Parametric Lifetime Analysis of Cylindrical Chambers for the Target Development Facility

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Introduction

Previous fatigue life calculations for the TDF reaction chamber were based upon conservative guidelines from the ASME Pressure Vessel Code. The magnitudes of the peak pressures generated at the chamber wall by the fireball shock were used with dynamic load factors restricted to be no less than unity. This procedure has been replaced by a less conservative but more accurate technique using the impulse value of the shock. The response is primarily determined by the impulse magnitude rather than the pulse shape or peak pressure if the mean pulse width is considerably less than mechanical vibration periods. This representation also facilitates the generation of parametric data. In earlier work, the maximum dynamic pressure was also conservatively doubled to account for uncertainties in the fireball numerical modeling. The current work does not use this additional factor. Procedures for the determination of the dynamic response have also been improved. In addition, fatigue calculations are now based upon strain criteria, which is necessary for an accurate assessment of the effects of intense dynamic loads from a limited number of shots.

Description of the Base Case

The base case design is a cylindrical shell with radius and effective height of 3 m and 2 m, respectively, and a wall thickness not less than 3 cm. Materials considered are 2.25 Cr-1 Mo ferritic steel and 6061-T6 aluminum, unwelded and welded. The target yield is 200 MJ with the corresponding impulse of 110 Pa-s. The pressure pulse is shown in Fig. 1. (For comparison, the corresponding 800 MJ result in Fig. 2 has a much higher pressure, but the impulse is only slightly larger.) With these parameters and 2% damping, displacement and stress histories are determined from the relevant axisymmetric harmonics.

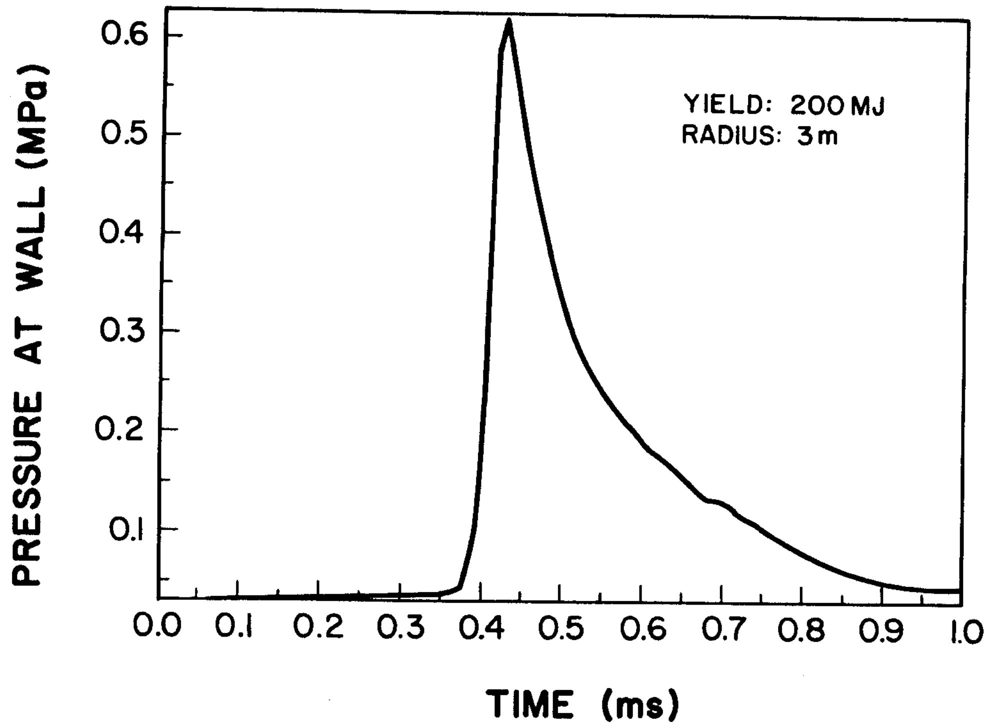

Fig. 1. Dynamic pressure at first wall.

