# Fatigue Stress Analysis of the Sandia TDF Reaction Chamber

R.L. Engelstad, E.G. Lovell and G.A. Moses

September 1984

UWFDM-594

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

# Fatigue Stress Analysis of the Sandia TDF Reaction Chamber

R.L. Engelstad, E.G. Lovell and G.A. Moses

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

September 1984

UWFDM-594

# FATIGUE STRESS ANALYSIS OF THE SANDIA TDF REACTION CHAMBER

R.L. Engelstad

E.G. Lovell

G.A. Moses

Fusion Technology Institute
Nuclear Engineering Department
University of Wisconsin
Madison, Wisconsin 53706

September 1984

UWFDM-594

## INTRODUCTION

The Target Development Facility (TDF) reaction chamber will be subjected to a mechanical shock from the cavity gas after each target ignition. This impulsive pressure produces transient stresses in the cylindrical shell wall which are characterized by an oscillatory response with decreasing amplitude. The useful lifetime of the chamber will be influenced by the mechanical fatigue of the wall material. Such lifetime estimates have been determined and are discussed in this report.

## GENERAL PROCEDURE

The method follows the guidelines of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.[1] It allows for fatigue damage from cyclic loading as well as creep rupture damage which could take place during extended hold times. Generally both effects would occur simultaneously and thus "creep-fatigue interaction" has been used to describe the problem. The procedure depends upon interaction relations for the material. For discussion purposes, typical design curves are shown in Fig. 1. These relations can be represented as

$$\sum_{j=1}^{p} (n/N_d)_j + \sum_{k=1}^{q} (t/T_d)_k \leq D \qquad (1)$$

where: D = total creep-fatigue damage

$n_j$ = number of applied cycles of loading condition, j

$N_{dj}$ = number of design allowable cycles of loading condition, j

$t_k$ = time duration of load condition, k

$T_{dk}$ = creep rupture time for the k-th stress acting alone.

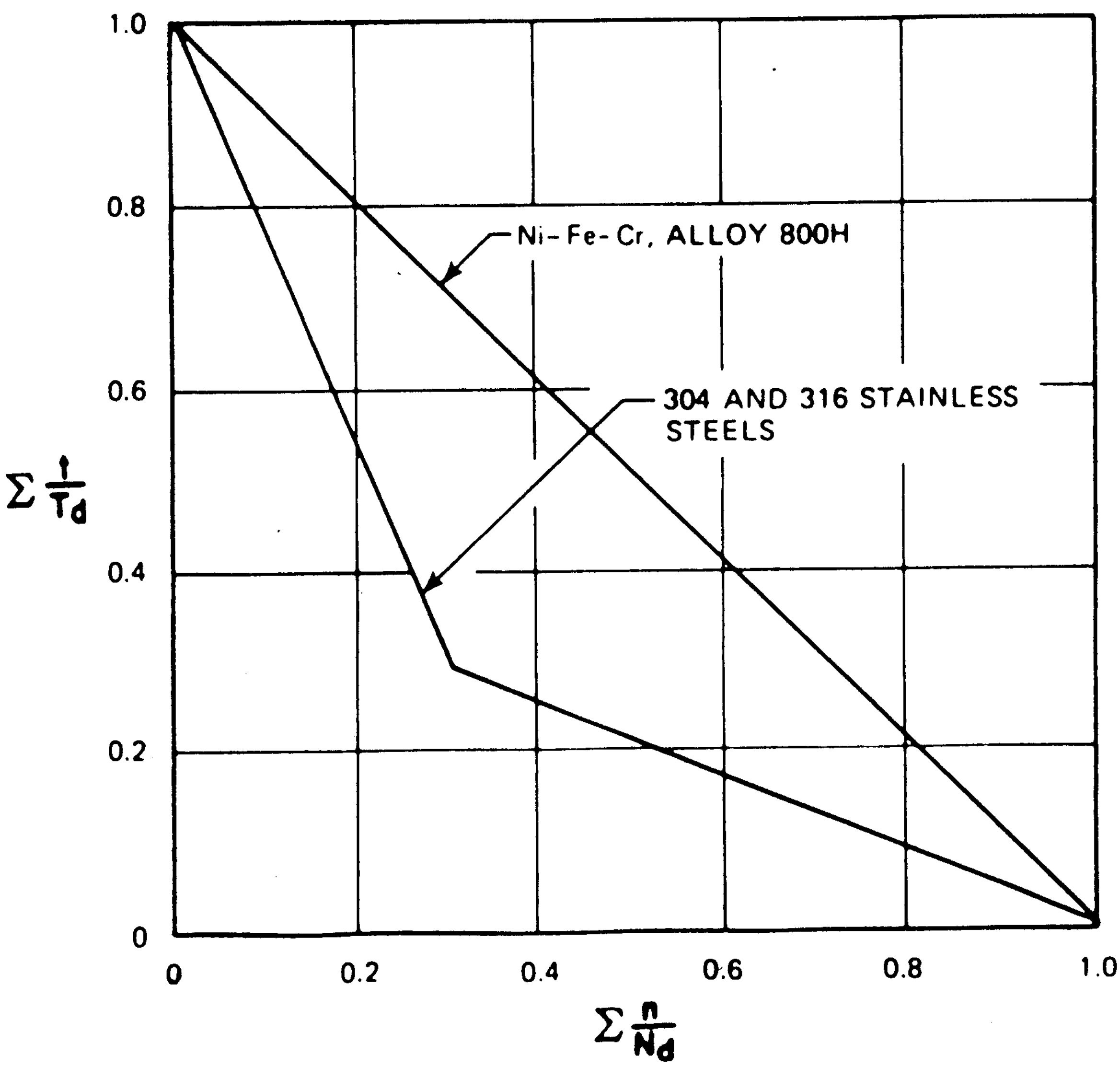



Fig. 1. ASME creep-fatigue damage criteria.

The abscissa of Fig. 1 identifies fatigue damage in the absence of creep damage while similarly the ordinate represents rupture damage without fatigue. Failure is predicted when either of these, acting alone, reaches a value of 1.0. When acting together, failure is predicted when the sum becomes equal to D. The linear interaction curve for alloy 800 H (Ni-Fe-Cr) shows that the two effects are mutually independent. However, the nonlinear curve for stainless steel represents degradation of fatigue by creep and vice versa, with failure predicted at values of D which are less than 1.0.

For the TDF reaction chamber, the steady loads are produced by hydrostatic pressure and dead weight. The corresponding stresses are not large and more significantly, occur at room temperature. Under these circumstances, creep is not considered to be an important design problem.

The ASME Section III fatigue design curves are based upon strain controlled tests but are presented in terms of alternating stress intensity, i.e., alternating strain multiplied by the elastic modulus. A safety factor of at least 2 on stress and 20 on life is used and the curves also incorporate an additional factor accounting for mean stress effects.

The recommended procedure requires a determination of the dynamic principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) at critical points. From these, the stress differences $S_{ij} = \sigma_i - \sigma_j$, are calculated. The extremes of the range through which each of the stress differences fluctuates are found along with the absolute value of the range for each $S_{ij}$. The alternating stress intensity, "$S_{alt}$," is one half of the largest magnitude of the stress range. This parameter is then used with the appropriate fatigue design curve. (Modulus scaling and UTS interpolation are used if necessary.)

## TDF FATIGUE ANALYSIS

For the cylindrical shell of the TDF reaction chamber, stresses are determined for a specific thickness, length, diameter, material and target yield. A conservative damping level of 2% critical is used in all calculations.[2,3] Shield water inertia is assessed but its damping characteristics are ignored.[4] Both flexural and membrane stresses are included in the analysis. Since this is a plane stress problem in which the two non-zero principal values are of the same sign, the largest stress difference is $\sigma_1$, i.e., $S_{13}$. A typical result is shown in Fig. 2 for $\sigma_1$ and from such a response the alternating stress intensity is directly found.

A specific chamber could be required to sustain a number of target ignitions, N, of essentially the same yield. Then, of course, a stress history such as Fig. 2 would be repeated N times. The ASME cumulative damage code specification is independent of the sequence of the various load cycles. Thus for the TDF application, the criterion would be based upon N cycles corresponding to the first positive to first negative extreme, N cycles for the second positive peak to the second negative, etc. Using this procedure with Eq. (1) and the appropriate fatigue design curve, the number of allowable ignitions can be determined.

## BASE CASE - 3 m RADIUS/200 MJ YIELD

The basic cavity parameters used correspond to a 200 MJ yield and a 3 meter radius chamber for which the peak impulsive pressure at the wall is 0.64 MPa. The pulse profile is shown in Fig. 3(a). In addition to using this loading, the maximum pressure was also conservatively doubled to 1.28 MPa for reasons associated with the fireball code calculations.

