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SUMMARY AND CONCLUSIONS

This paper summarizes results of a study by Stone & Webster Engineering Corporation (SWEC) of the structural capacity of the Surry Nuclear Power Station reactor containment building. In this study an analysis was conducted to determine the minimum pressure required to produce yielding stresses in all load resisting elements, the location in the pressure boundary where such yielding would first occur, and the effects of changes in liner temperature on the response of the containment to pressurization. This paper discusses the design bases, details of construction, inherent conservatisms of the containment, and the Structural Acceptance Test. It describes the SWEC analysis; presents an abridgment of the results; and makes certain observations based on those results. The paper shows that Nuclear Regulatory Commission design criteria and standard design practice combine to guarantee a minimum yield capacity for a large dry pressurized water reactor concrete containment of at least twice the design pressure loading. Containment response at penetrations and at the junction of the wall and the foundation mat are also described. The study led to the following conclusions:

- The minimum theoretical yield capacity of the Surry containment is 119 psig. The design pressure is 45 psig. First tensile yielding of the reinforcement and liner would occur in the hoop direction in free membrane zones of the wall at locations away from structural discontinuities.

- The inside hoop reinforcing bars would be the first structural elements to yield provided there is no significant temperature differential through the concrete wall. The liner would be the last element to yield.

- Liner temperature changes affect strains in the liner and reinforcement, radial displacement of the pressure boundary, and widths of cracks in the concrete. Temperature change also affects the pressure at which the reinforcement would begin to yield.

- Liner temperature changes do not affect the full yield capacity of the wall over the range of temperatures considered.

- Cracks would not form in the liner under loss of coolant accident (LOCA) conditions because the liner would be in a state of biaxial compression.

- The liner is not likely to crack at full yield capacity because the liner material is very ductile and the most severe liner strains, which occur at penetrations, are only slightly greater than the yield strain.

DESCRIPTION OF SURRY CONTAINMENT

The containment analyzed is a right cylinder with a hemispherical dome. The cylinder is outfitted with an equipment hatch, a personnel hatch, and numerous penetrations for piping, electrical conduits, and instrumentation leads. The cylinder has an inside diameter of 126.0 ft and a wall thickness of 4.5 ft; the dome is 2.5 ft thick. A 10 ft thick foundation mat supports the structure. Concrete design is based on a minimum compressive strength of 3.0 ksi.

The concrete in the cylinder and dome is reinforced with continuous 2.25 in. diameter (No. 18S) steel reinforcing bars arrayed in the meridional and hoop directions. Supplemental reinforcing steel was installed around all penetrations to account for stress concentrations. Heavy reinforcement was provided at the junction of the cylinder wall and the foundation mat to control flexure and shear at this discontinuity. The cylinder also contains tangential/diagonal reinforcement designed to resist earthquake forces. The foundation mat is reinforced with 2.25 in. diameter reinforcing steel in radial and circumferential arrays at the top and in a rectilinear pattern at the bottom. Reinforcement is ASTM A408 Grade 50 with a minimum yield-strength of 50 ksi. Reinforcing steel was proportioned using the ultimate strength design (USD) method with combinations of various factored loads. These loads include the pressure (45.0 psig) and temperature (280°F) effects caused by a postulated LOCA, earthquake force, internal and external missiles, tornado wind, pipe rupture forces, and working loads. The largest single demand for strength in the pressure boundary comes from application of the LOCA pressure, which was factored by 1.5.

The containment is fully lined throughout with 0.375 in. thick steel plate in the cylinder, 0.5 in. plate in the dome, and 0.25 in. plate covering the foundation mat. All liner welds are leaktight and shrouded with steel test channels. Liner steel is ASTM 516 Grade 60 with a minimum yield strength of 32 ksi.

It was a licensing requirement that no credit be allowed for the load carrying capacity of the liner. It also was a requirement that the capacity of cracked concrete to resist earthquake forces be ignored, so the

tangential/diagonal reinforcing steel had to be designed to withstand all of the earthquake shear force.

