Lifetime Analysis of the TDF Reaction Chamber

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Abstract

Lifetime considerations for the reaction chamber of the SNL light ion fusion target development facility include mechanical fatigue analysis because of shock pressures generated in the chamber gas after each target ignition. The oscillatory response of the structural wall from the repetitive dynamic overpressure is identified, including the effects of damping. Fatigue lifetime calculations have been done in accordance with ASME guidelines utilizing cumulative damage criteria. It is shown that the primary design goal of 15,000 shots at a yield of 200 MJ can be met with aluminum or steel chambers having radii from 1.5 to 3 m with practical wall thicknesses.

Introduction

The target development facility (TDF) is a proposed research installation of Sandia National Laboratories intended for qualification and testing of ICF targets for the light ion fusion program. The usage rate is estimated at 10 shots per day for 5 years, i.e. approximately 15,000 shots. At this time, the reaction chamber is considered to be a capped cylindrical shell structure, submerged in a water shield as shown in Fig. 1. The oscillatory response of the chamber wall and the large number of shots suggest that mechanical fatigue may be an important design issue. An assessment of fatigue life is summarized in the work which follows. Additional details are available in UWFDM-656 [1].

Pressure Pulse Considerations

The dynamic load is assumed to be uniformly distributed over the chamber wall. A typical pulse is shown in Fig. 2. The impulse value of such a shock is a key parameter in the analysis. The mechanical response is essentially determined by the impulse magnitude rather than the pulse shape and peak pressure if the mean pulse width is considerably less than vibration periods. This approach is both accurate and convenient for parametric studies.

Procedure and Description of the Base Case

The base case design is a chamber with radius and effective height of 3 m and 2 m, respectively, and a wall thickness not less than 3 cm. Materials used are welded 6061-T6 aluminum and 2.25 Cr-1 Mo ferritic steel. Target yield is 200 MJ with the corresponding impulse 110 Pa-s. With these parameters and 2% damping [2], displacement and stress histories have been determined using the relevant axisymmetric harmonics.

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. 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 ex-