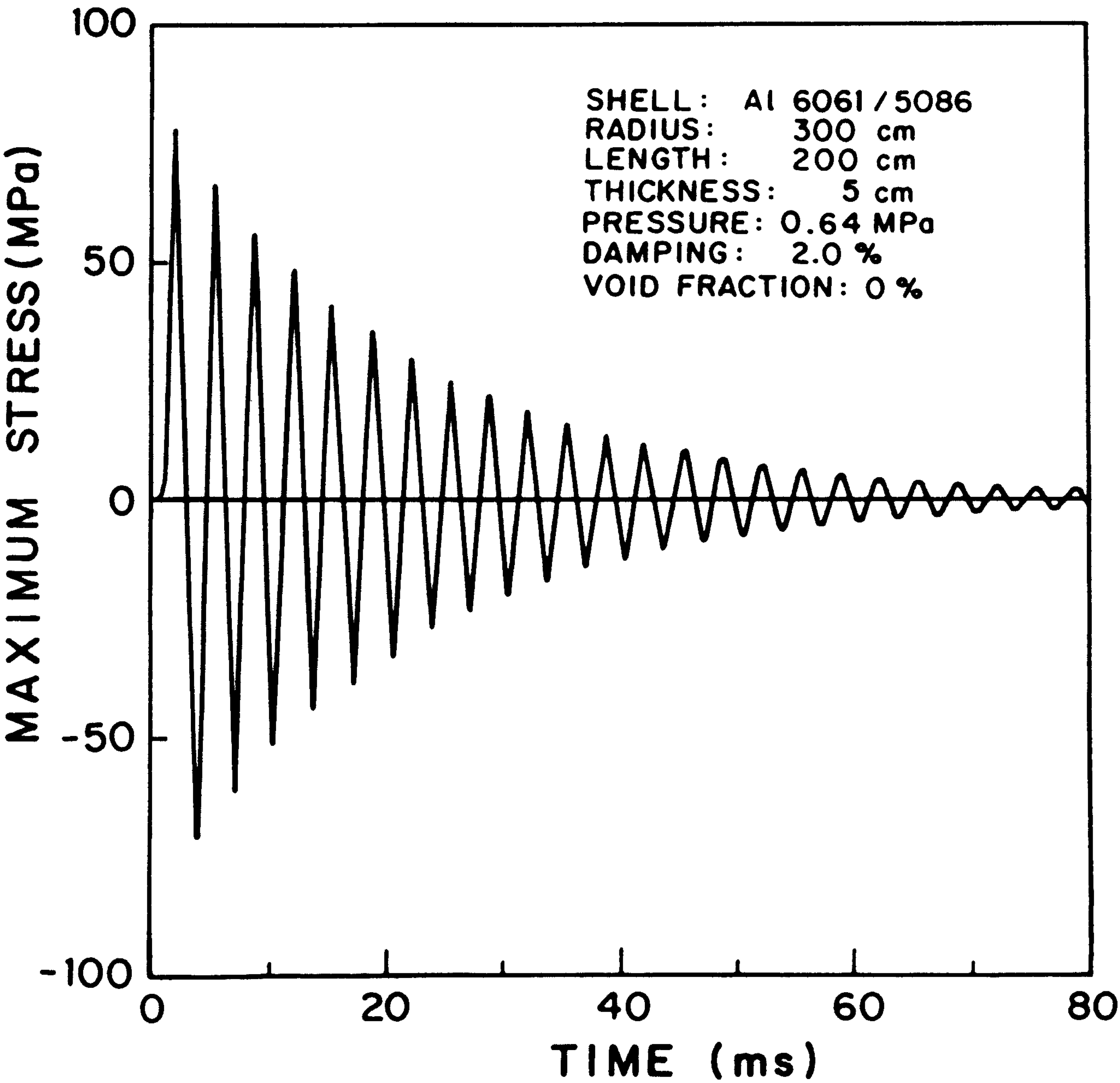
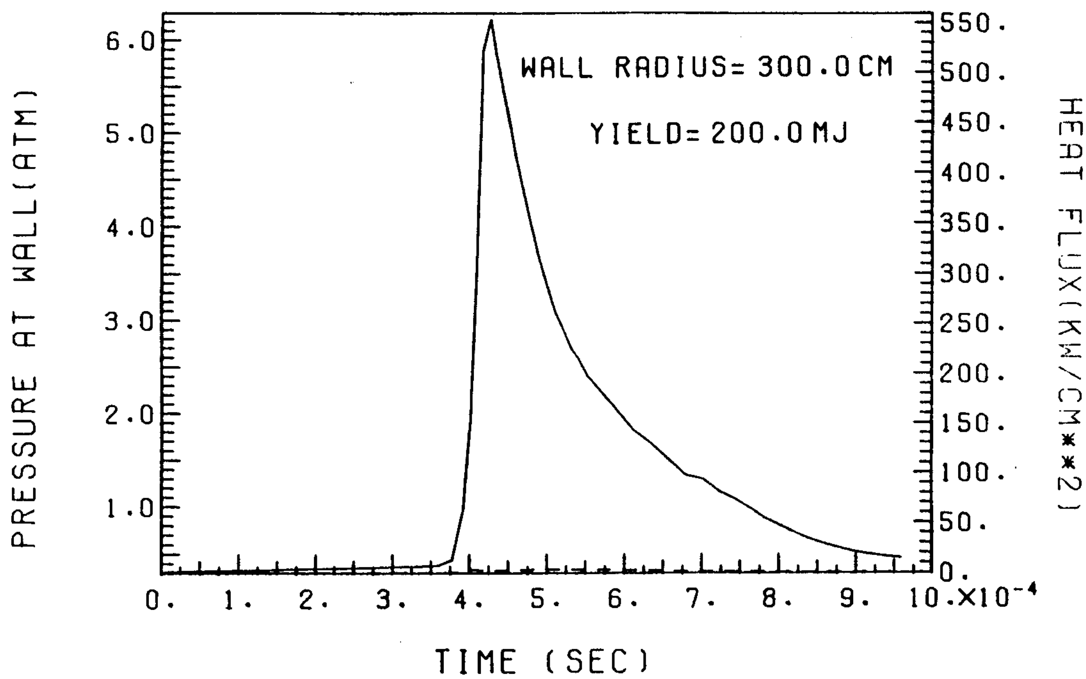



Fig. 2. First wall stress history.



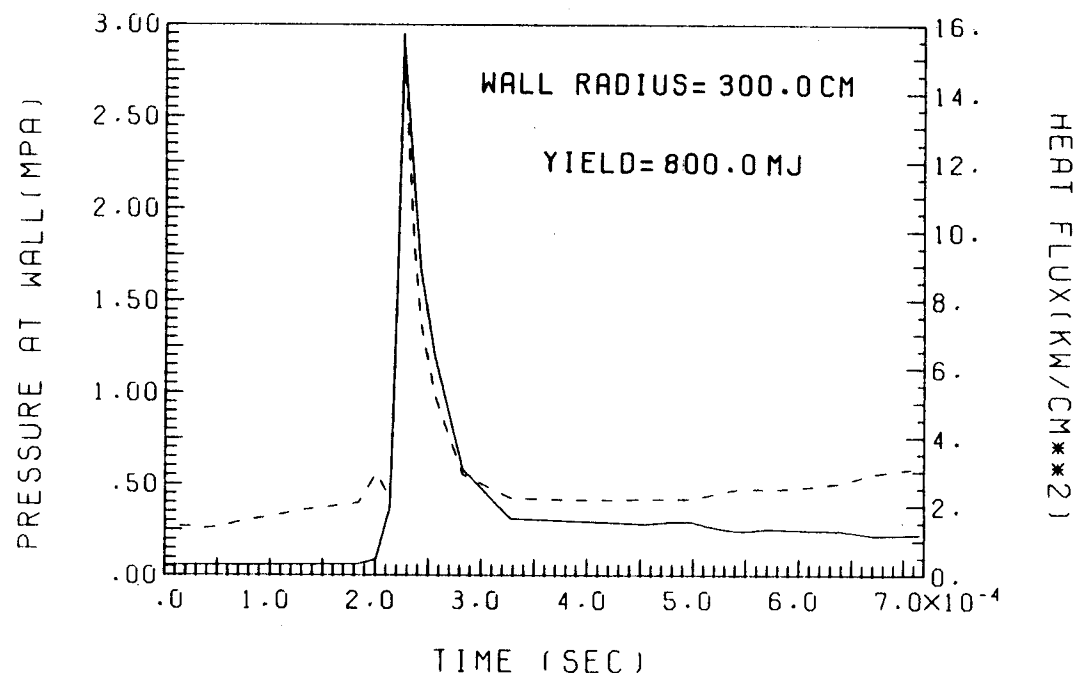




Fig. 3. Pressure and heat flux at first wall.

The first material considered for the vessel was 2-1/4 Cr-1 Mo steel, a ferritic alloy widely used in the nuclear industry. Its physical properties are well documented and general characteristics include low radiation damage and activation, good fabricability and strength. For ASME purposes it would be included in the category for carbon, low alloy, high tensile steels. The design data for Fig. I-9.1 and Table I-9.1 of ASME[1] was incorporated directly into the UW fatigue code and the data has also been reconstructed in Fig. 4.

The second material considered for the TDF reaction chamber was aluminum 6061-T6. It is generally regarded as a low activation material and easily fabricated. This alloy is strain hardenable and shows a significant loss of strength from welding. The high cycle fatigue properties of unwelded ALCOA 6061-T6 were presented by Powell et al.,[5] and are reproduced in Fig. 5. The curve includes a derating factor of 2 on stress. The stress-based fatigue results for this material identify the best life estimates for Al 6061-T6, i.e., best in the sense that there has been no assessment of degradation from fabrication.

The other extreme to consider is the effect of welding on fatigue life of this alloy. The American Society of Civil Engineers has developed design guidelines[6] which have been adopted by major commercial suppliers. The relevant code information has been replotted in Fig. 6. According to ASCE, the curve has a built-in safety factor of 1.35. Test results for plate samples[7] indicate that the ASCE design formulas provide factors of safety against failure under repeated loading of at least 1.35, the margin being larger for low cycle data.

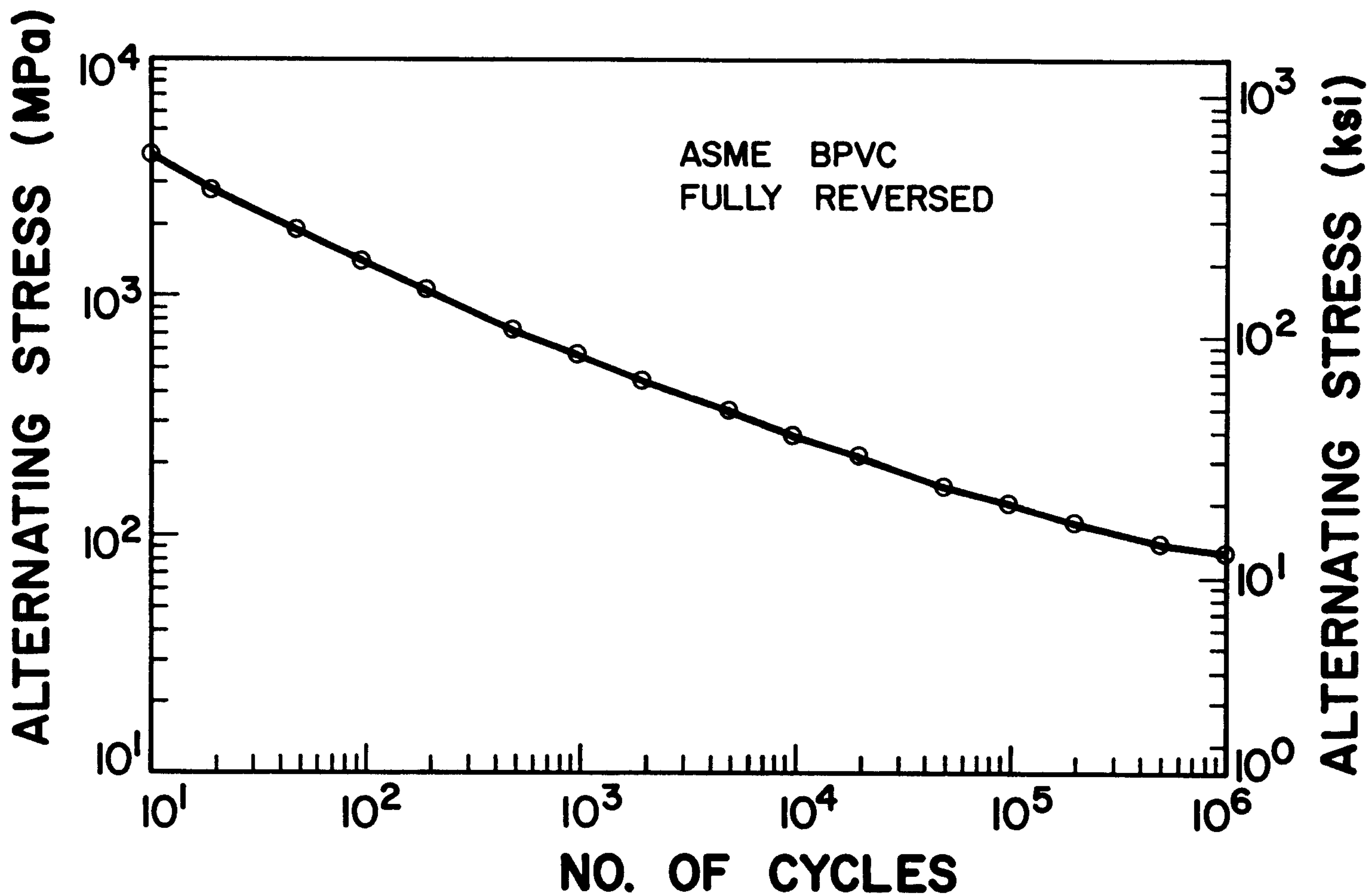



Fig. 4 Fatigue design data for low alloy, high strength steels.

