AFRPL-TR-70-115

FINAL REPORT ON THE DEVELOPMENT OF THE TILT-EDGE BELLOWS CONCEPT

L. E. Hulbert, T. M. Trainer, N. D. Ghadiali

Battelle Memorial Institute
Columbus Laboratories

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October 1970

Air Force Rocket Propulsion Laboratory
Directorate of Laboratories
Air Force Systems Command
Edwards Air Force Base
California

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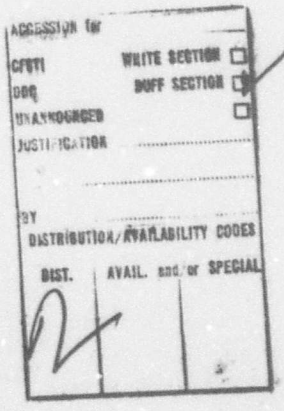

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FORWORD

This report summarizes research conducted under USAF Contract No. F04611-68-C-0031 from January 1, 1968, through September, 1970. The Contract was established under Air Force Budget Program Structure No 623058, AFSC Project No. 3058, Program Element No. 6.24.05.18.F. The work was performed by the Battelle Memorial Institute, Columbus Laboratories for the Air Force Rocket Propulsion Laboratory, Directorate of Laboratories, Edwards Air Force Base, with Captain A. B. Spencer and Lt. E. Lantzer serving as contract managers. The principal contributors to the report were Mr. T. M. Trainer, Program Manager, Dr. L. E. Hulbert, Division Chief, and Dr. D. T. Hunter and Mr. N. D. Ghadiali, Research Engineers.

This technical report has been reviewed and is approved.

Edwin L. Lantzer
1st Lt., USAF
Project Engineer

ABSTRACT

A two and one-half year program was conducted to investigate the tilt-edge bellows concept. This involved the idea that the stresses at the convolution root and crown welds of a welded bellows could be minimized by appropriately tilting the convolution midsurfaces near the root and crown. The research program involved an extensive theoretical analysis of various convolution cross-sectional shapes to optimize the shape with respect to the maximum stress as well as the weld bead stresses. A particular optimized bellows with a 3.5-inch OD was fabricated and tested. The results of the tests verified that the tilt-edge bellows had superior fatigue resistance. Further, the fatigue failures occurred at positions away from the welds which verified that the weld bead stresses were small. Elimination of fatigue failures at the convolution and end fitting welds also resulted in reduced scatter in bellows fatigue life. This should allow fatigue life predictions to be made with greater confidence for tilt-edge bellows than for conventional welded bellows designs.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued) Page

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

GLOSSARY OF WELDED BELLOWS TERMS

Bellows Axis - Centerline of the bellows

Bending Moment - Bending couple acting on the bellows at a point. This couple is obtained by integrating through the thickness of the bellows the stresses anti-symmetrically distributed about the bellows midsurface.

Chill Blocks - Rings clamped onto a pair of bellows diaphragms adjacent to the point in which the diaphragms are to be welded together. These rings act as heat sinks during the welding operation.

Chord Angle - The angle subtended between the cone passing through the ID and OD weld beads of a bellows leaf and the plane passing through the ID weld bead of the leaf normal to the bellows axis.

Circumferential Direction - Direction tangent to the circle of intersection between the bellows midsurface and the plane drawn normal to the bellows axis.

Convolution - One of a set of identical elements of a bellows. In a welded bellows, one convolution is composed of two leaves.

Crown - The point of maximum diameter of a bellows convolution.

Diaphragm - One of a pair of stamped annular rings that are to be welded together at the ID to form a bellows convolution.

Flat - The straight sections of a welded bellows diaphragm adjacent to the ID or OD weld. These sections are made without curvature so that the chill blocks can make intimate contact with the diaphragms during the welding operation. In conventional welded bellows bellows, the "flats" are truely flat and perpendicular to the bellows axis. In the tilt-edge bellows the "flats" are, in fact, segments of cones.

ID - Inside Diameter

Inner Surface - Surface of the bellows leaves that would be wetted by a fluid filling the bellows. Because of the way that the shells are defined for computer program NONLIN, this is also the surface in the direction of the "inner normal" for all of the mathematical models used in NONLIN in this research

study.

Leaf - One half of a bellows convolution. The terms "leaf" and "diaphragm" are essentially interchangeable. However, "diaphragm" will be used in this report to denote the stamped rings before they are welded together. The term "leaf" will be used to denote the same stamped rings after they have been assembled into a bellows. The terms "upper leaf" and "lower leaf" will be used to denote the upper and lower leaves of a convolution welded at the ID when the tilted edges of the convolution are sloping downward.

Membrane Force - The resultant force acting at the point of the bellows in the direction of the midsurface of the bellows. This force is obtained by integrating through the bellows thickness the stresses that are symmetrically distributed about the bellows midsurface.

Normal Direction - The direction along the normal drawn to the bellows midsurface at any point.

OD - Outside diameter. Bellows will often be identified in terms of the nominal OD in the text. Thus, the term 3-inch bellows will mean a bellows with an OD of approximately 3 inches.

Outer Surface - The surface of the bellows leaves on the outside of the bellows. Also, the shell surface in the direction of the outer normal.

Pitch - Axial length subtended by one convolution. The pitch may be measured as the distance between the centers of two adjacent crown weld beads.

Root - The point on the bellows convolution having minimum distance from the axis.

Span - The radial distance subtended by a bellows convolution. Span = 0.5 (OD - ID)

Spring Rate - The ratio between the axial force applied to a bellows and the axial deformation of the bellows.

Strain Range - The total difference in the strain imposed at a point of the bellows over a half cycle of a fatigue test. For a deflection fatigue test the strain range is the difference between the strain measured (or calculated) at the point of maximum axial compression and the strain at the point of maximum axial extension.

Sweep - A corrugation formed into the bellows diaphragm. It usually consists of a segment of a torus. Bellows may be formed of one or more sweeps and are often characterized in terms of the number of sweeps. Most of the bellows in this study are 3-sweep bellows.

Sweep Radius - The toroidal radius of a sweep. (Not the cylindrical radius of the torus segment.)

Surface Stress - Stress in the surface fibers of the bellows thickness. The surface stress is obtained by adding together the stresses due to the membrane forces and bending moments.

Tilt Angle - The angle between the outer normal for the conical section (flat) at the bellows root or crown and the bellows axis. For zero tilt angle the flat is normal to the bellows axis and thus the normal is directed along the axis.

SECTION I

INTRODUCTION

Under USAF Contract No. 04(611)-10532, an extensive experimental and theoretical study was made of formed and welded bellows and of diaphragms. As described, AFRPL Report TR 68-22,[1] one of the major conclusions of this study was that welded bellows, as they were being made, were unreliable under cyclic load conditions leading to fatigue failure. The scatter in the fatigue life data was so great that no meaningful correlation could be obtained between measured fatigue life and either the theoretically predicted, or experimentally measured maximum strains.

It was apparent that the reason for the erratic fatigue behavior of welded bellows was that the maximum strains occurred at the welds. Thus one of the determining factors in establishing the fatigue life of a welded bellows was the quality of the welding operation. It was known that even the highest quality welds degrade the material in the heat affected zones adjacent to the welds. Further, there is a considerable variability to be expected in the quality of the welds that are made on thin materials even with the best possible welding practices.

As a result of a theoretical study of welded bellows designs carried out under the above mentioned contract[1], a promising idea for changing the shape of the welded bellows cross section was discovered. To describe this shape change, it is first noted that welded bellows are formed with flat sections (called "flats") at the root and crown of each leaf. These flats are intended to mate with relatively heavy rings which act as heat sinks for the bellows when the root and crown welds are made.

In conventional welded bellows, the flats are normal to the bellows axis. As noted above, the maximum strains in such bellows occurred at the welds. By theoretical analysis, it was shown that tilting the bellows flats at an angle to the bellows axis could drastically reduce the stresses at both the root and crown welds.

Although this study was entirely theoretical, it showed that the effects of tilting the convolution edges (which will henceforth be called the tilt-edge effect) gave promise of eliminating many of the disadvantages described above for welded bellows. On the basis of this study, the Air Force Rocket Propulsion Laboratory initiated a new contract with Battelle-Columbus in January, 1968, to conduct theoretical and experimental investigations of the new tilt-edge welded bellows concept.

The initial phase of the research study consisted of a theoretical parameter study to determine by computer analysis the effects of changing tilt angles, span, pitch, and sweep radius, on the performance characteristics of tilt-edge welded bellows. This study demonstrated that tilt angles could be found which minimized the weld stresses for the range of bellows parameters studied. As a consequence of this parameter study, it was determined that the reduction in stresses at the root and crown welds mainly resulted from a reduction of the bending stresses. For conventional bellows the stresses

at the weld were predominantly bending stresses. The optimum tilt angles occurred when the bending stresses at the weld were minimized or eliminated.

The second phase of the research contract involved the design of an optimum configuration for a 3.5-inch tilt-edge bellows. A number of these bellows were fabricated and tested. The results of the tests verified that the tilt-edge design would perform as predicted by the theoretical analysis. In particular, fatigue failure at the welds was suppressed and fatigue lives were dramatically increased.

The present report summarizes the entire research program and gives many results of the theoretical and experimental analyses conducted. As a result of this investigation, it was concluded that the tilt-edge bellows concept does indeed permit design of superior welded bellows.

Two appendices are included in this report. Appendix A describes a detailed investigation of the stresses in the neighborhood of the weld beads. Appendix B gives a description of some new subroutines developed in this program to improve the capability of Program NONLIN.

SECTION II

ANALYSIS OF GEOMETRIC PARAMETER VARIATIONS

Welded bellows have so many design parameters that it would be prohibitively expensive to conduct a complete parametric study. Incomplete but extensive parameter studies of conventional welded bellows have been made previously with somewhat inconclusive results[2]. Nevertheless, a limited parametric study of tilt-edge bellows was considered necessary in the present study to determine the range of applicability of the tilt-edge bellows concept. Such a parameter study was also necessary to achieve a sufficient understanding of the concept to permit the design of tilt-edge bellows with optimum performance. An initial investigation was directed toward studying the effect of changing tilt angles on the stress distributions near the welds. Subsequent investigations considered the effect of changes in certain bellows dimensions on the stresses at the welds and on the angle of tilt necessary to achieve minimum stresses at the welds.

In this section, a description will be given first of the study of the effects of varying the tilt angles at the root and crowns of 2, 3, and 4-inch bellows, each with three sweeps. Following this, investigations into the effects of changing span, sweep radius and convolution pitch are described. Unless otherwise noted, the thickness was taken to be 0.005 inches in all bellows described in this section.

Nomenclature for Tilt-Edge Welded Bellows

A physical understanding of the various parameters used to describe tilt-edge welded bellows is important in order to appreciate better the effects of these parameters on the stress-deflection behavior of the bellows.

Figure 1 shows the cross section of a single convolution of a typical three-sweep, tilt-edge welded bellows, and the major parameters studied in the present investigation are indicated. The term "three sweep" denotes the number of toroidal sections (three) used in a leaf of the bellows. Conical segments, called "flats", are at the inside and outside diameter welds. These flat surfaces are required so that the chill blocks used in the welding process can make full contact with the bellows leaves and thereby effectively absorb the heat created during welding. During the present study, the sweep radii of the curved sections were normally assumed to be the same for all sweeps in a leaf. Finally, it is noted that the chord angles of the diaphragms are measured in a positive sense from the horizontal in a counterclockwise direction.

Figure 2 shows the cross section of a complete convolution with the dimensional parameters which were used to define the midsurface configurations of the tilt-edge bellows to be discussed in this report. These measurements are consistent with the required input data for Battelle's computer program NONLIN. NONLIN was used to perform the theoretical design studies reported herein. Note that the outer normal points down for the upper leaf and up for the lower leaf. In shell parts 2, 4, and 9 the outer normal points to the sweep center of curvature. For these sweeps the radius is entered in NONLIN as a negative value.

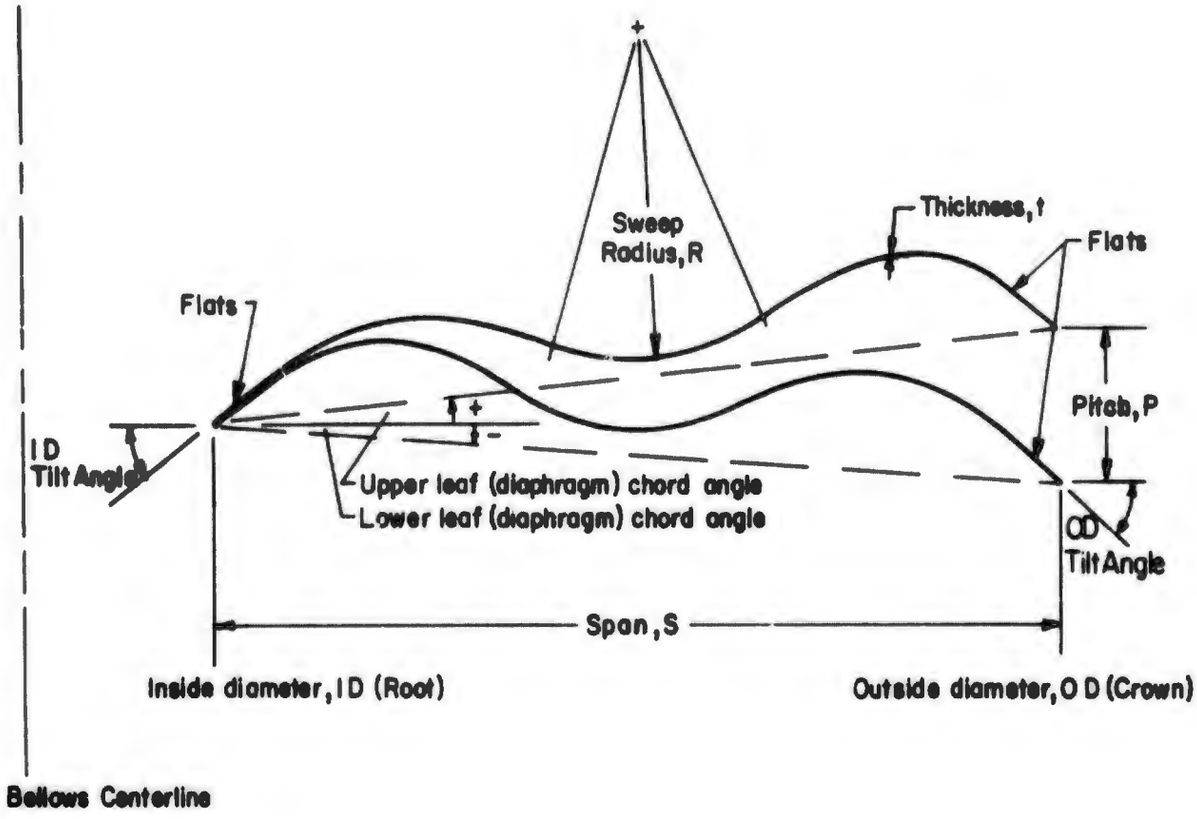

FIGURE 1. CROSS SECTION OF ONE CONVOLUTION OF A TYPICAL TILT-EDGE WELDED BELLOWS

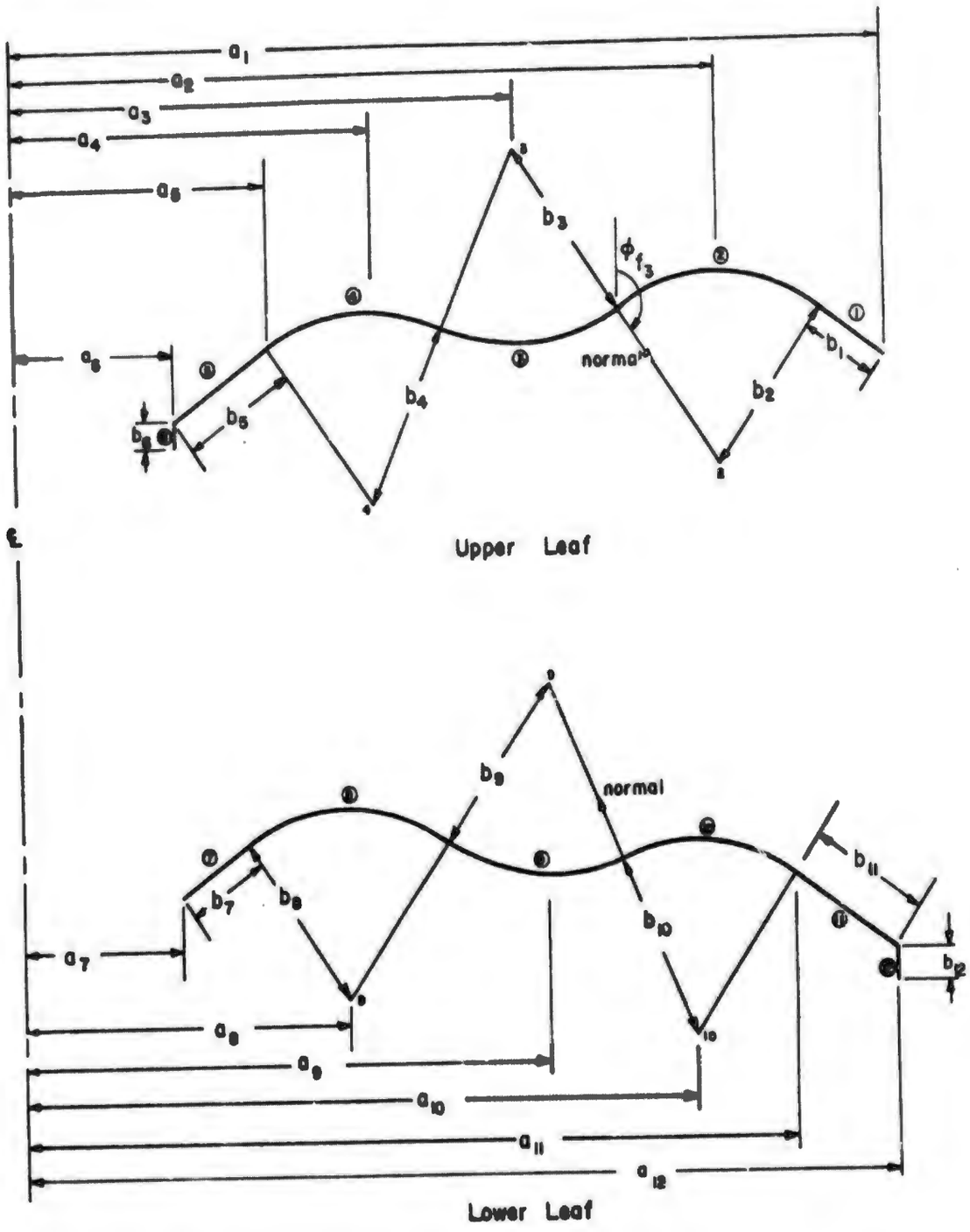

FIGURE 2. CONFIGURATION OF ONE CONVOLUTION OF A TYPICAL TILT-EDGE BELLOWS. NUMBERS IN CIRCLES REFER TO THE PART NUMBERS OF THE MATHEMATICAL MODEL

Figure 3 depicts the typical mathematical model used to represent each bellows studied. The model consisted of four leaves (two convolutions) so that the stresses in the second and third leaves would not be affected by the boundary conditions imposed at the OD of the upper and lower leaves. Cylindrical rings were used to represent the weld beads at both the inner and outer leaf junctions. The lengths of the cylindrical sections were taken equal to the vertical distance between the centerlines of the upper and lower leaves at each weld. Normally, each leaf had three sweeps of equal radius plus conical segments at inside and outside ends of each leaf. In all cases, the bellows models were subjected to both an axial deflection loading and an internal pressure loading; calculations were made using linear, elastic, thin shell theory.

Determination of Optimum Tilt Angles for Tilt-Edge Welded Bellows

As stated earlier, Battelle's previous study of welded bellows demonstrated that tilting the flat sections of the edges of a welded bellows would lead to significant reduction in the stress levels near the root and crown diameter welds. Because of the importance of minimizing the weld stresses to achieve an "optimum" bellows design, the present study began with the investigation of the effects of inside and outside diameter tilt angles on the weld stresses in specific welded bellows shapes.

The previous study of the 4-inch, three-sweep bellows showed that the variations in the tilt angle at either the root or the crown had little effect on the stress distributions elsewhere in the bellows if the tilt angle was more than about 30°. Full use was made of this characteristic in a preliminary study of the effects of tilt angle on the weld stresses. In this preliminary study, models were set up as shown in Figures 4 and 5. These models consisted of the conical sections and parts of the torus sections nearest the root and crown welds. Models with tilt angles from 35° to 60° were analyzed for pressure loads and also for axial deflection loads. Membrane forces (N_1, N_2, N_3, N_4) and bending moments (M_1, M_2, M_3, M_4) taken from the analysis of the 4-inch bellows with 35° tilt angles were applied to the edges of the models. The results of this study combined with the previous analysis involving lower tilt angles are summarized in Figures 6 through 9. These figures show the ratio of the surface stresses at the welds to the maximum surface stress in the convolution (surface stress reduction ratio). The existence of tilt angles giving minimum stress conditions is clearly indicated. Although the angles for minimum stresses in the upper and lower leaves for pressure and deflection loads were not all the same, ID and OD tilt angles greater than 45° gave suitably low stresses.

The surface stresses in Figures 6 through 9 are the sum of the bending stresses and the membrane stresses. It is recalled that the membrane stress is constant through the thickness while the bending stress is antisymmetric about the bellows midsurface. An examination of the Figures shows that the large stresses at smaller tilt angles were almost entirely the result of bending stresses since the inner and outer surface stresses are almost equal in magnitude and of opposite sign.

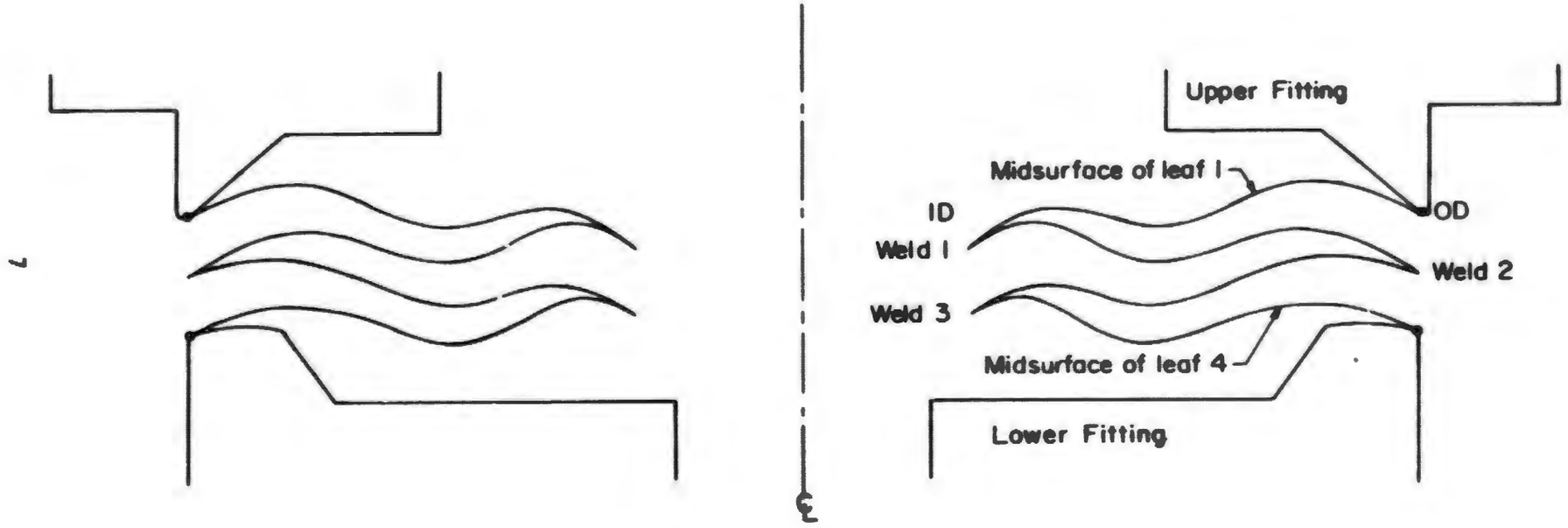

FIGURE 3. TYPICAL MATHEMATICAL MODEL USED IN STUDY OF OPTIMUM TILT-EDGE WELDED BELLOWS

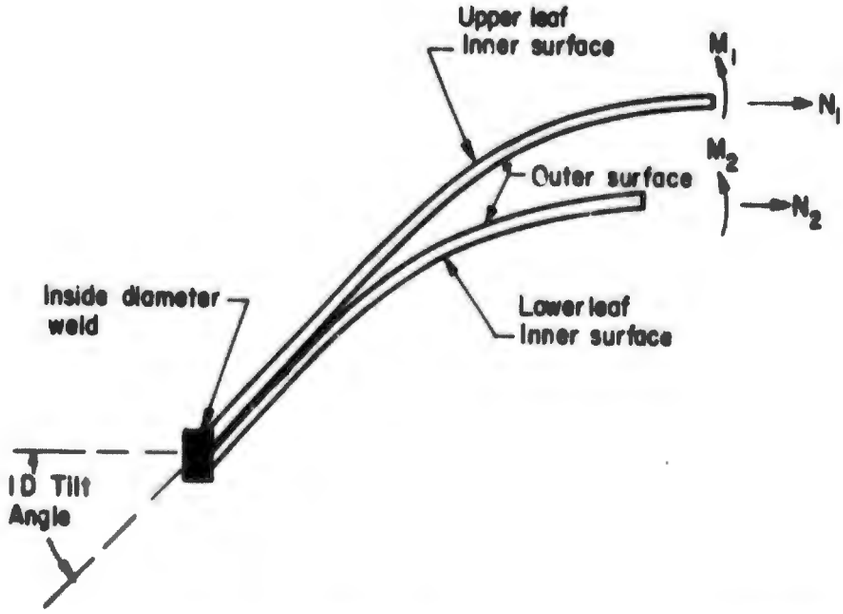

FIGURE 4. MATHEMATICAL MODEL OF INSIDE DIAMETER WELD AREA FOR TILT ANGLE STUDY OF 4-INCH BELLOWS

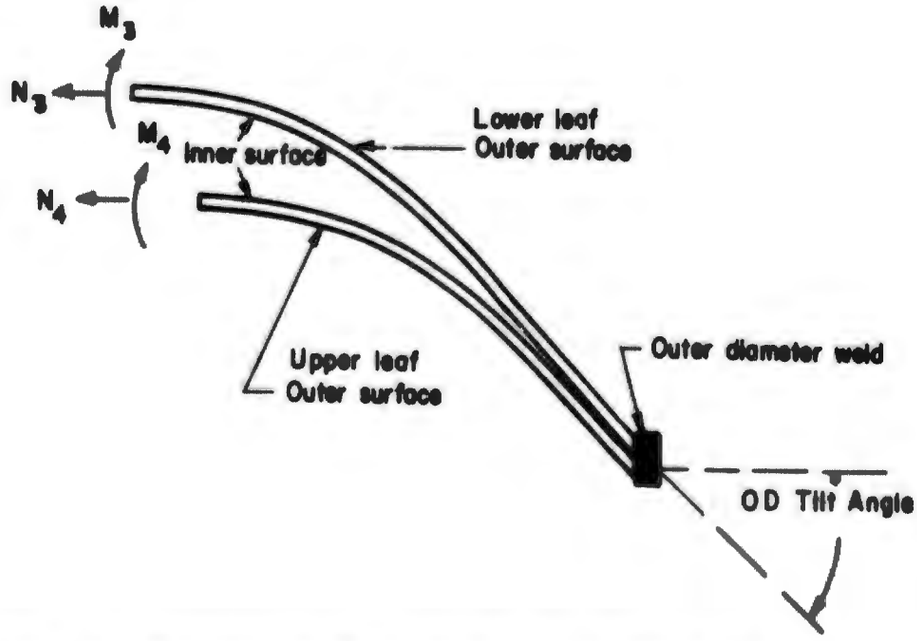

FIGURE 5. MATHEMATICAL MODEL OF OUTSIDE DIAMETER WELD AREA FOR TILT ANGLE STUDY OF 4-INCH BELLOWS

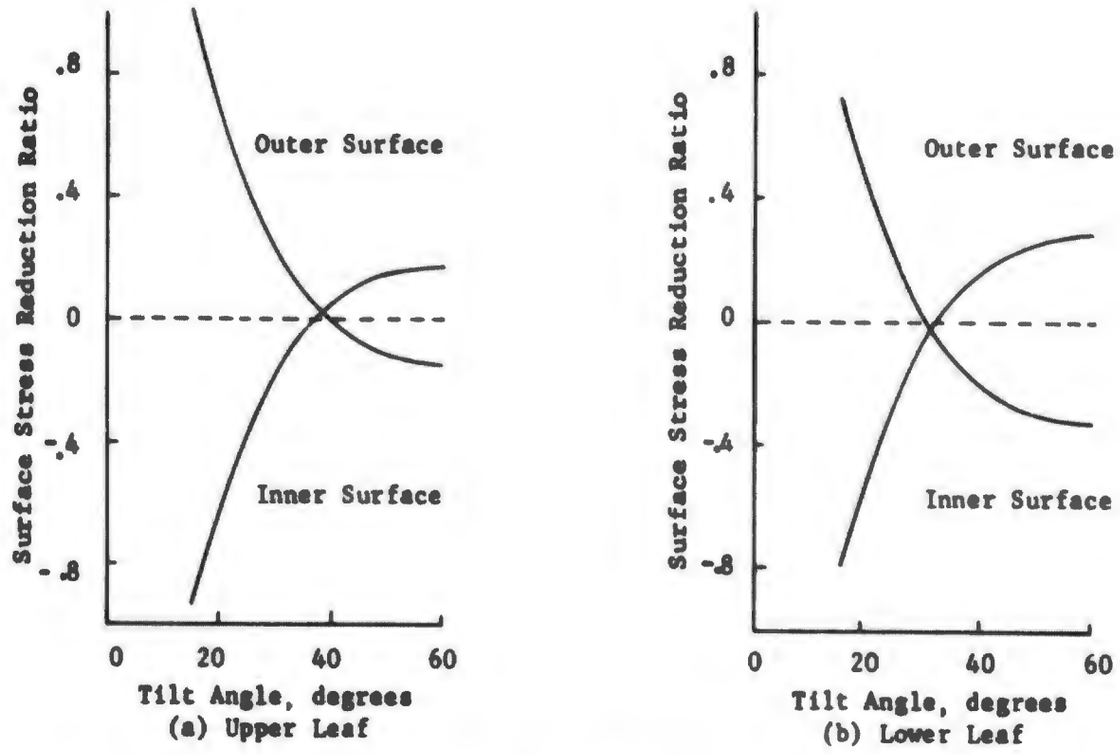

FIGURE 6. INSIDE DIAMETER MERIDIONAL WELD STRESS RATIOS FOR VARIOUS ID TILT ANGLES, 4-INCH WELDED BELLOWS, DEFLECTION LOADING

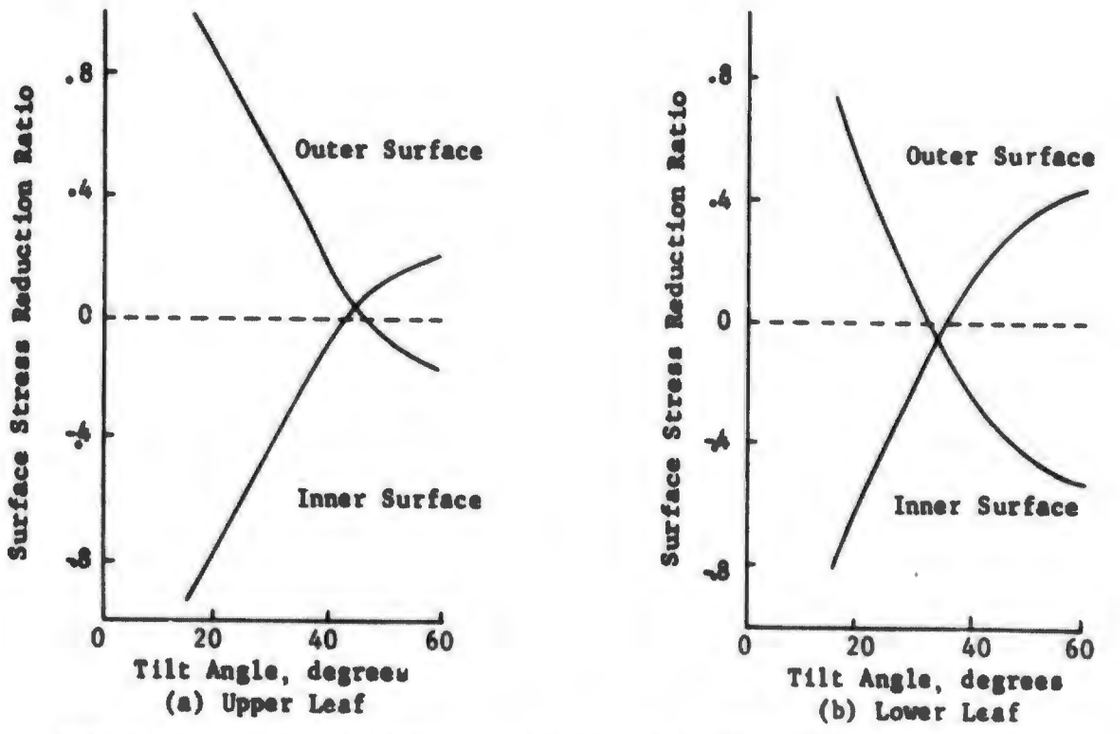

FIGURE 7. INSIDE DIAMETER MERIDIONAL WELD STRESS RATIOS FOR VARIOUS ID TILT ANGLES, 4-INCH WELDED BELLOWS, PRESSURE LOADING