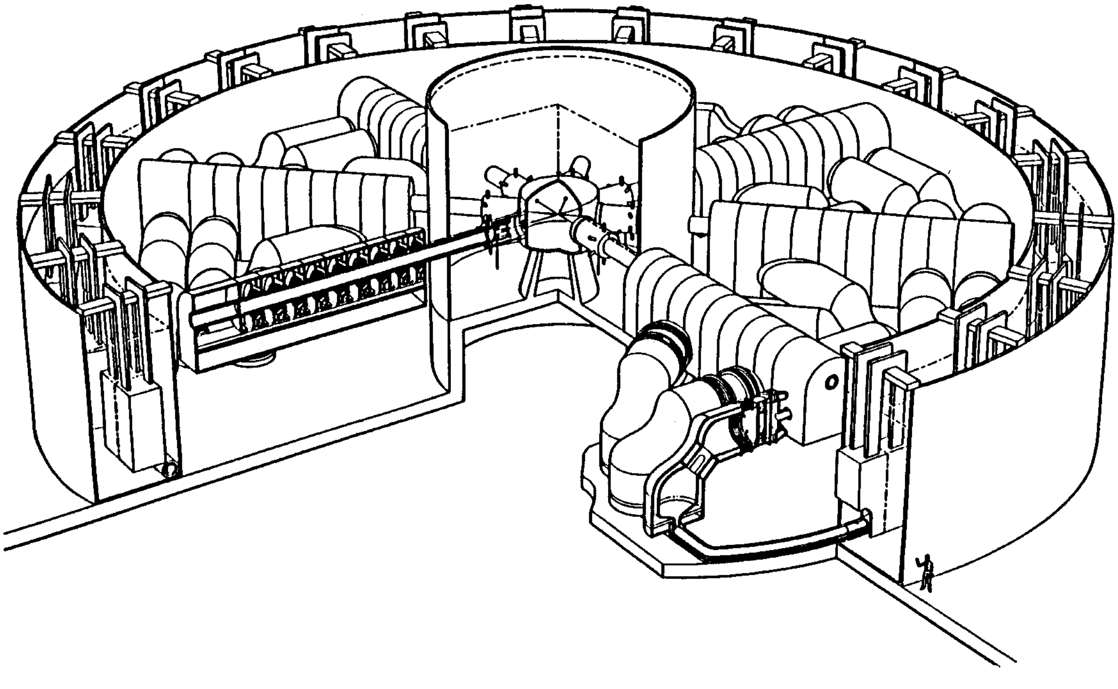

Fig. 1. Light Ion Target Development Facility Concept.

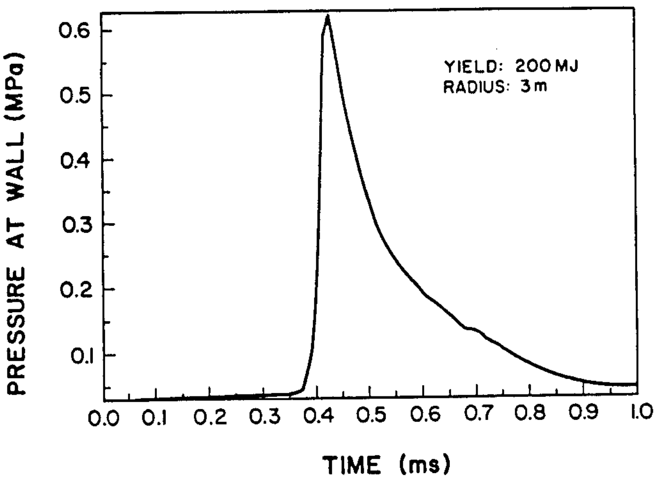

Fig. 2. Dynamic Pressure at First Wall.

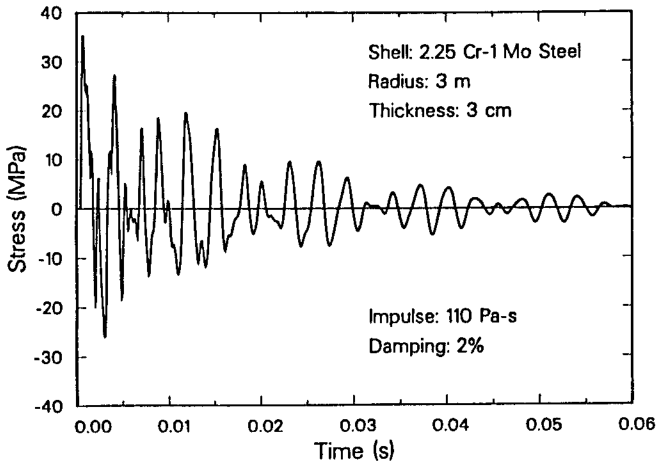

Fig. 3. TDF Cylindrical Shell Flexural Mechanical Stress.

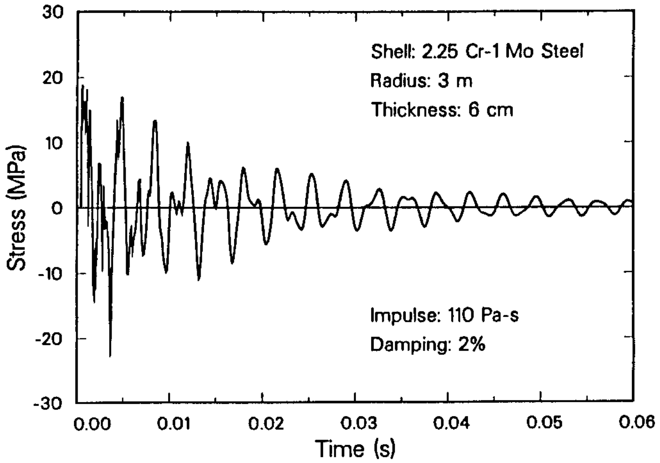

Fig. 4. TDF Cylindrical Shell Flexural Mechanical Stress.

