SEISMIC QUALIFICATION REPORT FOR VERTICAL HOLD-UP TANKS AT THE R. E. GINNA PLANT

Prepared for

ROCHESTER GAS & ELECTRIC COMPANY
89 East Avenue
Rochester, New York

September 1983

Prepared by

STEVENSON & ASSOCIATES
458 Boston Street
Topsfield, Massachusetts

CERTIFICATION

The undersigned, a registered Professional Engineer, competent in the field of component stress analysis, certifies that to the best of his knowledge and belief the analysis calculations for the subject tanks as presented in this seismic stress report comply with the provisions of the applicable portions of the ASME Boiler and Pressure Vessel Code, Section III. Nuclear Power Plant Components and standard acceptable engineering practice.

Components: Vertical Hold-up Tanks
Plant: R. E. Ginna

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SEISMIC QUALIFICATION REPORT FOR

VERTICAL HOLD-UP TANKS

AT THE R. E. GINNA PLANT

Revision 0, September 1983

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1. INTRODUCTION

The ability of hold-up tanks to withstand dead weight, internal pressure, and SSE seismic force is investigated in this evaluation.

The hold-up tanks are vertical thin cylindrical shells with spherical heads. There are three identical units located at the ground level. Each tank is welded to the support skirt which is anchored to the concrete mat through eight (8) bolts equally spaced around the base ring. Each hold-up tank is classified as an ASME III, Class C, storage tank with a design pressure of 15 psi. The total volume of a tank is 4,165 ft^3.

Figure 1 shows sketches of a hold-up tank and the skirt support. The Appendix attached to the end of the report contains the analytical calculations for the hold-up tanks.

Analysis is made assuming the tank is full of water with a total weight of water of 265 kips and a total weight of steel of 16.7 kips.

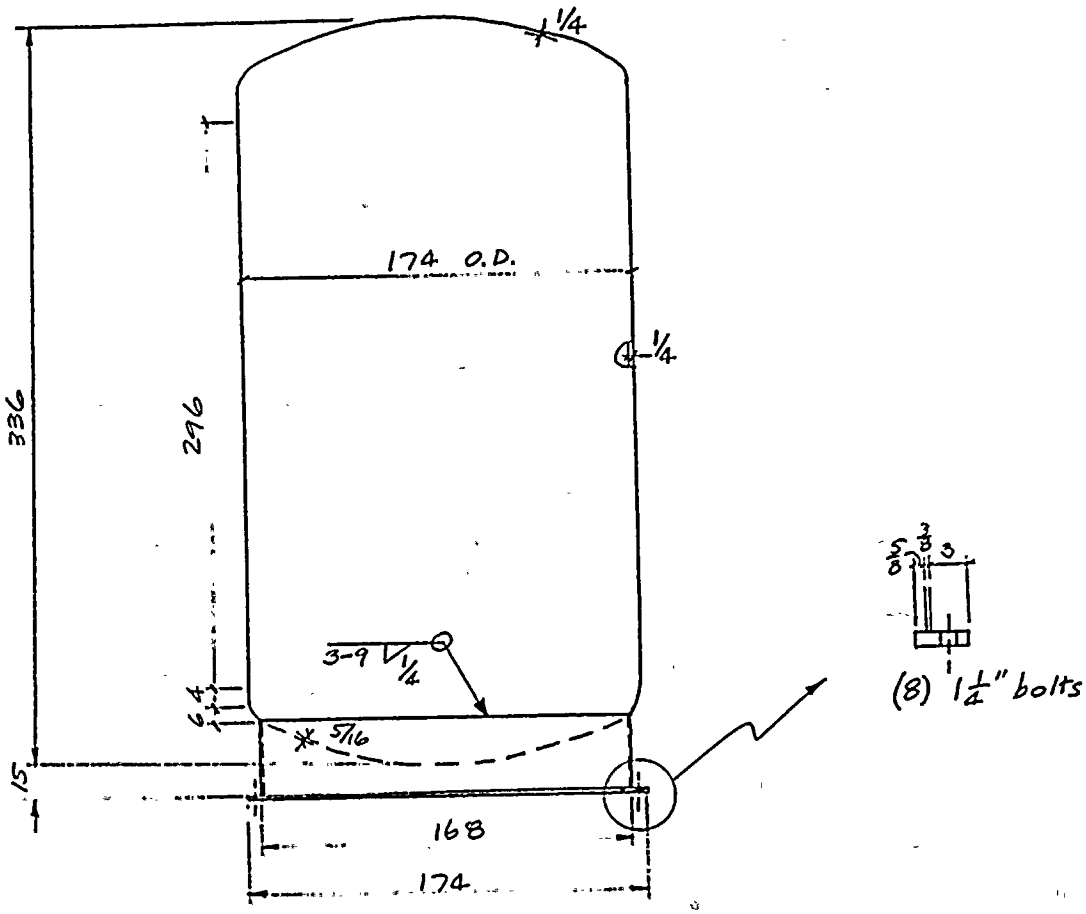

FIGURE 1
ELEVATION VIEW OF VERTICAL HOLD-UP TANK

2. RESULTS

The results of the analysis indicate that all parts of the hold-up tanks resist the combination of the dead weight, pressure, and faulted seismic load within acceptance criteria.

Results of the dynamic modal response are summarized in Table 1. The components of the hold-up tanks were checked for stresses due to dead weight, pressure, and seismic forces shown in Table 1. Table 2 summarizes the results of stress analysis.

The minimum factor of safety in the shell was found to be 3.56 for the maximum principal stress calculated for the prescribed loadings. The minimum factor of safety in the skirt support is 2.13 for the skirt-tank welding. The analysis indicated that the anchor bolt stress due to dead weight was greater than uplift caused by horizontal seismic excitation; thus, there is no tension developed in the anchor bolts.

MODES	CONVECTIVE MODE	IMPULSIVE MODES		VERTICAL MODE
		MODE 1	RIGID MODE	
Frequency (Hz)	0.45	10.5	-	15.2
Spectral Acceleration (g)	0.12	0.247	0.17	0.145
Base Shear (k)	4.1	50.5	11.4	-
Base Moment (k-in)	1200	10000	180	-

TABLE 1 MODAL RESPONSES

COMPONENT	MAXIMUM STRESS (ksi)	ALLOWABLE STRESS (ksi)	MINIMUM SAFETY FACTOR
TANK WALL			
Material Stress	10.0	35.6	3.56
Axial Compression	1.8	28.4	15.8
Shear	0.76	13.2	17.4
SKIRT SHELL			
Material Stress	2.76	36	13.0
Axial Compression	2.66	33.6	12.6
Shear	0.53	25.3	47.7
BASE RING			
Bending Stress	11.5	39.6	3.44
Skirt-Tank Welding	16.9	36	2.13

TABLE 2 CALCULATED MAXIMUM STRESSES AND ALLOWABLE STRESSES AT VARIOUS LOCATIONS

3. LOAD CRITERIA AND FAILURE MODE ASSUMPTIONS

Analysis loads for the hold-up tank consist of the dead weight of the tank and content, pressure, and seismic loads in two horizontal and the vertical directions. The seismic loads are defined by the site specific ground response spectrum for R. E. Ginna as specified by the USNRC [1] for a ZPA of 0.17g. Figure 2 shows the response spectrum curve. The full spectrum was used for the horizontal analysis. Two thirds of the full spectrum was used for the vertical analysis.