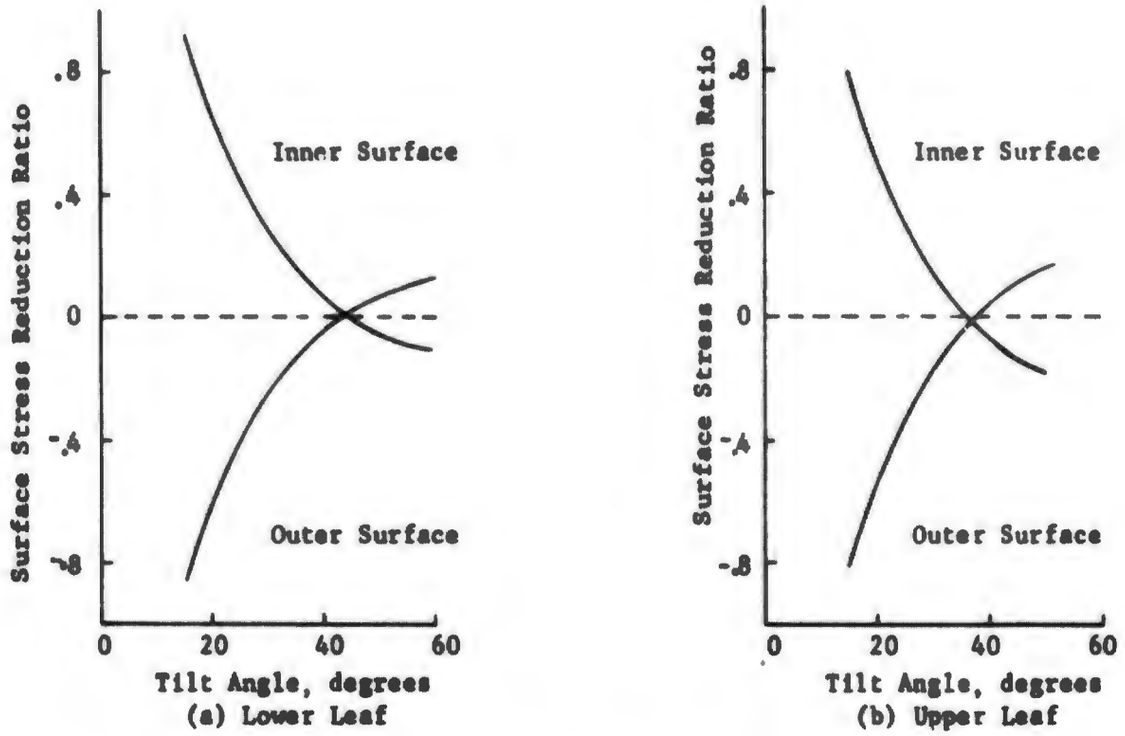

FIGURE 8. OUTSIDE DIAMETER MERIDIONAL WELD STRESS RATIOS FOR VARIOUS OD TILT ANGLES, 4-INCH WELDED BELLOWS, DEFLECTION LOADING

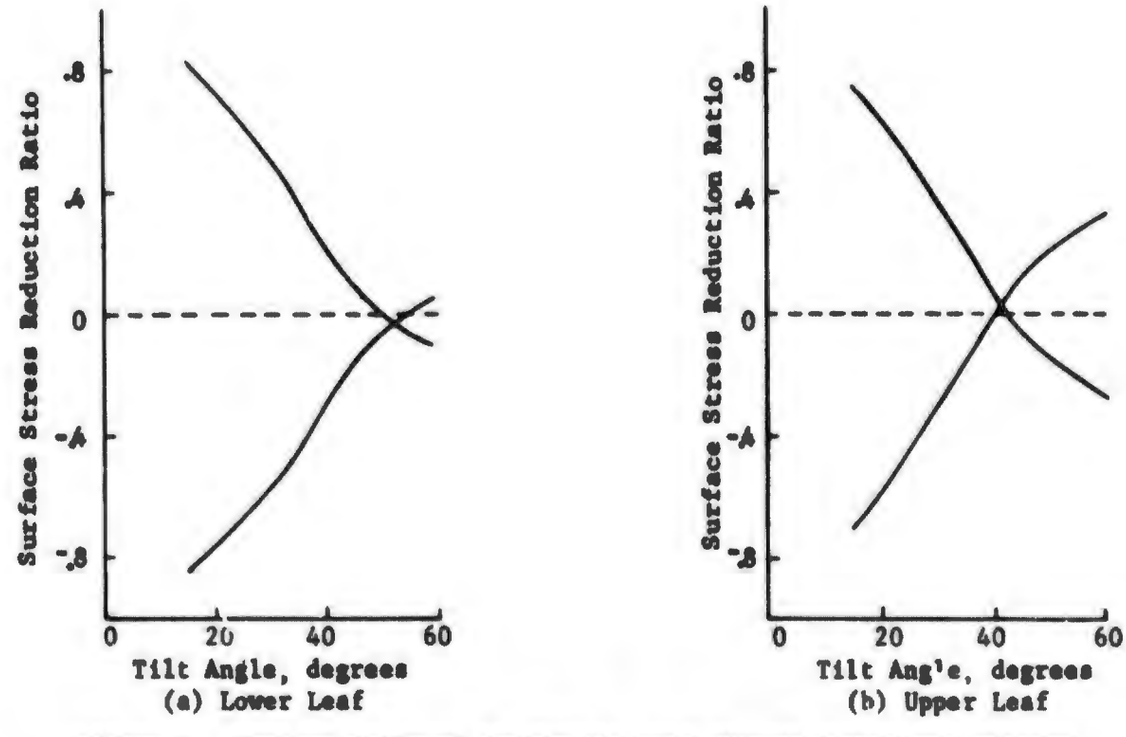

FIGURE 9. OUTSIDE DIAMETER MERIDIONAL WELD STRESS RATIOS FOR VARIOUS OD TILT ANGLES, 4-INCH WELDED BELLOWS, PRESSURE LOADING

The point at which the inner and outer stress curves cross is the point of zero bending stress. It is clear that this is the optimum tilt angle for the particular loading condition. Although the stresses for the conventional bellows with zero tilt angles are not shown, it was determined that stresses for these bellows were predominantly bending stresses. Thus the effect of increasing tilt angles was to reduce the bending stresses at the weld. At the optimum tilt angle the bending stresses were eliminated and the load was transferred from one leaf to the next by membrane action only.

At the higher tilt angles, the crossover in the sign of the surface stresses indicated a reversal in the bending moment. These reversed bending moments tended to bend the leaves toward each other. Since the leaves were already in contact along the flats, this reversed bending was suppressed and the stresses at the welds were thereby considerably reduced. If leaf contact was not accounted for in the theory, the predicted weld stresses were always conservative. Because of this, no attempt was made to account for the effects of the leaf interference at the welds except in the final design.

In further studies of the tilt angle effects, computer analyses were carried out for models of 2-inch and 3-inch bellows with various tilt angles. These studies used models having two complete bellows convolutions as shown in Figure 3. Table 1 lists the dimensions of a 2-inch bellows with 40° ID and 45° OD tilt angles. Table 2 lists the dimension of a corresponding 3-inch bellows with 45° ID and 50° OD tilt angles.* Analyses were made of other bellows identical to these except for the tilt angles and the lengths of the conical sections. Items indicated by asterisks in the tables must be changed to change the tilt angle. In each case the length of the conical section was chosen to give the same OD and ID as the bellows shown in Tables 1 and 2.

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*Tables 1 and 2 list bellows dimensions in the format used for input into computer program NONLIN. The columns with heading "Outer Normal" give the angle between the outer normal and the upward bellows axis. These angles are measured at the initial and final ends of the bellows part when going in the direction of integration taken in NONLIN. This direction is from OD to ID on the upper leaf and from ID to OD on the lower leaf. For conical and cylindrical parts, the outer normal has constant direction. Thus, the final angle is not needed. The columns headed "a" and "b" list values of the radial dimensions a_i drawn in Figure 2 for the shell parts. As indicated earlier, negative values of b_2, b_4, and b_9 mean that the outer normal points toward the center of curvature of these toroidal shell sections.

TABLE 1. DIMENSIONS OF ONE CONVOLUTION OF MATHEMATICAL MODEL OF A 2-INCH TILT-EDGE WELDED BELLOWS, SPAN = 0.3536 INCH, THICKNESS = 0.005 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
		Upper Leaf			
1	Conical	225*	--	1.04480	.02974*
2	Toroidal	225*	145	.96165	-.08785
3	Toroidal	145	205	.86085	.08785
4	Toroidal	205	140*	.78665	-.08785
5	Conical	140*	--	.73020*	.05088*
		ID Weld Bead			
6	Cylindrical	90	--	.69120	.00652*
		Lower Leaf			
7	Conical	-40*	--	.69120	.03360*
8	Toroidal	-40*	35	.77335	.08785
9	Toroidal	35	-25	.87415	-.08785
10	Toroidal	-25	45*	.94835	.08785
11	Conical	45*	--	1.0147*	.04850*
		OD Weld Bead			
12	Cylindrical	90	--	1.04480	0.00707*

* These dimensions vary as the tilt angles at the inside and outside diameters are changed.

TABLE 2. DIMENSIONS OF ONE CONVOLUTION OF MATHEMATICAL MODEL OF A 3-INCH, TILT-EDGE WELDED BELLOWS, SPAN = 0.5304 INCH, THICKNESS = 0.005 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
		Upper Leaf			
1	Conical	230*	--	1.56720	.03697*
2	Toroidal	230*	145	1.44247	-.13177
3	Toroidal	145	205	1.29127	.13177
4	Toroidal	205	135*	1.7997	-.13177
5	Conical	135*	--	1.08679*	.07070*
		ID Weld Bead			
6	Cylindrical	90	--	1.03680	.00707*
		Lower Leaf			
7	Conical	-45	--	1.03680	.04252*
8	Toroidal	-45*	35	1.16002	.13177
9	Toroidal	35	-25	1.31122	-.13177
10	Toroidal	-25	50*	1.42252	.13177
11	Conical	50*	--	1.52347*	.06802*
		OD Weld Bead			
12	Cylindrical	90	--	1.56720	.00778*

* These dimensions vary as the tilt angles at the inside and outside diameters are changed.

Tables 3 through 6 list calculated meridional and circumferential surface stresses on the upper and lower bellows leaves at the welds for 2-inch bellows with different tilt angles. Tables 7 through 10 list similar stresses for 3-inch bellows. The stresses due to axial loading are given for an assumed unit compression per unit length of bellows (i.e., 1-inch deflection for a 1-inch long bellows). Pressure stresses are given for a 1 psi pressure load. For comparison, the range of maximum bellows stresses for each particular load condition is listed under each table. This maximum stress always occurred on one of the bellows sweeps.

Tables 3 and 5 show a minimum deflection stress at the welds of the 2-inch bellows for ID tilt angles between 45° and 50° and for OD tilt angles between 50° and 55°. In contrast, the pressure stresses tended to decline slightly even at the highest calculated tilt angles.

A study of Tables 7 through 10 indicates that the optimum ID tilt angle was 45° and the optimum OD tilt angle was 50° for the 3-inch bellows. A comparison of the tabulated weld stresses with the maximum bellows stress listed under each table shows that significant reduction of the weld stresses was achieved at each optimized tilt angle for both loading conditions.

From the results of this study, it was determined that optimum tilt angles could be found that gave significant reduction in weld stresses for both pressure loads and axial deflection loads. In fact, the weld stress reductions are of sufficient magnitude that complete prevention of weld failures could be expected in bellows made with the optimum tilt angles.

Effects of Variations in Span

In general, increasing the span of a conventional welded bellows decreases the axial deflection stresses and increases the stresses due to pressure loading. These effects on the stress levels are well known to the manufacturers and designers of such bellows. Such knowledge is often applied whenever a designer wishes to increase the deflection capability of a given bellows for which low design pressures are specified.

To study the effect of changing span for the tilt-edge welded bellows, a 3.5-inch mathematical model with a span of 0.6188 inch was analyzed. The results from this analysis were compared with results obtained for a 3.5-inch bellows with a span length of 0.378 inch. The tilt angles at the ID and OD for both sizes were 45° and 50°, respectively. The upper and lower leaf chord angles were +5° and -5°, respectively, for both bellows. The sweep radii and the pitch for the bellows with 0.6188 inch span were slightly larger than for the second bellows. Stresses were compared for both internal pressure and for axial deflection loadings.

Figures 10 through 13 are computer machine plots of the outer surface meridional stresses for the upper and lower leaves of the two bellows models. Because of the somewhat unconventional nature of the plots, they will be explained in some detail here. It is noted that this same format will be used throughout the remainder of this report for plotting the stress distributions.

TABLE 3. MAXIMUM INSIDE DIAMETER WELD STRESSES IN A 2-INCH, TILT-EDGE WELDED BELLOWS, UNIT AXIAL COMPRESSION PER UNIT BELLOWS LENGTH

ID Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
40	Upper Leaf	51,500	-59,500	20,600	-6,800
40	Lower Leaf	29,700	-21,600	30,800	8,900
45	Upper Leaf	31,000	-38,800	19,200	3,700
45	Lower Leaf	16,800	-8,800	27,600	14,400
50	Upper Leaf	34,200	-42,200	26,200	9,300
50	Lower Leaf	3,800	4,800	38,400	32,500

Maximum bellows stress for all cases was between 156,000 and 175,000 psi.

TABLE 4. MAXIMUM INSIDE DIAMETER WELD STRESSES IN A 2-INCH, TILT-EDGE WELDED BELLOWS, INTERNAL PRESSURE OF 1 PSI

ID Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
40	Upper Leaf	690	-820	440	40
40	Lower Leaf	440	-310	520	230
45	Upper Leaf	440	-570	380	120
45	Lower Leaf	300	-180	450	260
50	Upper Leaf	400	-520	390	150
50	Lower Leaf	120	-4	460	370

Maximum bellows stress for all cases was -1030 psi.

TABLE 5. MAXIMUM OUTSIDE DIAMETER WELD STRESSES IN A 2-INCH, TILT-EDGE WELDED BELLOWS, UNIT AXIAL COMPRESSION PER UNIT BELLOWS LENGTH

OD Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
45	Upper Leaf	-25,800	30,700	-19,800	-6,700
45	Lower Leaf	-50,700	45,900	-23,600	8,900
50	Upper Leaf	-16,300	27,200	-19,200	-11,300
50	Lower Leaf	-36,400	31,600	-23,200	400
55	Upper Leaf	-8,200	13,500	-28,600	-26,000
55	Lower Leaf	-40,900	35,900	-30,500	-3,800

Maximum bellows stress for all cases was between 156,000 and 175,000 psi.

TABLE 6. MAXIMUM OUTSIDE DIAMETER WELD STRESS IN A 2-INCH, TILT-EDGE WELDED BELLOWS, INTERNAL PRESSURE OF 1 PSI

OD Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
45	Upper Leaf	370	-460	390	180
45	Lower Leaf	700	-620	460	30
50	Upper Leaf	270	-360	360	200
50	Lower Leaf	530	-450	420	100
55	Upper Leaf	150	-230	370	290
55	Lower Leaf	500	-420	420	120

Maximum bellows stress for all cases was -1030 psi.

TABLE 7. MAXIMUM INSIDE DIAMETER WELD STRESSES IN A 3-INCH, TILT-EDGE WELDED BELLOWS, UNIT AXIAL COMPRESSION PER UNIT BELLOWS LENGTH

ID Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
35	Upper Leaf	22,600	-28,300	11,600	-200
35	Lower Leaf	7,900	-2,100	15,900	9,300
40	Upper Leaf	10,300	-15,600	10,800	6,200
40	Lower Leaf	-4,600	10,000	14,900	16,100
45	Upper Leaf	1,400	-6,200	10,700	11,300
45	Lower Leaf	-14,000	18,900	14,600	21,700

Maximum bellows stress for all cases was -119,000 psi.

TABLE 8. MAXIMUM INSIDE DIAMETER WELD STRESSES IN A 3-INCH, TILT-EDGE WELDED BELLOWS, INTERNAL PRESSURE OF 1 PSI

ID Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
35	Upper Leaf	950	1,170	640	80
35	Lower Leaf	490	260	700	390
40	Upper Leaf	570	-780	560	220
40	Lower Leaf	105	110	600	530
45	Upper Leaf	280	-480	500	330
45	Lower Leaf	-190	390	530	650

Maximum bellows stress for all cases was -1790 psi.

TABLE 9. MAXIMUM OUTSIDE DIAMETER WELD STRESSES IN A 3-INCH TILT-EDGE WELDED BELLOWS, UNIT AXIAL COMPRESSION PER UNIT BELLOWS LENGTH

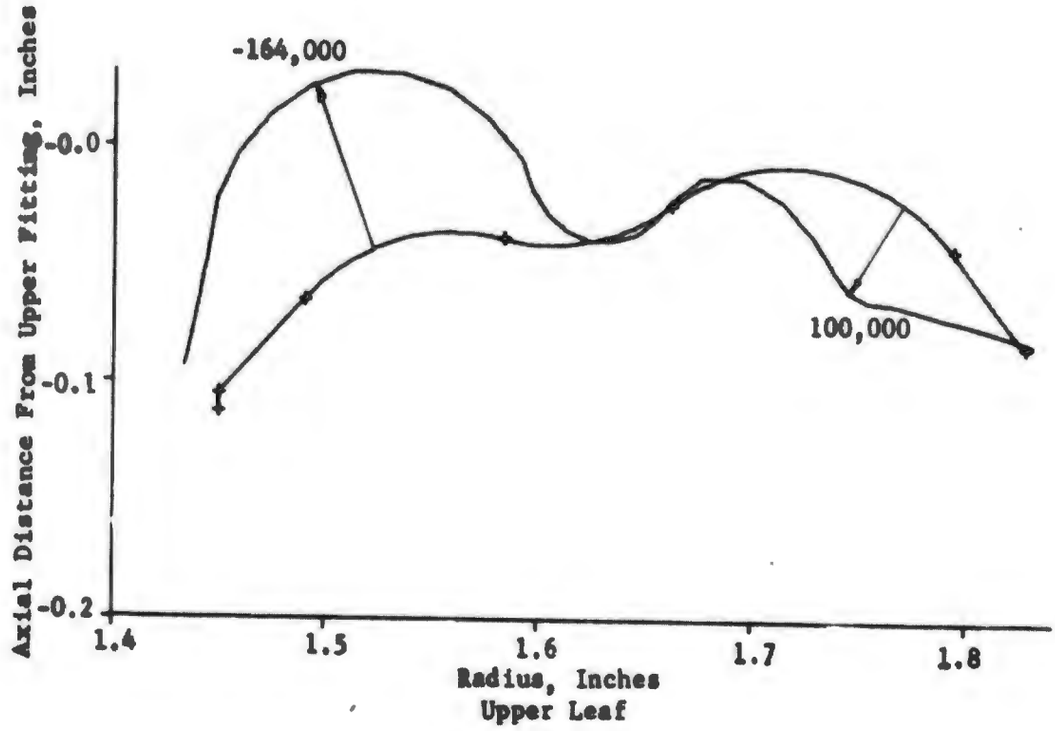
OD Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
40	Upper Leaf	-22,900	19,400	-13,400	1,400
40	Lower Leaf	-5,800	9,400	-9,800	-7,400
45	Upper Leaf	-14,300	11,000	-13,300	-3,700
45	Lower Leaf	2,900	500	-10,100	-12,800
50	Upper Leaf	-7,300	4,300	-13,300	-8,000
50	Lower Leaf	10,100	-7,000	-10,600	-17,600
60	Upper Leaf	700	-3,200	-15,000	-14,700
60	Lower Leaf	18,900	-16,400	-13,800	-25,800

Maximum bellows stress for all cases was -119,000 psi.

TABLE 10. MAXIMUM OUTSIDE DIAMETER WELD STRESSES IN A 3-INCH, TILT-EDGE WELDED BELLOWS, INTERNAL PRESSURE OF 1 PSI

ID Tilt Angle, degrees		Meridional Stress, psi		Circumferential Stress, psi	
		Inner	Outer	Inner	Outer
40	Upper Leaf	950	-800	650	80
40	Lower Leaf	360	-510	500	290
45	Upper Leaf	680	-540	590	190
45	Lower Leaf	100	-240	460	400
50	Upper Leaf	470	-340	560	280
50	Lower Leaf	-110	-210	430	500
60	Upper Leaf	190	-70	550	450
60	Lower Leaf	-410	290	460	690

Maximum bellows stress for all cases was -1790 psi.



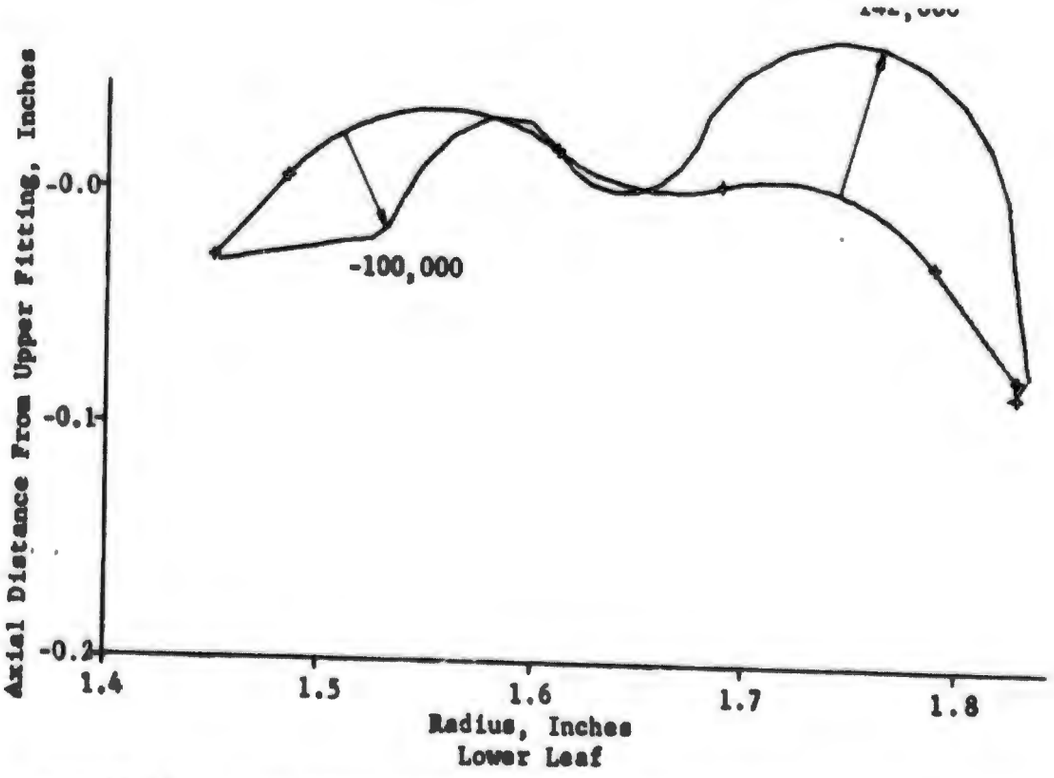
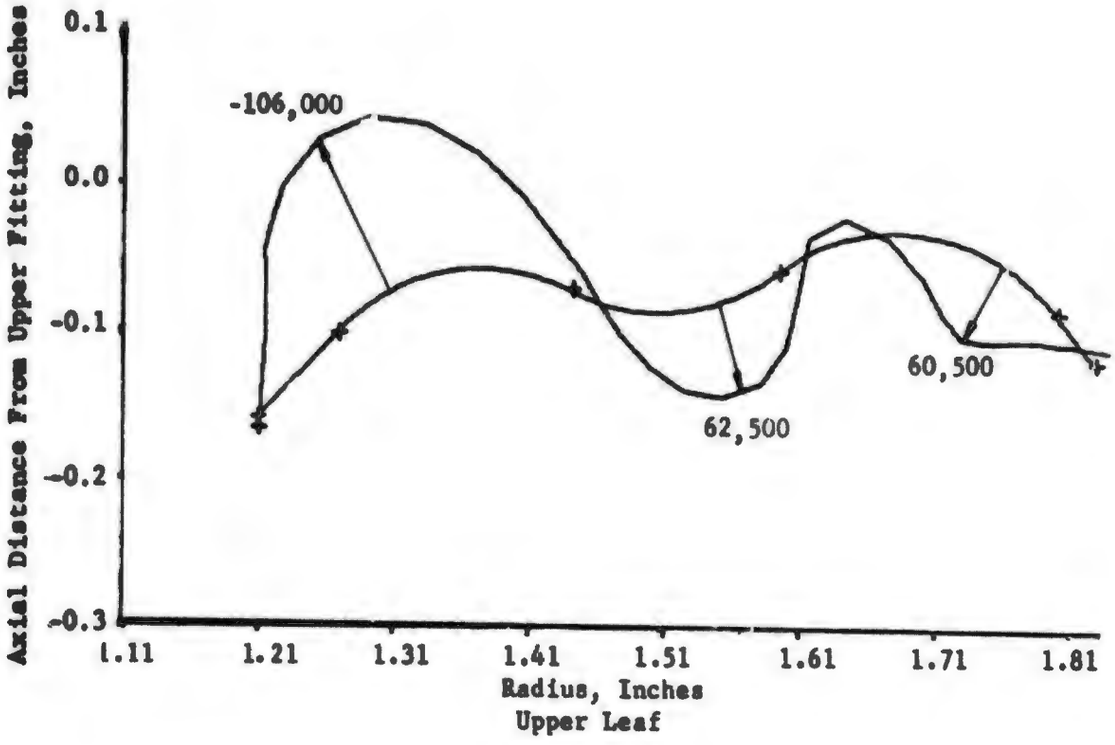


FIGURE 10. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3.5-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.10-INCH SWEEP RADII AND 0.378-INCH SPAN (Unit Deflection Per Unit Bellows Length)



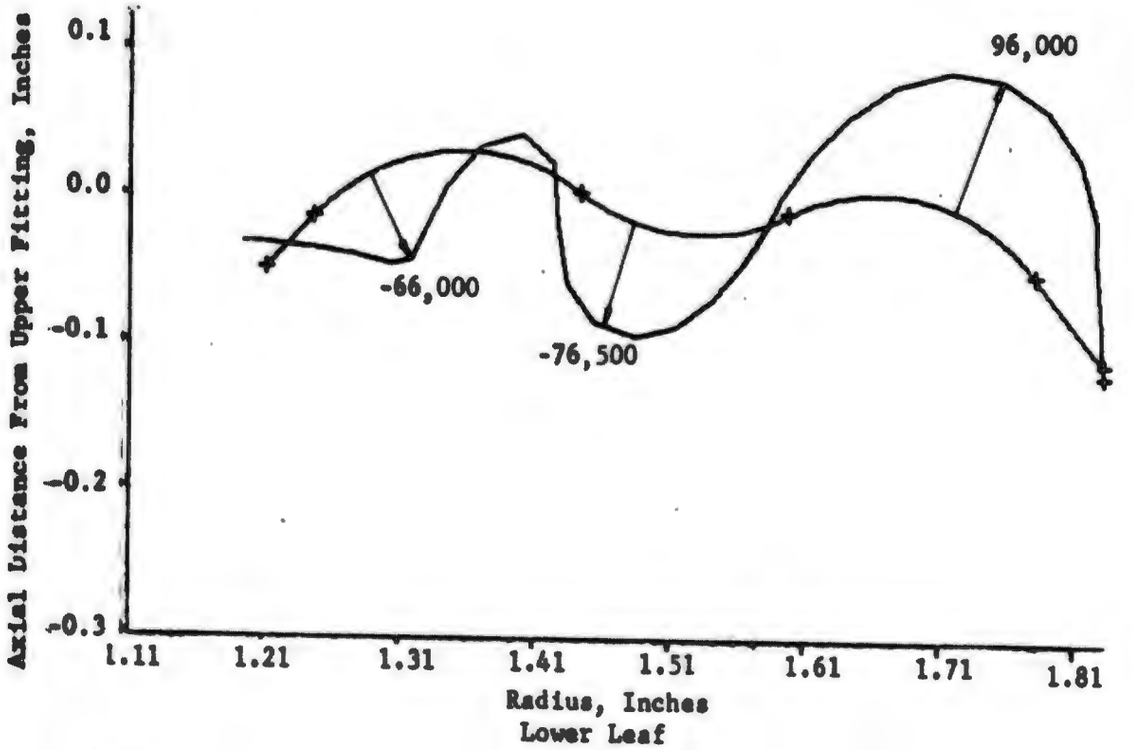
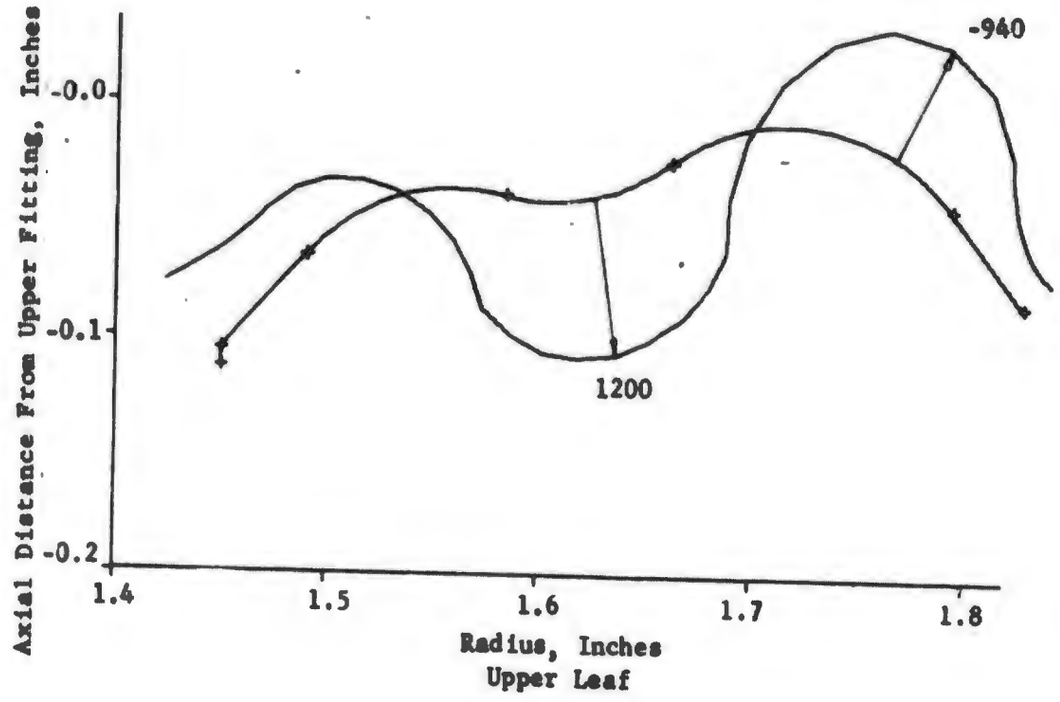


FIGURE 11. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3.5-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.15373-INCH SWEEP RADII AND 0.6188-INCH SPAN (Unit Deflection Per Unit Bellows Length)



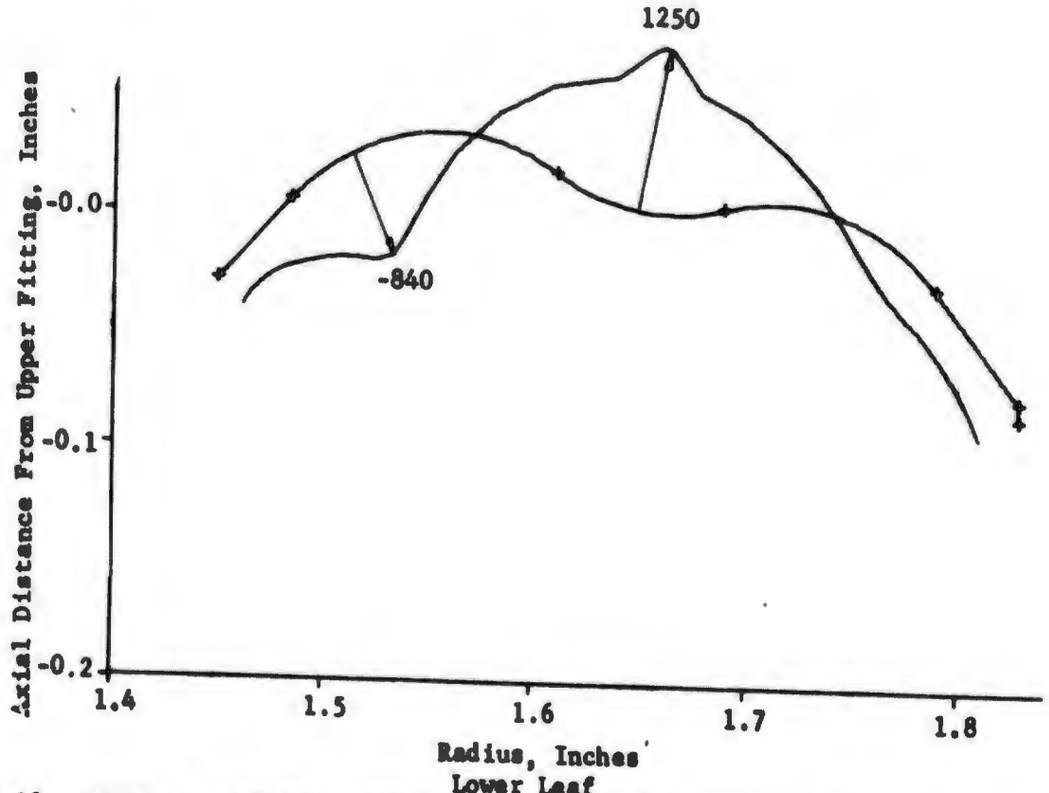
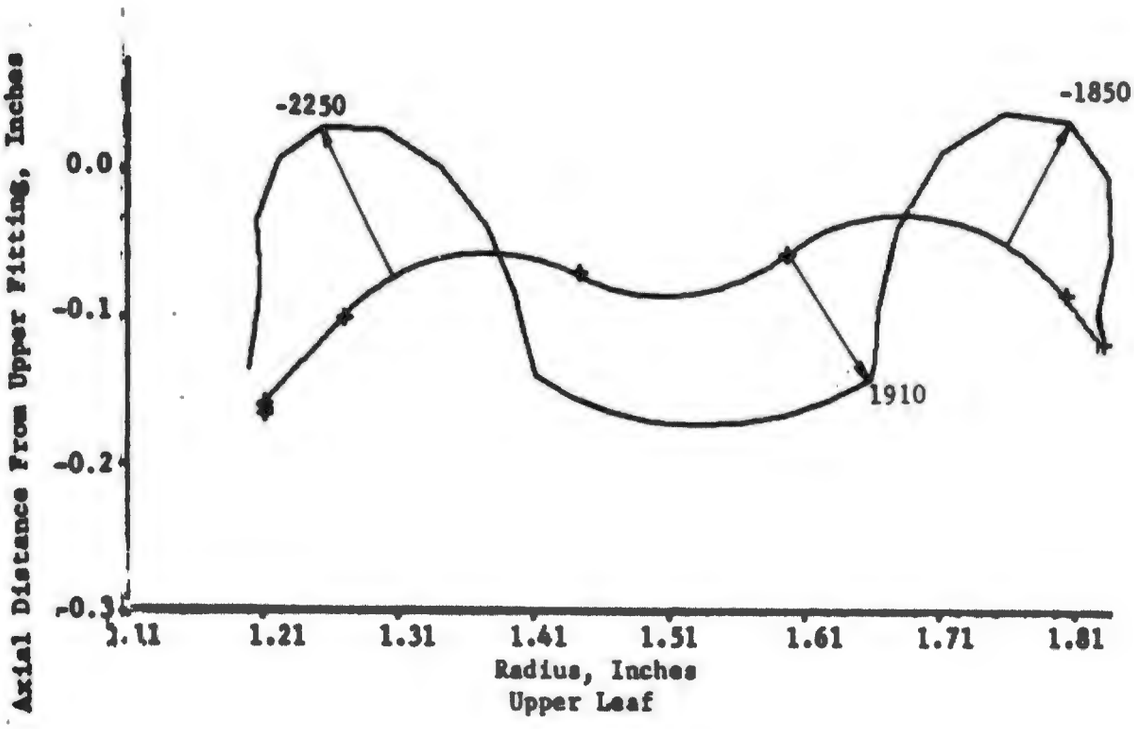


FIGURE 12. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3.5-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.10-INCH SWEEP RADII AND 0.378-INCH SPAN (Pressure = 1 psi)



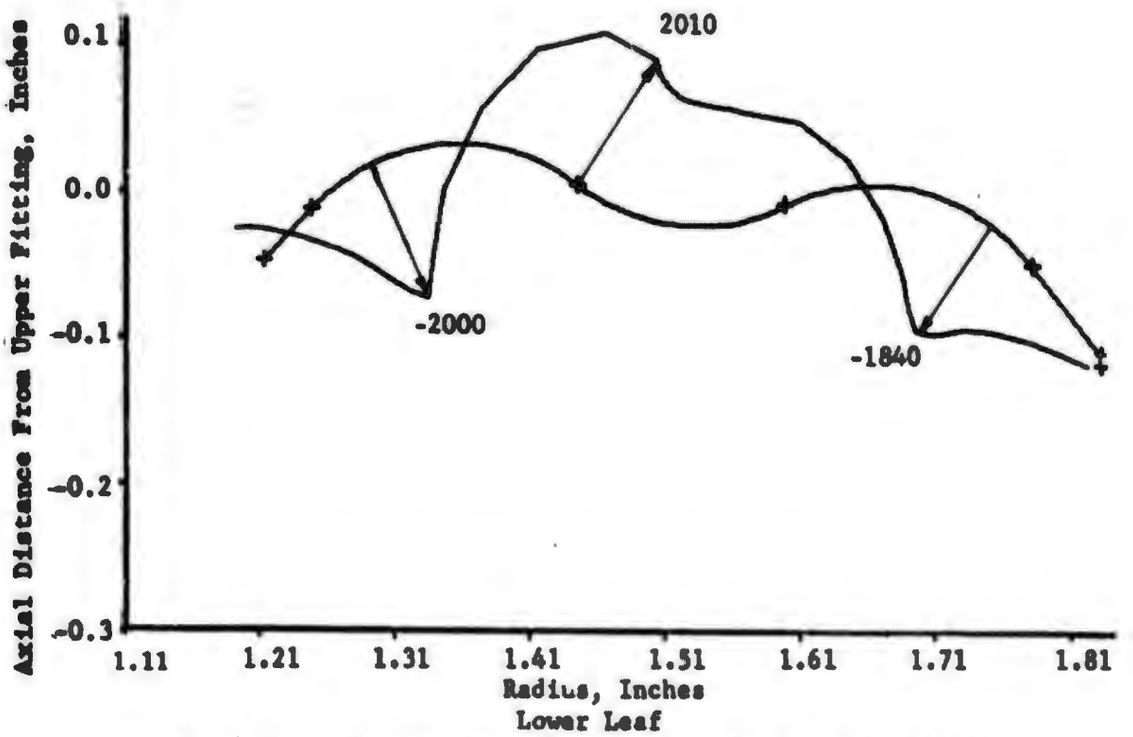


FIGURE 13. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3.5-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.15373-INCH SWEEP RADII AND 0.6188-INCH SPAN (Pressure = 1 psi)

The figures show stress curves overlaid on curves showing the midsurface shape of the bellows leaves. Crosses were plotted on the bellows leaf curves to show the points of intersection of adjacent shell parts. These crosses serve to show the number and placement of the shell parts used in the mathematical model. The crosses also are an aid in identifying which of the curves is the bellows leaf.