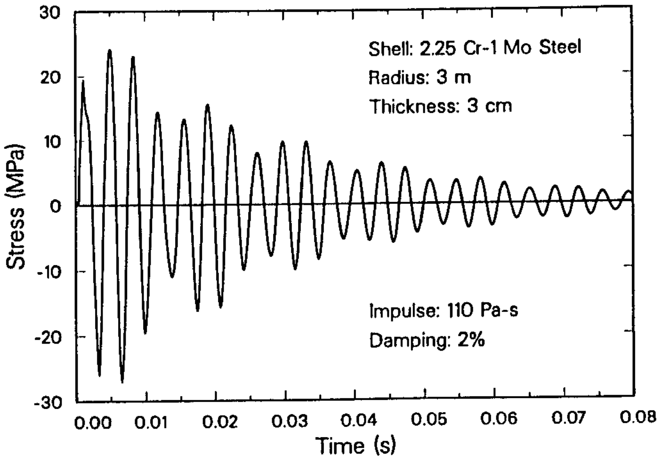

Fig. 5. TDF Cylindrical Shell Circumferential Mechanical Stress.

cludes 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.

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 [3]. 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 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.

Fatigue Results

The fatigue strain-range data for welded aluminum 6061-T6 was obtained from design guidelines of the American Society of Civil Engineers [4]. The 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. Corresponding data for 2.25 Cr-1 Mo, shown in Fig. 9., was obtained from the work of Booker et al., at ORNL [5]. These data, characterized for the design of nuclear steam generators, were accepted for inclusion in ASME Code Case N-47 [3]. Data were ob-

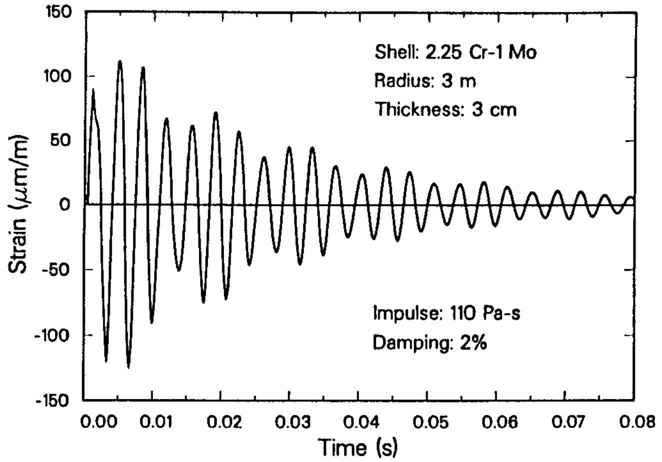

Fig. 6. TDF Cylindrical Shell Circumferential Mechanical Strain.

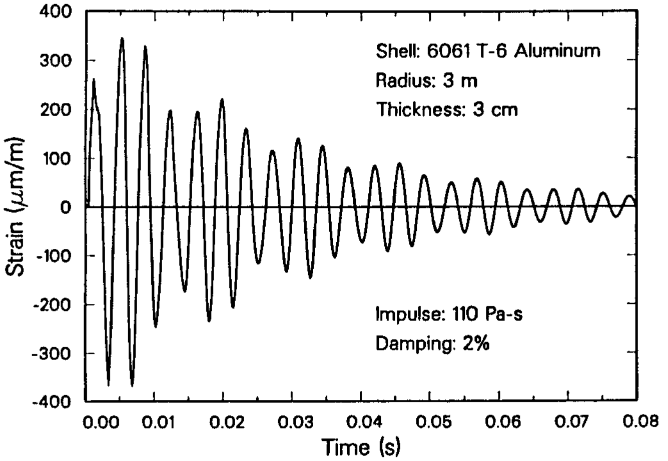

Fig. 7. TDF Cylindrical Shell Circumferential Mechanical Strain.

tained from fully reversed constant amplitude strain-controlled fatigue tests at a strain rate of approximately 4×10^{-1} s^{-1}.