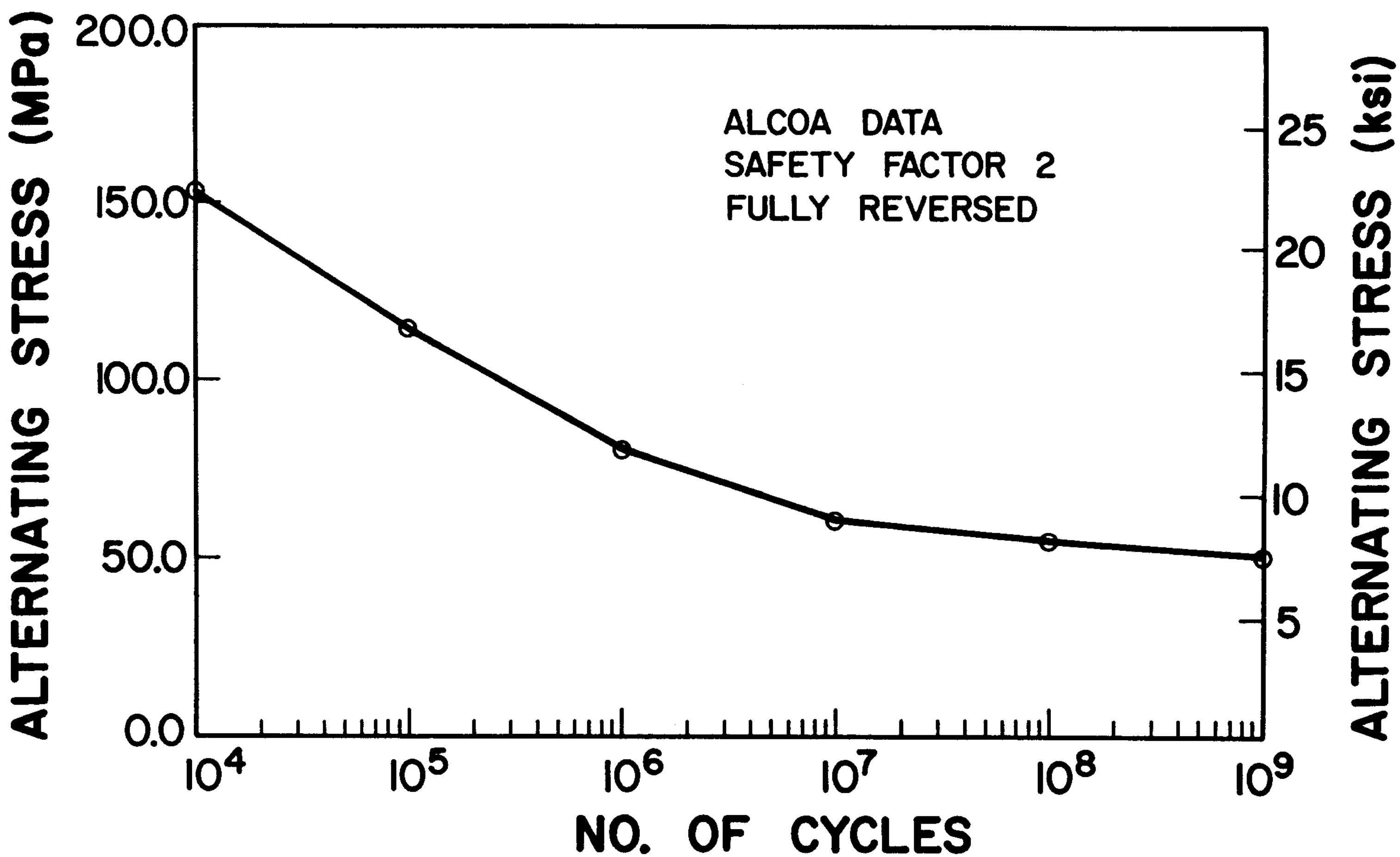



Fig. 5 Fatigue data for unwelded Al 6061-T6.

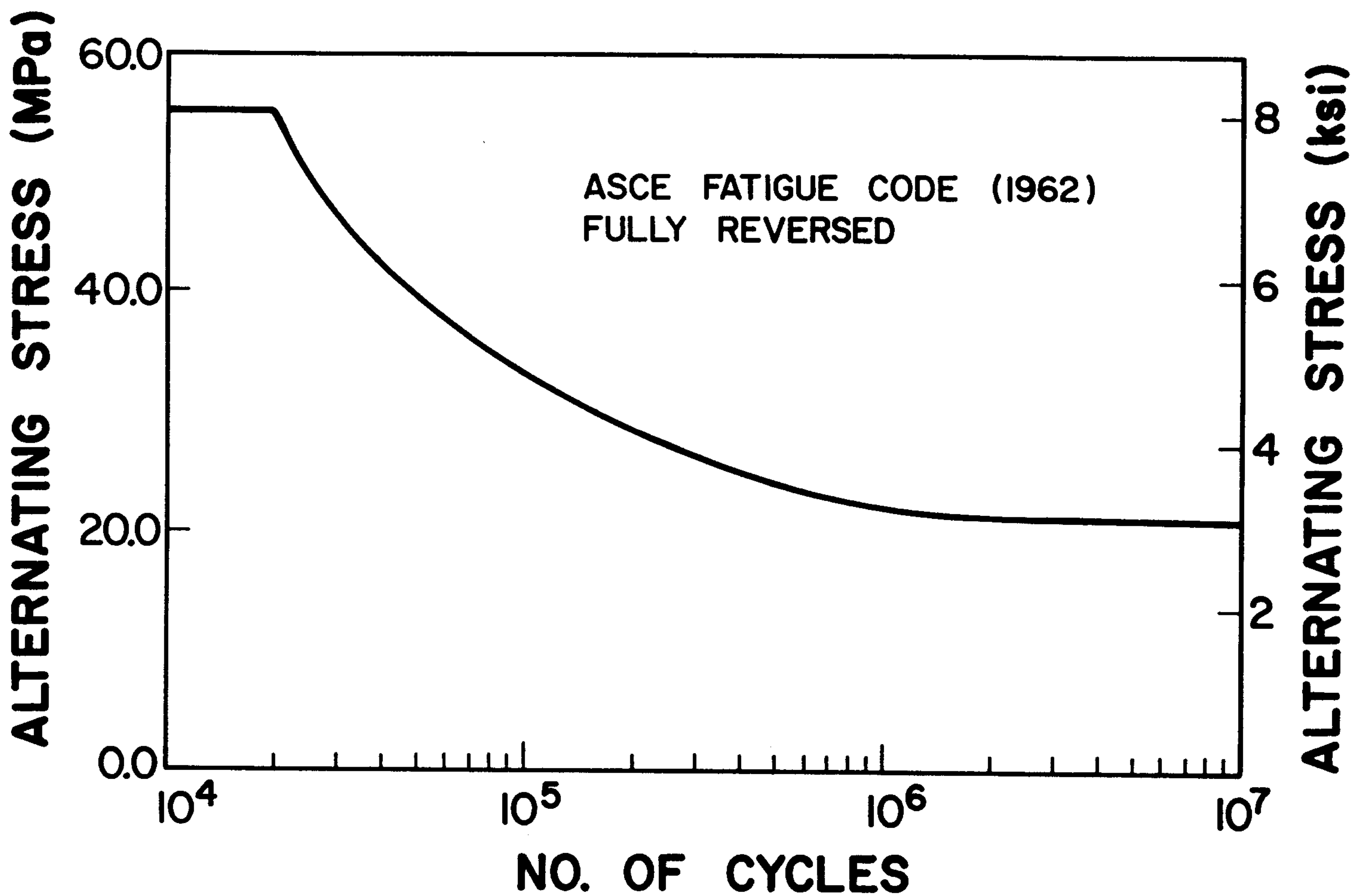



Fig. 6 Fatigue design data for welded Al 6061-T6.

The base case results for high strength steel are shown in Fig. 7. It can be seen that the design goal of 15,000 ignitions can be met with a wall as thin as 3.6 cm. Because of the apparent fatigue life beyond the design goal, an additional variation in the calculations was considered. The number of low yield (200 MJ) shots was specified at 15,000 and the number of extra high yield (800 MJ) shots which could be sustained was determined for a particular wall thickness. The pressure pulse for these limited 800 MJ shots is shown in Fig. 3(b). The corresponding fatigue results are presented in Fig. 8 based upon the best estimate of the impulsive pressure and its doubled value for the 3 m chamber of low alloy, high strength steel.

Results for unwelded Al 6061-T6 are presented in Fig. 9 for 200 MJ yields and a chamber radius of 3 meters. The unwelded aluminum compares favorably with steel. However, this is not the case for welded Al 6061-T6 as shown by Fig. 10. Achieving the design goal of 15,000 shots for a single vessel at the double pressure would require a very thick wall.

PARAMETRIC COMPARISONS FOR DIFFERENT CHAMBER SIZES AND YIELDS

Fatigue life calculations were also carried out for various combinations of yield and chamber radius. The relevant dynamic wall pressures as determined by Uesaka and Moses[8] are listed in Table 1. Generally, computations were done for the "single pressure," "double pressure" and the three materials discussed previously. The base case results corresponding to a yield of 200 MJ and a radius of 3 m were presented in Figs. 7, 9 and 10. Every combination is not presented. In some cases, the material yield stress was exceeded. In others, calculations were not necessary (redundant) when the design goal was shown to be possible under more severe conditions. For example, since a 3 m steel chamber can sustain the 200 MJ overpressure of 0.64 MPa, it will also be