A damping value of 7% was used for the first impulsive mode consistent with the Systematic Evaluation Program for Seismic Review of R. E. Ginna [2]. A damping level of 0.5% was used for the convective (fluid) response analysis as suggested in Reference 3.

Failure modes considered in this evaluation include:

- tank wall yielding
- tank wall buckling
- skirt shell yielding
- skirt shell buckling
- base ring bending
- failure of skirt-tank welding

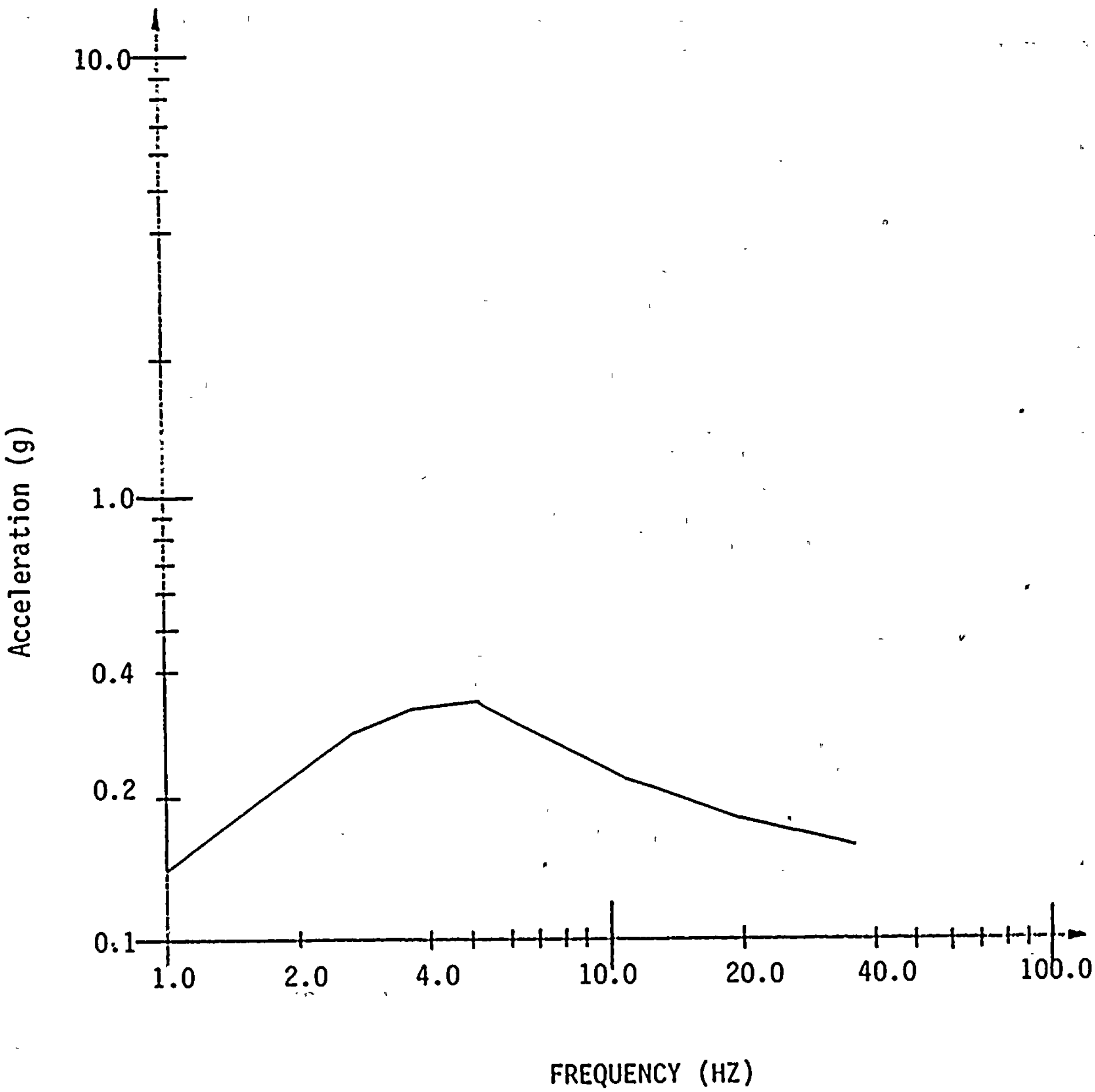

FIGURE 2
USNRC SITE SPECIFIC GROUND RESPONSE
SPECTRUM FOR R. E. GINNA (7% DAMPING)

4. ALLOWABLE STRESS CRITERIA

Allowable stress criteria used in this analysis are based on ASME code, Section III, Division I [4], Subsections NC and NF; and for shell buckling, the criteria developed in Reference 5. They are summarized as follows:

For the tank wall yielding,

$$\sigma_m \leqslant 2S,$$

where σ_m = maximum principal stress
S = allowable stress from Ref. 4, Table I-7.2

For skirt material yielding,

$$F_t = 1.2\ S_y,$$
$$F_b = 1.1\ F_t,$$

where F_t = allowable tensile stress,
F_b = allowable bending stress,
S_y = material yield stress at temperature.

For welding,

Allowable Stress = 2S,

where S = allowable stress obtained from Ref. 4, Table NF-3292 1-1.

For tank wall buckling in bending,

$$\text{Allowable Stress} = (0.605\gamma + \Delta\gamma)\ \frac{Et}{R}\ ,$$

where E = material Young's modulus at temperature,
t = thickness of cylindrical shell,
R = radius of cylinder,

$$\gamma = 1\text{-}0.731\ (1\text{-exp}\ (-\frac{1}{16}\sqrt{\frac{R}{t}})),$$

$\Delta\gamma$ = pressurization effect (see Ref. 5).