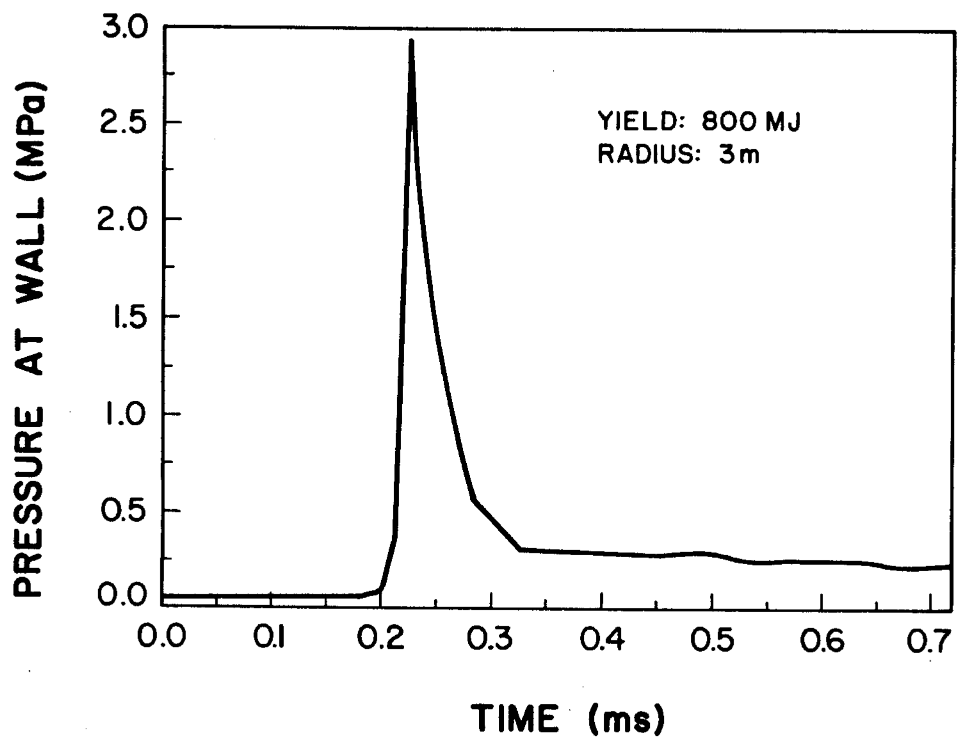

Fig. 2. Dynamic pressure at first wall.

Vibration Frequencies

Only axisymmetric modes contribute to the dynamic response since the applied pressure is assumed to have no circumferential variation. Furthermore, because the shock is also axially uniform, the participating modes are characterized by symmetry with respect to midspan, i.e. modes with an odd number of half waves. Frequencies for eight of the twenty-four cases used in fatigue computations are listed in Tables 1 and 2. Values for even numbers of half waves are tabulated but were not used. The natural frequencies are primarily dependent upon the radius and only moderately influenced by thickness changes. In addition, steel and aluminum results are very similar since frequencies depend upon the ratio of elastic modulus to density, a factor which is nearly the same for the two materials.

Mechanical Response

Maximum axial flexural stress occurs at the ends of the cylinder. Results for a 3 cm steel wall are shown in Fig. 3. Increasing the wall thickness will decrease the peak stress. For example, the maximum stress can be reduced by more than a factor of two by doubling the wall thickness as indicated in Fig. 4. (Note that the stress scales are different.) This stress distribution is characterized by a rather steep axial gradient and thus can be controlled by a localized increase in thickness near the ends, i.e. a hub. In the greater percentage of the shell which excludes the ends, the dominant stress is circumferential. The design thickness is based upon this value which is more uniformly distributed and also of smaller amplitude. For comparison purposes, Fig. 5 is the circumferential stress history corresponding to Fig. 3.

Table 1. Axisymmetric Natural Frequencies for 2.25 Cr-1 Mo Steel Shells

f = frequency (Hz) Modulus = 216.2 GPa

n = half wave no. Density = 7825 kg/m^3

R = radius (cm) Poisson's ratio = 0.26

t = thickness (cm) Length = 200 cm

R = 150, t = 3		R = 150, t = 6		R = 300, t = 3		R = 300, t = 6	
n	f	n	f	n	f	n	f
1	559.29	1	564.00	1	282.00	1	291.22
2	569.59	2	603.80	2	301.90	2	362.34
3	602.06	3	718.87	3	359.44	3	532.44
4	672.00	4	934.46	4	467.23	4	799.95
5	790.36	5	1251.21	5	625.60	5	1154.22
6	960.65	6	1660.79	6	830.39	6	1589.00
7	1181.30	7	2156.09	7	1078.04	7	2101.29
8	1449.18	8	2732.64	8	1366.32	8	2689.61
9	1761.42	9	3387.81	9	1693.90	9	3353.20
10	2115.88	10	4120.02	10	2060.01	10	4091.61
11	2511.05	11	4928.33	11	2464.16	11	4904.60
12	2945.92	12	5812.11	12	2906.05	12	5792.01
13	3419.77	13	6770.97	13	3385.48	13	6753.72
14	3932.10	14	7804.64	14	3902.32	14	7789.68
15	4482.56	15	8912.93	15	4456.46	15	8899.83
16	5070.91	16	10095.70	16	5047.85	16	10084.14
17	5696.95	17	11352.87	17	5676.44	17	11342.60
18	6360.55	18	12684.36	18	6342.18	18	12675.17
19	7061.60	19	14090.12	19	7045.06	19	14081.84
20	7800.02	20	15570.11	20	7785.05	20	15562.61

Table 2. Axisymmetric Natural Frequencies for 6061-T6 Aluminum Shells

f = frequency (Hz)

n = half wave no.