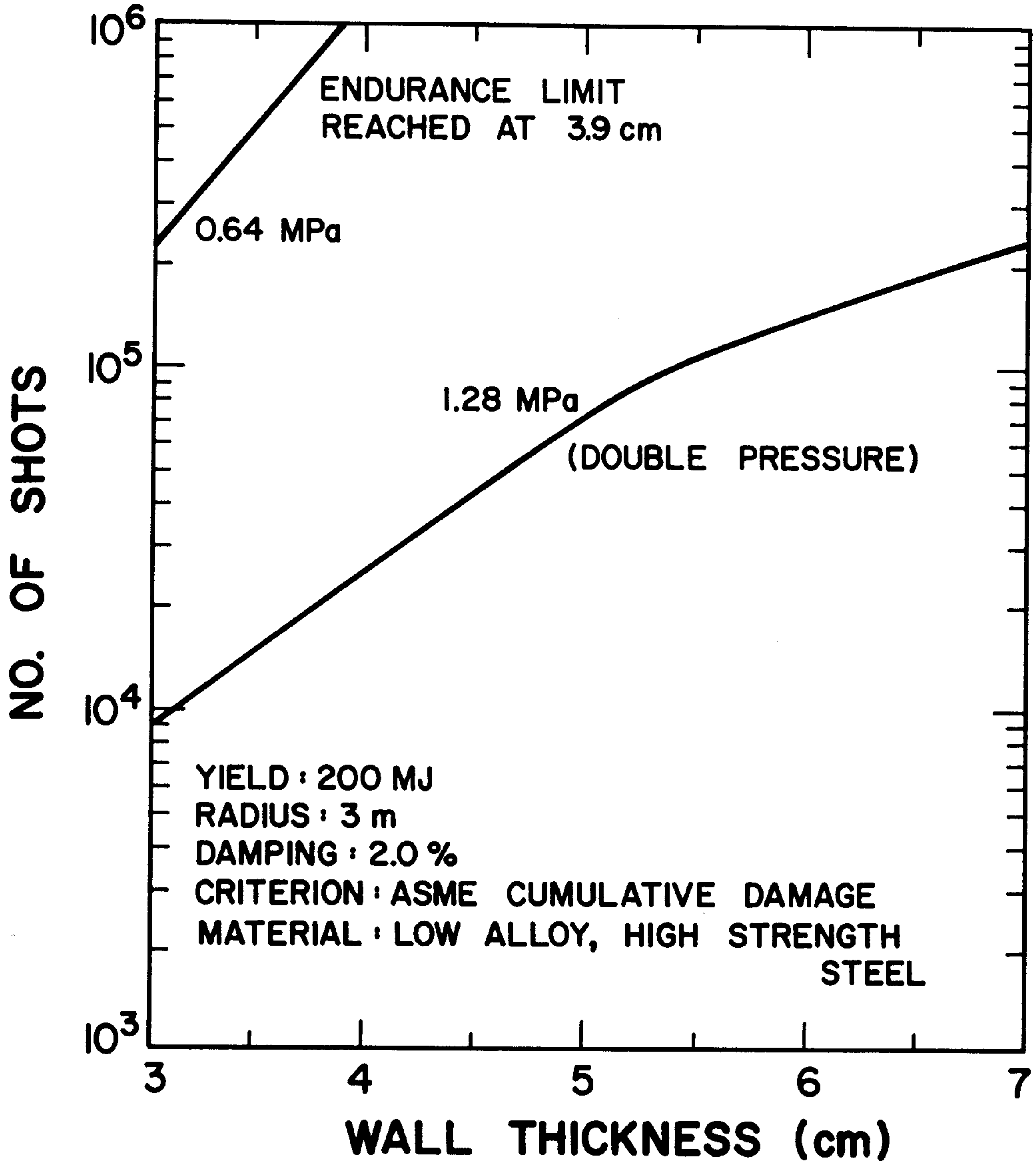



Fig. 7 Fatigue life of 3 m steel chamber for 200 MJ yield.

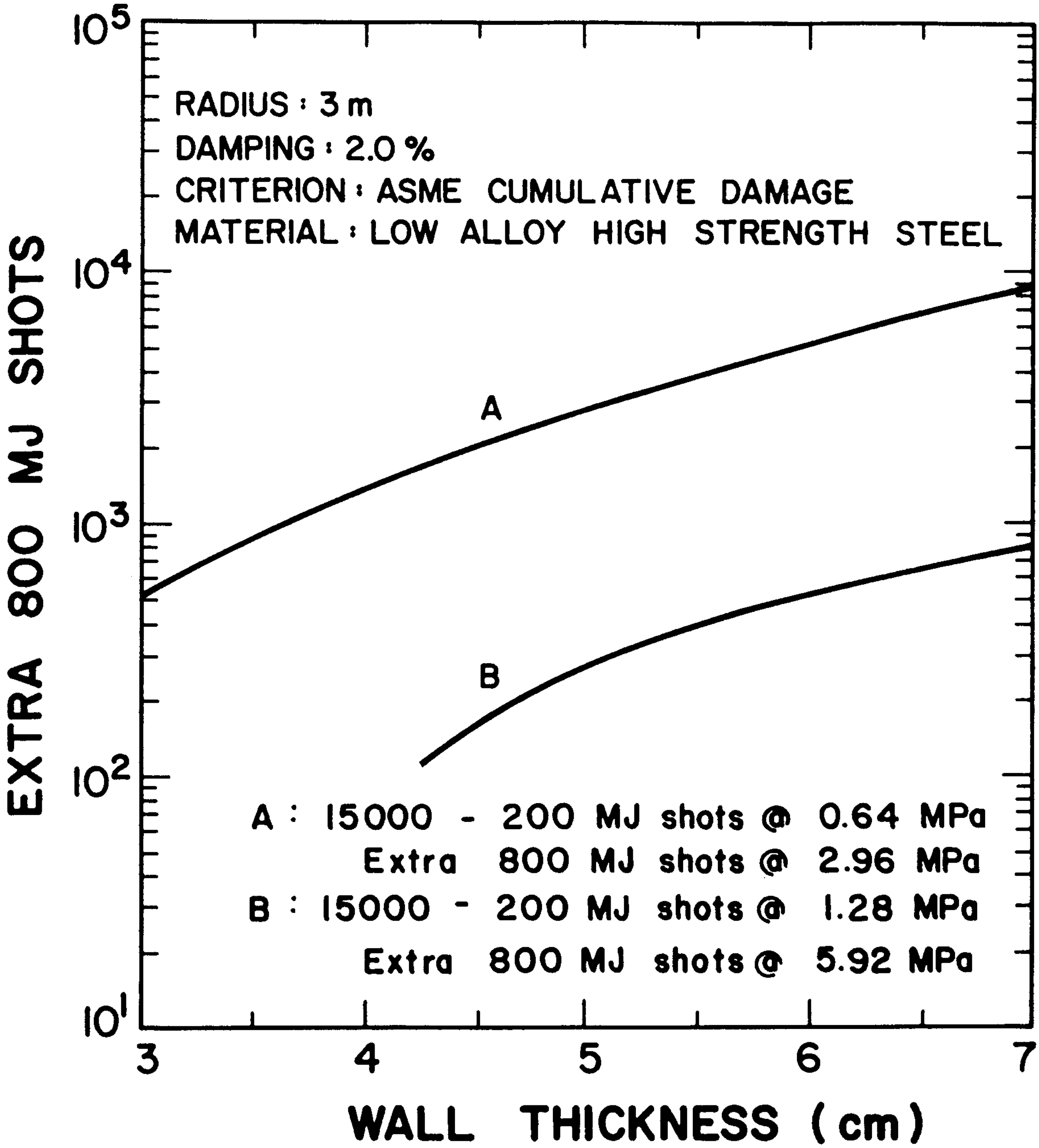



Fig. 8 Fatigue life of 3 m steel chamber for combined yields.

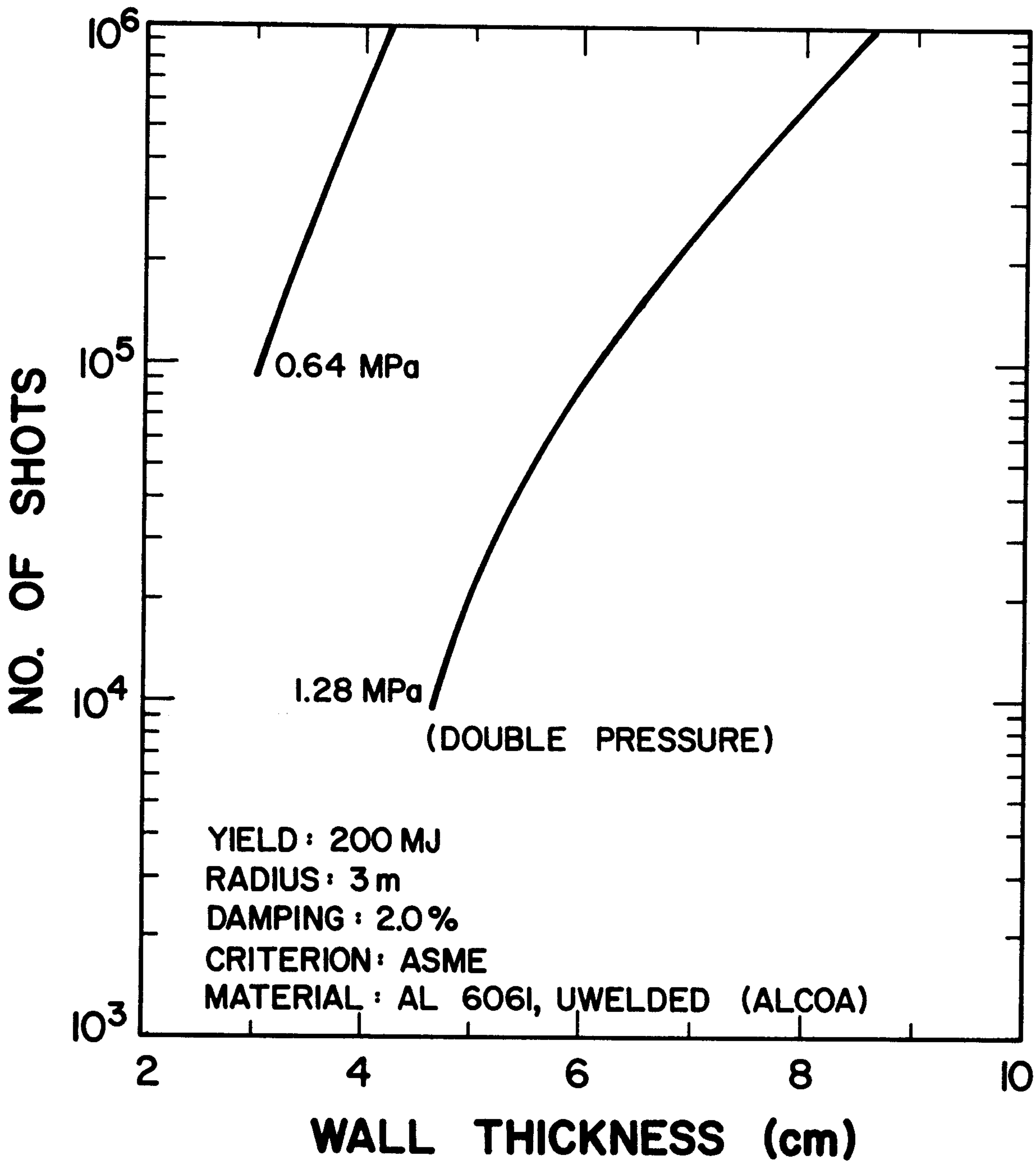



Fig. 9 Fatigue life of 3 m unwelded Al chamber for 200 MJ yield.