For skirt shell buckling in axial compression, the same equation as for tank wall was used except,

$$\gamma = 1\text{-}0.901\ (1\text{-exp}\ (-\frac{1}{16}\sqrt{\frac{R}{t}}))\ ,$$

and $\Delta\gamma$ = 0.

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For tank wall buckling in shear,

$$\text{Allowable Stress} = (1+\bar{P})^{\frac{1}{2}} \tau_{cr}$$

where $$\tau_{cr} = \frac{0.63E}{\left(\frac{L}{R}\right)^{0.5} \frac{R}{t}^{1.25}}$$

$\bar{P}$ = pressure effect (see Ref. 5)
L = length of shell

For skirt shell buckling in shear, the theoretical lower bound for an infinitely long strip with simply supported edges in shear [6] with a "knock-down" factor of 0.84 was used as follows,

$$\text{Allowable Stress} = 4.5 \frac{\pi^2 E t^2}{12(1-\nu^2)b^2}$$

where ν = Poisson's ratio
b = height of skirt

5. METHOD OF ANALYSIS

The dynamic response analysis procedure and charts developed in Reference 7 are adopted in this evaluation. Response parameters, such as frequency, participation factor, participating mass, and moment arm were read directly from charts. The sloshing effect was also incorporated. Since the charts were developed for flat bottom tanks, the space below the hold-up tanks surrounded by the skirt shell was conservatively assumed to be full of water.

6. REFERENCES

1. USNRC Letter LS05-81-06-068, "Site Specific Ground Response Spectra for SEP Plants Located in the Eastern United States," June 17, 1981.

2. Murray, R. C., et al, "Seismic Review of the Robert E. Ginna Nuclear Power Plant as Part of the Systematic Evaluation Program," NUREG/CR-1821, p. 85, November 1980.

3. Coates, D. W., "Recommended Revisions to Nuclear Regulatory Commission Siesmic Design Criteria," NUREG/CR-1161, pp. 114-120, May 1980.

4. ASME, Boiler and Pressure Vessel Code, Section III, Division I, 1980.

5. Stevenson & Associates, "Seismic Qualification Report for the Refueling Water Storage Tank at the R. E. Ginna Plant," August 1983.

6. Timoshenko, S. P. and Gere, J. M., "Theory of Elastic Stability," Second Edition, McGraw-Hill, p. 383, 1961.

7. Haroun, M. A. and Housner, G. W. , "Seismic Design of Liquid Storage Tanks," Journal of the Technical Council of ASCE, Vol. 107, No. TCI, pp. 191-207, April 1981.

APPENDIX A

ANALYTICAL CALCULATIONS

SYSTEM Vertical Hold-up Tank

COMPONENT NAME Vert. Hold-up Tank COMPONENT Nº N/A

LOCATION Auxiliary Building ELEVATION 236'

COMPONENT SAFETY FUNCTION: ACTIVE ☐ PASSIVE 1 ☐ 2 ☒

S-LIST PAGE Nº N/A

METHOD OF ANALYSIS: Analytical Stress Analysis

SPECTRAL CURVES USED: R.E. Ginna Site Specific Ground Response Spectra (see 83C2209-DR-005, File 3)

DAMPING VALUE ASSUMED: 7%

ACCEPTANCE BEHAVIOR CRITERIA USED:

ASME B&PV Code, Section III, 1980.

COMPUTER CODE USED: N/A

REMARKS:

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Introduction

The ability of the three vertical holdup tanks to withstand dead weight, internal pressure and seismic force is investigated in this evaluation.

Analysis loads consists of full weight of the tank and the fluid content, internal pressure, and seismic force as specified in USNRC letter LS05-81-06-068, "Site Specific Ground Response Spectra for SEP Plants Located in the Eastern United States," June 17, 1981, for R.E. GINNA. Sloshing effect under seismic event is also considered.

The dynamic response analysis follows the requirements of NUREG/CR-1161. The charts developed by Haroun and Housner (1981) are used to predict the horizontal seismic response. According to NUREG/CR-1821 (p.85), a composite damping of 7% is used in the analysis. For the convective horizontal response, rigid tank

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assumption is made using a damping level of 0.5%.

The acceptance criteria are based on the following:

1. Tank wall material stresses: the axial, hoop, and shear stresses developed in the tank wall are compared to material allowables per ASME code NC-3900

2. Skirt base material stresses: The stresses developed in the skirt shell, base ring, and weldments are compared to material allowables calculated per ASME code NF-3300.

3. Tank wall and skirt shell buckling: The stresses developed in tank wall and skirt shell that have the potential for buckling are compared with the criteria developed in the RWST report.

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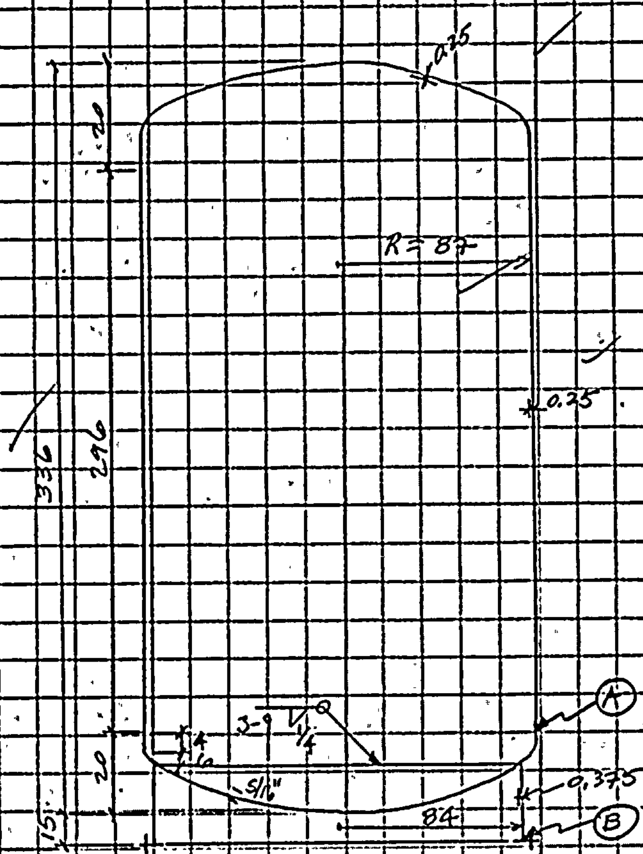

Holdup Tanks

Design conditions:

