NASA CONTRACTOR REPORT

NASA CR-2439

NASA CR-2439

EXPERIMENTAL EVALUATION OF STRESSES IN CYLINDRICALLY HOLLOW (DRILLED) BALLS

by L. J. Nypan

Prepared by
CALIFORNIA STATE UNIVERSITY
Northridge, Calif. 91324
for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR 2439		
4. Title and Subtitle EXPERIMENTAL EVALUATION OF STRESSES IN CYLINDRICALLY HOLLOW (DRILLED) BALLS		5. Report Date AUGUST 1974 6. Performing Organization Code
7. Author(s) L. J. Nypan		8. Performing Organization Report No. None
9. Performing Organization Name and Address California State University 18111 Nordhoff Street Northridge, California 91324		10. Work Unit No. 11. Contract or Grant No. NGL-05-062-002
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		13. Type of Report and Period Covered Contractor Report 14. Sponsoring Agency Code

15. Supplementary Notes

Final Report. Project Manager, Harold H. Coe, Fluid System Components Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

An experimental stress analysis was undertaken to evaluate stresses within cylindrically hollow (drilled) bearing balls proportioned for 40, 50, and 60 percent mass reductions. Strain gage rosettes were used to determine principal strains and stresses in the steel ball models statically loaded in various orientations. Results are reported for 127 mm (5 in.) OD balls under 44, 500 N (10, 000 lb) loads. Similitude considerations permit these results to be applied to calculate stresses in actual size drilled bearing balls proportioned to these mass reductions.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Bearings; Ball bearings; Drilled ball; Stress	Unclassified - unlimited Category 15

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	128	$4.75

* For sale by the National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. SUMMARY

An experimental stress analysis was undertaken to evaluate stresses within cylindrically hollow (drilled) bearing balls proportioned for 40, 50, and 60% mass reductions. Strain gage rosettes were used to determine principal strains and stresses in the steel ball models statically loaded in various orientations.

Results are reported for 127 mm (5 in) OD balls under 44,500 N (10,000 lb) loads. Similitude considerations permit these results to be applied to calculate stresses in actual size drilled bearing balls proportioned to these mass reductions.

II. INTRODUCTION

Aircraft gas turbine engines currently operate in a speed range of 1.5 to 2 million DN (bearing bore in mm times shaft speed in rpm). It is estimated that engine designs of the next decade will require bearings to operate at DN values of 3 to 4 million. In this DN range, the reduction in bearing fatigue life due to the high centrifugal forces developed between the rolling elements and outer race becomes prohibitive.

To solve the problem of reduced fatigue life in high-speed ball bearings various methods of reducing centrifugal force have been proposed. One of these is to reduce the ball mass by "drilling" a cylindrical hole through them using electrolytic machining techniques. Full-scale bearing tests with cylindrically hollow (drilled) balls have demonstrated that operation at speeds to 3 million DN is possible (1).[1] Fracture of the drilled balls has also been experienced during the operation of the full-scale bearings.

Analysis of these failures and of the effect of changes in ball geometry on high speed bearing operation has been handicapped by the difficulty of application of theory to predict stresses existing in the balls under bearing loads and centrifugal forces.

Strain gage techniques were used to determine the surface stress distribution in drilled balls proportioned for mass reductions of 40, 50, and 60 per cent.

---

[1] Numbers in parentheses designate references at end of report.

III. MODELS

Actual bearing balls dynamically loaded in a full scale ball bearing would be difficult to instrument for experimental stress analysis. The ball models used in this study were selected for ease of fabrication and instrumentation. They were turned from mild steel bar stock with a radius cutting tool to a 127 mm (5 in OD) spherical contour, bored to an ID calculated to provide the desired mass reduction of 40, 50, and 60 per cent, and then chamfered as actual bearing balls. Figure 1 gives model dimensions. The mild steel material simplified metal cutting. Its lack of hardness and low value of yield stress were not problems as care was taken to insure that strains were always within the elastic range. The 127 mm (5 in) model size seemed to be compatible with available 1 mm gage length strain gage rosettes and proved easy to position and load in a universal testing machine. TML ZFRA-1 (1 mm gage length) 45^{0} strain gage rosettes were mounted on the models in locations shown in Figure 2.

The rosettes were mounted with one strain gage of each rosette aligned parallel to the axis of the hole or bore of the model. Other strain gages on the rosette backing were then automatically aligned at 45^{0} and 90^{0} to the axis of the hole. A line of rosettes was thus established parallel to the bore axis on the interior and exterior of the model. As the models were symmetric about the ball mid plane perpendicular to the bore only one half of the model was strain gaged. The strain gaged half was repositioned to replace the ungaged half and reloaded to obtain a complete strain distribution. Table 1 gives actual gage locations.

The location of the rosettes relative to the vertically downward compression loads applied to the model is defined by two angles, θ and ϕ.

Theta was taken as an angle of rotation about the axis of the bore of the model from an initial orientation with the line of rosettes directly under the load ($\theta = 0^{o}$ case). Data was taken at $\theta = 0^{o}$, 30^{o}, 60^{o} and 90^{o} orientations with the load. Phi was taken as an angle of inclination of the axis of the bore of the model with a horizontal plane imagined through the center of the model. Phi = 0^{o} is the symmetrically loaded case, while $\phi = 40^{o}$ resulted in the load being applied close to the edge of the hole as may be seen in Figure 4. Data was taken at $\phi = 0^{o}$, 20^{o}, and 40^{o} orientations with the load.

A 44,500 N (10,000 lb) load was usually required to obtain a response sufficient for accurate measurement in the 40 and 50% mass reduction models. This load was reduced for some of the more highly stressed cases and for the 60% reduction model to maintain model strains within the elastic range. In these cases the applied load was set at a simple fraction of the 44,500 N (10,000 lb) load, for example, 8,900 N (2,000 lb) on the 60% mass reduction model, and the measured strain corrected by this factor in order to have a constant basis for comparison of the response of all three models.

Figure 3 shows the models used, and Figure 4 shows a model positioned in the testing machine. The models were positioned by protractor to lines scribed on the models with a dividing head and height gage. Strains measured were very sensitive to load orientation.

IV. INSTRUMENTATION

A Baldwin-Lima-Hamilton Model 120 strain indicator was used to power a Wheatstone strain gage bridge incorporating a temperature compensating strain gage as one of the bridge arms. The strain indicator scope output jack was used to drive a Mosely 7000 A XY plotter to amplify and record the strain indicator signal. The recorder pen deflection was found to be linear with strain indicator unbalance, and the recorder could be calibrated so that 25.4 mm (1 in) of pen deflection corresponded to 100 micro mm/mm (100 micro in/in) of strain indicator unbalance. With this calibration, the recorder could provide a ± 190.5 mm (± 7.5 in) pen deflection. Standard commercial Baldwin-Lima-Hamilton and Budd switch and balance units were used to switch individual gages of the rosettes to the strain indicator and to provide initial zero adjustment for each gage. As each gage was switched to the strain indicator and the gage unbalance deflected the pen in the "X" direction a record was made by deflecting the pen 2.54 mm (.1 in) in the "Y" direction.

These records could later be read to .25 mm (.01 in) so that the resolution of the recording system was 1 micro mm/mm (1 micro in/in). Successive records of the gage readings while the model was undisturbed in the testing machine at constant load indicated an overall repeatability of ± 5 micro mm/mm (± 5 micro in/in) for the overall instrumentation system under this condition.

When a supposedly identical series of data records were taken on different days discrepancies of ± 20 micro mm/mm (± 20 micro in/in) could occasionally be detected. These were attributed to difficulty in obtaining identical model-load orientation, and strain gage and adhesive hysteresis effects superimposed on the above switch contact-strain indicator-recorder variations.

Figure 5 is a circuit diagram of the instrumentation. Figure 6 is an overall view of the physical arrangement of the apparatus.

V. RESULTS AND DISCUSSION

Strains read from the recorder charts were used to compute principal strains, stresses and angles, for each rosette. These are given in Tables 2, 3 and 4.

In these tables epsilon A is the axial strain, read from the output of a strain gage mounted parallel to the axis of the hole (bore) in the model. Epsilon B is the strain 45^0 to epsilon A, and epsilon C is the hoop strain, read from the strain gage mounted at 90^0 to epsilon A. The data reads from the top down from the outermost rosette, closest to the point of load application inward past the ball center line and on out to the outermost rosette on the other side of the ball, away from the loaded point.

Epsilon 1 and epsilon 2 are the computed principal strains. All strains are given in micro mm/mm (micro in/in) with ε_1 always being the algebraically larger (most positive) of the principal strains. σ_1 and σ_2 are the computed principal stresses in mega Newtons per square meter and kilo pounds per square incn, with σ_1 always the algebraically larger of the principal stresses. Alpna is the angle between ε_A and ε_1.

The stresses of Tables 2, 3 and 4 are plotted in Figures 7, 8 and 9 on an outline of the model with an indication of the location and direction of the load giving rise to these stresses. Exterior strains for the $\theta = 0^0$, $\phi = 0^0$ could not be obtained without disturbing the exterior gages by loading over them. This also prevented measurement of strains over half of the ball in the $\theta = 0^0$, $\phi = 20^0$, and 40^0 cases.

The principal stresses were calculated from the measured strains using equations from Dally and Riley.[2]

$$\varepsilon_{1,2} = \frac{1}{2}(\varepsilon_A + \varepsilon_C) \pm \frac{1}{2}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2} \qquad (1)$$

$$\sigma_1 = \frac{E}{1 - \nu^2} \quad (\varepsilon_1 + \nu\varepsilon_2) \tag{2}$$

$$\sigma_2 = \frac{E}{1 - \nu^2} \quad (\varepsilon_2 + \nu\varepsilon_1) \tag{3}$$

with values for modulus of elasticity, E, of 207 X 10^9 N/m^2 (30 X 10^6 lb/in^2) and a Poisson's ratio ν of 0.3. A test recalculation of the data with values of 200 X 10^9 N/m^2 (29 X 10^6 lb/in^2) and a 0.28 showed that maximum stresses are reduced by 2 to 5% when these smaller values are used.

In the course of loading the models, strain was observed to be proportional to load. From equations (1), (2), and (3) above, the calculated principal stresses are then proportional to load. As stress = force/(length)^2 and all dimensions of a model of specified mass reduction are proportional to model outer diameter, the data in tables 1, 2, and 3 may be used to calculate stresses for similar balls as

$$\frac{\text{Stress}_1}{\text{Stress}_2} = \frac{\text{Force}_1}{\text{Force}_2} \times \left(\frac{\text{OD}_2}{\text{OD}_1}\right)^2 \tag{4}$$

Examination of the data shows that the models can be very highly stressed by loads applied close to the edge of the hole. While this is not unexpected, the magnitudes of the principal stresses and their signs would seem to indicate that full scale bearings incorporating drilled balls should be designed with special attention to the prevention of edge loading.

The data suggest that the 40% mass reduction ball while having a mass and expected centrifugal loading of .6/.5 = 1.2 times that of the 50% mass reduction ball, might actually experience lower stresses than the 50% mass reduction ball. At load angles of $\phi = 20^0$ and 0^0, the 40% mass reduction model indicated maximum stresses only 58% and 62.5% as high as those of the 50% mass reduction model. The net effect of substituting a 40% mass reduction ball for a 50% mass reduction ball in a bearing then might be to reduce maximum stresses to 69.6% and 75% of the stresses previously existing in the bearing balls.

A similar comparison of the 60% mass reduction model indicates an expected centrifugal force of .4/.5 = .8 times that of the 50% mass reduction ball, but maximum stresses that are 152% and 158% of those in the 50% mass reduction ball with loads at $\phi = 20^0$ and 0^0. The net effect of substituting a 60% mass reduction ball for a 50% mass reduction ball might be to increase maximum stresses to 122% and 127% of the stresses previously existing.

Contact stresses will still be greatest for the 40% mass reduction ball in a high-speed bearing as these stresses are determined largely by the centrifugal force.

VI. CONCLUSION

The stress distribution in cylindrically hollow balls proportioned for mass reductions of 40, 50, and 60 per cent has been determined. Stresses are largest when loads are applied close to the edge of the hole. If cylindrically hollow balls are used in ball bearings it seems advisable to limit load applications to less than 20^0 from the ball center line. When load applications are held to angles less than 20^0 a 40% mass reduction ball should experience bending stresses due to centrifugal loading that are 75% of those experienced by a 50% mass reduction ball.

REFERENCES

1. Holmes, P. W. Evaluation of Drilled Ball Bearings at DN Values to Three Million, Volumes I and II, NASA CR-2004 and CR-2005, 1972.

2. Dally, J. W., and Riley, W. F., Experimental Stress Analysis, McGraw-Hill Book Company, New York, 1965

FIG 1a

40% MASS REDUCTION
DIMENSIONS mm (IN)

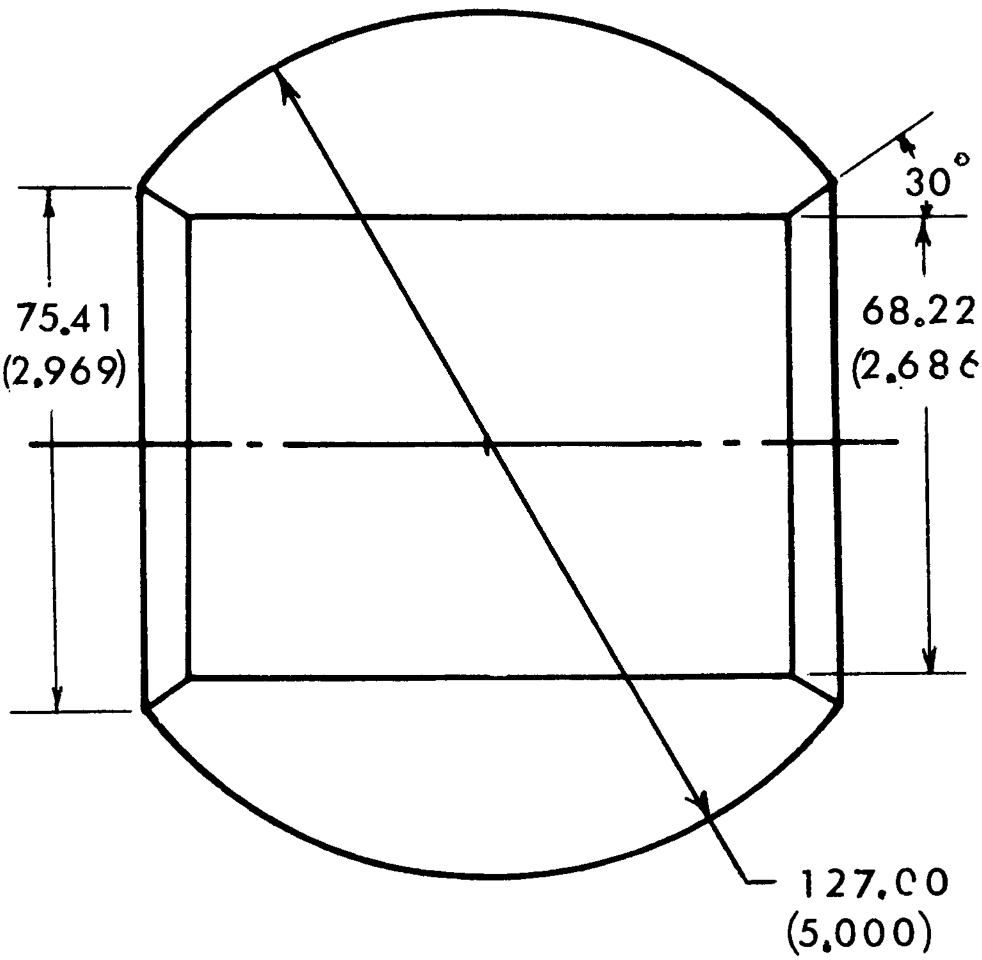


FIG 1b

50% MASS REDUCTION
DIMENSIONS mm (IN)

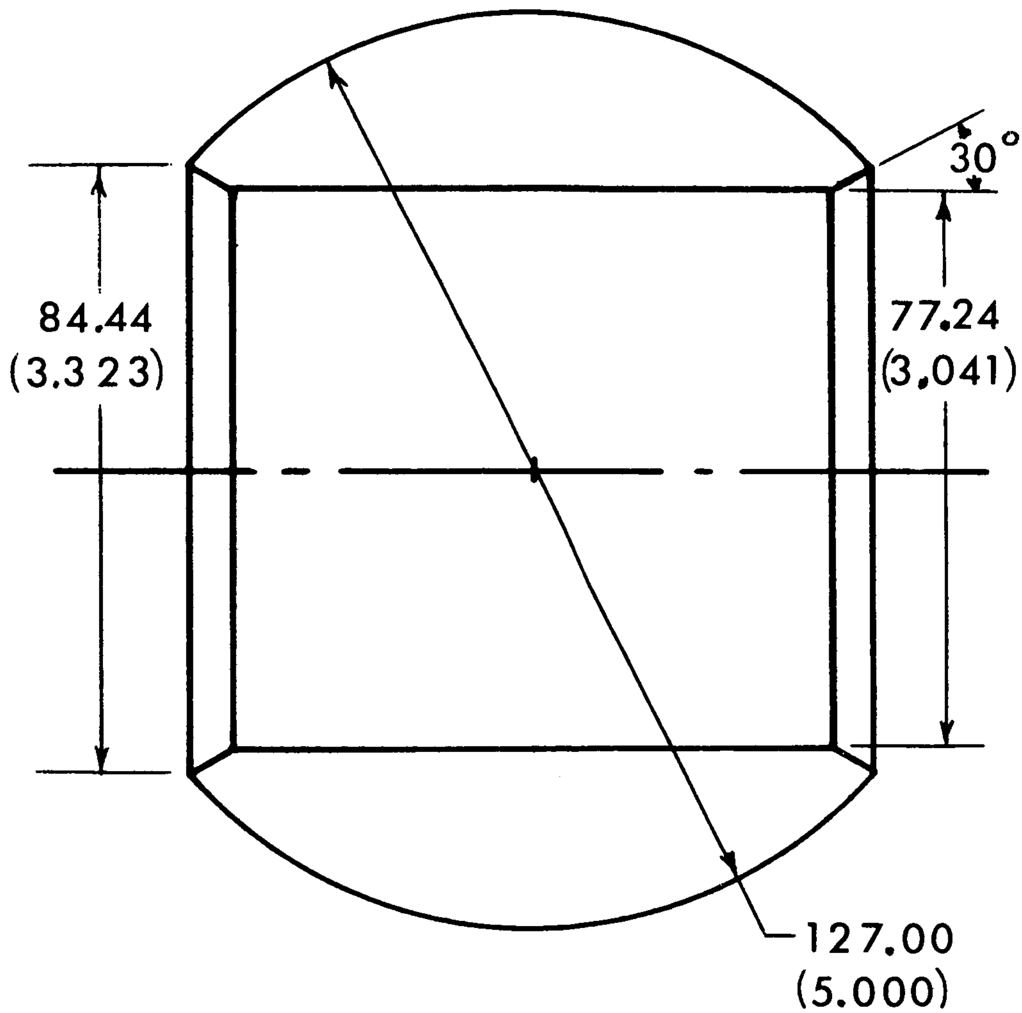


FIG 1c

PRINCIPAL
60% MASS REDUCTION
DIMENSIONS mm (IN)

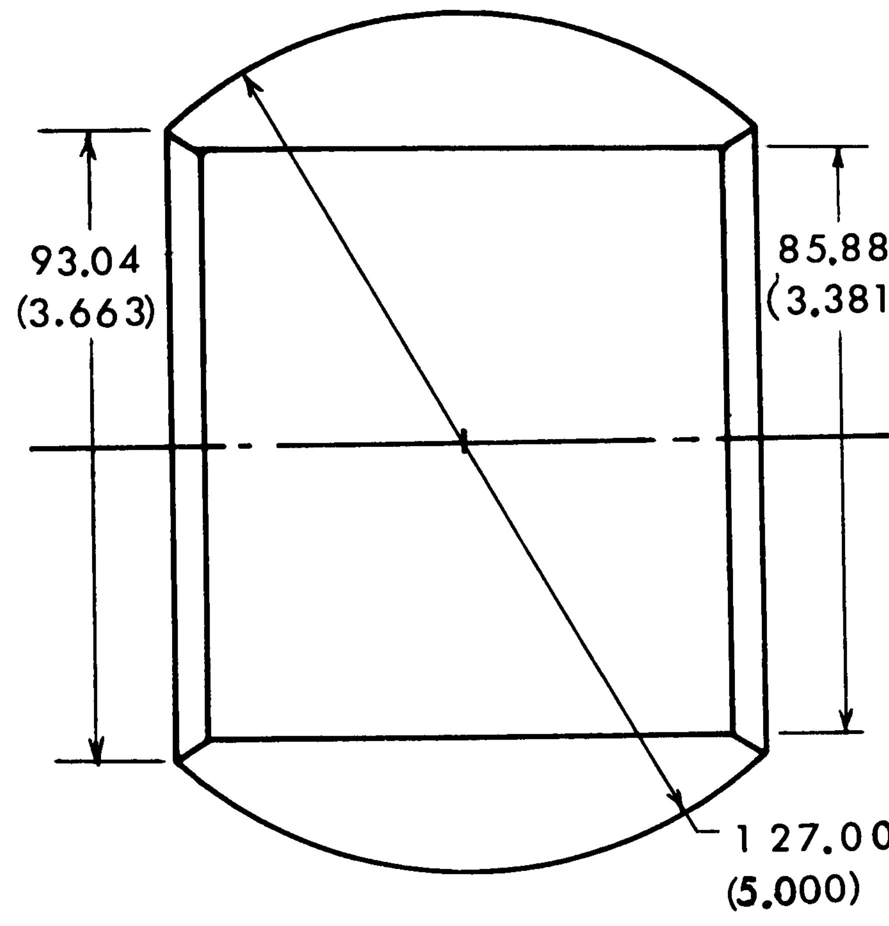


FIG 2a
STRAIN GAGE LOCATIONS
40% MASS REDUCTION

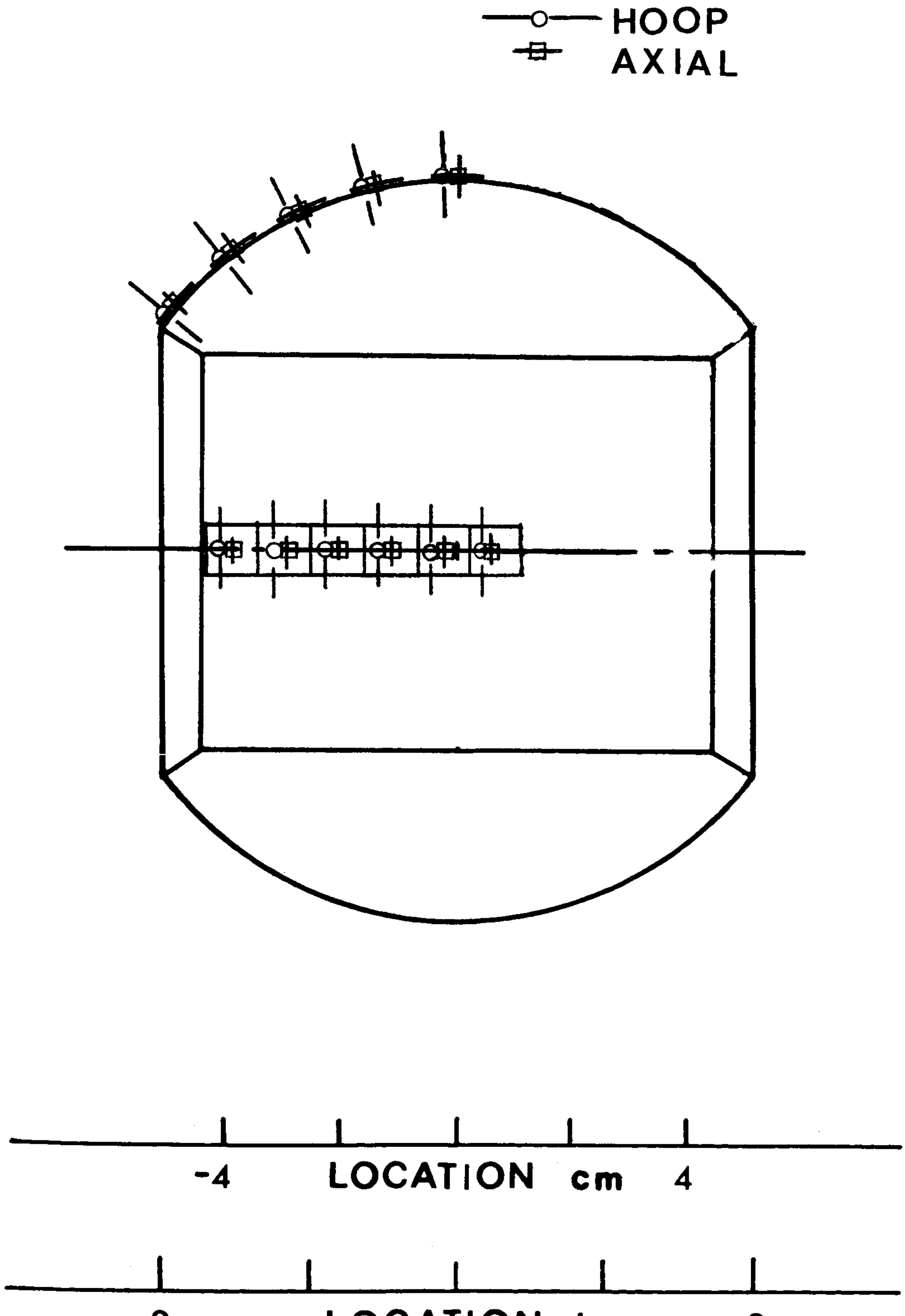


FIG 2b
STRAIN GAGE LOCATION
50% MASS REDUCTIONS

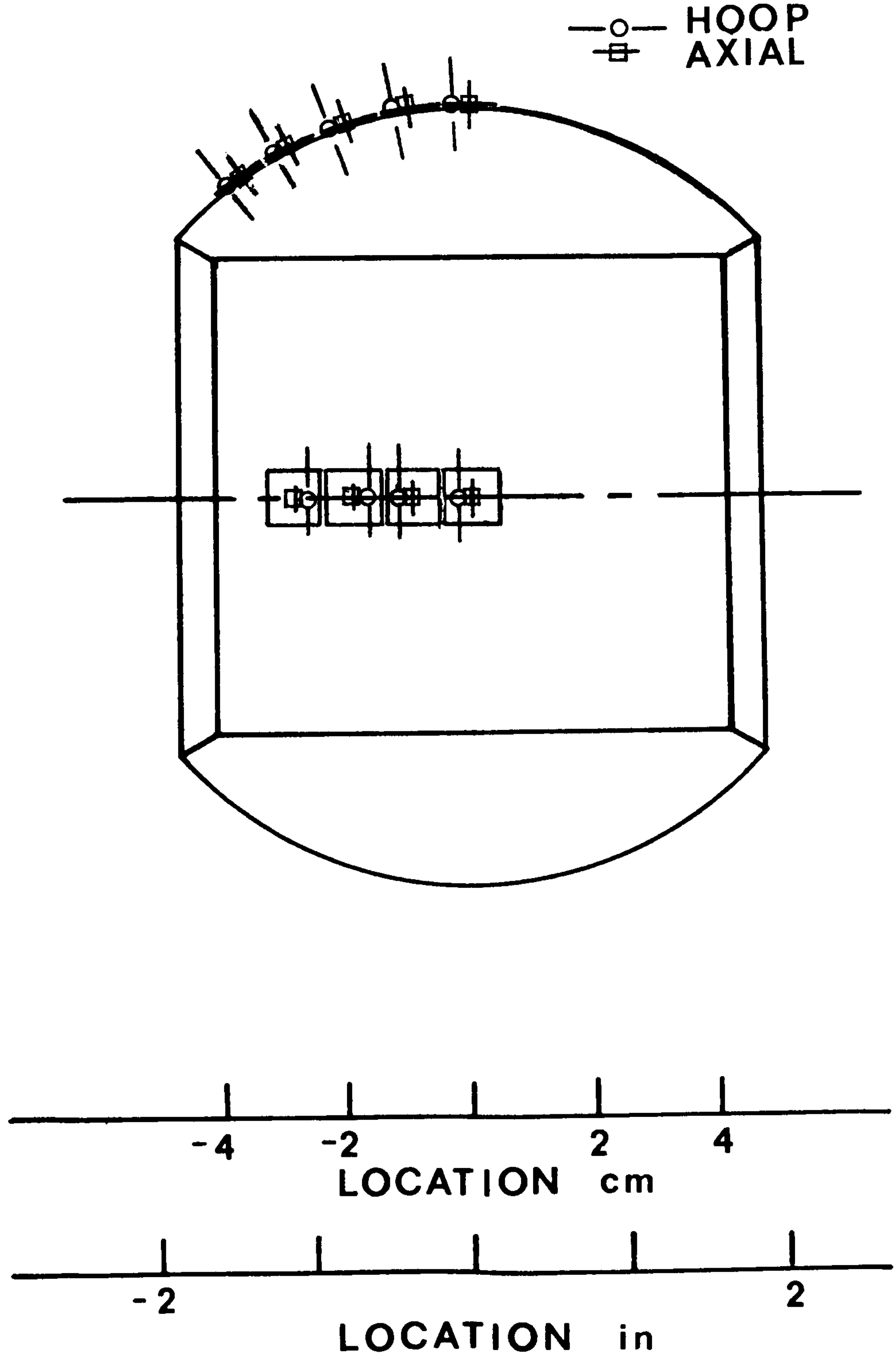
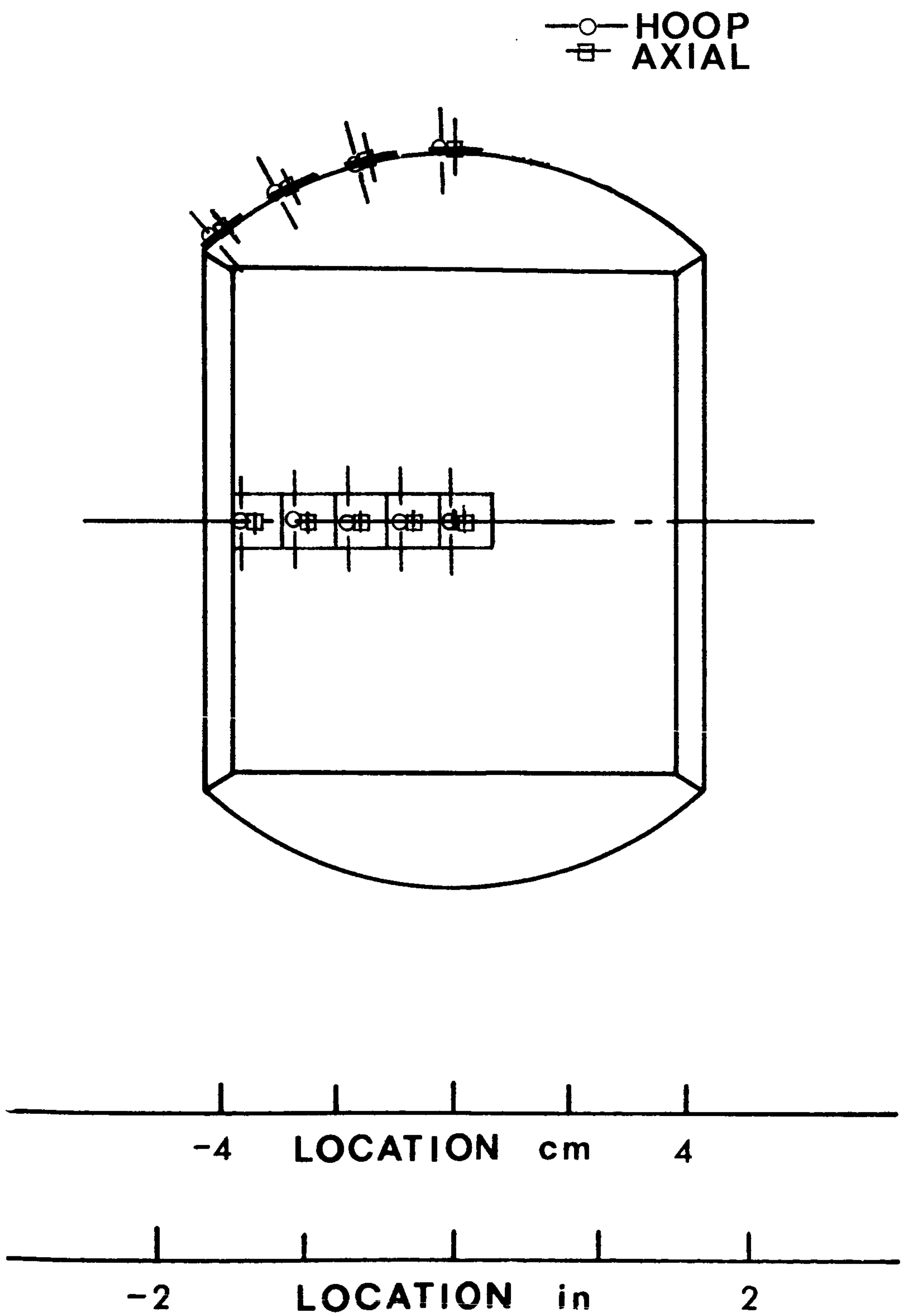


FIG2c
STRAIN GAGE LOCATIONS
60% MASS REDUCTION



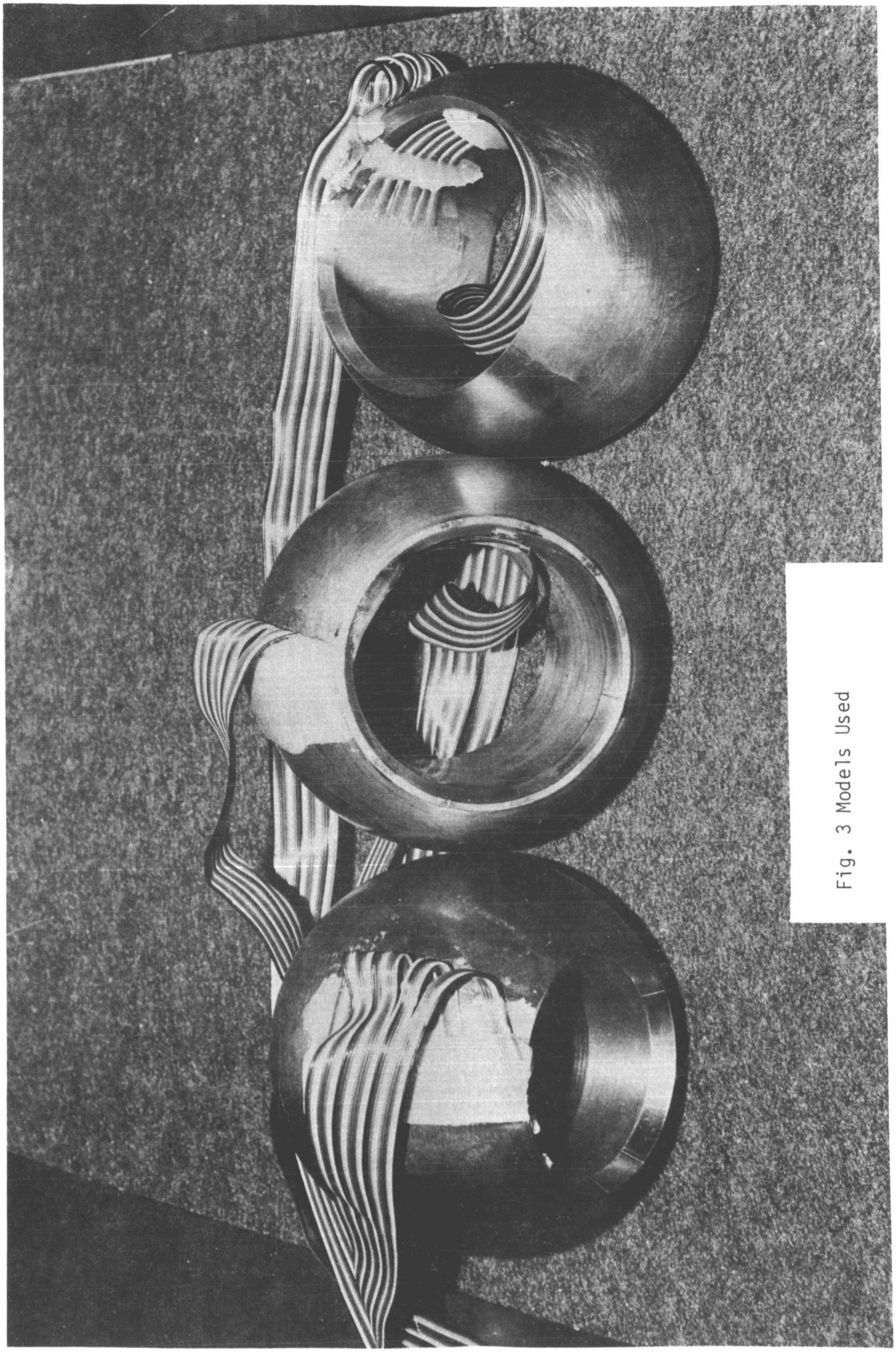


Fig. 3 Models Used

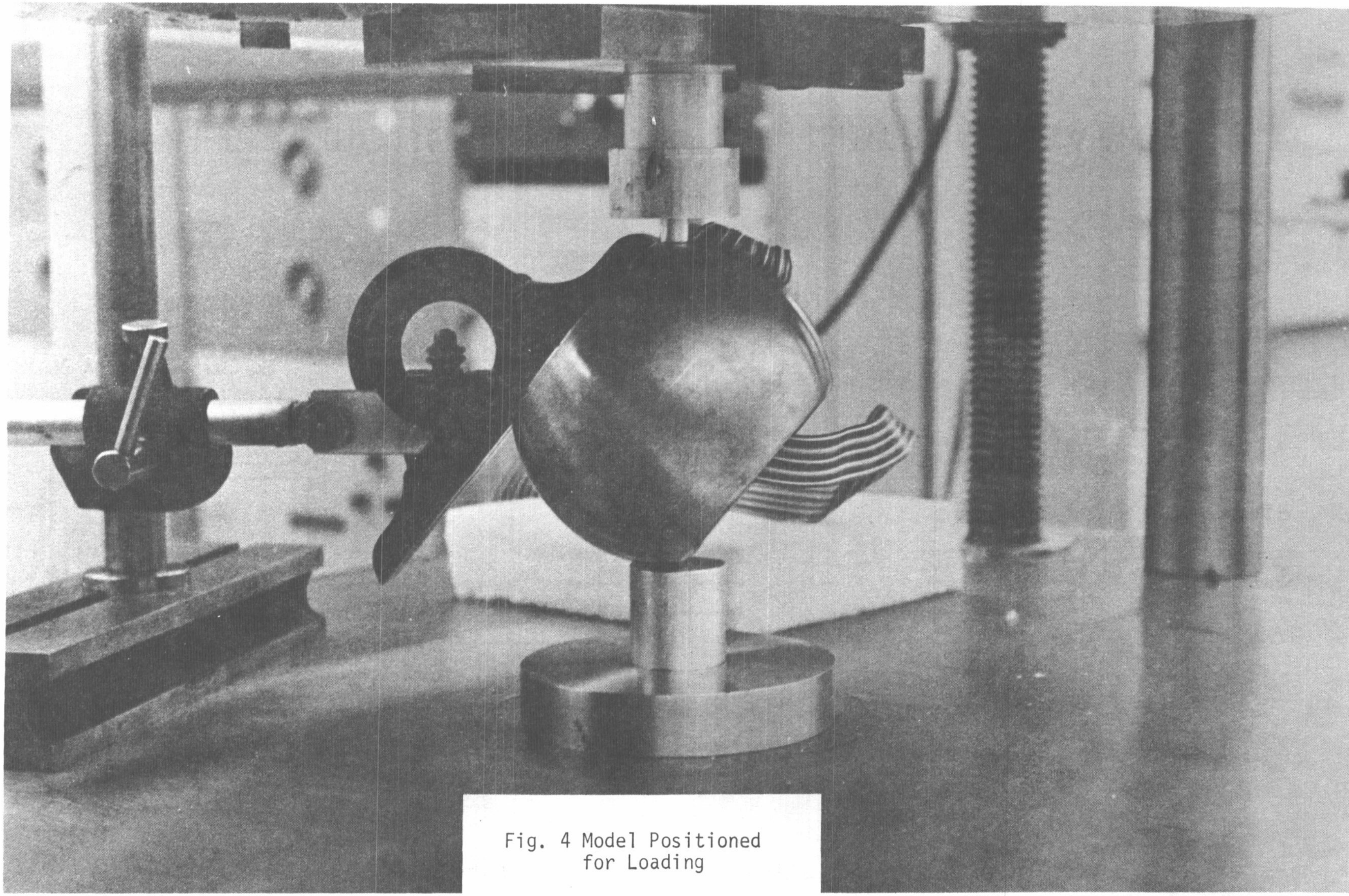


Fig. 4 Model Positioned for Loading

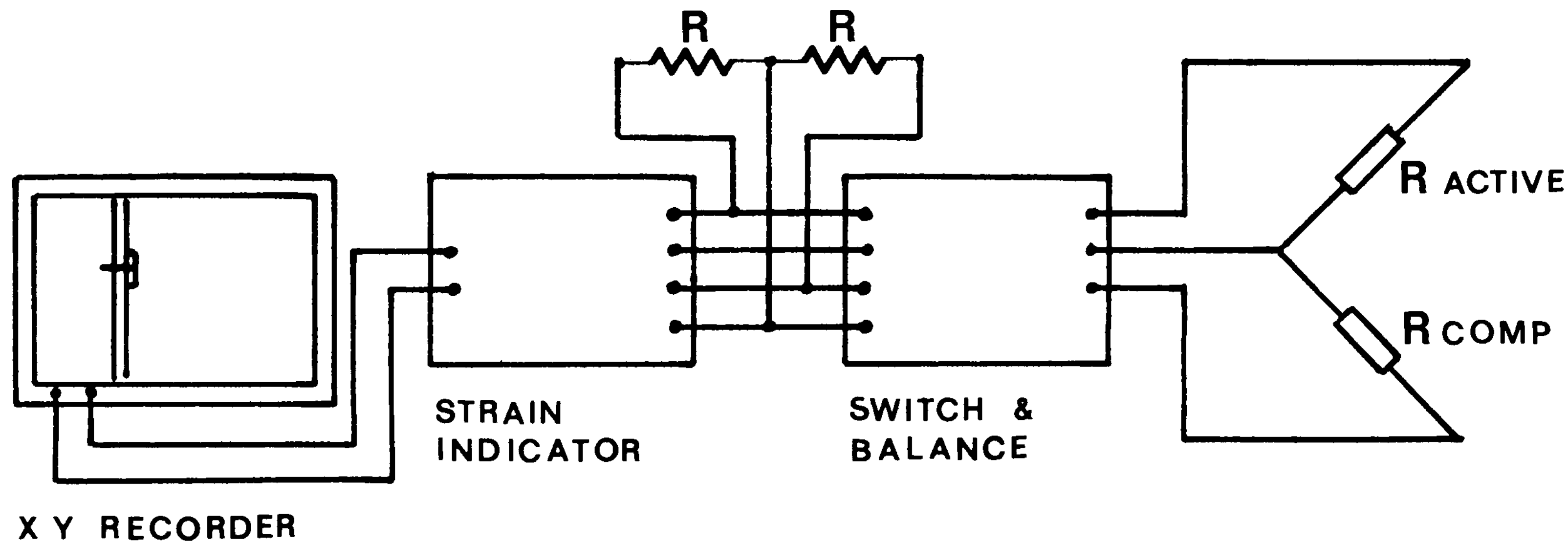


FIG 5 CIRCUIT DIAGRAM OF INSTRUMENTATION

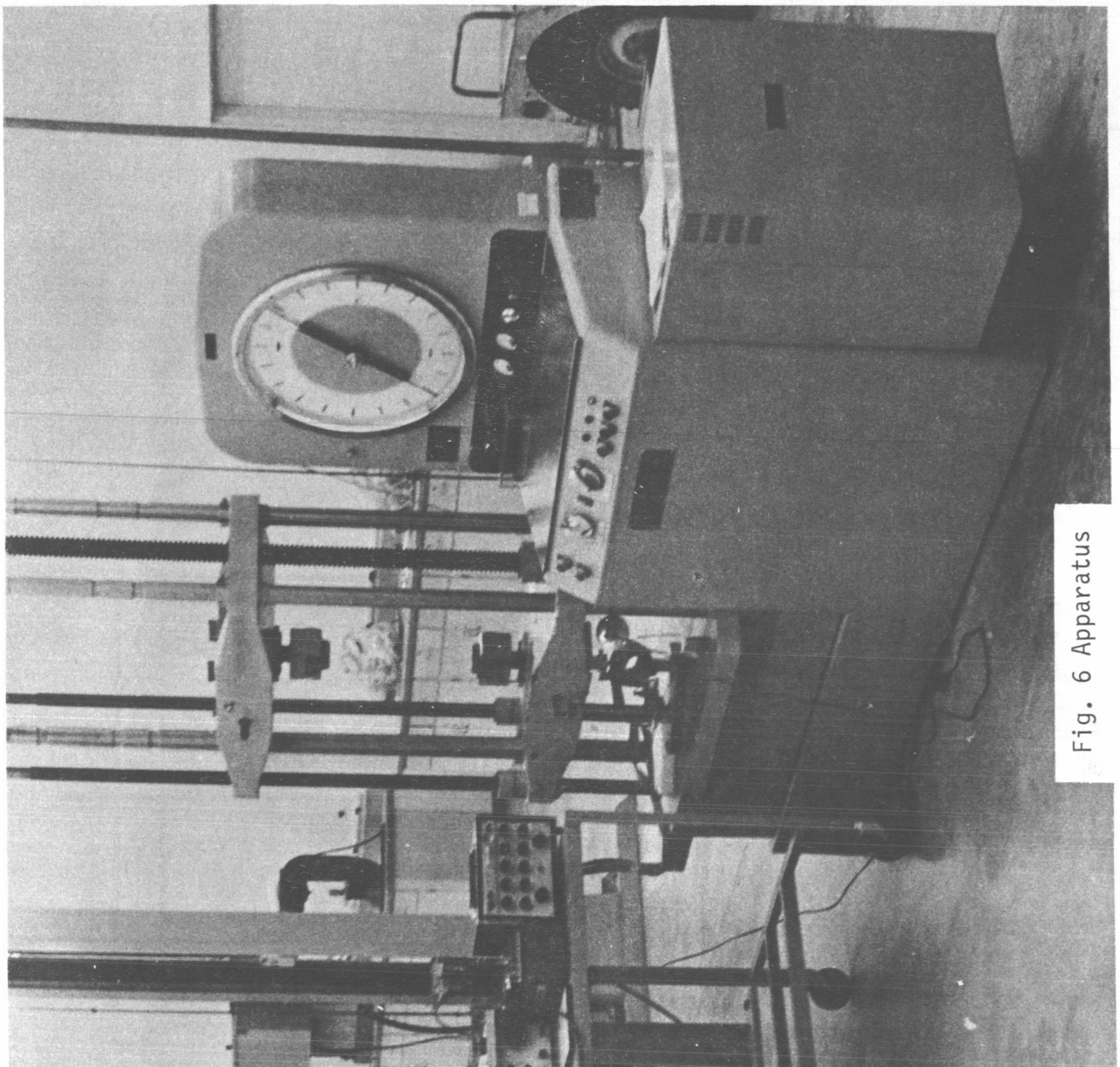


Fig. 6 Apparatus

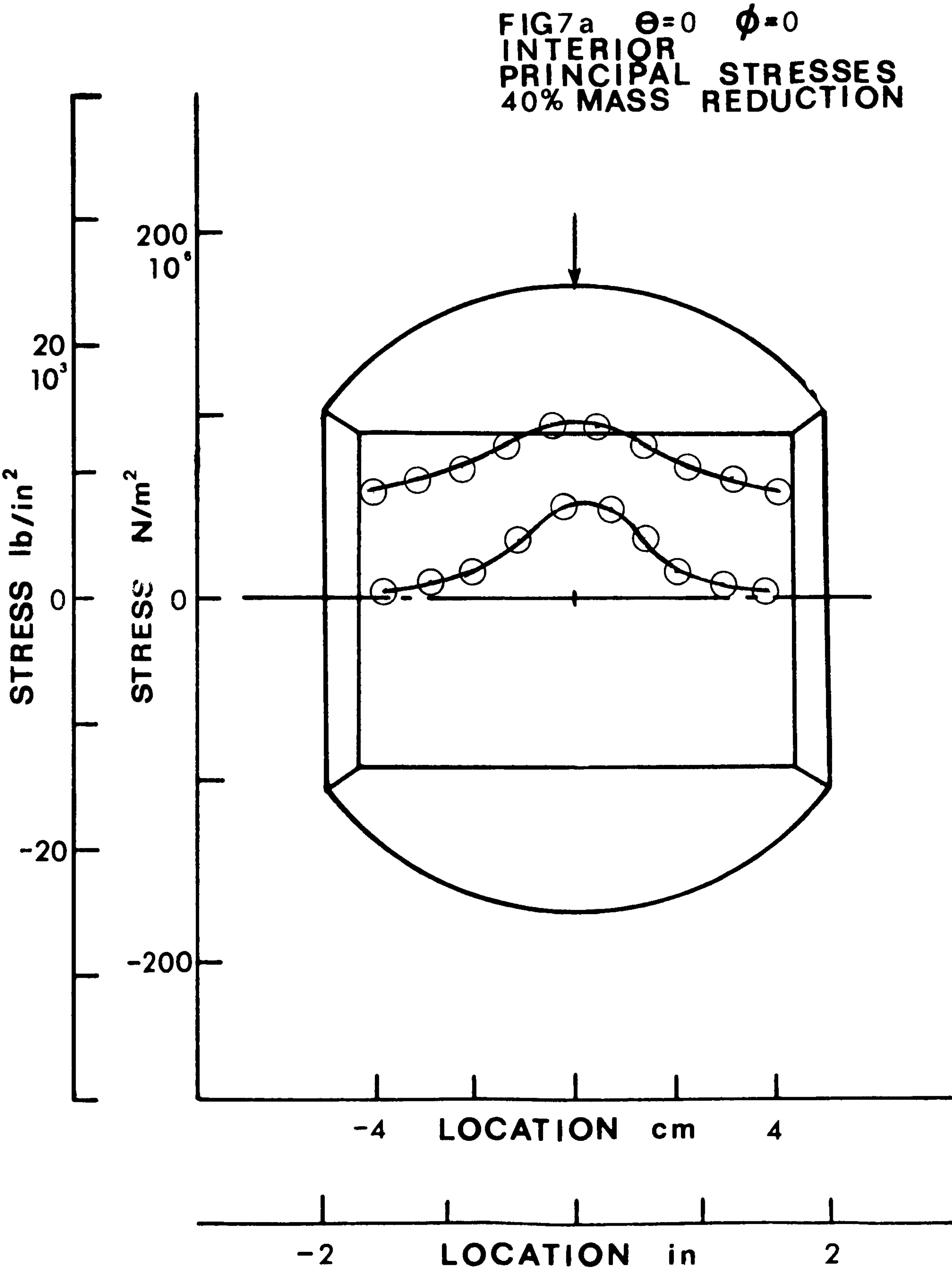


FIG7a Θ=0 φ=0
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

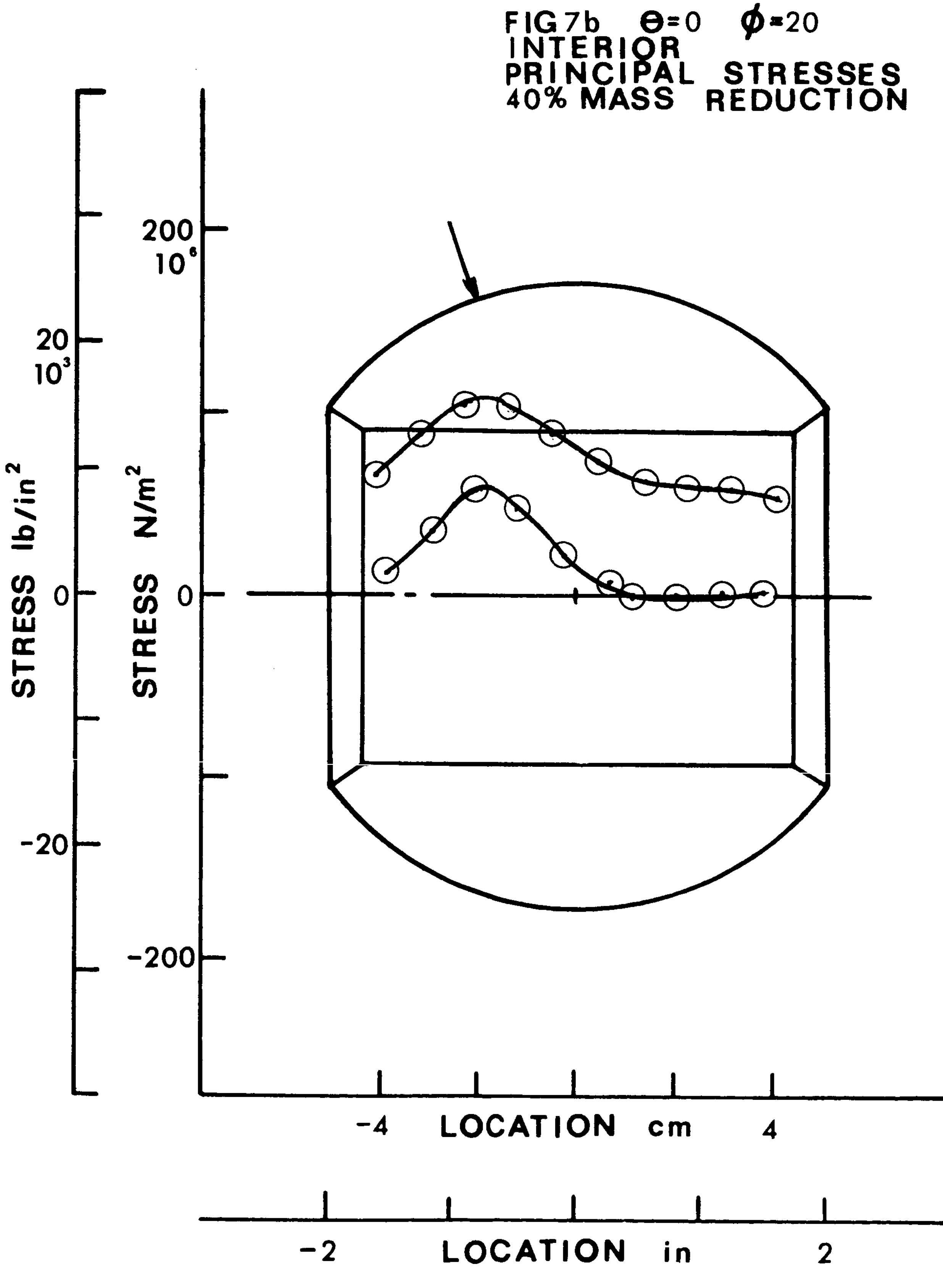


FIG 7b Θ=0 φ=20
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in^2
20
10^3
0
-20
STRESS N/m^2
200
10^6
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 7c $\Theta=0$ $\phi=40$
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