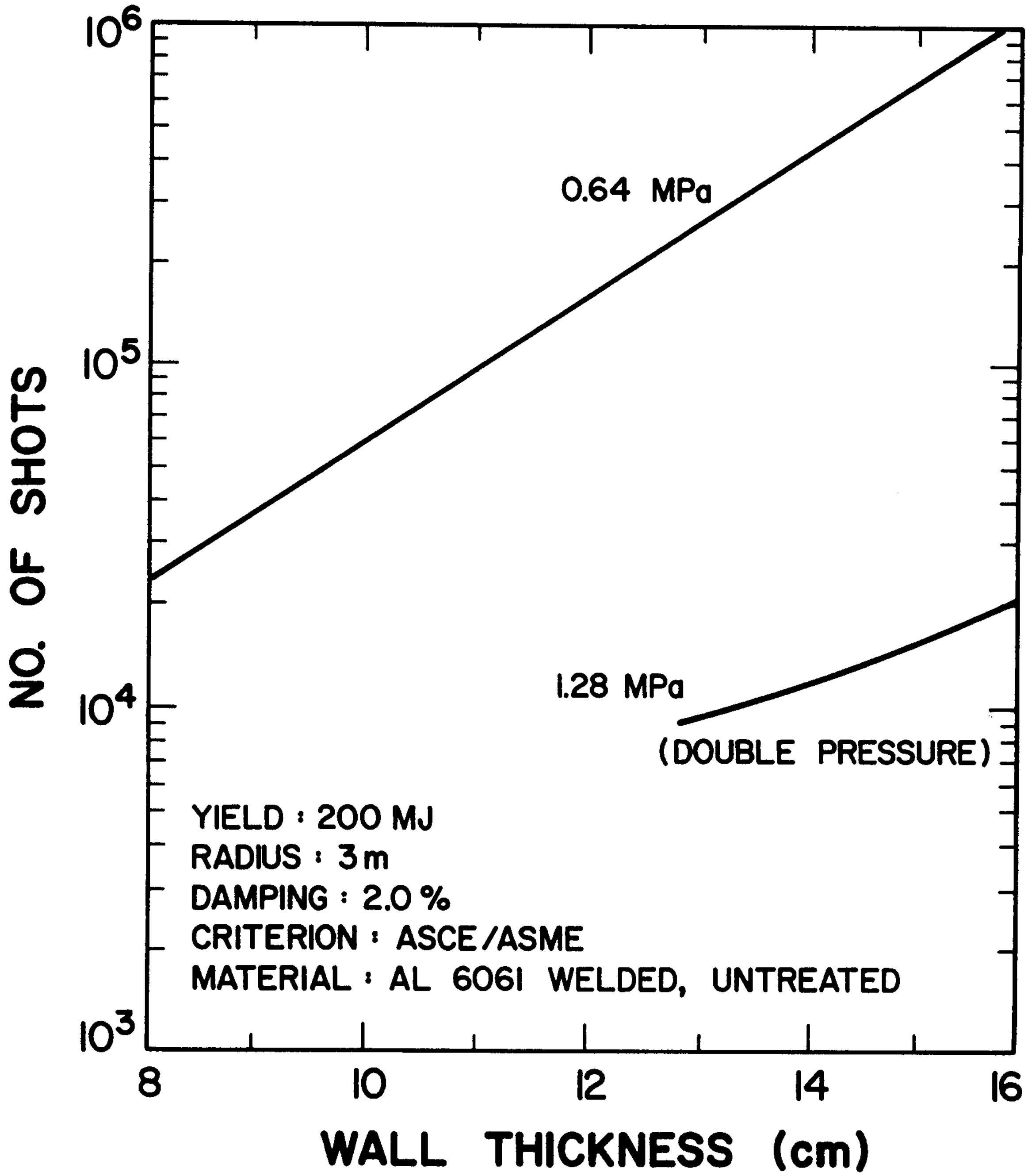



Fig. 10 Fatigue life of 3 m welded Al chamber for 200 MJ yield.

Table 1. Peak Dynamic Wall Pressure (MPa)

| | | Yield | | |
|---|---|---|---|---|
| | | 50 MJ | 200 MJ | 800 MJ |
| Radius | 1.5 m | 1.17 | 5.89 | 5.42 |
| | 3.0 m | 0.199 | 0.64 | 2.96 |
| | 6.0 m | 0.0668 | 0.134 | 0.365 |

satisfactory for 50 MJ shots which have an overpressure of 0.199 MPa. A summary is presented in Table 2, in which X denotes calculations presented, R denotes a redundant case and Y indicates yield stress limits exceeded. The corresponding fatigue life graphs are shown in Figs. 11-20.

## CONCLUSIONS

Results of cumulative damage fatigue stress calculations have been made for proposed TDF cylindrical chambers. These are presented in the form of parametric design curves for low alloy, high strength steel, unwelded and welded Al 6061-T6, covering a range of values for radius, thickness and target yield. It has been shown that the goal of 15,000 ignitions can be met for many chamber designs. For example, with the best estimate for dynamic wall pressure, steel chambers with radii of 1.5, 3 and 6 meters can sustain 15,000 shots at 50, 200 or 800 MJ. At the other extreme, design possibilities with welded Al 6061-T6 are more limited. Material yielding is predicted for some cases and a lifetime less than the design goal is the result for others. If necessary, in such cases objectives may be met by developing a more sophisti-

Table 2. Summary of Fatigue Calculations

| | | 50 MJ | 200 MJ | 800 MJ |
|---|---|---|---|---|
| 1.5 m | steel | X | X | R |
| | unwelded Al | X | X | R |
| | welded Al | X | Y | Y |
| 3.0 m | steel | R | X | X |
| | unwelded Al | R | X | X |
| | welded Al | R | X | Y |
| 6.0 m | steel | R | R | X |
| | unwelded Al | R | R | X |
| | welded Al | R | R | X |

X: Calculations Presented, R: Redundant, Y: Yield Stress Exceeded

cated wall design, replacing the chamber after its useful lifetime has been attained, or limiting the target yield.

## Acknowledgement

Support for this work has been provided by the U.S. Department of Energy.

## REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components.

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

3. "Development of Criteria for Seismic Review of Selected Nuclear Power Plants," H.M. Newmark and W.J. Hall, U.S. Nuclear Regulatory Commission Report, NUREG/CR-0098, 1978.

4. J.D. Stevenson, "Structural Damping Values as a Function of Dynamic Response Stress and Deformation Levels," Nucl. Eng. & Design 60, pp. 211-237, (1980).

5. J.R. Powell et al., "Design Studies of an Aluminum First Wall for INTOR," 4th Topical Meeting on Technology of Controlled Nuclear Fusion, Oct. 1980.

6. "Suggested Specifications for Structures of Aluminum Alloys 6061-T6 and 6062-T6," Report of Task Committee on Lightweight Alloys, J. Str. Div. ASCE, V.88, No. ST6, pp. 1-95, Dec. 1962.

7. G.E. Nordmark and J.W. Clark, "Fatigue of Joints in Aluminum Alloy 6061-T6," J. Str. Div. ASCE, pp. 35-50, Dec. 1964.

8. M. Uesaka and G.A. Moses, "Parametric Survey of Microfireball Calculations for the Light Ion Fusion Target Development Facility Design," University of Wisconsin Fusion Engineering Program Report UWFDM-533 (Aug. 1983).

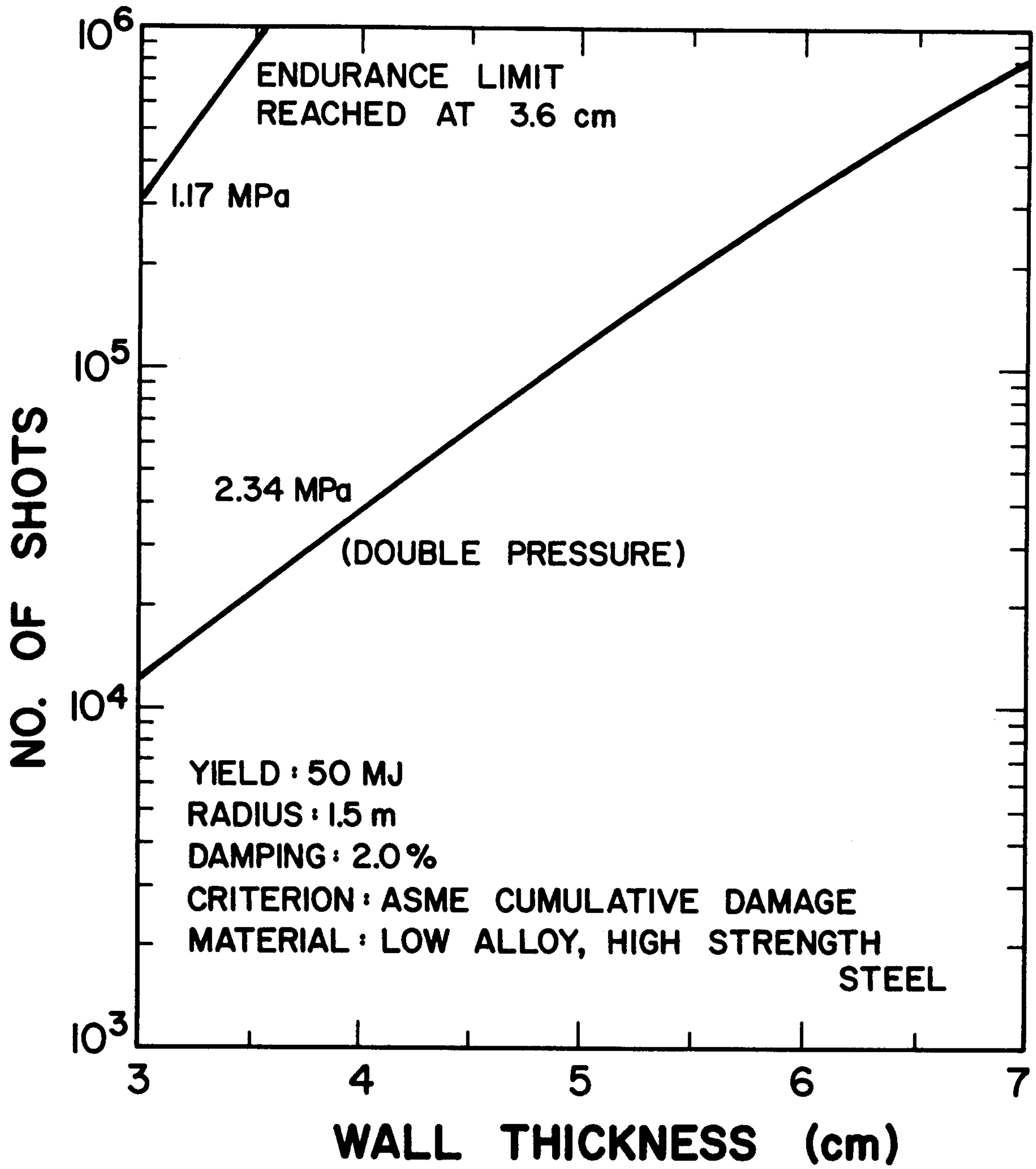



Fig. 11 Fatigue life of 1.5 m steel chamber for 50 MJ yield.