ASME III class C

Volume 4165 ft³

Pressure 15 psig

Temperature 200 °F

Tank Material 304 SS

Specific Gravity of Fluid 1.02

Skirt material A-283-58 Gr. C

$$\rho_s = \frac{490}{1728\,(386.4)} = 0.000734 \text{ lb-sec}^2/\text{in}^4$$

$E = 27700$ ksi (ASME III Appendix Table I-6.0)

for both tank and skirt

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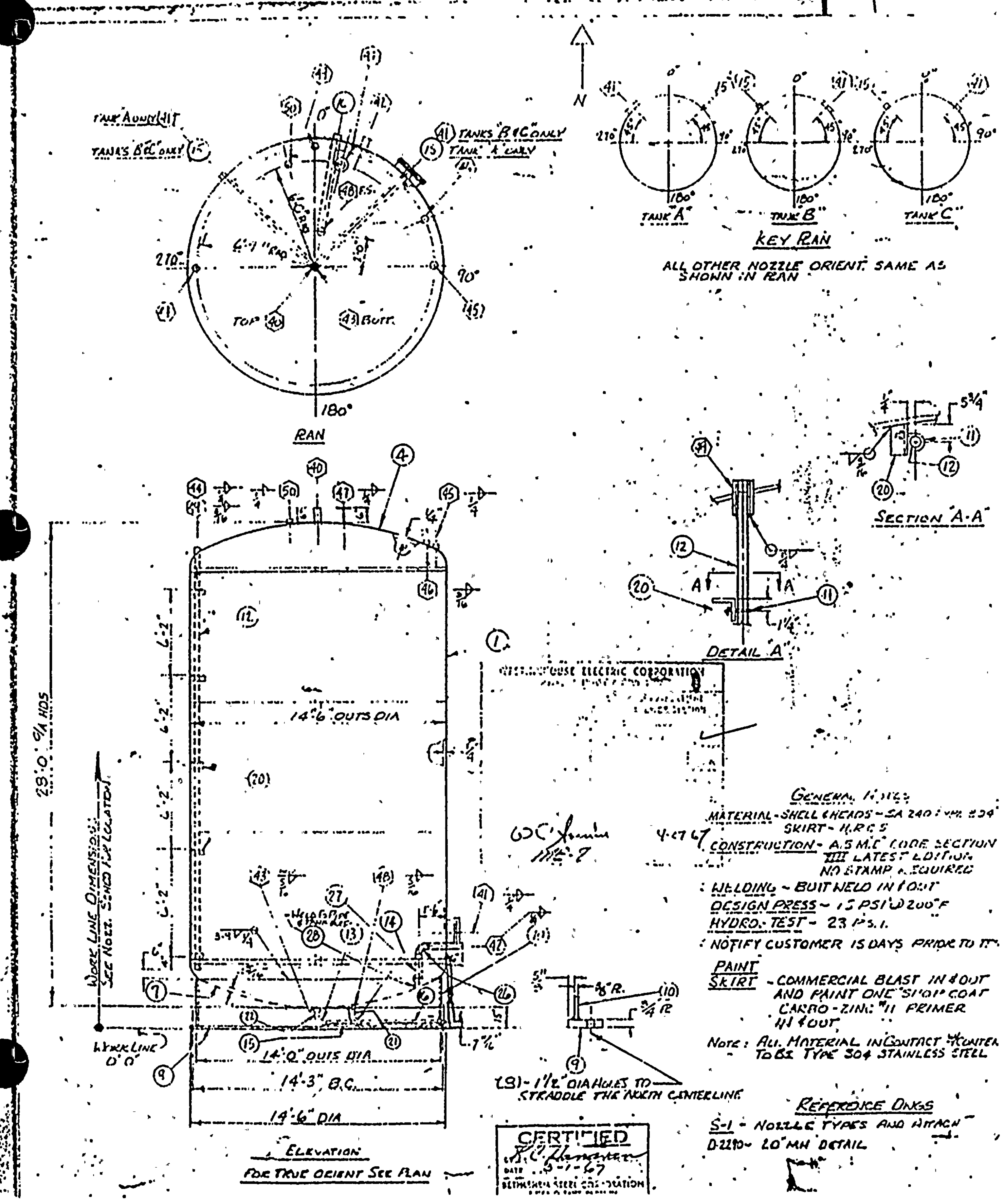

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Total weight of water

$= 1.02 \times 62.4 \times 4165 / 1000 = \underline{265}$ kips

Steel weight

Tank wall $\frac{490}{1728000} \times 2\pi (87)(\frac{1}{4})(304) = 11.8$ kips

Skirt $\frac{490}{1728000} \times 2\pi (84)(\frac{3}{8})(25) = 1.4$ kips

Tank Ends $2 \times \frac{490}{1728000} \times \pi (87^2 + 16^2)(\frac{1}{4}) = \underline{3.5}$ kips

$\underline{16.7}$ kips

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Dynamic Response

Use charts provided by Haroun.

Assume $H = 340$ in

$R = 87$ in

$t = 0.25$ in

$H/R = 3.9$

$t/R = 0.0029$

From charts:

$$\omega_f H \sqrt{\frac{\rho_s}{E}} = 0.115$$

$$\omega_f = 0.115 \sqrt{\frac{27.7 \times 10^6}{0.000734}} \Big/ 340 = 65.7 \text{ rad/sec}$$