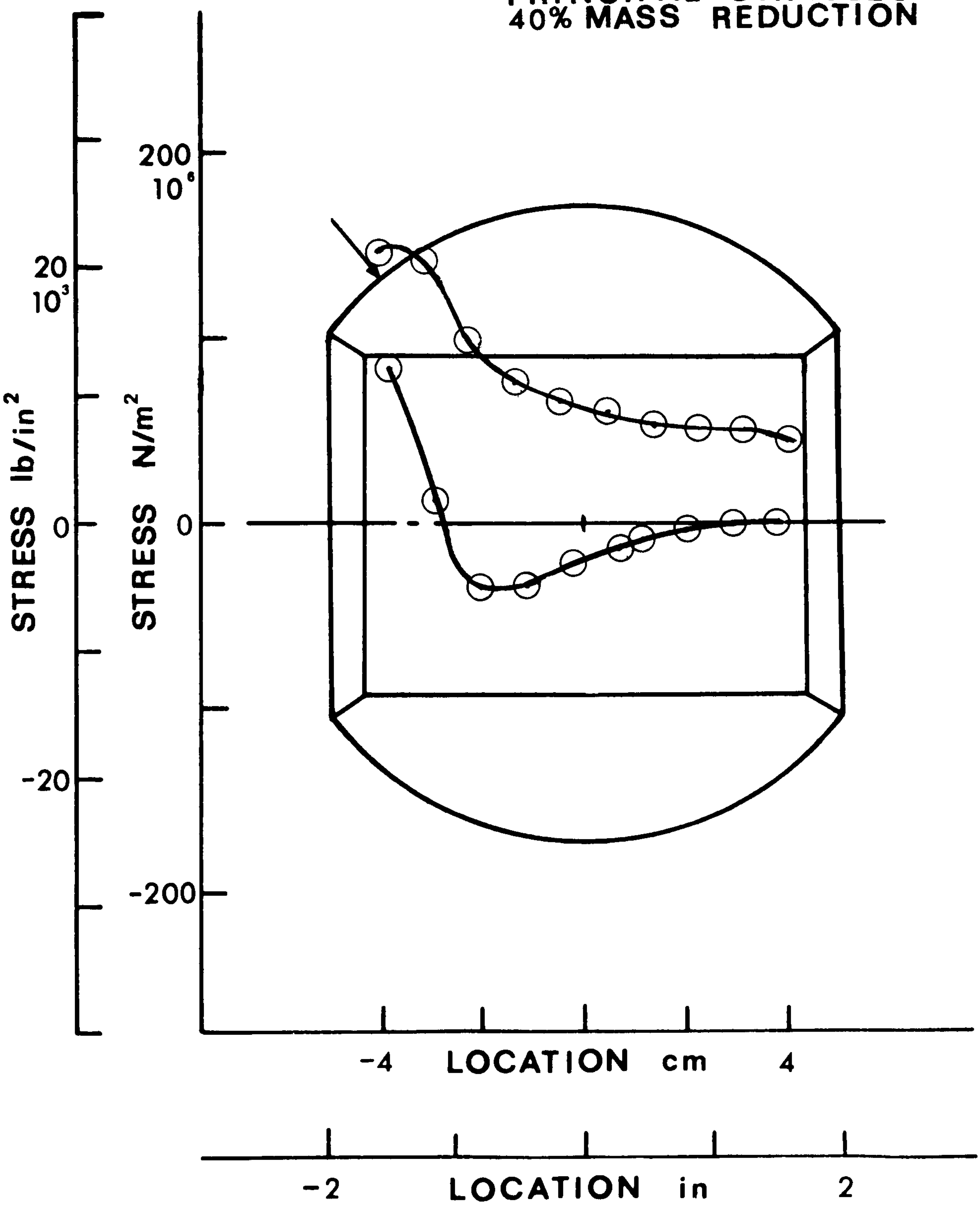


FIG 7d Θ=30 ϕ=0
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

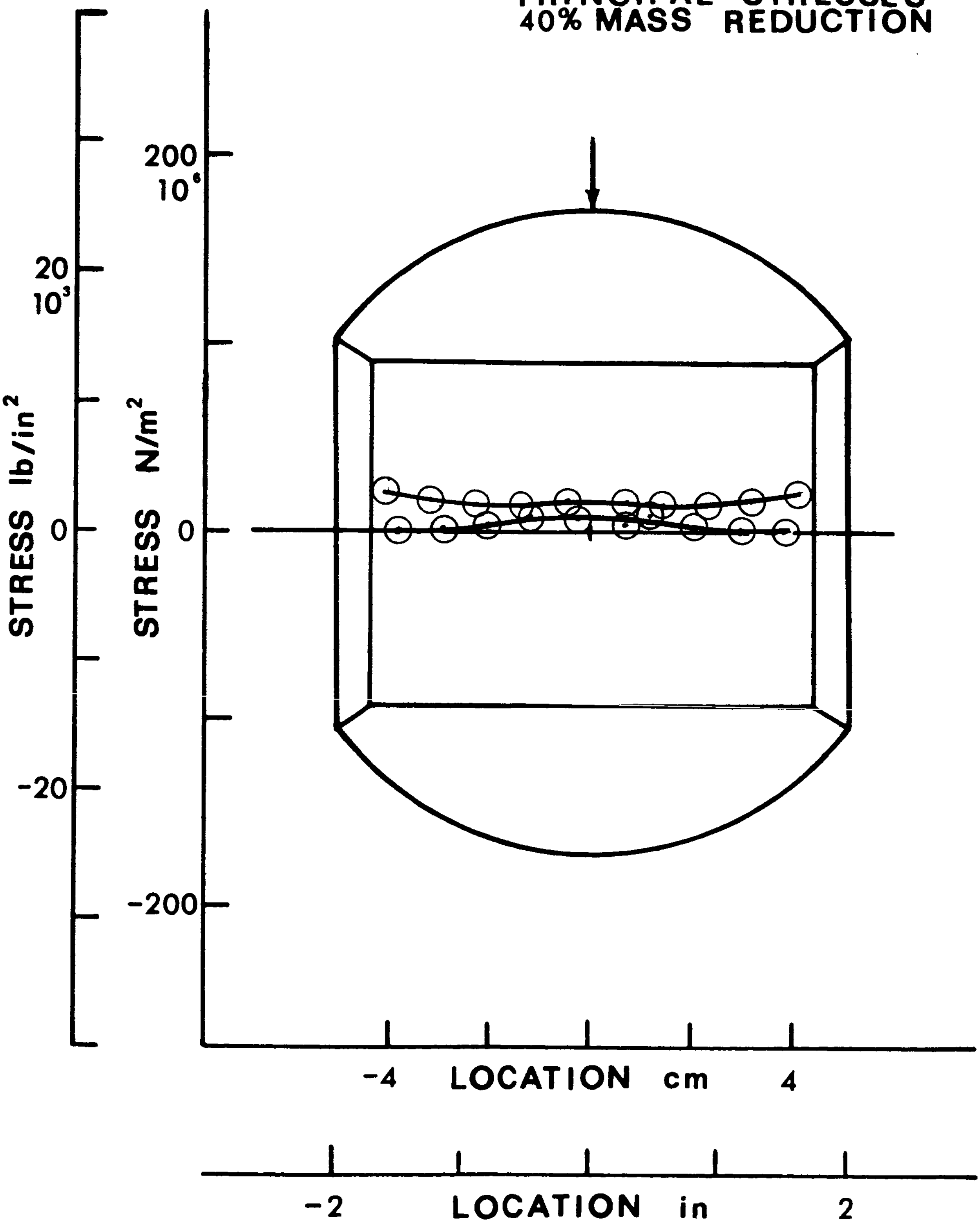


FIG 7e Θ=30 ϕ=20
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

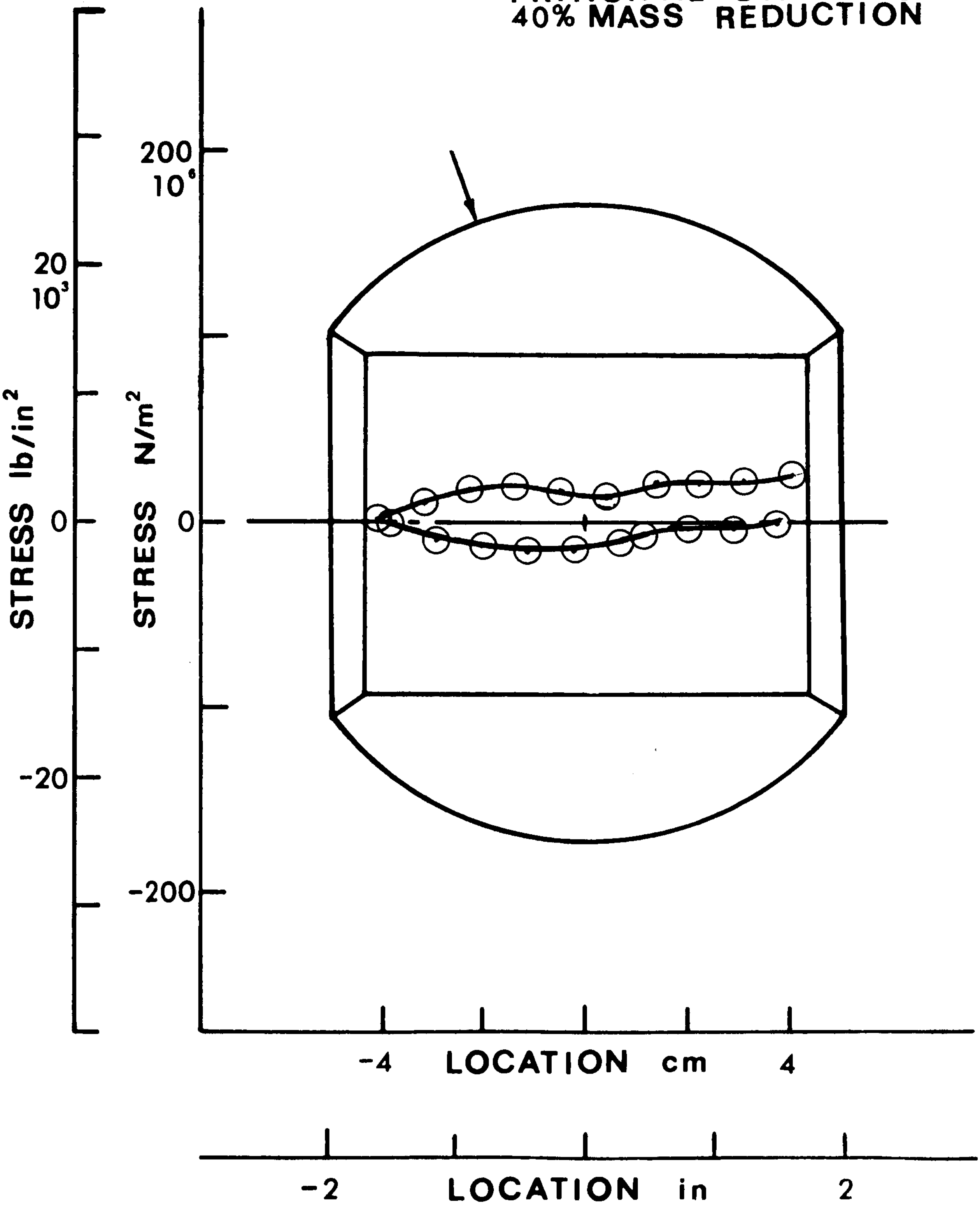


FIG 7f $\Theta=30$ $\phi=40$
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

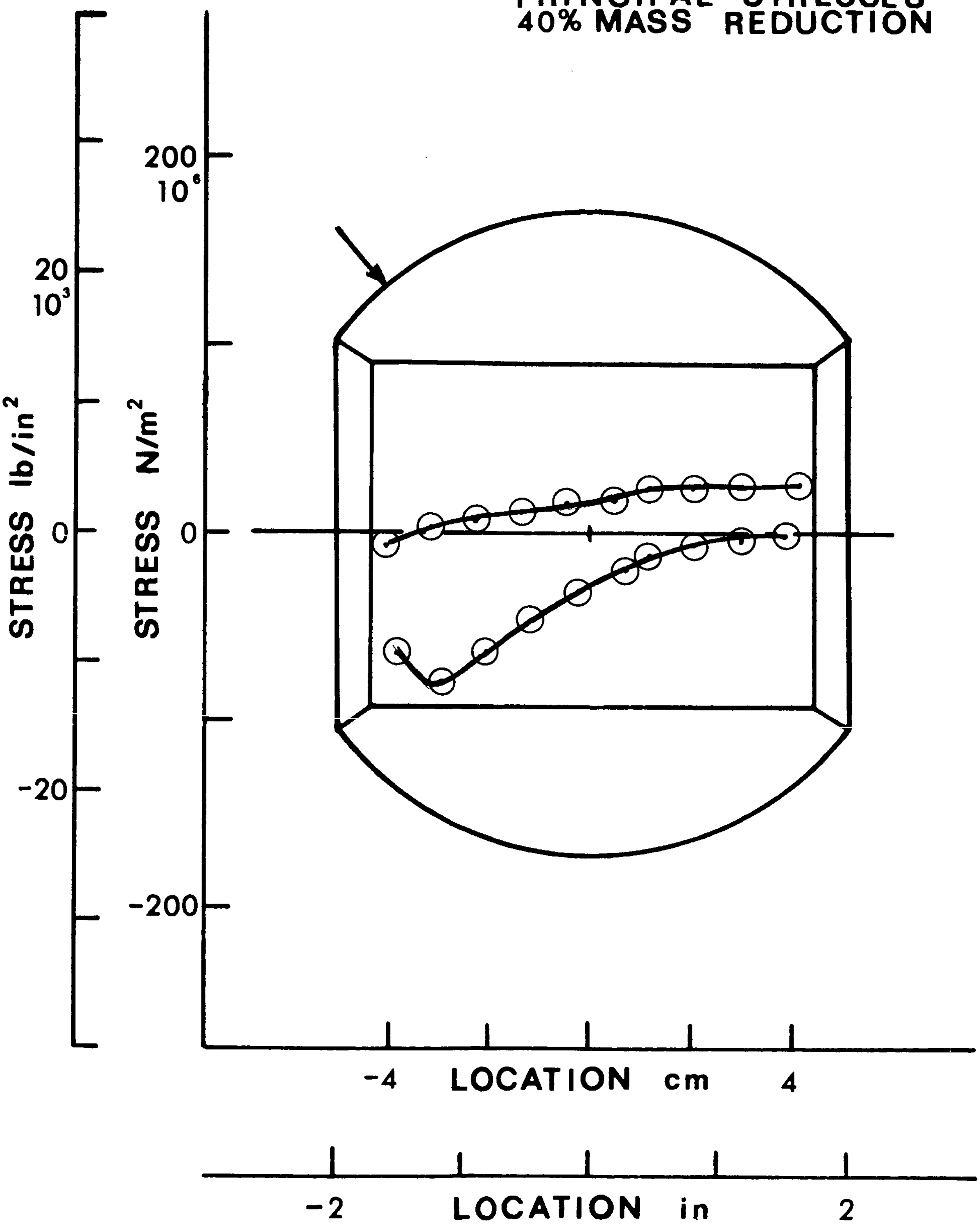
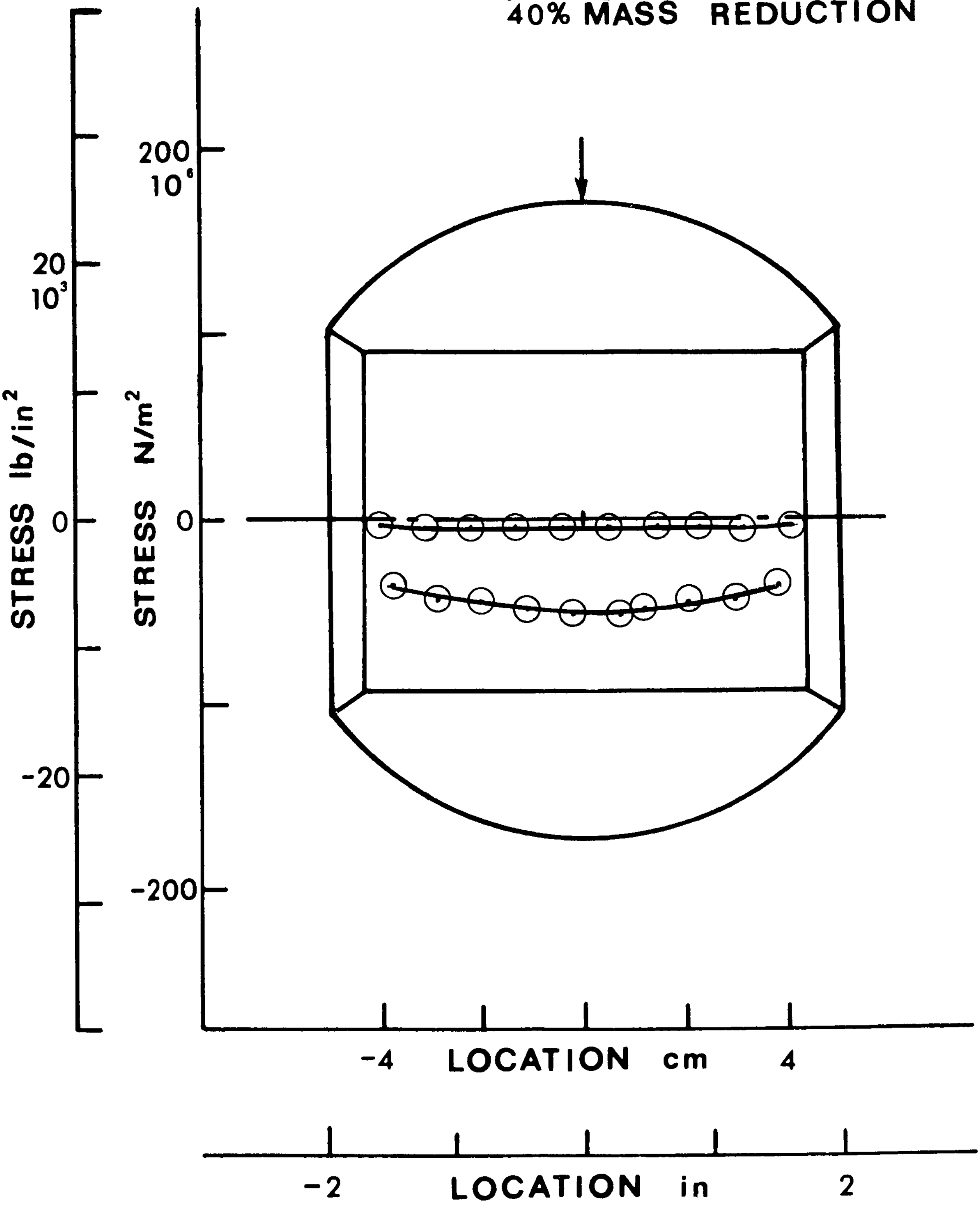


FIG 7g Θ=60 φ=0
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



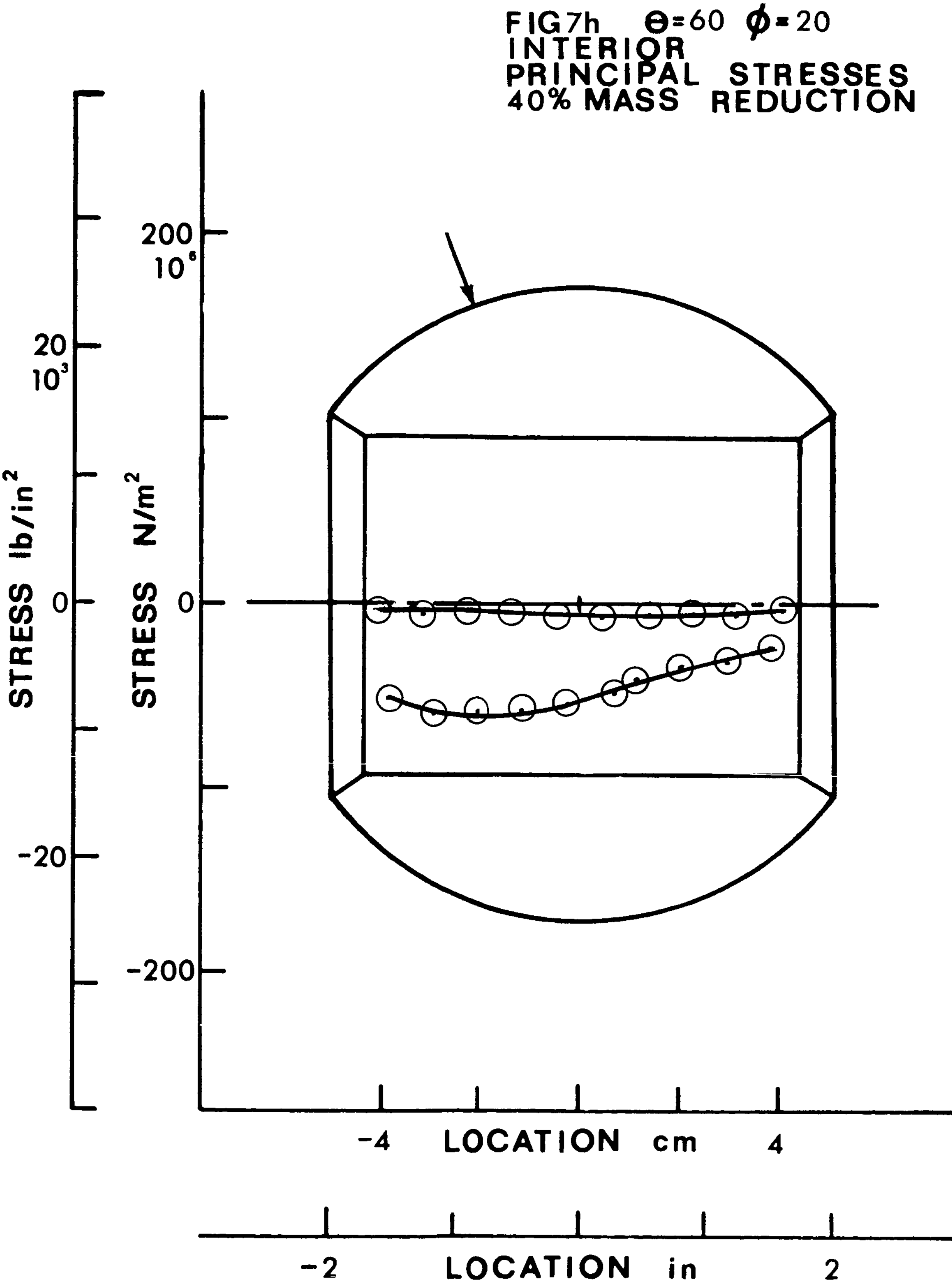


FIG7h Θ=60 ϕ=20
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in2
20
10³
0
-20
STRESS N/m2
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

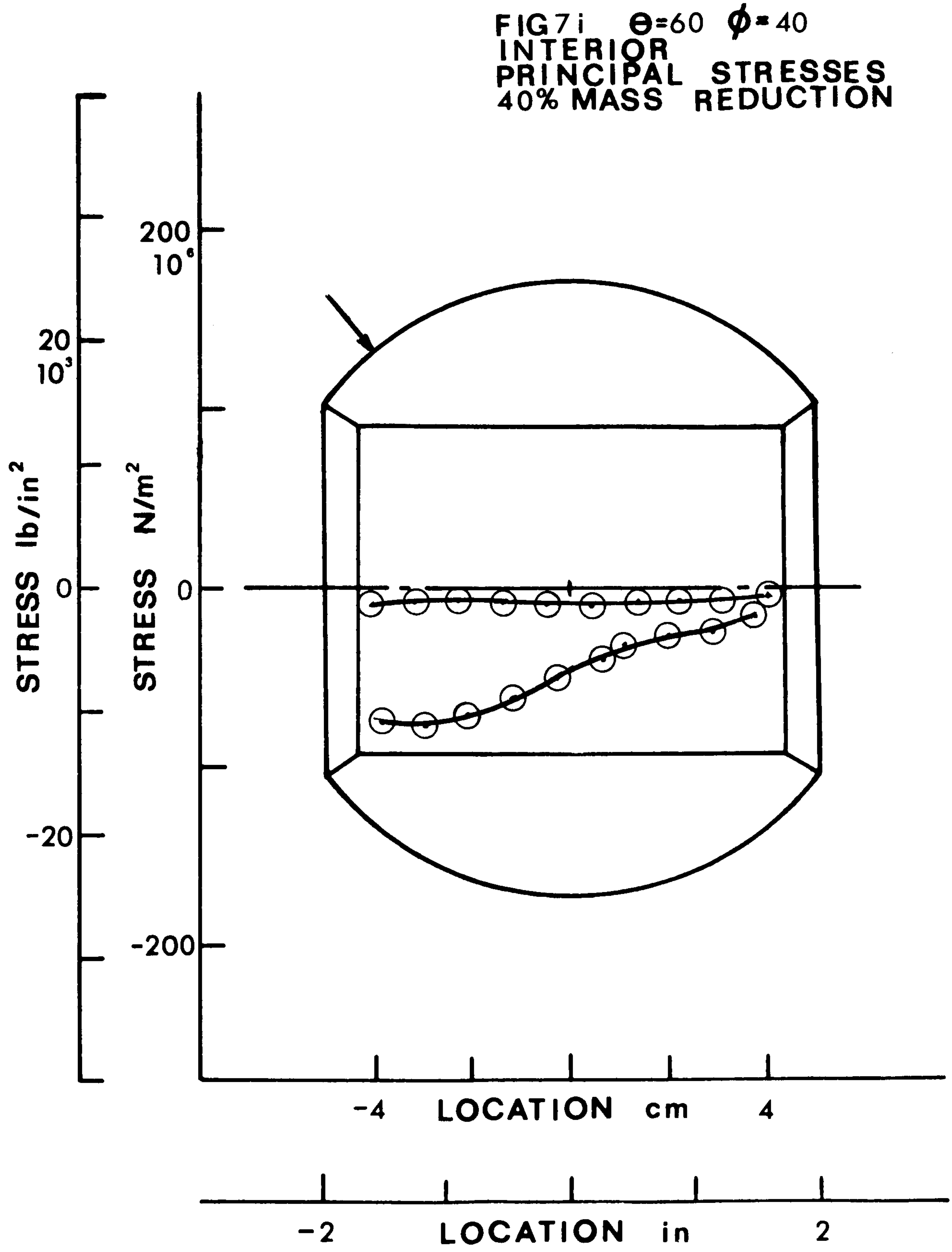


FIG 7i Θ=60 ϕ=40
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

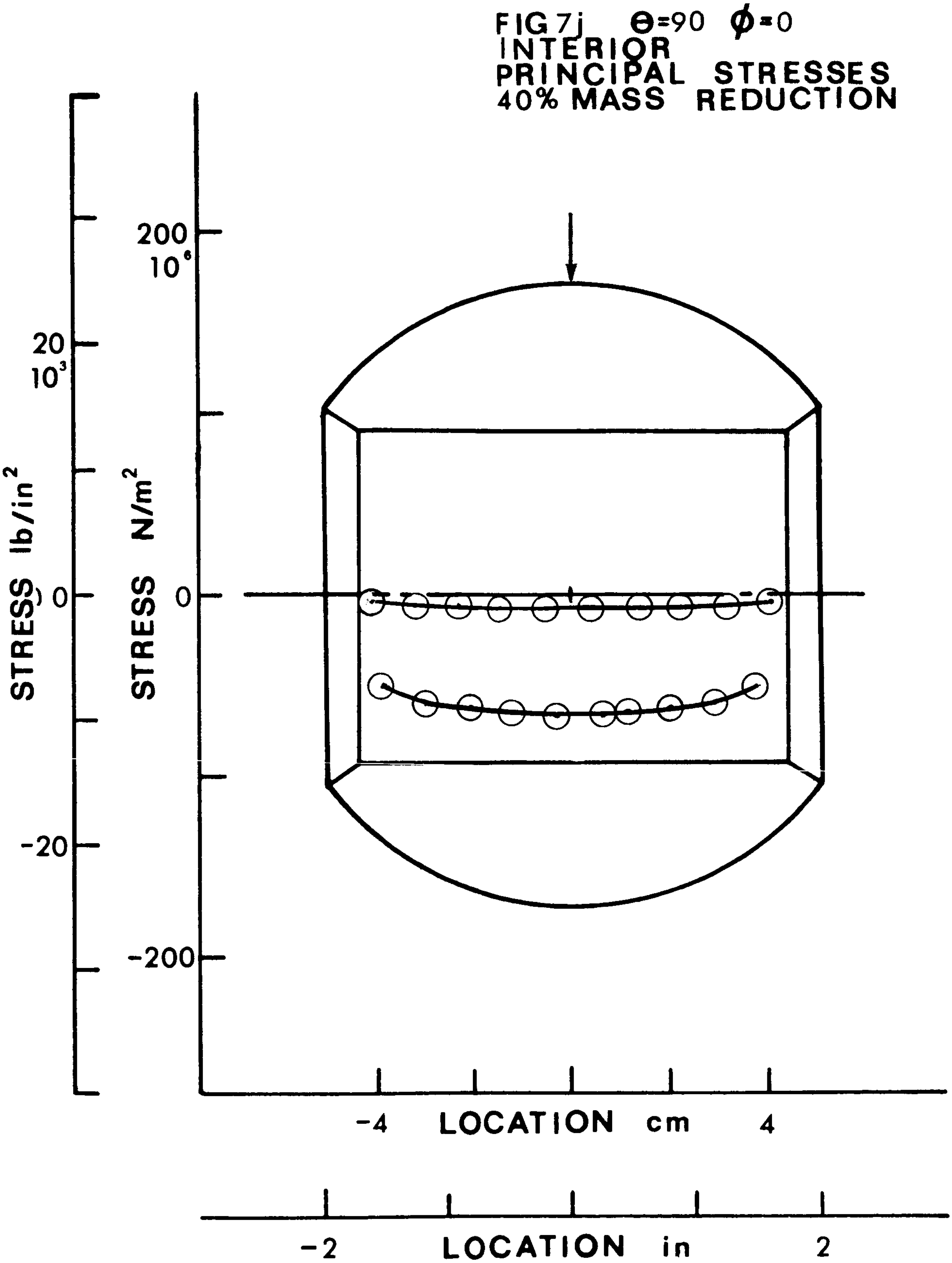


FIG 7j Θ=90 φ=0
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in^2
20
10^3
0
-20
STRESS N/m^2
200
10^6
0
-200
-4 LOCATION cm 4
-2 LOCATION in 2

FIG 7k $\Theta=90$ $\phi=20$
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

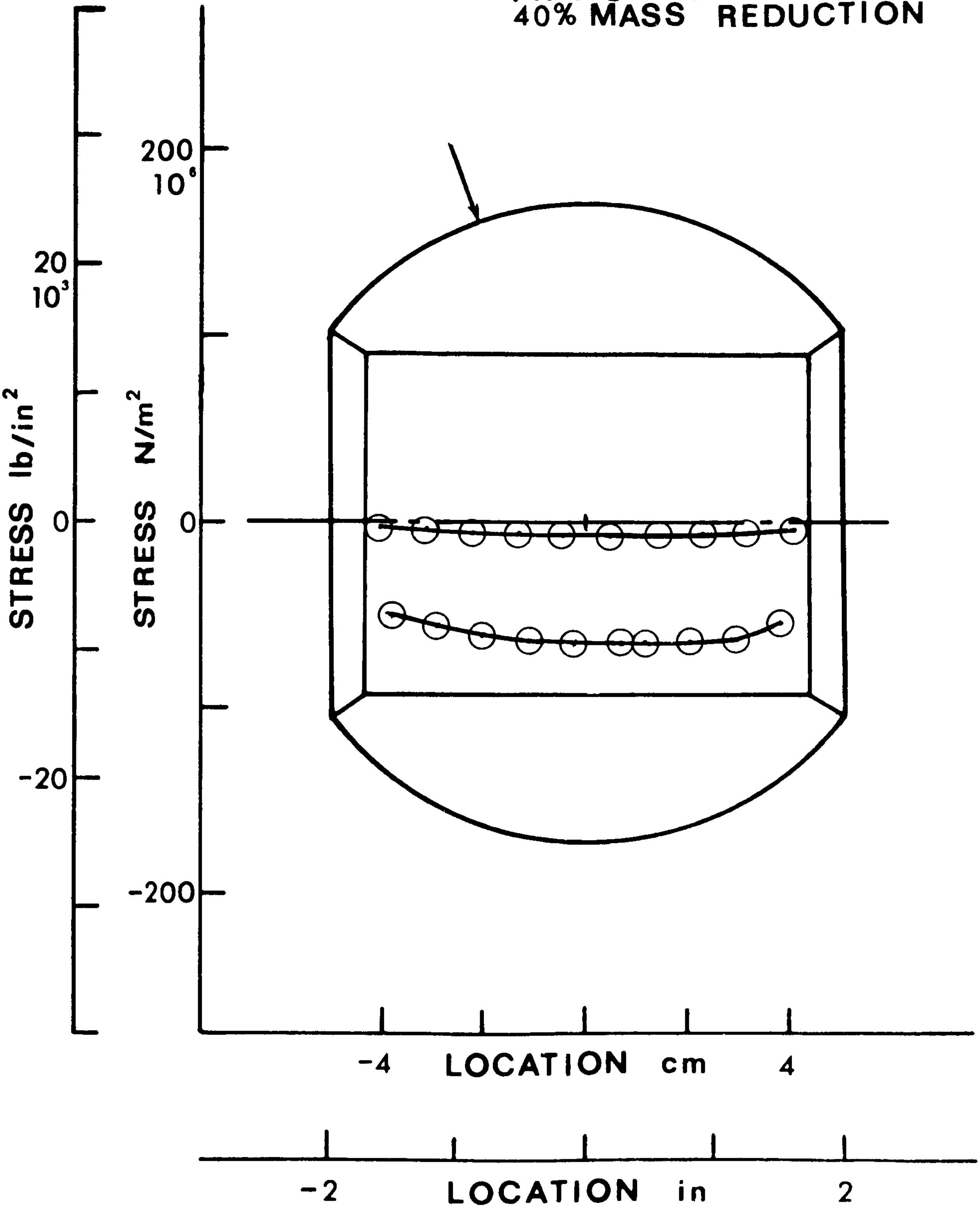
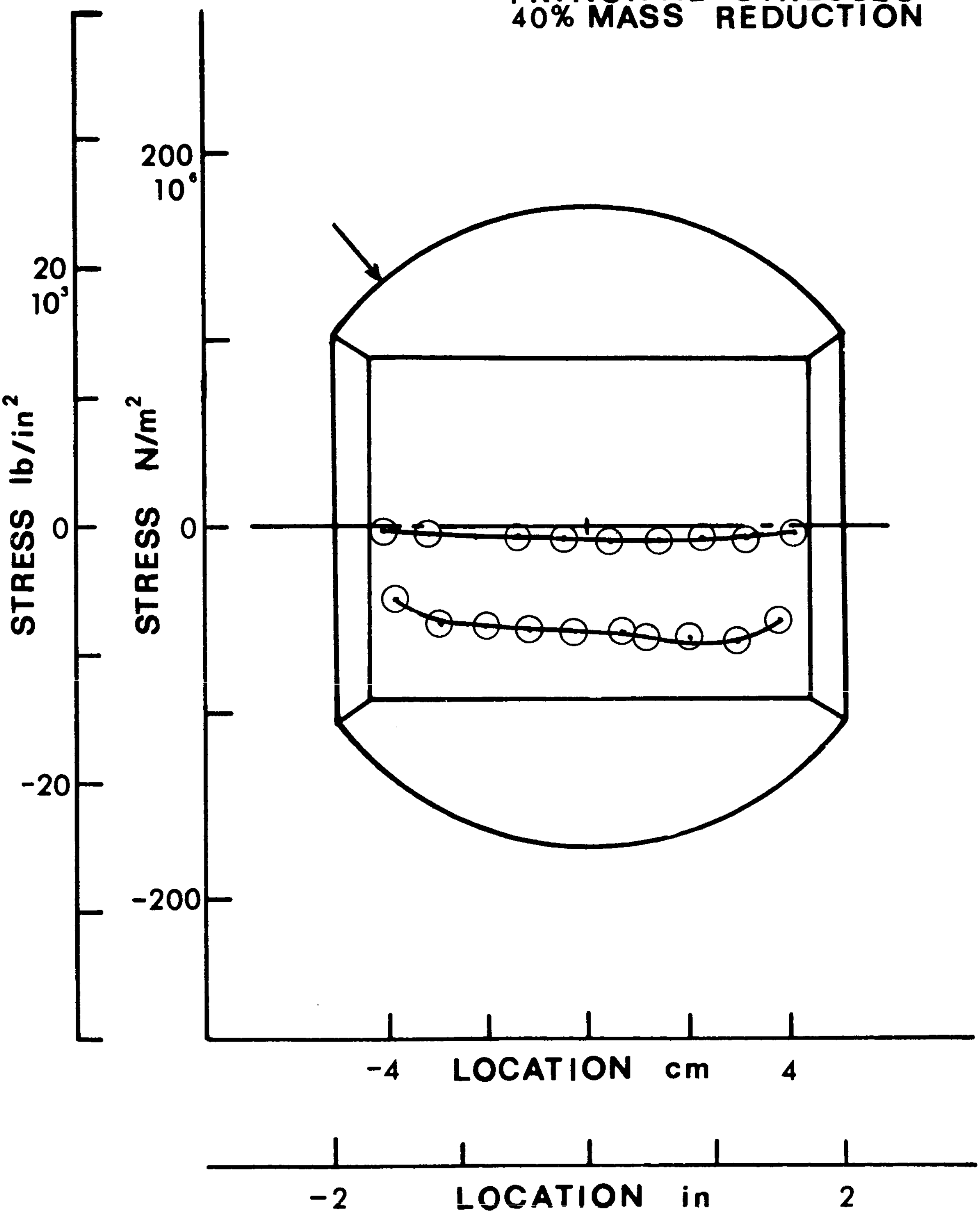


FIG 71 $\Theta=90$ $\phi=40$
INTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



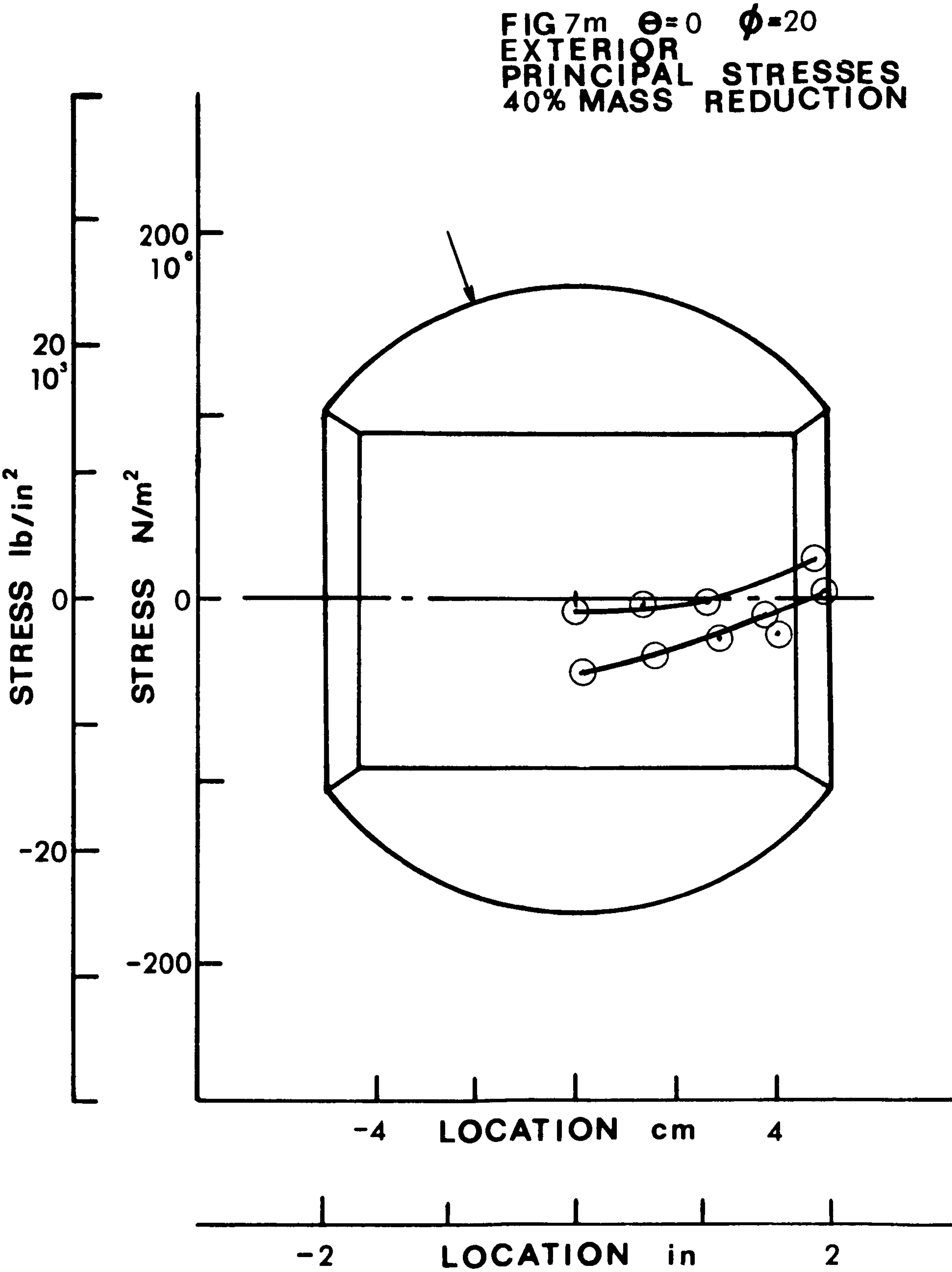
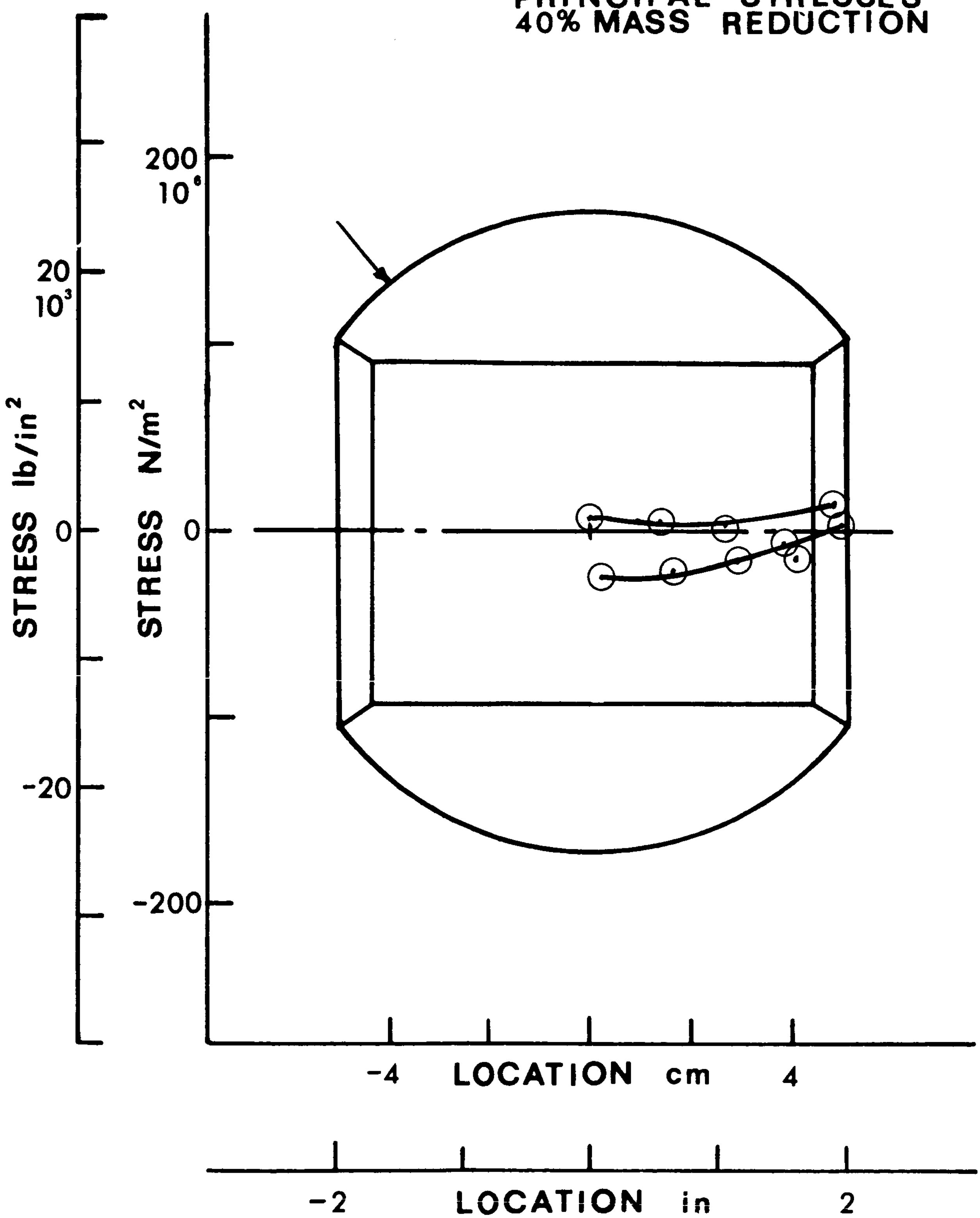