R = radius (cm)

t = thickness (cm)

Modulus = 68.95 GPa

Density = 2713 kg/m^3

Poisson's ratio = 0.33

Length = 200 cm

	R = 150, t = 3	R = 150, t = 6	R = 300, t = 3	R = 300, t = 6
n	f	f	f	f
1	536.48	541.20	270.60	279.84
2	546.81	581.07	290.53	350.79
3	579.32	695.79	347.89	519.17
4	649.14	909.49	454.75	782.68
5	766.79	1222.09	611.05	1130.90
6	935.39	1625.25	812.63	1557.84
7	1153.19	2112.11	1056.05	2060.68
8	1417.05	2678.40	1339.20	2638.04
9	1724.21	3321.64	1660.82	3289.18
10	2072.60	4040.34	2020.17	4013.70
11	2460.80	4833.60	2416.80	4811.35
12	2887.82	5700.85	2850.43	5682.00
13	3353.01	6641.71	3320.86	6625.54
14	3855.89	7655.93	3827.97	7641.91
15	4396.14	8743.34	4371.67	8731.06
16	4973.52	9903.80	4951.90	9892.96
17	5587.85	11137.23	5578.61	11127.59
18	6239.00	12443.56	6221.78	12434.93
19	6926.88	13822.74	6911.37	13814.98
20	7651.40	15274.74	7637.37	15267.71

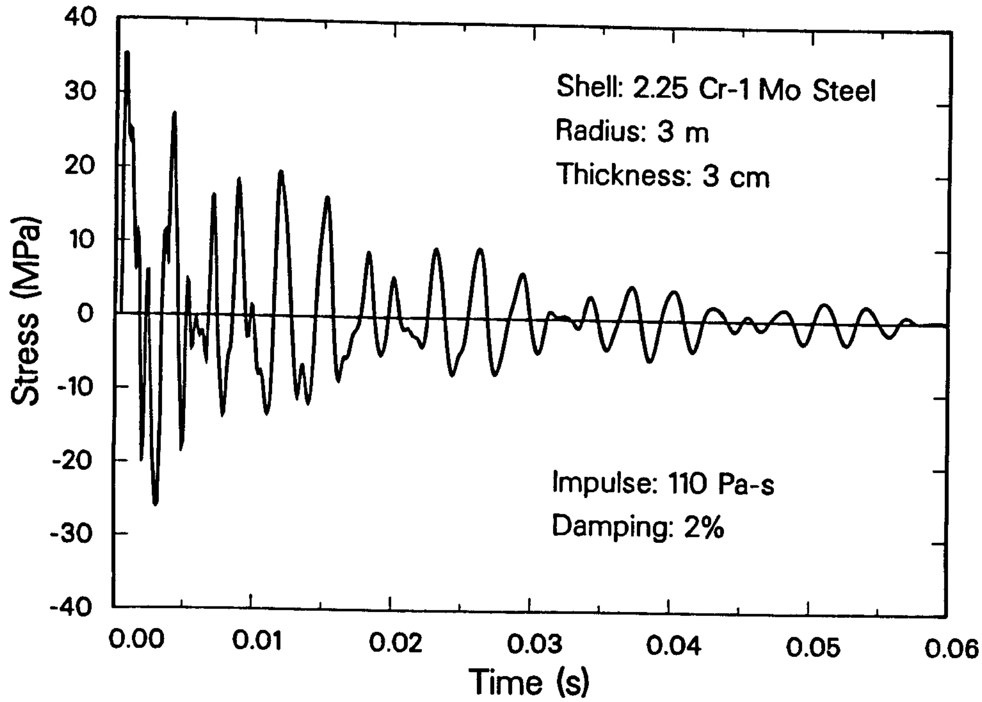

Fig. 3. TDF cylindrical shell flexural mechanical stress.