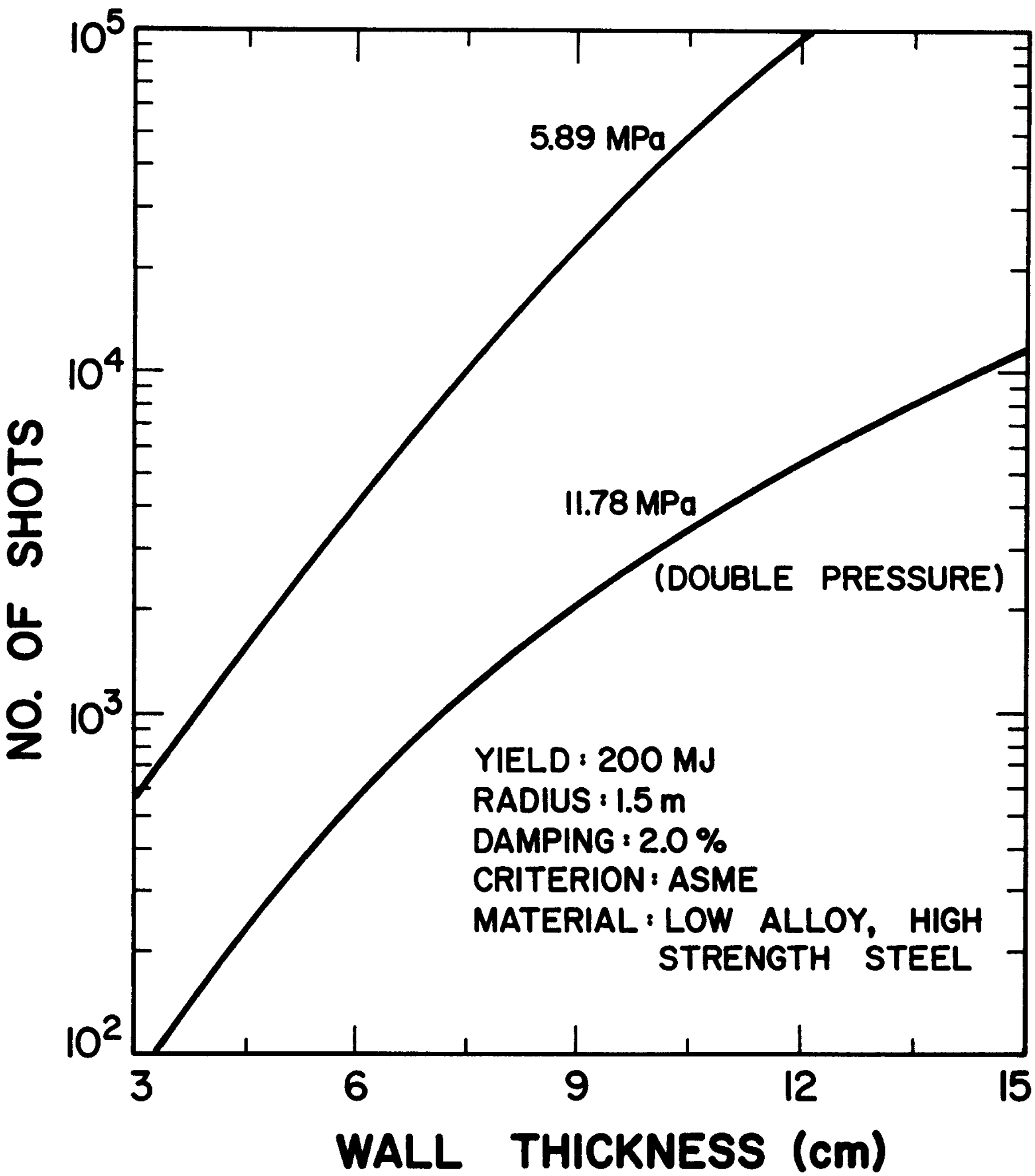



Fig. 12 Fatigue life of 1.5 m steel chamber for 200 MJ yield.

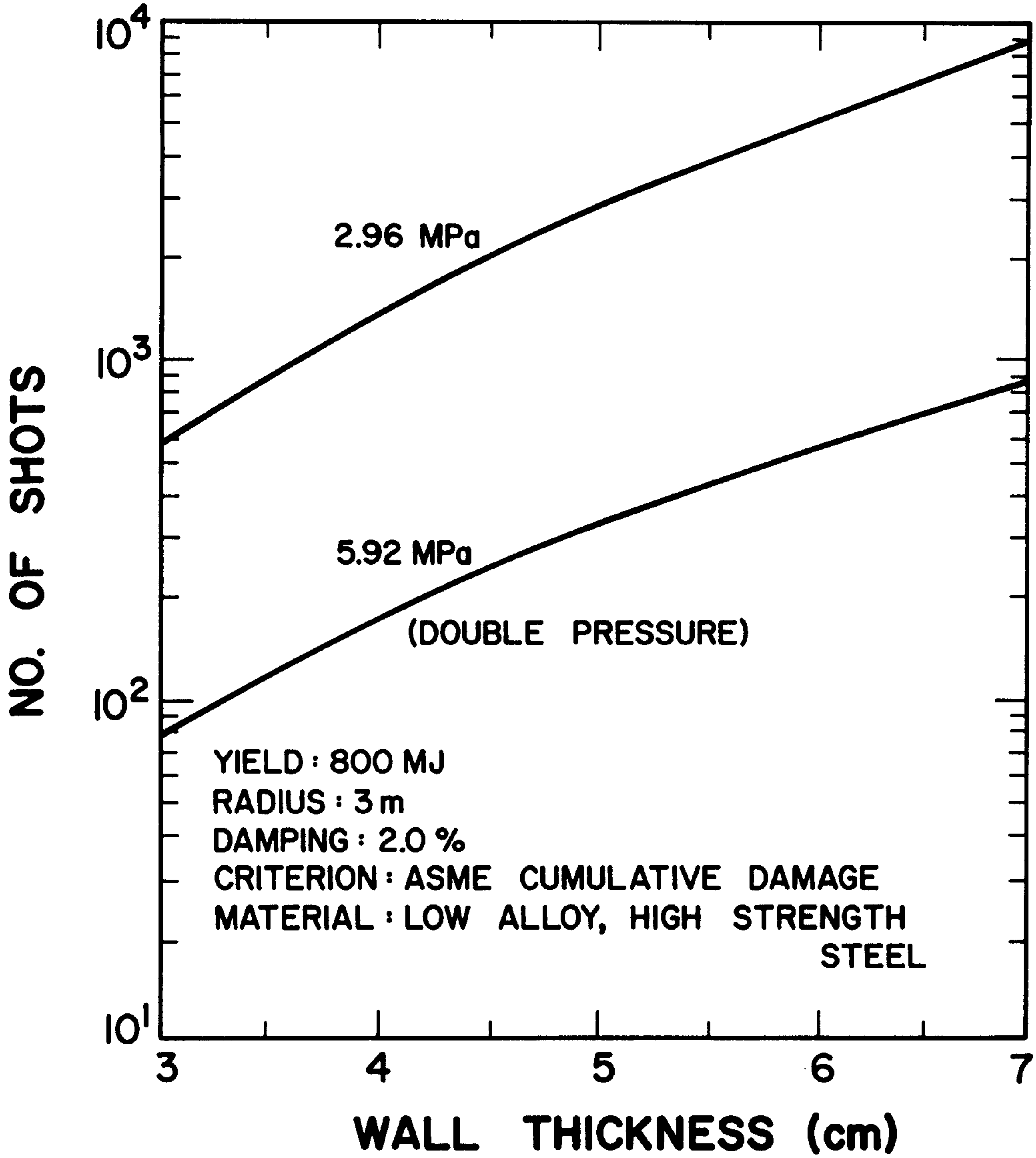



Fig. 13 Fatigue life of 3 m steel chamber for 800 MJ yield.

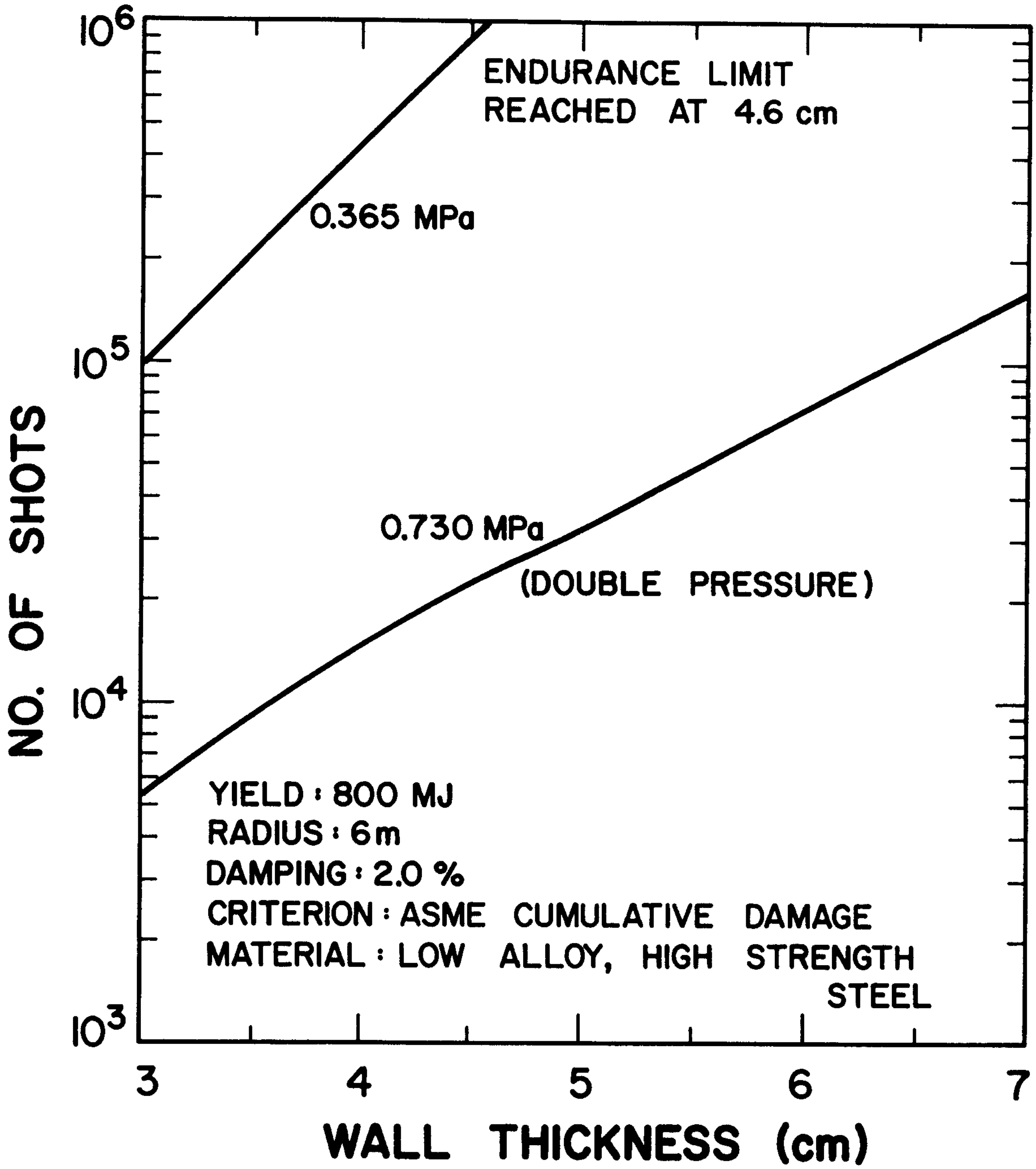



Fig. 14 Fatigue life of 6 m steel chamber for 800 MJ yield.