FIG 7m Θ=0 ϕ=20
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
10³
0
-20
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 7n Θ=0 ϕ=40
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



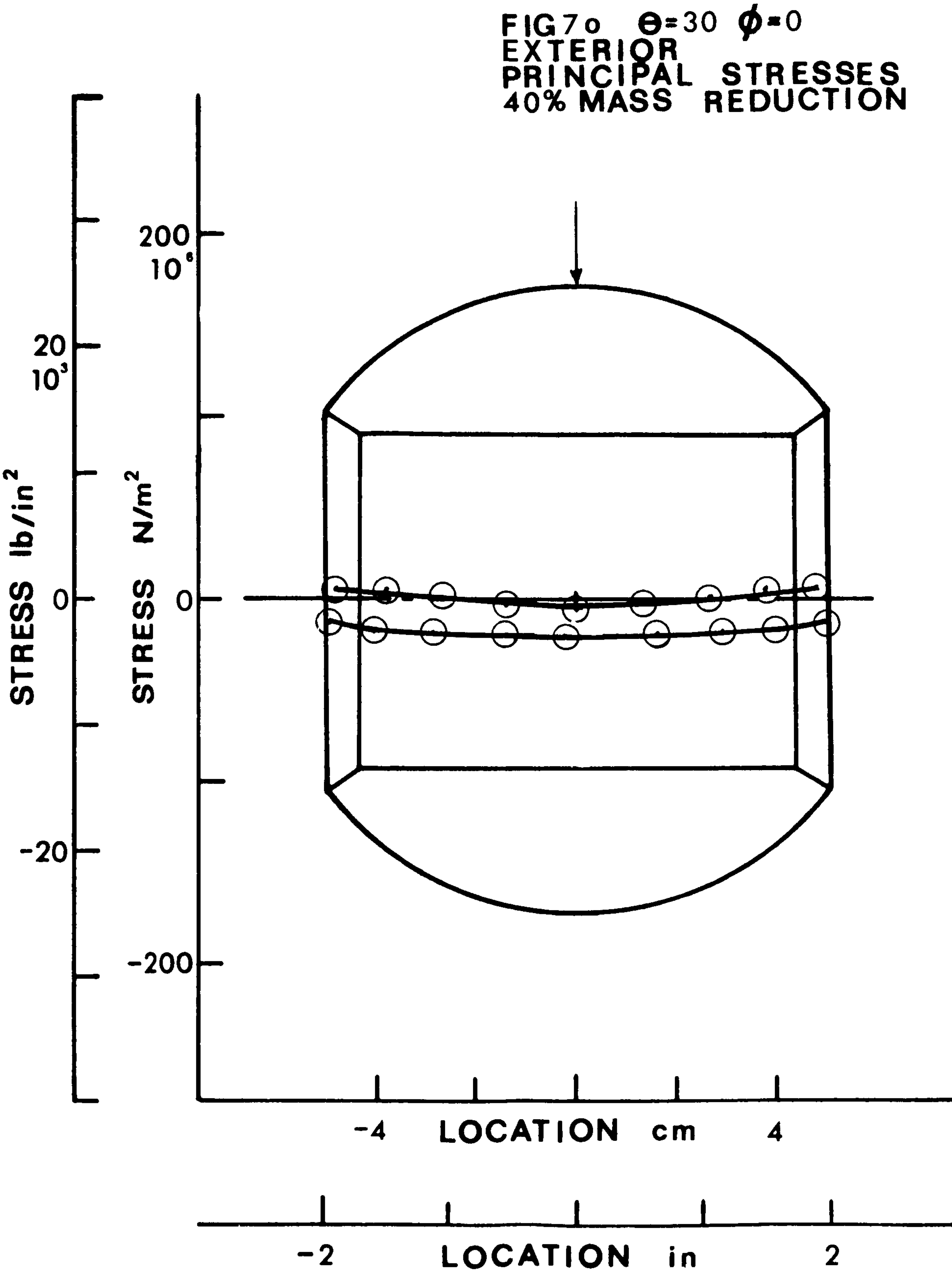


FIG7o Θ=30 φ=0
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
200
10⁶
20
10³
STRESS lb/in²
STRESS N/m²
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

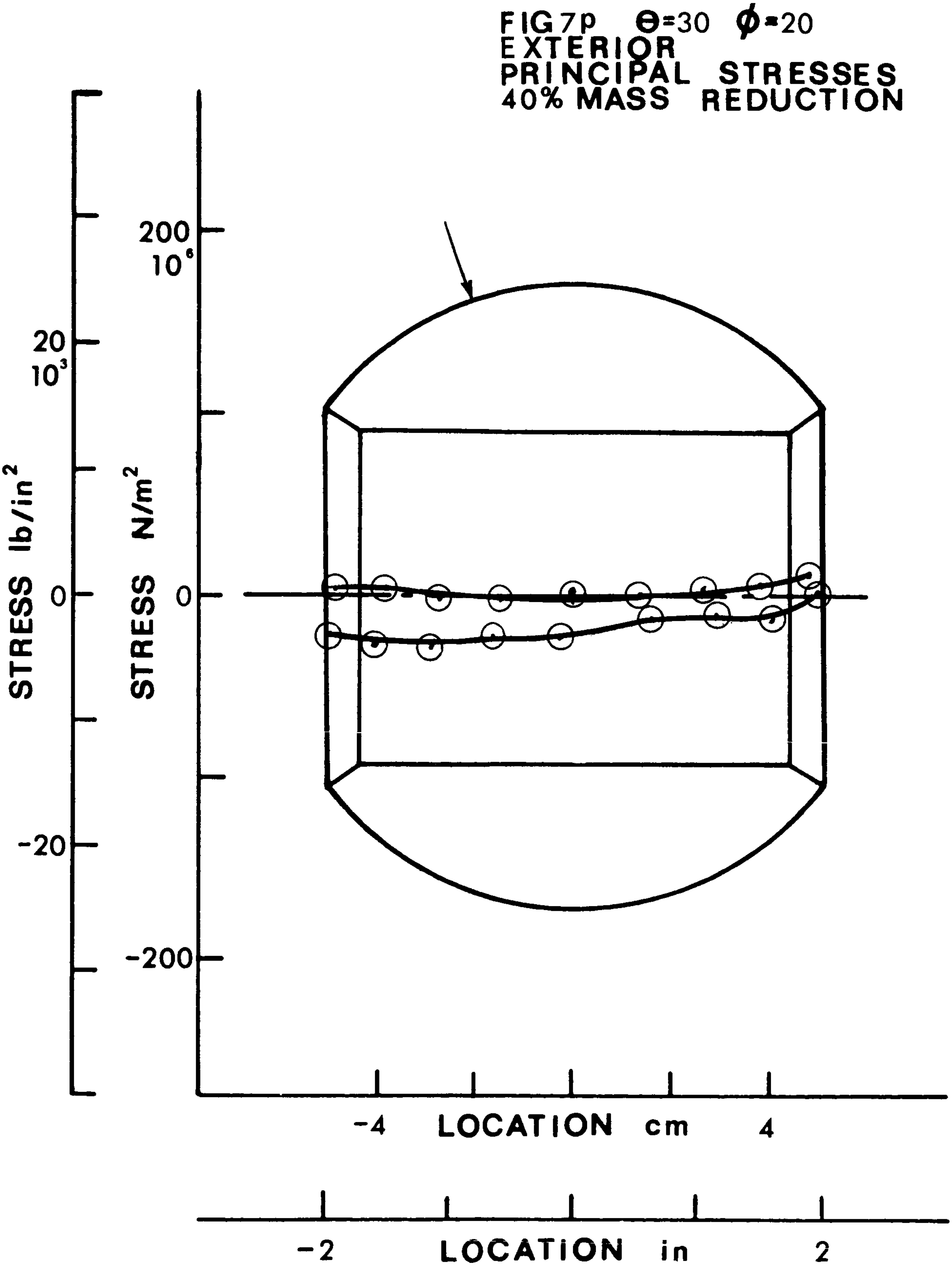
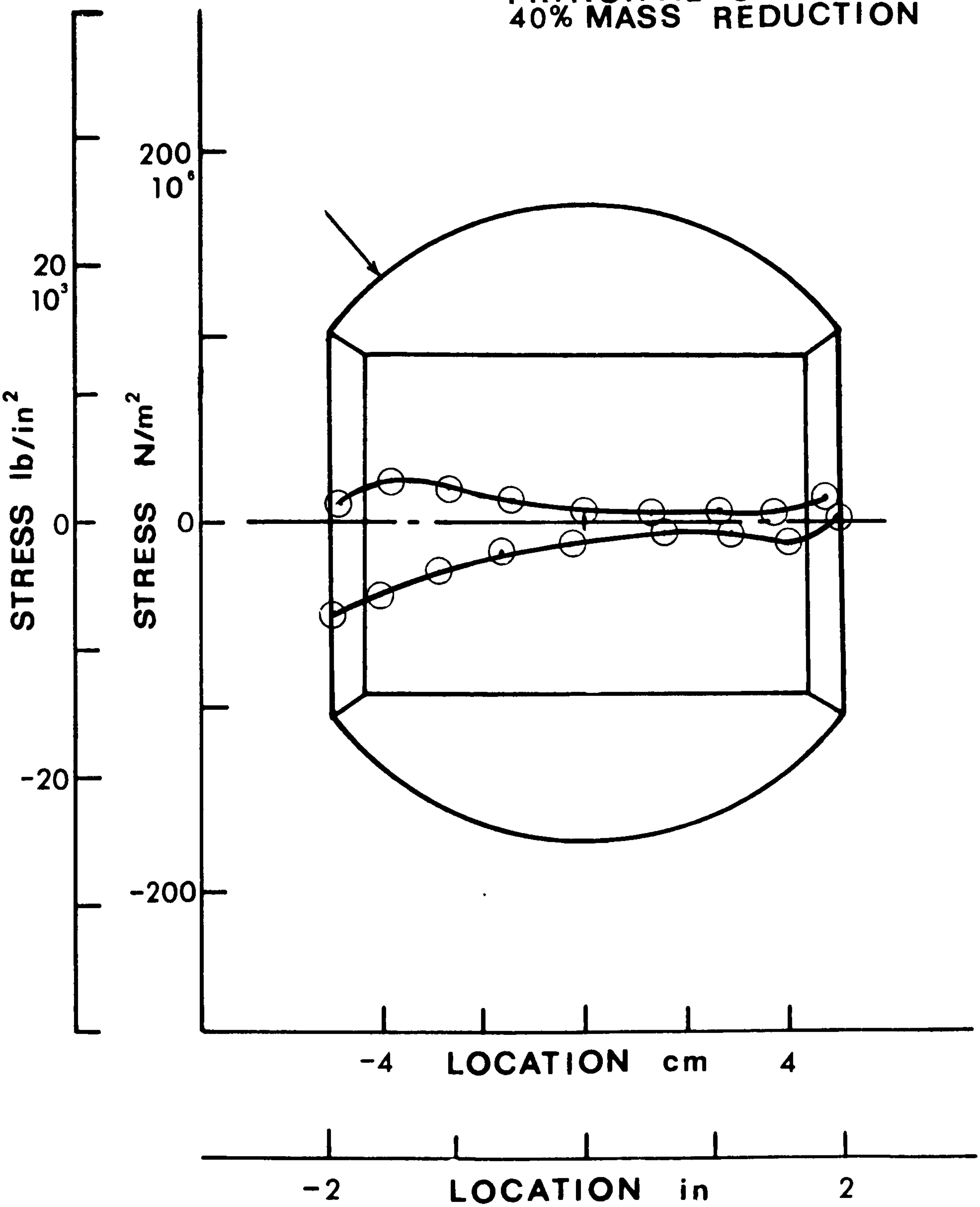


FIG 7p Θ=30 φ=20
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 7q Θ=30 ϕ=40
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



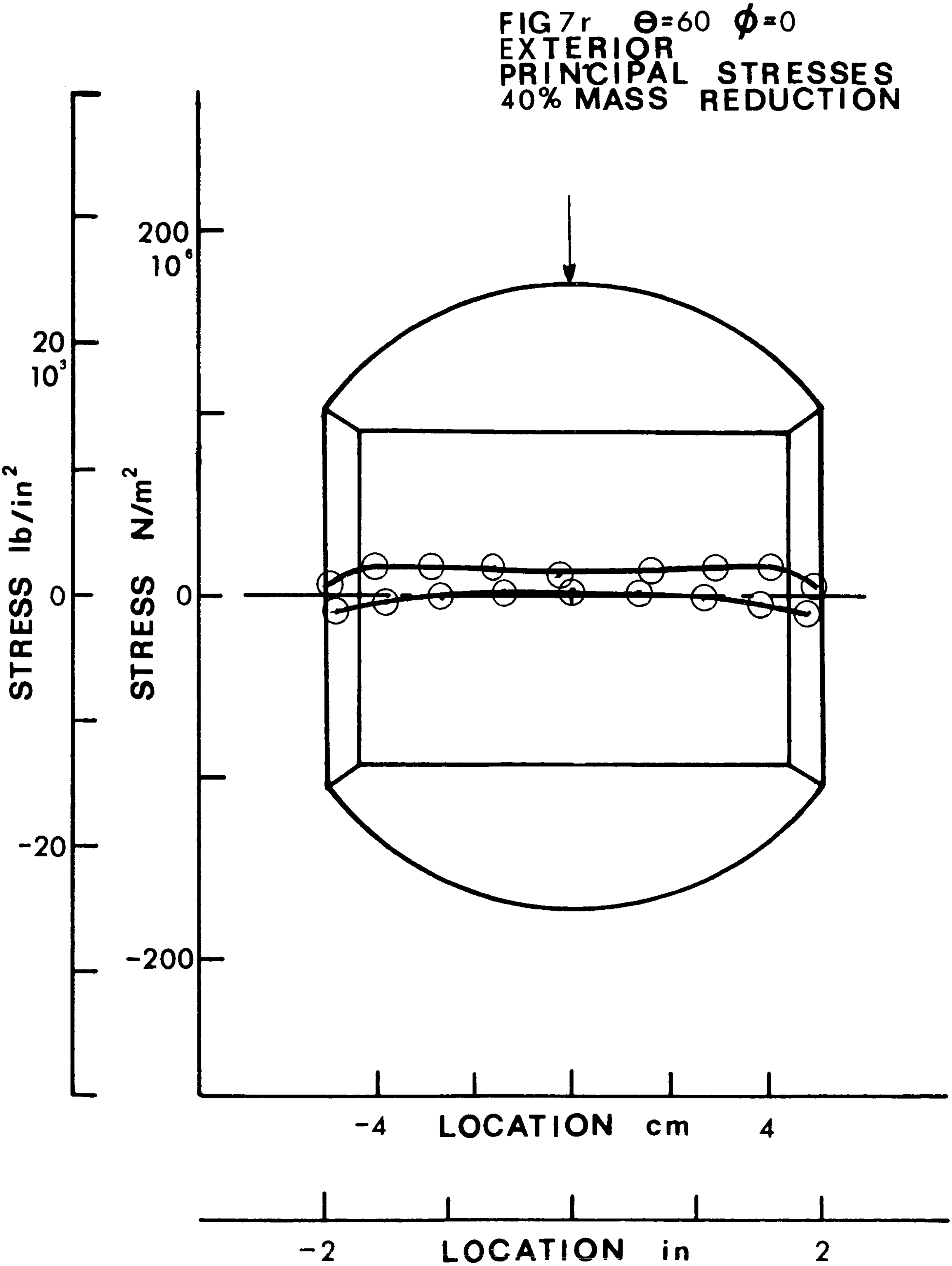


FIG 7r Θ=60 φ=0
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
200
10^6
20
10^3
0
0
-20
-200
STRESS lb/in²
STRESS N/m²
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 7s Θ=60 ϕ=20
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

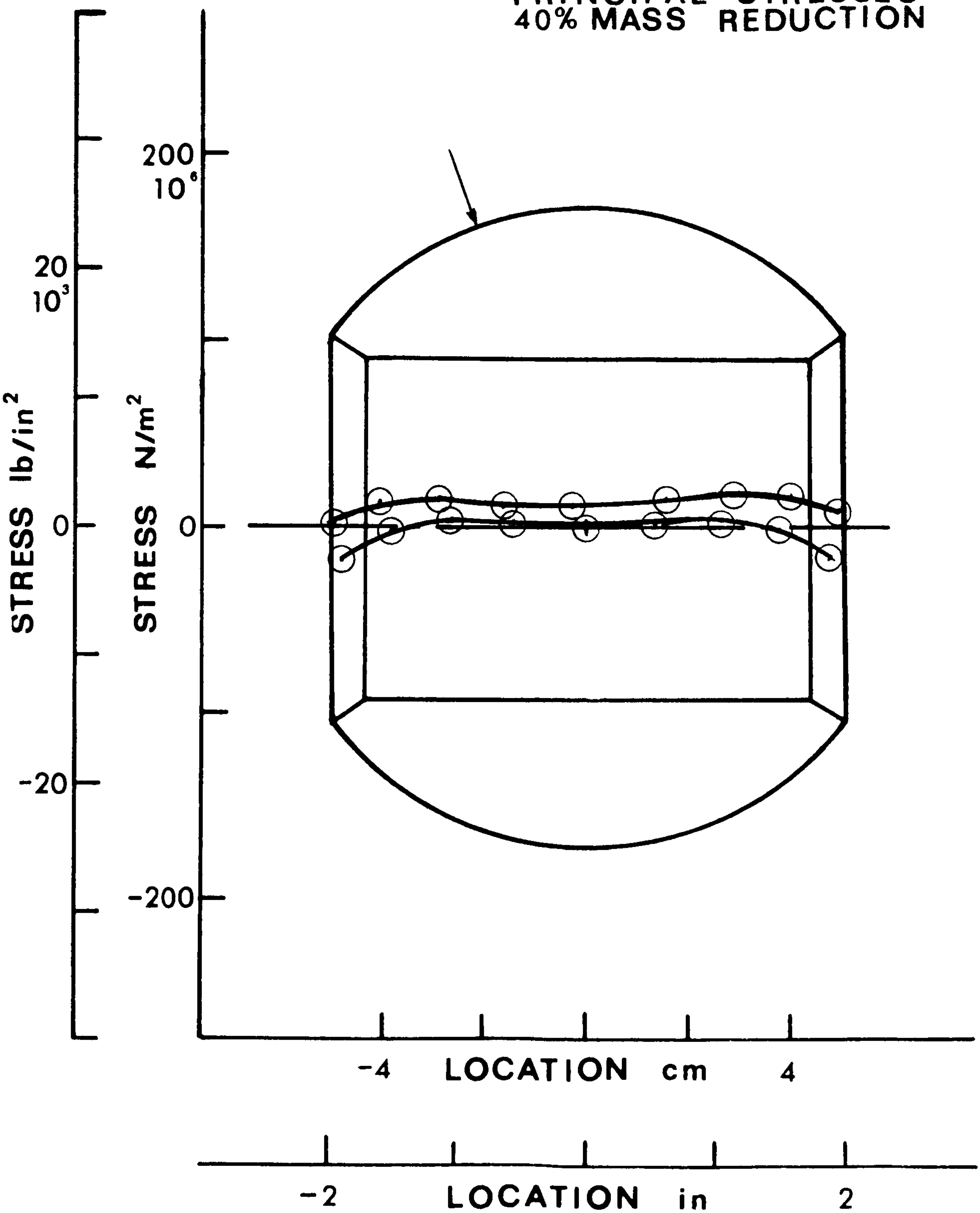


FIG 7t Θ=60 ϕ=40
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION

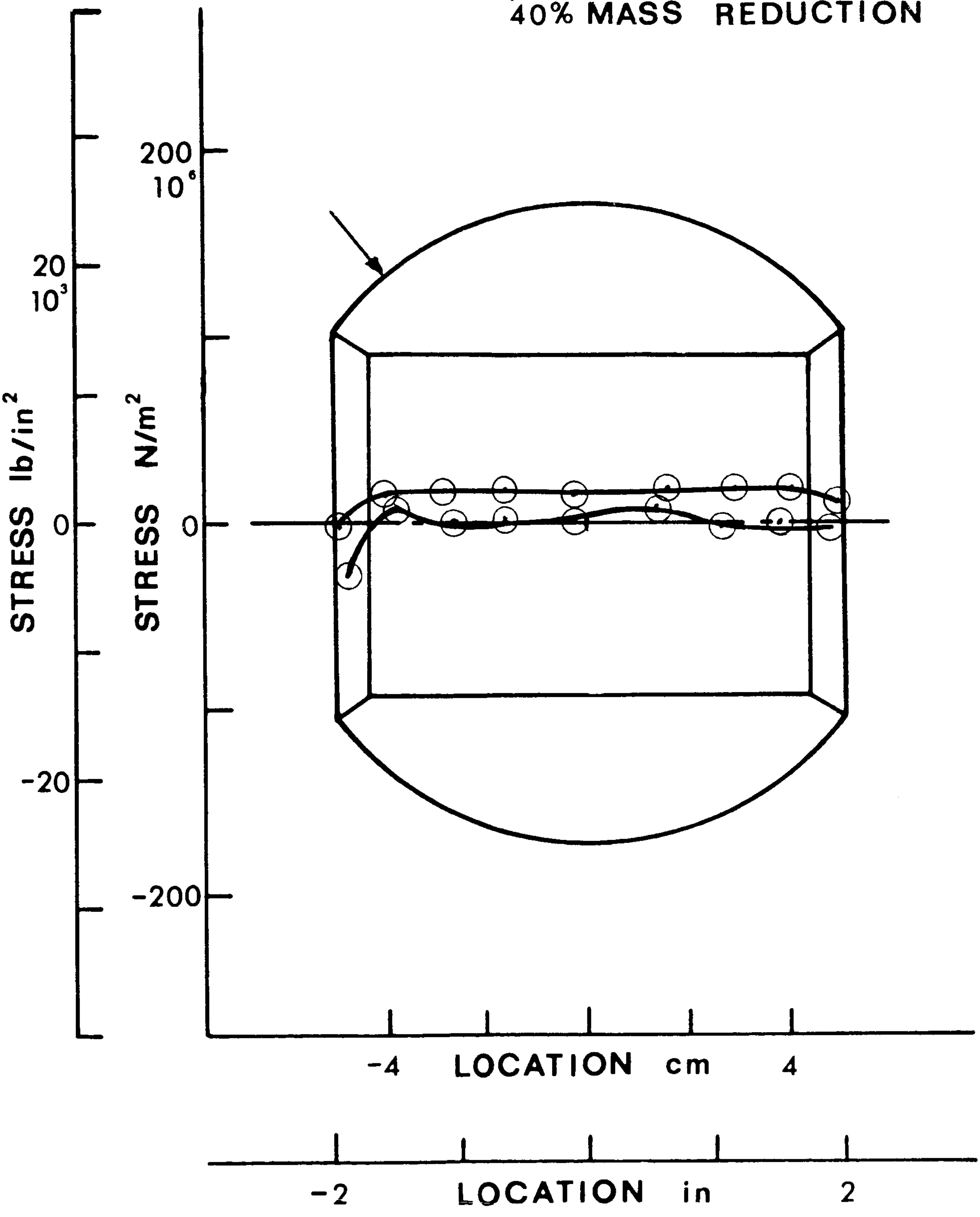
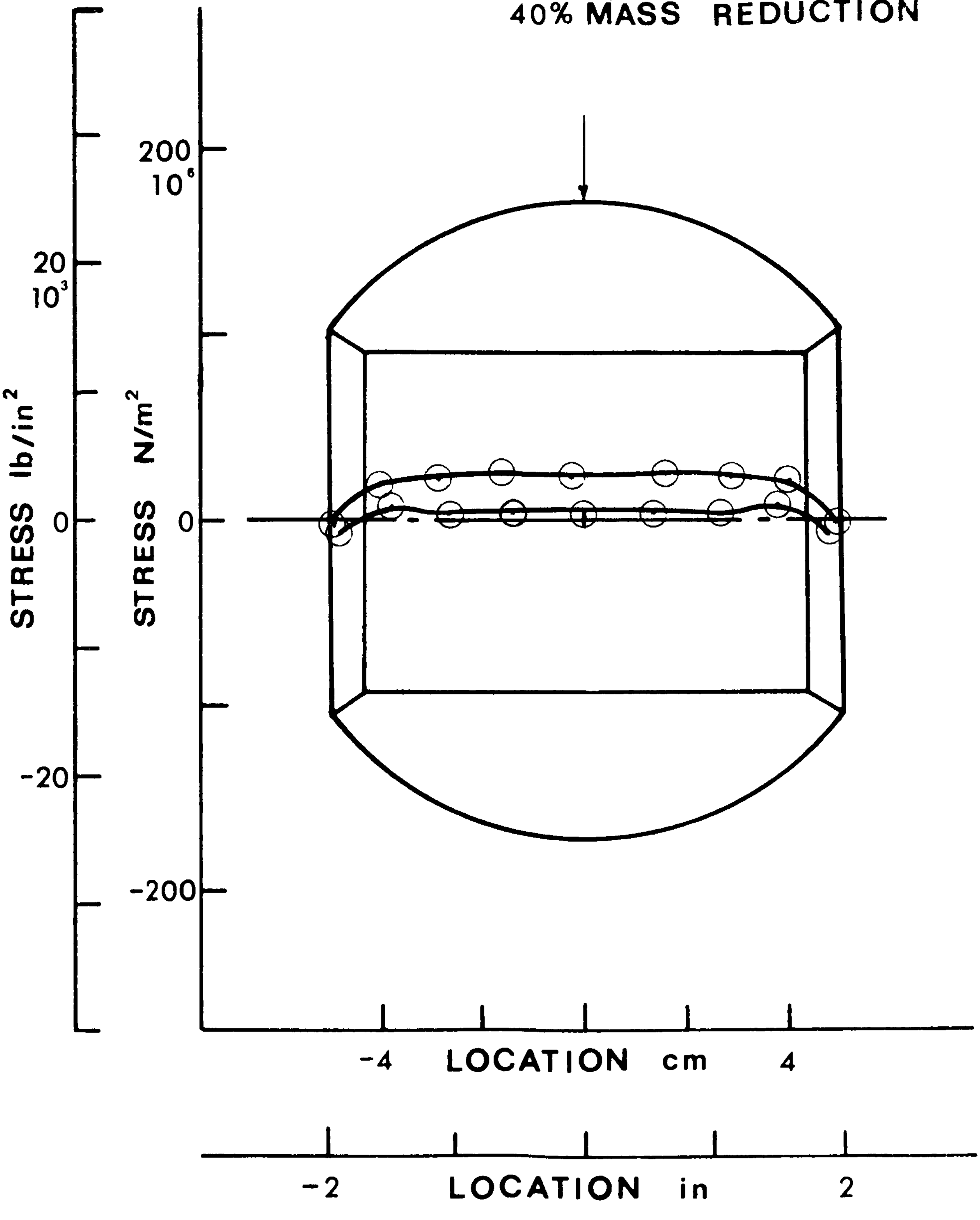


FIG 7u Θ=90 φ=0
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



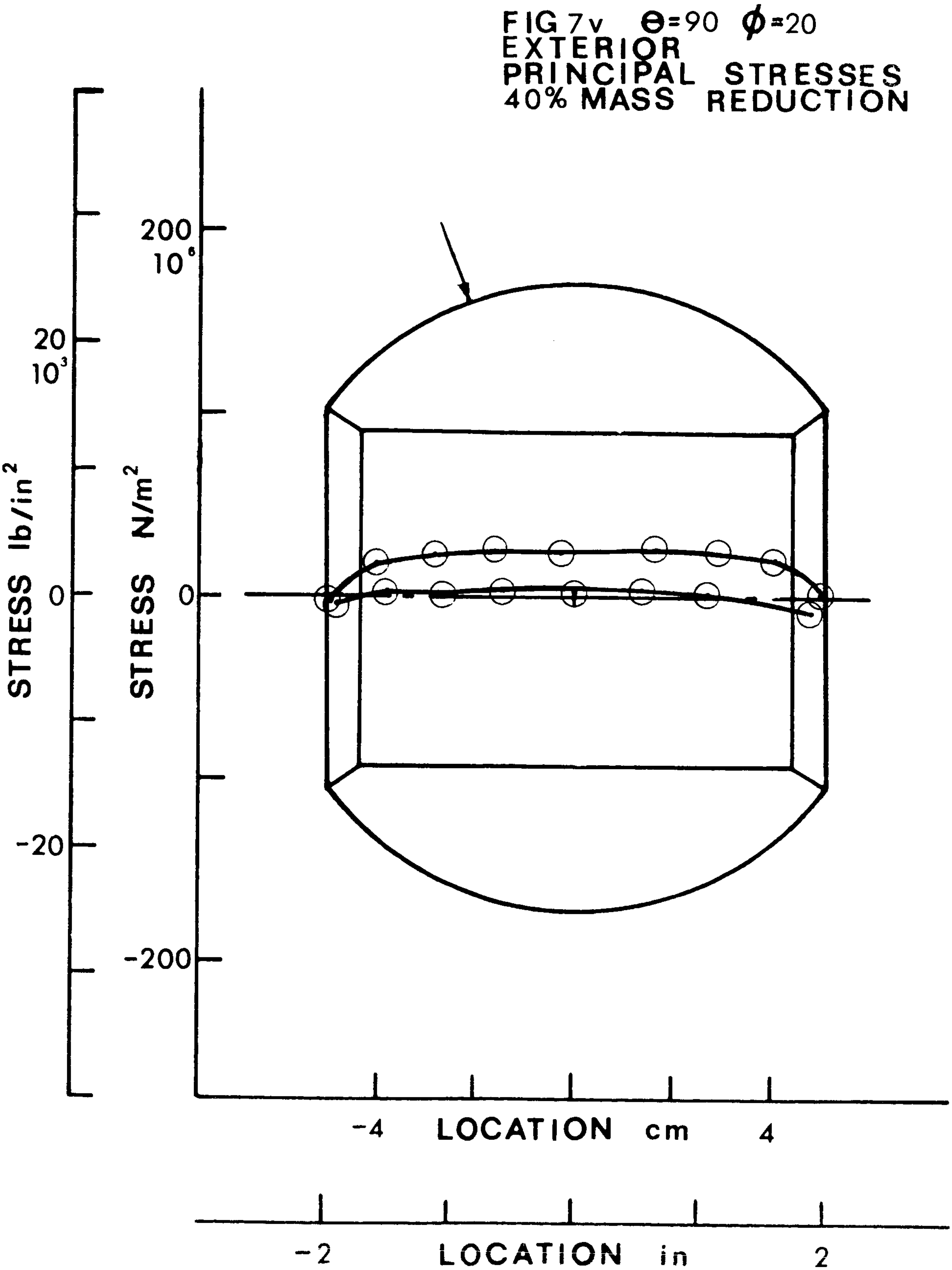
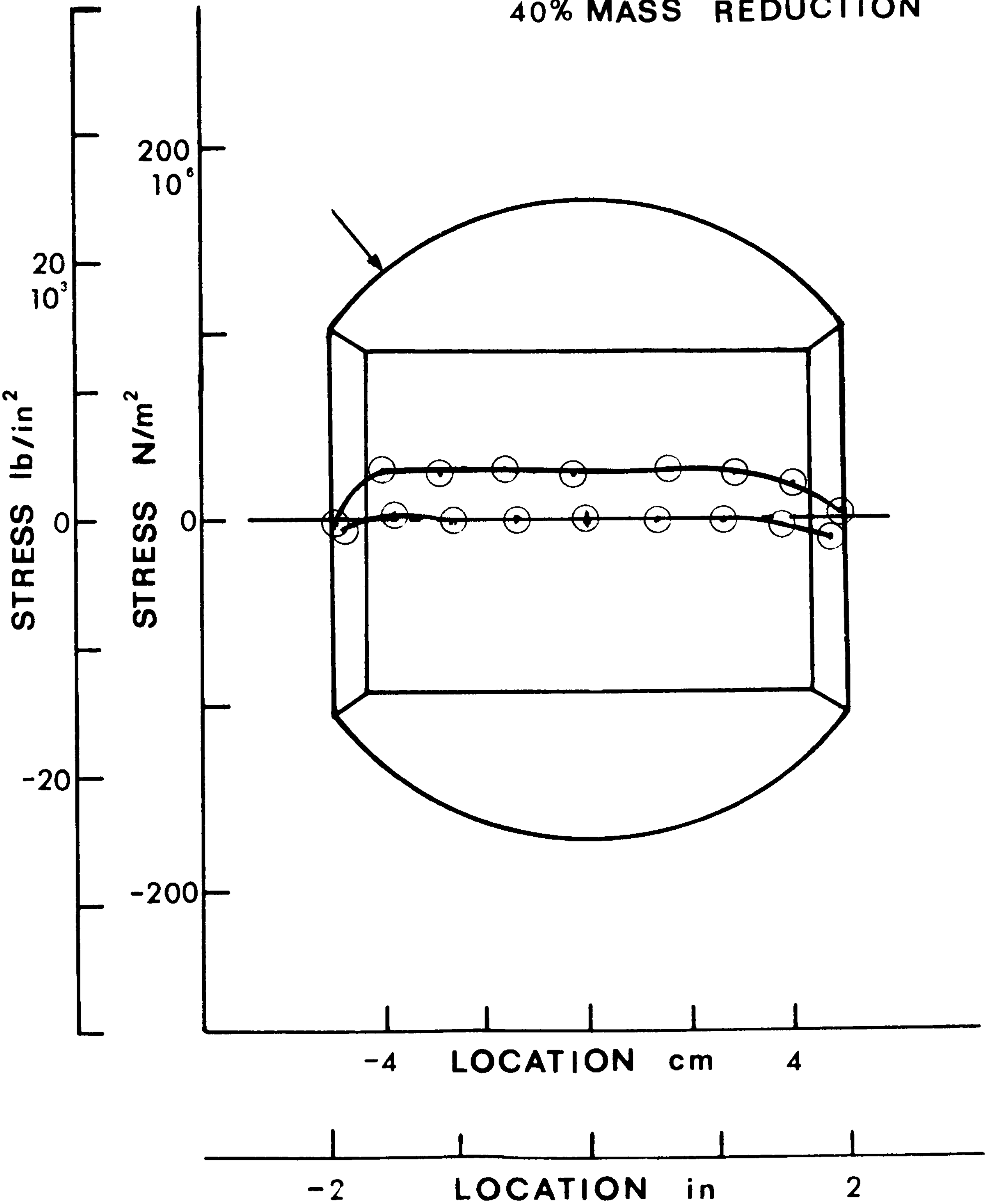


FIG 7v Θ=90 φ=20
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 7w $\Theta=90$ $\phi=40$
EXTERIOR
PRINCIPAL STRESSES
40% MASS REDUCTION



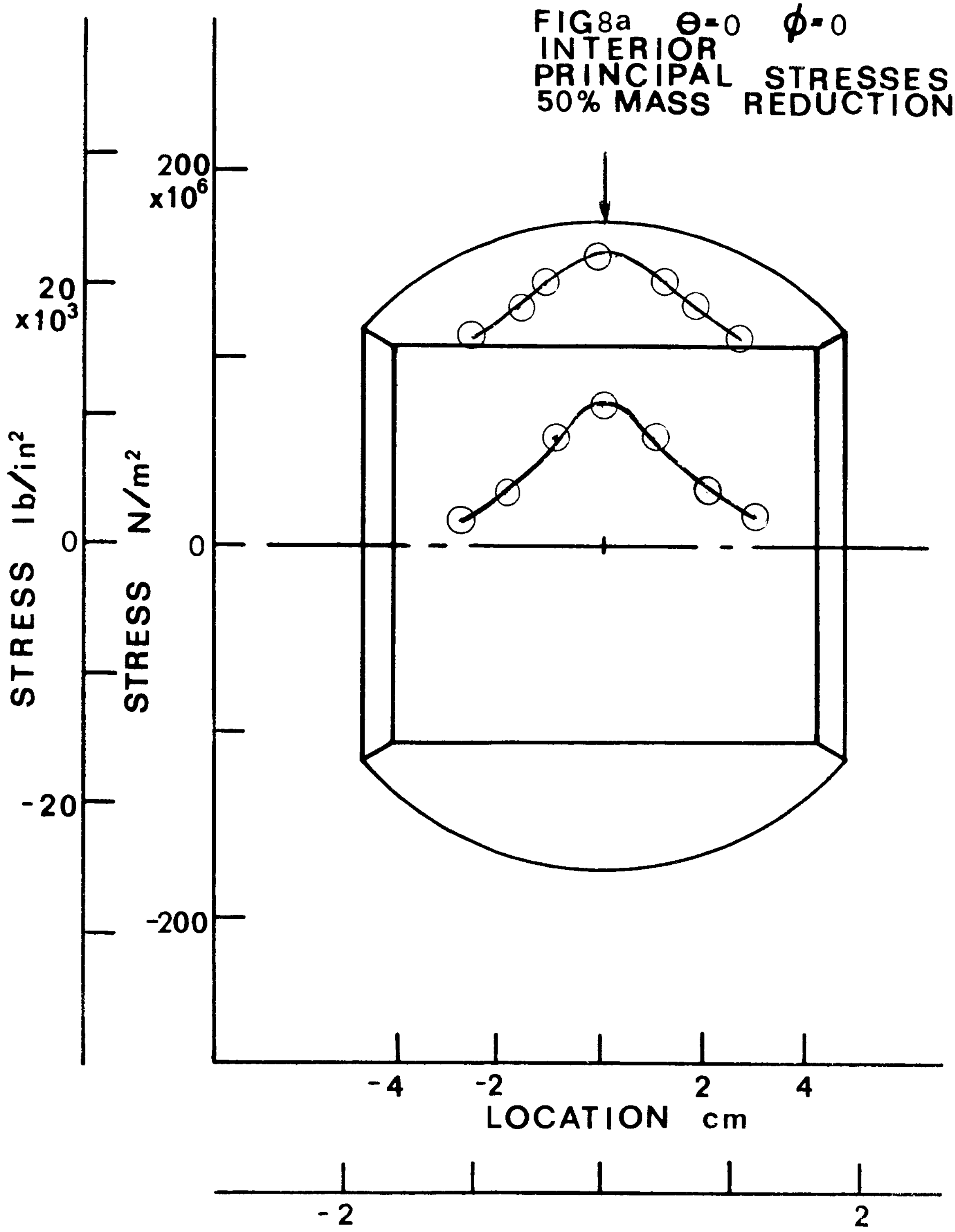


FIG 8a Θ=0 φ=0
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
20
x10³
0
-20
STRESS lb/in²
200
x10⁶
0
-200
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

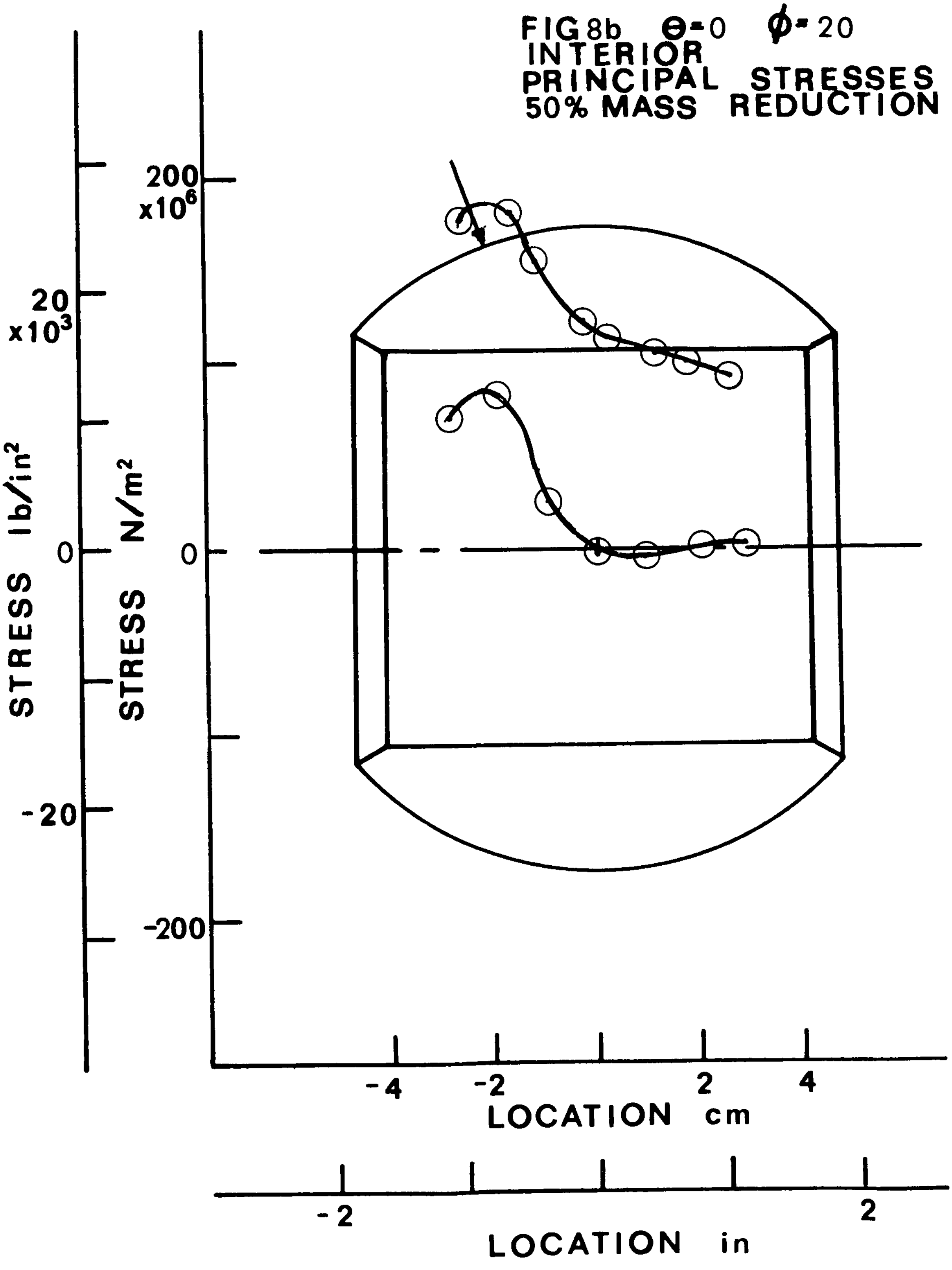


FIG 8b $\Theta = 0$ $\phi = 20$
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20 x10³
0
-20
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

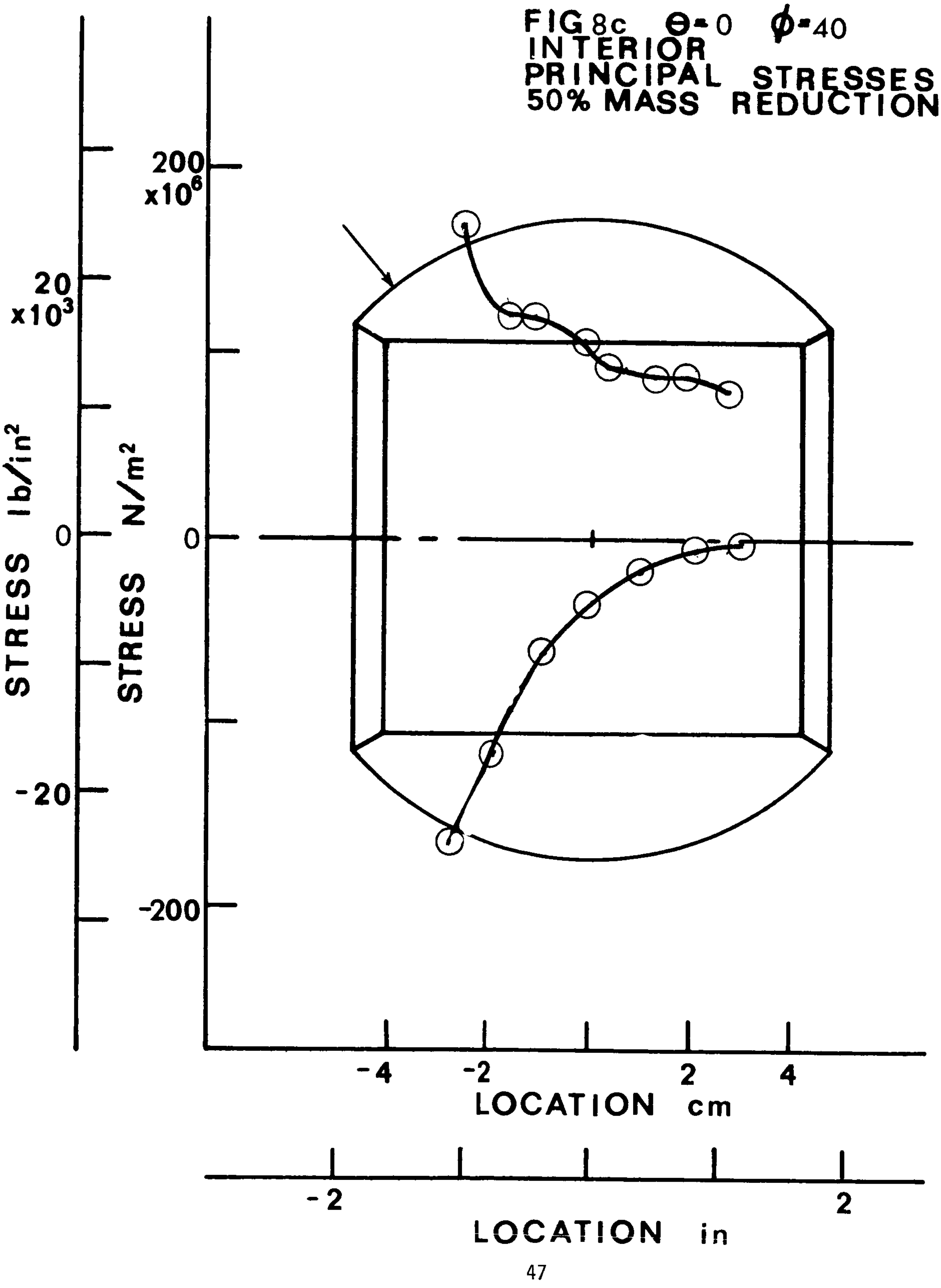


FIG 8c Θ=0 φ=40
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
20
x10³
0
-20
STRESS lb/in²
200
x10⁶
0
-200
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