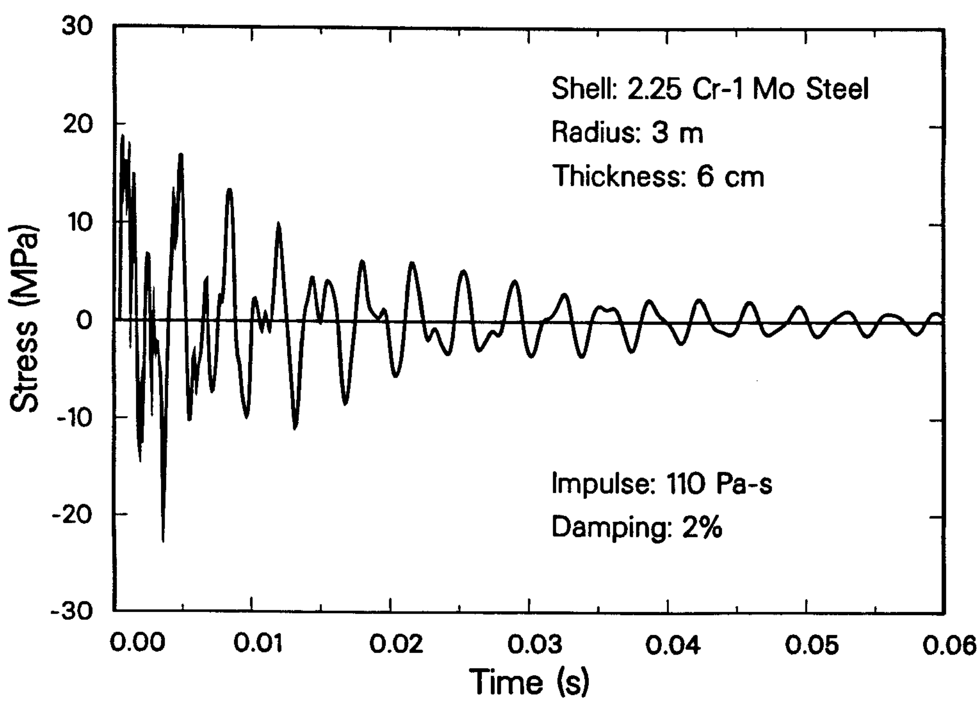

Fig. 4. TDF cylindrical shell flexural mechanical stress.

Fatigue Analysis

The stress and strain histories are characterized by multiple cycles of different amplitudes. Thus, cumulative damage criteria are used to assess chamber lifetimes. The ASME Pressure Vessel code procedures for cumulative damage are followed [1]. This involves the determination of the effects of the number of applied cycles of various amplitudes as compared with the number of corresponding design allowable cycles. Instead of the code's stress design curves, the material properties used consist of fully reversed alternating strain as a function of the number of cycles to failure. With such basic data, the guidelines call for safety factors of two on strain magnitude or twenty on cycles, whichever is more conservative. This is the only formal inclusion of a safety factor in the analysis and design.

A computer code has been developed for the determination of fatigue life. The principal steps in the program include accurately calculating both natural frequencies and mode shapes for a specific material, thickness, radius and length. The displacement and strain histories are then determined for each value of the impulsive loading. Typical examples are shown in Figs. 6 and 7 for steel and aluminum base cases with 3 cm walls. A counting procedure is applied to each history, assessing cumulative damage and comparing with stored data for strain amplitude as a function of cycles to failure. This results in identification of the number of shots permissible for a given chamber subjected to impulsive pressures spanning the range of interest. The process is then repeated completely for a change in one parameter, e.g., the wall thickness.

The fatigue strain-range data for welded aluminum 6061-T6 was obtained from design guidelines of the American Society of Civil Engineers [2]. The

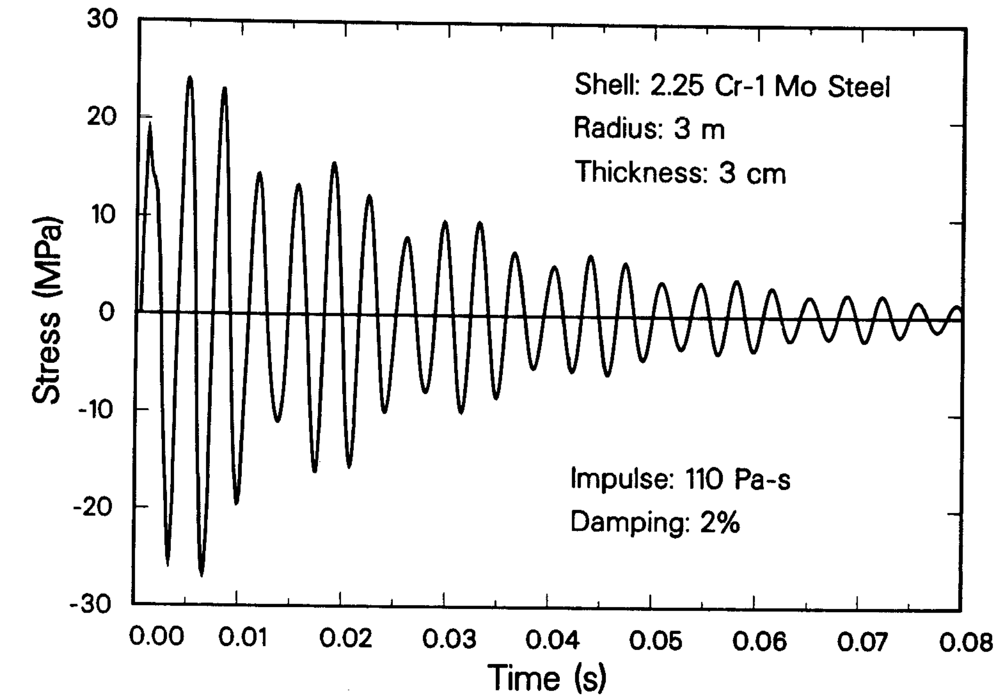

Fig. 5. TDF cylindrical shell circumferential mechanical stress.

