5C Design Criteria for
Reactor Building

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APPENDIX 5C

DESIGN CRITERIA FOR PRESTRESSED

CONCRETE REACTOR BUILDING

1. GENERAL

Safety of the vessel under extraordinary circumstances and proper performance of the reactor building at various loading stages are the main considerations in establishing of these criteria.

The two basic criteria are: 1) the integrity of the liner plate will be guaranteed under all loading conditions, and 2) the building will have a low-strain elastic response such that its behavior may be completely predictable under the required loadings. The strength of the building at working stress and over-all yielding will be equated to various combinations of loadings to insure safety. Proper performance of the building will be examined with respect to strength, the nature and the amount of cracking of concrete, the magnitude of deformations, as well as corrosion. The building will be designed and analyzed to meet performance and strength requirements under the following conditions:

a. Prior to prestressing.

b. At transfer of prestress.

c. Under sustained prestress.

d. At design loads.

e. At yield loads.

Appendix 5A, "Structural Design Bases", applies to all plant structures. This Appendix refers specifically to the reactor building to supplement the information in Appendix 5A. All design will be in accordance with the ACI Code 318-63 unless otherwise stated herein.

2. DESIGN APPROACH

The building will be analyzed by a finite element computer program for individual loading cases of dead load, live load, temperature and pressure. The program will output direct stresses, shear stresses, principal stresses and deflections at each element.

Stress plots will be made summing the stresses from required combinations of loading cases and areas of high stress will be identified. The modulus of elasticity at these locations will be modified to account for the non-linear stress-strain relationship at high compression and to account for cracking of concrete in areas of high tension. The building will then be reanalyzed by the computer if there are sufficient areas which require attention.

The forces and shears will be summed over the cross section and the total moment, axial force and shear will be determined. From these values, the straight-line elastic stresses will be computed and compared with the allowable values. The ACI code design methods and allowable stresses will be used for concrete and prestressed and non-prestressed reinforcing steel except as noted in these criteria.

At all loading stages a 1/3 increase in concrete compressive stresses for local concentrations of stress will be allowed. These high local stresses are present in every structure but they are seldom identified because of the simplifications made in the design analysis. High stress found in the non-linear stress plots will not be subjected to the same limitations (code values) which are imposed on those resulting from normal methods of analysis.

3. LOADING STAGES

3.1 PRIOR TO PRESTRESSING

Under this condition the building will be designed as a conventionally reinforced concrete structure. It will be designed for dead load, live loads (including construction loads) and a reduced wind load. Allowable stresses will be according to ACI-318-63 Code.

3.2 AT TRANSFER OF PRESTRESS

The reactor building will be checked for prestress loads and the stresses compared with the ACI-318-63 Code allowables with the following exceptions: ACI-318-63, Chapter 26 allows concrete stress of 0.60 f'_c at initial transfer. In order to limit creep deformations, the membrane compression stress will be limited to 0.30 f'_c, whereas in combination with flexural compression the maximum allowable stress will be limited to 0.60 f'_c per the ACI Code.

For local stress concentrations as predicted by the finite element analysis with non-linear stress distribution, 0.75 f'_c will be permitted when local reinforcing is designed to distribute and control these localized strains. Membrane tension will not be permitted under this loading condition but flexural tension will be permitted provided it does not jeopardize the integrity of the liner plate. When the flexural tensile stress exists, the section will be designed in accordance with Section 2605 of the ACI Code.

Stresses due to shrinkage, creep and elastic shortening of concrete will be taken into account, and flexural creep tending to relieve bending stresses will also be considered. Shear criteria will be in accordance with the ACI-318-63 Code, Chapter 26.

3.3 UNDER SUSTAINED PRESTRESS

The conditions for design and the allowable stresses for this case will be the same as shown in paragraph 3.2, except that the allowable tensile stress in non-prestressed reinforcing will be limited to 0.5 fy. The ACI limits the concrete compression to 0.45 f'_c for sustained prestress load. We are using values of 0.30 f'_c and 0.60 f'_c as described in paragraph 3.2, which bracket the ACI allowable value. However, with these same limits for concrete stress at transfer of prestress, the stresses under sustained load will be reduced due to creep.

3.4 AT DESIGN LOADS

This loading case is the basic "working stress" design. Under the design loads which include dead loads in combination with accident pressure loads and temperature, including the temperature effects on the liner, the same performance limits stated in 3.3 will apply with the following exceptions:

a. If the net membrane compression is below 100 psi it will be neglected and a cracked section will be assumed in the computation of flexural non-prestressed reinforcing steel. Flexural tensile stresses in non-prestressed reinforcing of 0.5 fy will be allowed.

b. When the maximum flexural stress does not exceed $6\sqrt{f'_c}$ and the extent of the tension zone is no more than 1/3 the depth of the section, non-prestressed reinforcing steel will be provided to carry the entire tension in the tension block. Otherwise, the non-prestressed reinforcing steel will be designed assuming a cracked section.

c. The problem of shear and diagonal tension in a prestressed concrete structure should be considered in two parts: membrane principal tension and flexural principal tension.