The curves showing the stresses were plotted in terms of the distance from the shell midsurface. The length along the normal drawn from a point on the bellows midsurface to the stress curve is proportional to the stress at that point of the midsurface. Positive stresses were drawn in the direction of the outer normal. Negative stresses were drawn in the direction of the inner normal. As mentioned previously, the outer normal points downward for the upper leaf and upward for the lower leaf.

The scale used in plotting the stresses was automatically calculated by the computing program so that the length depicting the maximum stress on the curve was less than the local radii of curvature. This permitted the stresses to be plotted as smooth curves. Because of this, the scale factors used to plot the curves turned out to be quite arbitrary. Instead of showing these scale factors, it was decided to show values of stress maxima. These maxima were typed on the figures for each stress curve.

The ordinate in the figures shows the axial distance in inches of the points of the bellows leaves from the upper end fitting of the two convolution mathematical model (Figure 3). As mentioned earlier, the center two leaves shown in Figure 3 were chosen for studying the stresses in typical bellows convolutions. Thus, according to the definition adopted in this report, leaf 3 of the mathematical model was chosen as the upper leaf on which stresses are given. The corresponding lower leaf was chosen as leaf 2 in Figure 3. Because of this choice of leaves, the axial coordinate for the "upper leaf" (leaf 3) in Figures 10 through 13 indicate that it was actually below the "lower leaf" (leaf 2) in the mathematical model.

The stress plots in Figures 10 through 13 show that the bellows with the longer span had lower maximum stresses than the shorter span bellows for the same relative axial compression and higher stresses for the same internal pressures. Thus, changes in span have the same effect on maximum stresses in tilt-edge bellows as in the conventional bellows. This result should help in the design of tilt-edge bellows since bellows designers can use the span to tailor the characteristics of tilt-edge bellows in the way that they have always used the span for design of conventional bellows.

Investigation of Sweep Radius Variation

An investigation of the effects of sweep radius variation was conducted for the 3-inch, and 3.5-inch, three-sweep bellows. For the 3-inch bellows with a 0.5304-inch span, sweep radii of 0.1186-, 0.1318-, and 0.146-inches were assumed. ID and OD tilt angles were 45° and 50°, respectively. For the 3.5-inch bellows with a span of 0.378 inch, sweep radii were 0.07 and 0.10 inches. Two 3.5-inch bellows models were analyzed for each sweep radius. One bellows had equal ID and OD tilt angles of 55°. The second bellows had equal tilt angles of 60°. All bellows had $\pm 5^\circ$ chord angles.

It can be seen from the above dimensions that the 3-inch bellows had sweep radius to span ratios of about 0.22, 0.25, and 0.27 while the sweep radius to span ratios of the 3.5-inch bellows were 0.19 and 0.27. Thus, the relative degrees of flatness of the sweep sections of the two sets of bellows were comparable. (However, the overall curvature of the convolutions for the 3.5-inch bellows was greater than that of the 3-inch bellows because of the larger tilt angles.) Solutions for all geometries were obtained for both axial deflection and pressure loadings.

Figures 14 through 17 show the outer surface, meridional stress distributions in the upper and lower leaves of the 3-inch bellows with sweep radii of 0.1186- and 0.146-inches. Results for the 60° tilt-angle models of the 3.5-inch bellows are presented in Figures 18 through 21. Very similar results were obtained for the 55° tilt-angle models. Note again that the stresses were plotted to different scales automatically chosen by the computer program. Numerical values of stresses at given locations were typed on the figures for reference. Tables 11 and 12 give the values of the maximum relative meridional stresses found at the inner and outer surfaces of the upper and lower leaves for all of the geometries and loadings considered in the study of the sweep radius variation.

Examination of the stress plots presented for the 3-inch bellows indicates that the general shape of the stress variation over the upper and lower leaves remained essentially unchanged. The stress values increased with increase in sweep radius in some locations and decreased with increase in sweep radius in other locations. The main trend occurred in the stress levels in the center sweeps of the upper and lower leaves. As the radii were increased, the stress levels increased for pressure loading and decreased for axial deflection loading. However, the values in Table 11, together with the stress distribution plots, indicate that although the convolution stress levels did not vary with sweep radius in a consistent manner at every point within the convolution, the overall maximum stress in the meridional direction for the axial deflection case remained relatively constant in both magnitude and location even though the sweep radius was increased twenty-two percent. For internal pressure loading, the location of the maximum stress changed, but its absolute magnitude varied less than six percent.

In contrast with the results obtained for the 3-inch, three-sweep bellows, Figures 18 through 21 and Table 12 demonstrate that the maximum stress levels in the sweeps of the 3.5-inch bellows increased with increase in the sweep radius for both axial deflection and pressure loadings. Quantitatively, the forty-three percent increase in sweep radius produced an eleven percent increase in the maximum meridional stress for pressure loading and a twenty percent increase for axial deflection loading.

A comparison of Figures 16 and 17 with Figures 20 and 21 shows much the same change in the pressure stress as the sweep radius was increased and the midsections of the bellows leaves became flatter. The bending stresses in the middle sweeps increased to the point that they became the largest stresses. Thus, for pressure loading the optimum sweep radii lay between 20 and 25 percent of the span for all of the bellows studied.

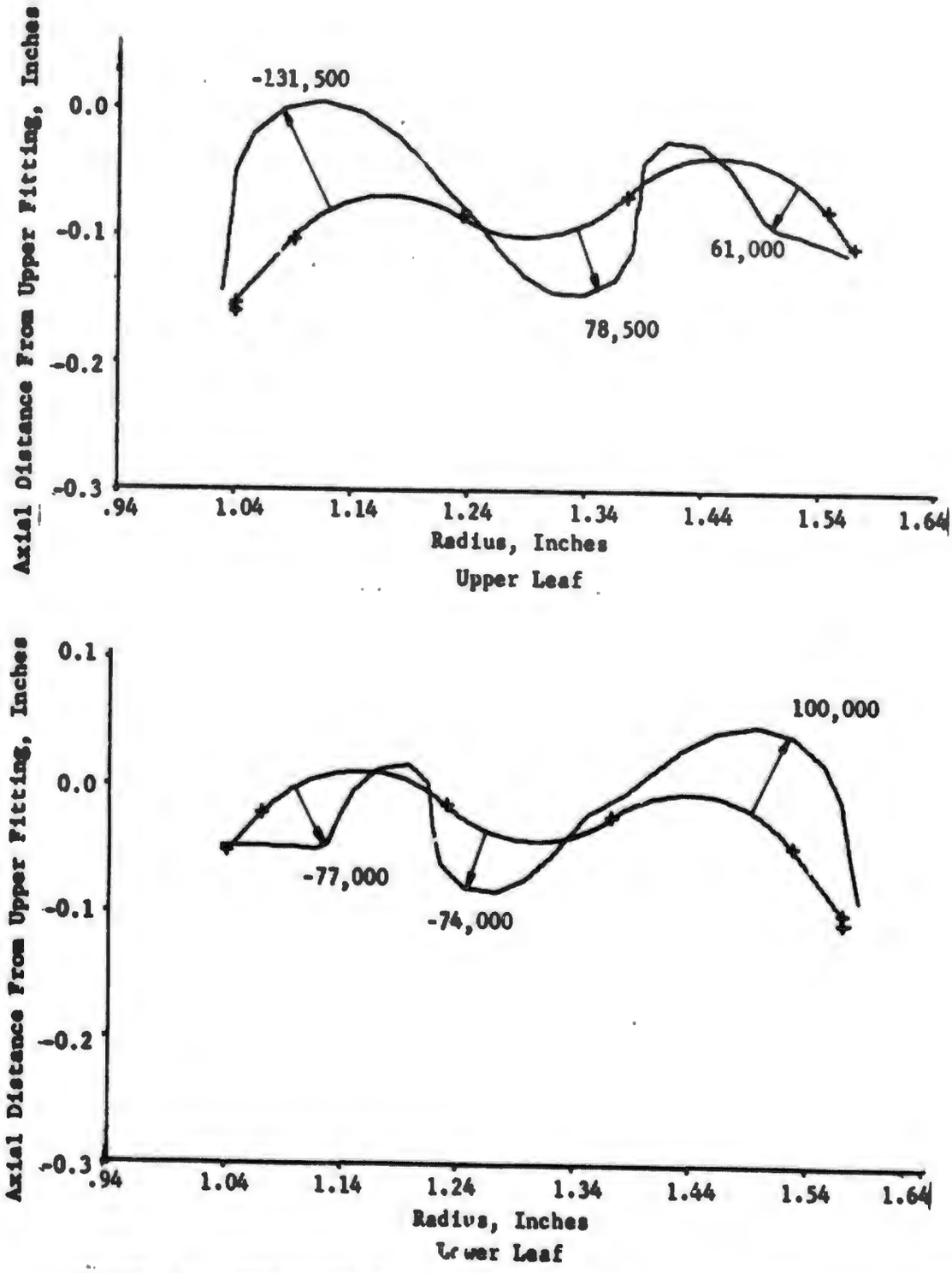
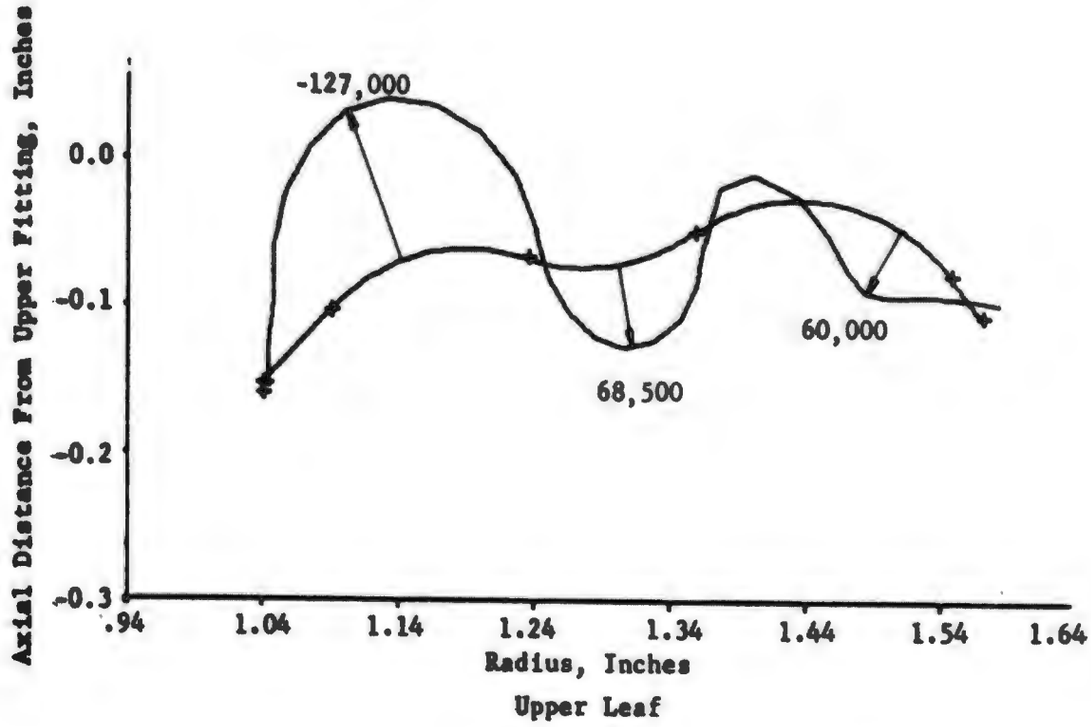


FIGURE 14. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.11859 SWEEP RADII, AND 0.5304-INCH SPAN (Unit Deflection Per Unit Bellows Length)



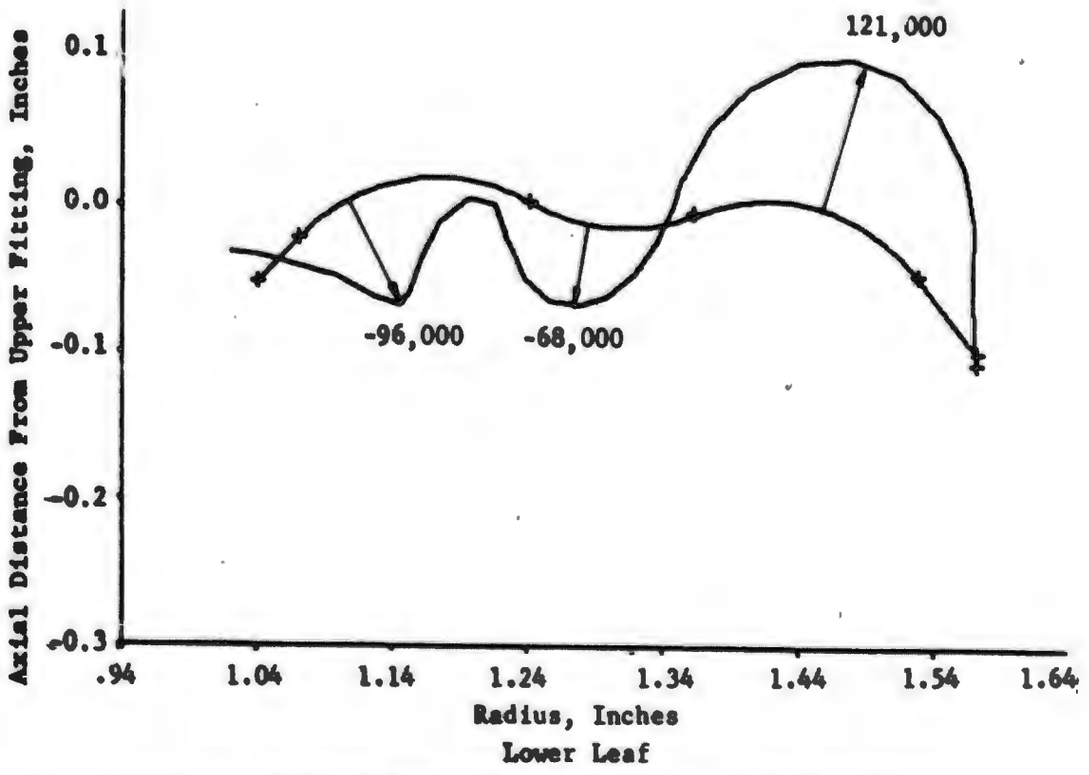
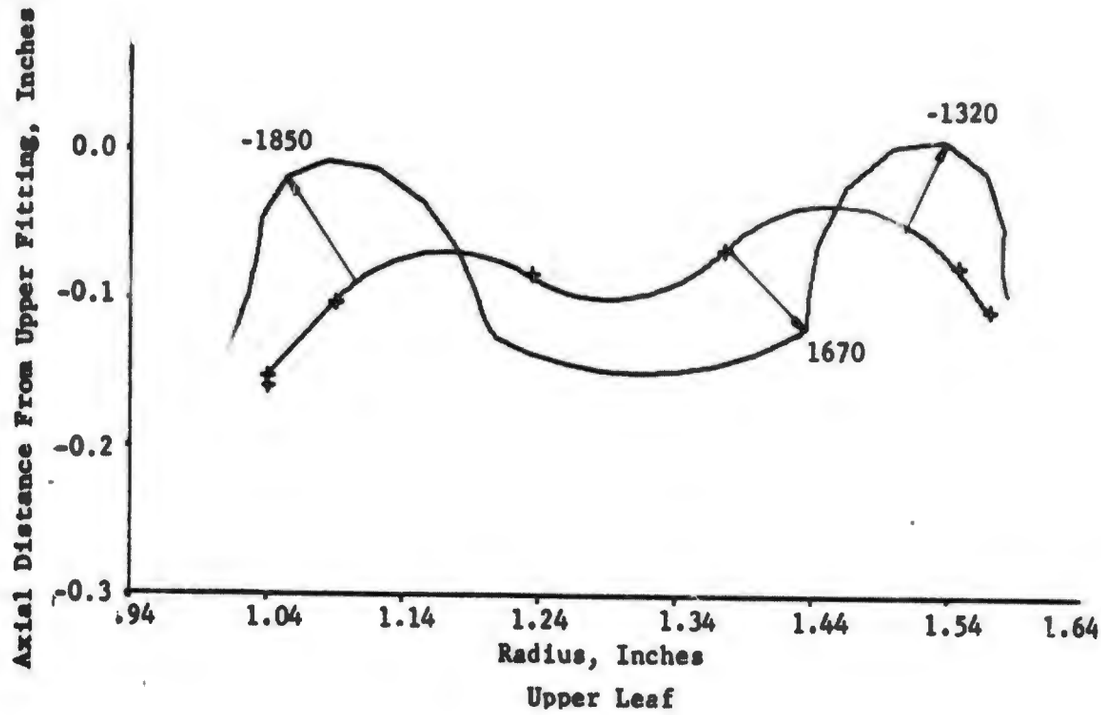


FIGURE 15. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES 0.14495-INCH SWEEP RADII AND 0.5304-INCH SPAN (Unit Deflection Per Unit Bellows Length)



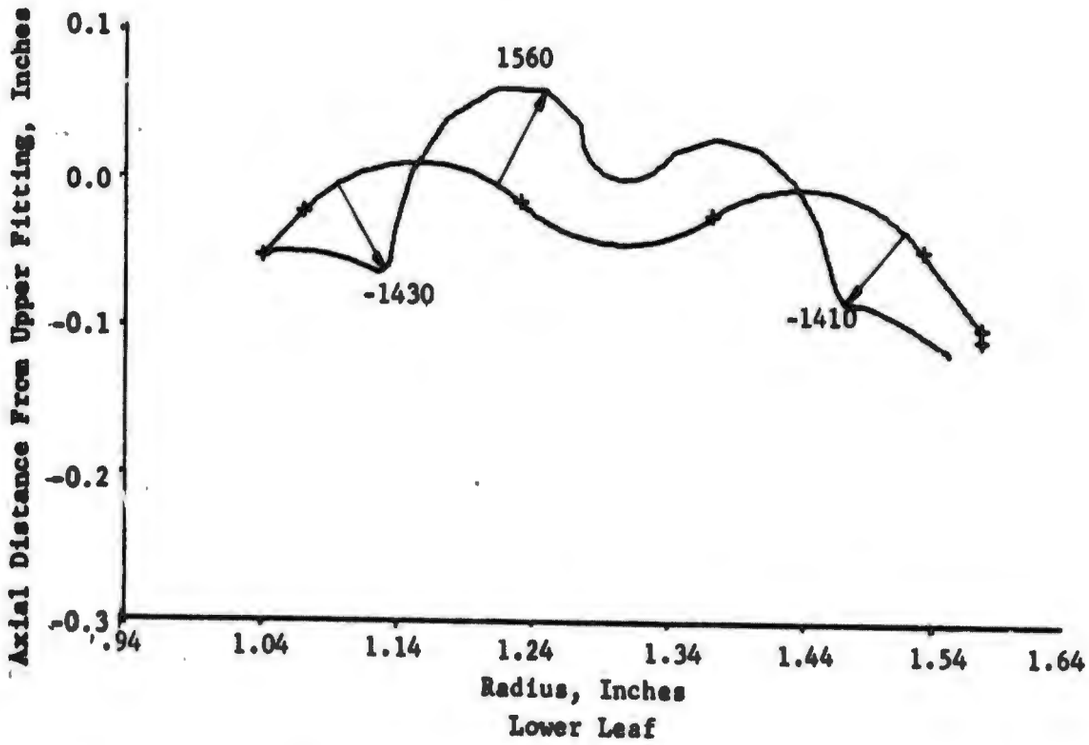
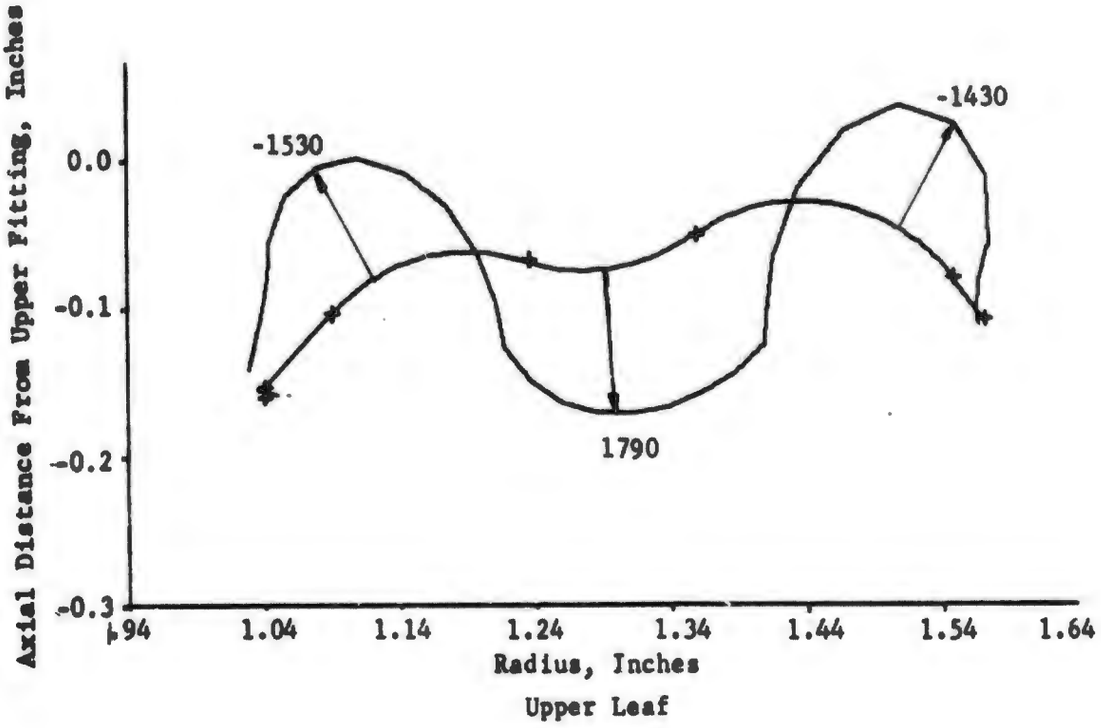


FIGURE 16. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.11859 SWEEP RADII, AND 0.5304-INCH SPAN (Pressure = 1 psi)



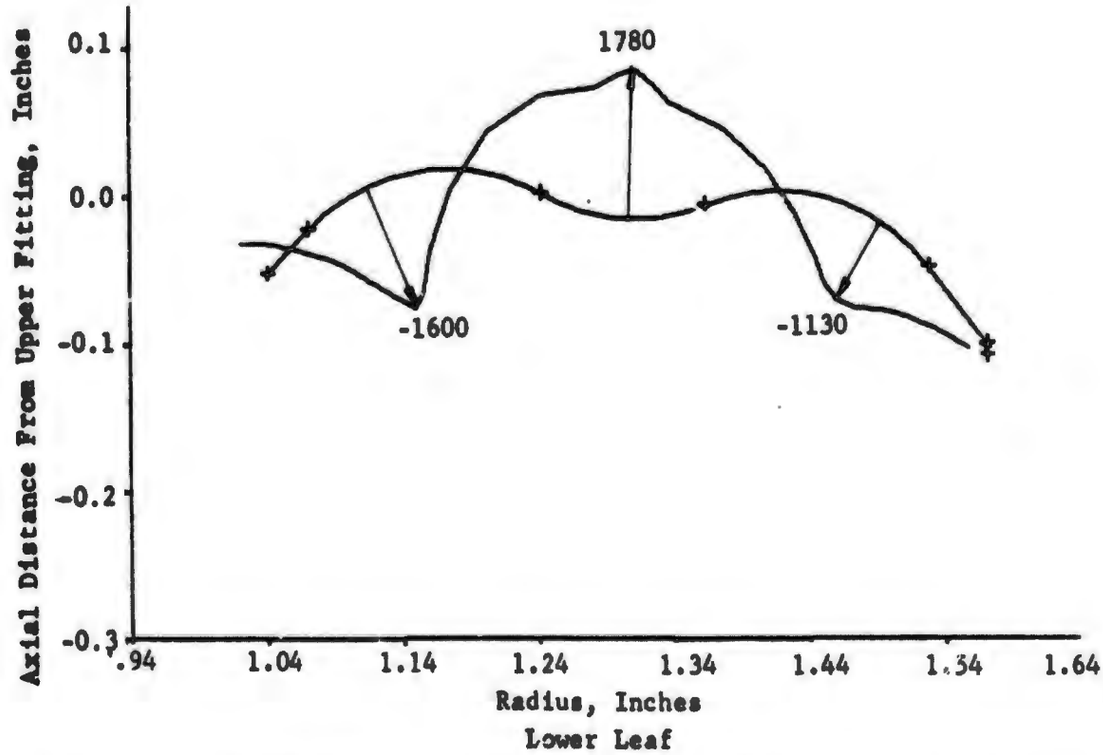
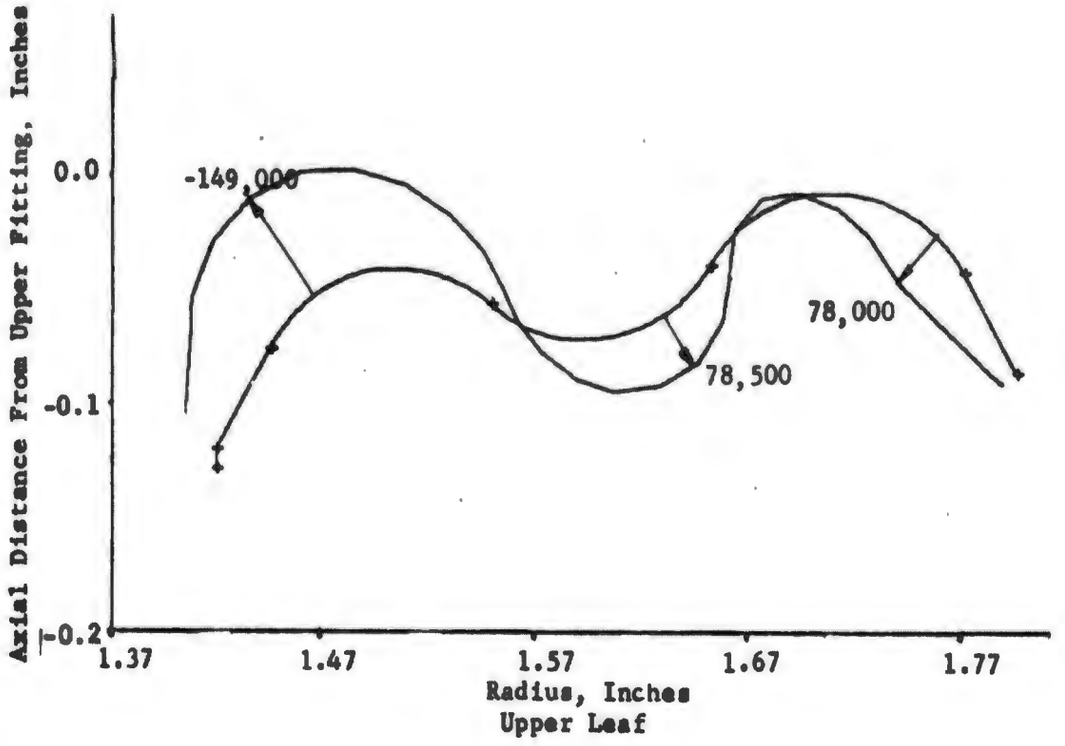


FIGURE 17. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3-INCH BELLOWS WITH 45° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.14495-INCH SWEEP RADII AND 0.5304-INCH SPAN (Pressure = 1 psi)



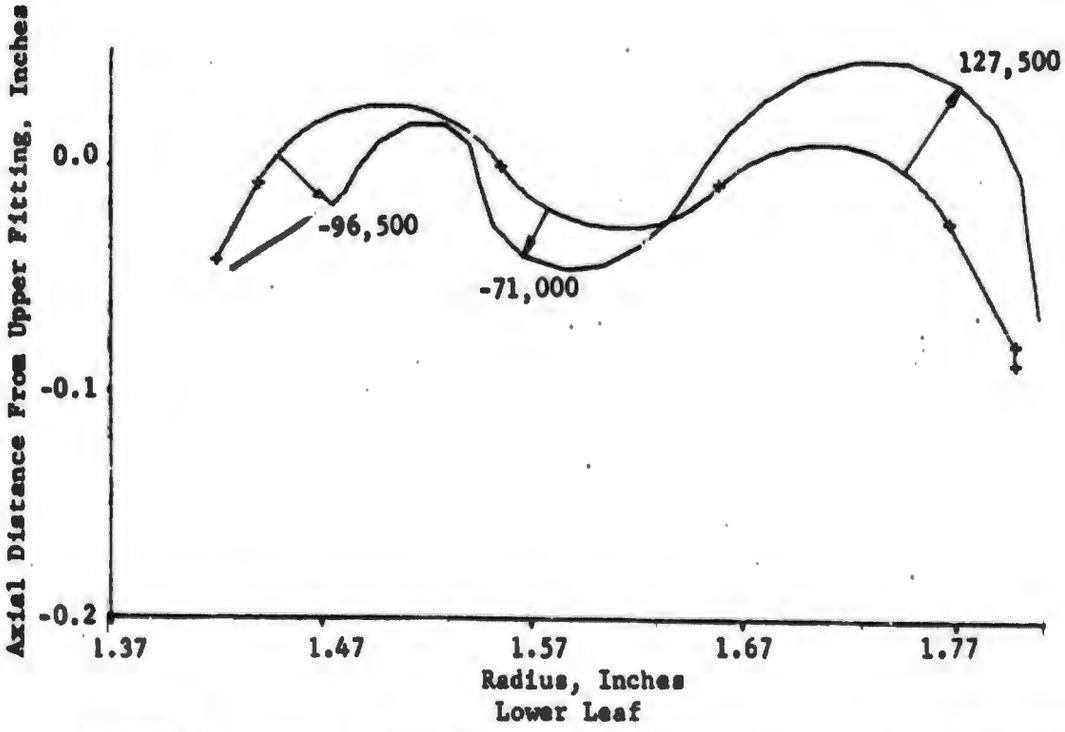


FIGURE 18. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3.5-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, ±5° CHORD ANGLES, 0.07-INCH SWEEP RADII AND 0.378-INCH SPAN (Unit Deflection Per Unit Bellows Length)