Note that only specified minimum yield strengths were used in the Surry design and in this study. However, actual yield strengths of reinforcing and liner steels are typically 10 percent higher than their minimum specified strengths. Production concrete strengths are typically 20 to 30 percent higher than specified design strengths.

In addition to the above conservatisms in the design basis, construction efficiency in placing reinforcement at the top of the foundation mat and around penetrations dictated spacing of the bars that resulted in approximately 10 percent excess reinforcement. The safety provisions of the USD method specify that strengths must be computed using material capacity reduction factors, which provide another conservatism.

All of these conservatisms contribute to the overall strength of the containment. As material strengths greater than the specified minimum were not included in the SWEC analysis, the results of that analysis are conservative.

ANALYSIS AND RESULTS

The SWEC analysis established shell behavior in the hoop and meridional directions in terms of liner and reinforcement stresses and strains, under various combinations of incremental pressures (P) and changes in liner temperature (ΔT), between P = 45 psig and 100°F ΔT, and P = 120 psig and 325°F ΔT. The analysis is based on the assumption of full compatibility between the liner and the reinforced concrete. Calculations were terminated at the latter point, with the reinforcement at approximately two times yield strain. Radial displacement of the cylinder wall under this condition would be approximately 2.5 in. The SWEC analysis did not examine the behavior of the containment at the ultimate (tensile) capacity of the reinforcement because the containment would have to expand several feet before ultimate stress and strain could be reached.

The method used to perform this analysis also was used to calculate strains and deflections under structural acceptance test conditions -- 52 psig and ΔT = 0°F. Analytical results were approximately 15 percent greater than observed values of liner strain and radial deflection. It is believed that the difference is due to the stiffness of the concrete blocks on the reinforcing between the cracks. Extrapolation of test results and further analysis indicate that observed and calculated values would be approximately the same at pressures above 65 psig.

Table 1 presents an abridgment of the stress and strain analysis results for the cylinder wall reinforcement and liner in the hoop direction in the free membrane zone, 65 ft above the foundation mat. Table 2 presents a similar abridgment for the meridional direction at the same location. Review of Tables 1 and 2 leads to the following observations:

- For any given ΔT, the reinforcement and the liner will yield at a lower pressure in the hoop direction than in the meridional direction.

- The liner can yield in compression in either the hoop or meridional direction because of the effect of temperature change.

- For $\Delta T = 200°F$, a change which could be associated with a LOCA, the liner remains in compression in the hoop direction until pressure reaches approximately 78 psig. The liner is the last load carrying element to reach tensile yielding strain, which occurs at 119 psig.

- Changes in liner temperature affect the strains in the liner and reinforcement, and the pressure at which the reinforcement begins to yield.

- Changes in liner temperature do not affect the full yield capacity of the containment.

An approximate but conservative analysis was made to evaluate stress and strain in the 1.0 in. thick liner plate and welds that secure the 8 in. diameter schedule 40 electrical penetrations. The analysis considered pressures from 100 to 120 psig and temperature changes from 100 to 325°F ΔT. It was determined that, as an upper bound, liner strains will not exceed three times general liner yielding strains. Therefore, the pressure boundary will remain intact at the penetrations over the range of pressures and temperatures changes considered in this analysis.

The thick, reinforced concrete (boss) around the equipment hatch was not included in this analysis. However, the boss is a very rigid inclusion in the membrane field of the containment wall. Because it is much stiffer than the membrane, cracks in the concrete in the hatch should be narrower than those in the free field.

Bounding calculations show that the connection between the wall and foundation mat is capable of withstanding 120 psig. The formation of a plastic hinge at this location, at a pressure which is well below the yield capacity of the containment, would prevent development of a shear force sufficient to cause the radial shear reinforcement to yield. Therefore, it is reasonable to presume that a gross shear slip would not occur and that the integrity of the liner would be maintained.

Liner strains measured during the structural acceptance test were very uniform except at penetrations. This indicates that the bond between the liner and the concrete was broken as the structure was strained during pressurization.

Concrete cracks which formed during the structural acceptance test, having essentially closed after depressurization, will open during any subsequent pressurization. Typical vertical cracks in the cylinder wall are spaced at approximately 2 ft. At test pressure, 52 psig, these cracks were observed to open to approximately 0.01 in.