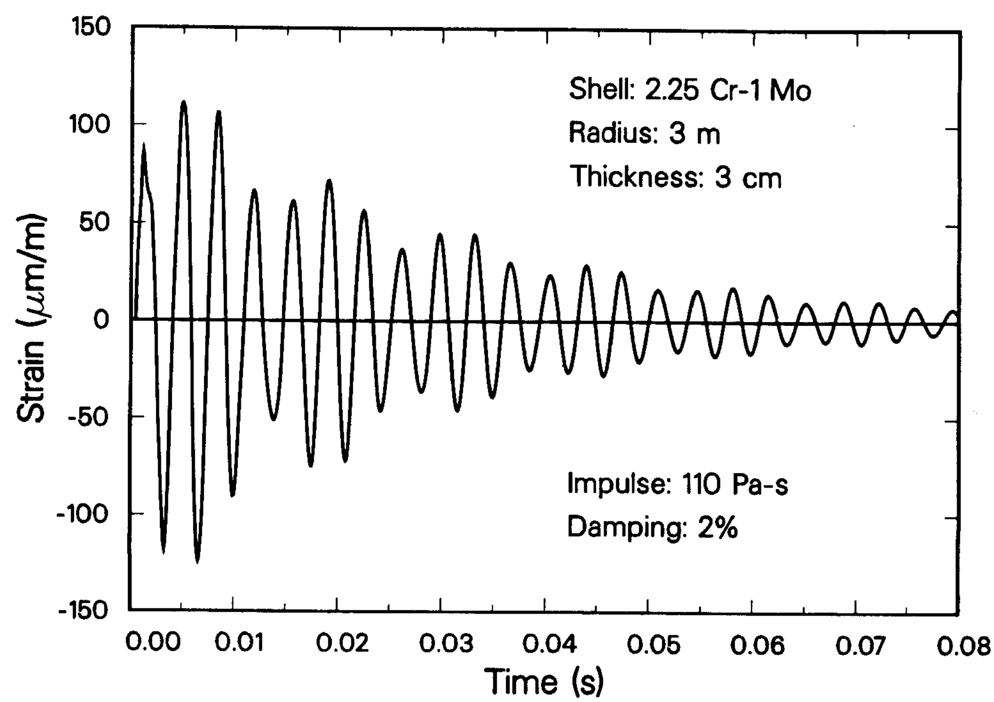

Fig. 6. TDF cylindrical shell circumferential mechanical strain.

given values had a built-in safety factor of 1.35. Test results for plate samples indicate that the ASCE formulas provide safety factors against failure under cyclic loading of at least 1.35. Accordingly, the original design data from ASCE has been derated by 1.35 and is shown in Fig. 8. The effects of welding on fatigue life can be determined by comparing data of Fig. 9 [3] with Fig. 8. Corresponding data for 2.25 Cr-1 Mo, shown in Fig. 10, was obtained from the work of Booker et al., at ORNL [4]. These data, characterized for the design of nuclear steam generators, were accepted for inclusion in ASME Code Case N-47 [1]. Data were obtained from fully reversed constant amplitude strain-controlled fatigue tests at a strain rate of approximately 4×10^{-1} s^{-1}.

Fatigue Life Results

The family of fatigue life design curves for welded aluminum chambers with various thicknesses and a radius of 3 m is presented in Fig. 11. Terminal points on the curves joined to vertical limits identify impulsive pressures which cause dynamic yielding. With a thickness of 3 cm and an impulse of 110 Pa-s (200 MJ) the lifetime corresponds to 32,300 shots as compared with the design objective of 15,000. The results are highly nonlinear. A small increase in the impulse will dramatically reduce the allowable number of shots. However, for this case, even if the impulse is conservatively doubled for reasons associated with fireball calculations, the design goal could still be realized with a 5 cm wall.

As can be seen from Fig. 12, the fatigue lifetime results for 1.5 m and 3 m radius chambers have similarities. Lifetime is based upon dynamic circumferential stress, a parameter which is radius-independent for a theoretical membrane shell of arbitrary length under radial impulsive pressure. This is