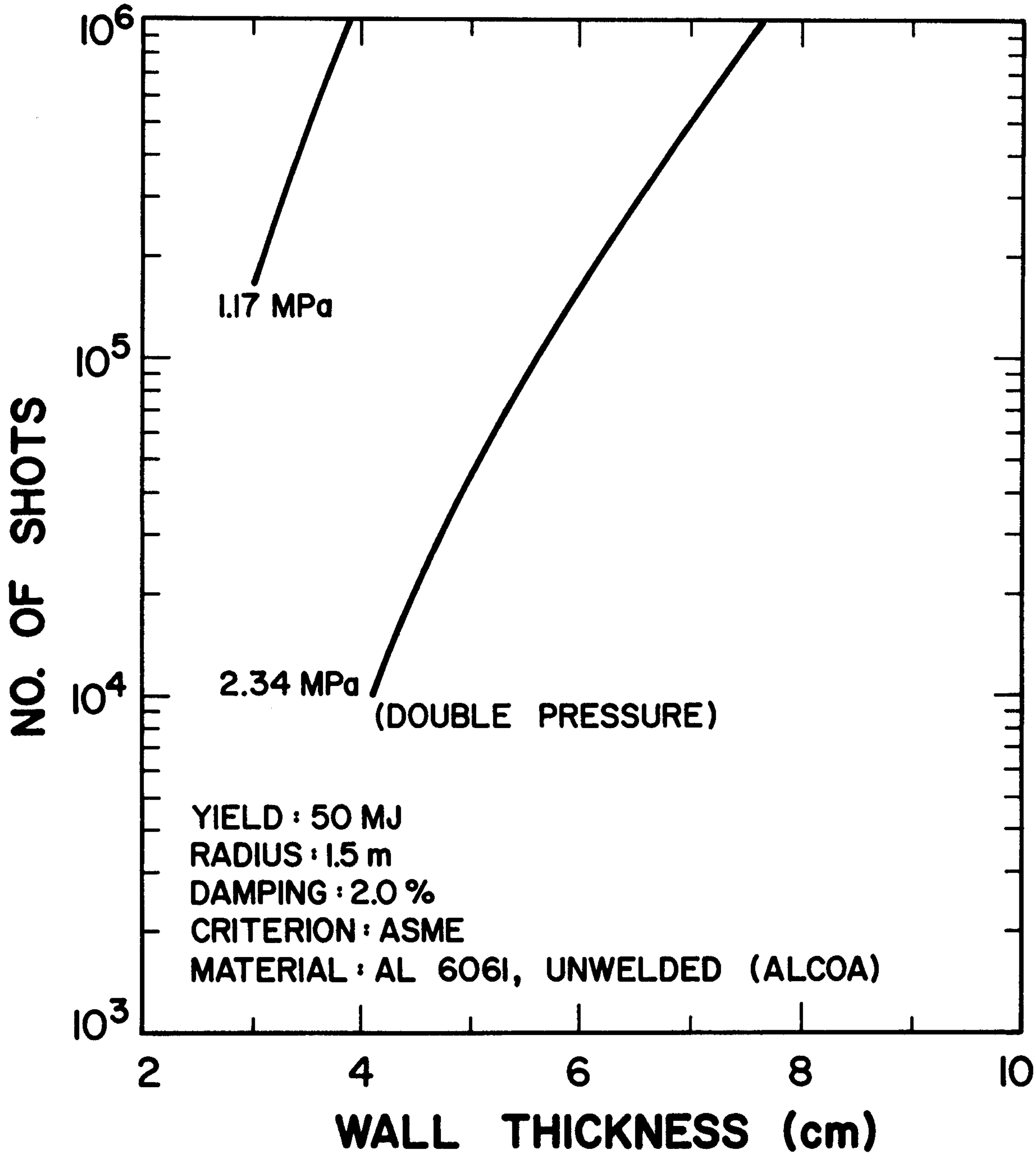



Fig. 15 Fatigue life of 1.5 m unwelded Al chamber for 50 MJ yield.

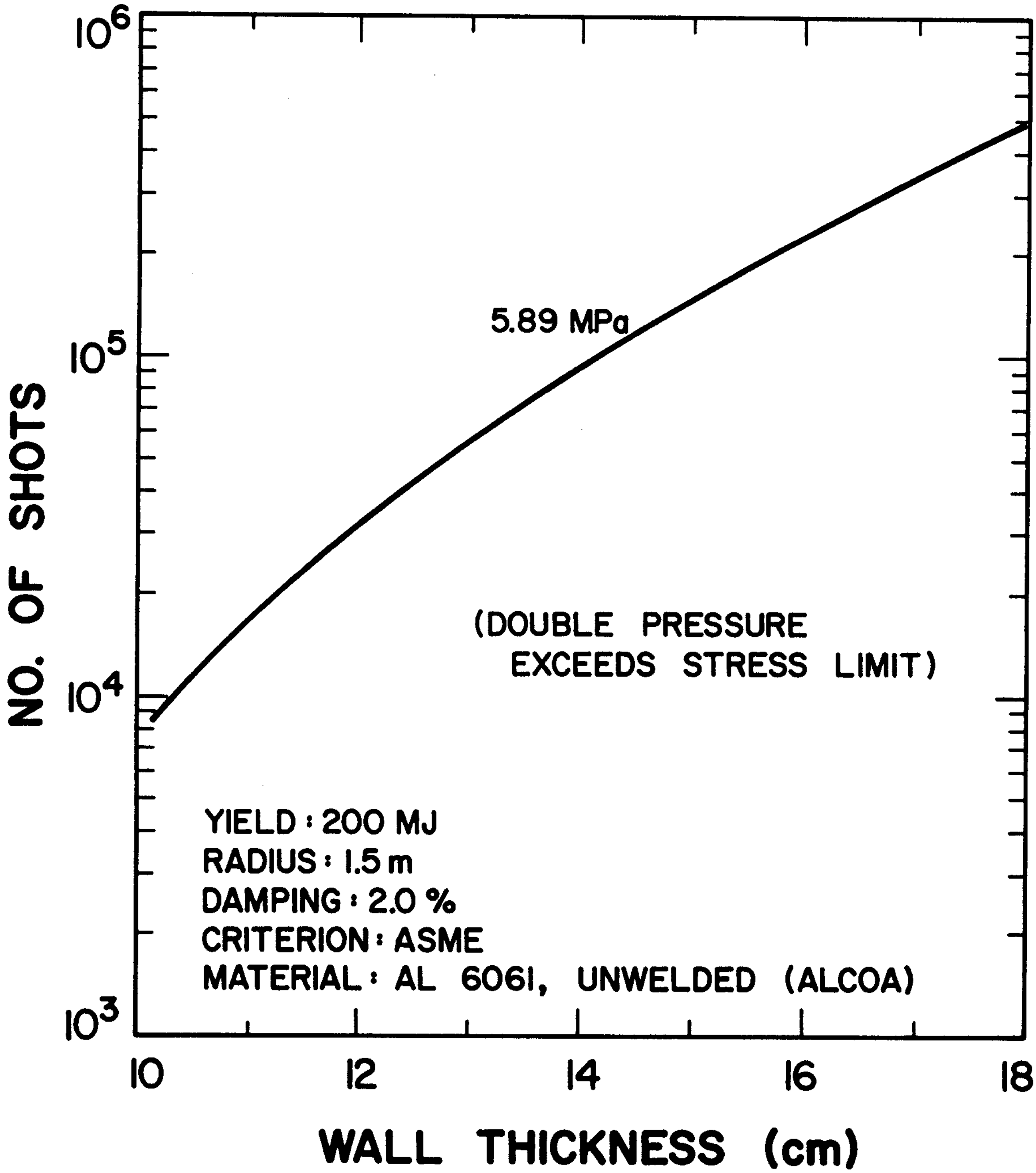



Fig. 16 Fatigue life of 1.5 m unwelded Al chamber for 200 MJ yield.

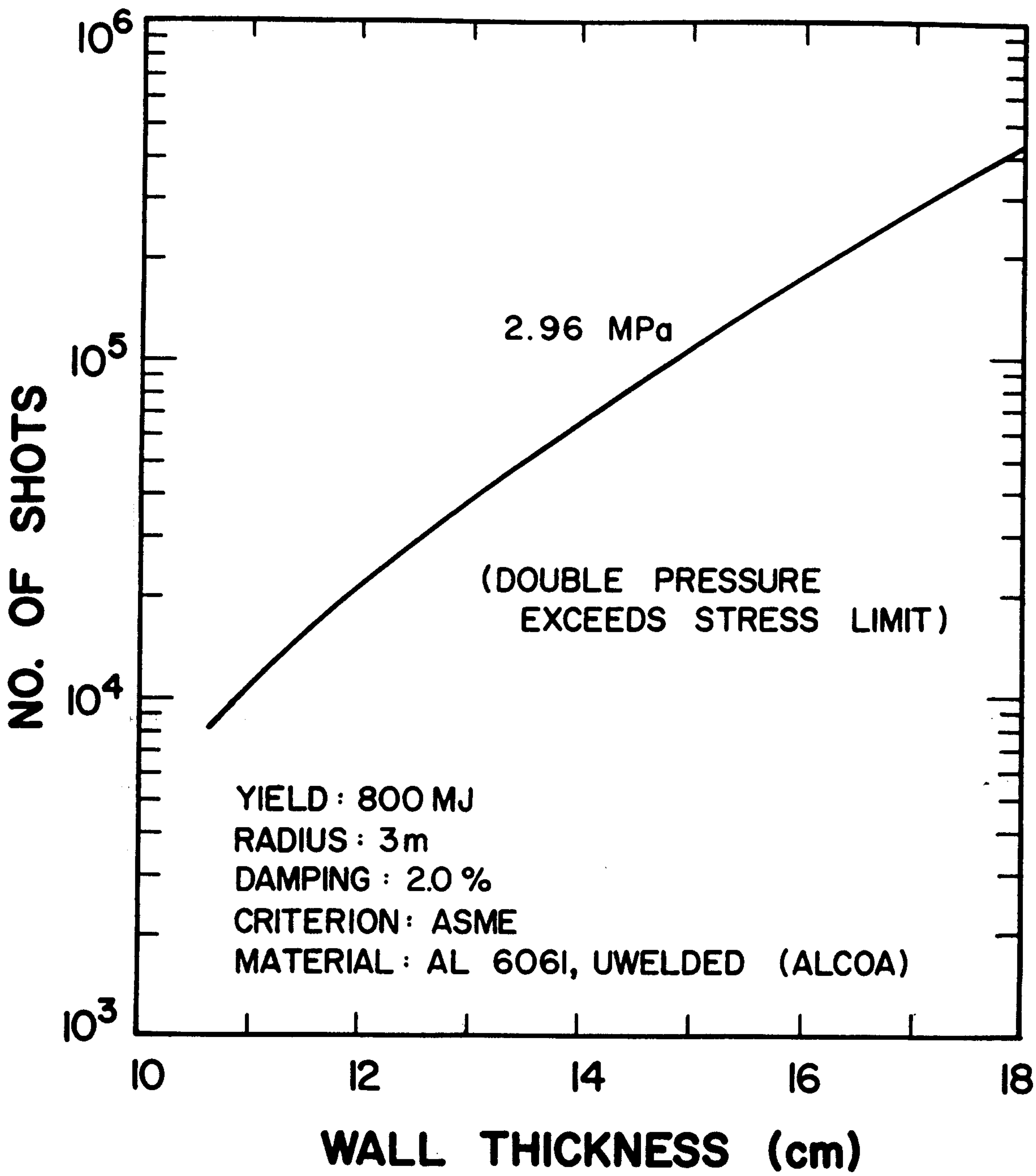



Fig. 17 Fatigue life of 3 m unwelded Al chamber for 800 MJ yield.