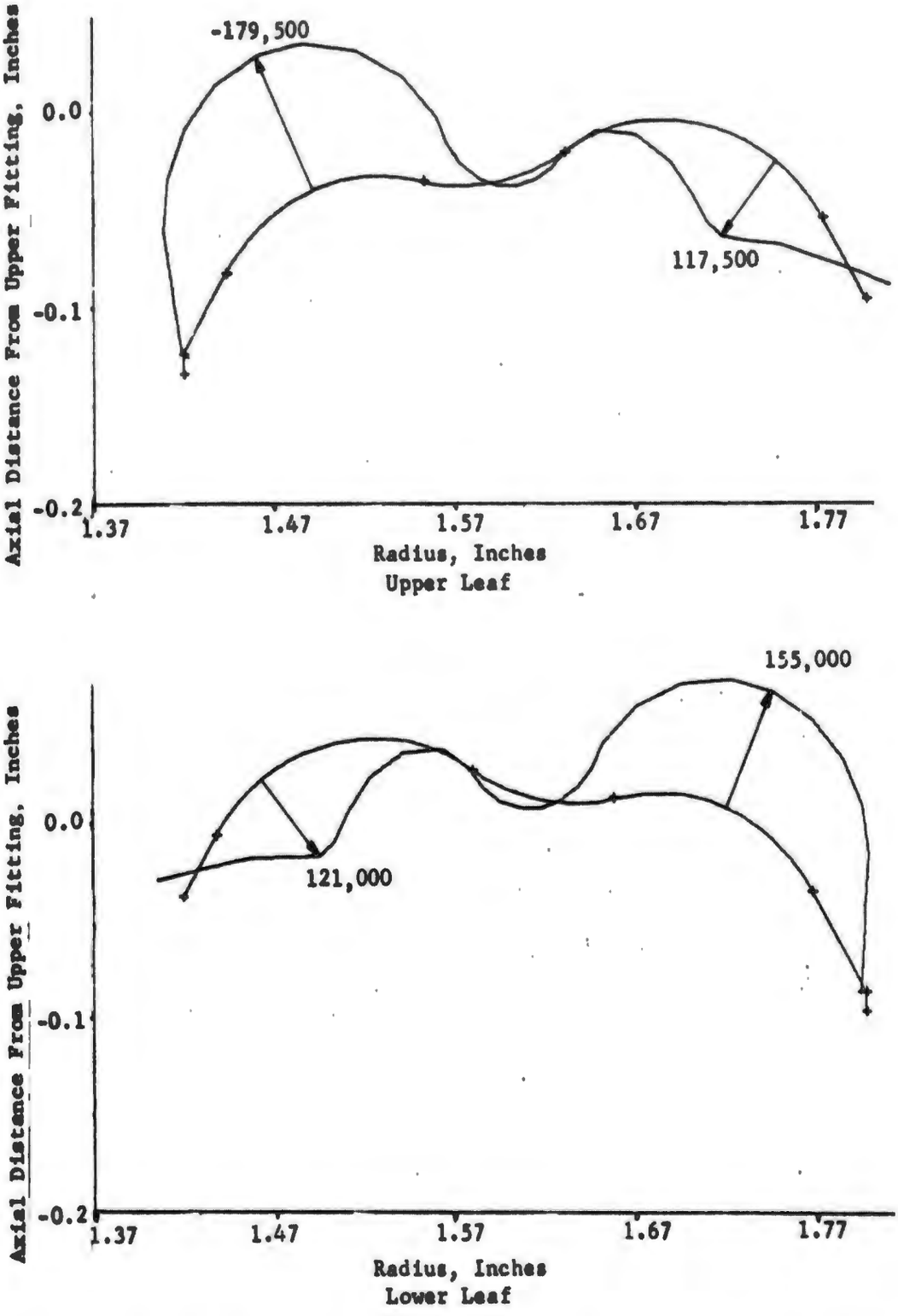
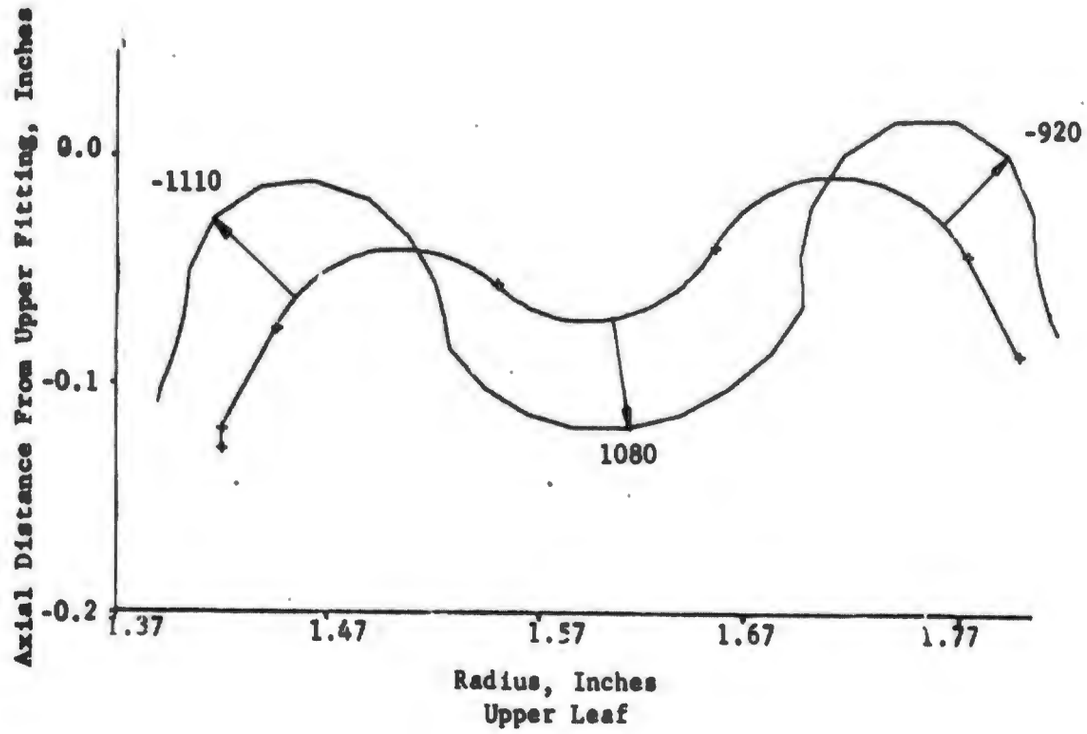


FIGURE 19. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 3.5-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, ±5° CHORD ANGLES, 0.10-INCH SWEEP RADII AND 0.378-INCH SPAN (Unit Deflection Per Unit Bellows Length)



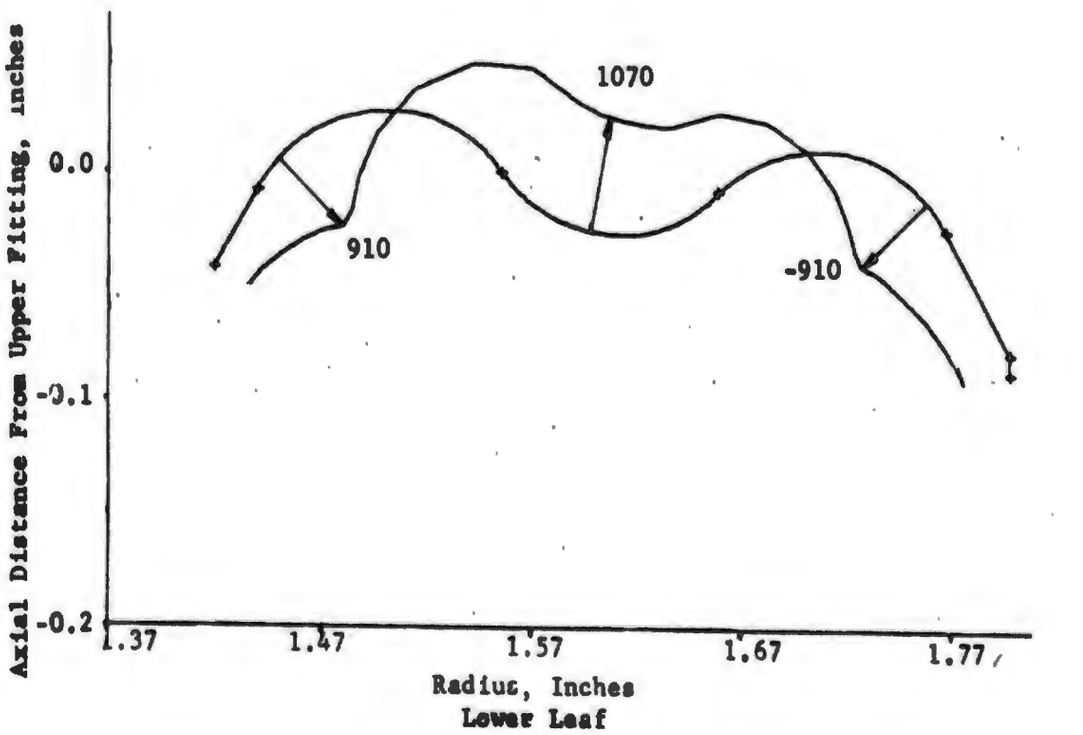
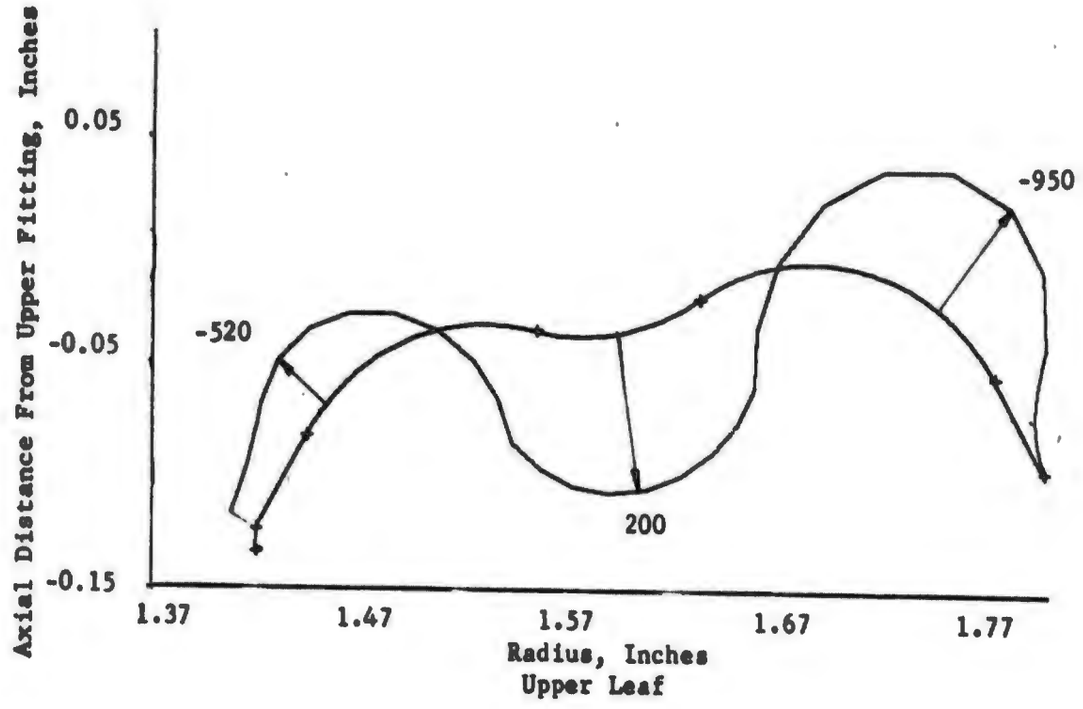


FIGURE 20. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3.5-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, 0.07-INCH SWEEP RADII AND 0.378-INCH SPAN (Pressure = 1 psi)



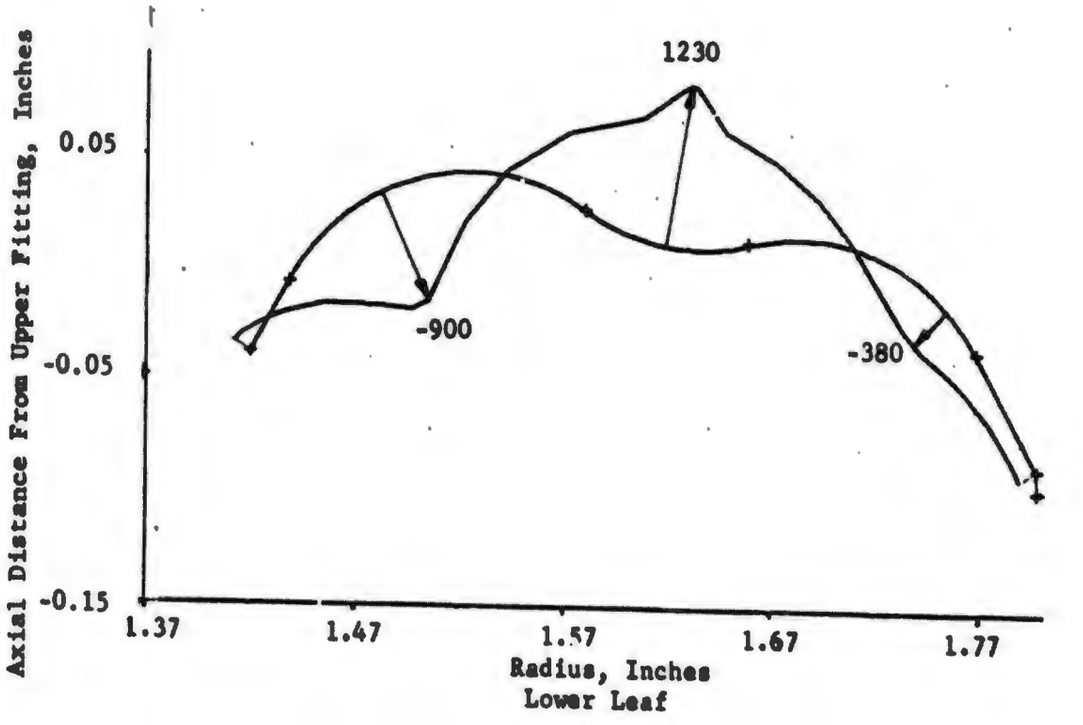


FIGURE 21. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 3.5-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, ±5° CHORD ANGLES, 0.10-INCH SWEEP RADII AND 0.378-INCH SPAN (Pressure = 1 psi)

TABLE 11. MAXIMUM RELATIVE MERIDIONAL STRESSES FOR 3-INCH, TILT-EDGE WELDED BELLOWS, SPAN = 0.5304 INCH, 45° ID AND 50° OD TILT ANGLE

Location of Stress	Sweep Radius, inches	Inner Surface Stress, psi	Outer Surface Stress, psi
		Unit Pressure Loading (a)	
Upper Leaf	0.11859	1,690	-1,850
Lower Leaf	0.11859	1,630	1,560
Upper Leaf	0.13177	1,760	-1,760
Lower Leaf	0.13177	1,600	1,560
Upper Leaf	0.14495	1,780	1,790
Lower Leaf	0.14495	1,800	1,780
		Unit Deflection Loading (b)	
Upper Leaf	0.11879	126,000	-131,000
Lower Leaf	0.11879	-104,000	100,000
Upper Leaf	0.13177	120,000	-126,000
Lower Leaf	0.13177	-107,000	103,000
Upper Leaf	0.14495	120,000	-127,000
Lower Leaf	0.14495	-126,000	121,000

(a) Unit internal pressure load was 1 psi. To get stresses in psi multiply values in table by pressure in psi.

(b) Unit compression in unit length bellows. To get stresses in psi due to axial deflection, multiply values in table by deflection and divide by free length.

TABLE 12. MAXIMUM MERIDIONAL STRESSES FOR 3.5-INCH, TILT-EDGE WELDED BELLOWS, SPAN = 0.378-INCH SWEEP RADIUS, = 0.07 INCH AND 0.10 INCH

Location of Stress	Sweep Radius, inches	Surface Stresses, psi			
		55° Tilt Angles		60° Tilt Angles	
		Inner	Outer	Inner	Outer
		Unit Pressure Loading (a)			
Upper Leaf	0.07	-1,090	1,080	-1,100	1,080
Lower Leaf	0.07	-1,070	1,090	-1,050	1,110
Upper Leaf	0.10	-1,190	1,230	-1,190	1,220
Lower Leaf	0.10	-1,240	1,210	-1,240	1,200
		Unit Axial Deflection			
Upper Leaf	0.07	136,000	-140,000	149,000	-154,000
Lower Leaf	0.07	-123,000	120,000	-137,000	133,000
Upper Leaf	0.10	170,000	-180,000	180,000	-189,000
Lower Leaf	0.10	-163,000	155,000	-171,000	163,000

(a) Unit internal pressure was 1 psi. To get stresses in psi multiply values in table by pressure.

(b) Unit compression in unit length bellows. To get stresses in psi due to axial deflection, multiply values in table by deflection and divide by free length.

At this optimum point, stresses in the center sweep were equal to the stresses in the inner sweep of the upper leaf. Note that the 3-inch bellows model with a sweep radius of 25 percent of the span was very near the optimum shape. The optimum sweep radius for the 3.5-inch bellows was less than 25 percent of the span. However, it is apparent that the maximum stress for a sweep radius of between 20 and 25 percent of the span was affected very little by the change in sweep radius.

A seemingly contradictory situation existed for the deflection loading of the 3- and 3.5-inch bellows. For the 3-inch bellows, changing the sweep radius did not affect the maximum stresses appreciably, while increasing the sweep radius for the 3.5-inch bellows significantly increased the maximum stresses. A detailed comparison of the stresses in Figures 14 and 15 with Figures 18 and 19 shows the same general trend in the stresses at different points of the bellows as the sweep radius was increased. However, the stresses at the inner sweep of the upper leaf of the 3-inch bellows (which were the largest stresses) decreased with increasing sweep radius. This was the principal difference between the two bellows. The apparent reason for this decrease seemed to be that the middle sweep in the 3-inch bellows participated more in the bending action as the sweep radius was increased. This apparently relieved the bending stresses in the inner sweep slightly. In contrast, the middle sweep was bent less in the case of the 3- and 5-inch bellows as the radius was increased. As seen in Figure 19, the stresses in the middle sweep were almost zero for both upper and lower leaves. This increased the bending deformation required in the inner and outer sweep sections and thus increased their bending stress.

An interesting result of the differences in the stresses in these bellows was that the spring rate for the 3-inch bellows decreased from 52.4 lb/in. for the smallest radius to 46 lb/in. at the largest radius, while the spring rate for the 3.5-inch bellows increased from 91 lb/in. to 109 lb/in. with an increase in radius from 0.07 inch to 0.10 inch.

It would appear from this study that there was a second order interaction between the tilt angles and the effect of changes in sweep radius on the deflection stresses. Although this interaction was not strong, it produced some interesting effects, one of which was that the optimum sweep radius was the same for both pressure and axial deflection loading of the 3-inch bellows with 40° ID and 45° OD tilt angles.

It would seem risky to draw general conclusions on the optimization of tilt-edge bellows with respect to sweep radius on the basis of the results reported above. However, it would appear that a reasonable choice of the sweep radius for a 3-sweep, tilt-edge bellows would be 25 percent of the span. For new designs, analyses can be made with one or two other radii to check whether this would be an optimum sweep radius.

Effects of Variation in Convolution Pitch

In a welded bellows, the pitch of a convolution is an important design parameter for several reasons. First, assuming a conventional welding process, the amount of pitch must be large enough to accommodate chill blocks of sufficient thickness that they can be effectively used to absorb the heat

generated in making the ID and OD weld beads. Second, because the pitch determines the length per convolution of a bellows, its value must be considered when determining the number of convolutions desired or required for a given bellows application. Also, since virtually all welded bellows applications require a certain compression capability for the bellows, the value of the pitch for any given convolution shape should be sufficient to allow the required compression stroke with minimum leaf interference since such interference greatly affects the fatigue life of the bellows.

The effects on both the stress distributions and maximum stress levels due to changes in convolution pitch of a three-sweep tilt-edge bellows were investigated for the 2-inch and 3-inch bellows, all having constant thickness of 0.005 inch. Two sets of tilt angles were used for the 2-inch mathematical model: (a) 45° at the ID with 50° at the OD and (b) 50° at the ID with 55° at the OD. For the 3-inch bellows model, tilt angles were 45° at the ID and 50° at the OD. All other model dimensions were the same as those given in Tables 1 and 2. Analyses were performed for axial deflection as well as internal pressure loadings.

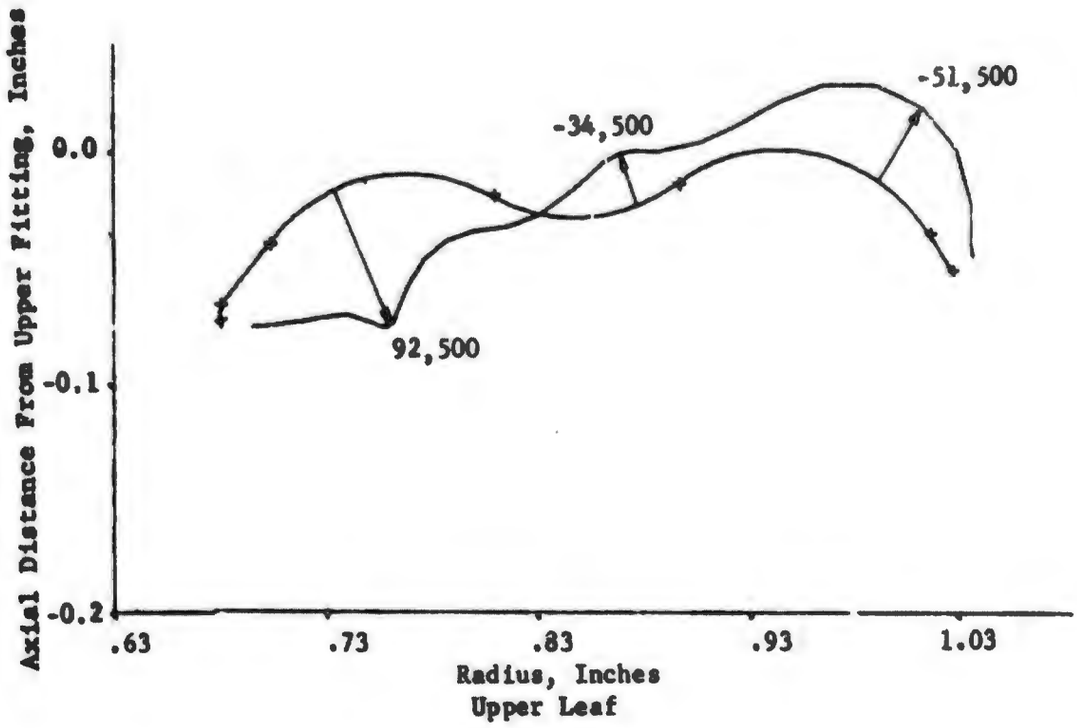
By varying the chord angles of the upper and lower leaves and keeping other major variables virtually constant, two values of pitch were obtained for each of the bellows models studied. Ratios of the pitch to span (P/S) for each of the bellows are shown in Table 13. This table shows the effects of pitch variation on the maximum stress levels in both the upper and lower leaves of a convolution. The numbers in parentheses refer to the location of the stress value in terms of the mathematical model part number shown in Figure 2. The effects of pitch variation on the meridional stress distribution throughout the 2-inch, tilt-edge bellows convolution for both loadings considered can be seen in Figures 22 through 29. These results are typical and so stress distribution plots for the other models studied are not presented.

Relative stresses due to axial deflection are shown in two ways in Table 13. The values of the relative maximum stresses corresponding to unit compressive deflection per unit length of bellows show that, for a fixed deflection per unit length of bellows, an increase in pitch caused a marked increase in the maximum stress values. In other words, the deflection capabilities of the bellows, or their abilities to deflect in proportion to their lengths, changed significantly with change in their pitch. Alternatively, the values of maximum stresses for a deflection of one inch per convolution show that, for a fixed deflection per bellows convolution, an increase in pitch had much less effect on the maximum stress levels. This increase in deflection stress levels with increasing pitch was entirely consistent with results obtained from all other types of bellows. It is interesting to note that although the stress values were increased and the stress distribution in the lower leaf was changed somewhat, the location of the maximum stress for the two bellows sizes investigated was unaltered by changes in convolution pitch. For each of the six models studied, the maximum meridional stress for deflection loading occurred in the upper leaf sweep nearest the inside diameter. Indeed, the maximum deflection stress was found to be on this sweep in nearly all of the geometries studied in this research program.

TABLE 13. MAXIMUM RELATIVE MERIDIONAL STRESSES IN TILT-EDGE WELDED BELLOWS OF DIFFERENT CONVOLUTION PITCH

Bellows Description		Relative Stress for Unit Deflection per Unit Bellows Length (a)	Relative Stress for Inch of Deflection per Convolution (b)	Relative Stress Due to Internal Pressure (c)
2-inch, 45° ID, 50° OD, P/S = 0.129	Upper Leaf	79,000 (8)	1,760,000	-930 (9)
	Lower Leaf	-97,000 (4)	-2,160,000	+960 (3)
2-inch, 45° ID, 50° OD, P/S = 0.192	Upper Leaf	-132,200 (10)	-1,930,000	-910 (9)
	Lower Leaf	158,200 (4)	-2,310,000	+990 (3)
2-inch, 50° ID, 55° OD, P/S = 0.141	Upper Leaf	85,500 (8)	1,740,000	-970 (9)
	Lower Leaf	-104,900 (4)	-2,140,000	+950 (3)
2-inch, 50° ID, 55° OD, P/S = 0.229	Upper Leaf	-157,000 (10)	-1,900,000	-910 (9)
	Lower Leaf	-190,000 (4)	-2,300,000	+930 (3)
3-inch, 45° ID, 50° OD, P/S = 0.196	Upper Leaf	-106,900 (10)	-1,030,000	1760 (8)
	Lower Leaf	-125,900 (4)	-1,210,000	-1760 (4)
3-inch, 45° ID, 50° OD, P/S = 0.290	Upper Leaf	-214,500 (10)	-1,400,000	1740 (8)
	Lower Leaf	-231,000 (4)	-1,500,000	-1920 (4)

(a) To obtain stresses (in psi) due to deflection, multiply values by deflection and divide by free length of bellows.
(b) To obtain stresses (in psi) due to deflection, multiply values by deflection per convolution in inches.
(c) To obtain stresses (in psi) due to internal pressure, multiply values by pressure in psi.



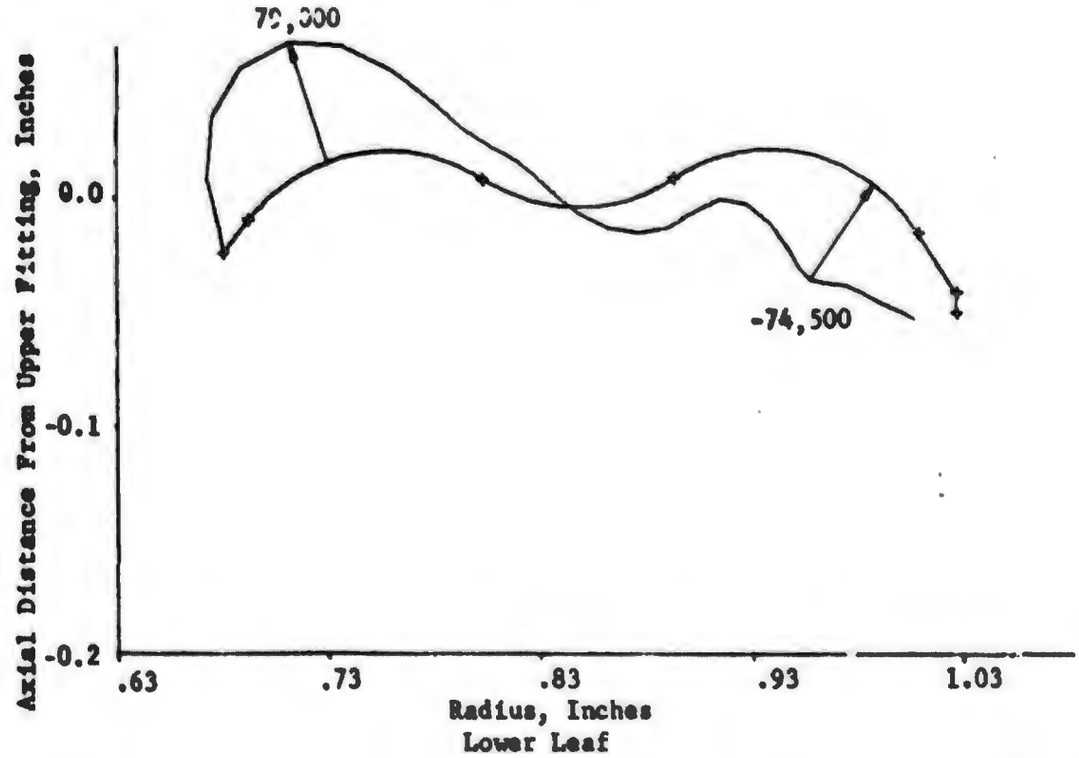


FIGURE 22. INNER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII AND 0.3476-INCH SPAN (Unit Deflection per Unit Bellows Length)

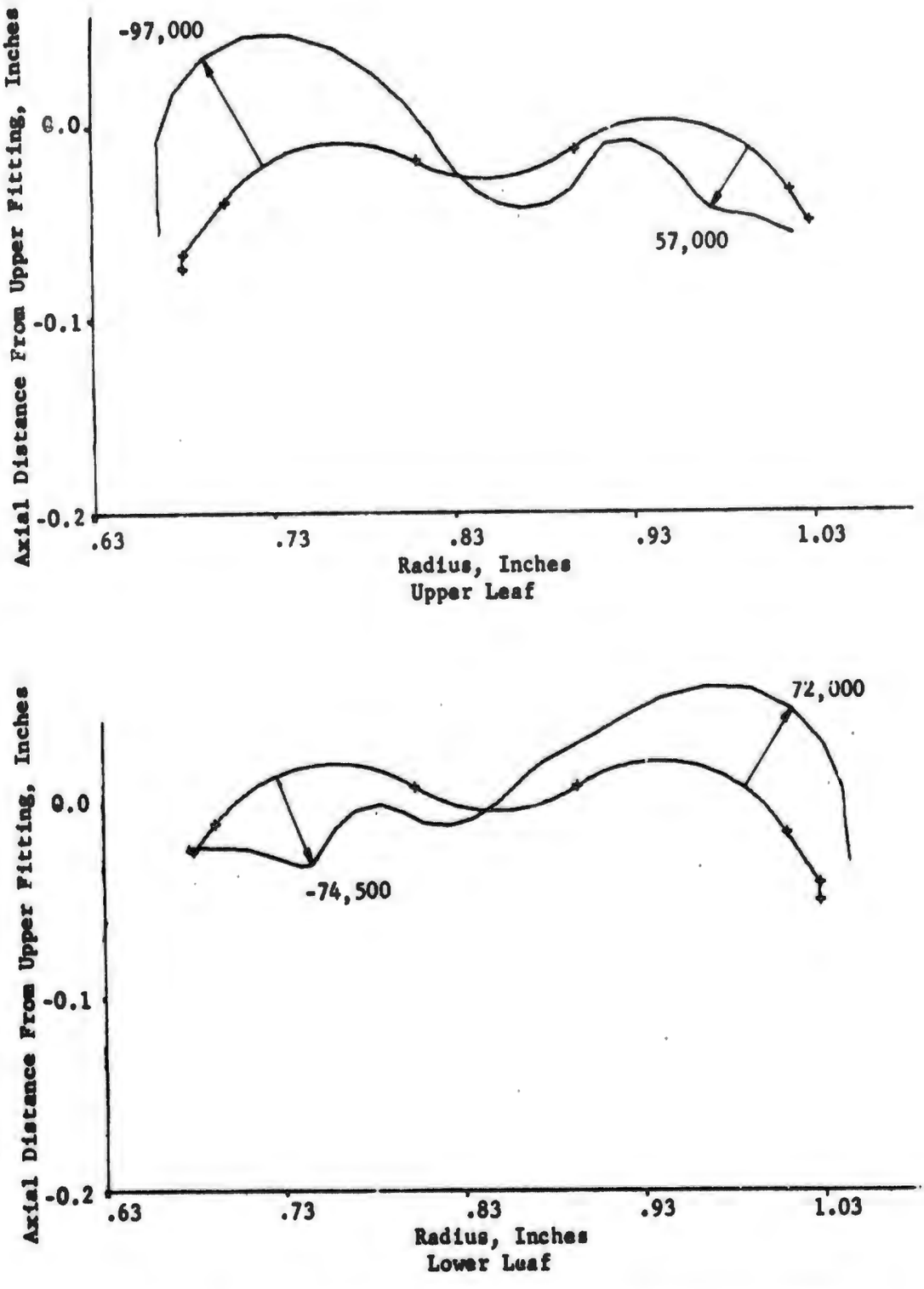


FIGURE 23. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII AND 0.3476-INCH SPAN (Unit Deflection per Unit Bellows Length)