The family of fatigue life design curves for welded aluminum chambers with various thicknesses and a radius of 3 m is presented in Fig. 10. 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. 11, the fatigue lifetime results for 1.5 m and 3 cm 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 an important

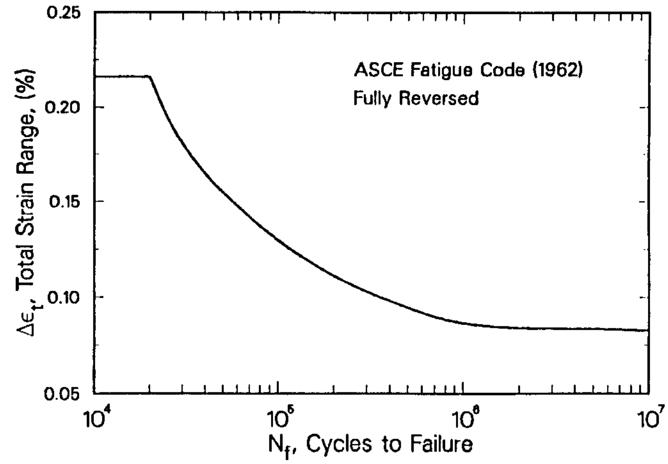

Fig. 8. Fatigue Data for Welded 6061-T6 Aluminum.

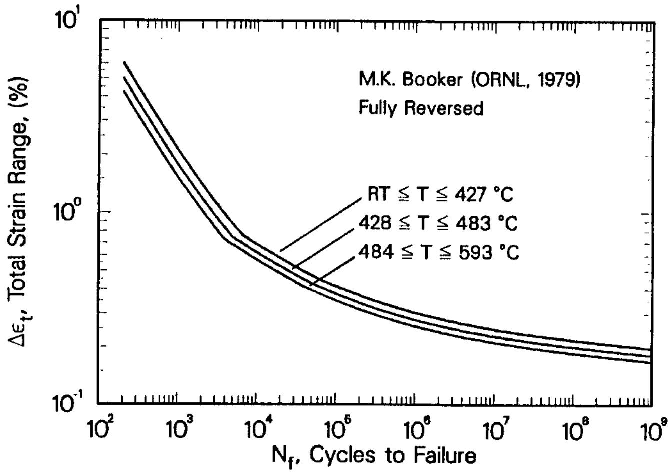

Fig. 9. Fatigue Data for 2.25 Cr-1 Mo Steel.

effect, but the complex multiharmonic response for finite shells coupled with nonlinear fatigue criteria constitute strong influences as well. The corresponding design curves for steel chambers in Figs. 12 and 13 show the superior fatigue characteristics of 2.25 Cr-1 Mo. It should also be noted that while it appears that lifetimes of smaller 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 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 chambers of practical size.

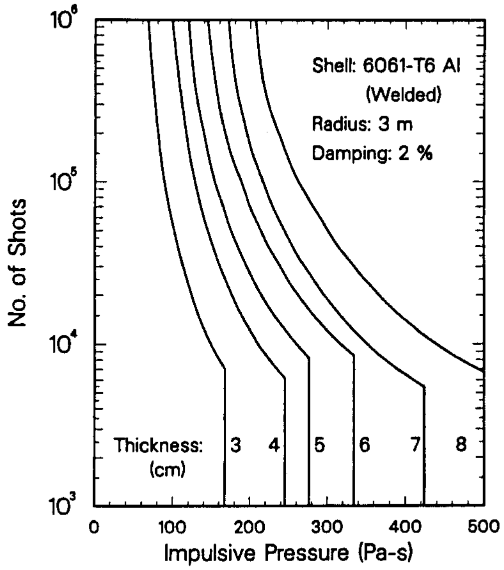

Fig. 10. Fatigue Life of TDF Cylindrical Shell.

