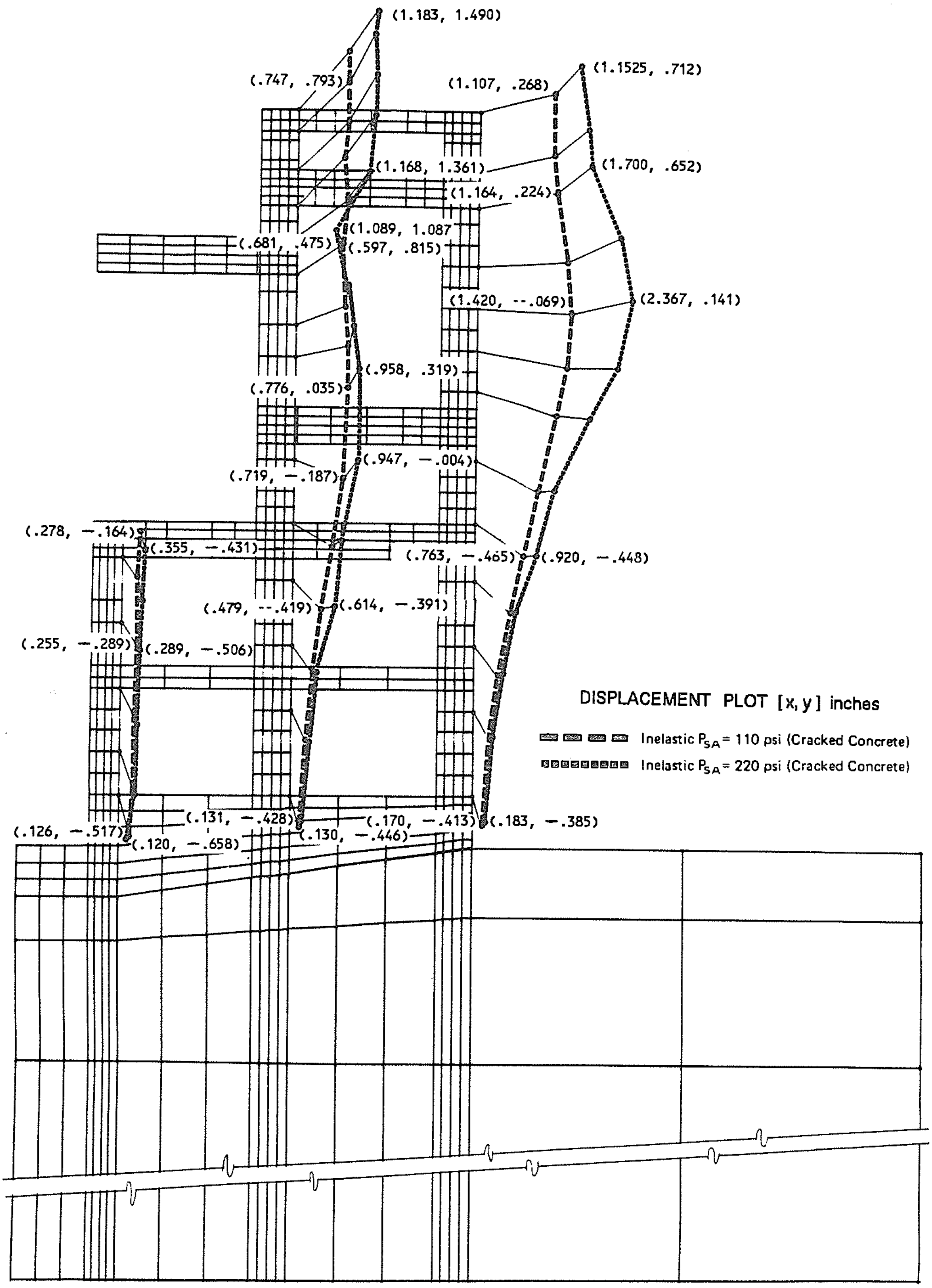


FIGURE 2

FINEL MODEL &
DISPLACEMENT PLOTS