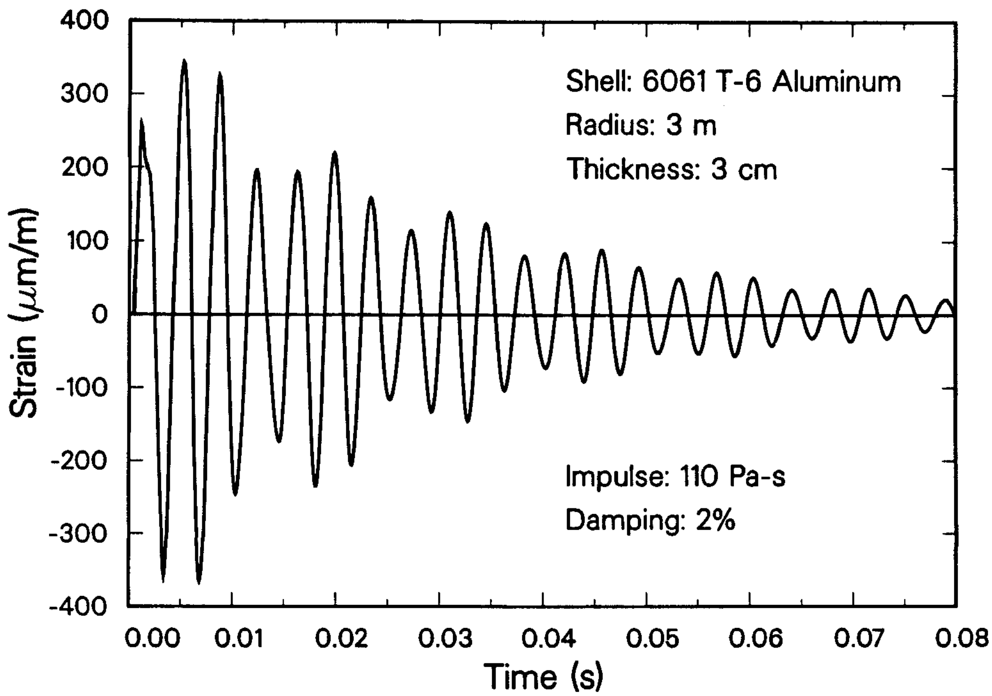

Fig. 7. TDF cylindrical shell circumferential mechanical strain.

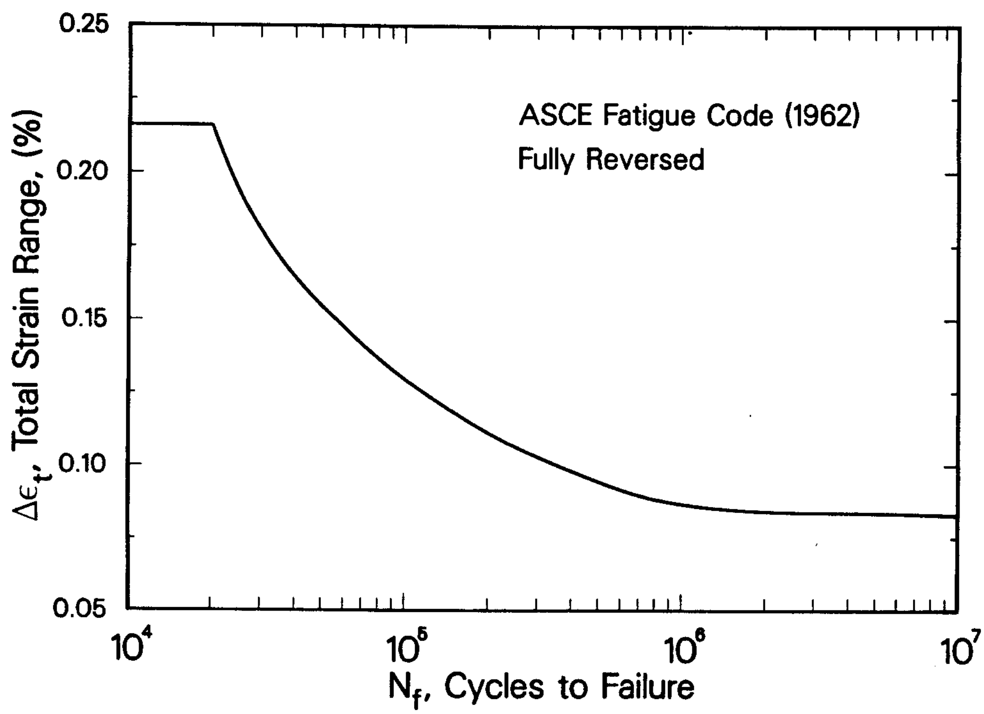

Fig. 8. Fatigue data for welded 6061-T6 aluminum.