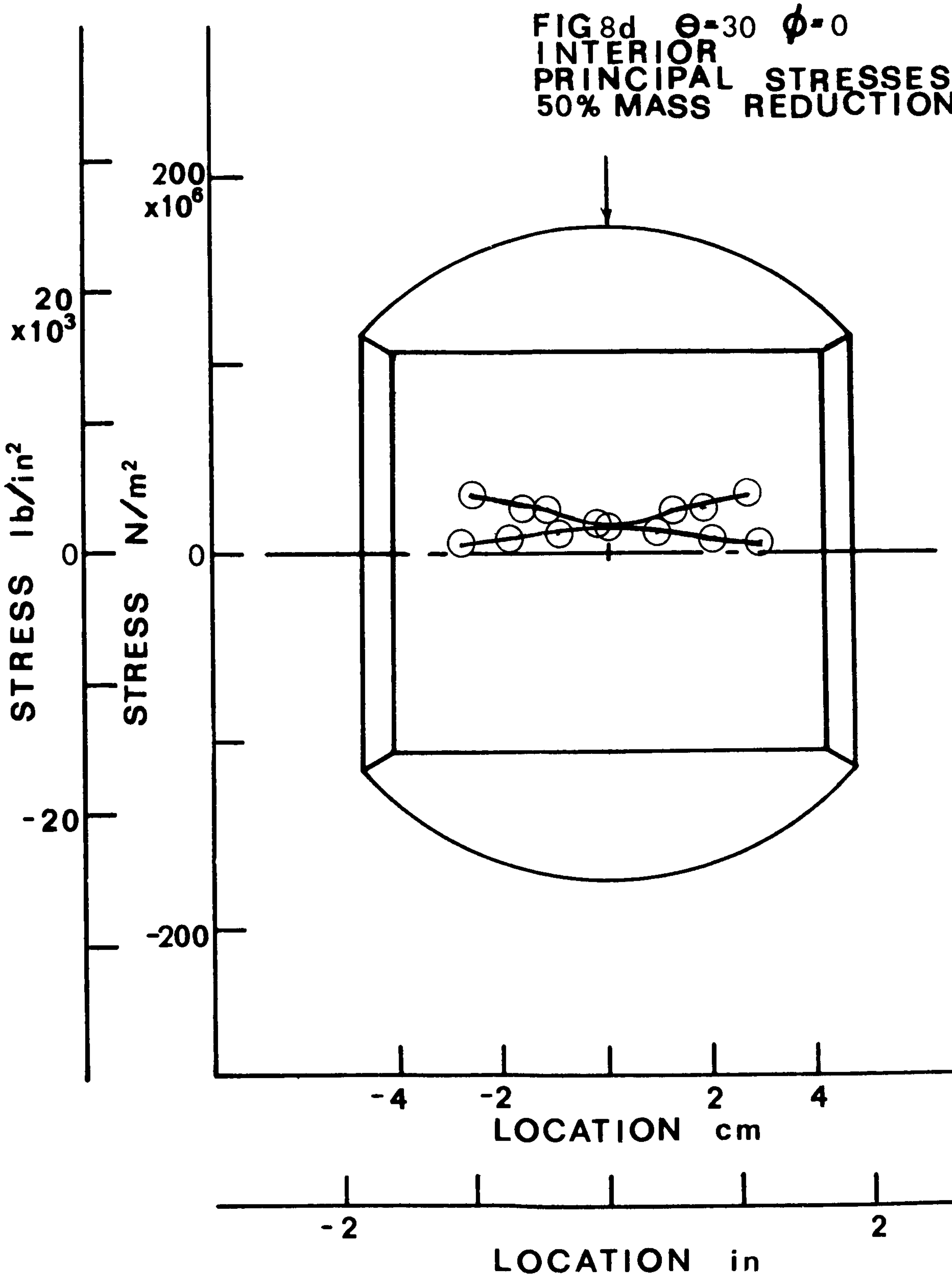


FIG 8d Θ=30 φ=0
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
200
x10⁶
20
x10³
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

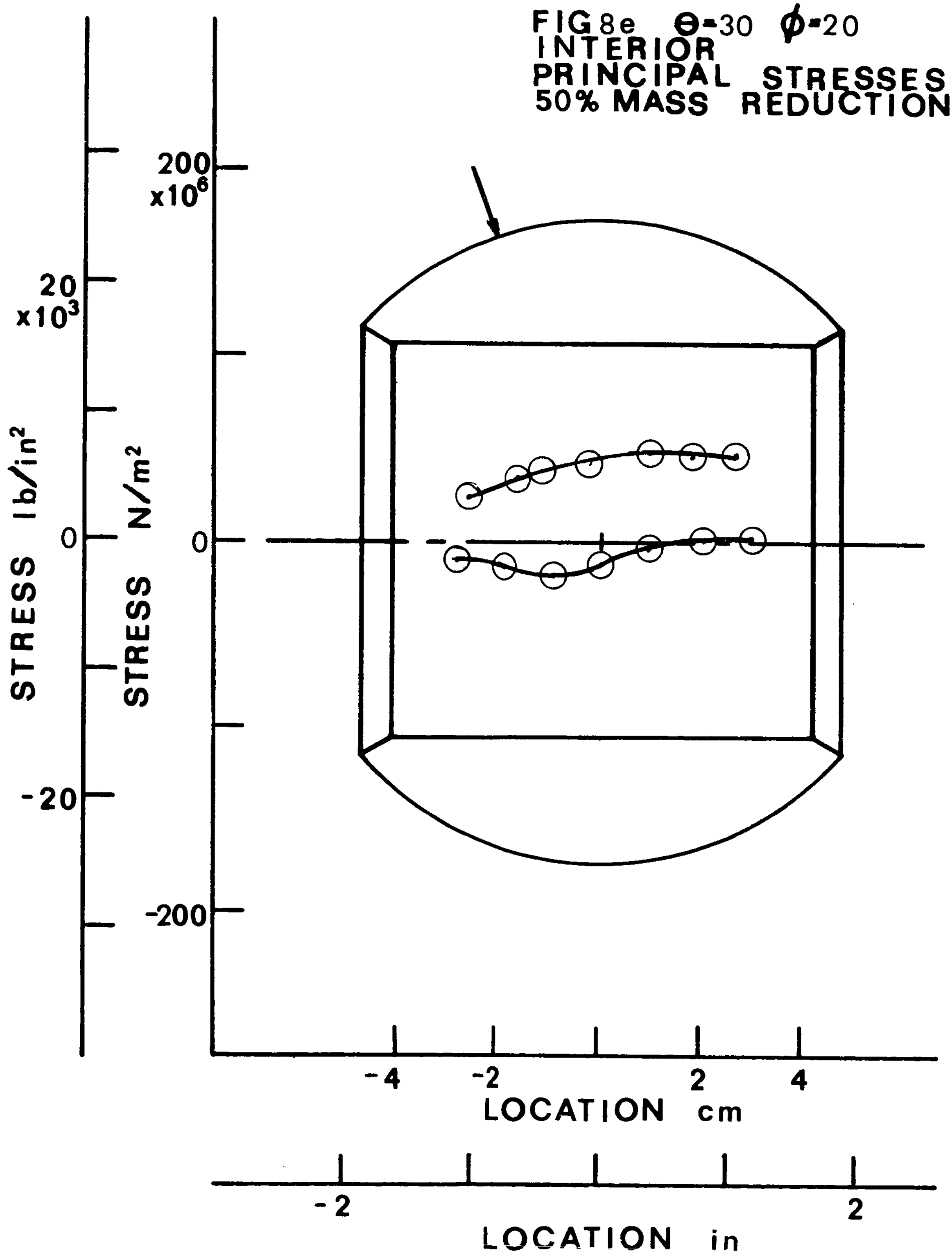


FIG 8e Θ=30 φ=20
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
20 x10³
0
-20
STRESS lb/in²
200 x10⁶
0
-200
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

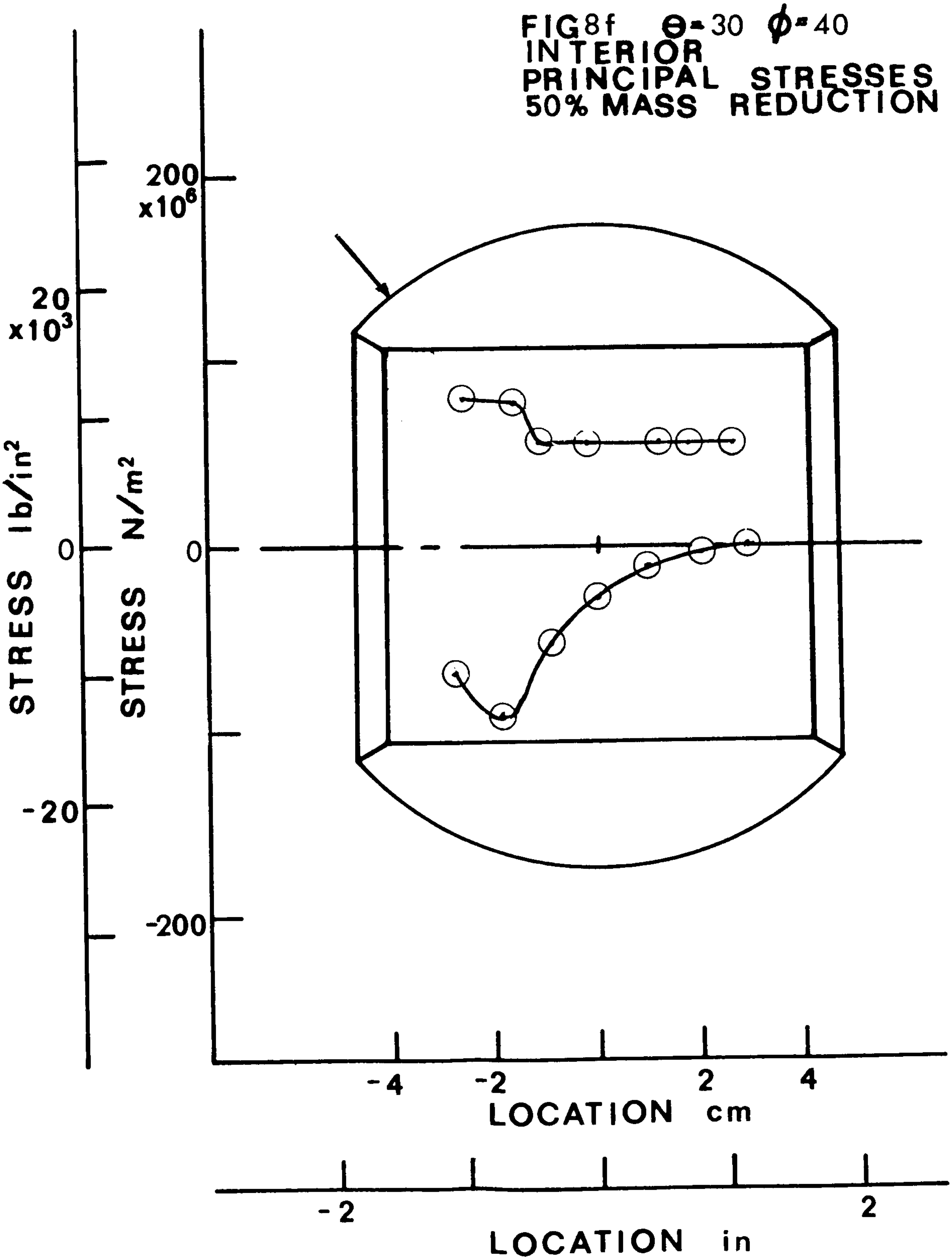


FIG 8f Θ=30 Φ=40
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
STRESS lb/in^2
STRESS N/m^2
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

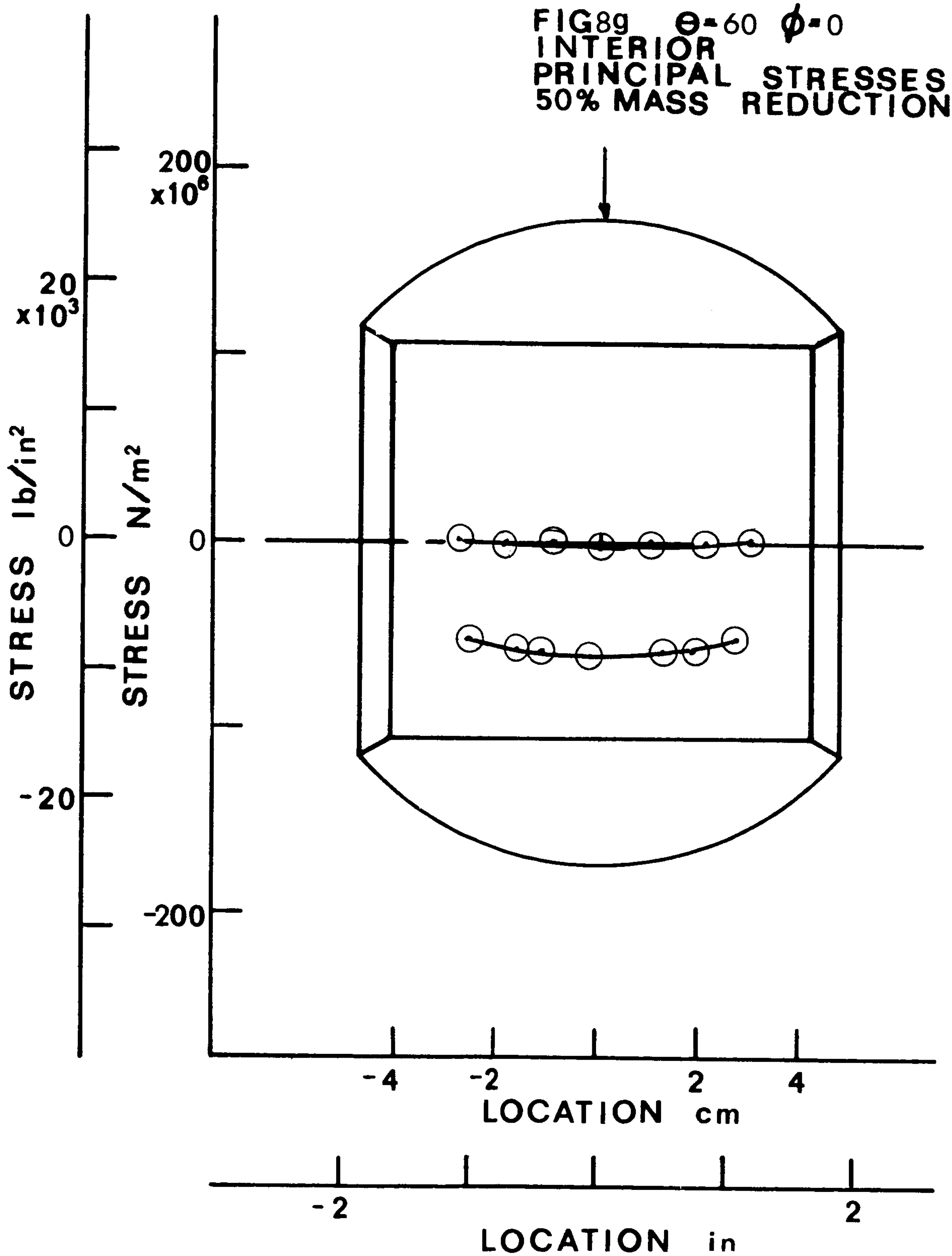


FIG8g Θ=60 φ=0
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10⁶
20
x10³
STRESS lb/in²
STRESS N/m²
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

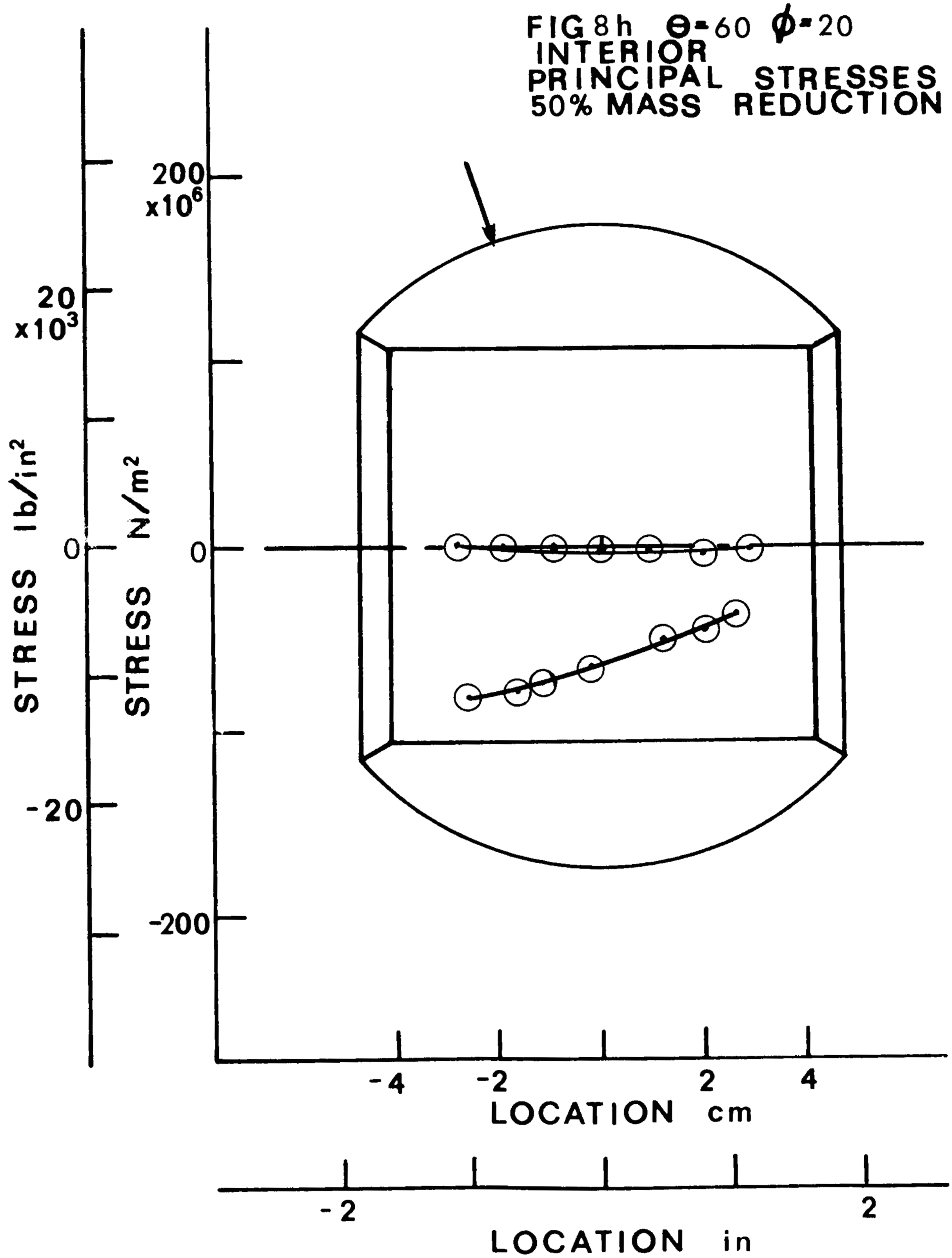


FIG 8h Θ=60 φ=20
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20 x10³
0
-20
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

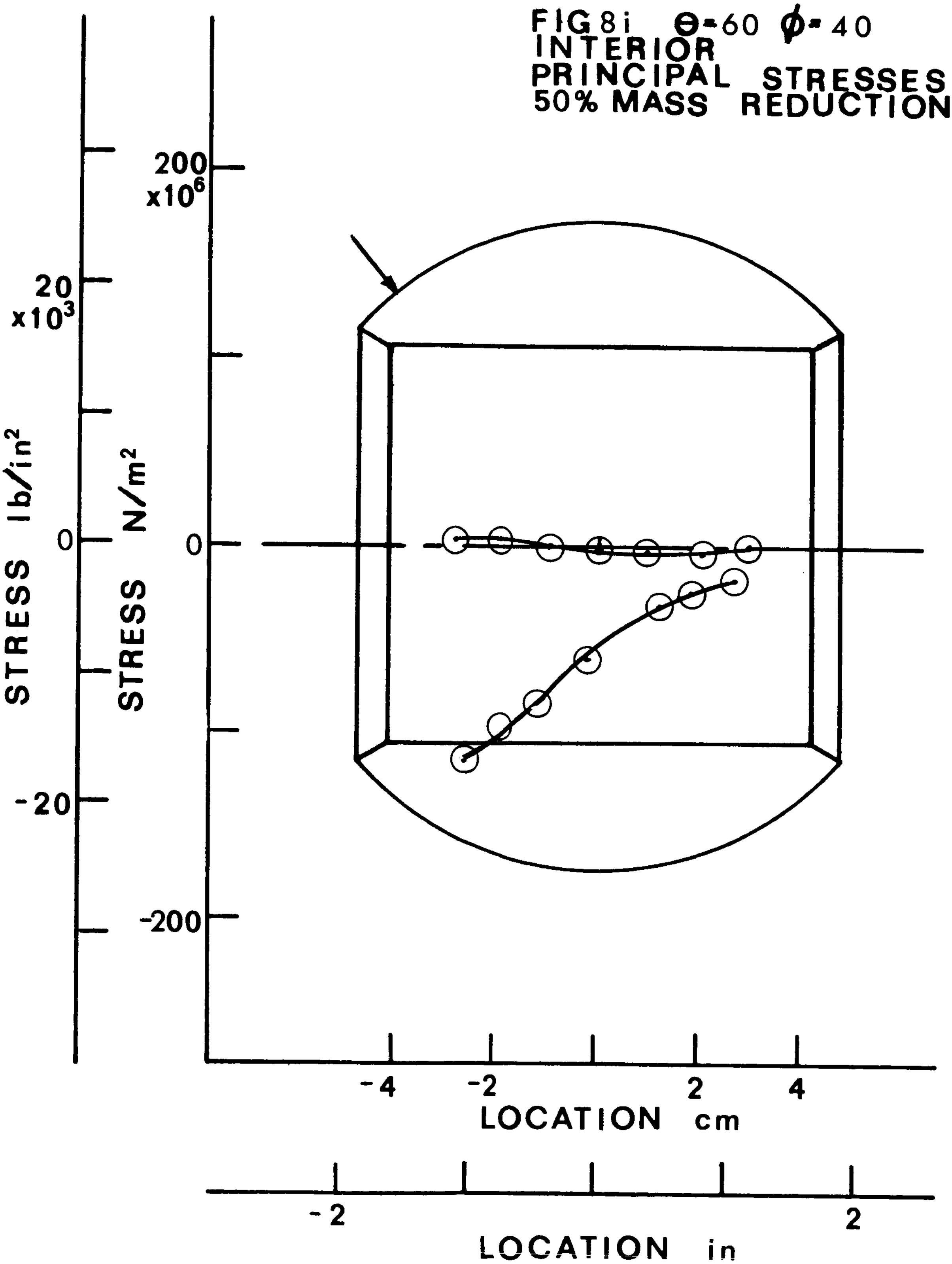


FIG 8i Θ=60 Φ=40
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
0
0
-20
-200
STRESS lb/in²
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

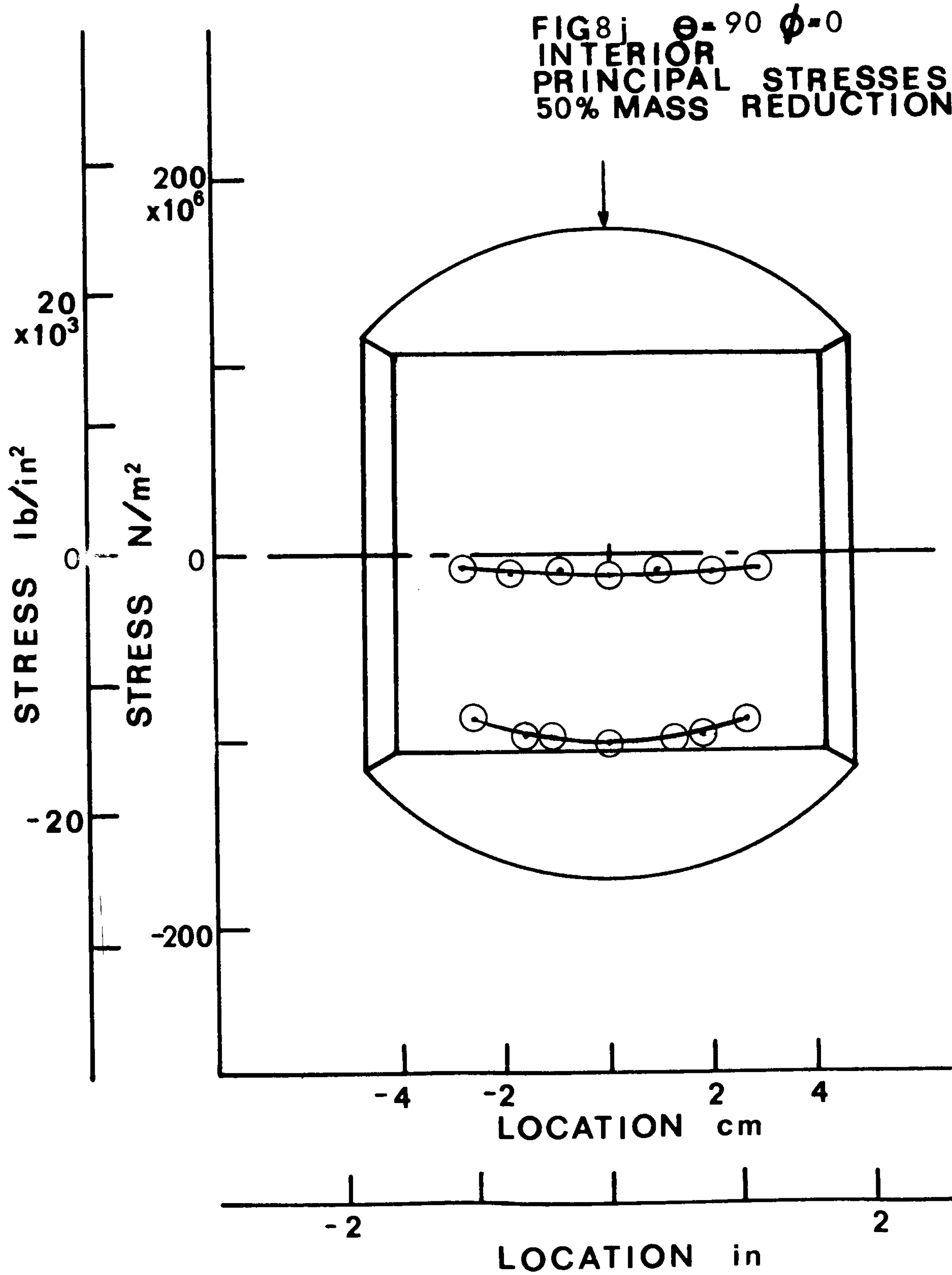


FIG8j $\Theta=90$ $\phi=0$
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
STRESS lb/in^2
STRESS N/m^2
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

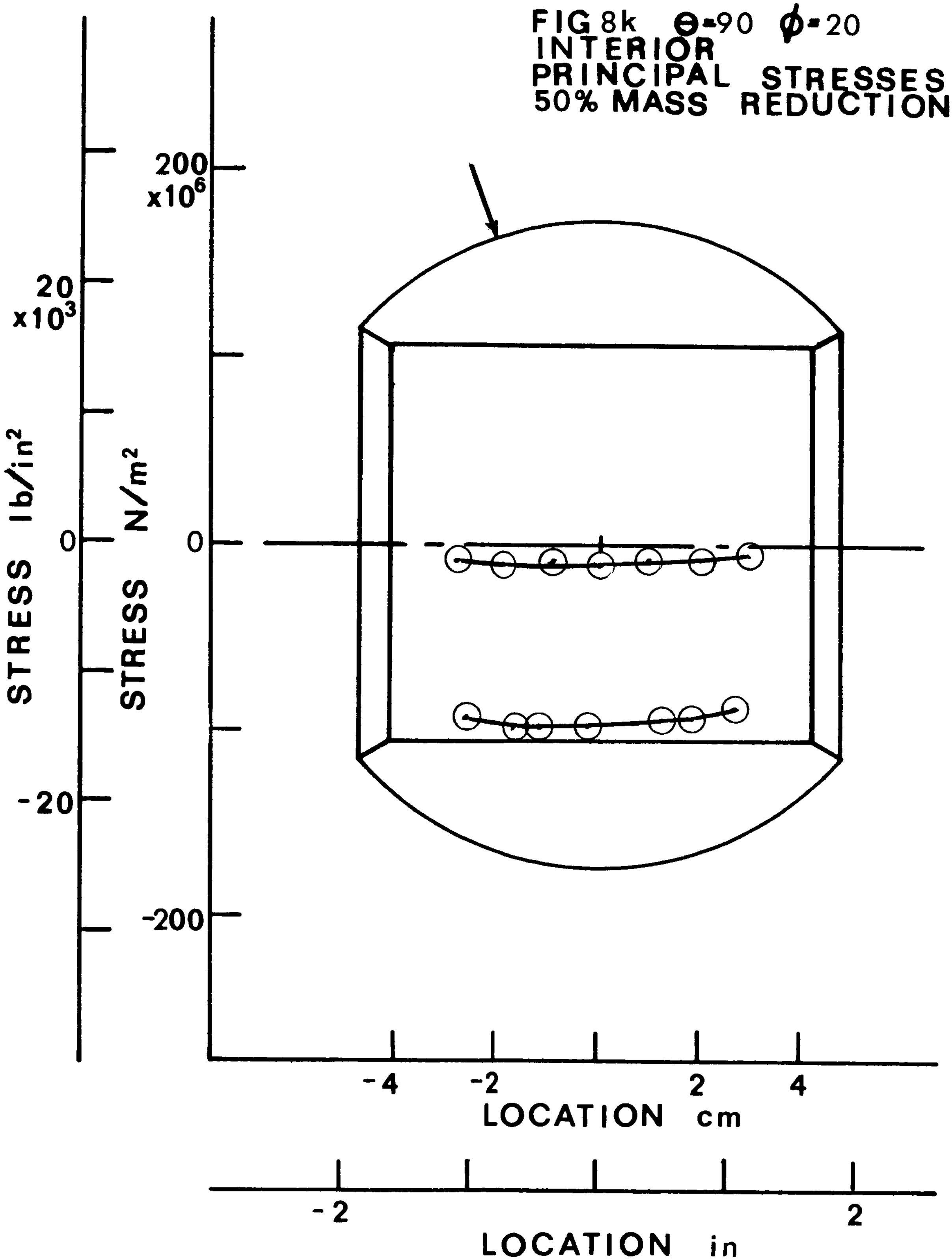


FIG 8k Θ=90 ϕ=20
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
x10³
0
-20
200
x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

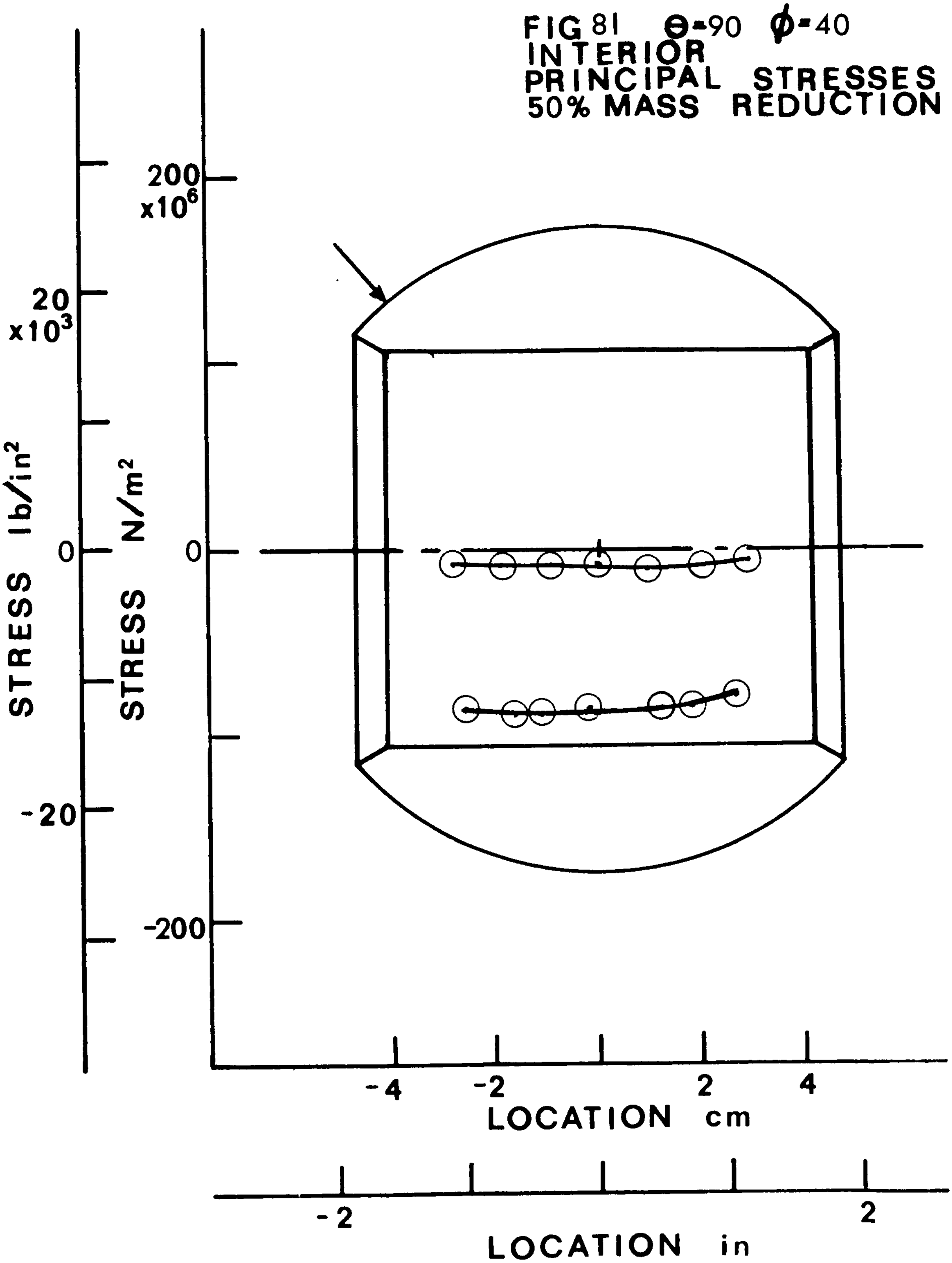


FIG 81 Θ=90 Φ=40
INTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
STRESS lb/in^2
STRESS N/m^2
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

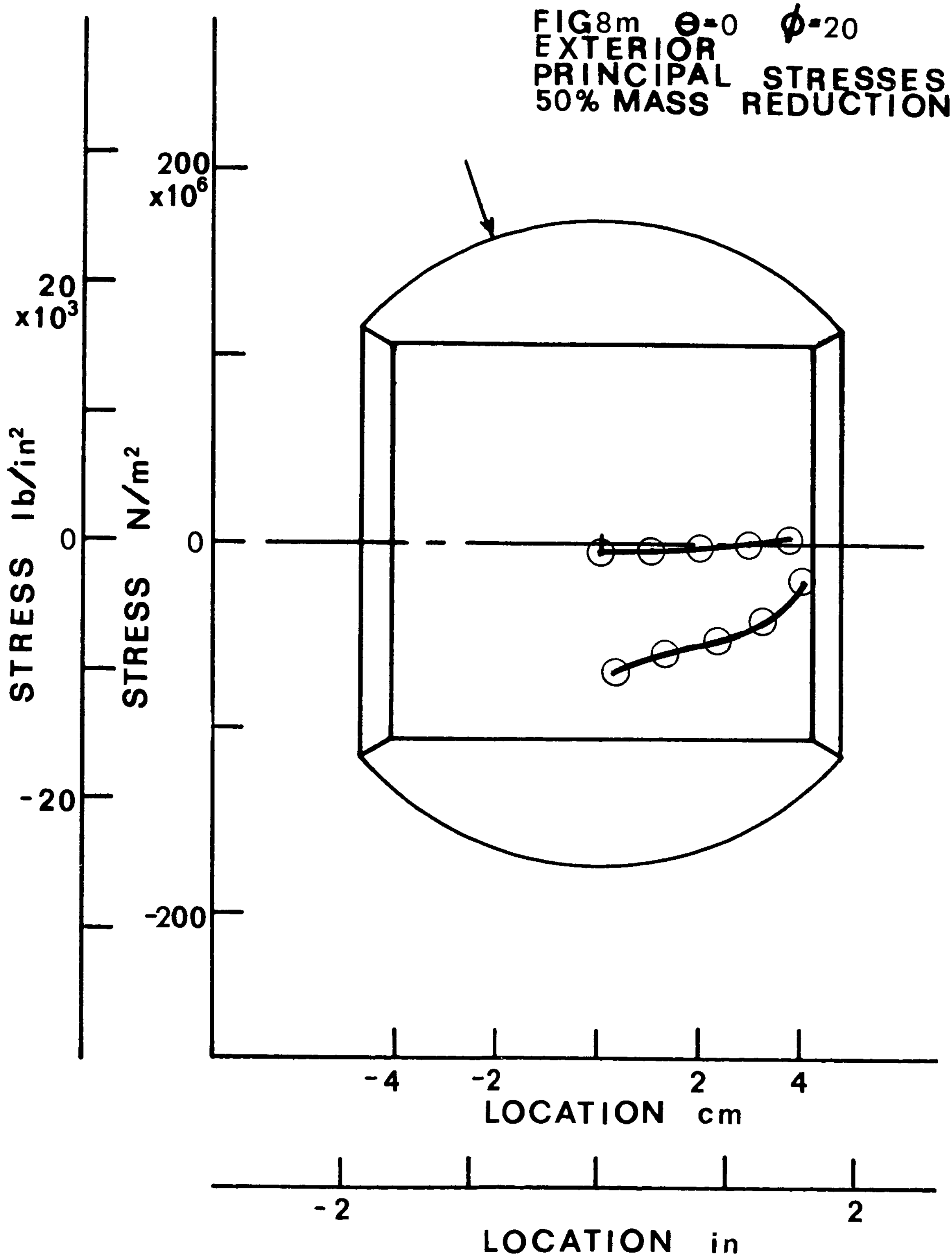


FIG 8m Θ=0 φ=20
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
20 x10³
0
-20
STRESS N/m²
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

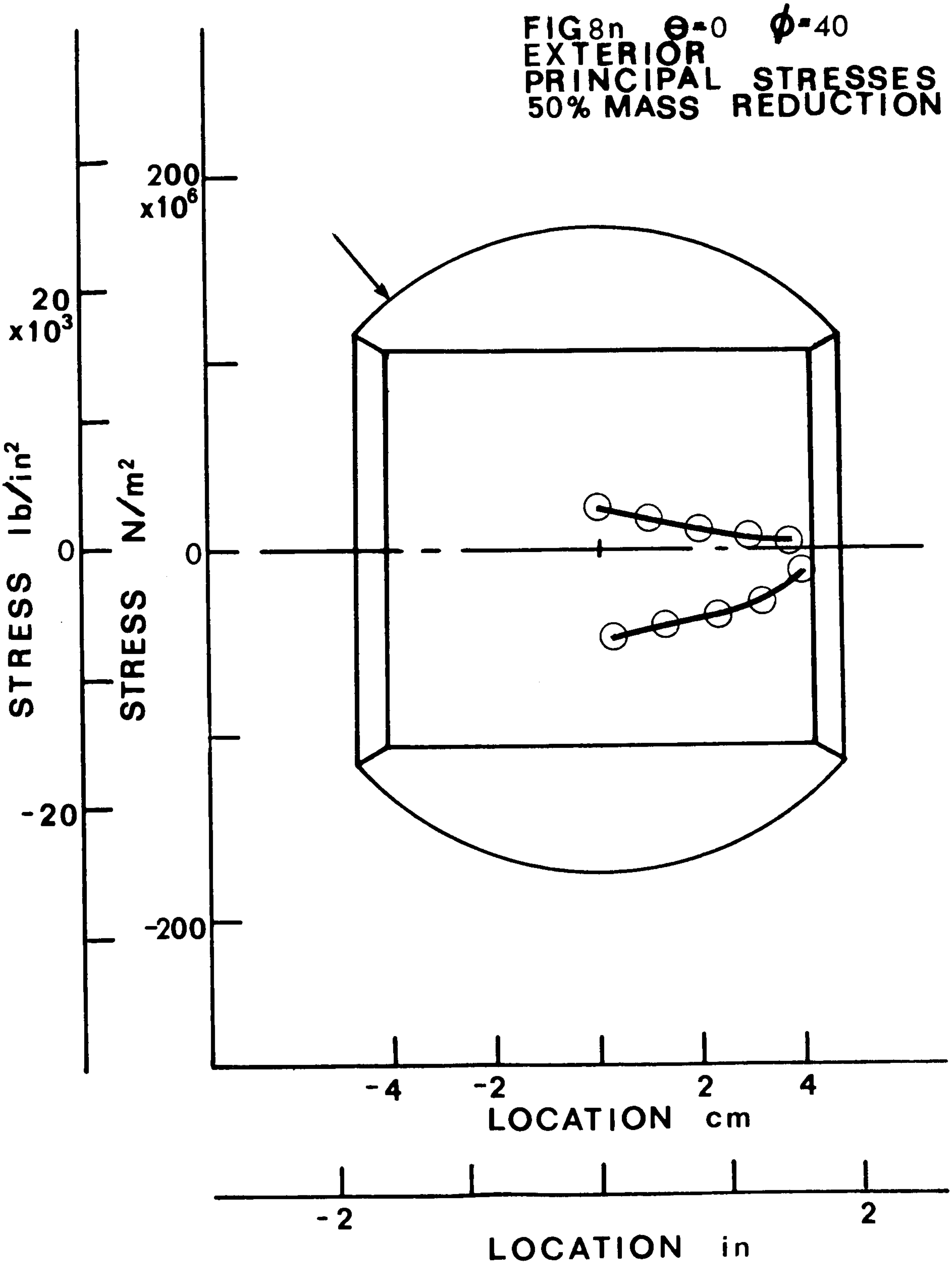


FIG 8n Θ=0 φ=40
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
0
0
-20
-200
STRESS lb/in²
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

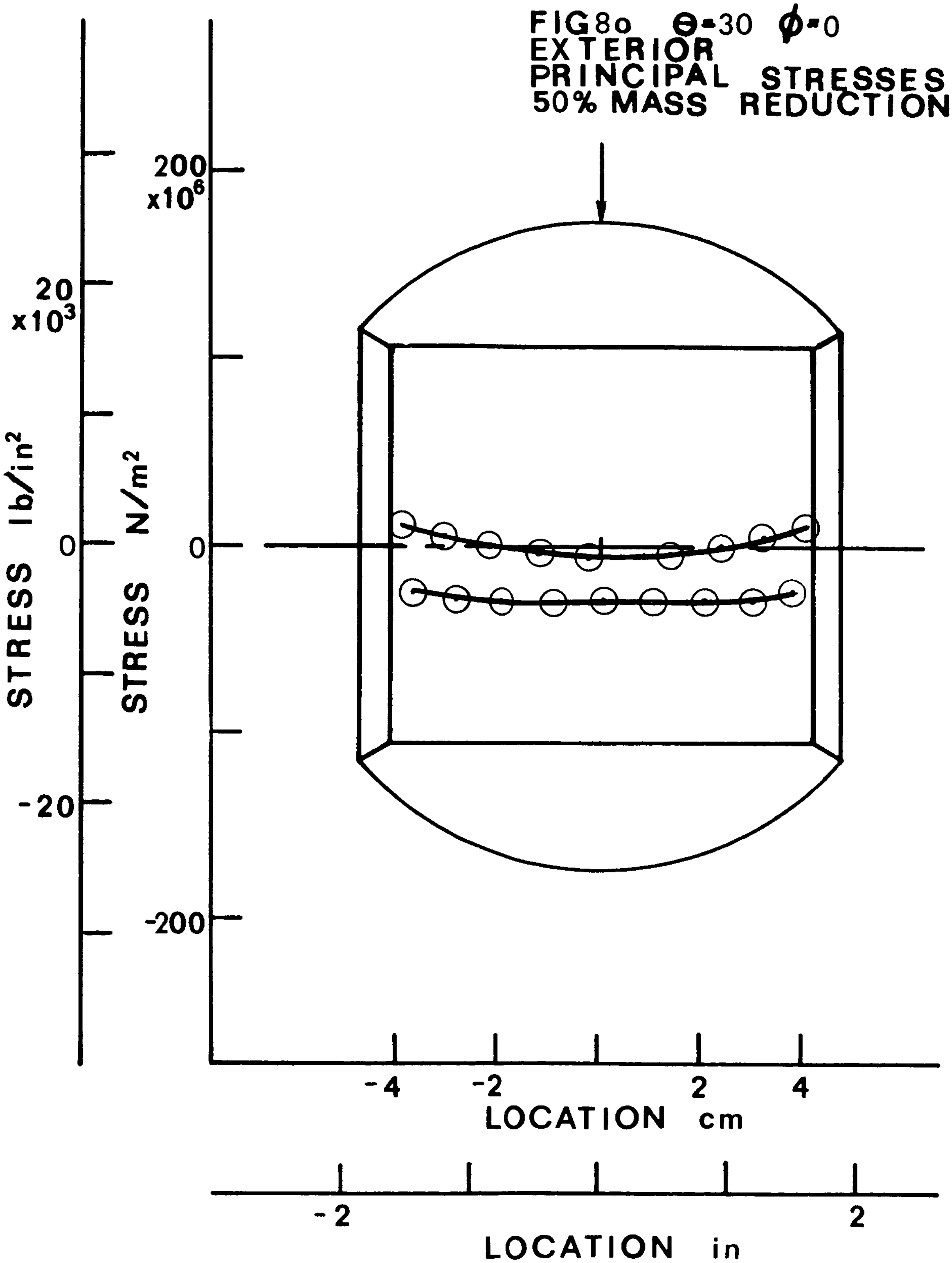


FIG 8o Θ=30 φ=0
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20 x10³
0
-20
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