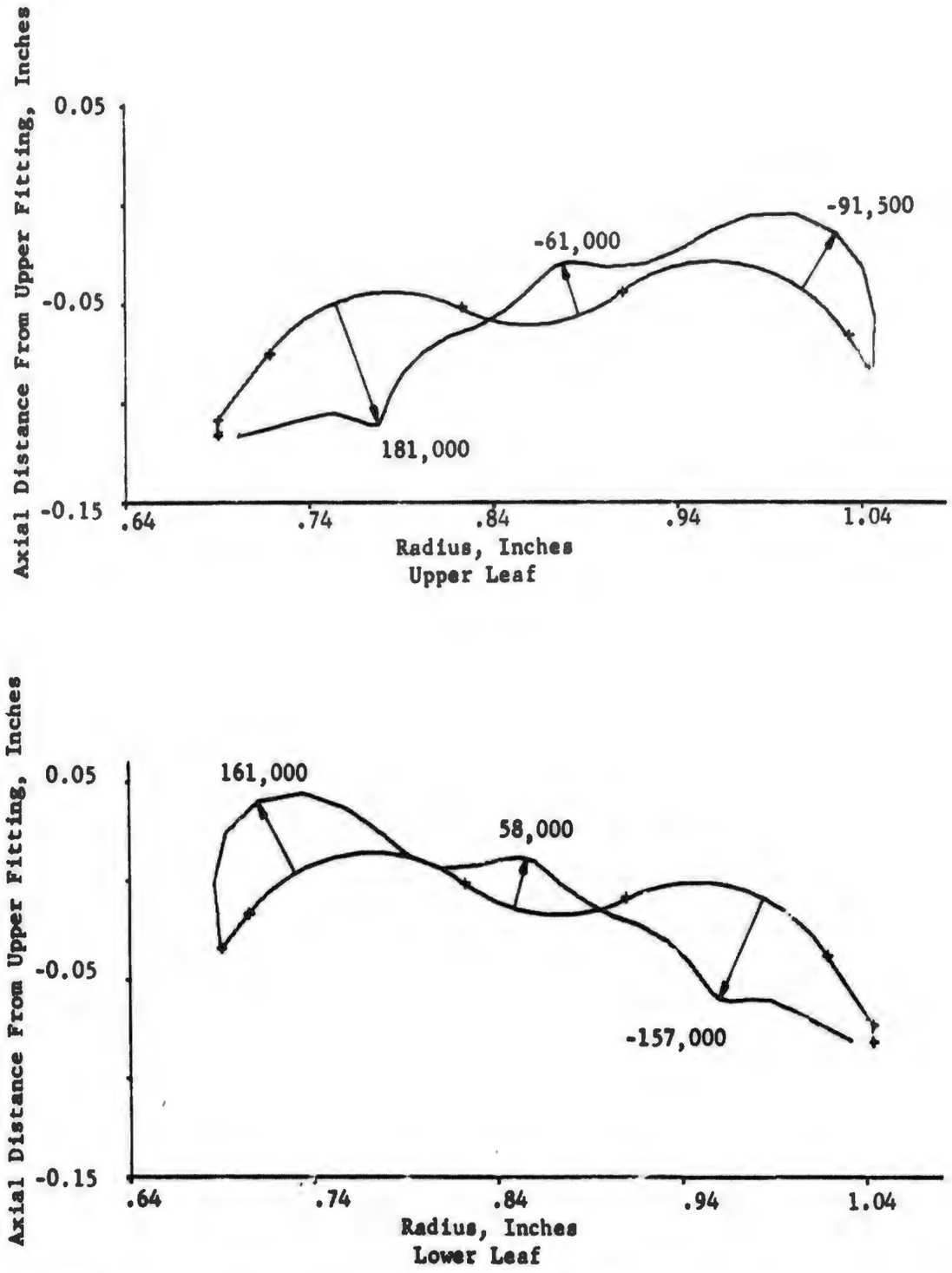


FIGURE 24. INNER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±5° CHORD ANGLES, 0.08785-INCH SWEEP RADII AND 0.3536-INCH SPAN (Unit Deflection per Unit Bellows Length)

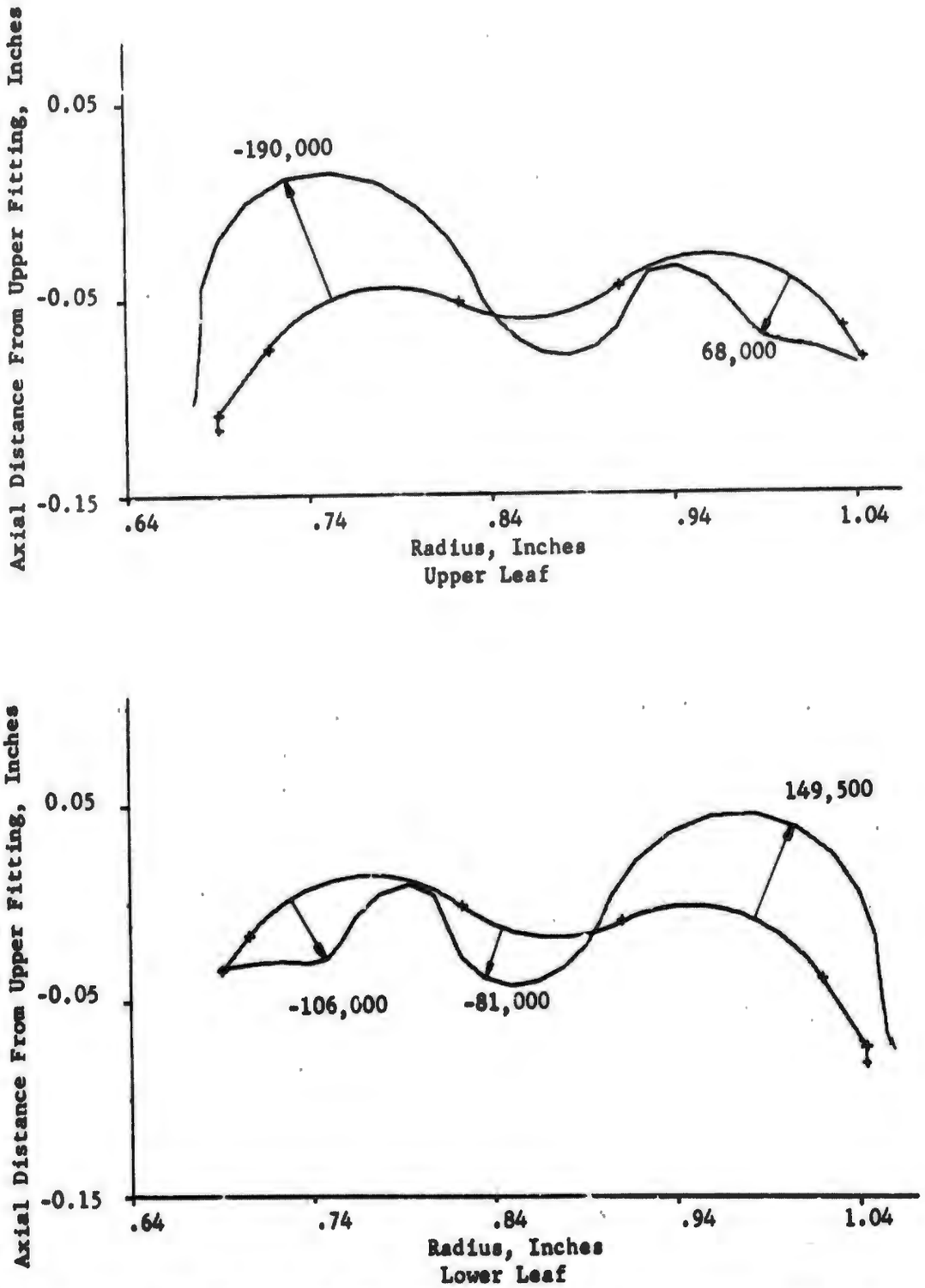
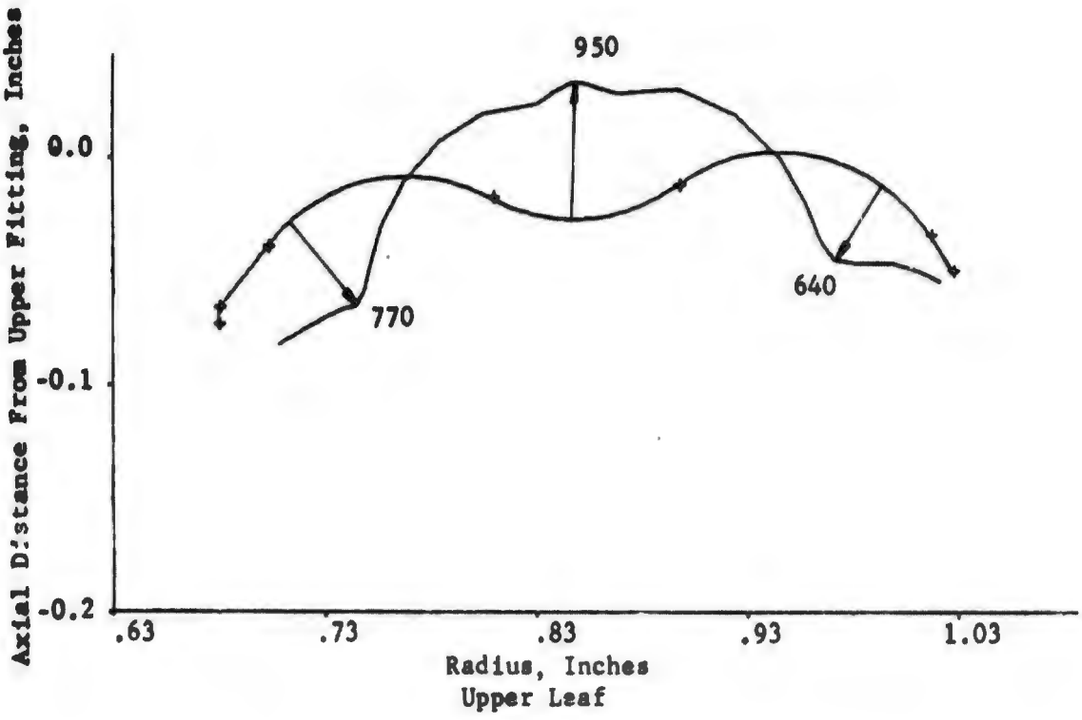


FIGURE 25. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±5° CHORD ANGLES, 0.08785-INCH SWEEP RADII AND 0.3536-INCH SPAN (Unit Deflection per Unit Bellows Length)



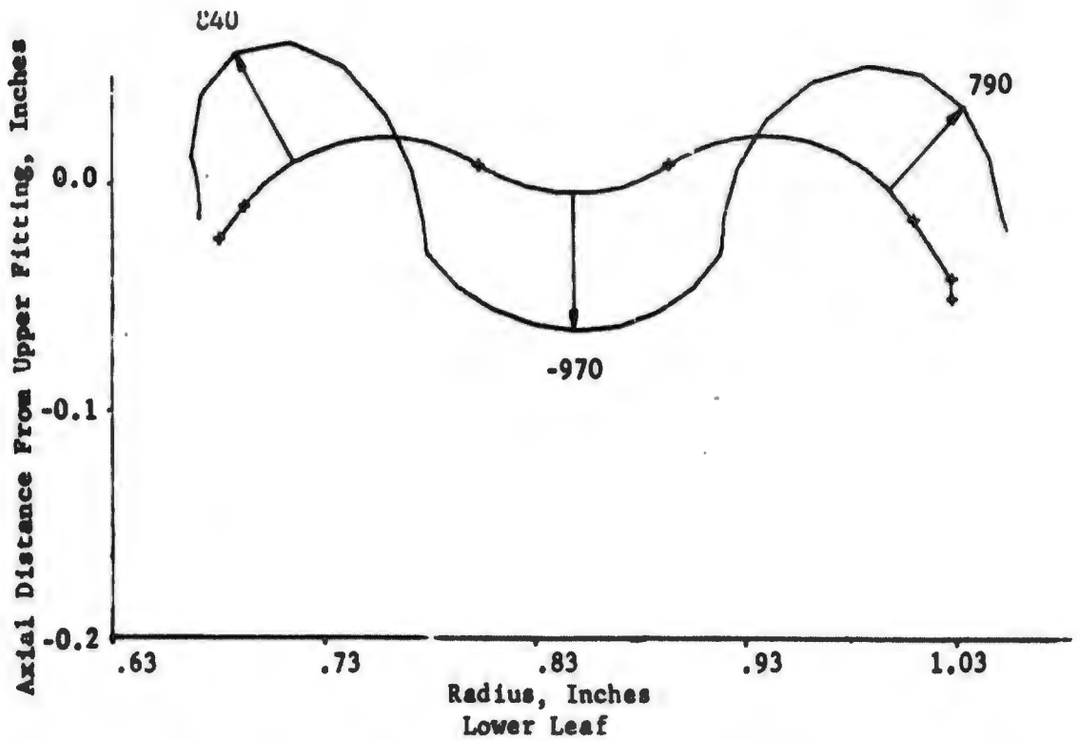


FIGURE 26. INNER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII AND 0.3476-INCH SPAN (Pressure = 1 psi)

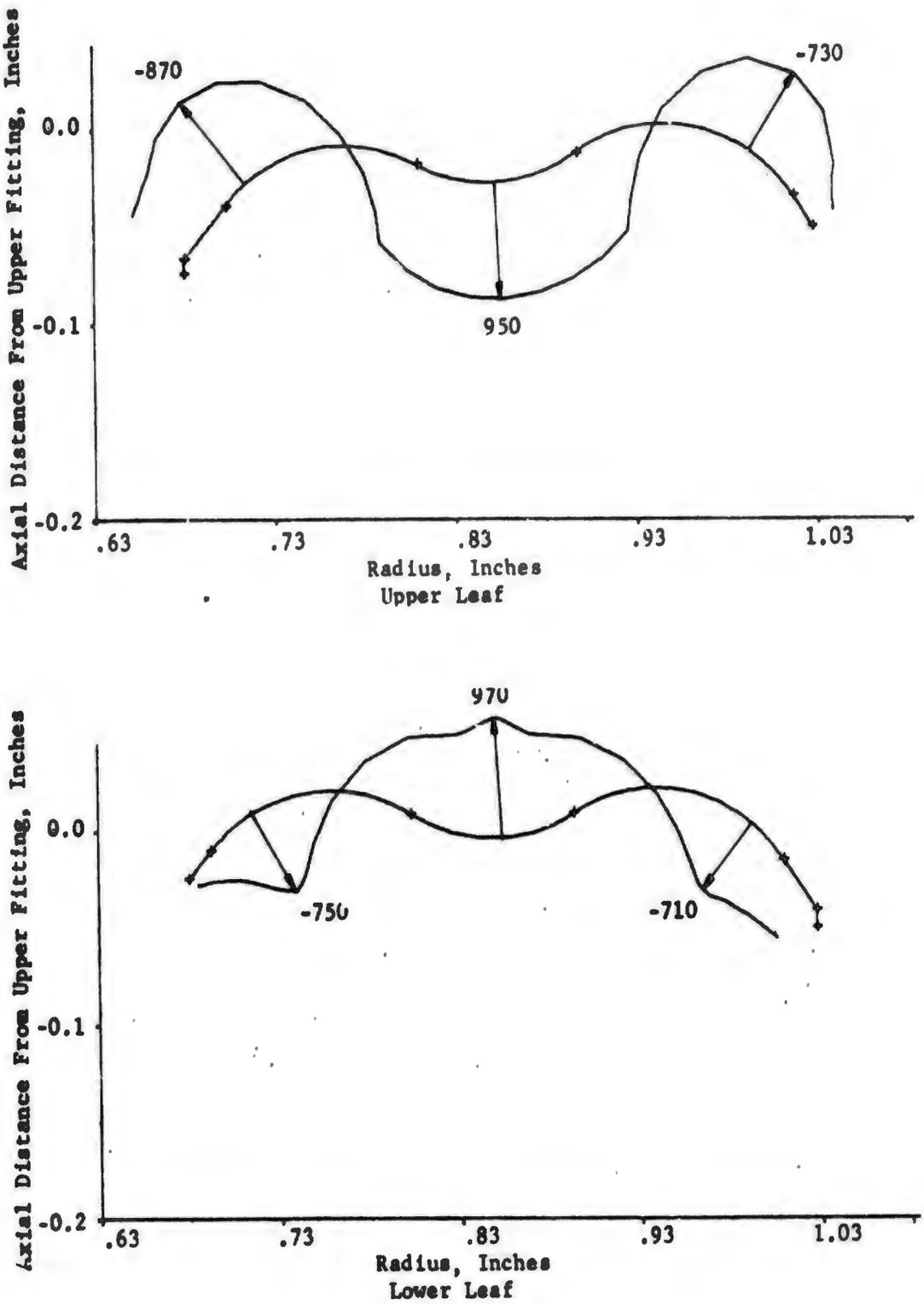


FIGURE 27. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII AND 0.3476-INCH SPAN (Pressure = 1 psi)

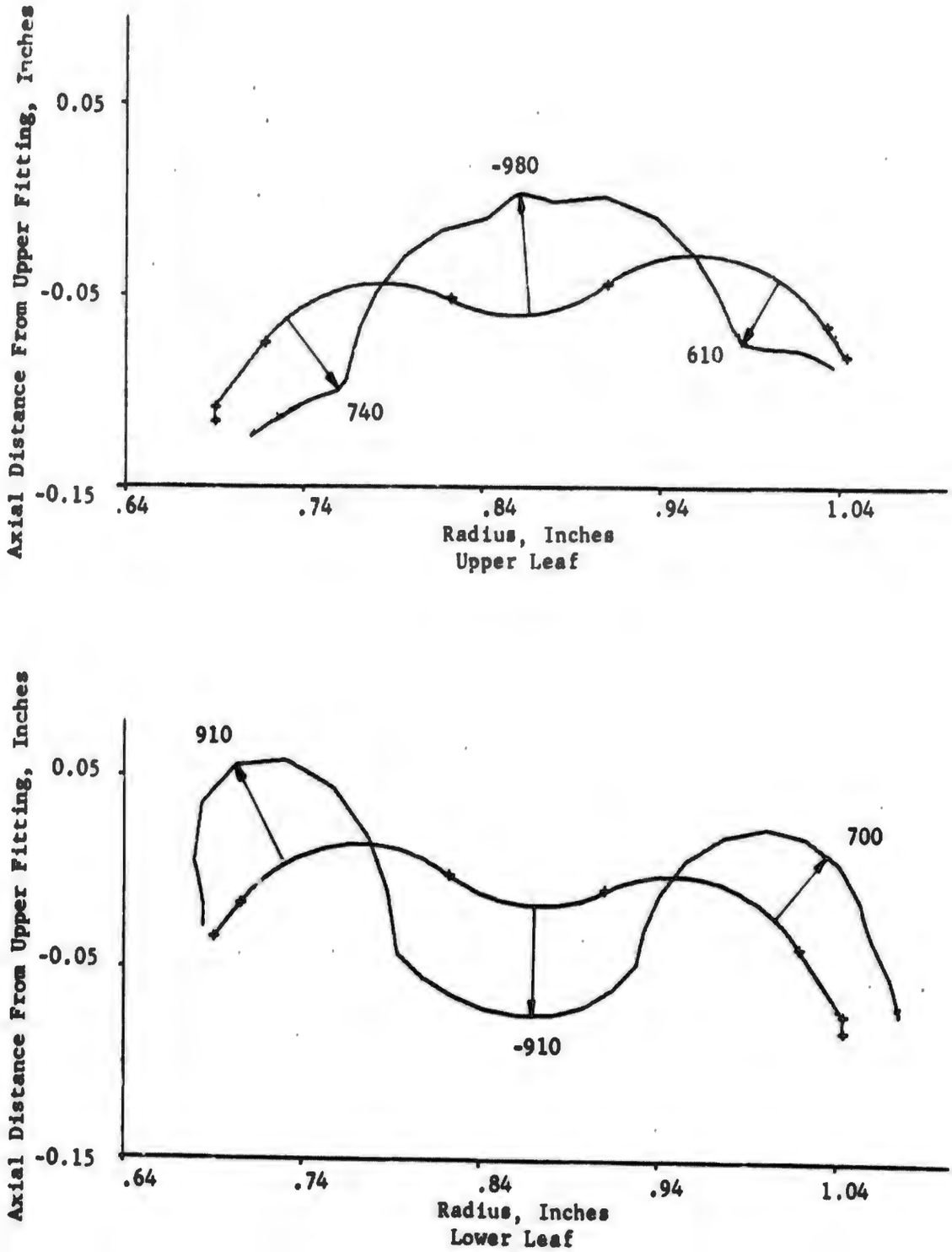


FIGURE 28. INNER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 2-INCH BELLOWS WITH 50° ID, 50° OD TILT ANGLES, ±5° CHORD ANGLES, 0.08785-INCH SWEEP RADII AND 0.3536-INCH SPAN (Pressure = 1 psi)

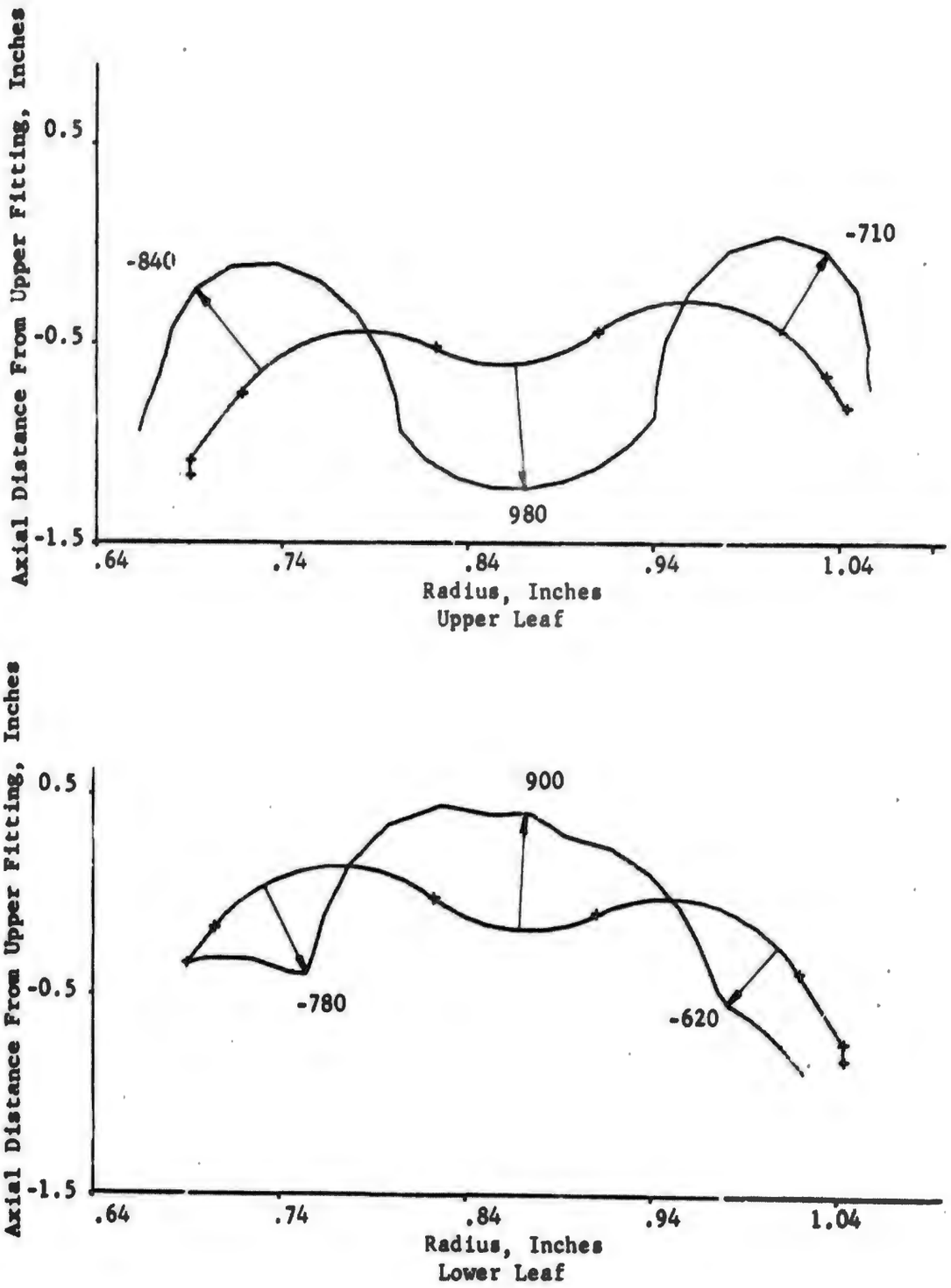


FIGURE 29. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 2-INCH BELLOWS WITH 50° ID, 55° OD TILT ANGLES, ±5° CHORD ANGLES, 0.08785-INCH SWEEP RADII AND 0.3536-INCH SPAN (Pressure = 1 psi)

In contrast to the rather predictable trend noted for the deflection stresses, the effects of pitch on the pressure stresses was less clear-cut. An examination of the Figures 26 through 29 shows that for the 2-inch bellows, the maximum stress occurred on the middle sweep and switched from the lower leaf to the upper leaf as the pitch was increased. This result was caused by the relative decrease in the arch of the upper leaf and increased arch of the lower leaf as the pitch is increased. It is pointed out in the section on effects of sweep radius that the center sweep exhibited an increased bending stress with decreasing radius under pressure loading.

For the 3-inch bellows, the pressure loading caused maximum stress on the inner sweep nearest the bellows root. At the smaller pitch, the maximum stress was on the upper leaf and increased with increasing pitch. Although an analysis was not made of the 3-inch bellows for pitch to span ratio smaller than 0.2, it is clear that the maximum stress would have occurred on the lower leaf in this case. It appears from a study of the results for pressure loading, that an optimum pitch can be found for pressure stresses at which the maximum stresses in the upper and lower bellows leaves are equal. This seems to occur at pitch to span ratios between 0.15 and 0.02, but depends on the overall arch of the upper and lower leaves. The study of deflection loads also indicated that the pitch should be kept as low as possible. As noted earlier, the restraints imposed by practical considerations such as the welding process and the desirability of operating the bellows in compression would seem to prevent making a bellows with the optimum pitch. Thus, the pitch of tilt-edge welded bellows will be determined by practical considerations in the same way that pitch is determined for conventional welded bellows.

SECTION III

OPTIMIZATION OF BELLOWS CONVOLUTION CROSS-SECTIONS

A major objective of the present study was the determination of optimum convolution shapes in 1-inch, 2-inch, and 3-inch bellows. These shapes were to have minimum stress conditions at the welds and minimum overall stresses both for axial deflection and for internal pressure loads. In addition to minimizing stresses in the bellows convolutions, minimizing stresses in the end bellows leaf where it is welded to some end fitting was also considered. Stress analysis results are presented in this section for certain selected convolution shapes for a 1-, 2-, 3-, and 3.5-inch bellows. Also, a description is given of an investigation that was made into the effects of varying the shape of the bellows end leaves on the stresses near the end fitting welds.

Selection of Optimum Convolution Shapes

As described in the previous sections, the parametric analyses indicated that a sweep radius of between 20 and 25 percent of the span would be near the optimum for a pressure loading and that chord angles between ±2.5° and ±5° would be desirable for deflection loaded bellows. It was also determined that tilt angles could be found that gave acceptably low stresses in the weld areas for bellows in the 1- to 4-inch range. Convolution shapes were selected within these ranges of parameters for the 1-, 2-, and 3-inch sizes. Tables of the specified dimensions for these bellows are given in Tables 14 through 16 in NONLIN format as in Table 1*. The thickness of the 1-inch bellows was taken as .004 inch because of its smaller size. The outer surface meridional stresses for the 1- and 2-inch bellows are given for internal pressure and axial compression loading in Figures 30 through 33. Similar stress distributions for the 3-inch bellows are given in Figures 10, 11, 14, and 15.

In addition to these bellows, considerable study was given to a 3.5-inch bellows to develop a bellows configuration that could be compared with a conventional welded bellows that had been investigated under the previous research contract. Dimensions of two optimized bellows are given in Tables 17 and 18. Stresses in these two bellows shapes were shown in Figures 12, 13, 16, 17, 19, and 21. The analytical results reported in this section clearly demonstrated that it was possible to design tilt-edge bellows with optimized stress distributions for a range of bellows diameters. The principal interaction noted between tilt angle and bellows size was that the tilt angles must be made steeper for the smaller diameter bellows to achieve satisfactory weld stress reductions. This effect seemed to be more an interrelation between the bellows span and thickness than an effect of the bellows radius. This was demonstrated by the two optimum shapes for the 3.5-inch bellows for which the shorter span had the higher tilt angles.

Alternatively, by invoking geometric similarity, these bellows shapes could be interpreted as 3.5-inch bellows with thicknesses of from

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* See footnote to page 11 for a description of the entries in these tables.

TABLE 14. AN OPTIMUM CONVOLUTION SHAPE FOR A 1-INCH TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 60°, OD TILT ANGLE = 60°, SPAN = 0.1868 INCH

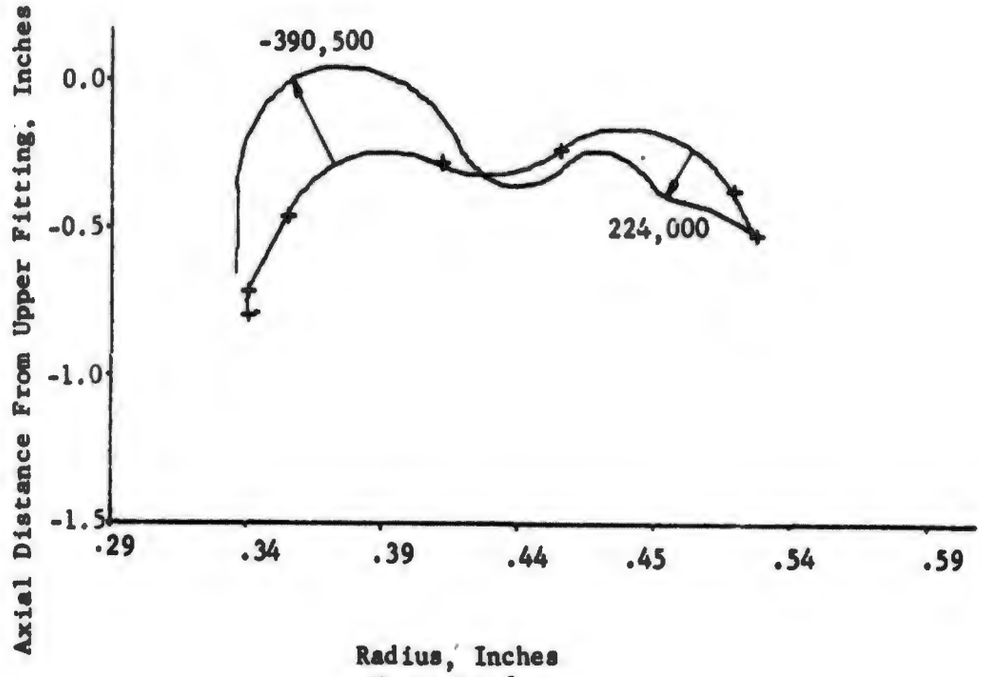
Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
1	Conical	240	--	0.52740	0.01708
2	Toroidal	240	145	0.48082	-0.04392
3	Toroidal	145	205	0.43042	0.04392
4	Toroidal	205	120	0.39332	-0.02392
5	Conical	120	--	0.35528	0.02936
6	Cylindrical	90	--	0.34060	0.00800
7	Conical	-60	--	0.34060	0.01606
8	Toroidal	-60	35	0.38667	0.04392
9	Toroidal	35	-25	0.43707	-0.04392
10	Toroidal	-25	60	0.47427	0.04392
11	Conical	60	--	0.51231	0.03018
12	Cylindrical	90	--	0.52740	0.00800

TABLE 15. AN OPTIMUM CONVOLUTION SHAPE FOR A 2-INCH, TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 50°, OD TILT ANGLE = 60°, SPAN = 0.3476 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
1	Conical	240.000	--	1.03000	0.01982
2	Toroidal	235.000	145.633	0.94531	-0.08635
3	Toroidal	145.633	207.050	0.84781	0.08635
4	Toroidal	207.050	130.000	0.76879	-0.08635
5	Conical	130.000	--	0.70264	0.03531
6	Cylindrical	90.000	--	0.67944	0.00777
7	Conical	-50.000	--	0.67944	0.01875
8	Toroidal	-50.000	31.000	0.75764	0.08635
9	Toroidal	31.000	-31.650	0.84734	-0.08635
10	Toroidal	-31.650	60.000	0.93796	0.08635
11	Conical	60.000	--	1.01274	0.03452
12	Cylindrical	90.000	--	1.03000	0.01000

TABLE 16. AN OPTIMUM CONVOLUTION SHAPE FOR A 3-INCH TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 45°, OD TILT ANGLE = 50°, SPAN = 0.5304 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
1	Conical	230	--	1.56720	0.03697
2	Toroidal	230	145	1.44247	-0.13177
3	Toroidal	145	205	1.29127	0.13177
4	Toroidal	205	135	1.17997	-0.13177
5	Conical	135	--	1.08679	0.07070
6	Cylindrical	90	--	1.03680	0.00707
7	Conical	-45	--	1.03680	0.04252
8	Toroidal	-45	35	1.16002	0.13177
9	Toroidal	35	-25	1.31122	-0.13177
10	Toroidal	-25	50	1.42252	0.13177
11	Conical	50	--	1.52347	0.06802
12	Cylindrical	90	--	1.56720	0.00777