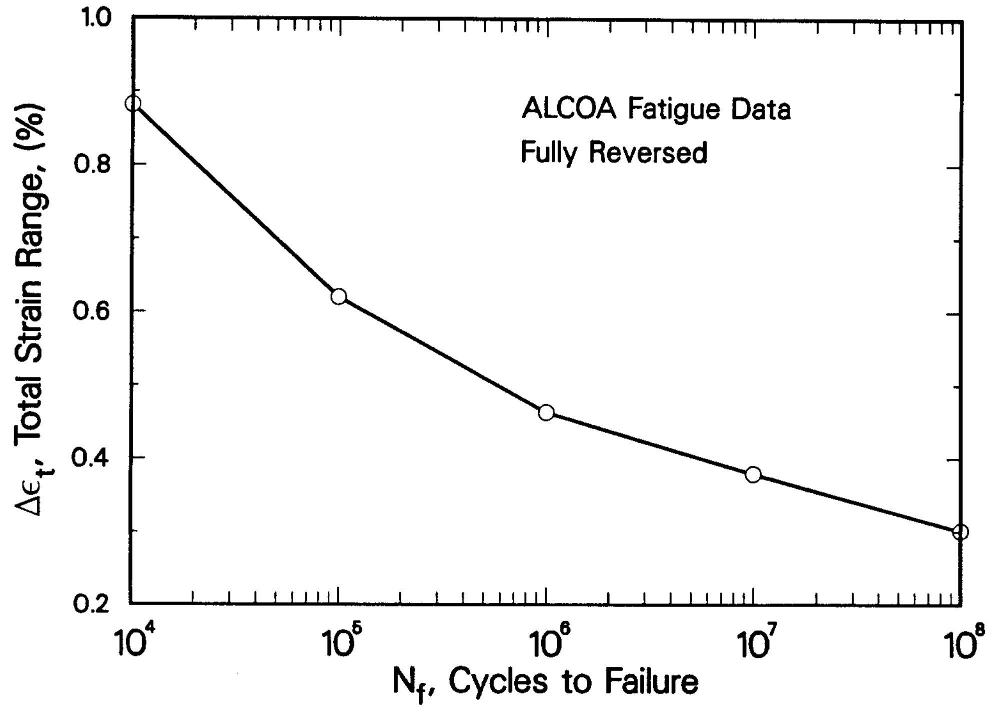

Fig. 9. Fatigue data for unwelded 6061-T6 aluminum.

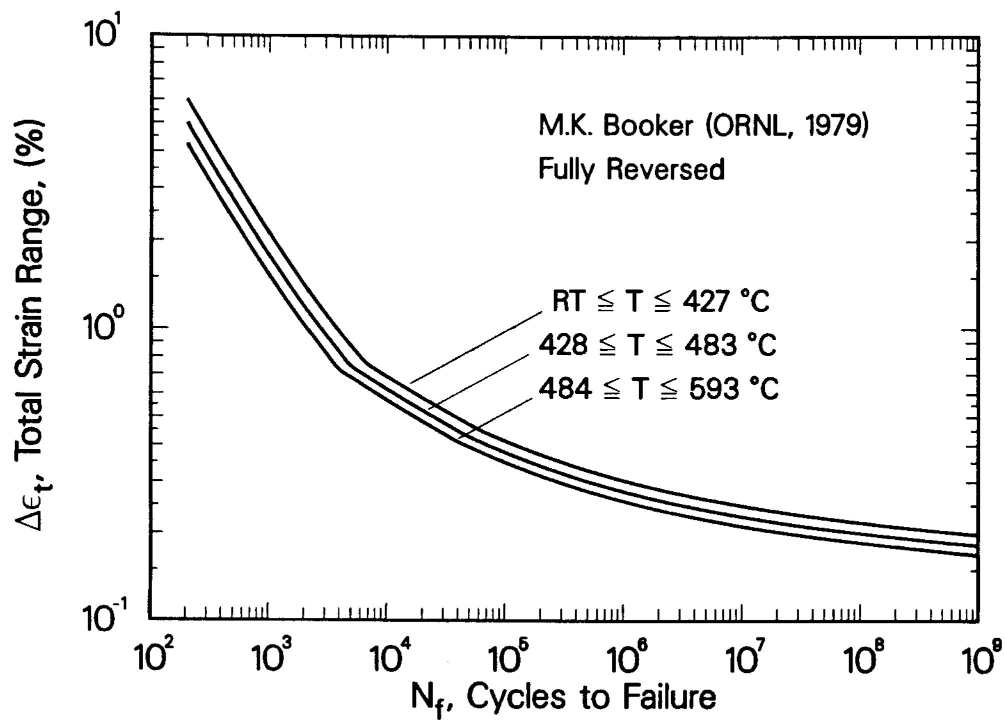

Fig. 10. Fatigue data for 2.25 Cr-1 Mo steel.