   Under the action of wind and earthquake, horizontal forces producing shear in the plane of the shell will result in diagonal or principal tensile stresses (membrane principal tension). Membrane principal tension is not critical at transfer or design loads and will be checked for the yield load conditions only. At design loads the membrane principal tension will be controlled by limiting the allowable shear stress to $1.5\sqrt{f'_c}$, which takes into account a 1/3 increase for earthquake or wind over the $1.1\sqrt{f'_c}$ value allowed by the ACI Code Chapter 12. For shear stress exceeding $1.5\sqrt{f'_c}$ non-prestressed reinforcement will be provided so that the component in the direction of principal tension will carry the excess tensile force within the allowable stress of the reinforcement of 0.5 fy.

   Flexural principal tension is the tension associated with secondary bending in planes perpendicular to the surface of the shell and shear stresses normal to the shell. At design loads the section will be under slight membrane compression stress. The present ACI Code provisions for shear as a measure of diagonal or principal tension are adequate for either of these cases. For the case of zero membrane stress to 100 psi membrane compressive stress the provisions of ACI Code Chapter 12 will apply. For the case of membrane compressive stress above 100 psi the provisions of Chapter 26 will apply.

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3.5 AT YIELD LOADS

The building will be checked for the factored loads and load combinations given in Appendix 5A, and compared with the yield strength of the structure. The yield strength of the structure is defined for our design, as the upper limit of elastic behavior of the effective load carrying structural materials. For steels, (both prestressed and non-prestressed) this limit is considered to be the guaranteed minimum yield given in the appropriate ASTM specification. For concrete, the yield strength is limited by the ultimate value of bond per ACI-318-63, and the 28 day ultimate compressive strength for concrete in flexure (f'_c), and limits on the principal tension stresses as stated below.

The maximum strain will be held to that corresponding to ultimate stress (f'_c) and a straight-line distribution from there to the neutral axis assumed. For concrete membrane compression, the "yield" strength will be assumed as 0.85 f'_c to allow for local irregularities, in accordance with the ACI approach. The reinforcing steel forming part of the load carrying system will be allowed to go only to yield except as noted in following sections.

The yield capacity of all load carrying structural elements will be reduced by a capacity reduction factor (Ø) as stated in the basic structural design criteria. This factor will provide for "the possibility that small adverse variations in material strengths, workmanship, dimensions, control, and degree of supervision while individually within required tolerances and the limits of good practice, occasionally may combine to result in under-capacity" (refer ACI-318-63 Code, p. 66 - footnote).

A further definition of "yielding" is that deformation of the structure which will not cause strains in the steel liner plate to exceed 0.005 in./in. The yielding of non-prestressed reinforcing steel will be allowed, either in tension or compression, if the above restrictions are not violated. Yielding of the prestress tendons will not be allowed under any circumstances.

Principal concrete tension due to combined membrane tension and membrane shear, excluding flexural tension due to bending moments or thermal gradients, will be limited to $\cancel{3\sqrt{f'_c}}$ $3\sqrt{f'_c}$. Principal concrete tension due to combined membrane tension, membrane shear, and flexural tension due to bending moments or thermal gradients will be limited to $\cancel{6\sqrt{f'_c}}$. When the principal concrete tension exceeds the limit of $\cancel{6\sqrt{f'_c}}$ $6\sqrt{f'_c}$, bonded reinforcing steel will be provided in the following manner:

a. Thermal flexural tension - Bonded reinforcing steel will be provided in accordance with the methods of ACI-505. The minimum area of steel provided will be 0.15 per cent in each direction.

b. Bending moment tension - Sufficient bonded reinforcing steel will be provided to resist the moment on the basis of cracked section theory using the yield stresses stated above with the following exception: When the bending moment tension is additive to the thermal tension, the allowable tensile stress in the reinforcing steel will be fy minus the stress in reinforcing due to the thermal gradient as determined in accordance with the methods of ACI-505.

Shear stress limits and shear reinforcing for radial shear will be in accordance with Chapter 26 of ACI 318 with the following exceptions:

1. Formula 26-12 of the code shall be replaced by

$$V_{ci} = K_{\triangle v} \ bd\sqrt{f'_c} + \frac{M_{cr}}{\frac{M}{V} - \frac{d}{2}} + V_d \qquad (1)$$

Where: $M_{cr} = \frac{I}{y}\,(6\sqrt{f'_c} + f_{pe} - f_d)$

$K_{\triangle v} = (1.75 - \frac{0.036}{np} + 4.0\ np)$ but not less than 0.6

fpe = Compressive stress in concrete due to prestress only, after all losses, (including the stress due to any secondary moment) at the extreme fiber of the section at which tension stresses are set up due to applied loads.

M = bending moment due to externally applied loads excluding secondary moment due to prestress.

V = shear force due to externally applied loads including secondary shear due to prestress.

2. Formula 26-13 of the code shall be replaced by

$$V_{cw} = 3.5\ b'd\ \sqrt{f'_c}\left(\sqrt{1 + \frac{fpc}{3.5\sqrt{f'_c}}}\right) + V_p \qquad (2)$$

Where V_p = Radial shear component of effective prestress due to curvature of tendon, at the section considered. All other notations are in accordance with Chapter 26 ACI-318.

(1) This formula is based on the recent tests and work done by Dr. A. H. Mattock of the University of Washington.

(2) This formula is based on the commentary for Proposed Redraft of Section 2610 - ACI-318 by Dr. A. H. Mattock, dated December 1962.