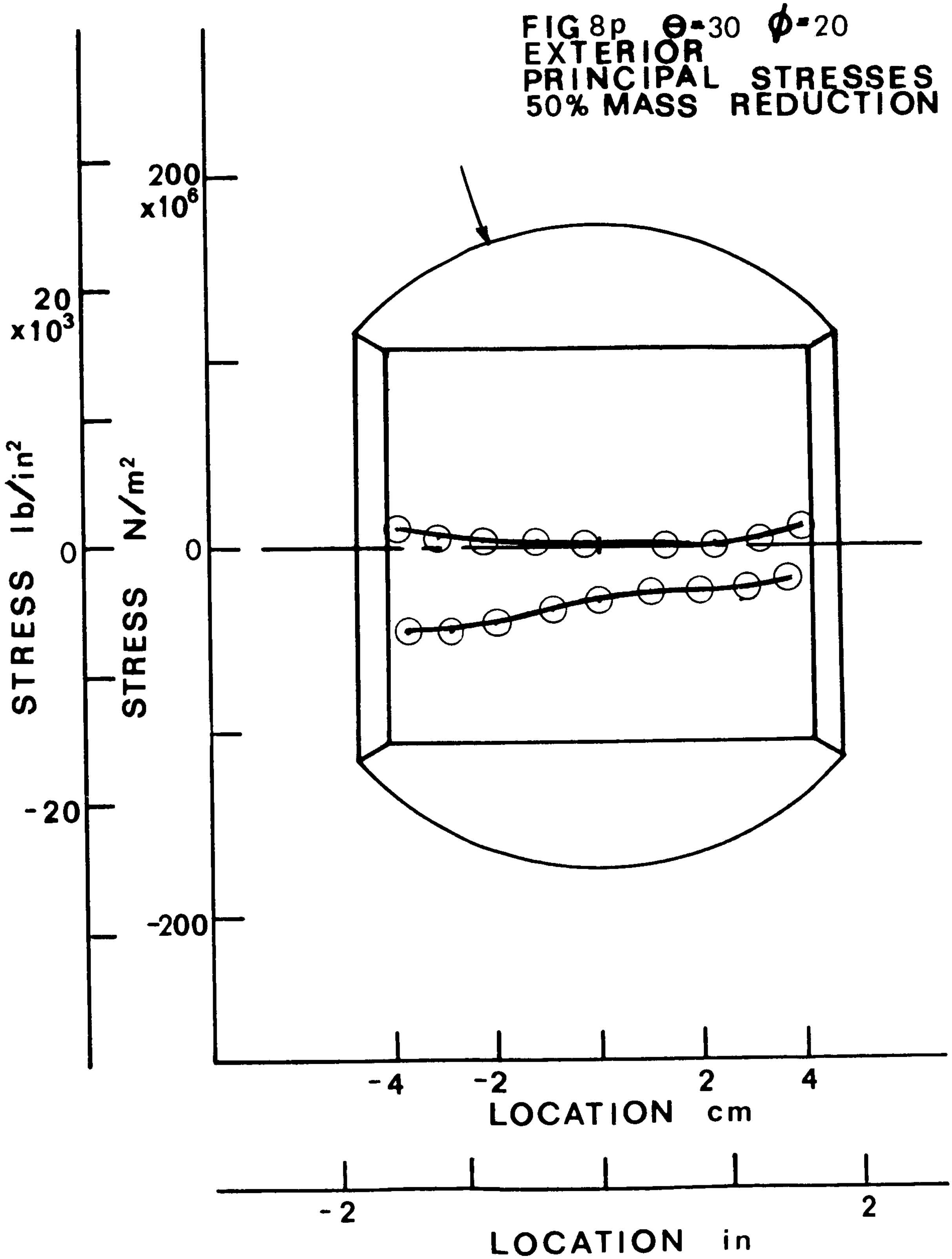


FIG 8p Θ=30 φ=20
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
20 x10³
0
-20
STRESS N/m²
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

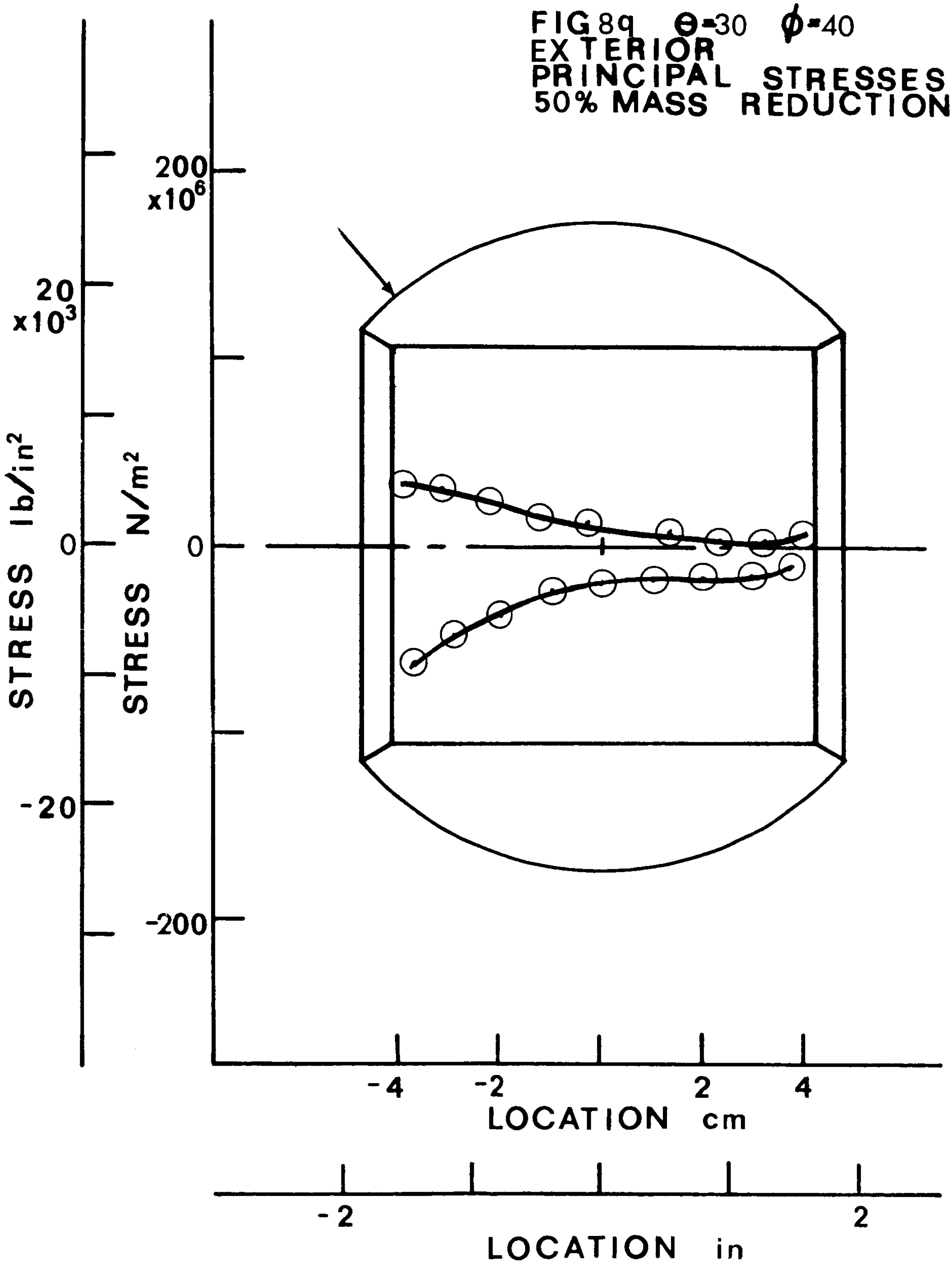


FIG 8q Θ=30 ϕ=40
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20 x10³
0
-20
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

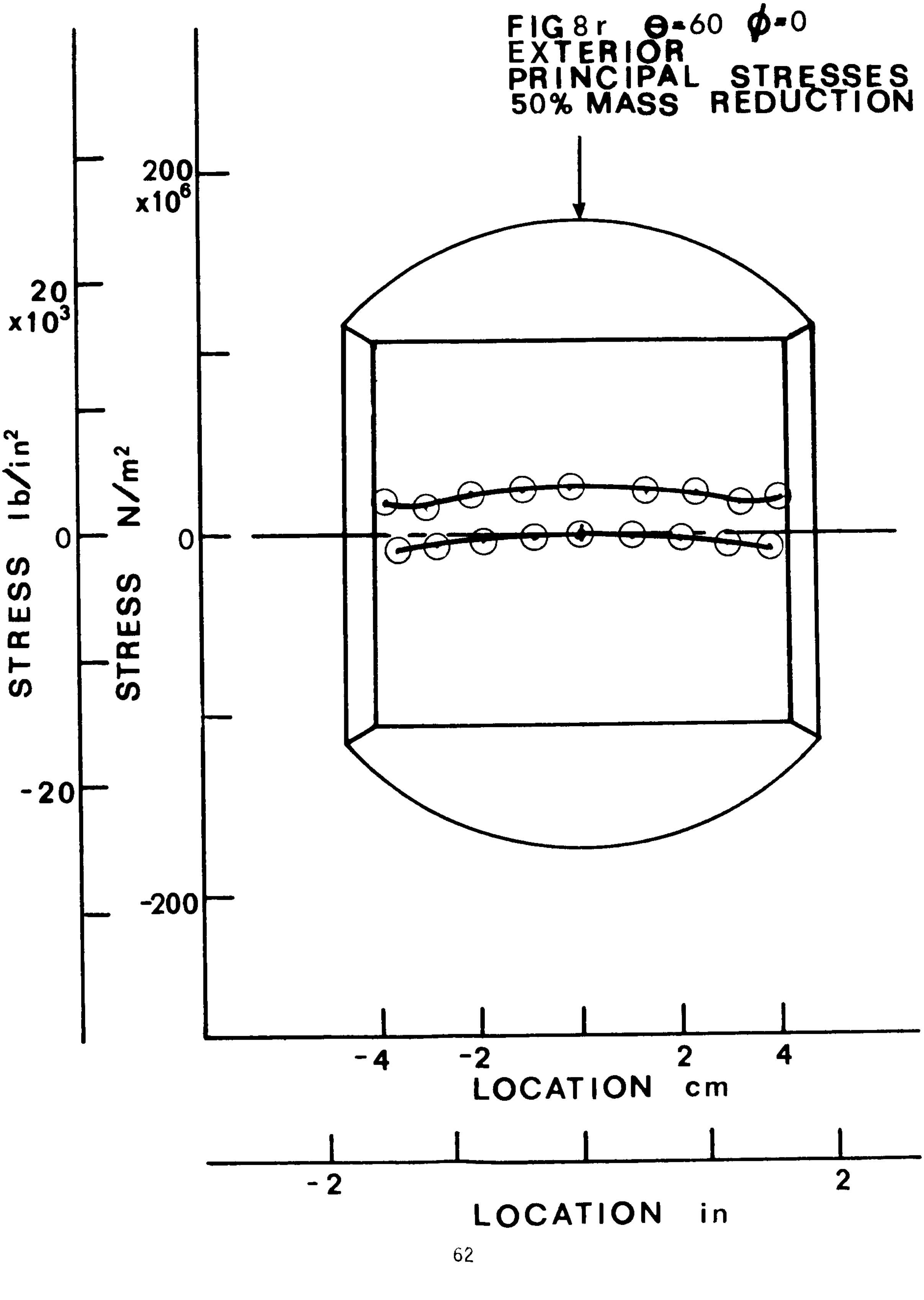


FIG 8r Θ=60 φ=0
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
0
0
-20
-200
STRESS lb/in^2
STRESS N/m^2
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

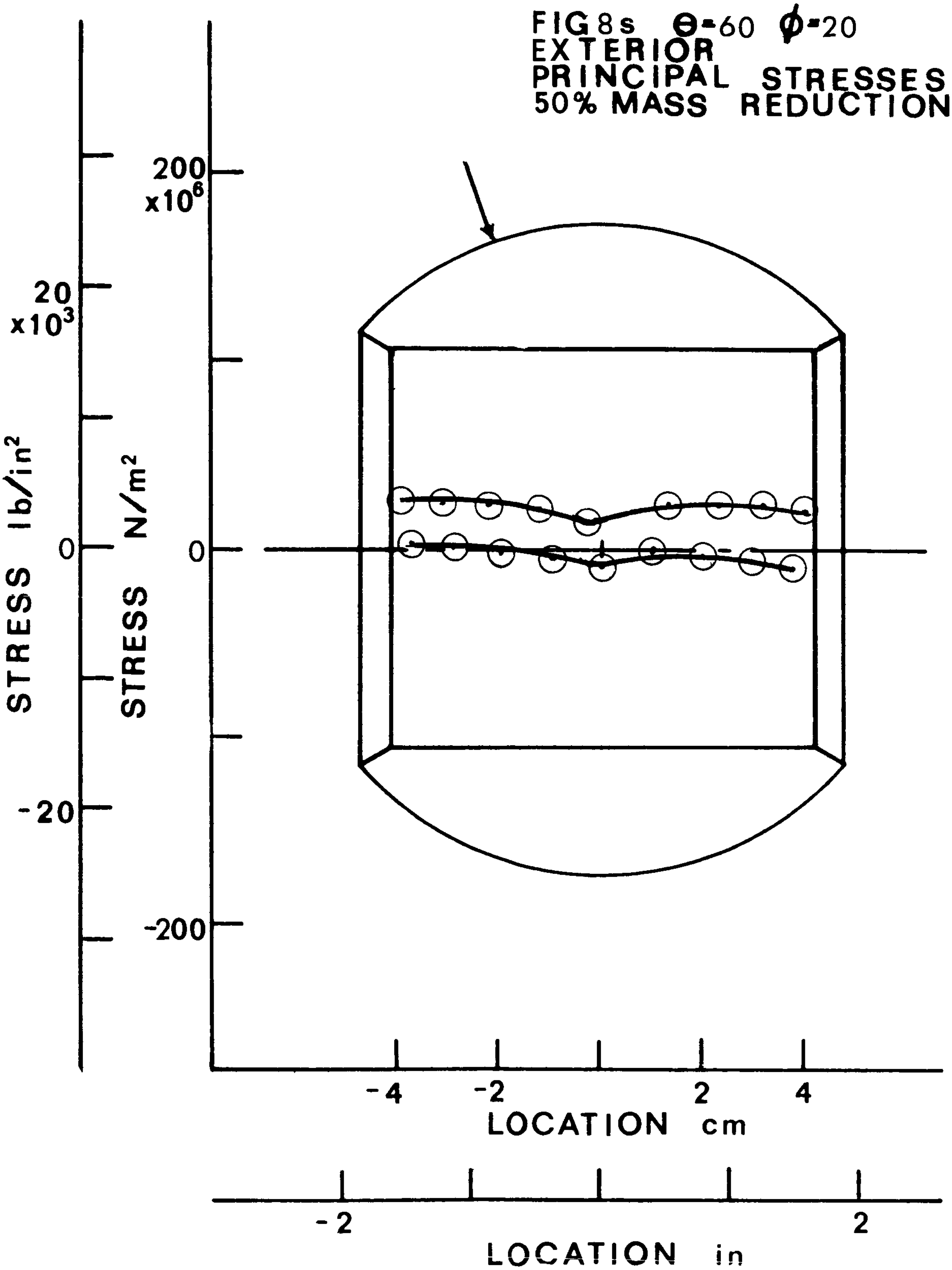


FIG 8s Θ=60 Φ=20
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
STRESS lb/in^2
STRESS N/m^2
0
0
-20
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

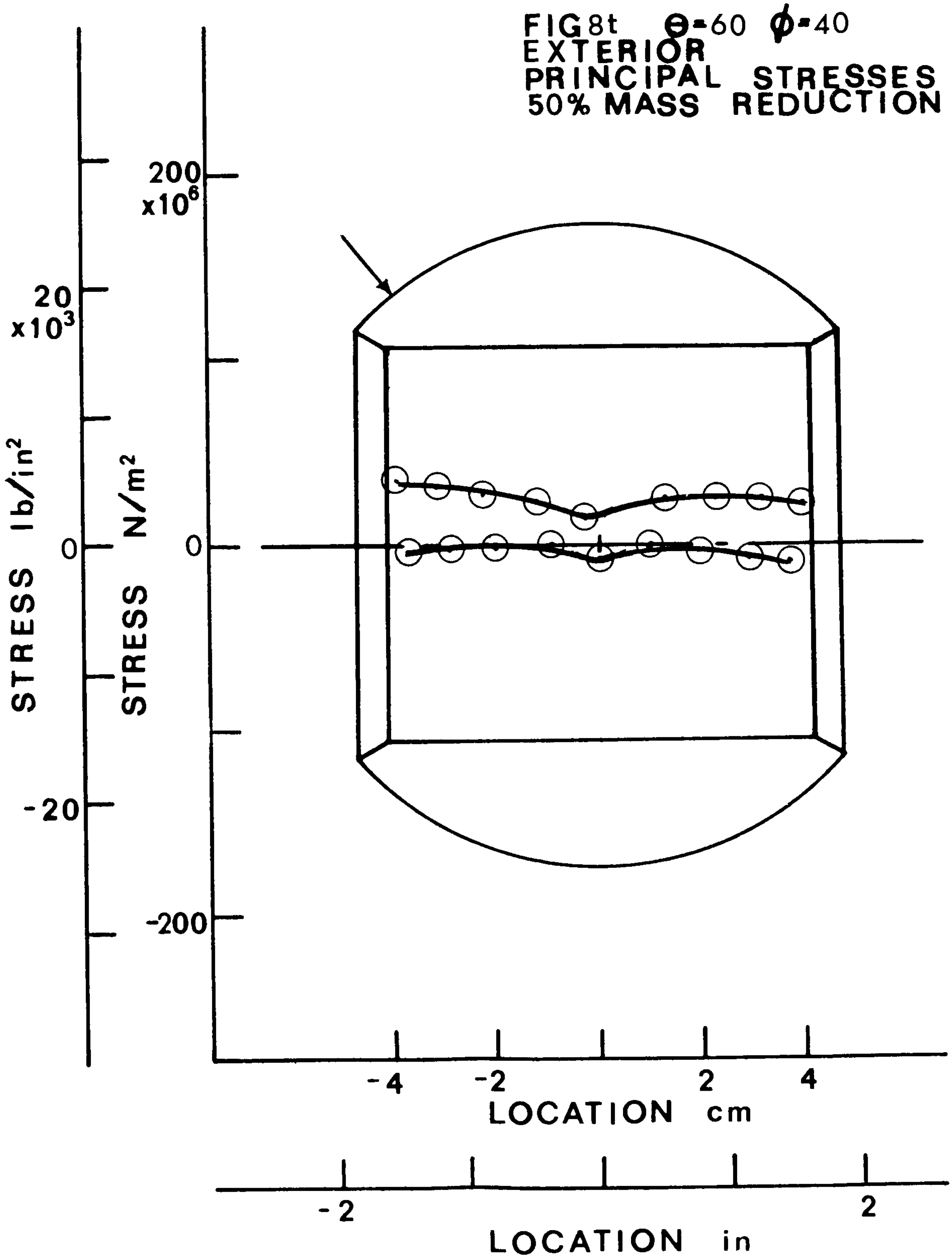


FIG 8t θ=60 φ=40
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
200
x10^6
20
x10^3
0
0
-20
-200
STRESS lb/in²
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

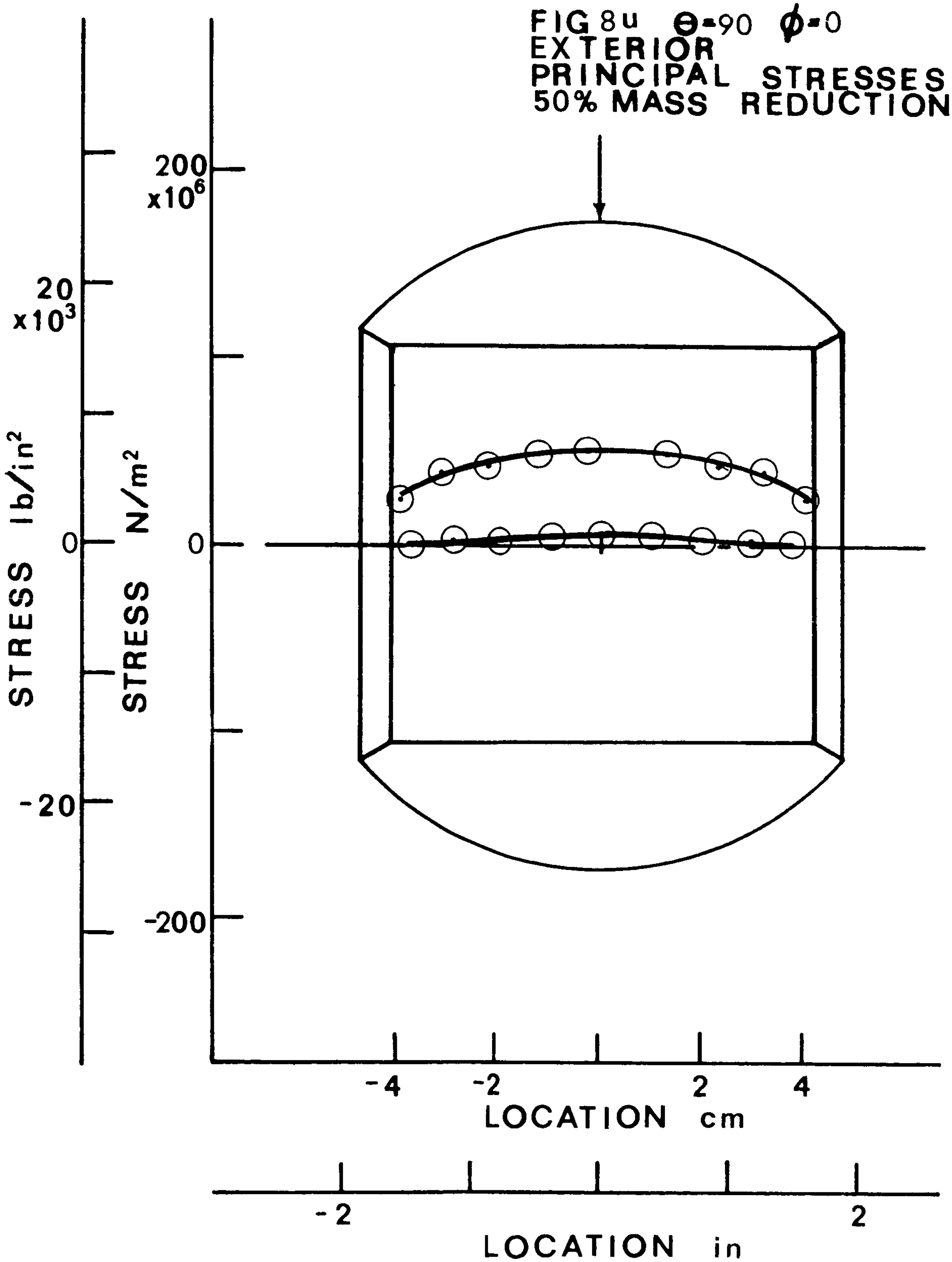


FIG 8u Θ=90 φ=0
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
20
x10³
0
-20
STRESS lb/in²
200
x10⁶
0
-200
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

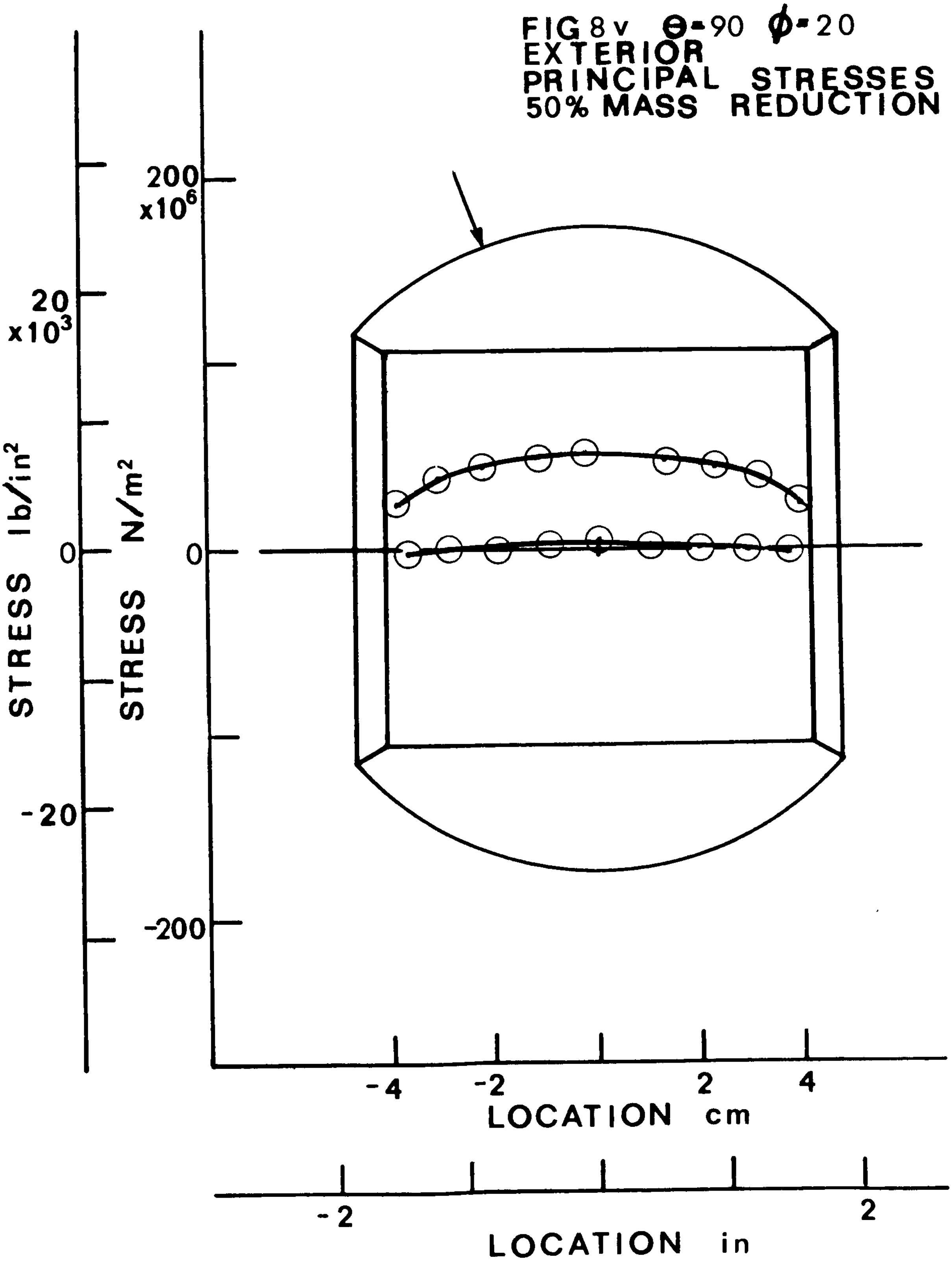


FIG 8 v Θ=90 φ=20
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
20 x10³
0
-20
STRESS lb/in²
200 x10⁶
0
-200
STRESS N/m²
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

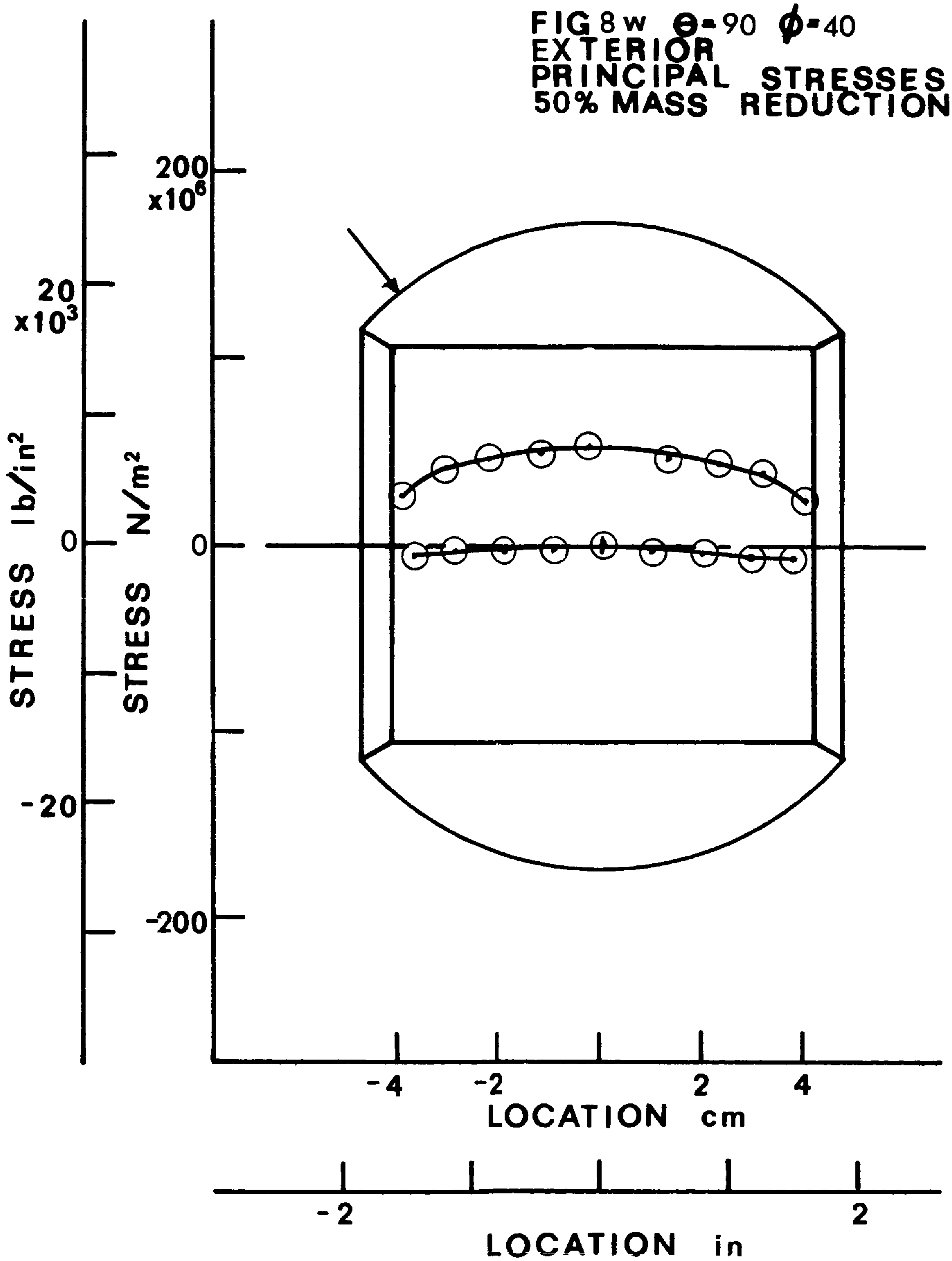


FIG 8w Θ=90 φ=40
EXTERIOR
PRINCIPAL STRESSES
50% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20 x10³
0
-20
200 x10⁶
0
-200
-4
-2
2
4
LOCATION cm
-2
2
LOCATION in

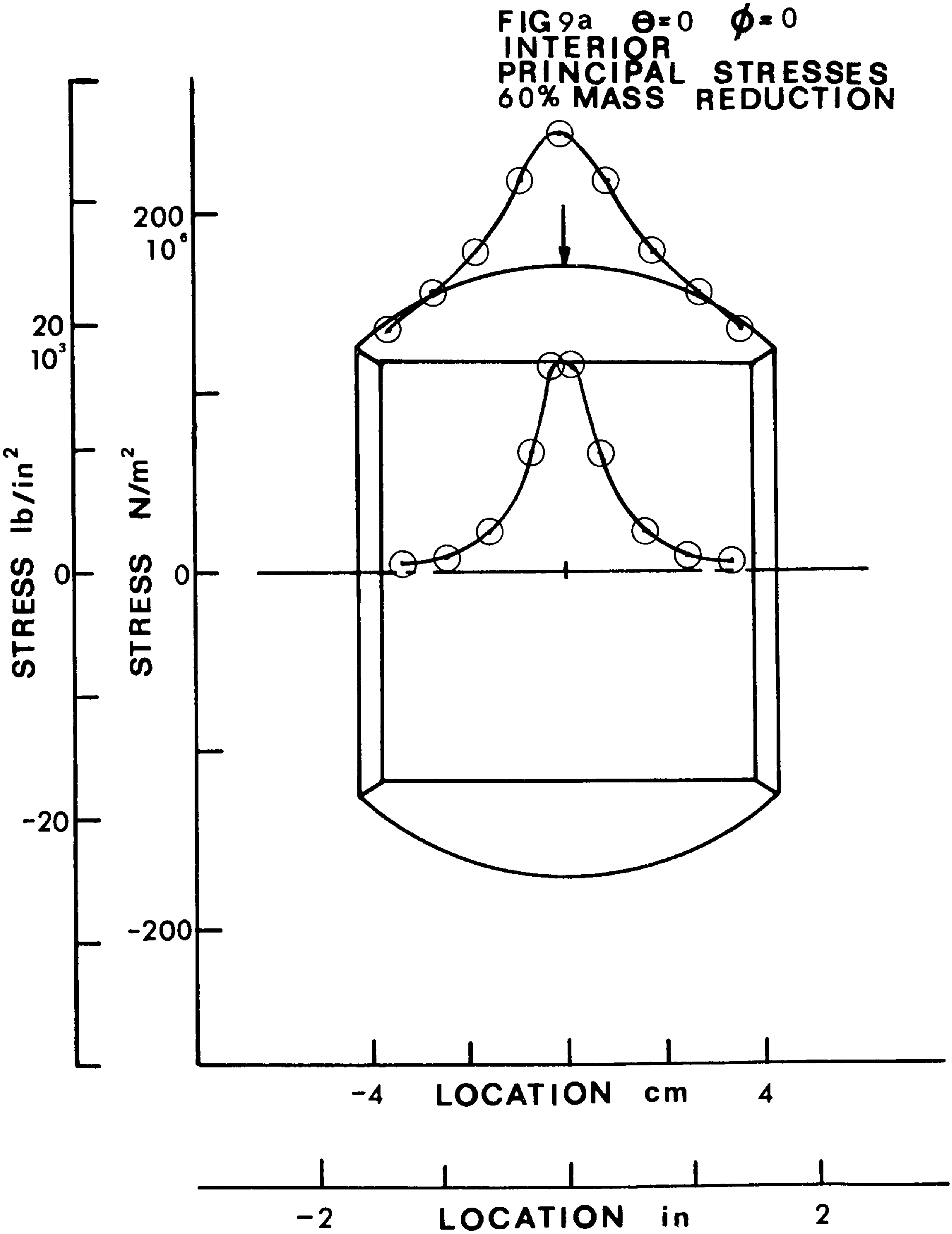


FIG 9a Θ=0 φ=0
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

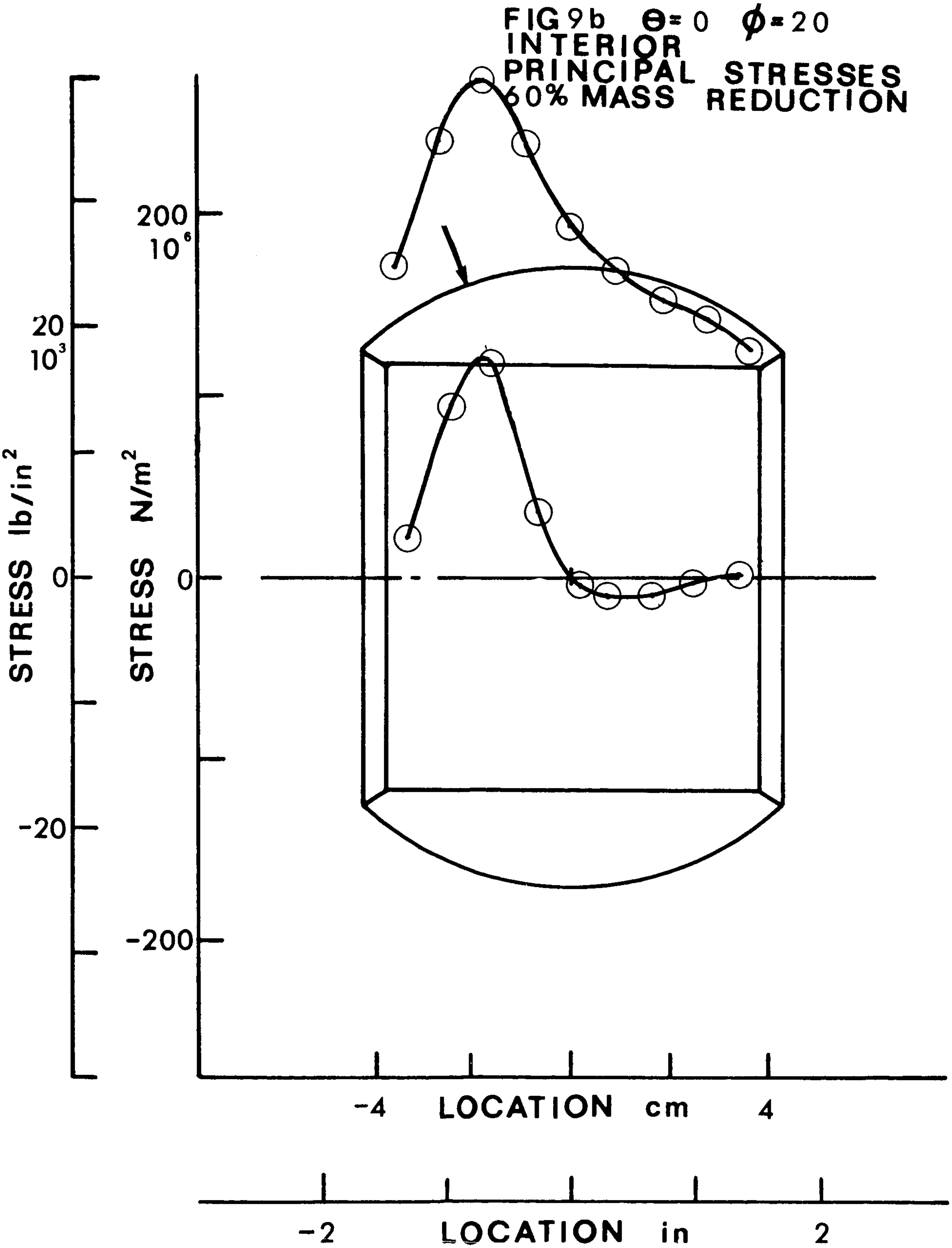


FIG 9b Θ= 0 ϕ= 20
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
200
10⁶
20
10³
STRESS lb/in²
STRESS N/m²
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

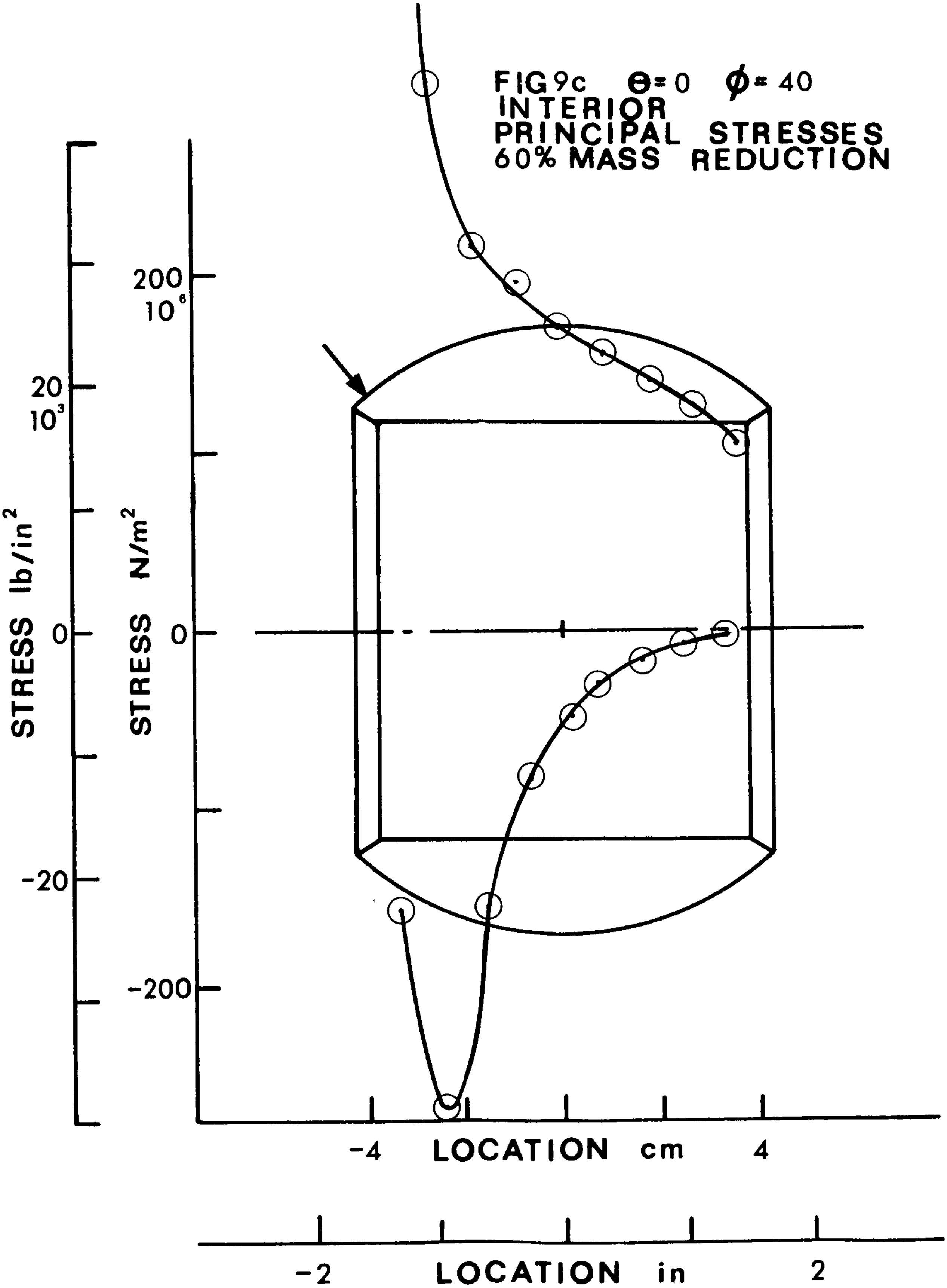


FIG 9c Θ=0 φ=40
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
10³
0
-20
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

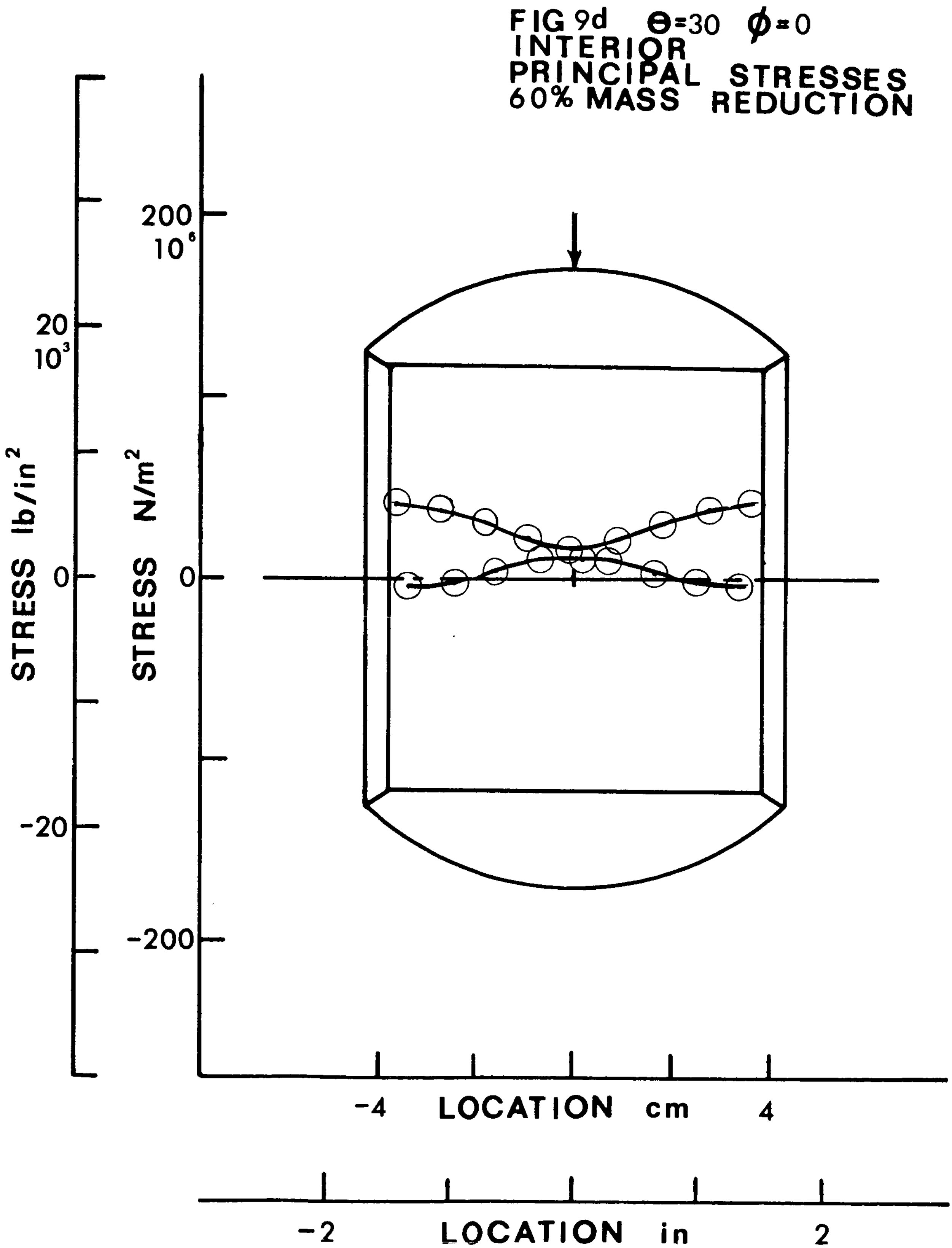


FIG 9d Θ=30 φ=0
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
200
10⁶
20
10³
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 9e θ=30 ϕ=20
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION

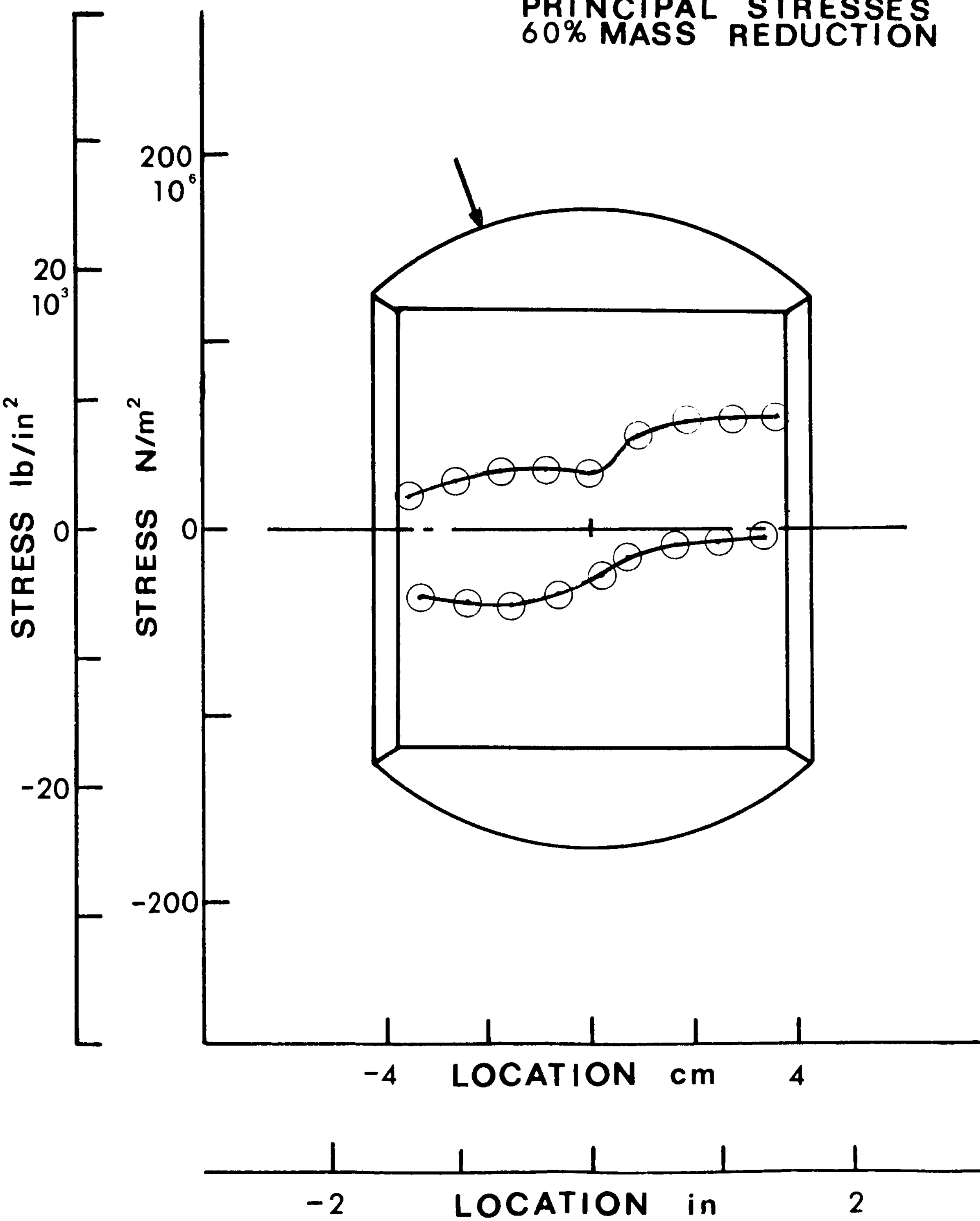
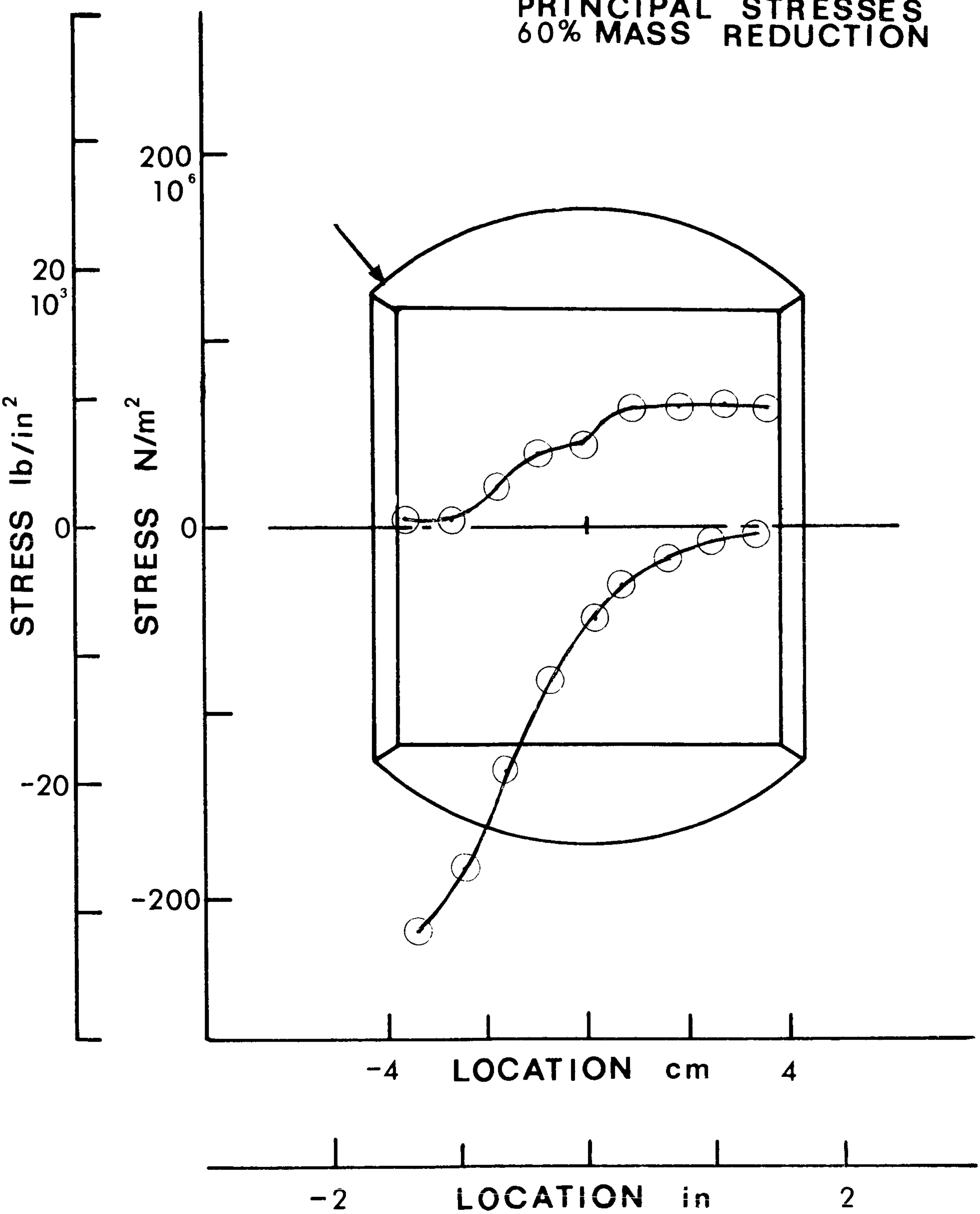