Frequency $f_1 = 10.5$ Hz

Participation factor $\beta_1 = 1.61$

$m_f/m = 0.70$

$H_f/H = 0.585$

$m_r/m = 0.93$

$H_r/H = 0.452$

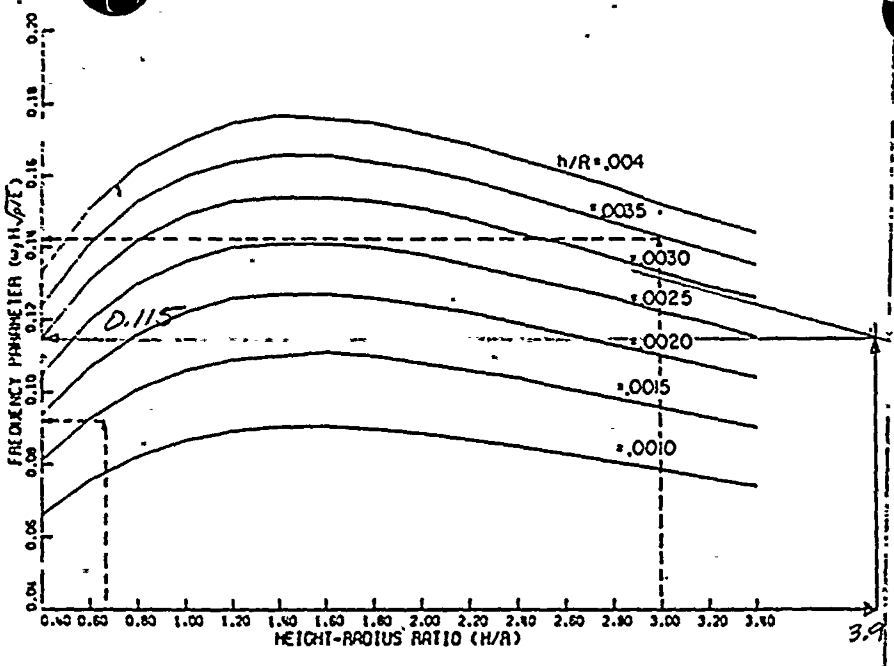

FIG. 5.—Frequency Parameter, $\omega_f H \sqrt{\rho/E}$

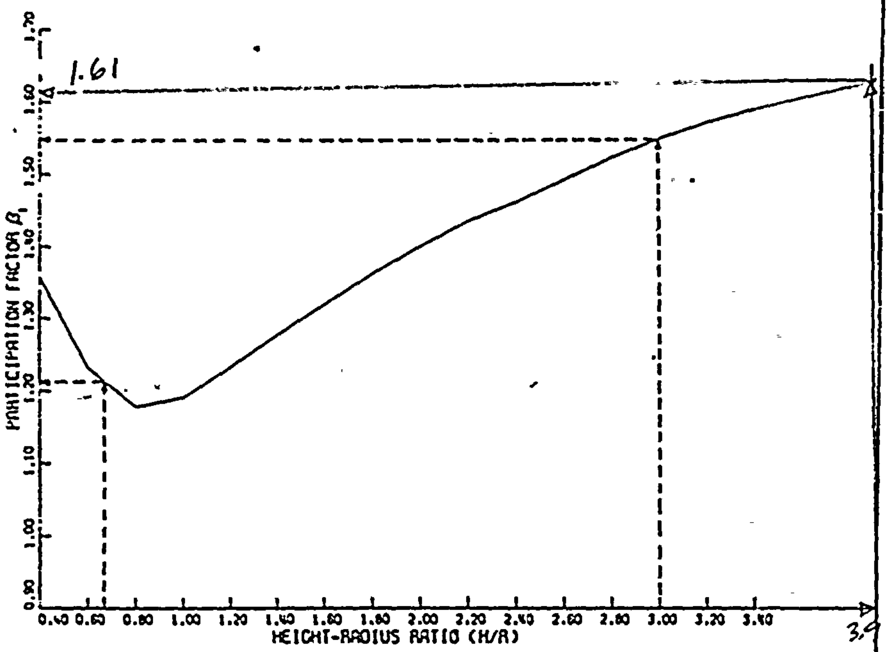

FIG. 6.—Modal Participation Factor, β_1

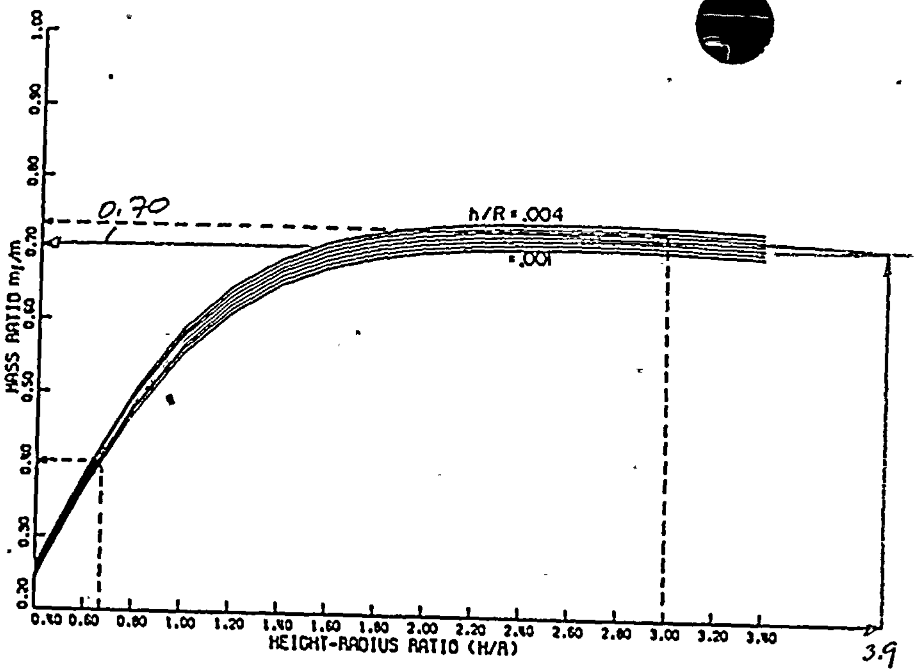

FIG. 7.—Equivalent Mass, m_f

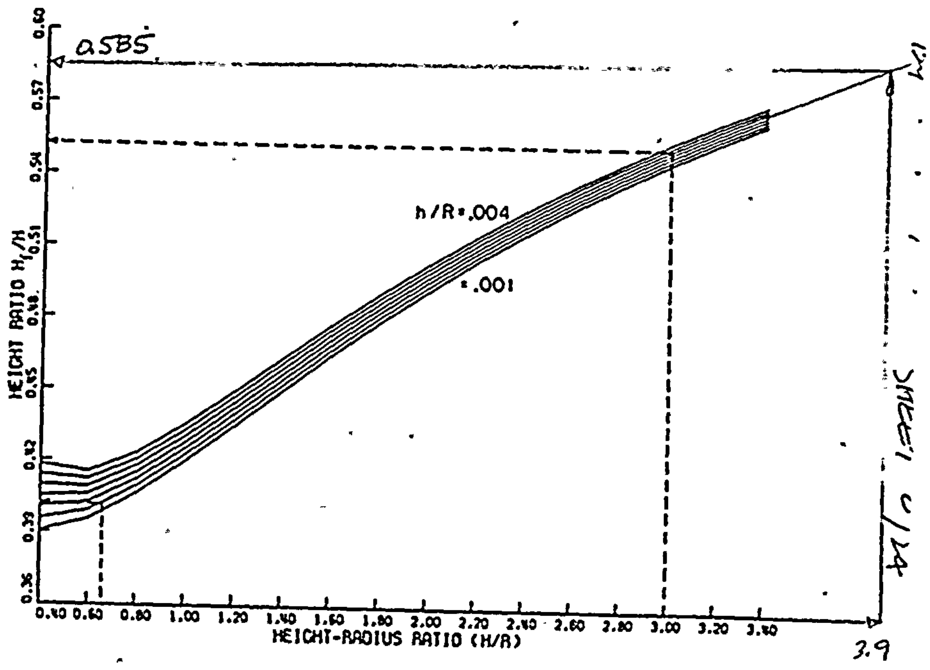

FIG. 8.—Equivalent Height, H_f

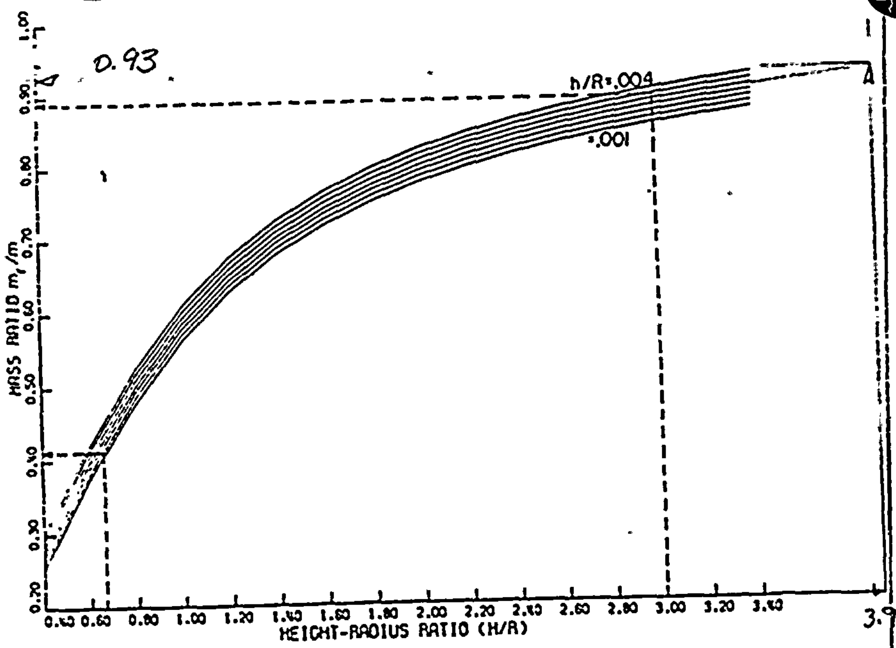

FIG. 9.—Equivalent Mass, m_r

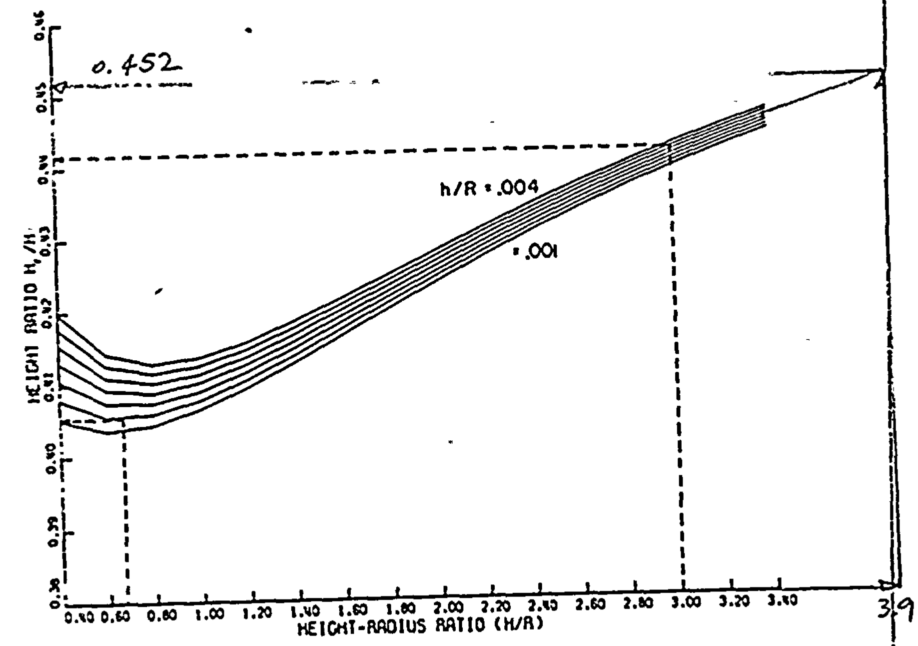

FIG. 10.—Equivalent Height, H_r

in which $\{\phi\}_1$ = the fundamental mode shape of vibration; an[illegible] = the modal amplitude of the fundamental mode. Because the mo[illegible]pes are normalized in such a way that the maximum amplitude of the radial component of shell displacement is 1.0, then one can estimate the maximum radial component of shell displacement by

$$|w_{max}| = \beta_1 S_{df} \qquad (13)$$

in which β_1 = the modal participation factor of the fundamental mode of vibration; and S_{df} = the spectral displacement corresponding to the fundamental natural frequency ω_f.

With the aid of Eq. 12, one can express the base shear force (due to the hydrodynamic pressure and the shell inertia force) as