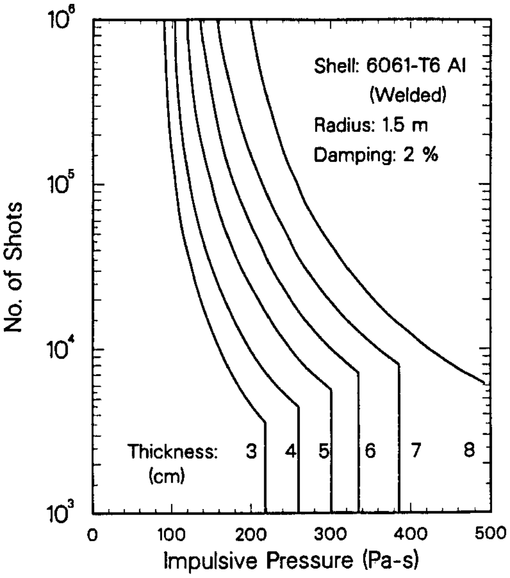

Fig. 11. Fatigue Life of TDF Cylindrical Shell.

Acknowledgement

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[1] R.L. Engelstad, E.G. Lovell, "Parametric Lifetime Analysis of Cylindrical Chambers for the Target Development Facility," University of Wisconsin Fusion Technology Institute Report UWFDM-656, Oct. 1985.

[2] "Damping Values for Seismic Design of Nuclear Power Plants," Regulatory Guide 1.61, U.S. Nuclear Regulatory Commission, 1973.

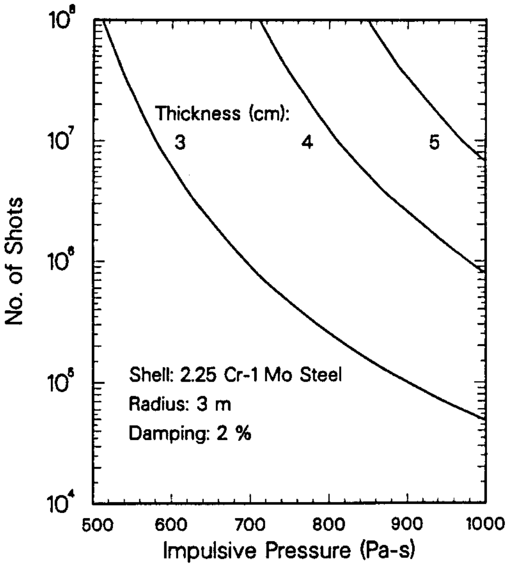

Fig. 12. Fatigue Life of TDF Cylindrical Shell.

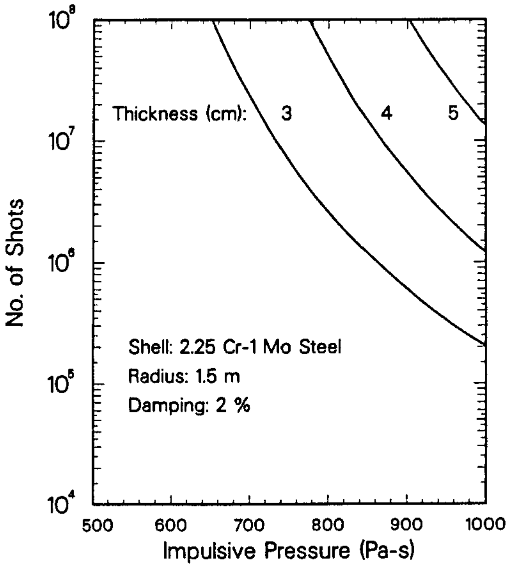

Fig. 13. Fatigue Life of TDF Cylindrical Shell.

[3] ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components.

[4] "Suggested Specifications for Structures of Aluminum Alloys 6061-T6 and 6062-T6," Report of Task Committee on Lightweight Alloys, J. Str. Div. ASCE, Vol. 88, ST6, pp. 1-95, 1962.

[5] M.K. Booker, J.P. Strizak, C.R. Brinkman, "Analysis of the Continuous Cycling Fatigue Behavior of 2.25 Cr-1 Mo Steel," Oak Ridge National Laboratory Report ORNL-5593, Oak Ridge, TN, 1979.