FIG 9f $\Theta=30$ $\phi=40$
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION



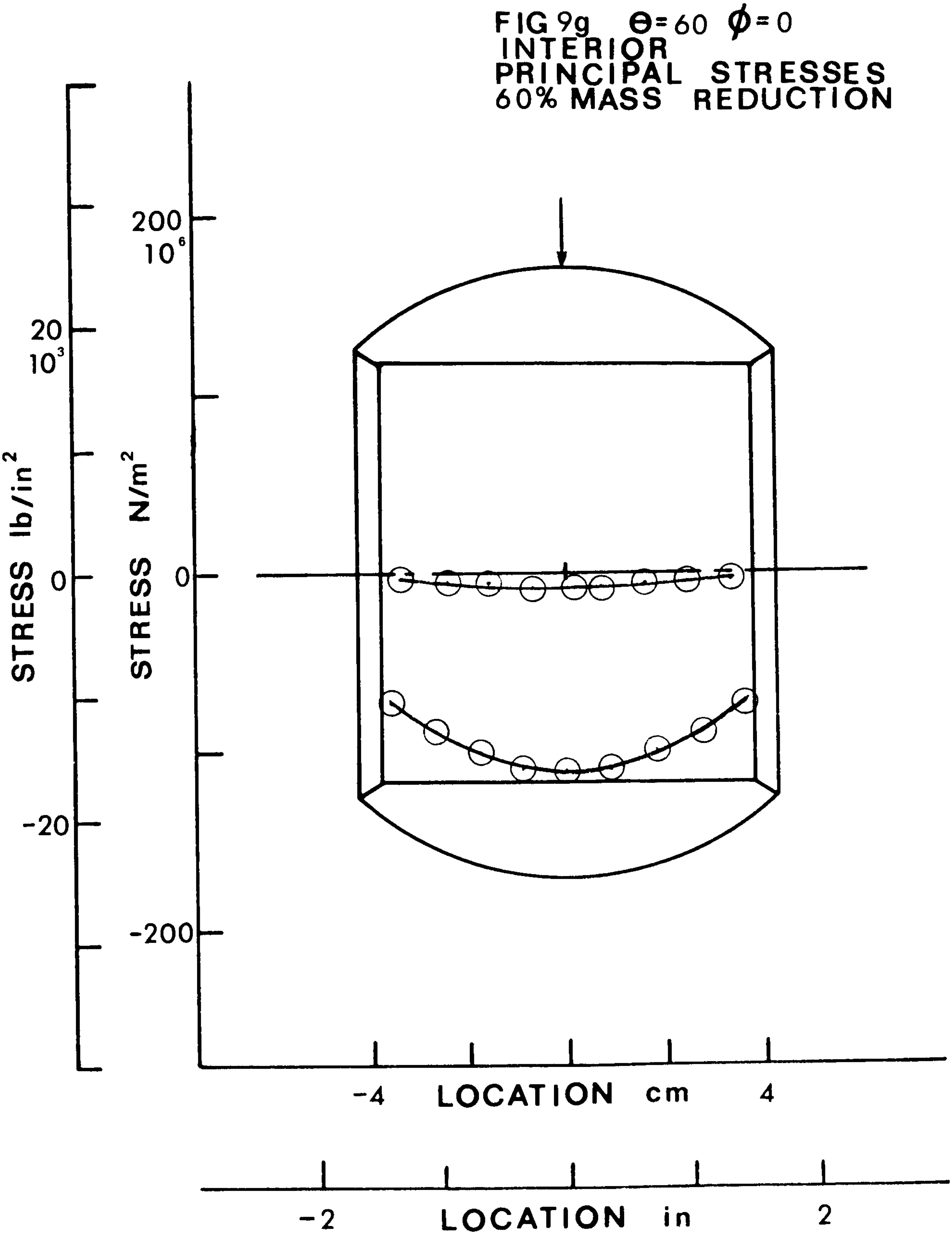


FIG 9g Θ=60 φ=0
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
200
10⁶
20
10³
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

FIG 9h $\Theta = 60$ $\phi = 20$
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION

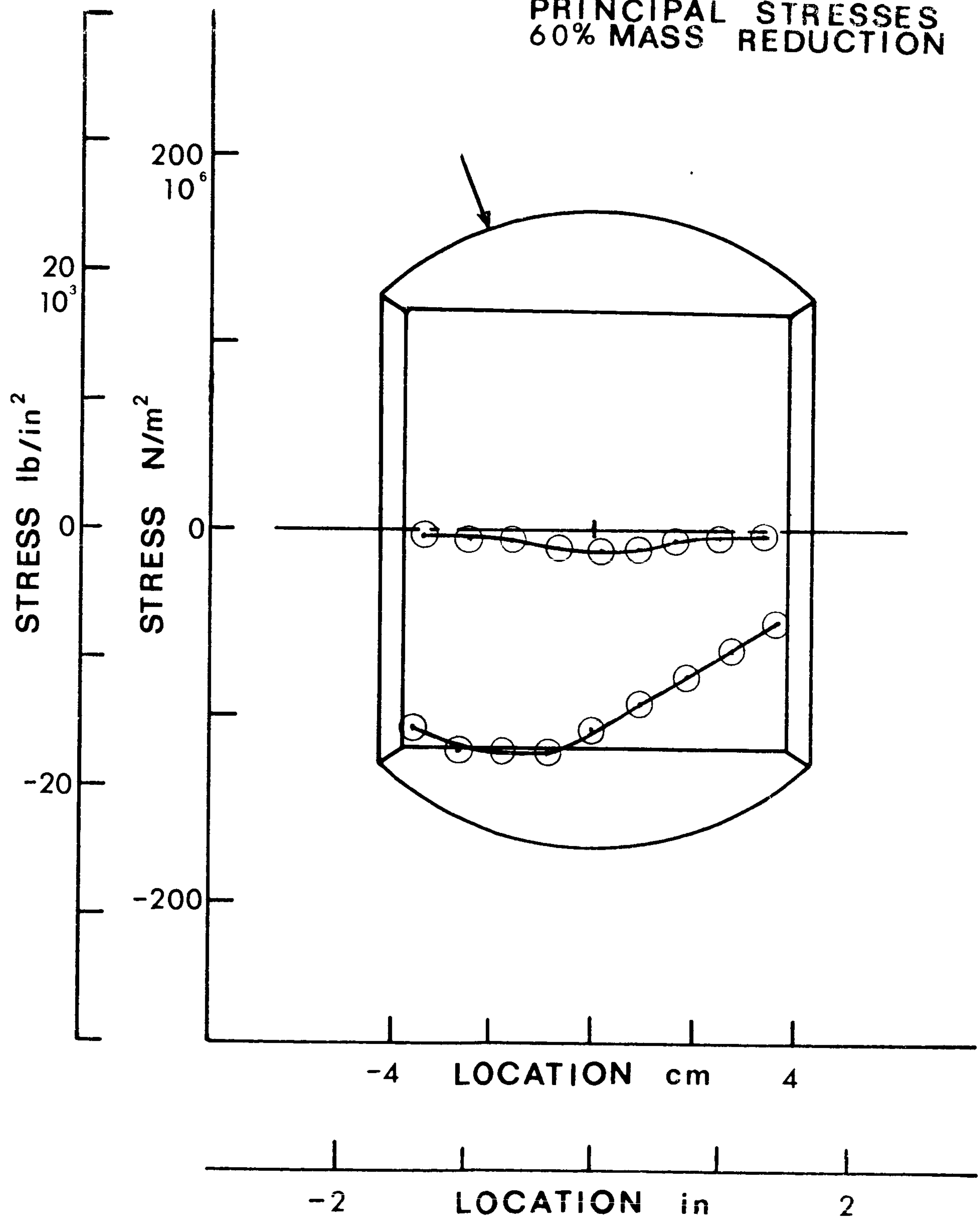


FIG 9i $\Theta=60$ $\phi=40$
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION

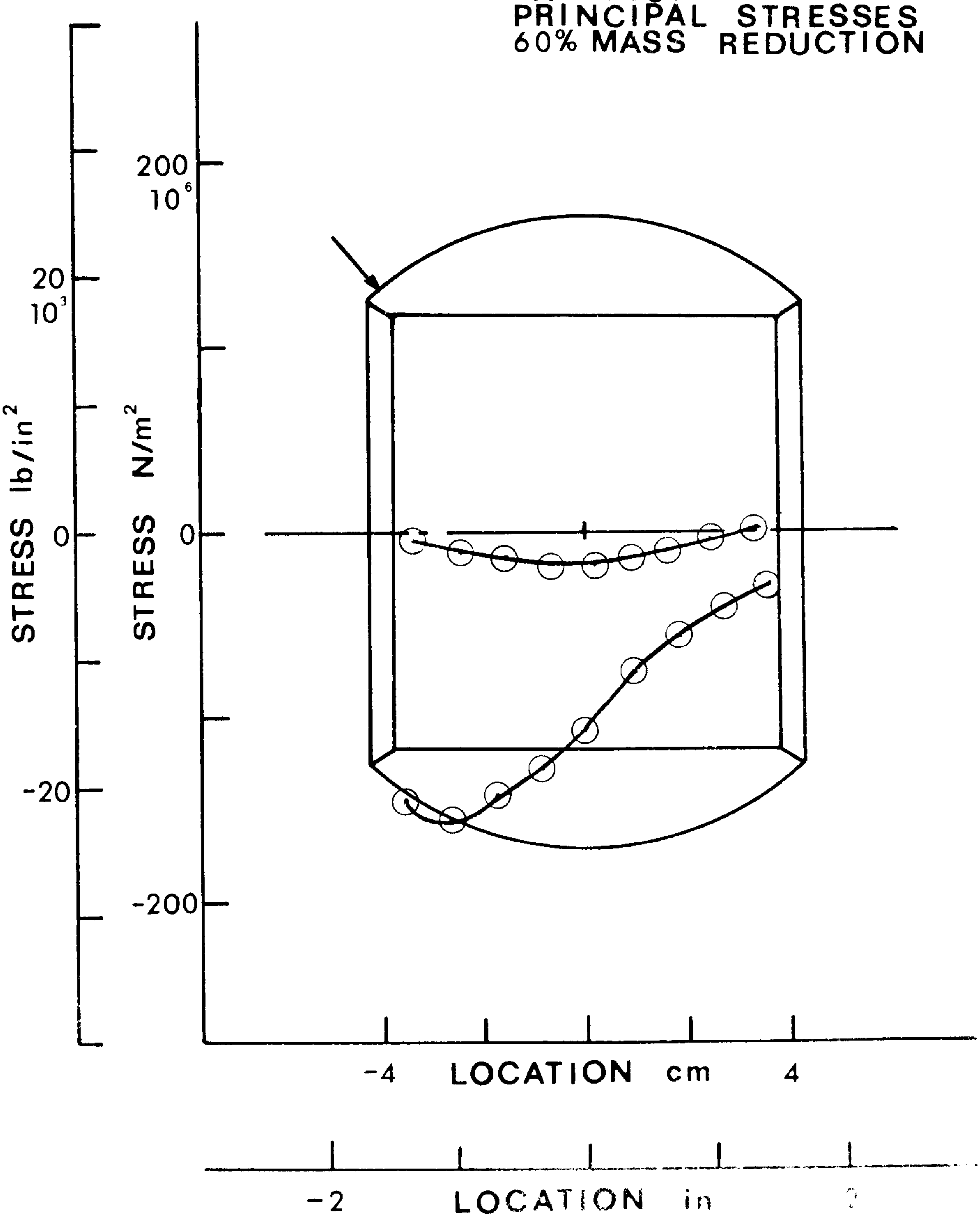
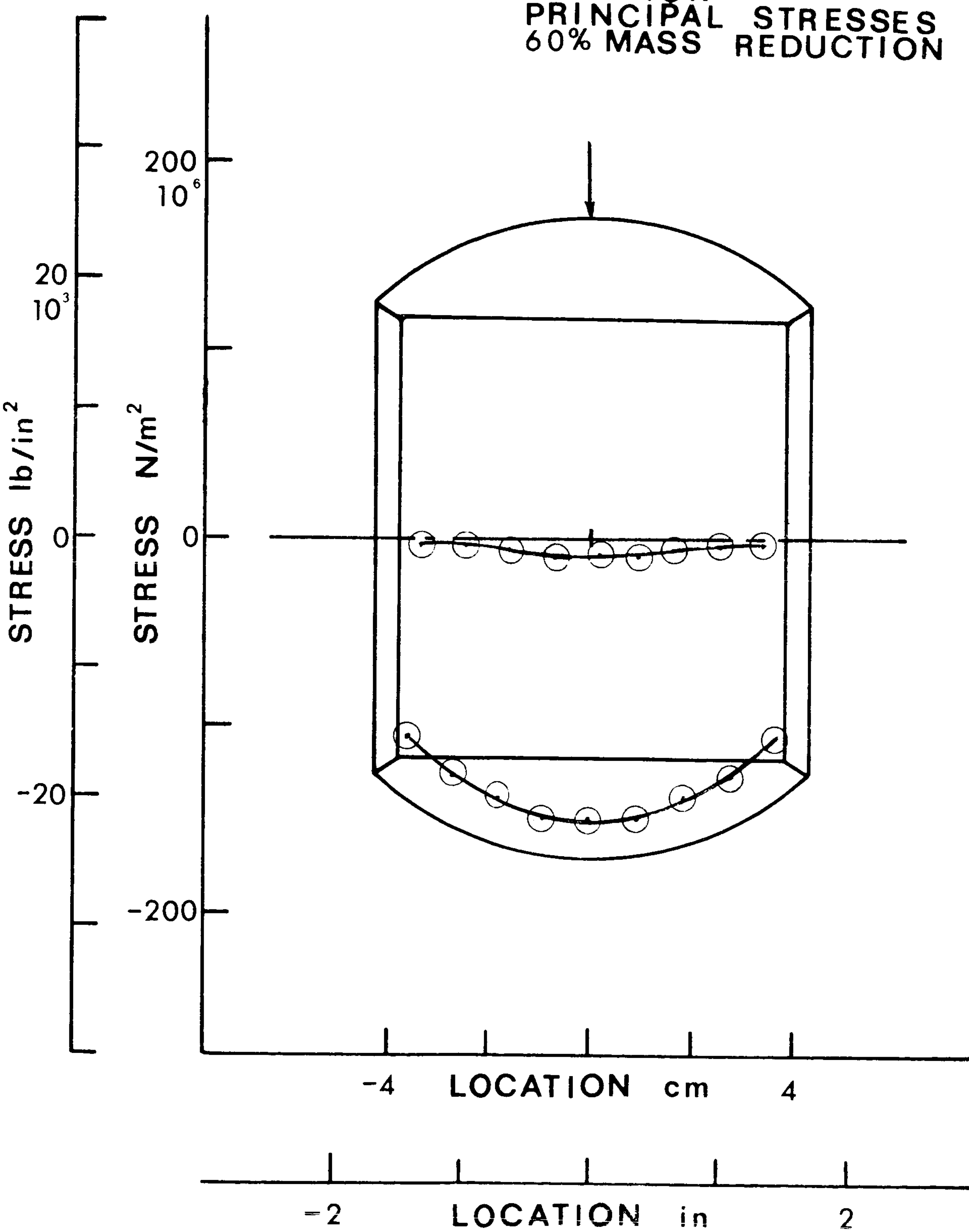


FIG 9j $\Theta=90$ $\phi=0$
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION



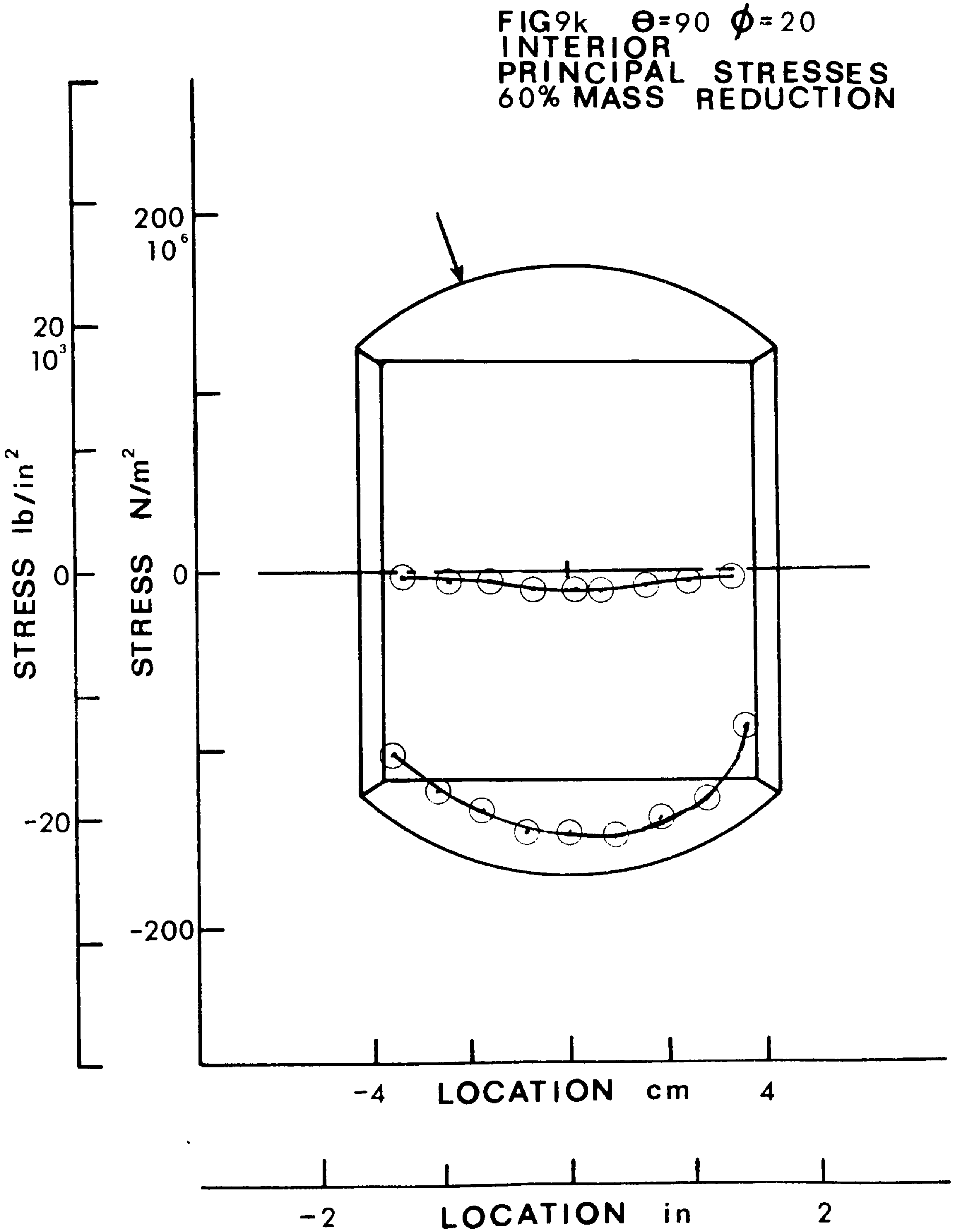


FIG9k Θ=90 φ=20
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
200
10⁶
20
10³
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

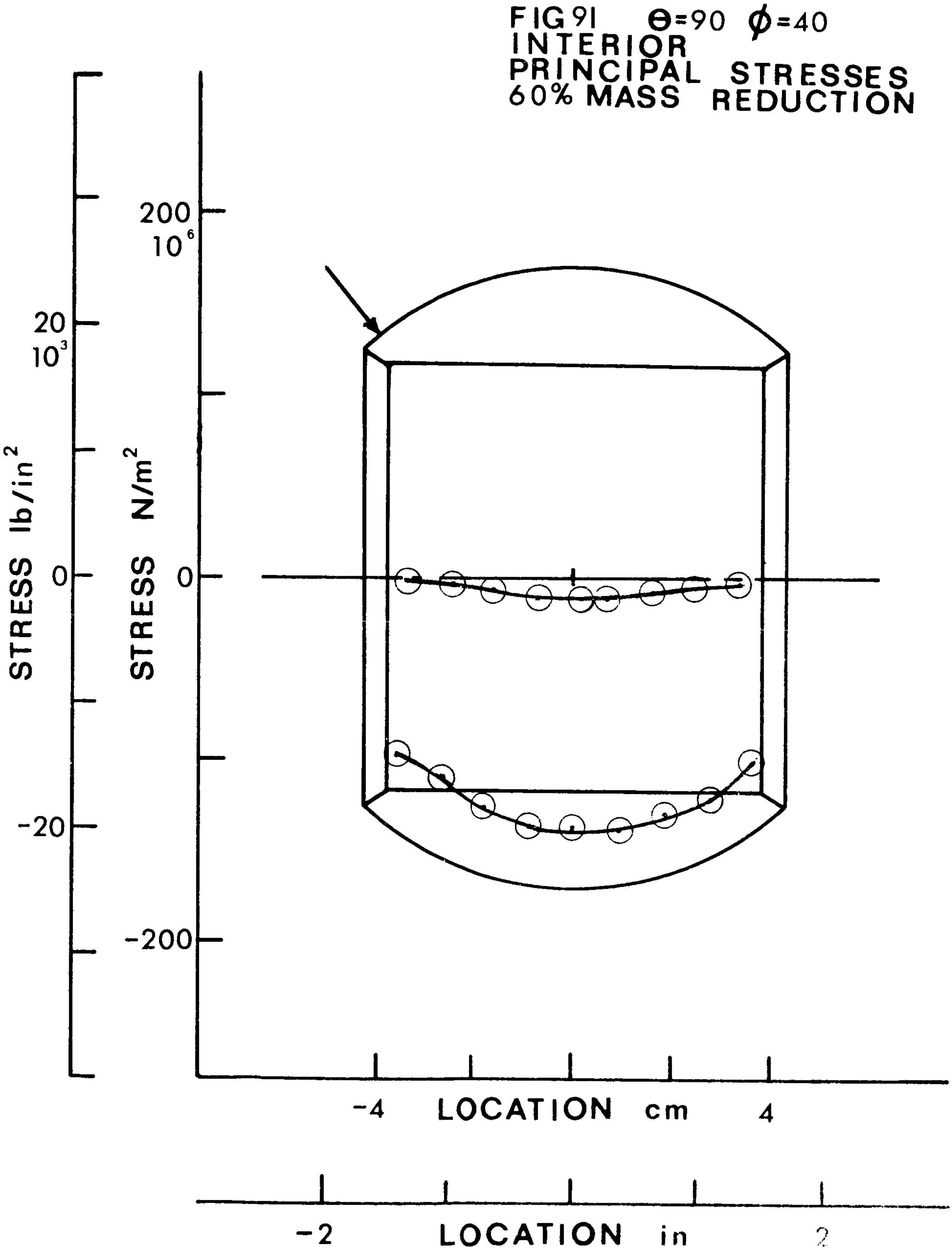


FIG 91 Θ=90 ϕ=40
INTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

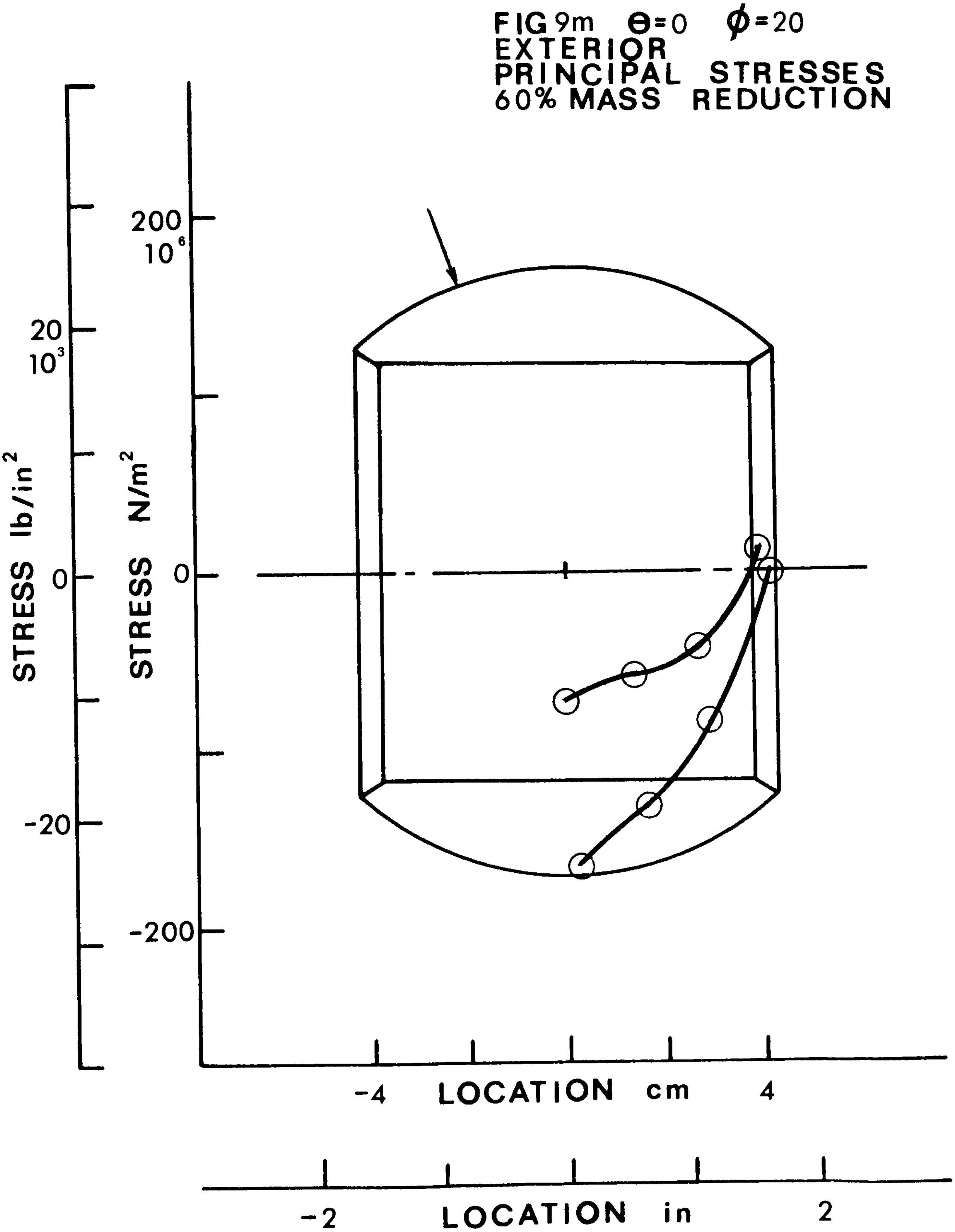


FIG 9m Θ=0 φ=20
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in^2
STRESS N/m^2
20
10^3
0
-20
200
10^6
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

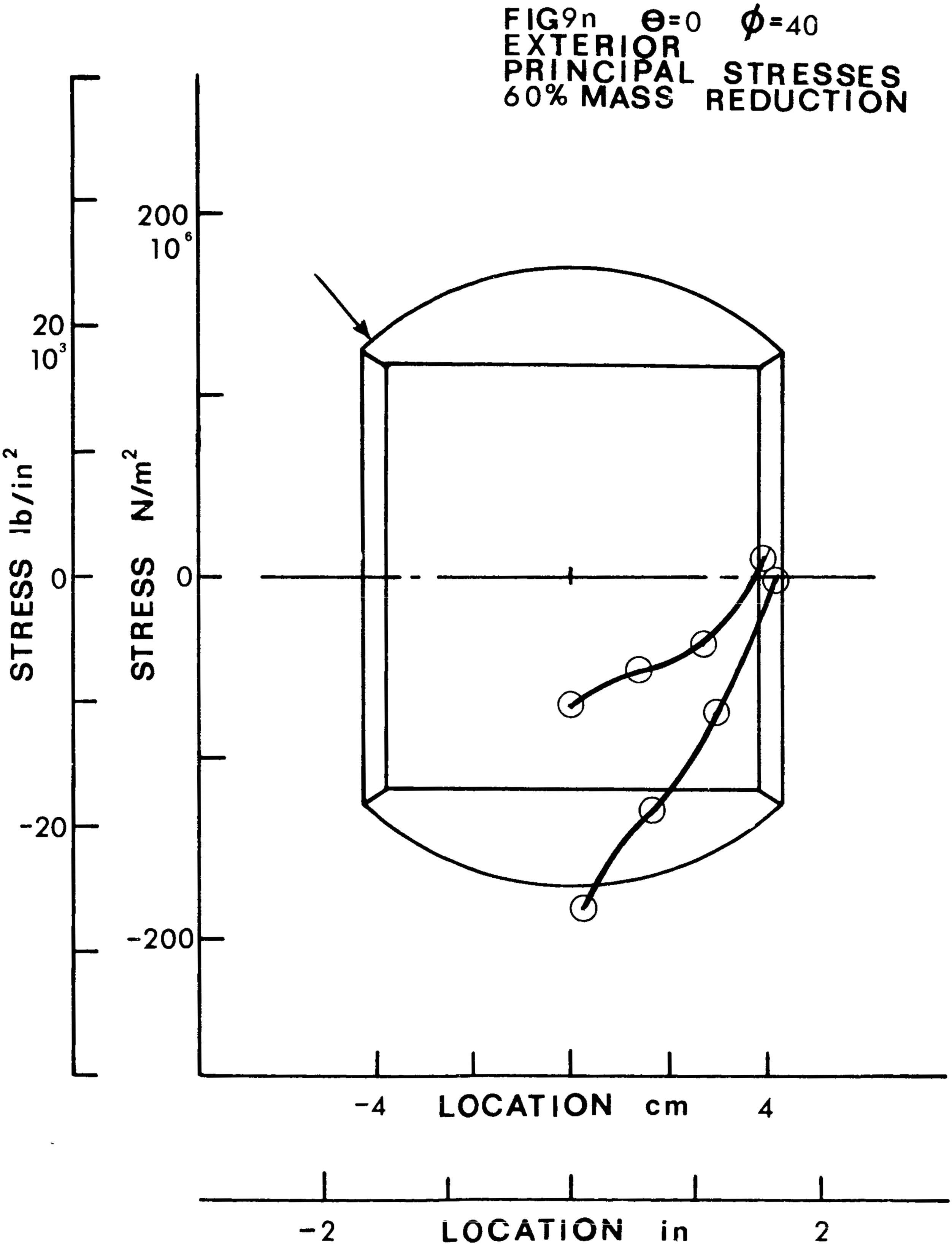


FIG9n Θ=0 φ=40
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
200
10⁶
20
10³
STRESS lb/in²
STRESS N/m²
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

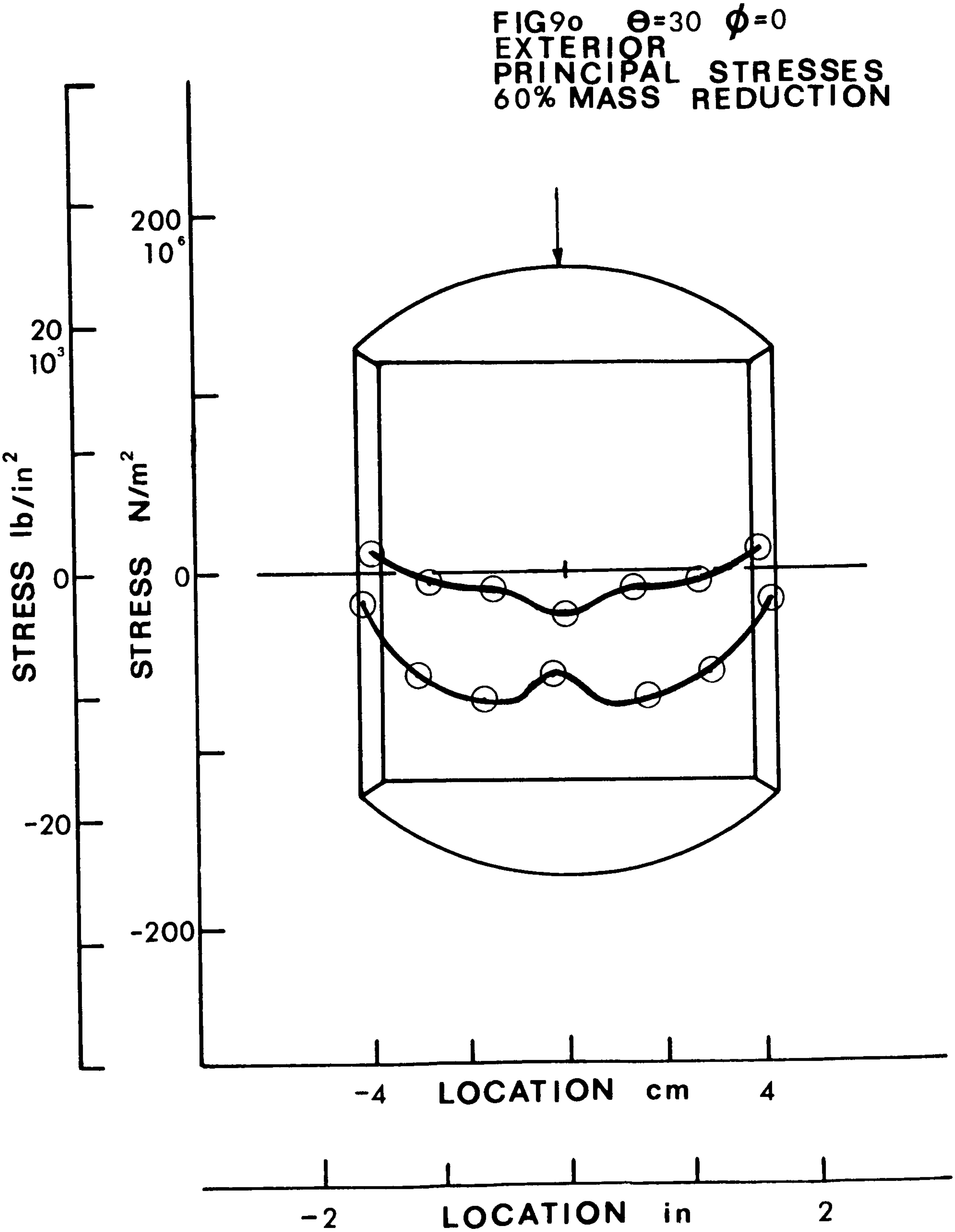


FIG9o Θ=30 φ=0
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

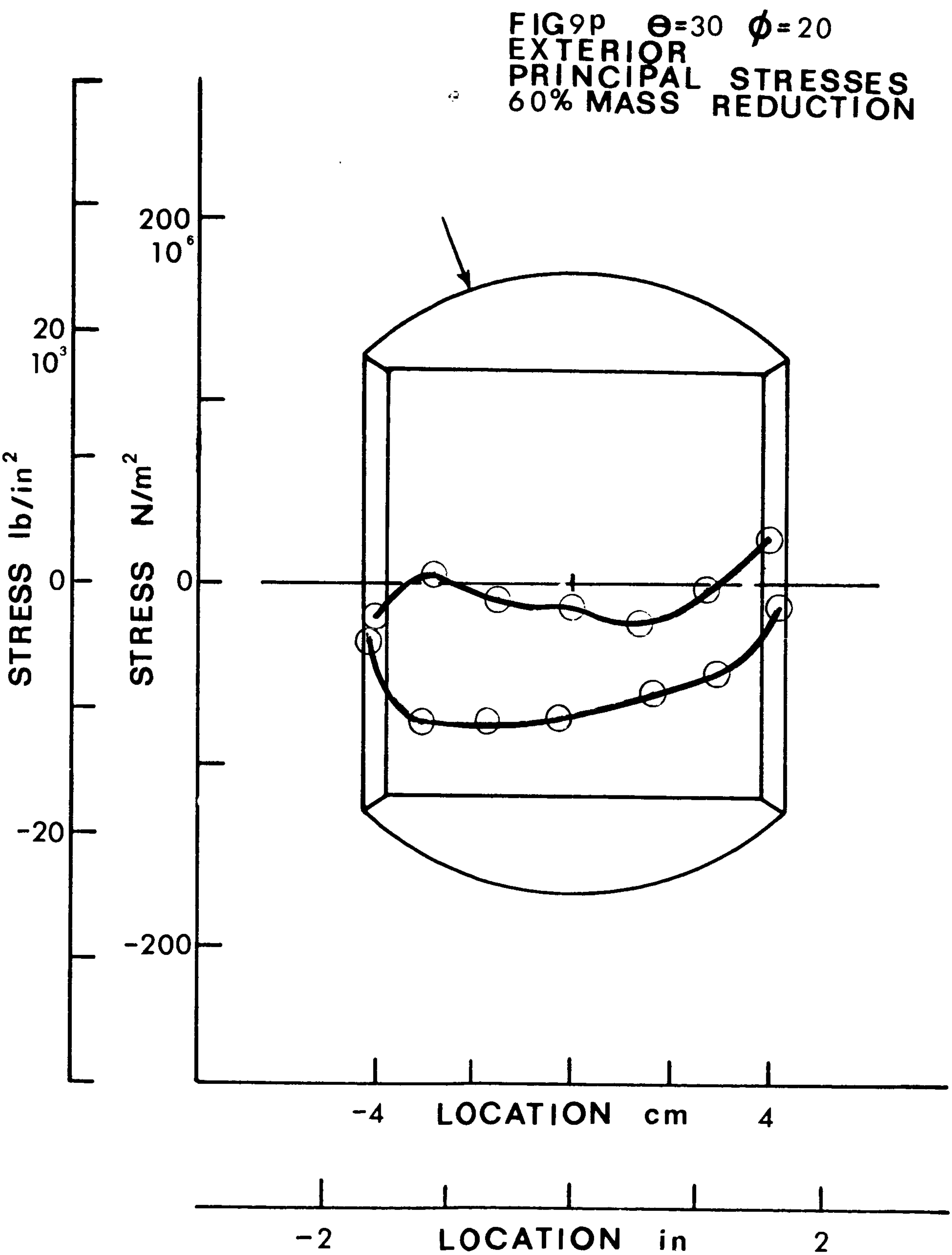


FIG9P Θ=30 ϕ=20
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
200
10⁶
20
10³
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

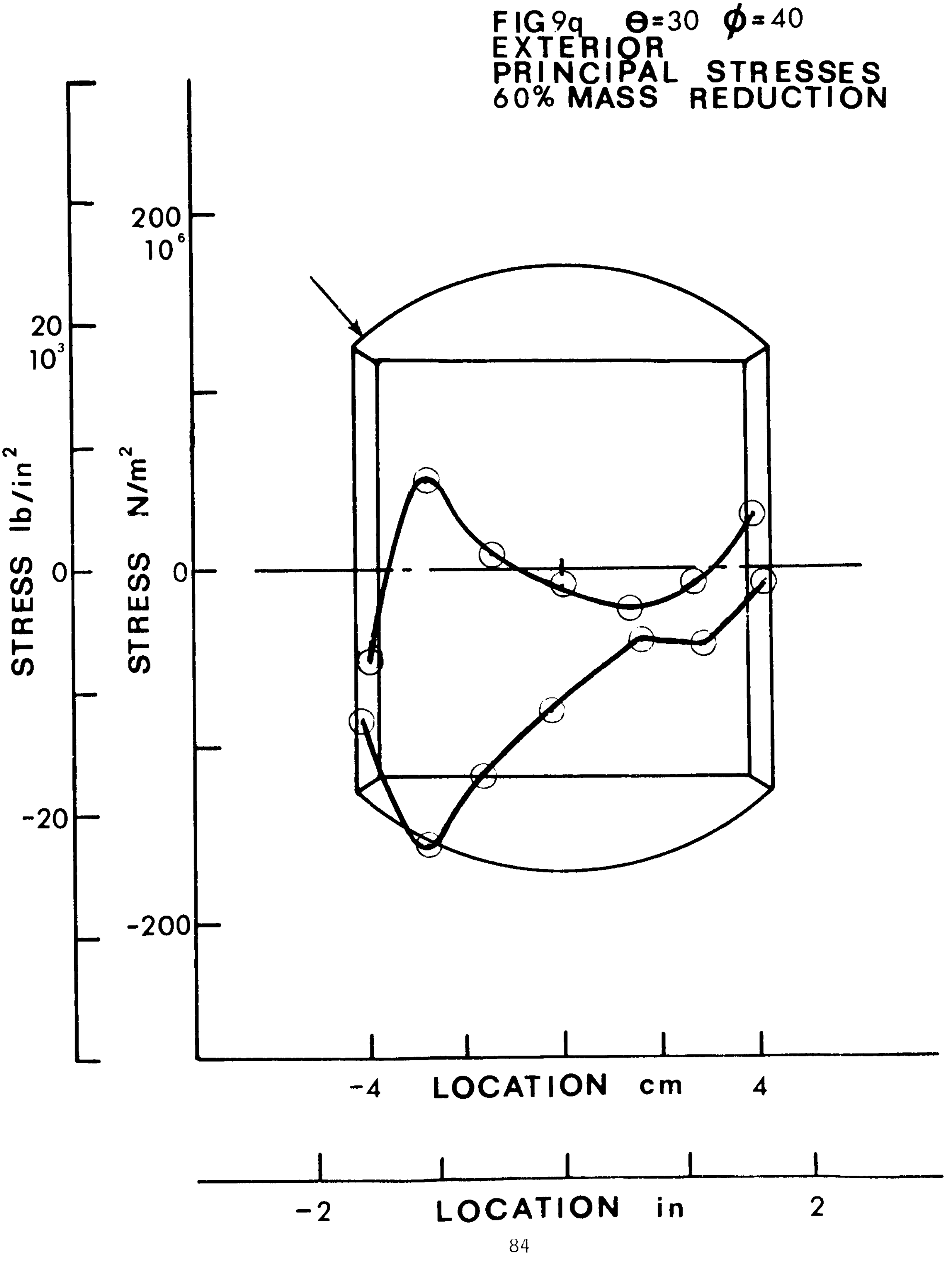


FIG 9q Θ=30 φ=40
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
10³
0
-20
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

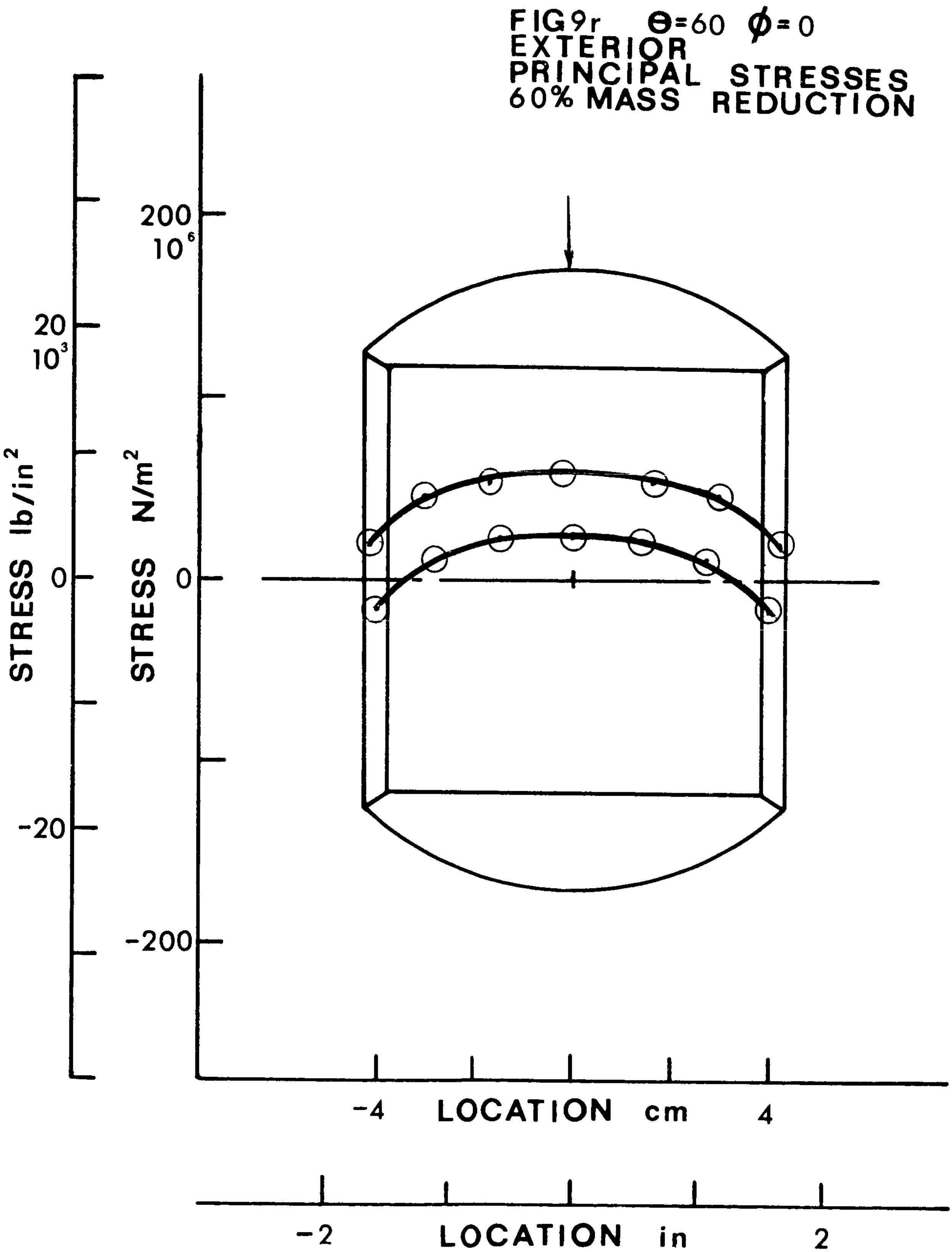


FIG9r Θ=60 ϕ=0
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in2
20
10³
0
-20
STRESS N/m2
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