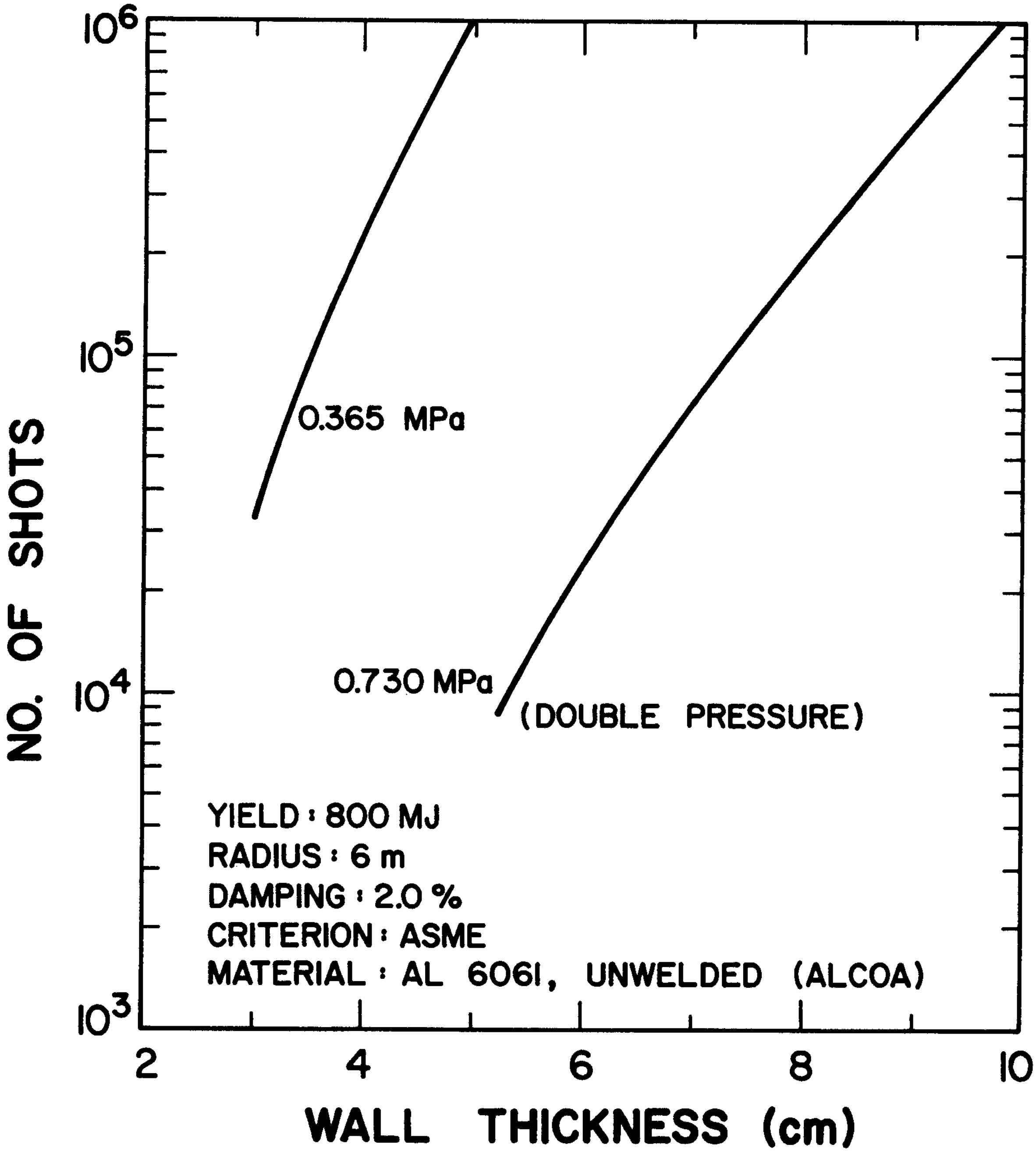



Fig. 18 Fatigue life of 6 m unwelded Al chamber for 800 MJ yield.

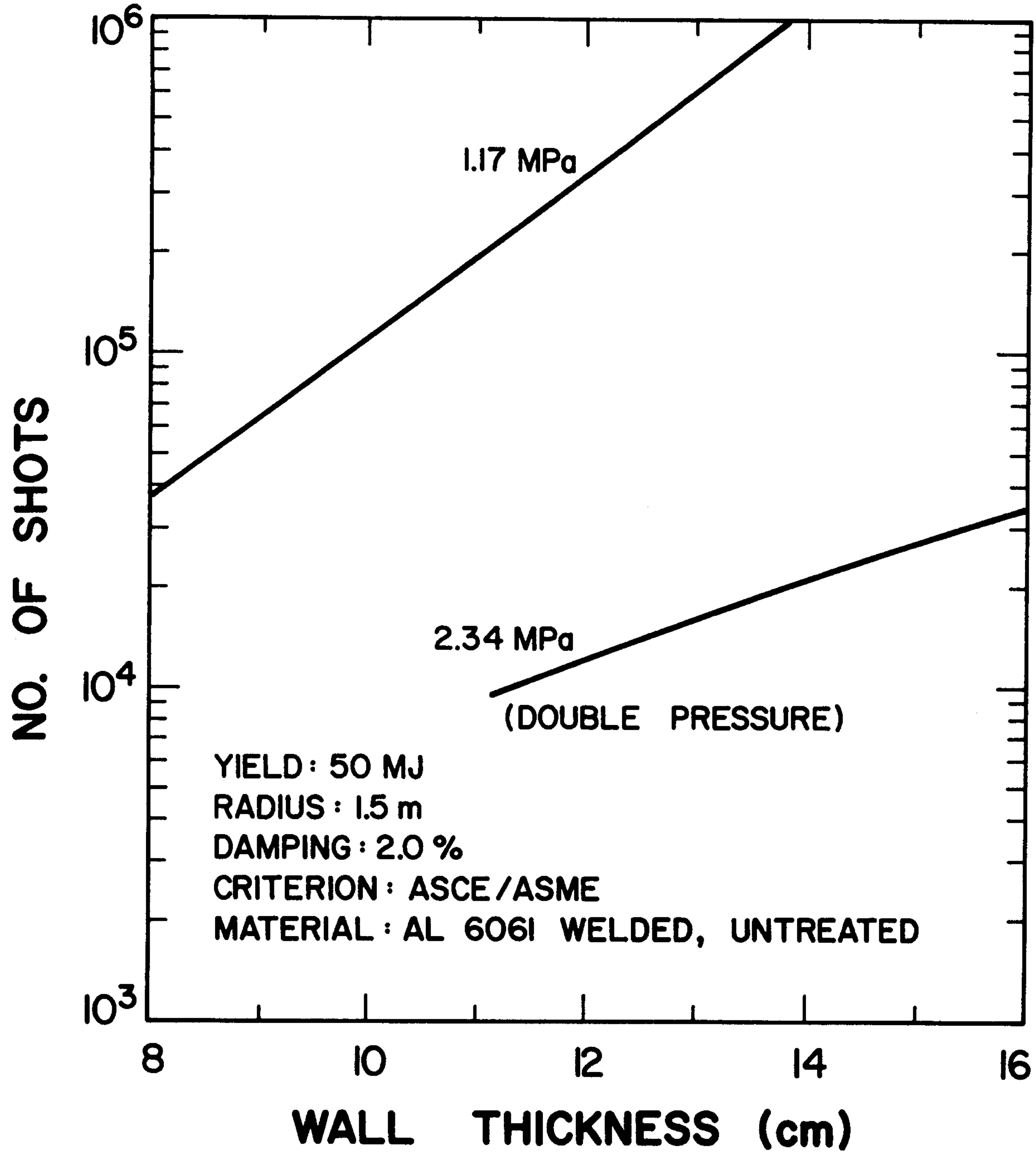



Fig. 19 Fatigue life of 1.5 m welded Al chamber for 50 MJ yield.

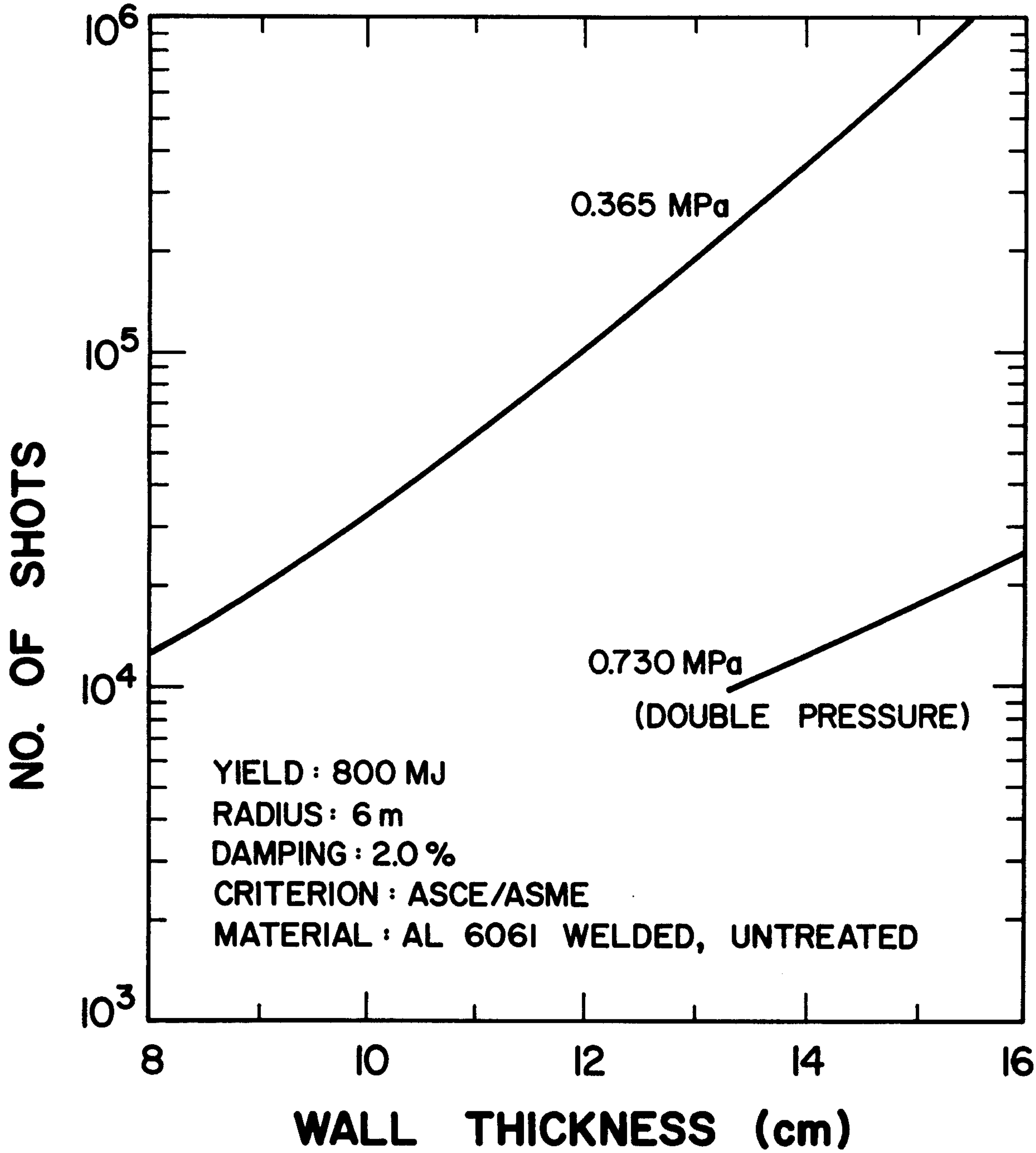



Fig. 20 Fatigue life of 6 m welded Al chamber for 800 MJ yield.