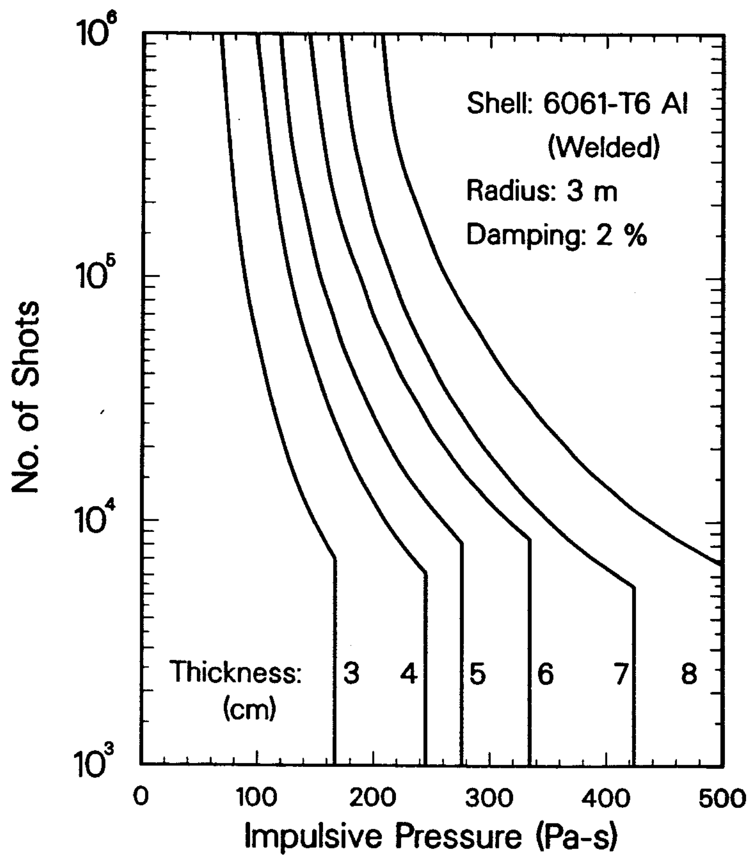

Fig. 11. Fatigue life of TDF cylindrical shell.

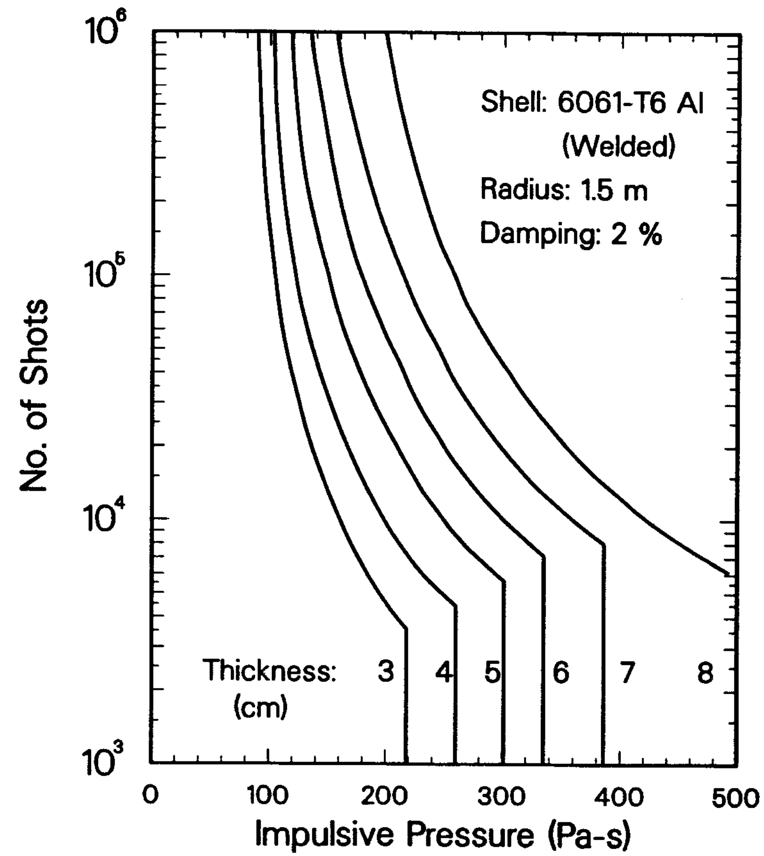

Fig. 12. Fatigue life of TDF cylindrical shell.

an important effect, but the complex multiharmonic response for finite length shells coupled with nonlinear fatigue criteria constitute strong influences as well. The corresponding design curves for steel chambers in Figs. 13 and 14 show the superior fatigue characteristics of 2.25 Cr-1 Mo steel. It should also be noted that while it appears that lifetimes of small chambers are higher, larger impulsive loads may be generated in a smaller chamber for the same yield.

Conclusions

The TDF fatigue lifetime analysis has been made for steel and aluminum cylindrical chambers with a range of size parameters and impulsive pressures. Lifetime for steel chambers is considerably better than aluminum. However, it has been shown that a 3 m radius aluminum chamber can sustain 15,000 shots at a yield of 200 MJ with a wall as thin as 3 cm. It appears that the chamber size can be reduced and still carry increased loads if the thickness is increased appropriately. Combinations of 200 MJ and higher yield shots are possible. In general, the results indicate that the design objectives can be met with ample safety factors and cylindrical chambers of practical size.

Acknowledgement

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