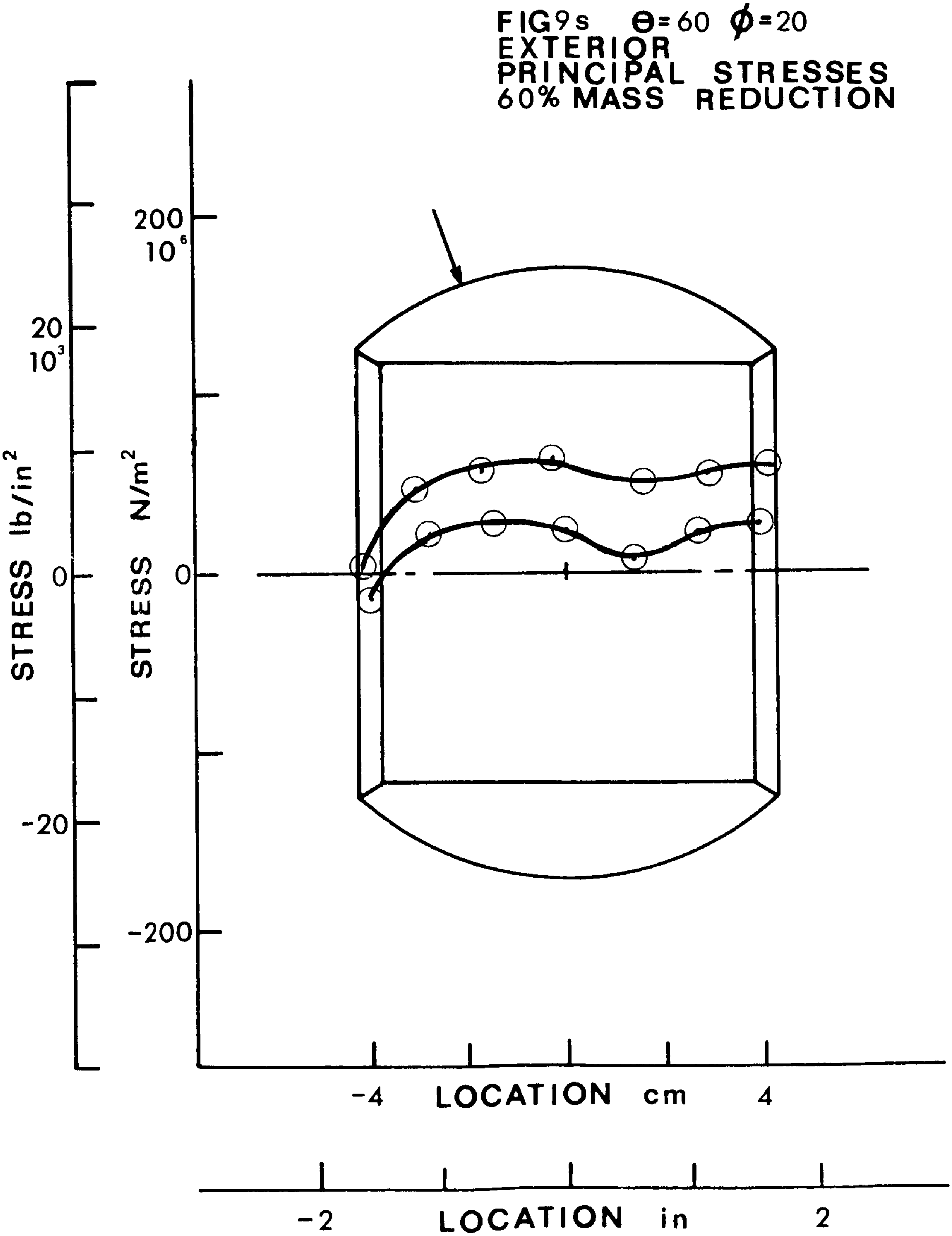


FIG9s Θ=60 φ=20
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
10³
0
-20
200
10⁶
-200
-4
LOCATION cm
4
-2
LOCATION in
2

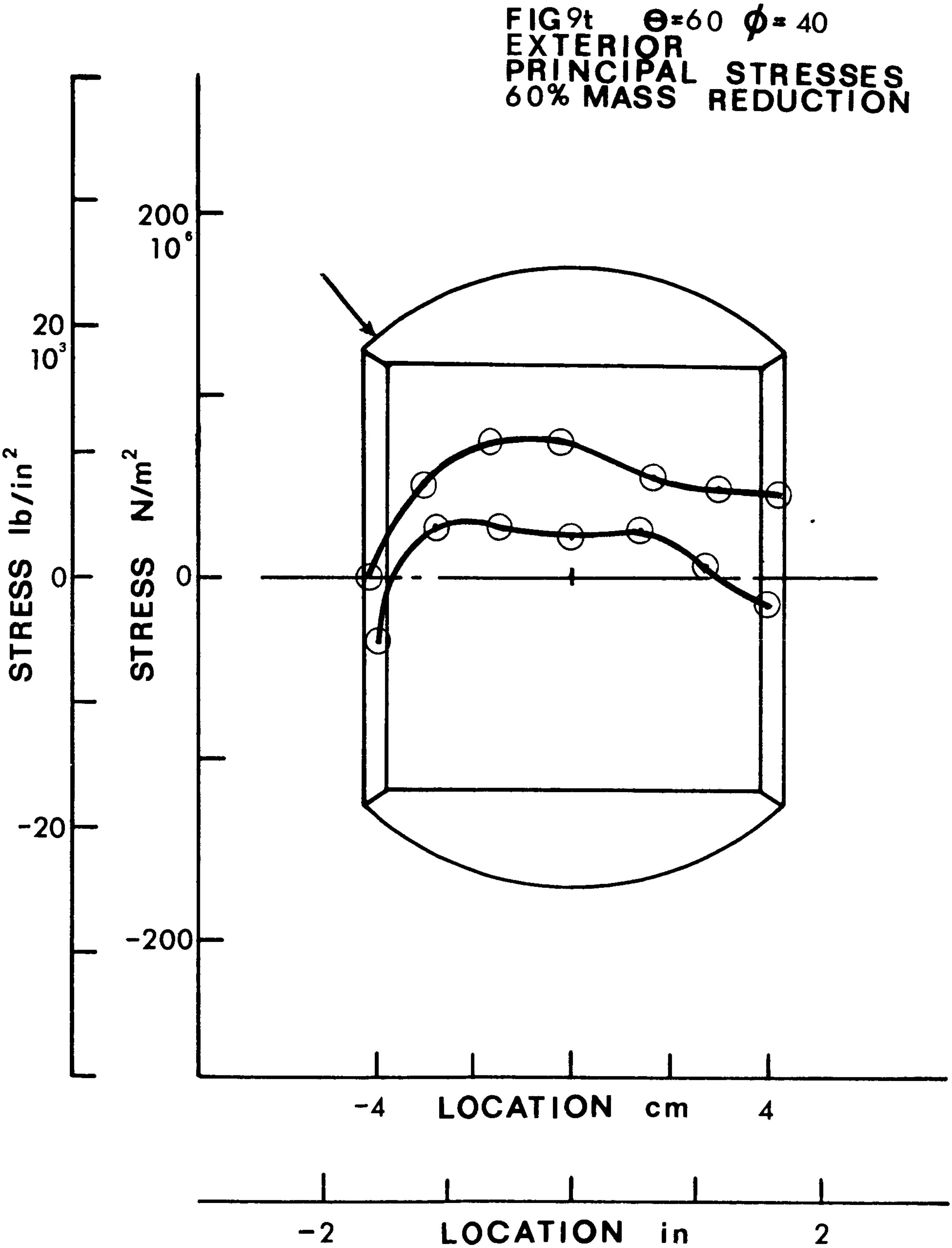


FIG 9t Θ=60 φ= 40
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
STRESS N/m²
20
10³
0
-20
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

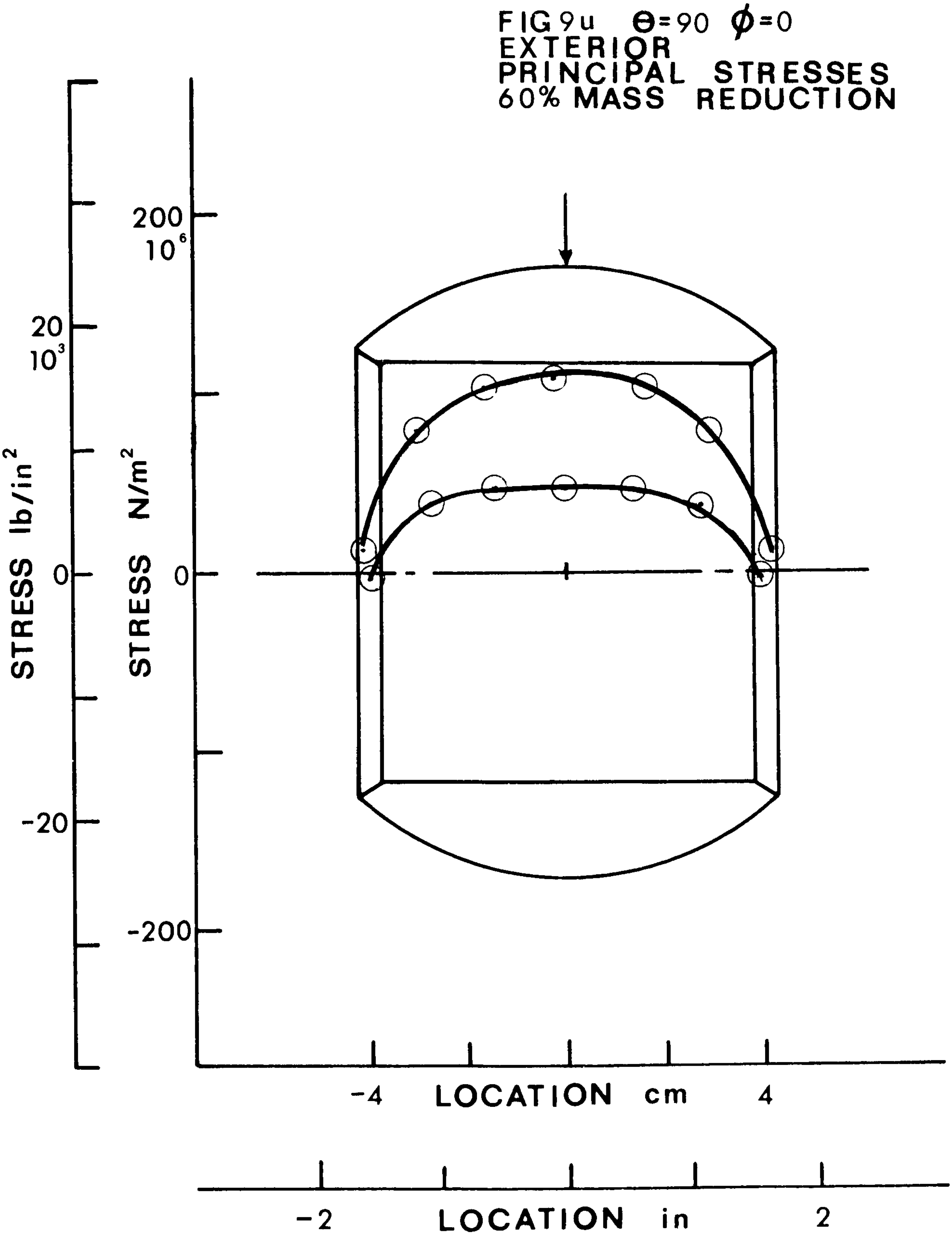


FIG 9u Θ=90 φ=0
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

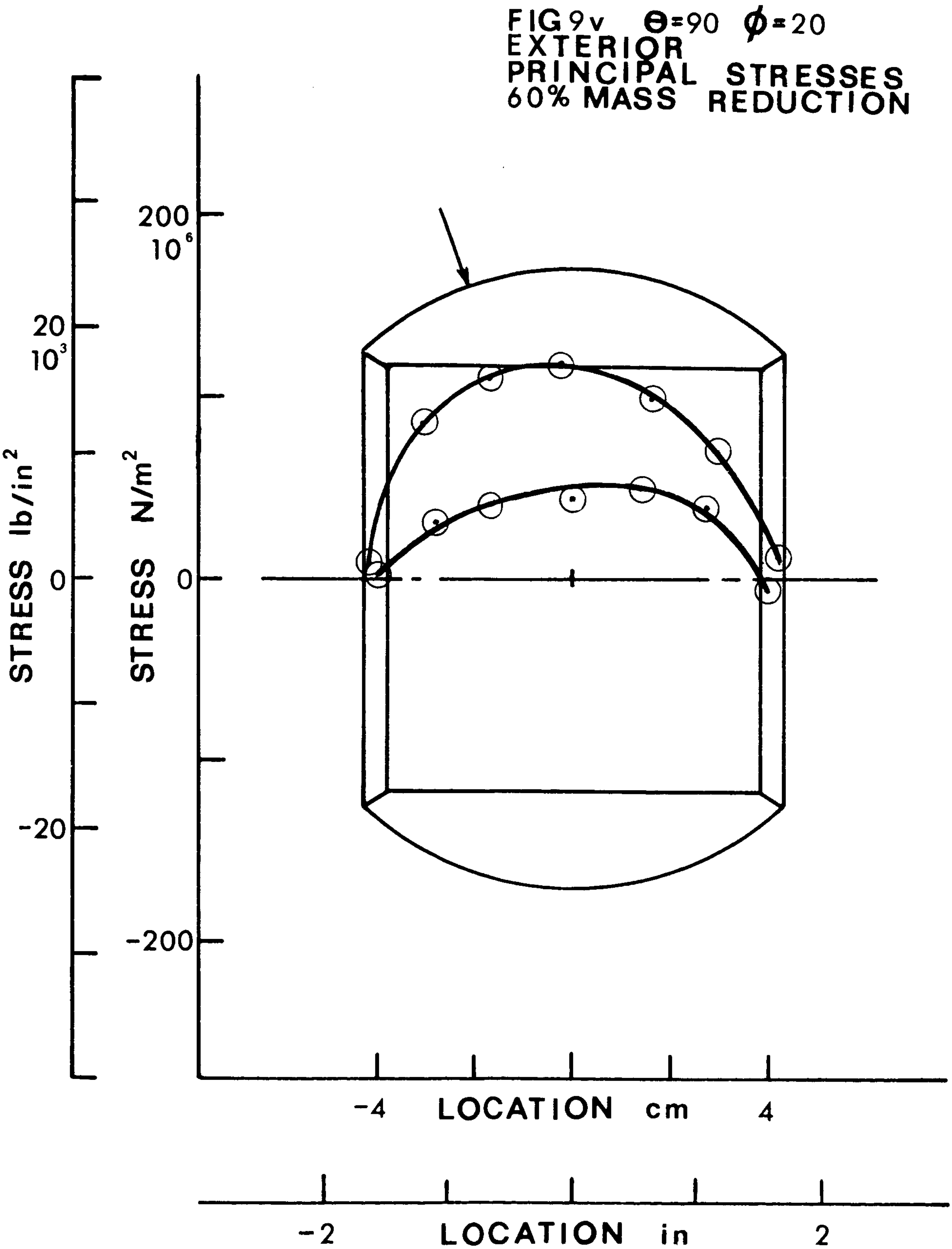


FIG 9v Θ=90 ϕ=20
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
200
10^6
20
10^3
STRESS lb/in^2
STRESS N/m^2
0
0
-20
-200
-4
LOCATION cm
4
-2
LOCATION in
2

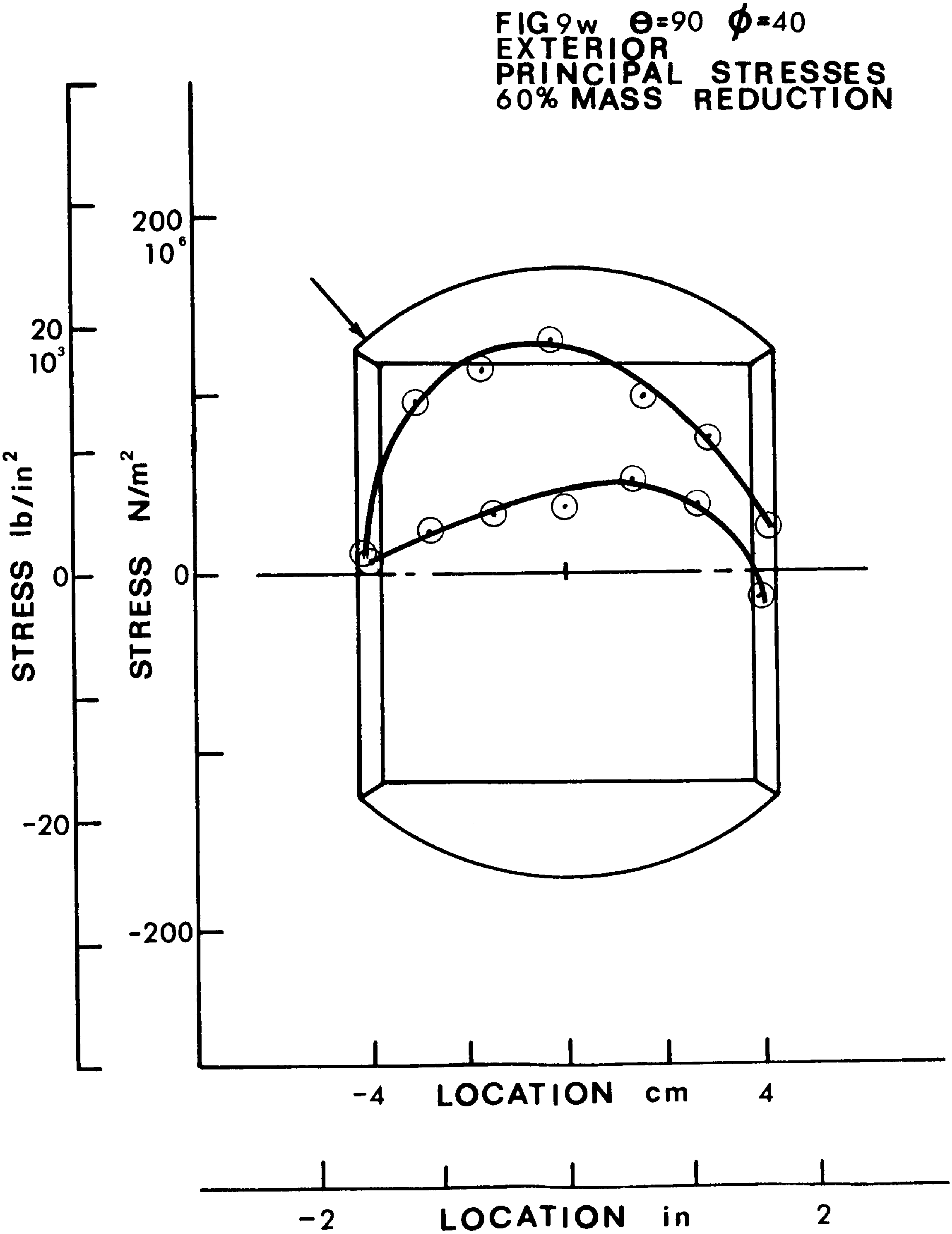


FIG 9w Θ=90 ϕ=40
EXTERIOR
PRINCIPAL STRESSES
60% MASS REDUCTION
STRESS lb/in²
20
10³
0
-20
STRESS N/m²
200
10⁶
0
-200
-4
LOCATION cm
4
-2
LOCATION in
2

TABLE I STRAIN GAGE LOCATIONS
DISTANCE FROM BALL MIDPLANE TO GAGES

40% MASS REDUCTION MODEL

Interior Axial & 45° Gages		Hoop Gages		Exterior Axial & 45° Gages		Hoop Gages	
mm	IN	mm	IN	mm	IN	mm	IN
- 6.9	-.27	-4.6	-.18	0.0	0.0	2.3	.09
2.3	.09	4.6	.18	11.4	.45	13.7	.54
11.4	.45	13.7	.54	22.9	.90	25.1	.99
20.6	.81	22.9	.90	34.3	1.35	36.6	1.44
29.8	1.17	32.0	1.26	45.7	1.80	48.0	1.89
38.8	1.53	40.9	1.61				

50% MASS REDUCTION MODEL

Interior Axial & 45° Gages		Hoop Gages		Exterior Axial & 45° Gages		Hoop Gages	
mm	IN	mm	IN	mm	IN	mm	IN
0.0	0.00	2.3	.09	0.0	0.00	2.3	.09
9.7	.38	11.9	.47	9.9	.39	12.2	.48
19.3	.76	17.0	.67	19.6	.77	21.6	.85
29.0	1.14	26.7	1.05	28.7	1.13	30.8	1.21
				36.8	1.45	39.2	1.54

60% MASS REDUCTION MODEL

Interior Axial & 45° Gages		Hoop Gages		Exterior Axial & 45° Gages		Hoop Gages	
mm	IN	mm	IN	mm	IN	mm	IN
- .8	-.03	1.5	.06	.8	.03	3.1	.12
8.1	.32	10.4	.41	15.0	.59	17.0	.68
17.0	.67	19.3	.76	38.7	1.13	31.0	1.22
25.9	1.02	28.3	1.11	40.2	1.58	42.4	1.67
34.8	1.37	37.1	1.46				

TABLE 2a

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
30 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 0. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-65.	100.	277.	277.	-65.	58.5	8.491	4.1	0.594	1.0
-58.	122.	310.	310.	-58.	66.5	9.647	7.9	1.153	0.6
-30.	146.	325.	325.	-30.	71.8	10.418	15.3	2.225	0.2
35.	201.	358.	358.	35.	83.8	12.150	32.4	4.693	-0.8
103.	254.	392.	392.	103.	96.1	13.945	50.1	7.269	-1.3
100.	246.	386.	386.	100.	94.6	13.715	49.0	7.114	-0.6
35.	201.	358.	358.	35.	83.8	12.150	32.4	4.693	-0.8
-30.	146.	325.	325.	-30.	71.8	10.418	15.3	2.225	0.2
-58.	122.	310.	310.	-58.	66.5	9.647	7.9	1.153	0.6
-65.	100.	277.	277.	-65.	58.5	8.491	4.1	0.594	1.0

THETA = 0. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-38.	130.	306.	306.	-38.	67.0	9.713	12.2	1.773	0.7
41.	205.	378.	378.	41.	88.7	12.868	35.1	5.089	0.8
128.	254.	420.	420.	128.	104.2	15.120	57.7	8.366	2.0
92.	235.	432.	433.	91.	104.0	15.085	47.9	6.944	3.6
-23.	163.	396.	397.	-24.	88.7	12.858	21.6	3.128	3.2
-74.	130.	343.	343.	-74.	72.9	10.577	6.6	0.952	0.6
-91.	112.	302.	302.	-91.	62.5	9.059	-0.1	-0.016	-0.9
-86.	107.	287.	287.	-86.	59.4	8.614	0.0	0.001	-1.0
-77.	99.	282.	282.	-77.	58.9	8.536	1.7	0.250	0.6
-67.	90.	257.	257.	-67.	53.9	7.812	2.3	0.331	0.9

THETA = 0. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
102.	390.	569.	589.	102.	147.0	21.316	83.8	12.155	0.1
-119.	123.	645.	670.	-144.	142.4	20.660	13.0	1.883	10.1
-301.	26.	523.	532.	-310.	99.7	14.465	-34.1	-4.951	5.8
-266.	30.	412.	415.	-269.	75.9	11.014	-32.8	-4.757	3.6
-199.	62.	353.	353.	-199.	66.7	9.679	-21.2	-3.079	1.6
-152.	72.	309.	309.	-152.	59.9	8.686	-13.5	-1.957	0.8
-119.	82.	270.	270.	-119.	53.3	7.727	-8.7	-1.255	-1.0
-93.	86.	253.	253.	-93.	51.2	7.423	-3.9	-0.566	-1.0
-75.	60.	242.	242.	-75.	49.9	7.237	-0.6	-0.080	0.6
-61.	70.	216.	216.	-61.	45.0	6.522	0.8	0.121	1.5

TABLE 2b

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 30. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-28.	30.	95.	95.	-28.	19.7	2.857	0.1	0.014	1.6
-20.	23.	77.	77.	-20.	16.2	2.348	0.7	0.095	3.2
-3.	44.	60.	64.	-7.	14.0	2.032	2.8	0.411	-13.1
36.	53.	33.	53.	16.	13.1	1.907	7.2	1.050	42.7
56.	37.	9.	66.	9.	15.6	2.265	6.5	0.949	-0.5
62.	11.	-2.	67.	-7.	14.8	2.145	2.9	0.427	-15.3
36.	53.	33.	53.	16.	13.1	1.907	7.2	1.050	42.7
-3.	44.	60.	64.	-7.	14.0	2.032	2.8	0.411	-13.1
-20.	23.	77.	77.	-20.	16.2	2.348	0.7	0.095	3.2
-28.	30.	95.	95.	-28.	19.7	2.857	0.1	0.014	1.6

THETA = 30. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
4.	6.	1.	5.	-0.	1.2	0.174	0.3	0.040	29.5
38.	-51.	-33.	67.	-62.	11.0	1.589	-9.5	-1.375	-28.2
63.	-71.	-43.	107.	-87.	18.4	2.662	-12.4	-1.805	-28.4
49.	-97.	-33.	121.	-105.	20.3	2.944	-15.6	-2.258	-34.3
-3.	-93.	12.	102.	-93.	16.9	2.450	-14.2	-2.064	42.8
-37.	-64.	52.	92.	-77.	15.6	2.265	-11.2	-1.622	29.1
-41.	82.	92.	113.	-62.	21.4	3.107	-6.3	-0.921	-20.2
-45.	66.	107.	111.	-49.	21.9	3.175	-3.6	-0.518	-9.1
-45.	31.	114.	114.	-45.	22.9	3.316	-2.5	-0.359	1.6
-40.	40.	125.	125.	-40.	25.7	3.726	-0.6	-0.083	0.9

THETA = 30. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
58.	-120.	-299.	58.	-299.	-7.2	-1.045	-64.0	-9.284	0.1
-2.	-355.	-253.	132.	-387.	3.7	0.532	-79.0	-11.460	-30.6
-77.	-319.	-109.	134.	-320.	8.6	1.243	-63.5	-9.214	-43.0
-105.	-235.	-13.	123.	-241.	11.5	1.669	-46.4	-6.727	37.7
-108.	-143.	61.	123.	-170.	16.3	2.370	-30.2	-4.385	27.4
-95.	-75.	89.	114.	-120.	17.7	2.567	-19.5	-2.825	19.0
-78.	77.	121.	135.	-92.	24.5	3.551	-11.8	-1.708	-14.6
-63.	54.	126.	129.	-66.	24.8	3.592	-6.1	-0.892	-6.7
-54.	31.	129.	129.	-54.	25.7	3.724	-3.5	-0.510	2.5
-43.	40.	132.	132.	-43.	27.1	3.929	-0.8	-0.115	1.5

TABLE 2c

DATA. PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
33.	-60.	-163.	33.	-163.	-3.6	-0.521	-34.8	-5.050	1.5
38.	-98.	-203.	39.	-204.	-5.0	-0.732	-43.7	-6.339	-3.7
45.	-99.	-210.	46.	-211.	-3.9	-0.569	-44.8	-6.503	-3.7
51.	-95.	-229.	51.	-229.	-4.0	-0.581	-48.6	-7.048	-1.2
54.	-102.	-242.	54.	-242.	-4.2	-0.608	-51.4	-7.449	-1.5
52.	-100.	-242.	52.	-242.	-4.7	-0.677	-51.5	-7.466	-1.0
51.	-95.	-229.	51.	-229.	-4.0	-0.581	-48.6	-7.048	-1.2
45.	-99.	-210.	46.	-211.	-3.9	-0.569	-44.8	-6.503	-3.7
38.	-98.	-203.	39.	-204.	-5.0	-0.732	-43.7	-6.339	-3.7
33.	-60.	-163.	33.	-163.	-3.6	-0.521	-34.8	-5.050	1.5

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
53.	-90.	-239.	53.	-239.	-4.2	-0.616	-50.7	-7.356	0.6
55.	-158.	-276.	62.	-283.	-5.3	-0.762	-60.0	-8.709	-8.0
55.	-169.	-266.	67.	-278.	-3.7	-0.538	-58.6	-8.505	-10.8
49.	-167.	-260.	61.	-272.	-4.7	-0.684	-57.6	-8.359	-10.9
35.	-162.	-240.	47.	-252.	-6.4	-0.935	-54.1	-7.850	-11.7
25.	-143.	-215.	34.	-224.	-7.5	-1.089	-48.6	-7.054	-10.9
23.	-43.	-178.	29.	-184.	-6.0	-0.869	-39.8	-5.774	9.5
20.	-58.	-158.	21.	-159.	-6.1	-0.888	-34.7	-5.027	3.5
18.	-67.	-149.	18.	-149.	-6.1	-0.880	-32.6	-4.734	-0.5
17.	-40.	-110.	17.	-110.	-3.6	-0.520	-23.9	-3.466	2.9

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
65.	-140.	-352.	65.	-352.	-9.2	-1.338	-75.6	-10.962	0.5
53.	-241.	-341.	76.	-364.	-7.6	-1.104	-77.5	-11.239	-13.1
28.	-250.	-290.	68.	-330.	-7.1	-1.031	-70.3	-10.197	-18.4
10.	-222.	-243.	48.	-281.	-8.2	-1.192	-60.6	-8.794	-19.9
-7.	-186.	-194.	26.	-227.	-9.5	-1.383	-49.9	-7.231	-21.2
-11.	-147.	-156.	13.	-180.	-9.3	-1.354	-40.0	-5.803	-20.6
-4.	-17.	-123.	12.	-139.	-6.7	-0.979	-30.8	-4.464	19.0
0.	-25.	-111.	8.	-119.	-6.3	-0.917	-26.5	-3.840	14.4
2.	-32.	-105.	5.	-108.	-6.2	-0.893	-24.3	-3.521	10.0
6.	-30.	-70.	6.	-70.	-3.4	-0.493	-15.5	-2.250	1.5

TABLE 2d

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 90. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
58.	-90.	-240.	58.	-240.	-3.2	-0.461	-50.6	-7.339	0.2
59.	-104.	-281.	59.	-281.	-5.7	-0.831	-59.9	-8.684	1.2
60.	-119.	-292.	60.	-292.	-6.3	-0.909	-62.3	-9.034	-0.5
60.	-122.	-303.	60.	-303.	-7.0	-1.019	-64.8	-9.396	-0.1
59.	-133.	-315.	59.	-315.	-8.1	-1.169	-67.6	-9.803	-0.8
58.	-124.	-309.	58.	-309.	-7.9	-1.144	-66.3	-9.613	0.2
60.	-122.	-303.	60.	-303.	-7.0	-1.019	-64.8	-9.396	-0.1
60.	-119.	-292.	60.	-292.	-6.3	-0.909	-62.3	-9.034	-0.5
59.	-104.	-281.	59.	-281.	-5.7	-0.831	-59.9	-8.684	1.2
58.	-90.	-240.	58.	-240.	-3.2	-0.461	-50.6	-7.339	0.2

THETA = 90. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
62.	-80.	-240.	62.	-240.	-2.2	-0.323	-50.4	-7.305	1.7
62.	-120.	-267.	63.	-268.	-4.0	-0.575	-56.6	-8.210	-3.0
60.	-145.	-286.	63.	-289.	-5.4	-0.783	-61.4	-8.903	-5.2
57.	-145.	-297.	59.	-299.	-7.0	-1.018	-63.9	-9.268	-4.0
53.	-168.	-302.	58.	-307.	-7.7	-1.118	-65.9	-9.553	-6.9
52.	-170.	-297.	58.	-303.	-7.4	-1.077	-65.0	-9.423	-7.6
55.	-85.	-302.	59.	-306.	-7.4	-1.079	-65.5	-9.507	6.1
59.	-94.	-299.	61.	-301.	-6.7	-0.969	-64.2	-9.317	4.1
60.	-92.	-297.	62.	-299.	-6.3	-0.914	-63.7	-9.243	4.2
58.	-100.	-257.	58.	-257.	-4.3	-0.630	-54.5	-7.899	-0.1

THETA = 90. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
57.	-80.	-220.	57.	-220.	-2.0	-0.297	-46.1	-6.689	0.3
52.	-122.	-243.	54.	-245.	-4.4	-0.635	-52.1	-7.551	-5.1
43.	-150.	-247.	51.	-255.	-5.8	-0.847	-54.4	-7.896	-9.2
37.	-162.	-251.	47.	-261.	-7.1	-1.028	-56.1	-8.143	-10.5
31.	-163.	-252.	40.	-261.	-8.6	-1.253	-56.7	-8.219	-10.2
29.	-178.	-250.	44.	-265.	-8.0	-1.159	-57.3	-8.312	-12.9
37.	-52.	-265.	49.	-277.	-7.7	-1.119	-59.7	-8.653	11.2
45.	-65.	-273.	52.	-280.	-7.2	-1.046	-60.2	-8.725	8.6
59.	-71.	-286.	56.	-292.	-7.1	-1.031	-62.6	-9.083	7.8
53.	-90.	-243.	53.	-243.	-4.5	-0.654	-51.6	-7.489	1.0

TABLE 2e

DATA. PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 0. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-0.	8.	87.	100.	-13.	21.8	3.160	3.9	0.569	19.6
-24.	-20.	-69.	-12.	-81.	-8.2	-1.191	-19.3	-2.795	24.8
24.	-44.	-103.	24.	-103.	-1.5	-0.224	-21.8	-3.162	-2.0
24.	-55.	-145.	24.	-145.	-4.4	-0.639	-31.4	-4.547	1.9
27.	-76.	-188.	27.	-188.	-6.7	-0.967	-40.9	-5.933	1.2
24.	-55.	-145.	24.	-145.	-4.4	-0.639	-31.4	-4.547	1.9
24.	-44.	-103.	24.	-103.	-1.5	-0.224	-21.8	-3.162	-2.0
-24.	-20.	-69.	-12.	-81.	-8.2	-1.191	-19.3	-2.795	24.8
-0.	8.	87.	100.	-13.	21.8	3.160	3.9	0.569	19.6

THETA = 0. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
3.	11.	58.	64.	-3.	14.4	2.085	3.6	0.529	17.7
-29.	-8.	-46.	-7.	-68.	-6.2	-0.899	-16.0	-2.316	37.0
43.	-23.	-83.	43.	-83.	4.1	0.598	-15.9	-2.313	-1.4
57.	-23.	-107.	57.	-107.	5.7	0.821	-20.4	-2.964	0.7
76.	-35.	-133.	76.	-133.	8.2	1.195	-25.1	-3.638	-1.8
57.	-23.	-107.	57.	-107.	5.7	0.821	-20.4	-2.964	0.7
43.	-23.	-83.	43.	-83.	4.1	0.598	-15.9	-2.313	-1.4
-29.	-8.	-46.	-7.	-68.	-6.2	-0.899	-16.0	-2.316	37.0
3.	11.	58.	64.	-3.	14.4	2.085	3.6	0.529	17.7

TABLE 2f

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44600 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 30. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-5.	46.	-18.	46.	-69.	5.8	0.843	-12.6	-1.828	41.8
-8.	46.	-36.	47.	-91.	4.5	0.659	-17.5	-2.545	39.2
10.	14.	-71.	30.	-91.	0.6	0.081	-18.6	-2.696	23.8
4.	-16.	-83.	10.	-89.	-3.8	-0.552	-19.5	-2.834	14.2
-0.	-42.	-90.	0.	-90.	-6.1	-0.888	-20.5	-2.969	1.9
4.	-16.	-83.	10.	-89.	-3.8	-0.552	-19.5	-2.834	14.2
10.	14.	-71.	30.	-91.	0.6	0.081	-18.6	-2.696	23.8
-8.	46.	-36.	47.	-91.	4.5	0.659	-17.5	-2.545	39.2
-5.	46.	-18.	46.	-69.	5.8	0.843	-12.6	-1.828	41.8

THETA = 30. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-15.	47.	-43.	48.	-106.	3.7	0.540	-20.9	-3.026	39.8
-2.	51.	-79.	59.	-140.	3.8	0.555	-27.8	-4.027	33.6
5.	18.	-104.	37.	-136.	-0.8	-0.119	-28.4	-4.123	25.5
9.	-1.	-95.	24.	-110.	-2.0	-0.286	-23.4	-3.400	19.8
17.	25.	-92.	45.	-120.	2.1	0.307	-24.3	-3.521	24.5
19.	-10.	-65.	21.	-67.	0.2	0.029	-13.8	-2.000	8.5
21.	17.	-49.	33.	-61.	3.3	0.479	-11.6	-1.679	20.8
-13.	45.	-18.	45.	-76.	5.1	0.733	-14.2	-2.062	43.8
-0.	45.	40.	52.	-12.	11.0	1.596	0.8	0.118	-25.7

THETA = 30. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
47.	77.	-183.	117.	-253.	9.4	1.357	-49.5	-7.185	25.8
46.	153.	-105.	168.	-227.	22.7	3.293	-40.1	-5.822	33.8
80.	91.	-113.	128.	-161.	18.1	2.627	-27.9	-4.041	24.0
57.	45.	-81.	77.	-101.	10.7	1.551	-17.8	-2.580	19.8
45.	12.	-66.	49.	-70.	6.4	0.932	-12.6	-1.832	11.0
30.	-0.	-40.	30.	-40.	4.1	0.602	-7.1	-1.030	4.1
24.	24.	-29.	35.	-40.	5.2	0.758	-6.7	-0.972	22.5
-15.	43.	-6.	43.	-64.	5.4	0.789	-11.6	-1.689	-42.6
-2.	43.	52.	57.	-7.	12.6	1.820	2.2	0.323	-16.8

TABLE 2g

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-0.	45.	-10.	45.	-55.	6.5	0.945	-9.5	-1.374	42.1
-11.	75.	51.	83.	-43.	16.0	2.314	-4.1	-0.600	-30.3
-6.	65.	56.	75.	-24.	15.5	2.245	-0.4	-0.059	-26.2
-5.	45.	57.	62.	-10.	13.5	1.953	1.9	0.275	-15.8
-2.	27.	50.	50.	-2.	11.3	1.633	2.9	0.425	-3.3
-5.	45.	57.	62.	-10.	13.5	1.953	1.9	0.275	-15.8
-5.	65.	56.	75.	-24.	15.5	2.245	-0.4	-0.059	-26.2
-11.	75.	51.	83.	-43.	16.0	2.314	-4.1	-0.600	-30.3
-0.	45.	-10.	45.	-55.	6.5	0.945	-9.5	-1.374	42.1

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-16.	33.	-37.	34.	-87.	1.8	0.259	-17.4	-2.530	40.0
-5.	61.	48.	69.	-26.	13.9	2.019	-1.2	-0.176	-26.1
8.	55.	58.	66.	-0.	15.0	2.183	4.5	0.646	-20.7
-6.	33.	51.	53.	-8.	11.5	1.665	1.8	0.263	-10.1
-4.	13.	48.	50.	-6.	10.9	1.578	2.1	0.308	9.5
-5.	50.	65.	70.	-10.	15.3	2.216	2.5	0.355	-14.9
-4.	71.	61.	82.	-25.	16.9	2.456	-0.1	-0.013	-26.3
-13.	76.	56.	86.	-43.	16.6	2.410	-3.9	-0.567	-28.8
-4.	49.	12.	50.	-42.	8.5	1.226	-6.1	-0.883	-40.0

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-14.	20.	-89.	29.	-132.	-2.4	-0.344	-28.1	-4.070	31.2
23.	55.	52.	60.	15.	14.7	2.132	7.5	1.083	-25.2
-16.	50.	73.	78.	-21.	16.3	2.362	0.6	0.181	-12.9
-14.	30.	78.	78.	-14.	16.8	2.434	2.1	0.309	1.2
-12.	14.	65.	67.	-14.	14.3	2.070	1.4	0.202	9.0
14.	60.	72.	77.	9.	18.1	2.619	7.4	1.067	-15.2
-9.	79.	63.	90.	-36.	18.0	2.617	-2.1	-0.302	-27.7
11.	83.	49.	86.	-26.	17.8	2.585	-0.1	-0.014	-35.1
4.	54.	23.	55.	-28.	10.6	1.539	-2.6	-0.381	-38.4

TABLE 2h

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
40 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 90. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-4.	-0.	-23.	3.	-30.	-1.4	-0.198	-6.6	-0.960	27.4
20.	25.	80.	89.	11.	21.0	3.044	8.6	1.242	19.9
-19.	42.	109.	109.	-19.	23.5	3.407	3.1	0.450	1.3
-17.	43.	116.	116.	-17.	25.3	3.663	4.0	0.579	2.8
-15.	43.	107.	107.	-15.	23.3	3.381	3.9	0.562	1.4
-17.	43.	116.	116.	-17.	25.3	3.663	4.0	0.579	2.8
-19.	42.	109.	109.	-19.	23.5	3.407	3.1	0.450	1.3
20.	25.	80.	89.	11.	21.0	3.044	8.6	1.242	19.9
-4.	-0.	-23.	3.	-30.	-1.4	-0.198	-6.6	-0.960	27.4

THETA = 90. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-0.	-10.	-18.	0.	-18.	-1.2	-0.177	-4.1	-0.595	-3.2
-5.	5.	76.	86.	-15.	18.6	2.691	2.4	0.351	18.5
-23.	22.	107.	110.	-26.	23.2	3.369	1.6	0.231	8.6
-17.	24.	115.	120.	-22.	25.7	3.729	3.2	0.471	10.4
-17.	25.	110.	114.	-21.	24.4	3.540	3.1	0.446	9.4
-20.	61.	120.	121.	-21.	26.0	3.778	3.5	0.508	-4.5
-21.	64.	110.	113.	-24.	24.0	3.484	2.3	0.330	-8.3
22.	47.	83.	83.	22.	20.4	2.965	10.6	1.535	5.1
-6.	13.	-20.	14.	-40.	0.4	0.064	-8.1	-1.179	37.5

THETA = 90. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-4.	-25.	-22.	2.	-28.	-1.5	-0.211	-6.2	-0.903	-26.6
25.	-22.	73.	124.	-26.	26.4	3.830	2.6	0.370	35.7
-33.	-5.	109.	121.	-45.	24.4	3.544	-2.0	-0.287	15.6
-28.	-0.	118.	131.	-41.	26.9	3.908	-0.3	-0.050	15.8
-30.	-0.	107.	117.	-40.	23.9	3.463	-1.1	-0.163	14.7
-34.	78.	122.	129.	-41.	26.5	3.849	-0.5	-0.078	-11.8
-30.	82.	111.	122.	-41.	25.0	3.624	-1.0	-0.152	-15.2
-30.	67.	83.	96.	-43.	18.9	2.740	-3.2	-0.469	-17.8
-0.	26.	-25.	28.	-53.	2.7	0.398	-10.1	-1.470	36.0

TABLE 3a

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 0. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-92.	204.	506.	506.	-92.	108.7	15.772	13.6	1.971	0.3
-44.	250.	562.	562.	-44.	124.8	18.095	28.3	4.105	0.9
72.	324.	594.	594.	72.	140.0	20.298	56.8	8.245	1.0
142.	382.	634.	634.	142.	153.8	22.307	75.5	10.950	0.7
142.	382.	634.	634.	142.	153.8	22.307	75.5	10.950	0.7
72.	324.	594.	594.	72.	140.0	20.298	56.8	8.245	1.0
-44.	250.	562.	562.	-44.	124.8	18.095	28.3	4.105	0.9
-92.	204.	506.	506.	-92.	108.7	15.772	13.6	1.971	0.3

THETA = 0. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
84.	412.	748.	748.	84.	175.8	25.491	70.1	10.166	0.3
140.	460.	750.	750.	140.	180.1	26.118	82.9	12.024	-1.4
-94.	264.	700.	702.	-96.	153.0	22.191	26.1	3.780	2.8
-180.	172.	586.	587.	-181.	121.1	17.567	-1.2	-0.167	2.3
-152.	212.	543.	543.	-152.	113.1	16.407	2.4	0.350	-1.4
-155.	280.	492.	511.	-175.	104.2	15.111	-4.9	-0.711	-9.5
-135.	158.	484.	484.	-136.	100.8	14.621	2.0	0.294	1.5
-118.	162.	438.	438.	-118.	91.5	13.273	3.0	0.442	-0.2

THETA = 0. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-1042.	42.	1056.	1057.	-1043.	169.1	24.521	-164.9	-23.921	-1.0
-730.	28.	748.	748.	-730.	120.3	17.445	-115.0	-16.674	-0.7
-469.	82.	670.	670.	-468.	120.4	17.467	-60.7	-8.810	1.0
-312.	106.	560.	560.	-312.	106.1	15.384	-32.8	-4.756	1.2
-290.	136.	498.	499.	-291.	93.6	13.579	-32.2	-4.665	-2.3
-209.	143.	450.	451.	-209.	88.2	12.795	-16.7	-2.424	-1.9
-153.	122.	431.	431.	-153.	87.6	12.707	-5.5	-0.793	1.7
-120.	132.	388.	388.	-120.	80.0	11.605	-0.8	-0.119	0.2

TABLE 3b

DATA: PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 30. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-17.	31.	135.	140.	-22.	30.3	4.398	4.5	0.659	10.1
5.	57.	103.	103.	5.	23.8	3.447	8.1	1.181	-1.8
32.	29.	82.	95.	19.	22.8	3.309	10.9	1.577	24.1
52.	44.	50.	58.	44.	16.2	2.349	13.9	2.023	-40.9
52.	44.	50.	58.	44.	16.2	2.349	13.9	2.023	-40.9
32.	29.	82.	95.	19.	22.8	3.309	10.9	1.577	24.1
5.	57.	103.	103.	5.	23.8	3.447	8.1	1.181	-1.8
-17.	31.	135.	140.	-22.	30.3	4.398	4.5	0.659	10.1

THETA = 30. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
44.	-82.	5.	133.	-84.	24.5	3.549	-10.0	-1.449	-39.8
56.	-111.	16.	184.	-112.	34.2	4.966	-13.0	-1.881	-41.1
31.	214.	45.	214.	-139.	39.2	5.684	-17.0	-2.470	-43.8
-25.	202.	128.	220.	-118.	42.0	6.097	-11.9	-1.726	-31.5
-40.	-90.	169.	251.	-122.	48.7	7.069	-10.6	-1.540	28.0
-56.	-16.	210.	239.	-85.	48.6	7.045	-3.1	-0.445	17.5
-61.	133.	217.	219.	-62.	45.6	6.610	0.8	0.119	-5.0
-57.	70.	223.	224.	-58.	46.9	6.802	2.2	0.312	2.7

THETA = 30. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-64.	-775.	-132.	580.	-776.	78.9	11.443	-136.8	-19.843	-43.6
-165.	-534.	116.	504.	-553.	76.9	11.147	-91.3	-13.247	37.3
-166.	291.	180.	340.	-328.	54.9	7.963	-51.4	-7.449	-29.3
-155.	216.	252.	312.	-215.	56.3	8.161	-27.6	-4.004	-19.7
-143.	-112.	254.	315.	-204.	57.7	8.372	-24.9	-3.615	20.1
-113.	-6.	271.	288.	-135.	56.2	8.154	-11.0	-1.597	11.5
-93.	104.	272.	273.	-94.	55.6	8.061	-2.7	-0.389	-2.3
-75.	79.	266.	267.	-76.	55.5	8.046	1.0	0.140	2.8

TABLE 3c

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
74.	-138.	-245.	82.	-253.	1.5	0.211	-52.0	-7.539	-9.1
80.	-128.	-275.	83.	-278.	-0.2	-0.022	-57.5	-8.335	-4.9
86.	-81.	-283.	89.	-284.	0.8	0.119	-58.4	-8.476	2.5
82.	-96.	-292.	82.	-292.	-1.2	-0.180	-60.8	-8.820	1.4
82.	-96.	-292.	82.	-292.	-1.2	-0.180	-60.8	-8.820	1.4
84.	-81.	-283.	89.	-284.	0.8	0.119	-58.4	-8.476	2.5
80.	-128.	-275.	83.	-278.	-0.2	-0.022	-57.5	-8.335	-4.9
74.	-138.	-245.	82.	-253.	1.5	0.211	-52.0	-7.539	-9.1

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
95.	-246.	-364.	122.	-390.	1.1	0.161	-80.3	-11.646	-13.0
90.	-240.	-350.	116.	-376.	0.7	0.105	-77.5	-11.248	-13.3
83.	-18.	-330.	108.	-355.	0.4	0.058	-73.4	-10.644	13.5
61.	-23.	-285.	83.	-307.	-2.1	-0.310	-64.1	-9.290	13.6
63.	-188.	-270.	80.	-290.	-1.6	-0.238	-60.4	-8.762	-13.4
53.	-146.	-225.	65.	-237.	-1.3	-0.192	-49.5	-7.179	-11.7
45.	-68.	-209.	46.	-210.	-3.9	-0.566	-44.6	-6.463	3.1
41.	-87.	-167.	44.	-170.	-1.6	-0.237	-35.6	-5.163	-6.5