$$Q(t) = \bar{m}_f \ddot{\eta}_1(t) + m_r \ddot{G}(t) \qquad (14)$$

Let x_f be the solution of the differential equation

$$\ddot{x}_f + 2\zeta_f \omega_f \dot{x}_f + \omega_f^2 x_f = -\ddot{G}(t) \qquad (15)$$

then Eq. 14 can be expressed more conveniently as

$$Q(t) = m_f \ddot{x}_f(t) + m_r \ddot{G}(t) \qquad (16)$$

in which $m_f = \beta_1 \bar{m}_f$. Similarly, the overturning moment due to the seismic forces applied to the bottom of the shell can be expressed as

$$M(t) = m_f H_f \ddot{x}_f(t) + m_r H_r \ddot{G}(t) \qquad (17)$$

Since the base force and moment due to shell deformability are proportional to the relative acceleration of the shell, one must rearrange Eqs. 16 and 17 before estimating the maximum seismic loads by means of a response spectrum. For example, one can rewrite Eq. 16 as

$$Q(t) = m_f[\ddot{x}_f(t) + \ddot{G}(t)] + [m_r - m_f]\ddot{G}(t) \qquad (18)$$

and consequently, the maximum base shear (including the convective component) can be estimated by

$$|Q_T|_{max} = \sqrt{(m_c S_{ac})^2 + (m_f S_{af})^2 + [(m_r - m_f)\ddot{G}_{max}]^2} \qquad (19)$$

in which S_{ac} and S_{af} = the spectral accelerations corresponding to the natural frequencies ω_c and ω_f, respectively.