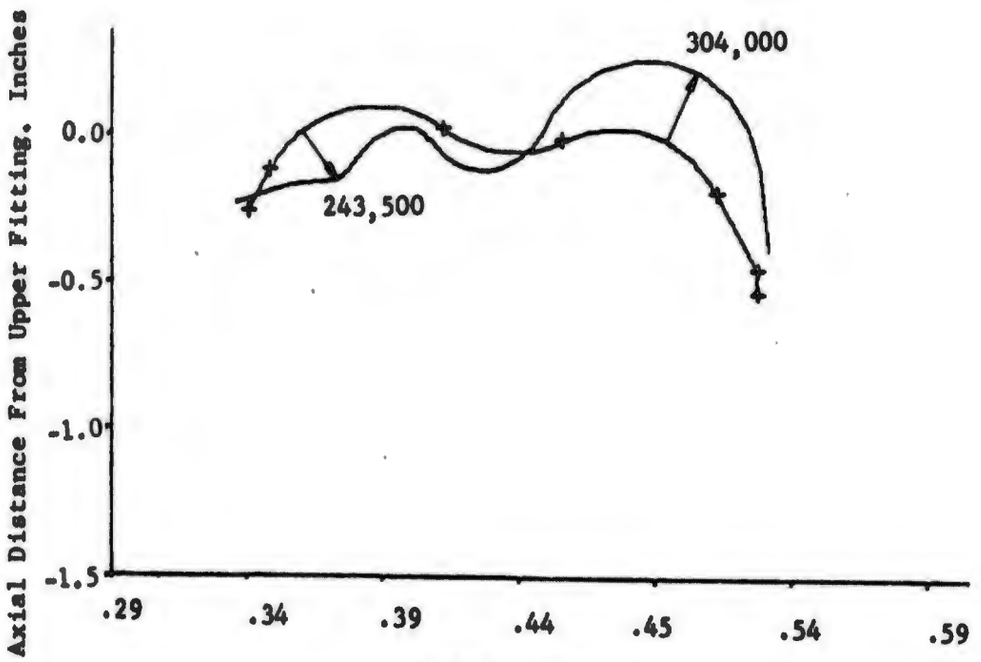
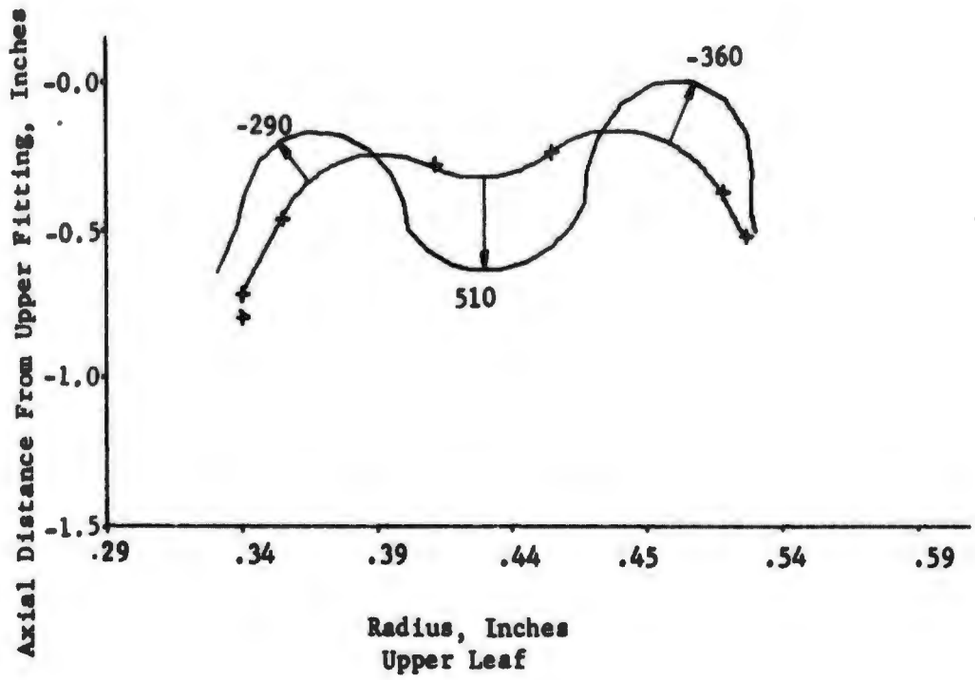


FIGURE 30. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 1-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, ±5° CHORD ANGLES, 0.04392-INCH SWEEP RADII, AND 0.1868-INCH SPAN (Unit Deflection Per Unit Bellows Length)



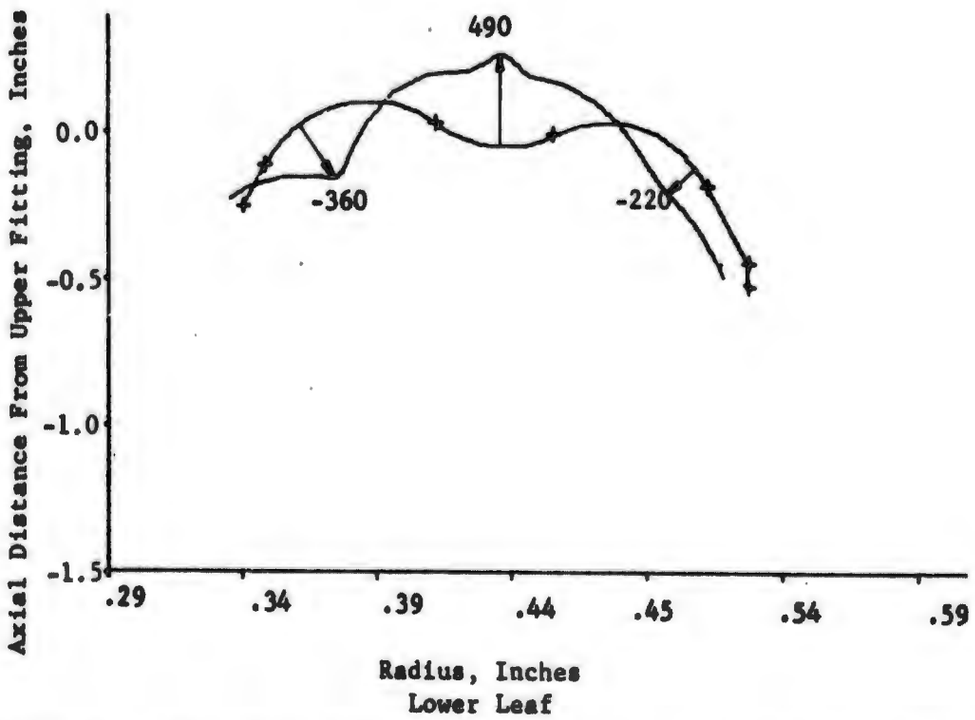


FIGURE 31. OUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 1-INCH BELLOWS WITH 60° ID, 60° OD TILT ANGLES, ±5° CHORD ANGLES, 0.04392-INCH SWEEP RADII, AND 0.1868-INCH SPAN (Pressure = 1 psi)

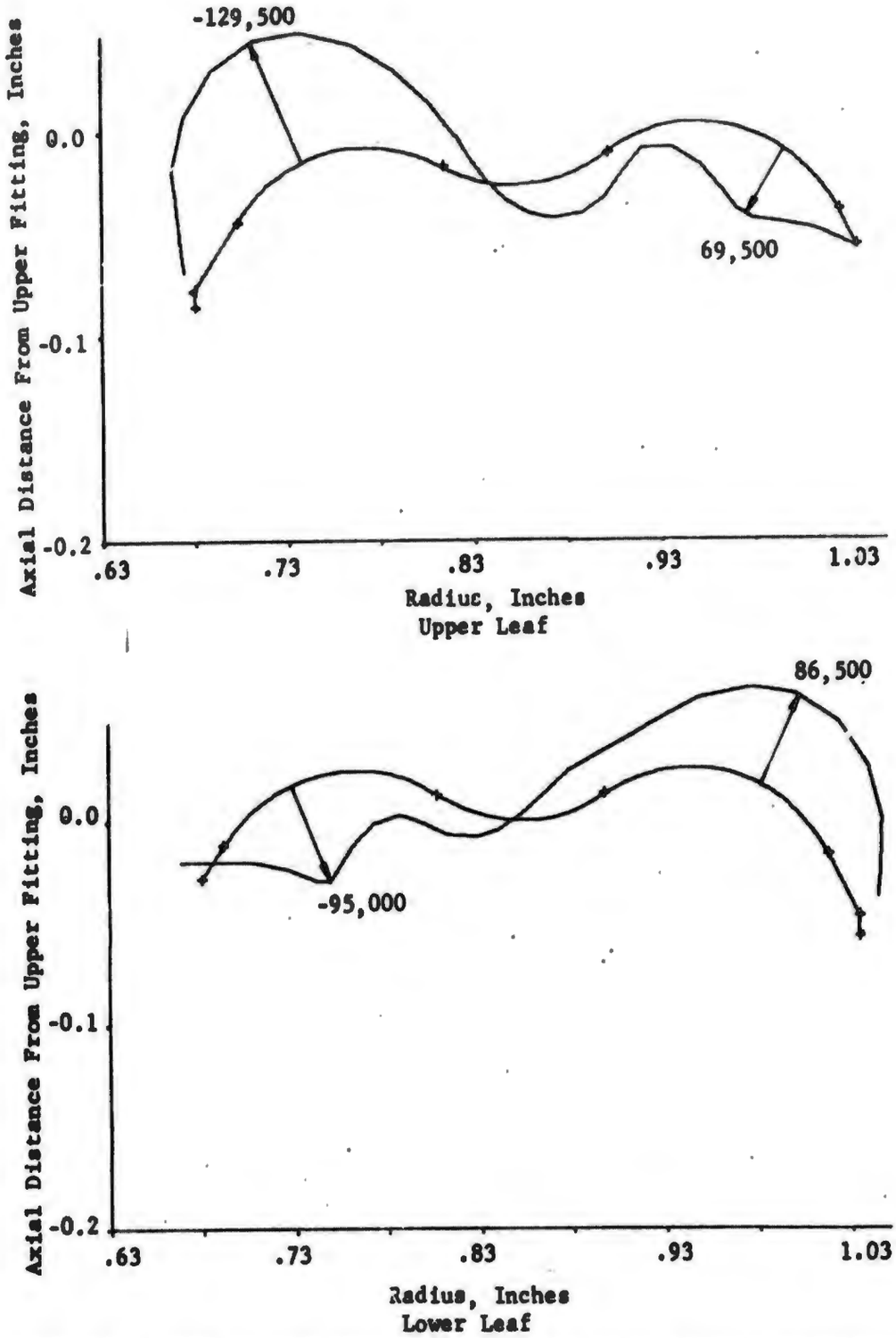
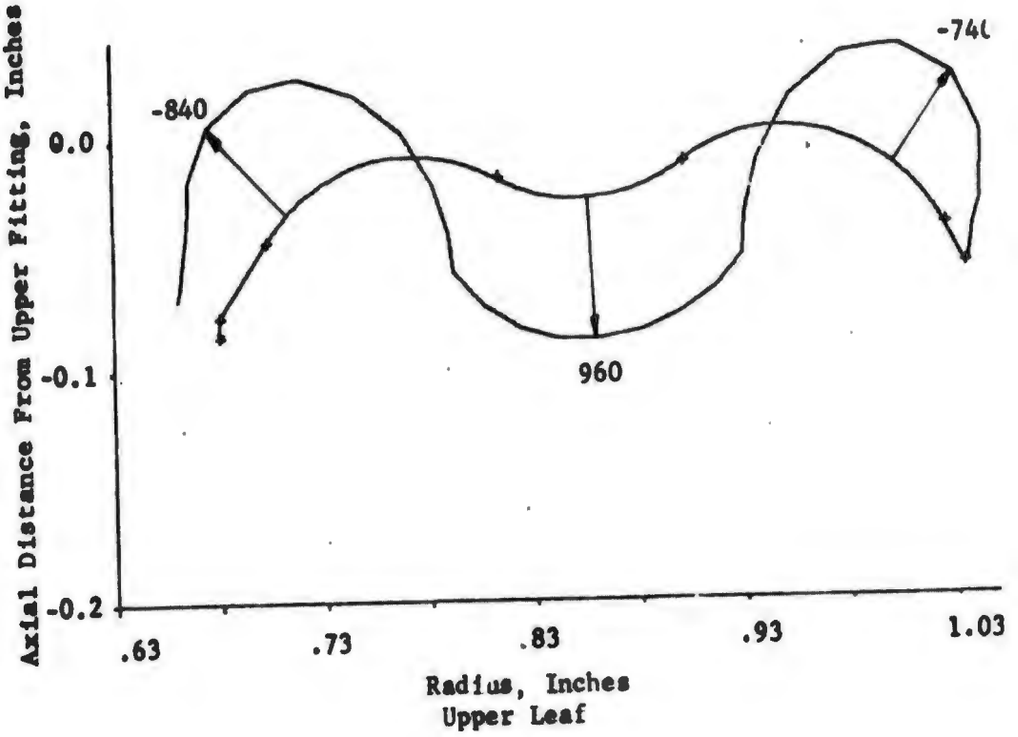


FIGURE 32. OUTER SURFACE MERIDIONAL STRESSES IN AN AXIALLY COMPRESSED 2-INCH BELLOWS WITH 55° ID, 60° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII, AND 0.3546-INCH SPAN (Unit Deflection Per Unit Length Bellows)



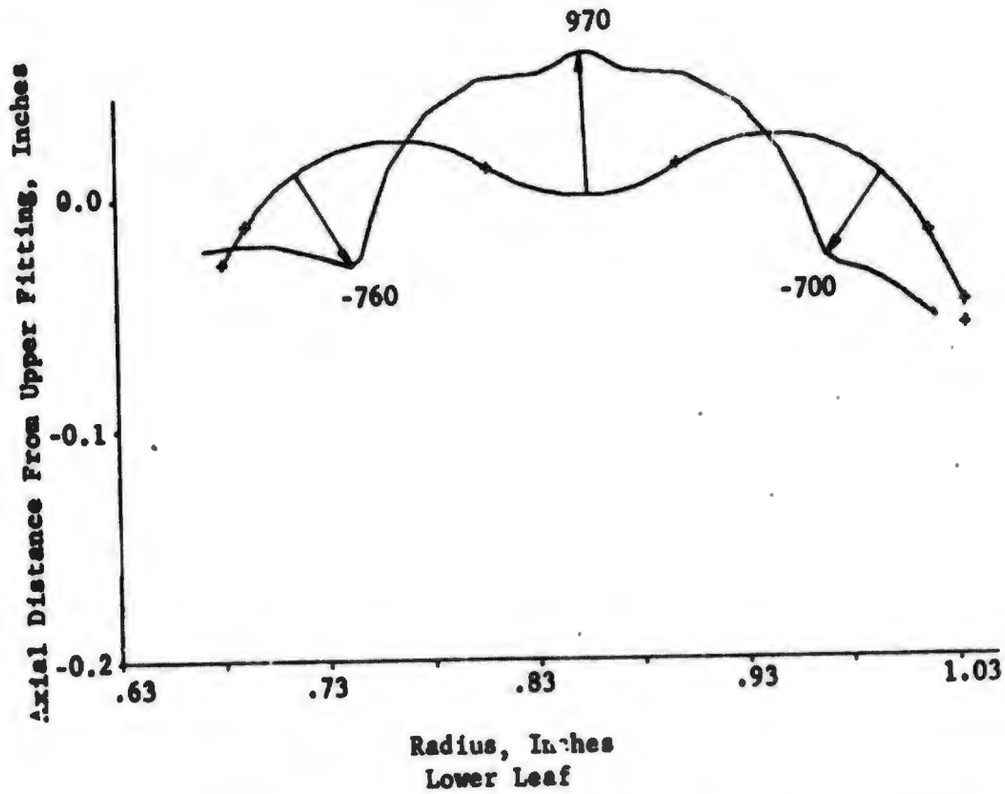


FIGURE 33. CUTER SURFACE MERIDIONAL STRESSES IN AN INTERNALLY PRESSURIZED 2-INCH BELLOWS WITH 55° ID, 60° OD TILT ANGLES, ±2.5° CHORD ANGLES, 0.08635-INCH SWEEP RADII, AND 0.3546-INCH SPAN (Pressure = 1 psi)

TABLE 17. AN OPTIMUM CONVOLUTION SHAPE FOR A 3.5-INCH TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 50°, OD TILT ANGLE = 50°, SPAN = 0.378 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
1	Conical	230.000	--	1.79730	0.05288
2	Toroidal	230.000	146.3167	1.68670	-0.10000
3	Toroidal	146.3167	193.2667	1.57522	0.10000
4	Toroidal	193.2667	130.0000	1.52989	-0.10000
5	Conical	130.0000	--	1.45329	0.05287
6	Cylindrical	90.0000	--	1.41930	0.00777
7	Conical	-50.0000	--	1.41930	0.04397
8	Toroidal	-50.0000	33.6000	1.52417	0.10000
9	Toroidal	33.6000	-13.3300	1.63483	-0.10000
10	Toroidal	-13.3300	50.0000	1.68098	0.10000
11	Conical	50.0000	--	1.75758	0.06179
12	Cylindrical	90.0000	--	1.79730	0.00777

TABLE 18. AN OPTIMUM CONVOLUTION SHAPE FOR A 3.5 INCH TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 45°, OD TILT ANGLE = 50°, SPAN = 0.6188 INCH

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
1	Conical	230	--	1.82840	0.04313
2	Toroidal	230	145	1.68288	-0.15373
3	Toroidal	145	205	1.50648	0.15373
4	Toroidal	205	135	1.37663	-0.15373
5	Conical	135	--	1.26792	0.08248
6	Cylindrical	90	--	1.20960	0.00707
7	Conical	-45	--	1.20960	0.04961
8	Toroidal	-45	35	1.35336	0.15373
9	Toroidal	35	-25	1.52976	-0.15373
10	Toroidal	-25	50	1.65961	0.15373
11	Conical	50	--	1.77738	0.07935
12	Cylindrical	90	--	1.82840	0.00777

0.005-inch for the 3.5-inch size to 0.014-inch for the 1-inch bellows expanded 3.5 times. Note that the 1-, 2-, and 3-inch bellows would have spans of .6538-, .6134-, and .6368-inches, respectively which are all comparable to the longer span 3.5-inch bellows. Using this point of view demonstrated that optimum tilt angles could be found for a bellows of a given size for a range of thicknesses. Clearly, optimum tilt angles increased as the thickness was increased.

Study of End Fitting Stresses

It was mentioned previously that nearly all of the bellows analyses were carried out with two convolution models as shown in Figure 3. The end leaves of this model were fixed at the outside ends to simulate heavy end fittings of the type shown in Figures 34 and 35*. Each analysis was examined for the effects of tilt angle on the end-fitting stresses as well as on the stresses in convolution welds. The general conclusion reached after studying the end-fitting stresses of all of the bellows analyzed was that tilt angles could be found that minimize the stresses at the end-fitting welds for either pressure or axial deflection loads. However, it was difficult to find tilt angles such that the end-fitting stresses for both pressure and axial deflection loads were satisfactorily reduced for the same tilt angle. Usually, the optimum tilt angles reduced stresses at the end-fitting welds, but these were not as low as the stresses at the convolution welds. In addition, the effect of the reversed bending and interleaf contact that reduces the stresses at the convolution welds is not present at the end-fitting.

Table 19 shows a comparison of the stresses at the upper and lower end fitting welds with the maximum bellows stresses and with the stresses at the ID and OD convolution welds. This table shows that at least one of the end fittings has an uncomfortably high stress for axial deflection loads compared to the maximum bellows stress. It is noted that the tilt angle at the upper end weld is usually lower than the optimum angle while the tilt angle at the lower end-fitting weld is usually higher than the optimum. It can be seen from Figure 3 that increasing the tilt angle at the upper end-fitting or decreasing the tilt angle at the lower end-fitting would lead to the possibility that the OD weld of the adjacent convolutions would interfere with the end fittings if the bellows were compressed.

Because of the design difficulties just described, an investigation was carried out to determine whether some simple geometric perturbation of the end leaf geometry could be found that would reduce the end fitting stresses to a level consistent with the stresses at the convolution welds. The two-convolution model of Figure 3 was used in the study to insure that the end-fitting stresses would represent the stresses in an actual bellows

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* End fittings of this type have been used in all of the bellows assemblies tested in this and the previous bellows study. Behavior of these assemblies may be considered representative of the behavior of welded bellows in valve applications.

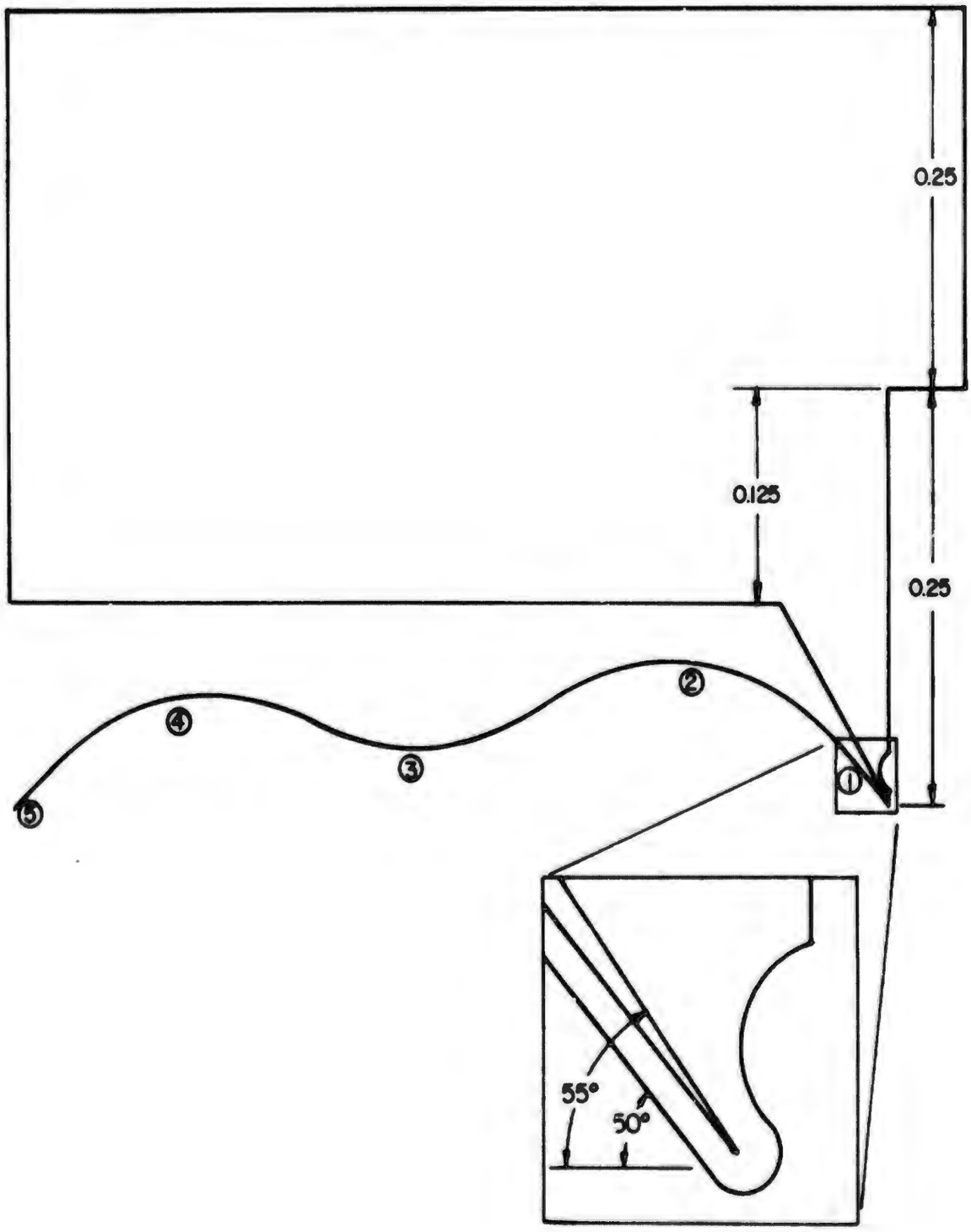


FIGURE 34. A TYPICAL UPPER END FITTING FOR A 3.5-INCH TILT-EDGE WELDED BELLOWS

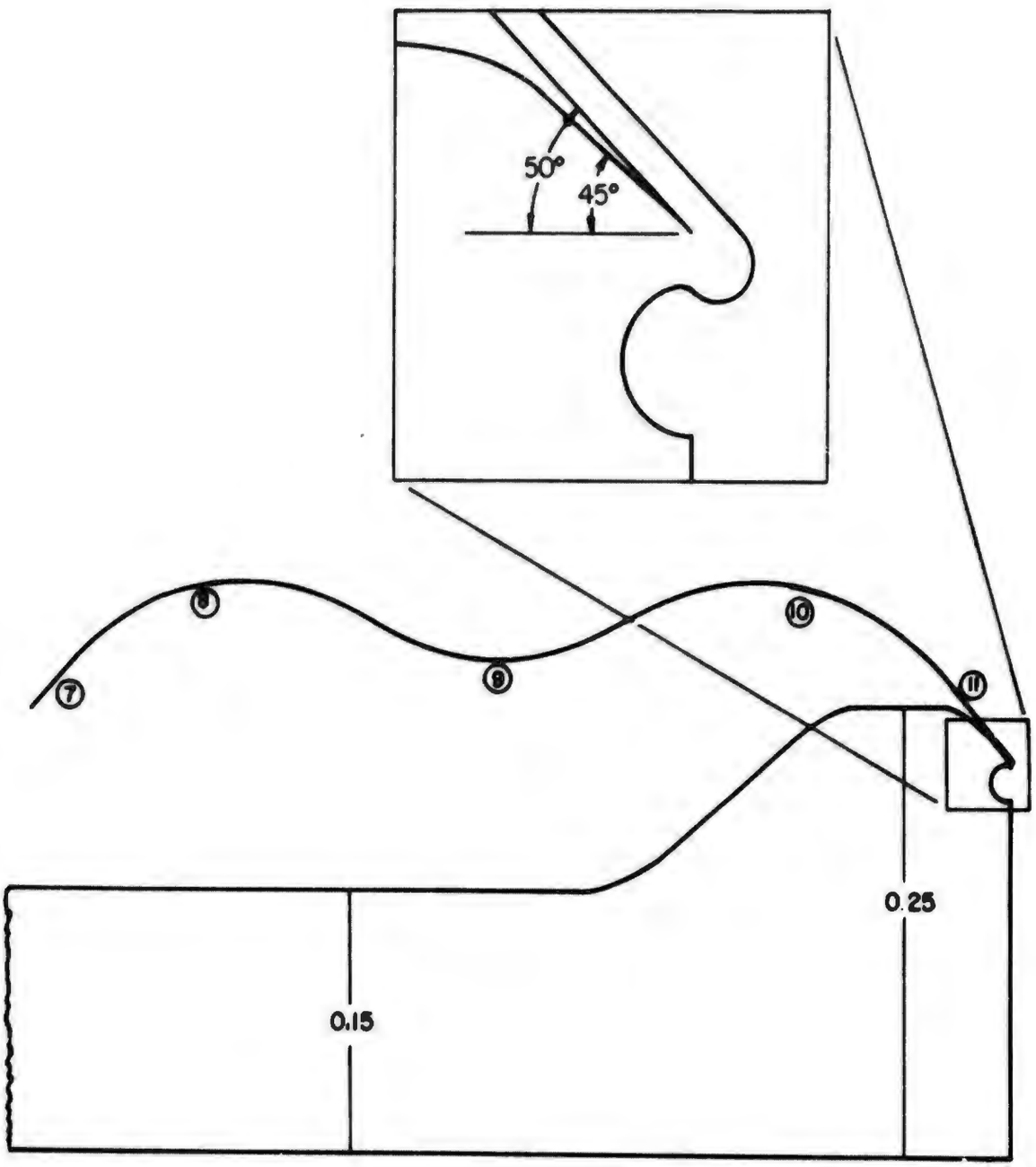


FIGURE 35. A TYPICAL LOWER END FITTING FOR A 3.5-INCH TILT-EDGE WELDED BELLOWS

TABLE 19. MAXIMUM WELD, FITTING, AND OVERALL RELATIVE STRESSES IN OPTIMUM SHAPED TILT-EDGE WELDED BELLOWS*

Bellows OD inches	Load Type	Maximum ID Weld Stress, psi	Maximum OD Weld Stress, psi	Maximum Fitting Stresses Lower psi	Maximum Fitting Stresses Upper psi	Overall Maximum Stress psi
1	Axial Compression	54,000	-61,000	-127,000	106,000	-318,000
1	Internal Pressure	-190	-210	50	-100	-520
2	Axial Compression	-27,000	-19,700	-13,500	24,500	100,700
2	Internal Pressure	-600	340	140	-180	-980
3	Axial Compression	18,044	-8,969	-37,427	32,380	-119,130
3	Internal Pressure	-530	530	1,770	-370	-1,790
3.5 **	Axial Compression	-26,800	-16,250	-77,300	67,200	-147,000
3.5 **	Internal Pressure	-520	520	380	-270	-1,250
3.5***	Axial Compression	22,300	13,850	-37,500	17,030	-105,000
3.5***	Internal Pressure	600	430	310	-200	-2,250

* To get stress (in psi) for axial deflection, multiply values by deflection and divide by free length of bellows. To get stress (in psi) for pressure loading, multiply values by pressure in psi.

** 0.378 inch span.

*** 0.6188 inch span.

assembly. The study was confined to the basic 3.5-inch bellows model with dimensions given in Tables 17 and 18. Variables considered in the study were the OD tilt angles of the end leaves, the lengths of the conical segments of the end leaves, the thicknesses of the end leaves and the addition of shape-stiffened segments such as conical or toroidal sections.

In spite of the possibility of the interference at the end fitting welds mentioned above, a study of tilt angles was conducted to verify the existence of optimum end fitting tilt angles. Such optimum tilt angles were found for the models studied. These tilt angles were not only different from the optimum angles required for the convolution welds but also were different for the upper fitting than for the lower fitting. The stresses at the upper and lower fittings for the optimum 3.5-inch bellows (span = 0.6188 inch) are given in Table 20 for three different sets of tilt angles. Minimum stress conditions at the upper fitting occurred for a 55° - OD tilt angle. However, at the lower fitting, an OD tilt angle of 45° minimized the pressure loading stresses, and a 35° tilt angle yielded the lowest deflection stresses although the optimum OD tilt angle for the middle leaves was 50°. As noted, this solution was not satisfactory because of the possibility of leaf interference at the end fittings under compression loading.

The effect on the end-fitting stresses of varying the length of the conical end segments at the end-fitting welds was investigated for the 3.5-inch bellows (span = 0.378 inch). It was found to be almost insignificant for the convolution shape studied. For the internal pressure loading, little change occurred in the stresses whether the end segments were lengthened or shortened. For the axial deflection case, halving the end segment length increased the fitting stresses less than 10 percent, while increasing the segment length by 50 percent decreased the stresses only about 10 percent. Therefore, varying the end-segment lengths appeared to be both an inefficient (for axial deflection) and an ineffective (for pressure loading) means of reducing the stress levels at the end-fitting welds.

Additional segments, both conical and toroidal, were added to the bottom end leaf of the 3.5-inch bellows (span = 0.378 inch) to determine if such end-fitting attachments would reduce the stress levels there. When added, both segment shapes reduced the axial deflection end-fitting stresses significantly, with the toroidal section being more effective than the conical section. However, the stress levels for the pressure loading case were then found to be excessive. No satisfactory compromise between the pressure loading case and axial deflection case was achieved for the shape-stiffened end segments studied. Thus, use of such additional segments was not considered promising as an effective means of optimizing the end-fitting stresses in a tilt-edge welded bellows.

Table 21 shows the effect on the end-fitting stresses of increasing the thickness of the end leaf attached at the lower fitting for the optimum 0.6188-inch span, 3.5-inch bellows shape. Results were obtained for the three thicknesses for leaf 4 (0.005 inch, 0.007 inch, and 0.009 inch). Leaves 1 through 3 had a constant thickness of 0.005 inch. This method of minimizing the fitting stresses was the most generally effective method studied. Table 21 clearly shows that increasing the end leaf thickness gave an adequate reduction in the end-fitting stresses for both the axial deflection and

TABLE 20. RELATIVE FITTING STRESSES SHOWING THE EFFECT OF END LEAF OD TILT ANGLE VARIATIONS FOR A 3.5-INCH, TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 45°, OD TILT ANGLE = 50°, SPAN = 0.6188 INCH

Location of Stresses	Axial Deflection Stresses, psi[a]				Internal Pressure Stresses, psi[b]			
	Meridional		Circumferential		Meridional		Circumferential	
	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Upper Fitting, Tilt Angle = 50°	-14,550	17,030	-4,370	5,120	24	-197	7	-59
Lower Fitting, Tilt Angle = 50°	34,600	-37,600	10,400	-11,250	-149	305	-45	91
Upper Fitting, Tilt Angel = 55°	-6,930	9,320	-2,080	2,800	-256	89	-77	27
Lower Fitting, Tilt Angle = 45°	30,900	-34,200	9,270	-10,300	69	98	21	29
Upper Fitting, Tilt Angle = 55°	-6,930	9,320	-2,080	2,800	-256	90	-77	27
Lower Fitting, Tilt Angle = 35°	18,800	-23,050	5,630	-6,920	660	-469	198	-141

(a) Unit axial deflection in a unit bellows length.
(b) For internal pressure of 1 psi

TABLE 21. RELATIVE FITTING STRESSES SHOWING THE EFFECT OF END LEAF THICKNESS FOR A 3.5 INCH, TILT-EDGE WELDED BELLOWS, ID TILT ANGLE = 45°, OD TILT ANGLE = 50°, SPAN = 0.6188 INCH

Location of Stresses	Axial Deflection Stresses, psi[a]				Internal Pressure Stresses, psi[b]			
	Meridional		Circumferential		Meridional		Circumferential	
	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
	Lower End Leaf Thickness = 0.005							
Upper Fitting	-14,550	17,030	-4370	5120	24	-197	7	-59
Lower Fitting	34,600	-37,600	10,400	-11,250	-149	305	-45	91
	Lower End Leaf Thickness = 0.007							
Upper Fitting	-16,450	-19,250	-4,930	5,770	32	-206	9	-62
Lower Fitting	24,200	-26,800	7,250	-8,030	96	14	29	4
	Lower End Leaf Thickness = 0.009							
Upper Fitting	-17,400	20,300	-5,210	6,100	34	-208	10	-63
Lower Fitting	16,850	-19,100	5,050	-5,740	174	-92	52	-28

(a) Unit axial deflection in a unit bellows length.
(b) For internal pressure of 1 psi

internal pressure loadings. Thus, optimum (minimum) end-fitting stresses were obtained for the 3.5-inch bellows. It should be mentioned that the effect of the increased bellows stiffness, due to the presence of a thicker end leaf, led to increases in the stresses in leaves 2 and 3 for an axial deflection loading. The stress level increases were not severe, particularly when compared with the sizeable reductions achieved in the end-fitting stresses. In an actual welded bellows assembly, the number of convolutions will be large enough that the effect of increasing the thickness of the two end leaves should be very small. The results of this section show that if the end-fitting stresses were too high for a particular welded bellows design, the most reliable remedy would be to increase the thickness of the end leaves. Although this would require the use of blanks of different thickness, it has the advantage to the manufacturer that different dies are not needed to form the end leaves. Assuming that the bellows manufacturer would accept the inconvenience of providing for increased thickness end leaves, it would appear that the end-fitting stresses can be reduced to acceptable levels for tilt-edge bellows by use of such end leaves.