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
97.	-427.	-473.	184.	-560.	3.6	0.526	-114.7	-16.641	-20.0
63.	-383.	-374.	160.	-471.	4.2	0.615	-96.1	-13.944	-23.1
43.	44.	-325.	120.	-402.	-0.1	-0.022	-83.2	-12.064	22.6
23.	26.	-234.	78.	-289.	-1.9	-0.279	-60.4	-8.764	22.8
15.	-195.	-184.	65.	-233.	-1.0	-0.152	-48.6	-7.048	-24.0
13.	-116.	-130.	33.	-150.	-2.7	-0.390	-31.9	-4.625	-19.4
15.	-42.	-112.	13.	-112.	-4.6	-0.669	-24.6	-3.574	3.4
15.	-63.	-76.	25.	-86.	-0.1	-0.017	-17.9	-2.597	-17.8

TABLE 3d

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 90. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
90.	-165.	-413.	90.	-413.	-7.7	-1.117	-87.7	-12.726	-0.4
93.	-173.	-449.	93.	-449.	-9.5	-1.374	-95.7	-13.883	0.5
100.	-174.	-456.	100.	-456.	-8.4	-1.213	-96.8	-14.045	0.4
91.	-179.	-467.	91.	-467.	-11.1	-1.615	-100.0	-14.499	0.9
91.	-179.	-467.	91.	-467.	-11.1	-1.615	-100.0	-14.499	0.9
100.	-174.	-456.	100.	-456.	-8.4	-1.213	-96.8	-14.045	0.4
93.	-173.	-449.	93.	-449.	-9.5	-1.374	-95.7	-13.883	0.5
90.	-165.	-413.	90.	-413.	-7.7	-1.117	-87.7	-12.726	-0.4

THETA = 90. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
92.	-184.	-431.	92.	-431.	-8.4	-1.220	-91.8	-13.308	-1.6
92.	-201.	-453.	93.	-454.	-9.9	-1.429	-96.8	-14.042	-2.2
94.	-140.	-452.	97.	-455.	-9.0	-1.307	-96.8	-14.035	4.1
83.	-138.	-449.	87.	-453.	-11.2	-1.617	-97.0	-14.069	4.8
91.	-211.	-453.	93.	-455.	-9.9	-1.442	-97.0	-14.072	-3.1
97.	-200.	-446.	98.	-447.	-8.2	-1.186	-95.0	-13.772	-2.7
98.	-143.	-440.	99.	-441.	-7.5	-1.087	-93.6	-13.570	3.0
99.	-151.	-412.	99.	-412.	-5.6	-0.810	-86.9	-12.605	0.6

THETA = 90. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
85.	-188.	-400.	88.	-402.	-7.4	-1.075	-85.4	-12.382	-3.6
83.	-180.	-410.	84.	-411.	-9.0	-1.306	-87.6	-12.708	-1.9
82.	-105.	-406.	89.	-413.	-8.0	-1.160	-87.7	-12.725	6.6
76.	-103.	-393.	82.	-399.	-8.5	-1.232	-85.2	-12.354	6.7
65.	-215.	-402.	73.	-407.	-11.2	-1.622	-87.5	-12.692	-5.8
73.	-198.	-393.	76.	-396.	-9.7	-1.409	-84.8	-12.305	-4.6
79.	-122.	-389.	81.	-391.	-8.2	-1.189	-83.4	-12.096	4.0
86.	-140.	-368.	86.	-368.	-5.5	-0.804	-77.8	-11.281	0.1

TABLE 3e

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 0. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-40.	42.	100.	101.	-41.	20.2	2.925	-2.4	-0.353	-4.9
-58.	70.	198.	198.	-58.	41.1	5.954	0.3	0.046	0.0
-64.	98.	248.	248.	-64.	52.0	7.546	2.3	0.340	-1.1
-70.	114.	280.	280.	-70.	58.9	8.544	3.1	0.456	-1.5
-76.	126.	326.	326.	-76.	68.9	9.996	5.0	0.719	-0.1
-70.	114.	280.	280.	-70.	58.9	8.544	3.1	0.456	-1.5
-64.	98.	248.	248.	-64.	52.0	7.546	2.3	0.340	-1.1
-58.	70.	198.	198.	-58.	41.1	5.954	0.3	0.046	0.0
-40.	42.	100.	101.	-41.	20.2	2.925	-2.4	-0.353	-4.9

THETA = 0. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-40.	23.	64.	65.	-41.	12.0	1.741	-4.9	-0.712	-6.0
-74.	39.	143.	143.	-74.	27.5	3.985	-7.1	-1.027	-1.2
-100.	57.	184.	185.	-101.	35.1	5.095	-10.3	-1.495	-3.0
-133.	67.	215.	217.	-135.	40.1	5.817	-15.9	-2.303	-4.2
-174.	63.	258.	259.	-175.	46.9	6.808	-22.1	-3.208	-2.8
-133.	67.	215.	217.	-135.	40.1	5.817	-15.9	-2.303	-4.2
-100.	57.	184.	185.	-101.	35.1	5.095	-10.3	-1.495	-3.0
-74.	39.	143.	143.	-74.	27.5	3.985	-7.1	-1.027	-1.2
-40.	23.	64.	65.	-41.	12.0	1.741	-4.9	-0.712	-6.0

TABLE 3f

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 30. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-2.	132.	50.	135.	-87.	24.8	3.592	-10.6	-1.535	-38.2
-16.	130.	98.	147.	-65.	28.9	4.196	-4.7	-0.682	-28.7
-16.	112.	112.	139.	-43.	28.6	4.146	-0.2	-0.032	-22.5
-16.	92.	128.	136.	-24.	29.4	4.258	3.7	0.542	-13.3
-16.	60.	130.	130.	-16.	28.5	4.129	5.2	0.757	-1.2
-16.	92.	128.	136.	-24.	29.4	4.258	3.7	0.542	-13.3
-16.	112.	112.	139.	-43.	28.6	4.146	-0.2	-0.032	-22.5
-16.	130.	98.	147.	-65.	28.9	4.196	-4.7	-0.682	-28.7
-2.	132.	50.	135.	-87.	24.8	3.592	-10.6	-1.535	-38.2

THETA = 30. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-0.	218.	120.	229.	-109.	44.6	6.472	-9.2	-1.329	-34.6
-10.	204.	146.	225.	-89.	45.0	6.532	-4.9	-0.704	-30.1
-22.	174.	148.	203.	-77.	40.9	5.926	-3.6	-0.526	-26.3
-34.	132.	138.	169.	-65.	34.1	4.939	-3.3	-0.482	-21.5
-46.	80.	138.	144.	-52.	29.2	4.235	-2.0	-0.292	-10.1
-40.	47.	119.	119.	-40.	24.4	3.536	-1.0	-0.150	-2.7
-33.	73.	107.	116.	-42.	23.5	3.402	-1.6	-0.231	-13.6
-26.	86.	85.	109.	-50.	21.3	3.092	-3.9	-0.563	-22.8
-7.	87.	28.	89.	-68.	15.6	2.261	-9.4	-1.361	-38.6

THETA = 30. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-28.	338.	118.	347.	-257.	61.3	8.897	-34.7	-5.040	-38.0
-72.	250.	126.	271.	-217.	46.8	6.788	-30.8	-4.473	-33.0
-78.	178.	118.	206.	-166.	35.5	5.148	-23.7	-3.433	-29.1
-74.	96.	98.	132.	-108.	22.7	3.289	-15.6	-2.260	-22.2
-76.	62.	94.	109.	-91.	18.6	2.697	-13.3	-1.926	-16.0
-60.	2.	96.	98.	-62.	18.0	2.609	-7.4	-1.066	5.8
-44.	33.	86.	87.	-45.	16.7	2.425	-4.3	-0.625	-5.2
-30.	51.	67.	77.	-40.	14.8	2.140	-3.8	-0.554	-16.9
-7.	55.	16.	56.	-47.	9.6	1.388	-6.9	-1.002	-38.6

TABLE 3g

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
41.	48.	-69.	69.	-97.	9.1	1.313	-17.3	-2.513	24.2
40.	28.	-68.	54.	-82.	6.7	0.979	-15.0	-2.179	18.9
39.	-0.	-100.	45.	-106.	3.1	0.444	-21.1	-3.059	11.8
37.	-26.	-110.	38.	-111.	1.0	0.149	-22.6	-3.278	4.1
36.	-46.	-114.	36.	-114.	0.5	0.067	-23.5	-3.410	-2.7
37.	-26.	-110.	38.	-111.	1.0	0.149	-22.6	-3.278	4.1
39.	-0.	-100.	45.	-106.	3.1	0.444	-21.1	-3.059	11.8
40.	28.	-68.	54.	-82.	6.7	0.979	-15.0	-2.179	18.9
41.	48.	-69.	69.	-97.	9.1	1.313	-17.3	-2.513	24.2

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
20.	-60.	-123.	21.	-124.	-3.8	-0.546	-26.7	-3.869	-3.4
27.	-38.	-118.	27.	-118.	-1.8	-0.268	-25.0	-3.632	3.0
33.	-5.	-109.	40.	-116.	1.2	0.178	-23.7	-3.435	12.5
36.	22.	-96.	54.	-114.	4.5	0.653	-22.2	-3.225	19.1
33.	47.	-53.	61.	-81.	8.4	1.219	-14.3	-2.076	26.5
29.	-15.	-113.	34.	-118.	-0.3	-0.047	-24.5	-3.553	10.4
31.	17.	-102.	49.	-120.	3.0	0.434	-24.0	-3.477	19.1
31.	43.	-91.	65.	-125.	6.3	0.910	-24.0	-3.481	25.1
34.	57.	-73.	74.	-113.	9.1	1.319	-20.6	-2.990	27.5

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
30.	40.	-134.	71.	-175.	4.2	0.615	-35.0	-5.073	24.1
40.	8.	-134.	56.	-150.	2.5	0.361	-30.3	-4.390	16.2
39.	-20.	-127.	42.	-130.	0.7	0.108	-26.7	-3.880	8.1
33.	-50.	-111.	34.	-112.	0.1	0.009	-23.1	-3.352	-4.3
27.	-71.	-43.	64.	-80.	9.1	1.320	-13.8	-2.006	-30.5
30.	-5.	-113.	39.	-122.	0.5	0.074	-25.0	-3.631	13.5
30.	26.	-99.	54.	-123.	3.9	0.562	-24.3	-3.519	21.6
30.	51.	-86.	70.	-126.	7.3	1.062	-23.9	-3.462	26.9
33.	62.	-73.	78.	-118.	9.6	1.396	-21.4	-3.110	28.6

TABLE 3h

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
50 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 90. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
33.	-53.	-118.	34.	-119.	-0.4	-0.062	-24.7	-3.581	-4.0
44.	-70.	-187.	44.	-187.	-2.7	-0.399	-39.5	-5.730	0.4
45.	-83.	-203.	45.	-203.	-3.6	-0.523	-43.1	-6.249	-0.9
44.	-96.	-226.	44.	-226.	-5.4	-0.782	-48.4	-7.018	-1.1
42.	-93.	-235.	42.	-235.	-6.5	-0.939	-50.6	-7.333	0.7
44.	-96.	-226.	44.	-226.	-5.4	-0.782	-48.4	-7.018	-1.1
45.	-83.	-203.	45.	-203.	-3.6	-0.523	-43.1	-6.249	-0.9
44.	-70.	-187.	44.	-187.	-2.7	-0.399	-39.5	-5.730	0.4
33.	-53.	-118.	34.	-119.	-0.4	-0.062	-24.7	-3.581	-4.0

THETA = 90. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
33.	-82.	-109.	46.	-122.	2.1	0.299	-24.5	-3.556	-15.9
49.	-102.	-182.	54.	-187.	-0.4	-0.062	-38.9	-5.638	-8.5
52.	-114.	-207.	57.	-212.	-1.5	-0.217	-44.3	-6.426	-7.9
49.	-126.	-223.	54.	-228.	-3.2	-0.464	-48.2	-6.994	-8.0
48.	-123.	-237.	51.	-240.	-4.8	-0.696	-51.0	-7.404	-5.7
55.	-60.	-223.	57.	-225.	-2.4	-0.345	-47.3	-6.855	4.9
56.	-48.	-207.	59.	-210.	-0.9	-0.135	-43.7	-6.336	5.9
55.	-34.	-183.	59.	-187.	0.6	0.089	-38.4	-5.575	7.1
42.	-20.	-115.	44.	-117.	2.0	0.287	-23.5	-3.415	5.9

THETA = 90. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
33.	-113.	-105.	67.	-139.	5.8	0.843	-27.1	-3.929	-24.1
55.	-136.	-182.	75.	-202.	3.3	0.484	-40.9	-5.927	-15.7
60.	-146.	-208.	78.	-226.	2.3	0.339	-46.1	-6.682	-14.1
59.	-156.	-225.	77.	-243.	0.9	0.127	-49.9	-7.242	-13.6
61.	-154.	-243.	74.	-256.	-0.7	-0.103	-53.1	-7.697	-11.3
67.	-15.	-217.	79.	-229.	2.4	0.343	-46.7	-6.772	11.5
67.	-0.	-202.	83.	-218.	4.0	0.580	-43.9	-6.366	13.3
62.	17.	-176.	83.	-197.	5.5	0.791	-39.1	-5.677	15.9
49.	26.	-111.	67.	-129.	6.5	0.938	-24.8	-3.595	17.7

TABLE 4a

DATA. PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 0. PHI = 0.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-172.	258.	646.	647.	-173.	135.2	19.608	4.9	0.706	-1.5
-190.	300.	744.	745.	-191.	156.2	22.661	7.5	1.081	-1.4
-152.	388.	826.	829.	-155.	177.8	25.789	21.4	3.097	-3.0
10.	548.	950.	955.	5.	217.4	31.531	66.3	9.612	-4.1
194.	622.	1014.	1014.	194.	243.8	35.356	113.2	16.415	-1.3
10.	548.	950.	955.	5.	217.4	31.531	66.3	9.612	-4.1
-152.	388.	826.	829.	-155.	177.8	25.789	21.4	3.097	-3.0
-190.	300.	744.	745.	-191.	156.2	22.661	7.5	1.081	-1.4
-172.	258.	646.	647.	-173.	135.2	19.608	4.9	0.706	-1.5

THETA = 0. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-138.	370.	792.	794.	-140.	170.9	24.791	22.3	3.238	-2.6
110.	590.	1022.	1023.	109.	239.9	34.795	94.6	13.720	-1.5
186.	600.	1146.	1150.	180.	273.7	39.701	119.3	17.299	3.8
-164.	372.	1098.	1105.	-171.	239.5	34.740	36.5	5.289	4.3
-292.	256.	934.	937.	-295.	192.9	27.983	-3.2	-0.468	3.0
-292.	334.	832.	836.	-296.	169.8	24.624	-10.2	-1.482	-3.2
-262.	270.	748.	749.	-263.	152.3	22.085	-8.7	-1.256	-1.5
-222.	258.	692.	693.	-223.	142.2	20.631	-3.4	-0.488	-1.4
-175.	236.	600.	601.	-177.	124.5	18.057	0.8	0.115	-1.8

THETA = 0. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-1545.	-30.	3190.	3339.	-1694.	643.4	93.319	-157.3	-22.819	9.9
-1790.	-330.	1835.	1879.	-1744.	308.2	44.700	-268.3	-38.914	6.3
-1050.	-40.	1260.	1269.	-1059.	216.2	31.363	-154.2	-22.363	3.6
-685.	225.	1065.	1066.	-686.	195.5	28.351	-83.2	-12.066	-1.1
-480.	170.	895.	896.	-481.	170.9	24.782	-48.2	-6.996	1.6
-367.	261.	795.	797.	-371.	155.9	22.605	-30.0	-4.348	-2.4
-285.	246.	699.	701.	-287.	139.7	20.261	-17.4	-2.518	-2.3
-219.	225.	618.	619.	-220.	125.7	18.226	-7.8	-1.126	-1.7
-159.	198.	504.	505.	-160.	103.9	15.065	-1.9	-0.280	-2.2

TABLE 4b

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 30. PHI = 0.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-68.	4.	197.	210.	-81.	42.2	6.126	-4.1	-0.597	12.3
-55.	32.	184.	188.	-60.	38.7	5.609	-0.8	-0.123	7.5
-19.	63.	138.	138.	-19.	30.1	4.363	5.1	0.737	-1.3
27.	78.	88.	94.	21.	22.8	3.312	11.1	1.616	-17.0
53.	63.	40.	64.	29.	16.6	2.402	10.9	1.584	34.2
27.	78.	88.	94.	21.	22.8	3.312	11.1	1.616	-17.0
-19.	63.	138.	138.	-19.	30.1	4.363	5.1	0.737	-1.3
-55.	32.	184.	188.	-60.	38.7	5.609	-0.8	-0.123	7.5
-68.	4.	197.	210.	-81.	42.2	6.126	-4.1	-0.597	12.3

THETA = 30. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
6.	-192.	-64.	138.	-196.	18.0	2.604	-35.1	-5.090	-38.9
32.	-214.	-72.	181.	-221.	26.0	3.778	-37.9	-5.492	-37.5
24.	-234.	-54.	207.	-237.	31.0	4.491	-39.8	-5.776	-40.0
-26.	-210.	18.	203.	-211.	31.8	4.609	-34.1	-4.952	42.0
-74.	-132.	94.	175.	-155.	29.2	4.236	-23.3	-3.379	29.7
-102.	186.	220.	264.	-146.	50.1	7.261	-15.2	-2.204	-19.1
-118.	128.	284.	289.	-123.	57.3	8.310	-8.2	-1.196	-6.3
-118.	80.	294.	294.	-118.	58.8	8.529	-6.8	-0.986	1.1
-102.	50.	290.	295.	-107.	59.7	8.664	-4.2	-0.607	6.3

THETA = 30. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
36.	-939.	-762.	338.	-1064.	4.2	0.613	-218.8	-31.727	-27.6
-186.	-885.	-426.	285.	-897.	3.7	0.531	-184.5	-26.760	-39.1
-267.	-660.	-108.	292.	-667.	20.8	3.021	-131.6	-19.093	40.2
-261.	-414.	111.	312.	-462.	39.4	5.709	-83.7	-12.138	30.6
-229.	-207.	207.	283.	-304.	43.5	6.314	-49.7	-7.214	21.0
-192.	222.	297.	350.	-245.	62.8	9.116	-31.8	-4.616	-17.4
-162.	156.	318.	330.	-174.	63.2	9.156	-17.1	-2.481	-9.0
-135.	102.	333.	333.	-135.	66.5	9.643	-8.0	-1.158	-0.4
-108.	81.	315.	316.	-109.	64.4	9.344	-3.3	-0.473	3.0

TABLE 4c

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
77.	-214.	-333.	94.	-350.	-2.5	-0.356	-73.2	-10.616	-11.4
97.	-227.	-414.	106.	-423.	-4.7	-0.688	-88.9	-12.897	-7.5
111.	-231.	-466.	116.	-471.	-5.8	-0.836	-99.1	-14.378	-5.3
115.	-225.	-512.	116.	-513.	-8.6	-1.247	-108.7	-15.768	-2.4
123.	-197.	-521.	123.	-521.	-7.6	-1.098	-110.0	-15.959	0.2
115.	-225.	-512.	116.	-513.	-8.6	-1.247	-108.7	-15.768	-2.4
111.	-231.	-466.	116.	-471.	-5.8	-0.836	-99.1	-14.378	-5.3
97.	-227.	-414.	106.	-423.	-4.7	-0.688	-88.9	-12.897	-7.5
77.	-214.	-333.	94.	-350.	-2.5	-0.356	-73.2	-10.616	-11.4

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
120.	-292.	-490.	138.	-508.	-3.2	-0.470	-106.1	-15.388	-9.7
132.	-318.	-548.	149.	-565.	-4.6	-0.668	-118.3	-17.161	-9.0
126.	-326.	-552.	144.	-570.	-6.1	-0.882	-119.8	-17.375	-9.2
110.	-306.	-550.	121.	-561.	-10.7	-1.559	-119.3	-17.298	-7.3
98.	-250.	-504.	102.	-508.	-11.5	-1.670	-108.5	-15.730	-4.4
84.	-164.	-440.	84.	-440.	-10.9	-1.574	-94.3	-13.683	1.5
70.	-176.	-368.	72.	-370.	-8.9	-1.294	-79.1	-11.478	-3.5
58.	-178.	-300.	67.	-309.	-5.9	-0.851	-65.6	-9.521	-8.8
42.	-172.	-216.	67.	-241.	-1.1	-0.164	-50.3	-7.294	-16.7

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
162.	-396.	-672.	185.	-695.	-5.3	-0.770	-145.4	-21.087	-9.3
147.	-429.	-720.	170.	-743.	-12.1	-1.748	-157.3	-22.809	-9.1
111.	-417.	-639.	141.	-669.	-13.6	-1.968	-142.5	-20.661	-11.1
76.	-369.	-573.	100.	-595.	-17.9	-2.589	-128.4	-18.625	-10.2
63.	-279.	-489.	71.	-497.	-17.8	-2.580	-108.1	-15.677	-6.7
39.	-111.	-345.	44.	-350.	-13.9	-2.022	-76.5	-11.093	6.2
30.	-126.	-258.	30.	-258.	-10.7	-1.551	-56.7	-8.220	-2.4
21.	-136.	-177.	37.	-193.	-4.8	-0.695	-41.3	-5.991	-15.2
9.	-123.	-96.	48.	-138.	1.5	0.222	-28.1	-4.079	-28.4

TABLE 4d

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL INTERIOR

THETA = 90. PHI = 0.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
137.	-206.	-506.	138.	-507.	-3.2	-0.471	-105.8	-15.343	-1.9
162.	-232.	-605.	162.	-605.	-4.4	-0.640	-126.5	-18.346	-0.8
169.	-264.	-656.	170.	-657.	-6.2	-0.905	-137.7	-19.967	-1.4
166.	-290.	-707.	166.	-707.	-10.4	-1.510	-149.5	-21.676	-1.3
172.	-284.	-707.	172.	-707.	-9.1	-1.315	-149.0	-21.614	-1.1
166.	-290.	-707.	166.	-707.	-10.4	-1.510	-149.5	-21.676	-1.3
169.	-264.	-656.	170.	-657.	-6.2	-0.905	-137.7	-19.967	-1.4
162.	-232.	-605.	162.	-605.	-4.4	-0.640	-126.5	-18.346	-0.8
137.	-206.	-506.	138.	-507.	-3.2	-0.471	-105.8	-15.343	-1.9

THETA = 90. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
135.	-186.	-490.	136.	-490.	-2.5	-0.360	-102.1	-14.812	-0.8
156.	-228.	-586.	156.	-586.	-4.5	-0.647	-122.6	-17.781	-1.0
164.	-272.	-636.	166.	-638.	-5.8	-0.846	-133.6	-19.382	-2.6
154.	-300.	-686.	160.	-688.	-10.6	-1.540	-145.4	-21.088	-2.4
164.	-303.	-690.	166.	-692.	-9.5	-1.374	-146.0	-21.168	-2.7
158.	-272.	-700.	158.	-700.	-11.8	-1.714	-148.3	-21.514	-0.1
162.	-256.	-658.	162.	-658.	-8.0	-1.165	-138.5	-20.092	-0.6
156.	-242.	-614.	156.	-614.	-6.4	-0.925	-129.0	-18.704	-1.0
132.	-224.	-416.	144.	-428.	3.5	0.514	-87.5	-12.686	-8.3

THETA = 90. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
135.	-159.	-468.	135.	-468.	-1.2	-0.176	-97.2	-14.096	0.7
153.	-207.	-558.	153.	-558.	-3.3	-0.474	-116.4	-16.883	-0.4
150.	-249.	-603.	151.	-604.	-6.9	-1.003	-126.9	-18.411	-1.7
141.	-291.	-645.	143.	-647.	-11.6	-1.686	-137.3	-19.914	-2.8
138.	-288.	-648.	139.	-649.	-12.6	-1.827	-138.1	-20.030	-2.4
141.	-249.	-657.	141.	-657.	-12.7	-1.847	-139.7	-20.267	0.6
147.	-243.	-618.	147.	-618.	-8.7	-1.264	-130.5	-18.921	-0.6
144.	-237.	-582.	144.	-582.	-6.9	-0.998	-122.5	-17.773	-1.4
120.	-228.	-486.	123.	-489.	-5.3	-0.774	-102.8	-14.912	-4.2

TABLE 4e

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 0. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-18.	14.	56.	56.	-18.	11.6	1.676	-0.3	-0.047	3.8
-116.	-130.	-316.	-84.	-348.	-42.8	-6.213	-84.8	-12.301	20.3
-150.	-168.	-490.	-92.	-548.	-58.3	-8.452	-130.8	-18.977	20.9
-162.	-234.	-638.	-110.	-690.	-72.0	-10.447	-164.4	-23.839	17.4
-150.	-168.	-490.	-92.	-548.	-58.3	-8.452	-130.8	-18.977	20.9
-116.	-130.	-316.	-84.	-348.	-42.8	-6.213	-84.8	-12.301	20.3
-18.	14.	56.	56.	-18.	11.6	1.676	-0.3	-0.047	3.8

THETA = 0. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-15.	9.	48.	49.	-16.	10.0	1.454	-0.3	-0.040	6.7
-124.	-87.	-255.	-68.	-311.	-36.6	-5.314	-75.3	-10.929	28.7
-210.	-81.	-399.	-62.	-547.	-51.4	-7.450	-128.6	-18.650	33.5
-327.	-87.	-531.	-72.	-786.	-70.0	-10.150	-183.6	-26.622	36.7
-210.	-81.	-399.	-62.	-547.	-51.4	-7.450	-128.6	-18.650	33.5
-124.	-87.	-255.	-68.	-311.	-36.6	-5.314	-75.3	-10.929	28.7
-15.	9.	48.	49.	-16.	10.0	1.454	-0.3	-0.040	6.7

TABLE 4f

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 30. PHI = 0.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-28.	-100.	6.	80.	-102.	11.2	1.620	-17.7	-2.562	39.6
-62.	44.	-158.	51.	-271.	-6.8	-0.992	-58.2	-8.437	36.3
-50.	34.	-226.	55.	-331.	-10.0	-1.456	-71.5	-10.373	31.5
-38.	-114.	-244.	-35.	-247.	-24.7	-3.586	-58.6	-8.500	7.3
-50.	34.	-226.	55.	-331.	-10.0	-1.456	-71.5	-10.373	31.5
-62.	44.	-158.	51.	-271.	-6.8	-0.992	-58.2	-8.437	36.3
-29.	-100.	6.	80.	-102.	11.2	1.620	-17.7	-2.562	39.6

THETA = 30. PHI = 20.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-56.	-112.	-118.	-47.	-127.	-19.4	-2.810	-32.0	-4.648	-19.4
-54.	126.	-194.	136.	-384.	4.7	0.677	-77.9	-11.305	37.2
-66.	56.	-228.	72.	-366.	-8.7	-1.256	-78.2	-11.344	34.1
-76.	24.	-228.	40.	-344.	-14.4	-2.090	-75.4	-10.938	33.3
-86.	-36.	-200.	-22.	-264.	-23.0	-3.331	-61.5	-8.926	31.0
-54.	54.	-128.	59.	-241.	-3.1	-0.447	-50.7	-7.353	37.8
-16.	-94.	56.	140.	-100.	24.9	3.616	-13.1	-1.902	36.2

THETA = 30. PHI = 40.

EPSILON A	EPSILON B	EPSILON C	EPSILON 1	EPSILON 2	SIGMA 1		SIGMA 2		ALPHA
MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MICRO M/M	MNSM	KSI	MNSM	KSI	DEG
-125.	-260.	-340.	-122.	-343.	-51.0	-7.404	-86.4	-12.525	-7.2
-194.	470.	-165.	470.	-829.	50.3	7.299	-156.4	-22.685	-44.4
-175.	210.	-190.	210.	-575.	8.5	1.238	-116.4	-16.881	44.5
-125.	70.	-180.	72.	-377.	-9.4	-1.362	-80.7	-11.709	41.5
-102.	-51.	-106.	-51.	-157.	-22.3	-3.233	-39.2	-5.681	43.9
-76.	24.	-96.	24.	-196.	-7.8	-1.137	-43.0	-6.235	42.4
6.	-75.	72.	158.	-80.	30.4	4.410	-7.4	-1.067	36.9

TABLE 4g

DATA, PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 60. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
2.	-110.	8.	120.	-110.	19.8	2.869	-16.8	-2.440	44.3
30.	185.	163.	207.	-14.	46.1	6.690	10.9	1.581	-26.5
37.	152.	220.	223.	34.	53.0	7.687	22.9	3.327	-7.2
40.	90.	240.	252.	28.	59.2	8.580	23.6	3.420	13.3
37.	152.	220.	223.	34.	53.0	7.687	22.9	3.327	-7.2
30.	185.	163.	207.	-14.	46.1	6.690	10.9	1.581	-26.5
2.	-110.	8.	120.	-110.	19.8	2.869	-16.8	-2.440	44.3

THETA = 60. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
2.	-80.	-48.	39.	-85.	3.1	0.451	-16.7	-2.422	-33.2
46.	158.	182.	195.	33.	46.6	6.755	20.8	3.017	-16.5
48.	130.	238.	239.	47.	57.5	8.341	27.0	3.916	3.9
46.	64.	246.	275.	17.	63.7	9.241	22.6	3.273	19.7
168.	212.	24.	233.	-41.	50.1	7.265	6.6	0.964	29.1
220.	178.	36.	233.	23.	54.5	7.902	21.2	3.069	14.3
246.	118.	44.	250.	40.	59.5	8.627	26.2	3.802	-7.5

THETA = 60. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
-9.	42.	-108.	54.	-171.	0.5	0.078	-35.1	-5.092	31.9
66.	123.	204.	205.	65.	51.0	7.402	28.7	4.170	4.9
72.	72.	276.	318.	30.	74.4	10.786	28.5	4.128	22.5
54.	45.	279.	332.	1.	75.5	10.957	22.9	3.315	23.6
57.	189.	219.	234.	42.	56.0	8.123	25.5	3.705	-16.1
30.	213.	162.	230.	-38.	49.7	7.214	7.0	1.014	-30.3
18.	-141.	84.	246.	-144.	46.1	6.681	-15.9	-2.310	40.1

TABLE 4h

DATA. PRINCIPAL STRAINS, STRESSES, AND ANGLE
FOR A 44500 N (10000 LB) LOAD ON 127 MM (5 IN) OD
60 PERCENT MASS REDUCTION MODEL EXTERIOR

THETA = 90. PHI = 0.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
23.	-33.	12.	68.	-33.	13.3	1.922	-2.9	-0.422	-41.9
88.	127.	305.	325.	68.	78.6	11.395	37.6	5.448	16.3
101.	156.	401.	429.	73.	102.4	14.855	45.9	6.660	16.2
102.	160.	421.	451.	72.	107.4	15.570	47.2	6.844	16.2
101.	156.	401.	429.	73.	102.4	14.855	45.9	6.660	16.2
88.	127.	305.	325.	68.	78.6	11.395	37.6	5.448	16.3
23.	-33.	12.	68.	-33.	13.3	1.922	-2.9	-0.422	-41.9

THETA = 90. PHI = 20.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
22.	-0.	18.	40.	-0.	9.1	1.321	2.7	0.393	-42.1
96.	64.	304.	371.	29.	86.3	12.522	31.9	4.620	26.3
112.	94.	404.	478.	38.	111.2	16.124	41.3	5.990	24.2
106.	118.	446.	508.	44.	118.5	17.184	44.6	6.473	21.5
102.	216.	404.	408.	98.	99.5	14.431	50.0	7.255	6.9
86.	188.	286.	286.	86.	70.9	10.280	39.0	5.663	-0.6
16.	72.	6.	72.	-50.	13.0	1.884	-6.5	-0.941	42.7

THETA = 90. PHI = 40.

EPSILON A MICRO M/M	EPSILON B MICRO M/M	EPSILON C MICRO M/M	EPSILON 1 MICRO M/M	EPSILON 2 MICRO M/M	SIGMA 1 MNSM	SIGMA 1 KSI	SIGMA 2 MNSM	SIGMA 2 KSI	ALPHA DEG
30.	42.	30.	42.	18.	10.8	1.563	7.0	1.009	0.0
102.	-0.	300.	425.	-23.	95.0	13.785	23.7	3.444	31.9
126.	27.	372.	503.	-5.	114.0	16.528	33.2	4.815	30.5
126.	33.	435.	572.	-11.	129.3	18.754	36.5	5.288	29.0
114.	279.	396.	398.	112.	98.1	14.229	52.6	7.628	-4.8
87.	252.	294.	311.	70.	75.4	10.943	37.1	5.386	-15.4
21.	-105.	15.	141.	-105.	24.9	3.611	-14.3	-2.068	-44.3

APPENDIX A Evaluation of Rectangular Cross Section Ring

A cylindrical steel ring was fabricated and strain gaged with two Micro-Measurements type EA 06-125 BB-120 gages (0.125 inch gage length) mounted with Eastman 910 cement along and perpendicular to the ring axis. Diametrically opposite to these gages a TML ZFRA-1 strain gage rosette (1 mm gage length) was mounted with a polyester cement. Ring dimensions are shown in figure A-1.

The cylindrical ring model was subjected to 7,000 lb. compressive loads with the gages vertically under the load, and oriented at 30^{o}, 60^{o}, and 90^{o} to the line of the load. Strain measurements were made in a succession of these tests. A Budd model P-350 strain indicator and a Baldwin model 120-B strain indicator were used in tests on successive days. The average of the MM and TML strain measurements are plotted in figure A-2. The TML and MM gages gave substantially identical results. The strain indicators differed significantly only in the 30^{o} measurement, which might be accounted for by a 2-1/4 degree difference in alignment of the ring in the two tests. Data values measured are given in Table A-1.

Ripperger and Davids in "Critical Stresses in a Circular Ring" Trans ASCE Vol. 112 pp 619-628, 1947, give a theory of elasticity solution for a ring of these proportions. Strains calculated from their result for a modulus of 203.5 x 109 N/m^2 (29.5 x 10^6 lb/in^2) are +992 x 10^{-6} M/M at $\beta = 0^{o}$, and -776 x 10^{-6} M/M at $\beta = 90^{o}$.

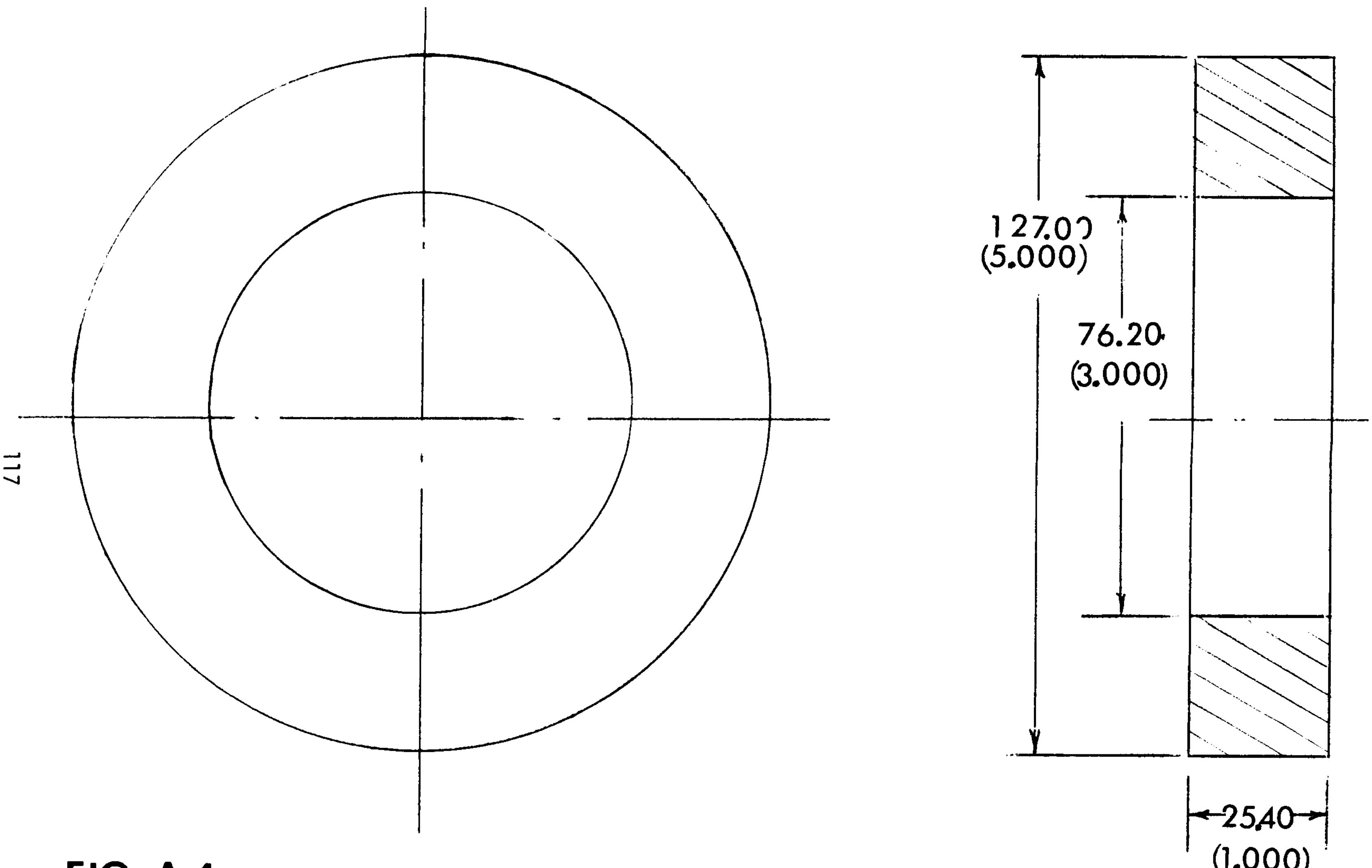


FIG A 1
RING DIMENSIONS mm (IN)

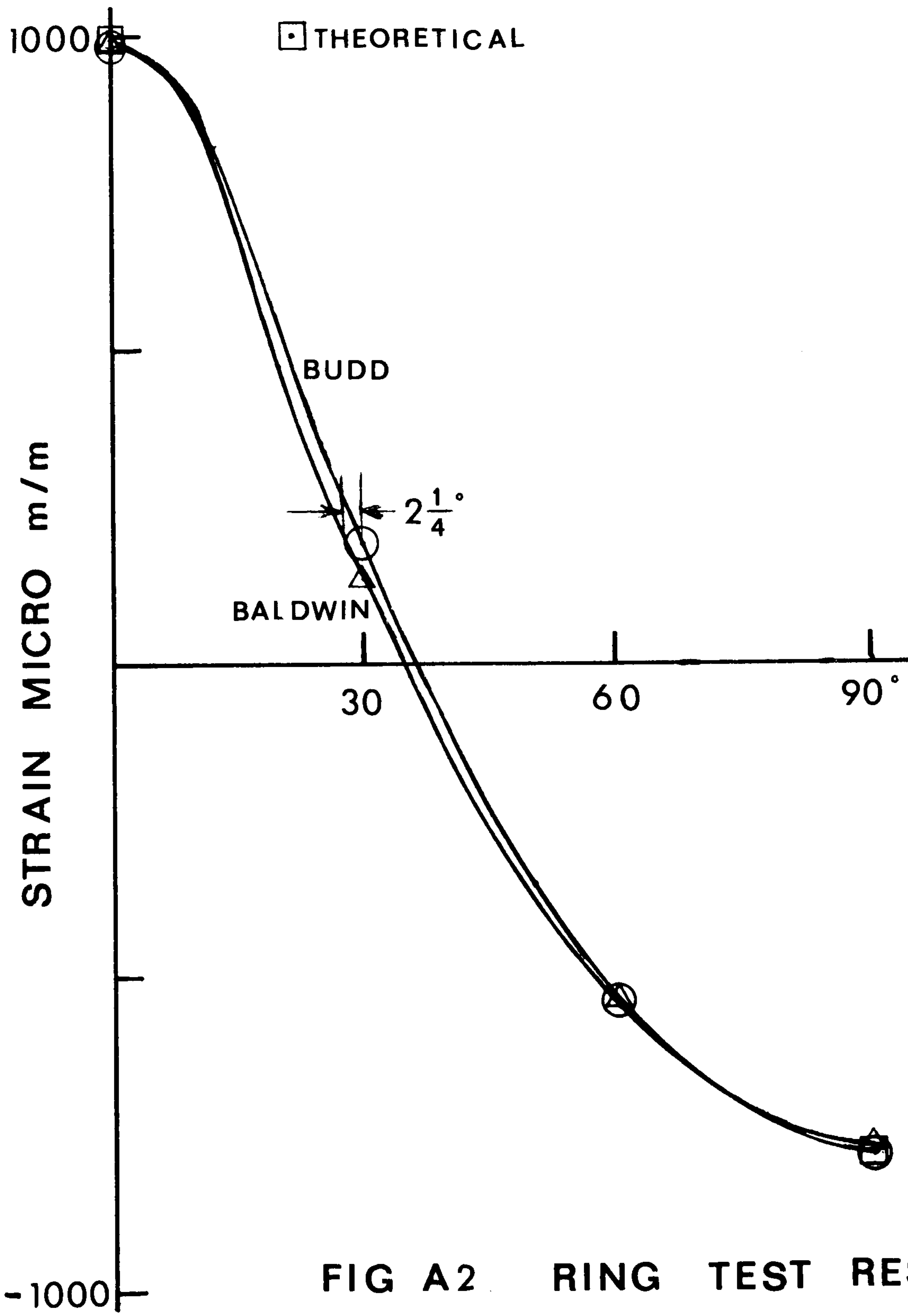


FIG A2 RING TEST RESULT

TABLE A-1

STRAIN MEASUREMENTS ON RING
MICRO M/M

Angle to Vertical	Maximum Strain MM Strain Gage		Maximum Strain TML Strain Gage	
	Budd	Baldwin	Budd	Baldwin
90^{0}	-785	-772	-793	-786
60^{0}	-539	-535	-556	-532
30^{0}	+191	+134	+187	+138
0^{0}	+982	+986	+998	+992

APPENDIX A-2 CURVED BEAM STRESS CALCULATIONS FOR CYLINDRICALLY HOLLOW BALLS

It may be convenient to consider a closed form solution to estimate stresses in a wide range of ball hollowness proportions. Using the formulations and notations of Timoshenho, "Strength of Materials," Part I, 3rd edition, Van Nostrand, New York, 1956.

Bending stresses are given by:

$$\sigma_A = \frac{M(h_1 - e)}{Aer_1} \quad , \quad \sigma_B = \frac{-M(h_2 + e)}{Aer_2} \tag{A1}$$

where

σ_A, σ_B = stress at inner and outer surfaces

M = bending moment

h_1, h_2 = distance from centroid of cross section to inner and outer surfaces

A = cross section area

r_1,r_2 = radii of curvature of inner and outer surfaces

$e = \bar{r}\,\frac{m}{m+1}$

$\bar{r}$ = radius of curvature of centroidal axis

m = cross section area constant

For each cross section the quantity m must be evaluated by performing an integration

$$mA = \int_A \frac{y\,dA}{\bar{r}-y} \tag{A2}$$

From Figure A3 this integral may be written

$$mA = \int_{r_1}^{r_2} (\bar{r}-v)\frac{dA}{v} = \bar{r}\int_{r_1}^{r_2} \frac{2\sqrt{r_2^2 - v^2}}{v}\, dv - A \tag{A3}$$

and

$$m = \frac{\bar{r}}{A}\left[2\int_{r_1}^{r_2} \sqrt{\left(\frac{r_2}{v}\right)^2 - 1}\; dv\right] - 1 \tag{A4}$$

for the cross section of a cylindrically hollow ball. The integral form indicated may be found in a table of integrals and evaluated at r_1 and r_2 to obtain

$$m = \frac{\bar{r}}{A}\quad 2r_2\left[\ln\left(\frac{1 + \sqrt{1 - \left(\frac{r_1}{r_2}\right)^2}}{\frac{r_1}{r_2}}\right) - \sqrt{1 - \left(\frac{r_1}{r_2}\right)^2}\right] -1 \tag{A5}$$

Timoshenho gives the bending moment in a ring due to a vertical point load as

$$M = \frac{P\bar{r}}{2}\left(\cos\beta - \frac{2}{\pi} \right) \tag{A6}$$

where β is the angle from the horizontal, so that the angle beta is $90^0 - \theta$ as used in the report body. P is the vertical load. In addition to the bending stresses given by equation A1, direct stress P/A also acts on the $\theta = 90^0$ cross section.

These equations have been programmed to calculate the stresses in the drilled balls. Results are shown in Table A2. The calculated values may be compared with measured values from Tables 2, 3 and 4 of this report.

Comparison of measured values with calculated values indicates that values measured with strain gage rosettes may be 24 to 41% higher than values calculated from curved beam theory for models proportioned for mass reductions of 40 to 60%. It would seem that the above theory is not an accurate predictor of measured stress values. It may still be useful for comparative studies.

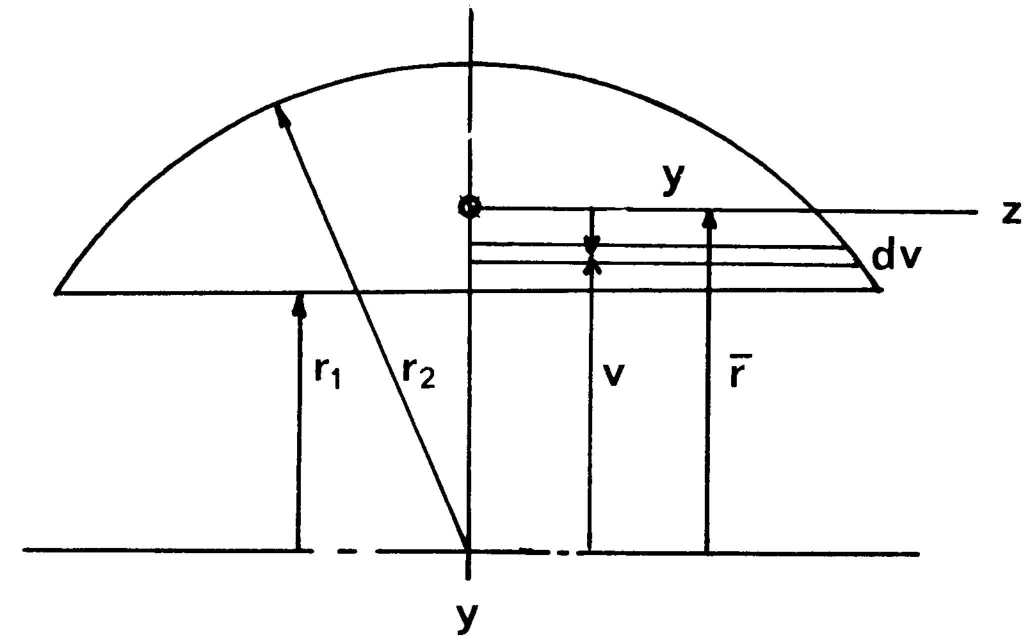


FIG A3 AREA CROSS SECTION

TABLE A2

CURVED BEAM STRESS CALCULATIONS

AND EXPERIMENTAL STRESS VALUES

MASS REDUCTION %	CALCULATED STRESS AT $\theta = 0^o$				CALCULATED STRESS AT $\theta = 90^o$				MEASURED STRESS AT $\theta = 0^o$		MEASURED STRESS AT $\theta = 90^o$	
	INTERIOR		EXTERIOR		INTERIOR		EXTERIOR		INTERIOR		INTERIOR	
	MNSM	KSI	MNSM	KSI	MNSM	KSI	MNSM	KSI	MNSM	KSI	MNSM	KSI
30	48.40	7.020	-40.06	-5.810	-39.06	-5.666	-17.60	2.553				
40	71.38	10.353	-66.38	-9.629	-53.92	-7.821	30.81	4.469	96.1	13.945	-67.5	-9.803
50	108.79	15.779	-111.17	-16.123	-77.85	-11.292	53.86	7.813	153.8	22.307	-99.9	-14.499
60	175.93	25.517	-194.86	-28.261	-120.1	-17.428	97.87	14.196	243.7	35.356	-149.4	-21.676
70	315.27	45.726	-375.34	-54.439	-206.4	-29.939	194.5	28.222				

U.S. GOVERNMENT PRINTING OFFICE: 1974—635-042/9