Fig. 5 displays the nondimensional parameter $(\omega_f H\sqrt{\rho/E})$ for different values of (H/R) and (h/R) in which ρ and E = the mass density and Young's modulus, respectively, of the shell material. These frequencies are for tanks completely filled with water; similar charts for partly filled tanks ~~completely filled with water; similar charts for partly filled tanks~~ and for different liquid contents can be found in Ref. 3. The remaining parameters β_1, (m_f/m), (H_f/H), (m_r/m), and (H_r/H) are displayed in Figs. 6, 7, 8, 9, and 10, respectively.

Illustrative Numerical Examples

Example 1.—Consider an open top tall tank whose dimensions are: R = 24 ft (7.32 m), L = 72 ft (21.96 m), and h = 1 in. (25.4 mm). The tank is assumed

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m = total mass of the liquid

$$= \rho_w \pi R^2 H$$

$$= \frac{62.4}{1728\,(386.4)} \pi (87)^2 (340)$$

$$= 7.56 \quad lb\text{-}sec^2/in$$

Sloshing mode

$$\tanh = \frac{e^u - e^{-u}}{e^u + e^{-u}}$$

$$m_s = 0.455 \pi \rho_w R^3 \tanh\left(\frac{1.84 H}{R}\right)$$

$$= 0.455 \pi (0.0000935) (87)^3$$

$$= 8.8 \quad lb\text{-}sec^2/in$$

$$\frac{H_s}{H} = 1 - \frac{R}{1.84 H} \tanh\left(\frac{0.92 H}{R}\right)$$

$$= 1 - \frac{87}{1.84 (340)} \tanh\left(\frac{0.92 (340)}{87}\right)$$

$$= 0.86$$

$$\omega_s^2 = \frac{1.84 g}{R} \tanh\left(\frac{1.84 H}{R}\right) = 8.17 \quad (rad/sec)^2$$

$$f_s = 0.45 \quad Hz$$

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Spectral Accelerations for Horizontal Earthquake

- $f_1 = 10.5\ Hz$, $\zeta = 7\%$

linear interpolation in log-log scale

$$Sa(5\%) = \exp\left(\ln 0.264 + (\ln 10.5 - \ln 10)\frac{\ln 0.235 - \ln 0.264}{\ln 12.5 - \ln 10}\right)$$

$$= 0.257\ g$$

$$C_T = -\exp\left(\ln 0.904 + (\ln 10.5 - \ln 10)\frac{\ln 0.6 - \ln 0.904}{\ln 12.5 - \ln 10}\right)$$

$$= -0.827$$

$$Sa(7\%) = 0.257 \times 10^{-0.827(0.07-0.05)}$$

$$= \underline{0.247\ g}$$

- $f_s = 0.45\ Hz$, $\zeta = 0.5\%$

linear extrapolation from available spectra

$$Sa(5\%) = \exp\left(\ln 0.336 + (\ln 0.45 - \ln 2.5)\frac{\ln 0.168 - \ln 0.336}{-\ln 2.5}\right)$$

$$= 0.092\ g$$

$$C_T = -\exp\left(\ln 1.81 + (\ln 0.45 - \ln 1.33)\frac{\ln 1.96 - \ln 1.81}{-\ln 1.33}\right)$$

$$= -2.45$$

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$$Sa(0.5\%) = 0.092 \times 10^{-2.45(-0.005-0.05)}$$

$$= 0.12\ g$$

*Reference for spectra: Calculation 83C2209
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Modal Combination of Horizontal Seismic Response

Mode	Shear at base of skirt (kips)	Moment at base of skirt (k-in)
1	$0.7 \times 756 \times 0.247 \times 0.3864 = 50.5$	$50.5 \times 0.585 \times 340 = 1.00 \times 10^4$
Rigid	$(0.93-0.7) \times 756 \times 0.17 \times 0.3864 = 11.4$	$(0.93 \times 0.452 - 0.7 \times 0.585) \times 756 \times 340 \times 0.17 \times 0.3864 = 180$
Sloshing	$88 \times 0.12 \times 0.3864 = 4.1$	$4.1 \times 0.86 \times 340 = 1200$
Combined (SRSS)	52	1.01×10^4

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Vertical seismic response

$$f_v = \frac{1}{4H} \Big/ \sqrt{\rho_w \left(\frac{2R}{Et} + \frac{1}{\lambda} \right)}$$

λ = bulk modulus for water = 312 ksi

$$f_v = \frac{1}{4 \times 320} \Big/ \sqrt{0.0000935 \left(\frac{2 \times 87}{27.7E6 \times 0.25} + \frac{1}{312000} \right)}$$

320 ← approximate

$= \underline{16.2 \text{ Hz}}$

Ref.: "Fluid-structure Interaction during Seismic Excitation" ASCE special Document. Prepared by Nuclear Structures and Materials Seismic Analysis Committee, 1982.

Bulk modulus see "Fluid Mechanics" by M.C. Potter and J.F. Foss 1975, p. 12

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Spectral Acceleration for vertical earthquake, assume 2/3 of horizontal

$$Sa(5\%) = \frac{2}{3}\exp\left(\ln 0.235 + (\ln 15.2 - \ln 12.5)\frac{\ln 0.196 - \ln 0.235}{\ln 20 - \ln 12.5}\right)$$

$$= 0.145\,g$$

C_T = use 0

$Sa = 0.145\,g$

Vertical seismic Response = 0.145 (Dead load Response)

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Stresses at different locations

- Max. axial compression at base of skirt shell (point B on page 4)

Dead load $\frac{265+16.7}{2\pi(84)(0.375)} = 1.42$ ksi

Vertical seismic $0.145 \times 1.42 = 0.20$ ksi

Horiz. seismic $\frac{10100}{\pi(84)^2(0.375)} = 1.22$ ksi

Combined $1.42 + (0.20^2 + 1.22^2)^{1/2} = 2.66$ ksi

- Max. shear at base of skirt shell (Horiz seismic only)

$\tau_{max} = \frac{52}{\pi(84)(0.375)} = 0.53$ ksi

- Max. hoop tension at base of the straight portion of tank (point A)

Dead load $\frac{1.02 \times 62.4 \times 320 \times 87}{(0.25)(1728000)} = 4.1$ ksi

Pressure $15 \times 87 / 0.25/1000 = 5.2$ ksi

Vertical Seismic $0.145 \times 4.1 = 0.6$ ksi

Horiz. seismic $\frac{52}{\pi(320)(0.25)} = 0.2$ ksi

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combined max. hoop tension $4.1+5.2+\sqrt{0.6^2+0.2^2} = \underline{9.9}$ ksi

- Minimum hoop tension at point (A) for design of buckling $4.1-0.6 = \underline{3.5 \text{ ksi}}$

- Maximum axial tension at point (A)

$$\frac{15 \times 87}{2 \times 0.25 \times 1000} = \underline{2.6 \text{ ksi}}$$

- Maximum axial compression at point (A) (Pressure neglected)