SECTION IV

ANALYSIS, FABRICATION AND EVALUATION OF TILT-EDGE BELLOWS DESIGNS

One of the objectives of the research study was to design, fabricate, and test a tilt-edge bellows with dimensions comparable to one of the conventional bellows tested in the previous bellows study. It was decided that the 3.5-inch OD, 347 stainless steel bellows described in Appendix H of Technical Report No. AFRPL-TR-68-22 would be used for comparison. A design study was therefore carried out to develop an optimized tilt-edge bellows with a 3.5-inch OD.

Because of the novelty of the tilt-edge bellows concept, it was decided to carry out a preliminary investigation of the fabricability of tilt-edge bellows to uncover any fabrication problems at an early stage of the contract. Such problems could then be remedied before the final bellows design was made. Further, the 4-inch OD tilt-edge bellows described in Appendix C of AFRPL Technical Report No. TR-68-22 (1) had sufficiently low weld stresses under axial loading that it could be expected to demonstrate fatigue failure in the convolutions rather than at the welds. Accordingly, it was decided to fabricate and test this bellows configuration, which will be called the interim bellows. The following section describes the investigation of the fabricability of tilt-edge bellows and then the fabrication and testing of the interim bellows. Following this, the design, fabrication, and testing of the optimized tilt-edge bellows will be described.

Fabrication and Evaluation of an Interim Tilt-Edge Bellows Design

As explained previously, the decision was made to fabricate and test an interim tilt-edge bellows configuration prior to the fabrication and evaluation of an optimized design. This interim test step was expected to provide a better understanding of the fabrication requirements and performance characteristics of tilt-edge bellows, thus increasing the probabilities of success with an optimized configuration.

Preliminary Fabrication Investigation

The major fabrication differences between a tilt-edge bellows and a standard welded bellows appeared to be associated with the flat portions near the inner and outer weld beads. In most standard welded bellows these portions of the convolutions are essentially perpendicular to the bellows centerline. Present welding procedures incorporate equipment based on this configuration.

In the tilt-edge bellows, the flat portions near the weld beads were to be tilted at some angle to the bellows centerline. Preliminary tests were conducted at Battelle to determine whether the tilting of the edges presents any problems in the use of standard welding equipment and procedures.

The tungsten inert-gas (TIG) welding process was selected as being representative of the procedures used by welded bellows manufacturers. A

tracked, motorized carrier was used to support a welding fixture and to drive it under a small TIG torch at controlled speeds. The welding fixture consisted of copper-infiltrated, tungsten carbide jaws capable of holding rectangular strips of metal approximately 3 inches by 3/8 inch.

Type 347 and Type 321 stainless steels were selected as being typical of the bellows materials used for rocket propulsion systems. A thickness of 0.005 inch was also selected as being typical. Pairs of metal strips were positioned in the weld fixture with the 3-inch dimension horizontal and with a measured amount of material protruding above the clamp face. The welding torch was placed directly above the strips at measured angles to simulate angular relationships between the eventual production bellows and the production welding torch.

Approximately 100 edge-burndown welding runs were made, varying the following welding parameters:

Travel speed: 5.5 to 18 in. per minute
Welding Current: 1.4 to 2.6 amp
Stickout Distance: 0.090 to 0.265 in.
Electrode-to-Work Distance: 0.008 to 0.015 in.
Gas Flow Rate: 8 to 20 cu ft per hr
Torch Inclination: 0 to 55° from vertical

Based on this work it was concluded that the tilt-edge bellows should present no unusual problems in the achievement of uniform weld beads using standard TIG welding procedures and equipment.

Bellows Manufacturer Selection

The interest of bellows manufacturers in participating in an experimental development effort can vary considerably depending on personnel, work load, and corporate policy. Six of the major manufacturers of welded bellows were selected in the first month of the program. Requests for quotations for price and delivery were sent for the following items:

(1) Six 4-inch welded bellows, with end fitting attached, having a convolution configuration like that determined during the previous bellows program [Contract No. 04(611)-10532].

(2) Fifty each of the blanked and formed male and female diaphragms of the configuration that would be used in making these bellows.

(3) A lot of from 12 to 24 welded bellows, approximately 4 inches OD, having an unspecified tilt-edge configuration to be determined during the present program, with end fittings attached.

(4) Two-hundred-fifty each of the male and female blanked and formed diaphragms of the design to be specified in Item (3).

The material was to be either Type 321 or Type 347 stainless steel, at the supplier's option. It will be noted that the request was intended to

select a manufacturer for both the interim bellows [Items (1) and (2)] and the optimized bellows [Items (3) and (4)].

Four quotations were received. The lowest quotation was received from the Sealol Corporation in Providence, Rhode Island. They also promised satisfactory delivery time. Sealol's bid was approximately 40 percent lower in cost than the next lowest bidder. Because Sealol was known to be a leading manufacturer of welded bellows and had submitted a very attractive quotation, Sealol was selected to manufacture the interim bellows. The performance on this requirement was expected to be a check on whether Sealol should subsequently be selected to make the optimized bellows.

Interim Bellows Fabrication

The fabrication of 6 interim bellows and the associated extra diaphragms was completed by Sealol without incident. When tests with these bellows (see below) showed interference between the end diaphragms and the end fittings (through design oversight), seven additional interim bellows were ordered. The extra diaphragms obtained with the original six bellows were used for the additional bellows. New end fittings with additional clearance were machined.

Figures 36 through 40 show the tooling fabricated by Sealol to achieve clamping and cooling of the diaphragms during welding of the interim bellows. The setups for making an inner convolution weld and an outer convolution weld are shown in Figures 36 and 37, respectively. Figure 38 shows a partial disassembly of the inner-convolution-weld tooling, while Figures 39 and 40 show a partial and a complete disassembly of the outer-convolution-weld tooling.

Interim Bellows Inspection

The inspection planned for the interim bellows was related to determining whether the bellows were as uniformly made as standard welded bellows. For this purpose, the weld beads were inspected for uniformity of size and color. The major dimensions were measured to determine dimensional uniformity. The visible parts of the diaphragms were also inspected for dents and scratches and other signs of handling damage. The same inspection procedures were applied to both sets of interim bellows.

According to the visual inspection, the bellows were comparable in quality to state-of-the-art welded bellows. Measurement of major dimensions such as free length, pitch length, and convolution inner and outer diameters also showed uniformity comparable to that achieved for standard welded bellows. The subsequent inspection of cross sections of failed bellows showed good weld bead and convolution uniformity.

Based on the inspection of the 13 interim bellows, it was concluded that tilt-edge bellows could be fabricated satisfactorily by present manufacturing techniques.

Interim Bellows Tests

Two types of experimental information were selected as being important for the interim bellows: (1) spring rate and (2) fatigue characteristics.

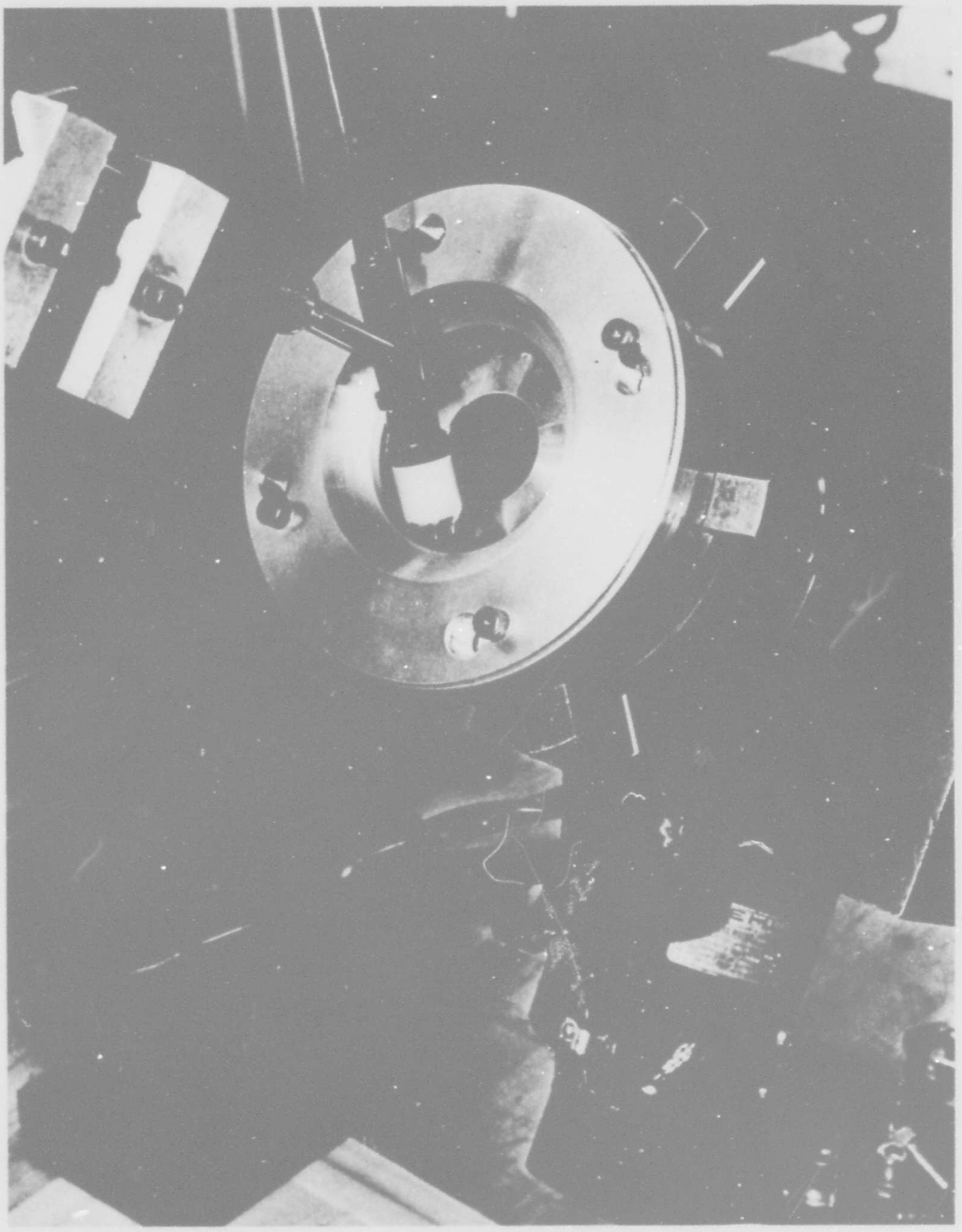


FIGURE 36. SETUP FOR MAKING AN INNER CONVOLUTION WELD

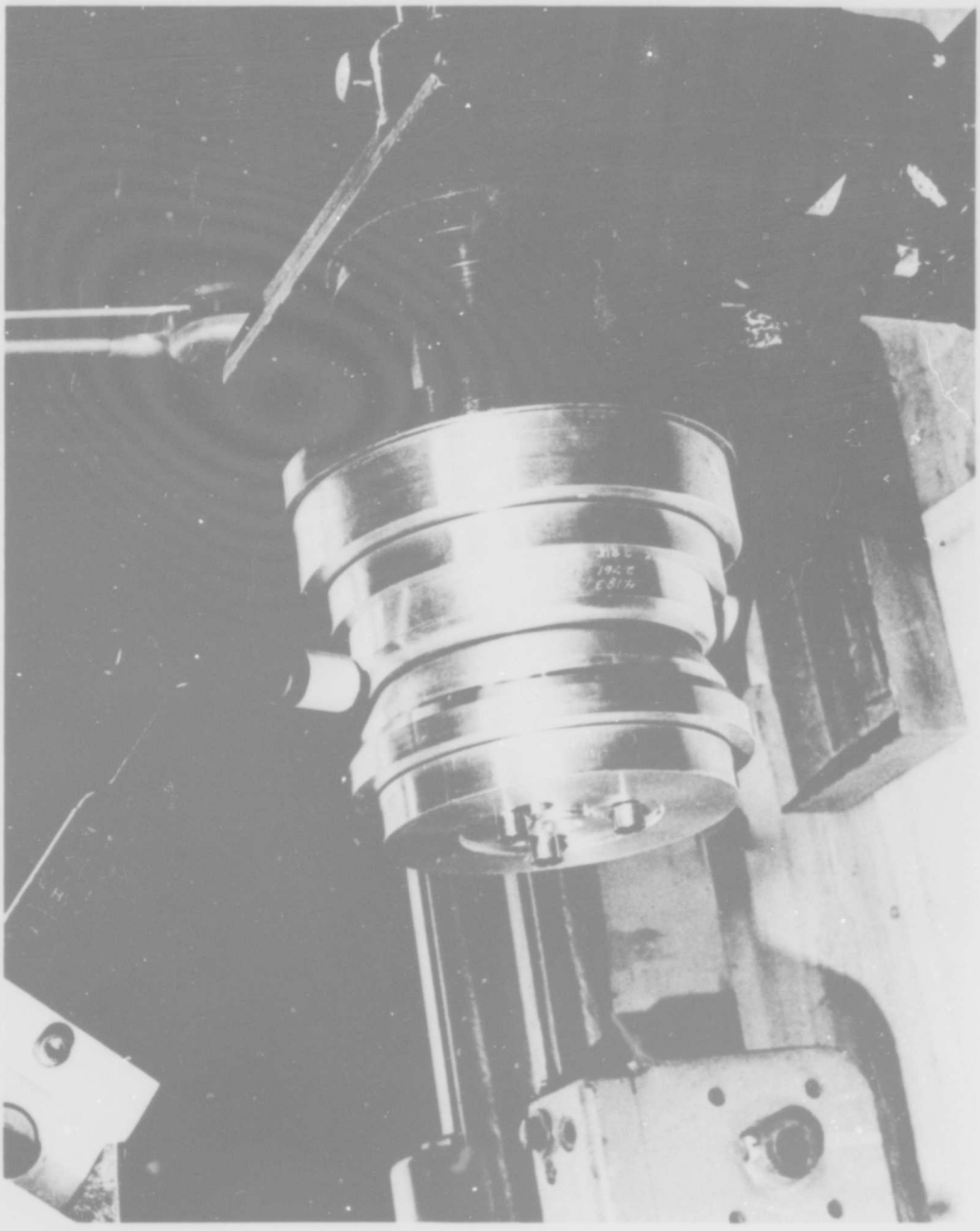


FIGURE 37. SETUP FOR MAKING AN OUTER CONVOLUTION WELD

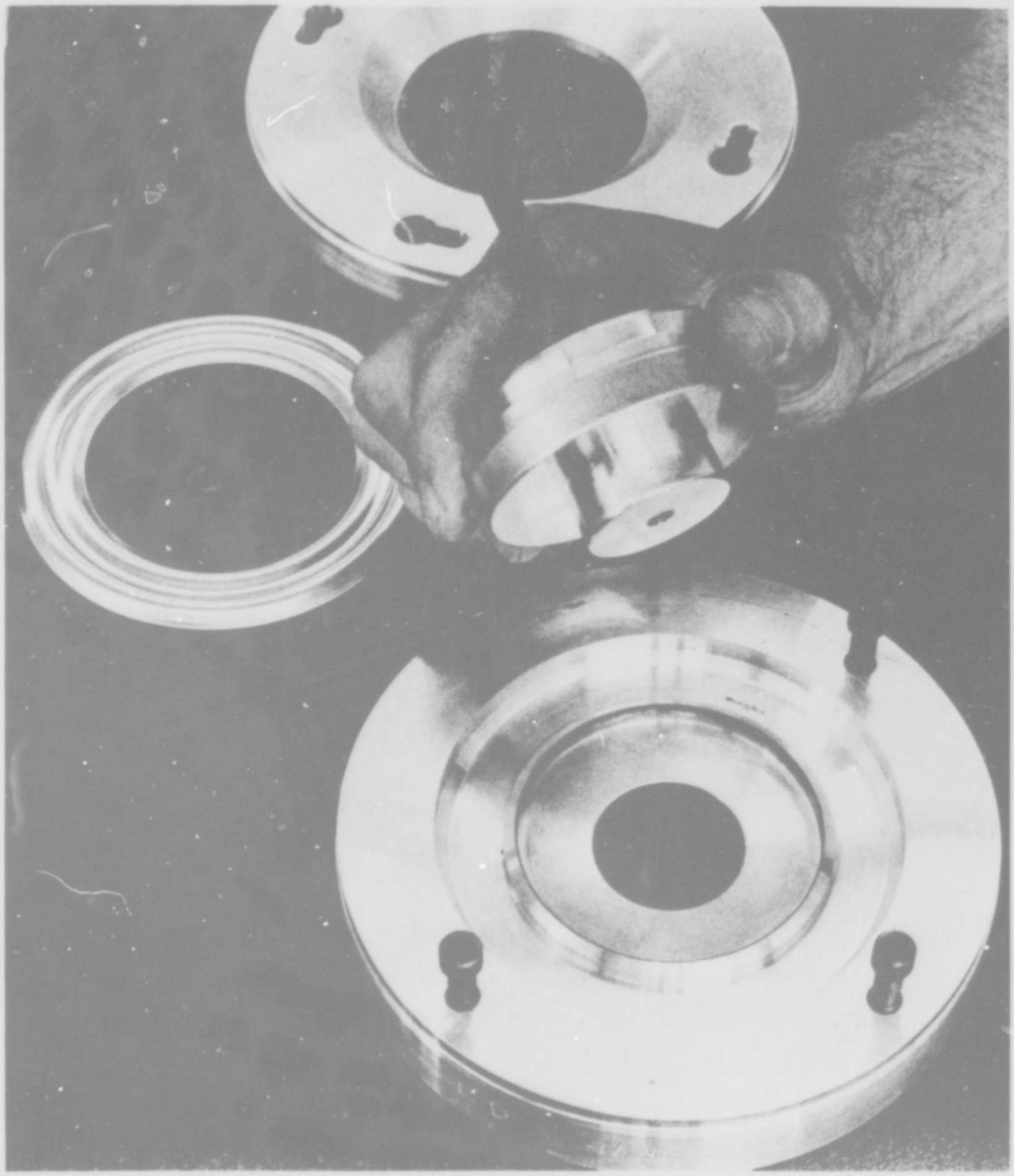


FIGURE 38. PARTIAL DISASSEMBLY OF THE INNER-CONVOLUTION-WELD TOOLING

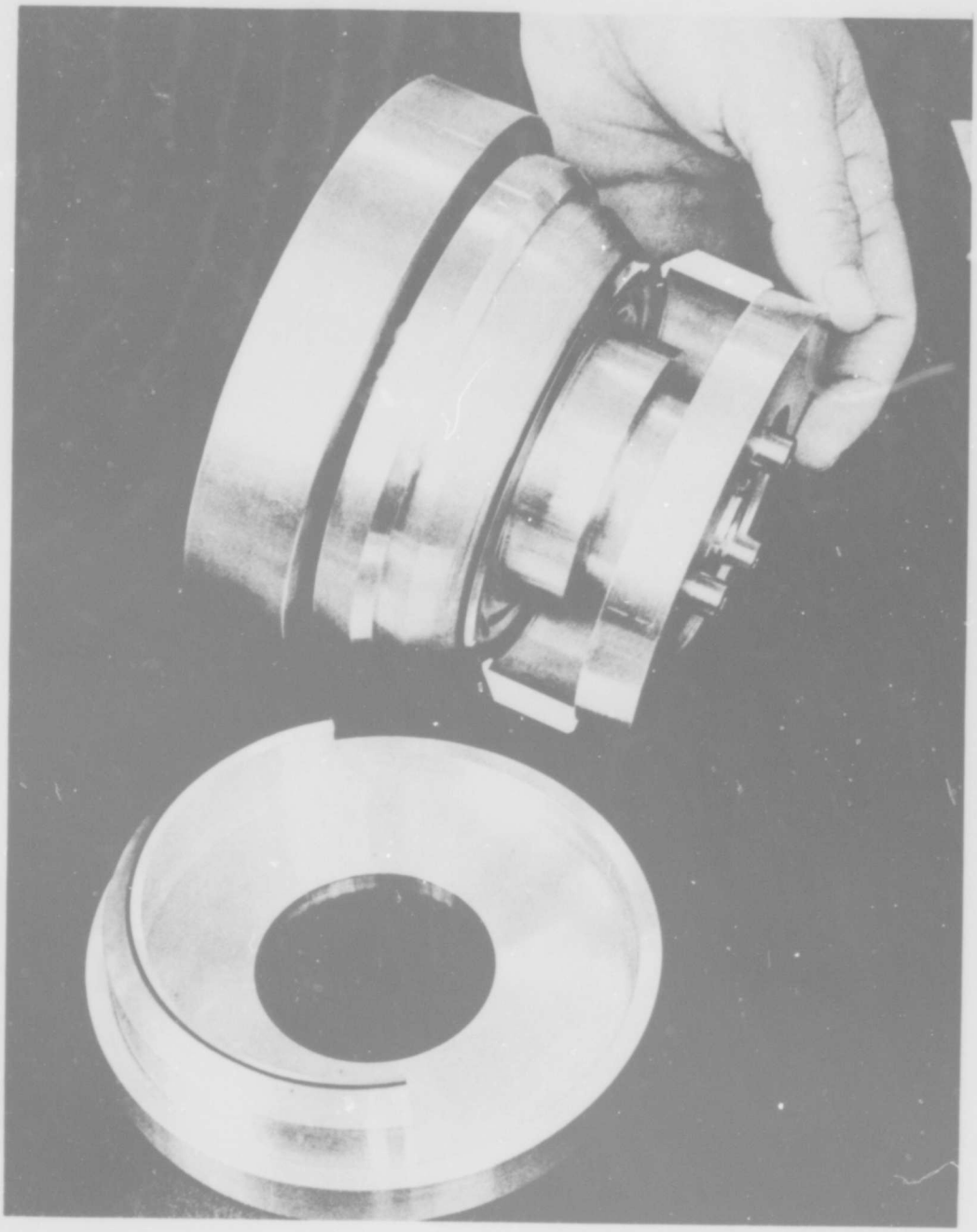


FIGURE 39. PARTIAL DISASSEMBLY OF THE OUTER-CONVOLUTION-WELD TOOLING

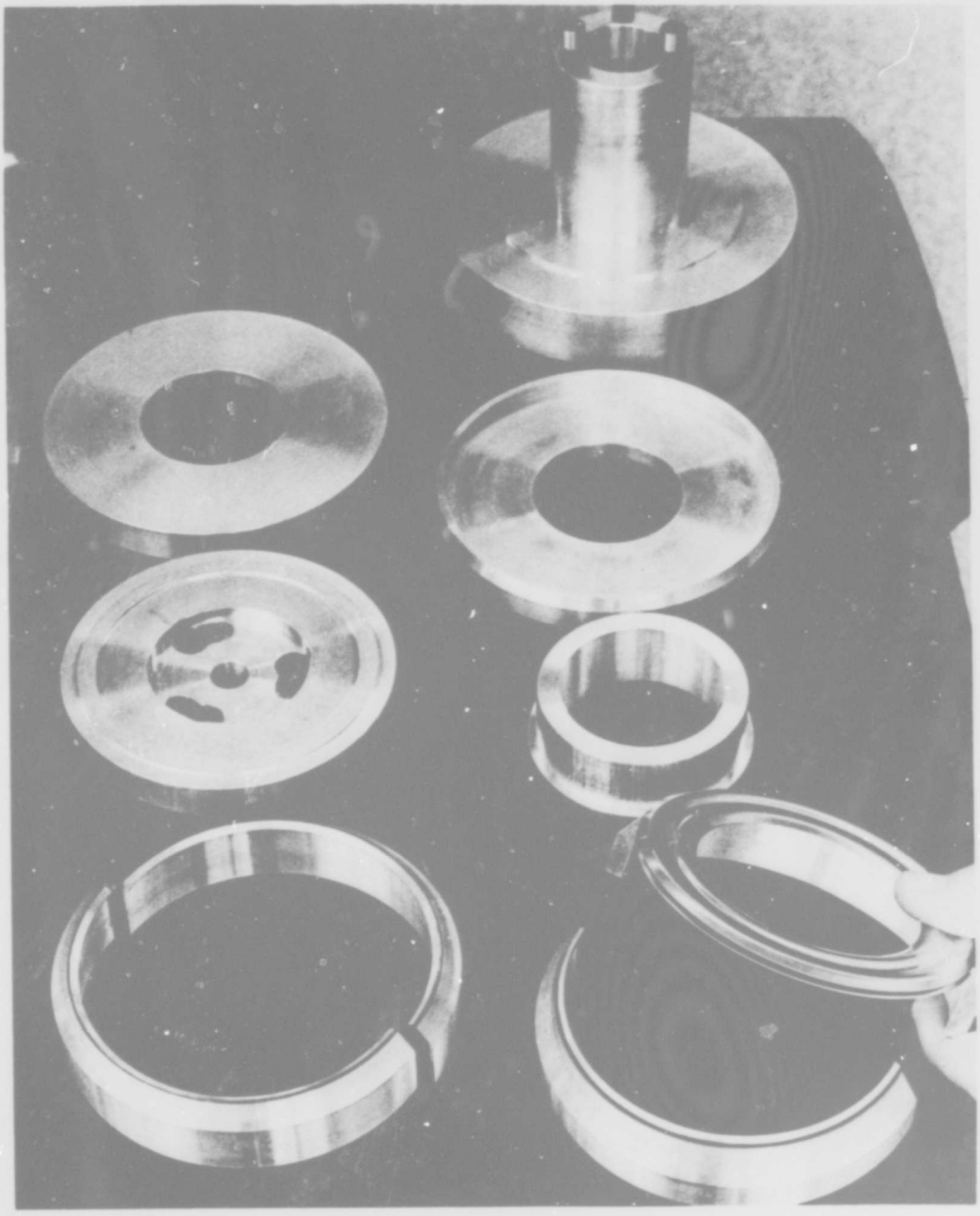


FIGURE 40. COMPLETE DISASSEMBLY OF THE OUTER-CONVOLUTION-WELD TOOLING

Spring Rate. Although calculations during the previous bellows program had shown that the spring rates of tilt-edge bellows could be made comparable to the spring rates of standard welded bellows, it was known that the tilted edges provided some stiffening to the diaphragms. Because spring rate is one of the principal design characteristics of welded bellows, it was important to show that the actual spring rates of a tilt-edge welded bellows could be approximated by the theoretical calculations.

Table 22 shows the spring rates measured for the 13 interim bellows with 1/2 inch compression and 1/2 inch extension. Also shown is the theoretical spring rate as determined by a linear calculation. The theoretical value compared very closely with the experimental extension values, as was the case with the standard bellows that were analyzed and tested during the previous program. Table 22 shows a lower compression spring rate than the extension spring rate. This same difference in compression and extension spring rates were also observed for the standard bellows tested in the previous program (page 22, Reference 1). This difference in spring rates was not investigated further for the interim bellows, since the primary interest was in the fatigue behavior of these bellows.

TABLE 22. THEORETICAL AND EXPERIMENTAL SPRING RATES FOR INTERIM BELLOWS SPECIMENS

Bellows No.	Spring Rate, lb/in.	
	1/2-Inch Compression	1/2-Inch Extension
KT-1	32.6	40.0
KT-2	31.7	39.8
KT-3	31.7	52.1
KT-4	31.8	39.2
KT-5	31.8	39.1
KT-6	32.2	39.7
KT-7	30.9	40.0
KT-8	30.1	40.6
KT-9	30.4	39.6
KT-10	30.6	40.1
KT-11	30.5	40.1
KT-12	31.1	39.1
KT-13	30.3	40.2
Theoretical Spring Rate (Linear)	40.8	40.8

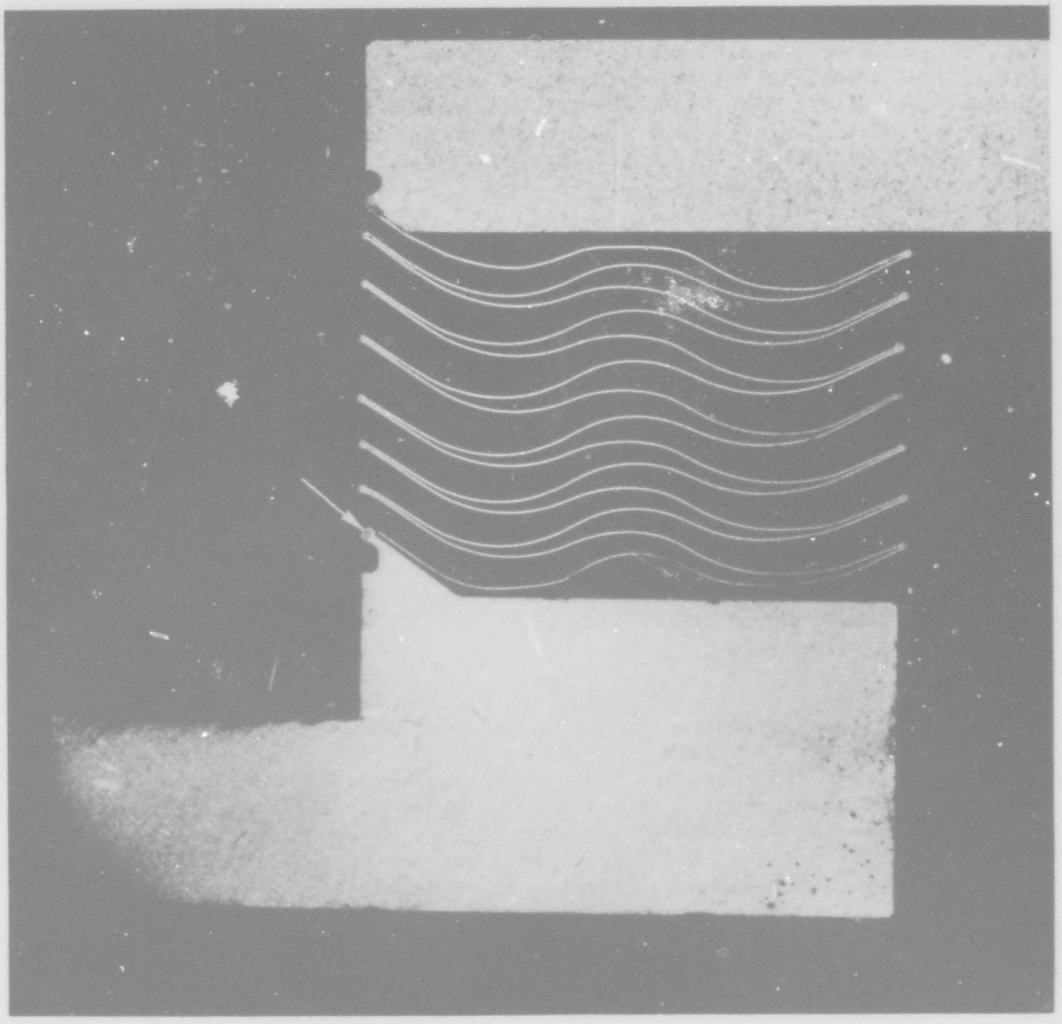
Fatigue Characteristics. A major purpose of the tilt-edge configuration was to prevent fatigue failure in the inner and outer weld beads. Because this had never been achieved intentionally in a design, the location of the fatigue failures was of prime importance. By achieving failure in the parent metal of the diaphragm, it was expected that the fatigue values of the bellows would be more predictable and uniform than for standard welded bellows, where failure occurs in the weld beads. Thus, the ability to estimate fatigue life from a strain calculation at the point of failure and the spread of the fatigue values were also important for the interim bellows. The fatigue machine developed during the previous program was used for these tests. The cycle rate was 80 cpm. Fatigue failure was indicated by the detection of small amounts of gas leakage.

The results with the first 6 interim bellows were erratic. The first two bellows failed at an end fitting because of interference (through design oversight) between the end convolutions and the end fittings (see Figure 41). The next three bellows were tested with increased amounts of extension instead of compression, to avoid end-fitting interference. Although failure occurred in the diaphragms in the area of maximum stress (see Figures 42 and 43), the fatigue values did not correlate well with the theoretical estimate nor with each other. Further, the sixth bellows failed at an end fitting. It was concluded that the tests had little value and that additional specimens were needed. Seven more bellows were ordered identical to the first six but with modified end fittings to avoid interference.

The results with the second batch of interim bellows were very promising. Six of the seven bellows developed fatigue cracks in the parent metal of the diaphragms in the area of highest stress. The seventh bellows failed prematurely at an end fitting. The end-fitting failure appeared to be caused by a poor weld.

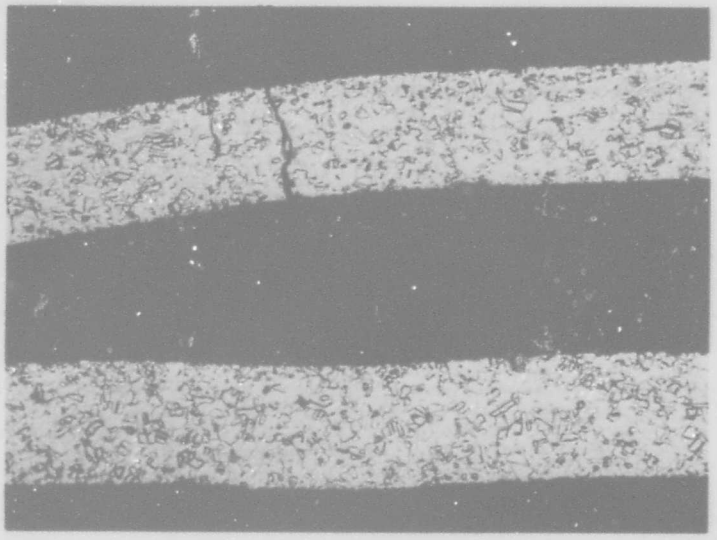
A linear calculation of the maximum strain range (total strain for the entire bellows deflection at the location of maximum strain) for the interim bellows with 1/2-inch compression and 1/2-inch extension gave a value of 3700 microinches/inch. This strain occurred near the intersection of the inner flat (conical section) and the first torodial section. Using Figure L-6 from the final report on the previous program (Figure L-6 is duplicated in Figure 44), two fatigue life ranges were estimated. If the bellows performed like formed bellows, the fatigue values would range from about 30,000 cycles to about 400,000 cycles. If the bellows performed like metal coupons (as hoped) the fatigue values would range from about 250,000 cycles to about 1,000,000 cycles.

As noted above, one bellows failed prematurely (at 6114 cycles) because of a poor weld. The other six bellows gave the following fatigue values: 112,115 cycles, 292,900 cycles, 356,142 cycles, 389,465 cycles, 511,952 cycles, and 904,207 cycles.