TABLE 1

CONTAINMENT MEMBRANE BEHAVIOR IN THE HOOP DIRECTION AT VARIOUS PRESSURES AND LINER TEMPERATURE CHANGES*

Pressure (psig)	Strain (ε_{IH})** and Stress (δ_{LH})***					
	ΔT 150°F		ΔT 200°F		ΔT 325°F	
	ε_{IH}	δ_{LH}	ε_{IH}	δ_{LH}	ε_{IH}	δ_{LH}
45	8.20×10^{-4}	-5.1	8.86×10^{-4}	-12.8	0.00105	-32.0
50	8.89×10^{-4}	-3.1	9.55×10^{-4}	-10.8	0.00112	-30.1
60	0.00103	1.0	0.00109	-6.8	0.00126	-26.1
70	0.00117	5.0	0.00123	-2.70	0.00140	-22.1
80	0.00130	9.1	0.00137	1.3	0.00154	-18.0
90	0.00144	13.1	0.00151	5.4	0.00167	-14.0
95	0.00151	15.1	0.00158	7.4	0.00175	-11.7
100	0.00158	16.7	0.00165	8.6	0.00195	-6.0
105	0.00165	18.6	0.00172	10.4	0.00229	4.1
110	0.00172	20.1	0.00181	14.7	0.00264	14.2
114	0.00180	23.4	0.00208	22.2	0.00291	22.2
118	0.00203	30.3	0.00236	30.3	0.00319	30.3
119	0.00210	32.0	0.00243	32.0	0.00326	32.0

Radial Deflection at Liner Yield (in.)

ΔT 150°F	ΔT 200°F	ΔT 325°F
1.59	1.84	2.46

NOTES:

*Assumes $E = 29 \times 10^6$ psi and $\alpha = 6.67 \times 10^{-6}$ (in./in.)/°F. Neither E or α were adjusted for temperature change.

**ε_{IH} = hoop strain inside hoop reinforcing bars (in./in.)

***δ_{LH} = hoop stress, liner (kips/in.^{2})

TABLE 2

CONTAINMENT MEMBRANE BEHAVIOR IN THE MERIDIONAL DIRECTION AT VARIOUS PRESSURES AND LINER TEMPERATURE CHANGES*

Pressure (psig)	Strain (ε)** and Stress (δ_{LM})***					
	ΔT 150°F		ΔT 200°F		ΔT 325°F	
	ε	δ_{LM}	ε	δ_{LM}	ε	δ_{LM}
45	6.02×10^{-4}	-11.6	7.01×10^{-4}	-18.4	8.99×10^{-4}	-32.0
50	6.52×10^{-4}	-10.1	7.51×10^{-4}	-16.9	9.70×10^{-4}	-32.0
60	7.52×10^{-4}	-7.2	8.51×10^{-4}	-14.0	0.00110	-31.0
70	8.51×10^{-4}	-4.3	9.50×10^{-4}	-11.1	0.00120	-28.1
80	9.51×10^{-4}	-1.4	0.00105	-8.2	0.00130	-25.2
90	0.00105	1.4	0.00115	-5.3	0.00140	-22.3
95	0.00110	2.9	0.00120	-3.9	0.00145	-20.8
100	0.00115	4.3	0.00125	-2.4	0.00150	-19.4
105	0.00120	5.8	0.00130	1.0	0.00155	-17.9
110	0.00125	7.2	0.00135	0.5	0.00160	-16.5
114	0.00129	8.4	0.00139	1.6	0.00164	-15.3
118	0.00133	9.6	0.00143	2.8	0.00168	-14.1
119	0.00134	9.8	0.00144	3.1	0.00169	-13.9

NOTES:

*Assumes $E = 29 \times 10^6$ psi and $\alpha = 6.67 \times 10^{-6}$ (in./in.)/°F. Neither E or α were adjusted for temperature change.

**ε = Meridional strain on all components (in./in.).

***δ_{LM} = Meridional stress, liner (kips/in.^{2})