Dead Load $\frac{11.8 + 3.5/2}{2\pi(87)(0.25)} = 0.1$ ksi

Horizontal seismic $\frac{10100}{\pi(87)^2(0.25)} = 1.7$ ksi

$\underline{1.8}$ ksi

- Maximum shear at point (A)

Horizontal seismic $\frac{52}{\pi(89)(0.25)} = \underline{0.76}$ ksi

- Maximum material stress (principal stress) at point (B)

$2.66/2 + \sqrt{(2.66/2)^2 + 0.53^2} = 2.76$ ksi

- Maximum material stress at point (A)

$(9.9-1.8)/2 + \sqrt{((9.9+1.8)/2)^2 + 0.76^2} = 10.0$ ksi

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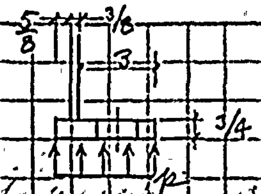

• Base ring

Bearing pressure p due to [illegible]

Dead weight $\dfrac{265+16.7}{2\pi(84)(4)} = 0.13$ ksi

width of base ring

Vertical seismic $0.145 \times 0.13 = 0.02$ ksi

Horizontal seismic $\dfrac{10100}{\pi(84)^2(4)} = 0.11$ ksi

Max. compression $0.13 + (0.02^2 + 0.11^2)^{1/2} = \underline{0.24 \text{ ksi}}$

Max. Tension 0

Maximum bending stress in the base ring plate

$$\sigma_b = \frac{0.24 \times 3^2/2}{\left(\frac{3}{4}\right)^2/6} = \underline{11.5 \text{ ksi}}$$

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- Skirt to base ring weldment
- Anchor bolts tension

} Since bearing pressure is always in compression, these stresses don't develop.

- Base shear can be assumed to be taken through friction between base ring and concrete mat.

- Skirt to tank weldment stress

Dead Load $\dfrac{(265+11.8+3.5/2)}{2\pi(84)\frac{3}{9}(0.707)(0.25)} = 9.0$ ksi

Vertical seismic $0.145 \times 9.0 = 1.3$ ksi

Horizontal seismic $\dfrac{10100}{\pi(84)^2\frac{3}{9}(0.707)(0.25)} = 7.7$ ksi

Maximum vertical stress $9.0+(1.3^2+7.7^2)^{1/2} = 16.8$ ksi

Maximum shear stress due to horiz. seismic

$\dfrac{52}{2\pi(84)\frac{3}{9}(0.707)(0.25)} = 1.7$ ksi

Combined maximum stress $(16.8^2+1.7^2)^{1/2} = 16.9$ ksi

Allowable Stresses

- Tank wall material

From ASME code Appendix Table I-7.2, for Type 304 stainless steel at 200°F

$S = 17.8$ ksi

For Level D service limit, Table NC-3921.6-1, yields

$\sigma_m \leq 2S = 35.6$ ksi

- Base skirt material

For A-283-58 Gr C material, the min. yield strength and the min. ult. tensile strength is assumed to be similar to A285 Gr C, and from Table I-7.1

min. yield strength = 30 ksi
min ultimate strength = 55 ksi

For Level D service limit, XVII-2000 and F-1370 give

$F_t = 1.2\, S_y = 36$ ksi

$F_b = \frac{0.66}{0.6} F_t = 39.6$ ksi (compact section since $b/t = 3/0.75 = 4 < 65/\sqrt{30} = 11.9$)

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- Welding

From Table NF-3292.1-1, S = 18 ksi

$$\text{Allowable} = \frac{1.2}{0.6} \times 18 = \underline{36} \text{ ksi}$$

- Tank wall buckling in bending
(Ref. NASA SP-8007)

$$\gamma = 1 - 0.731\left(1 - \exp\left(-\frac{1}{16}\sqrt{\frac{87}{0.25}}\right)\right) = 0.497$$

$$k = \frac{1.02 \times 62.4 \times 320}{1728000 \times 29000}\left(\frac{87}{0.25}\right)^2 = 0.05$$

$$\Delta\gamma = 0.056$$

$$\sigma_{\phi A} = (0.605\,\gamma + \Delta\gamma)\frac{27700 \times 0.25}{87} = \underline{28.4} \text{ ksi}$$

- Skirt shell buckling in axial compression

$$\gamma = 1 - 0.901\left(1 - \exp\left(-\frac{1}{16}\sqrt{\frac{84}{0.375}}\right)\right) = 0.453$$

$$\sigma_{\phi A} = 0.605 \times 0.453\,\frac{27700 \times 0.375}{84} = \underline{33.6} \text{ ksi}$$

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• Tank wall buckling in shear
(Ref. RWST Report)

$$\tau_{cr} = \frac{0.747 \times 0.84 \times 27700}{\left(\frac{320}{87}\right)^{1/2} \left(\frac{87}{0.25}\right)^{1.25}} = 6.0 \text{ ksi}$$

$$\bar{p} = \frac{1.09}{27700} \times \frac{320}{87} \times \left(\frac{87}{0.25}\right)^{2.5} \frac{1.02 \times 62.4 \times 320}{1728000}$$

$$= 3.85$$

$$\tau_A = (1 + 3.85)^{1/2} \, \tau_{cr} = \underline{13.2 \text{ ksi}}$$

• Skirt shell buckling in shear

The theoretical lower bound is given by Timoshenko & Gere (1961) for an infinitely long strip with simply supported edges in shear

$$\tau_{cr} = 5.35 \frac{\pi^2 E t^2}{12(1-\nu^2) \, b^2}$$

where b = width of strip or height of skirt = 25 in

Use same "knock-down" factor 0.84

$$\tau_{cr} = 0.84 \times 5.35 \frac{\pi^2 \, 27700}{12(1-\nu^2)} \left(\frac{0.375}{25}\right)^2 = \underline{25.3 \text{ ksi}}$$

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Summary Table for Margin of Safety

Location	Max. stress (ksi)	Allowable (ksi)
Tank wall		
Material stress	10.0 ✓	35.6 ✓
Axial compression	1.8 ✓	28.4 ✓
Shear	0.76 ✓	13.2 ✓
Skirt shell		
Material stress	2.76 ✓	36
Axial compression	2.66 ✓	33.6
Shear	0.53 ✓	25.3
Base ring		
Bending stress	11.5	39.6 ✓
Skirt-Tank Welding	16.9	36 ✓

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- Timoshenko, S.P. and Gere, J.M., "Theory of Elastic Stability," 2nd ed. McGraw-Hill (1961), p. 383
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