5X Aqua Regia 3D537

FIGURE 41. CROSS SECTION OF FIRST INTERIM BELLOWS (KT-4) SHOWING END-FITTING FAILURE AND END-FITTING INTERFERENCE



150X Glyceregia 3D723

FIGURE 42. CROSS SECTION OF FATIGUE FRACTURE IN INNER TOROIDAL SEGMENT OF FOURTH CONVOLUTION OF INTERIM BELLOWS KT-1

500X Glyceregia 3D725

FIGURE 43. FATIGUE FRACTURE IN FIGURE 42 AT HIGHER MAGNIFICATION

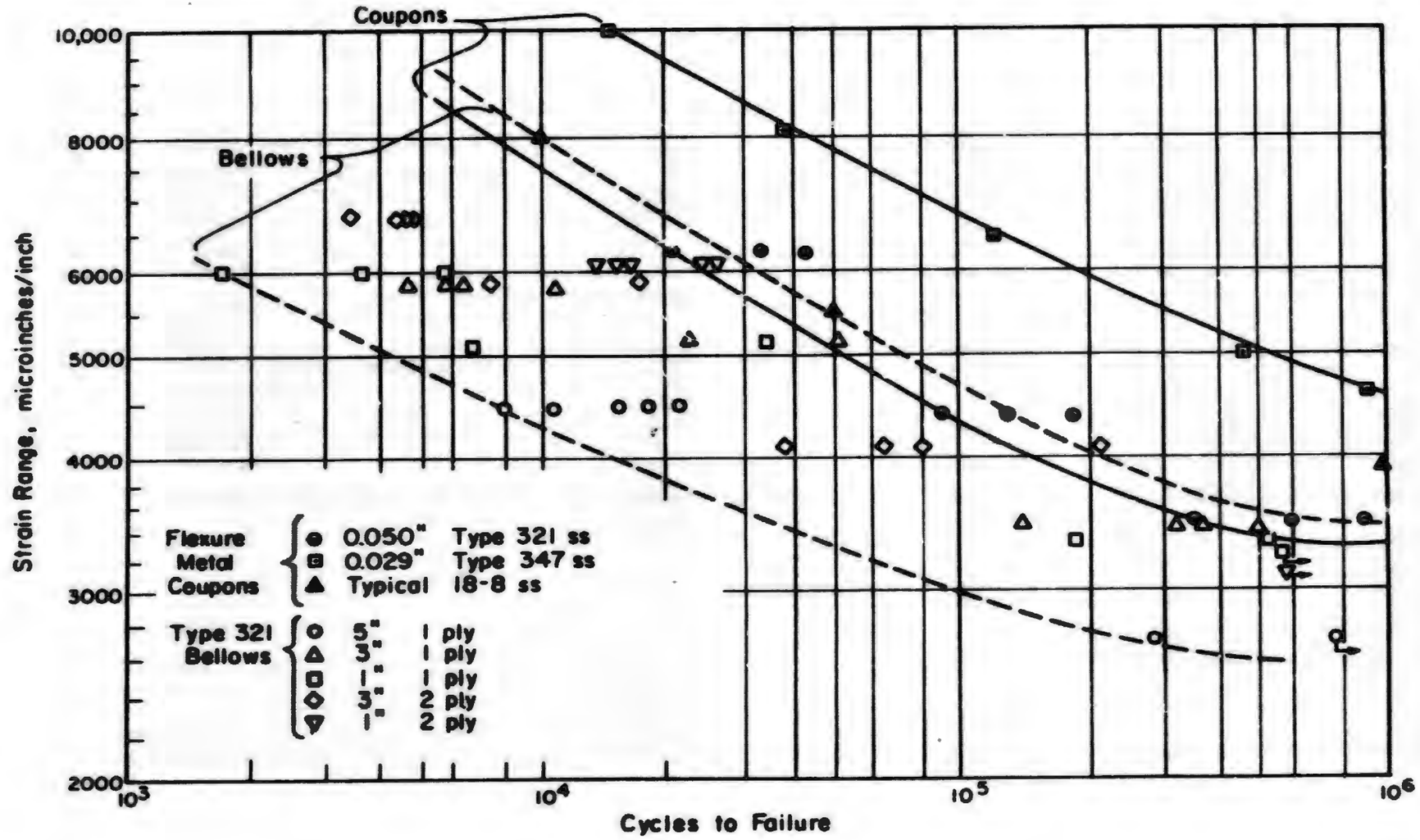


FIGURE 44 FATIGUE RESULTS OF STAINLESS STEEL FORMED BELLOWS AND STAINLESS STEEL COUPONS

Interim Bellows Conclusions

From the tests of the interim bellows, the following conclusions were made:

(1) The theoretical stress analysis procedure appeared to be even more applicable to the tilt-edge bellows configuration than it was to standard welded bellows.
(2) The average fatigue life of tilt-edge bellows could be estimated using data from bending-fatigue tests of sheet metal coupons made of the same material if some allowance was made for manufacturing variability in making the bellows.
(3) The fatigue life spread would be somewhat greater for the bellows than for the coupons, but much less than for standard welded bellows.
(4) In addition to minimizing stresses at the convolution welds, the stresses at the end fitting of the optimized bellows should be made as low as possible to minimize the possibility of early fatigue failure caused by unsound end-fitting welds.

Design, Fabrication, and Evaluation of an Optimum Bellows Configuration in Comparison With a Conventional Welded Bellows

As mentioned above, the conventional bellows selected for comparison was a 3.5-inch OD stainless steel bellows. This bellows had a thickness of about 0.005 inch and a span of 0.378 inch. The average spring rate for this bellows was 57 lb/in. Details of the stress analysis and testing of this bellows were reported in Appendix H and Appendix N of Technical Report No. AFRPL-TR-68-22.

The general objective in comparing a tilt-edge bellows to a conventional welded bellows was to demonstrate that a tilt-edge bellows could be used to replace the conventional bellows and would significantly outperform it. To achieve this objective, the tilt-edge welded bellows design parameters (i.e., number of convolutions, outside diameter, inside diameter, height, and spring rate) should be comparable to the standard welded bellows.

Two tilt-edge bellows configurations were developed for comparison with the standard bellows. In the first, all the major dimensions of the tilt-edge bellows were the same as for the standard bellows. One difference was that the tilt-edge bellows had three sweeps instead of the four sweeps used in the standard bellows. An odd number of sweeps was chosen to give the tilt-edge bellows convolution symmetry. The shape for this bellows was given in Table 17.

An analysis of this first tilt-edge configuration showed that the maximum stresses occurred well away from the weld areas, as desired. This

is shown in Figures 19 and 21. However, the tilt-edge bellows had a slightly higher calculated spring rate than the standard bellows. The maximum calculated pressure stress was about half that of the standard bellows, while the maximum calculated deflection stress was about the same as that of the standard bellows. This meant that the tilt-edge configuration was optimized with regard to pressure capability rather than deflection capability.

In a discussion with the Air Force Technical Monitor, it was agreed that most bellows applications of interest to the Rocket Propulsion Laboratory require increased deflection capability rather than increased pressure capability. It was decided that the span length could be increased by making the bellows ID smaller (from 2.838 inches to 2.328 inches) without detracting from the usefulness of the bellows. This bellows would have comparable pressure stresses, but lower deflection stresses than the standard bellows. Accordingly, a purchase request was made for a tilt-edge bellows having a 0.62-inch span. The dimensions of this bellows were essentially the same as those given in Table 18 except that the pitch was reduced to about 50 mil to correspond with the pitch of the conventional bellows. A purchase request was sent to Sealol Manufacturing Company for fabrication of these bellows.

During the final stages of fabrication, Sealol notified Battelle-Columbus that the diaphragms for the optimized bellows were not as close to the required dimensions as expected. This was caused by improper specification of the tilt angles by Sealol when the die drawings were made from the configuration drawings submitted by Battelle. Because most of the bellows cores (the convolution assemblies) had been completed, it was mutually agreed that a completed specimen would be sent to Battelle-Columbus, and that a stress analysis would be made to determine whether the bellows were sufficiently close to the desired configuration to be acceptable.

The sample bellows specimen was encapsulated in plastic at Battelle-Columbus, cross sectioned, and polished. Hardness indentations were made along the centerlines of the leaves of a typical convolution (see Figure 45). Measurements were made of the locations of these centerline points.

A two-convolution analysis model was then prepared. Some of the significant parameter deviations noted in the cross section were:

(1) The tilt angle at the ID was 38° as compared to a specified angle of 45°
(2) The tilt at the OD was 37° as compared to a specified angle of 50°
(3) The pitch of the bellows specimen was about twice the specified pitch
(4) The radii for the toroidal shells were significantly different than specified.

The results of the stress analysis (for axial deflection and pressure loading) for the specimen were compared to the corresponding results

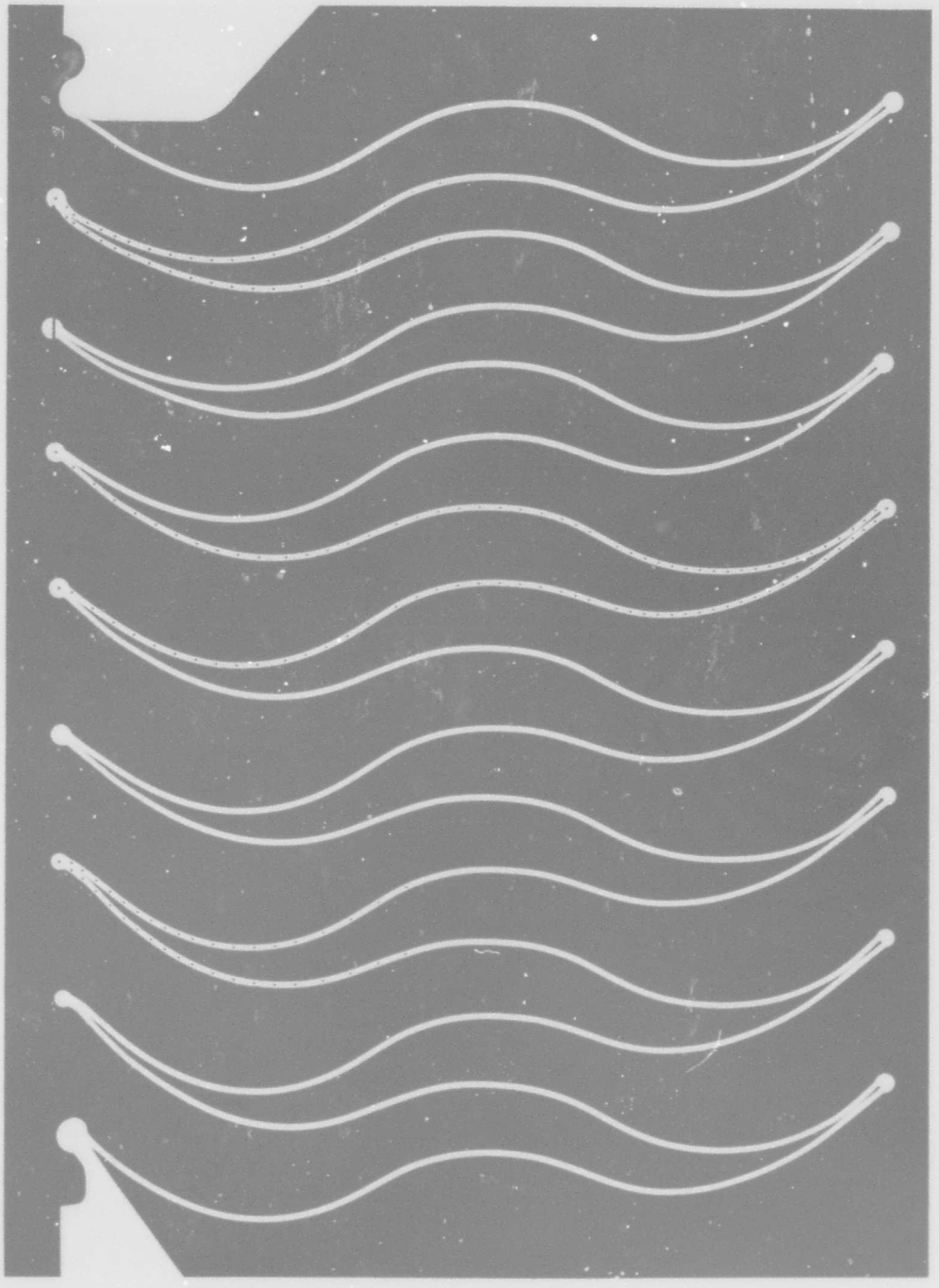


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FIGURE 45. CROSS SECTION OF UNSATISFACTORILY FABRICATED BELLOWS SPECIMEN

obtained for the optimized shape. Figures 46 and 47 are typical stress plots for the optimized shape; Figures 48 and 49 are the corresponding plots for the specimen. Although the maximum stresses and their locations for the specimen were comparable to the optimized shape, the weld area stresses, without exception, were considerably higher for the specimen than for the optimized shape. Also, the end fitting design was nc longer optimum.

Examination of the bellows cross section also showed that some of the convolutions had been crimped next to the outer diameter welds. This can be seen in Figure 45 for the convolutions adjacent to the end fittings. The decision was made that the bellows could not be used to evaluate the design.

Satisfactory Bellows Fabrication

Sealol agreed to remake the optimized bellows without additional charge. To facilitate the welding operation it was mutually agreed that the pitch be increased. This provided a better fit between the outer weld clamping fixture and the diaphragms with a two-part clamping insert. If the original pitch had been maintained, a three-part clamping insert would have been required. A slight increase in the flat portions near the inner and outer welds was also incorporated in the redesigned bellows to permit better fit with the clamping fixtures.

These changes in design were readily accomplished, using the computer analysis program to verify the acceptability of the revised dimensions. The revised design was sent to Sealol three days after the request for modification. The dimensions of this design are listed in Table 23.

When a sample specimen of the modified design was received at Battelle-Columbus, it too was encapsulated, cross sectioned, and measured. Figure 50 shows the bellows cross section. Figure 51 shows the typical convolution that was selected for measurement.

The measurements of the cross-sectioned bellows showed that the convolutions were very close to the dimensions given by the drawings for the theoretical bellows. A mathematical model was constructed from these measurements and analyzed with Program NONLIN. The thickness of the bellows leaves was measured at intervals along the leaves and this thickness variation was incorporated in the mathematical model. (Thickness variation of from 0.00450 to 0.00509 inch was recorded.) The outer surface meridional stresses for pressure and deflection loading are shown in Figures 52 and 53, respectively. These figures show satisfactorily low weld stresses. The predicted upper and lower end-fitting stresses were -460 and +310 psi, respectively, for a 1-psi pressure, and 3,400 and 26,400 psi for a unit deflection. These stresses were slightly higher than the convolution weld stresses. However, it was believed that these stresses were sufficiently lower than the maximum stresses in the parent metal of the convolutions that failure would not be expected at the end-fitting welds.

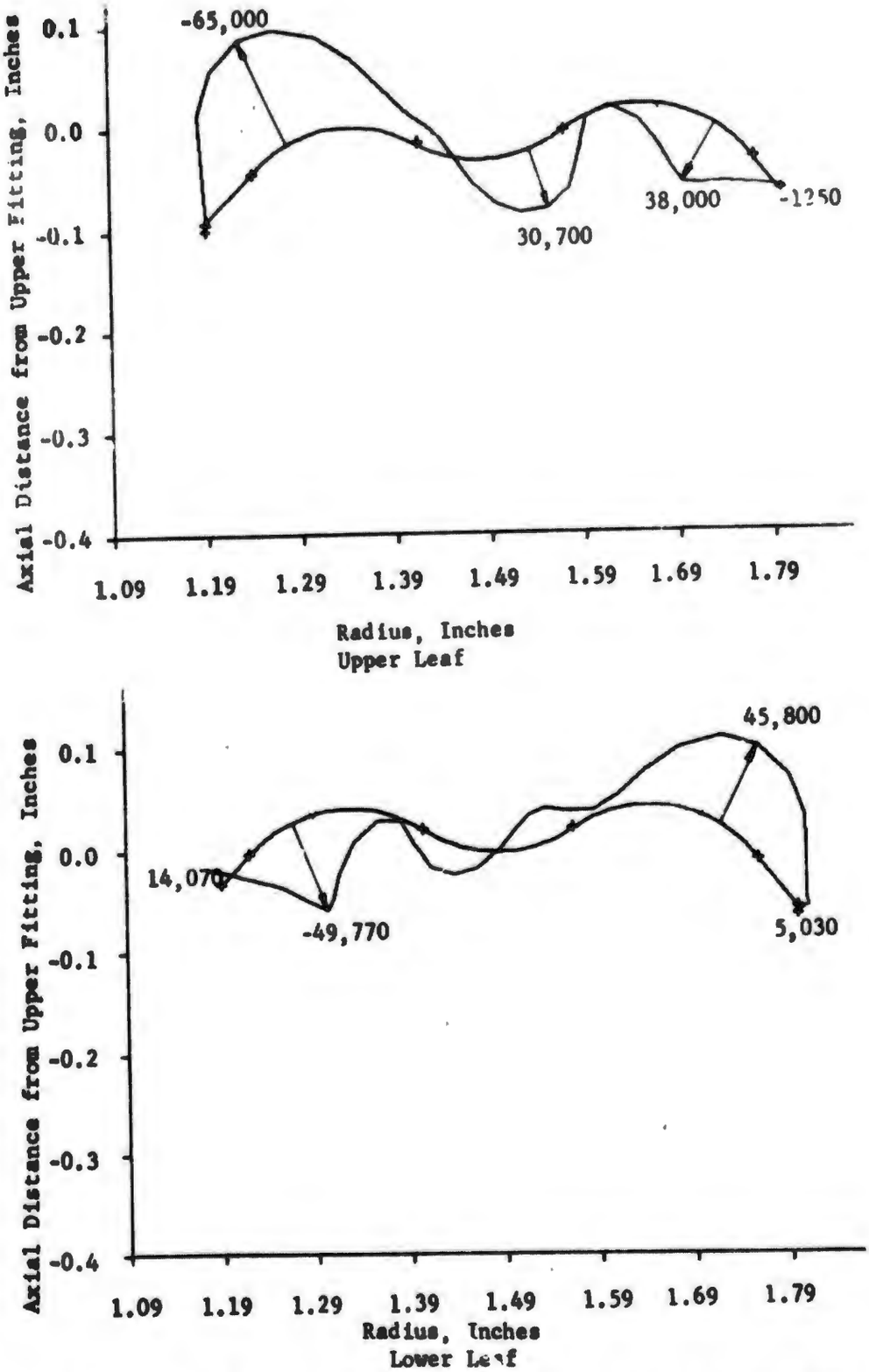


FIGURE 46. OUTER SURFACE MERIDIONAL STRESSES IN THE 3.5-INCH WELDED BELLOWS AS DESIGNED (Unit Axial Compression Per Unit Bellows Length).

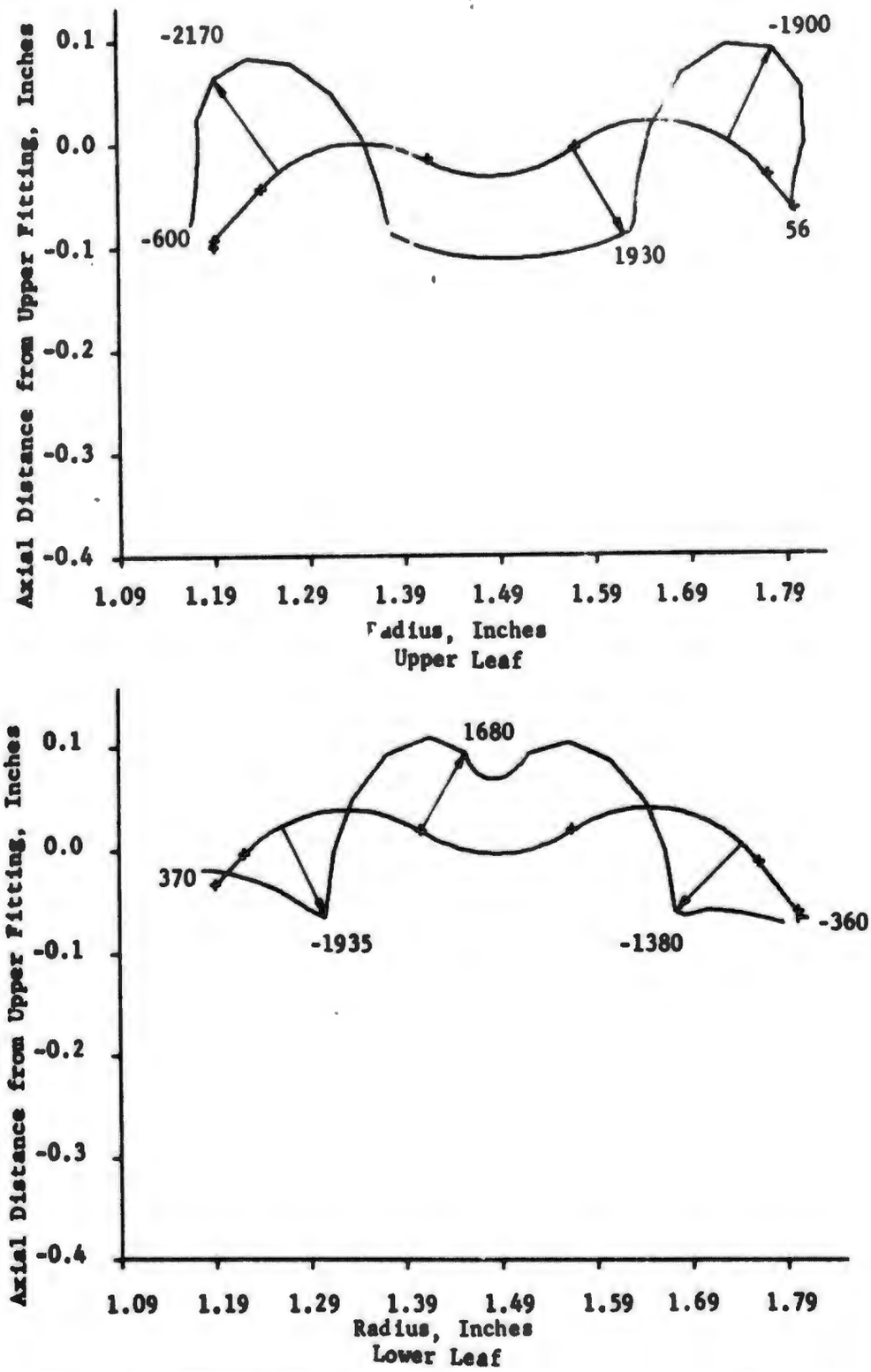


FIGURE 47. OUTER SURFACE MERIDIONAL STRESSES IN A 3.5-INCH WELDED BELLOWS AS DESIGNED (Internal Pressure = 1 psi).

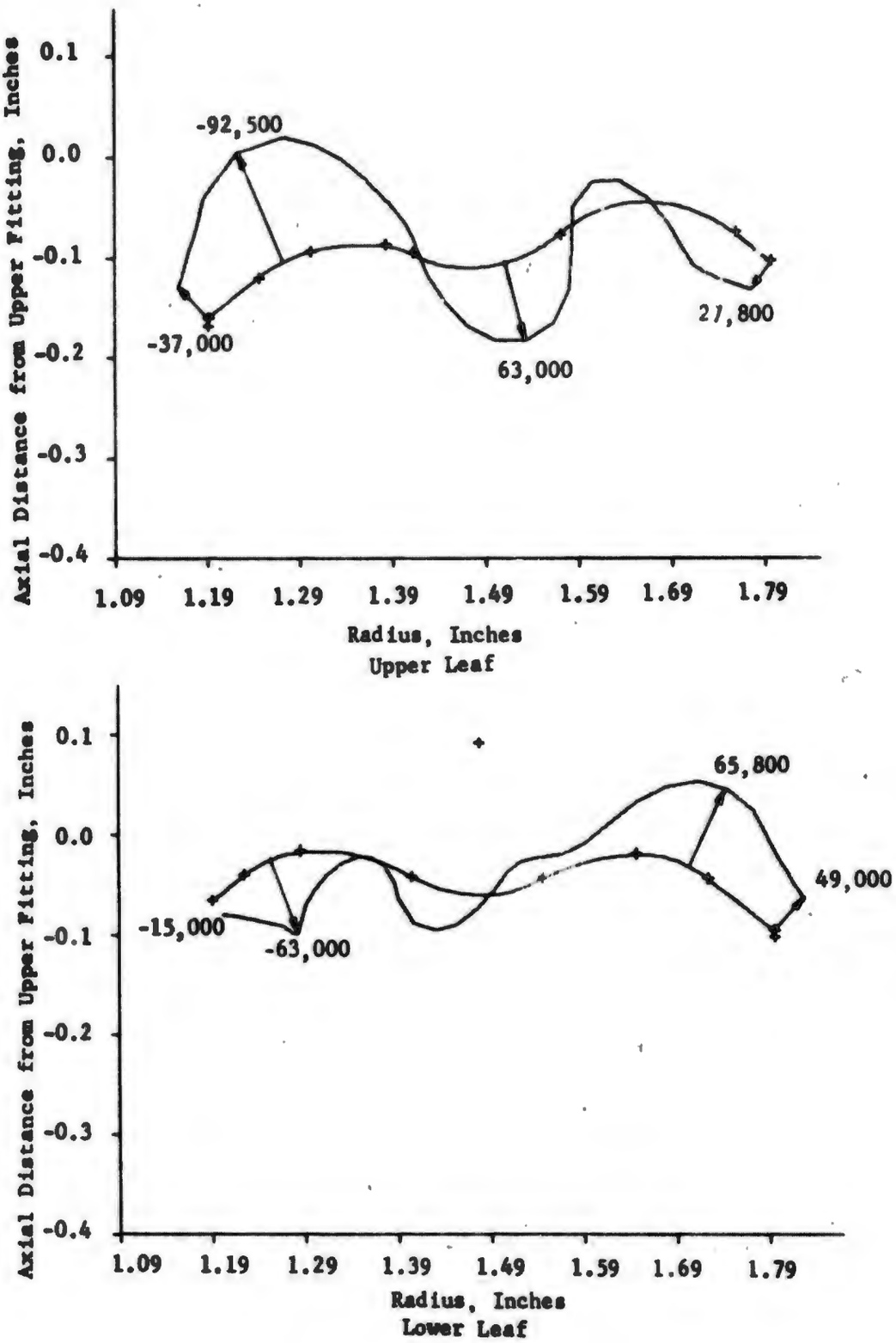


FIGURE 48. OUTER SURFACE MERIDIONAL STRESSES IN THE 3.5-INCH WELDED BELLOWS AS FABRICATED (Unit Axial Compression Per Unit Bellows Length).

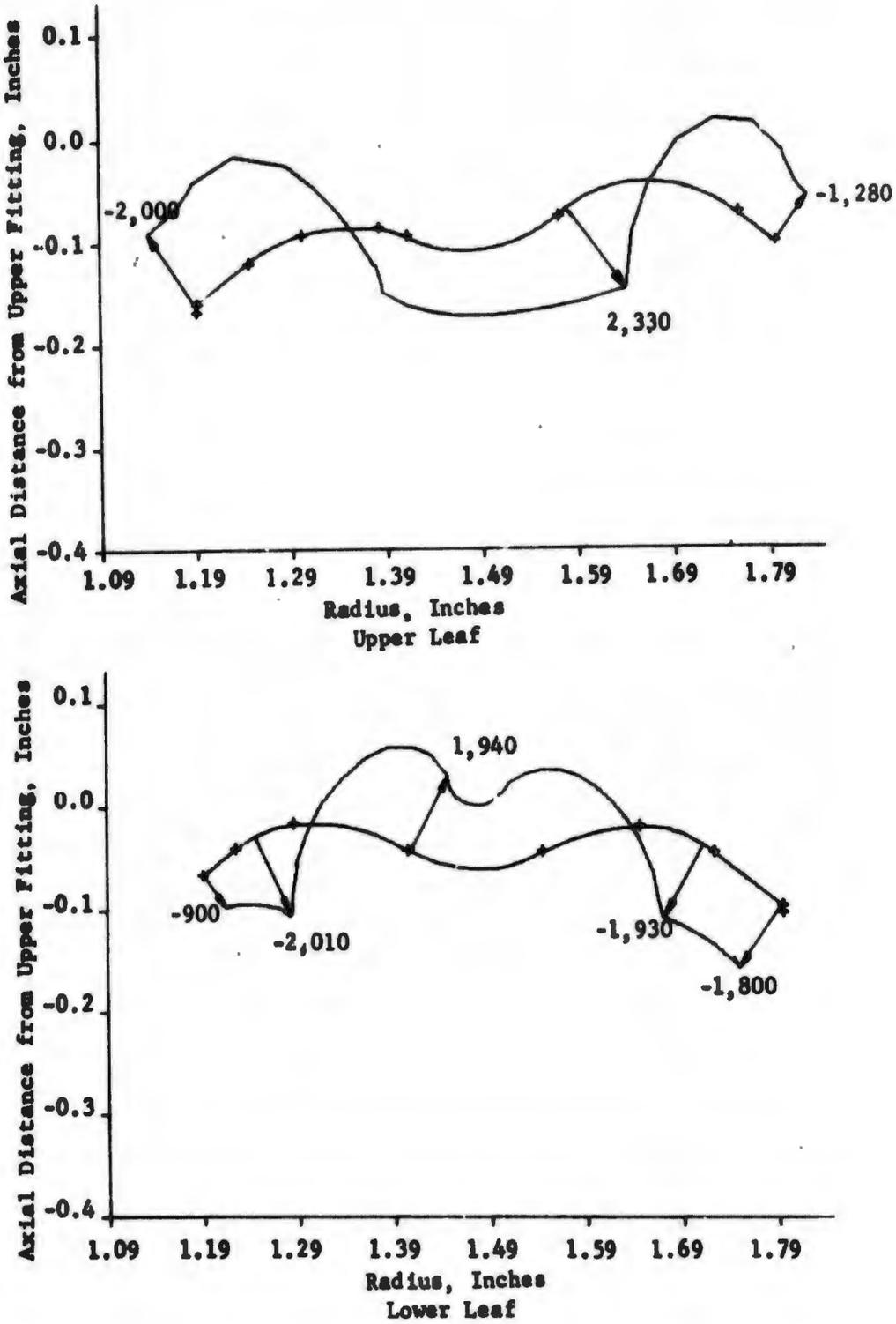


FIGURE 49. OUTER SURFACE MERIDIONAL STRESSES IN THE 3.5-INCH WELDED BELLOWS AS FABRICATED (Internal Pressure = 1 psi).

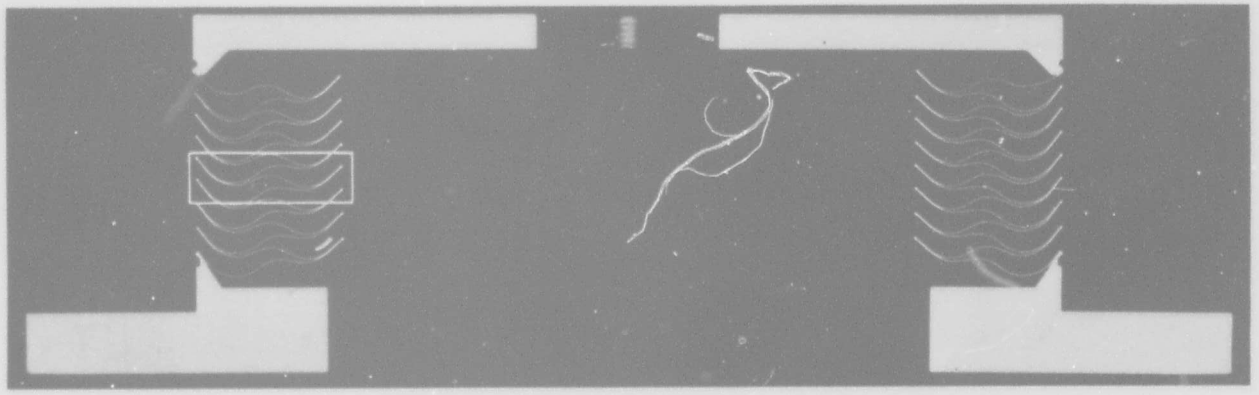


FIGURE 50. CROSS SECTION OF MODIFIED OPTIMIZED BELLOWS SPECIMEN

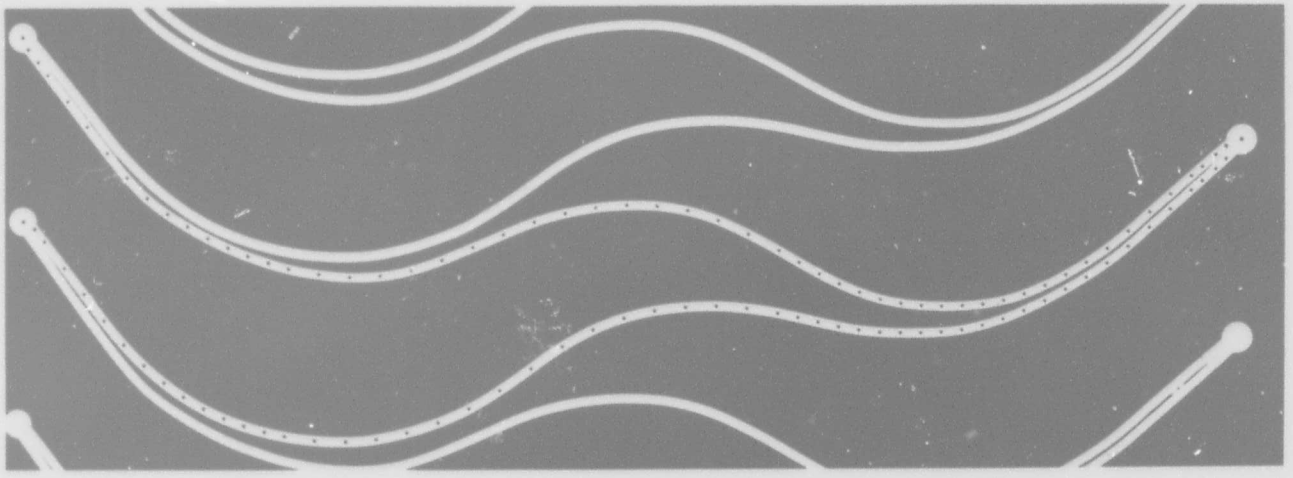


FIGURE 51. CONVOLUTION OF MODIFIED OPTIMIZED BELLOWS SPECIMEN SELECTED FOR MEASUREMENT

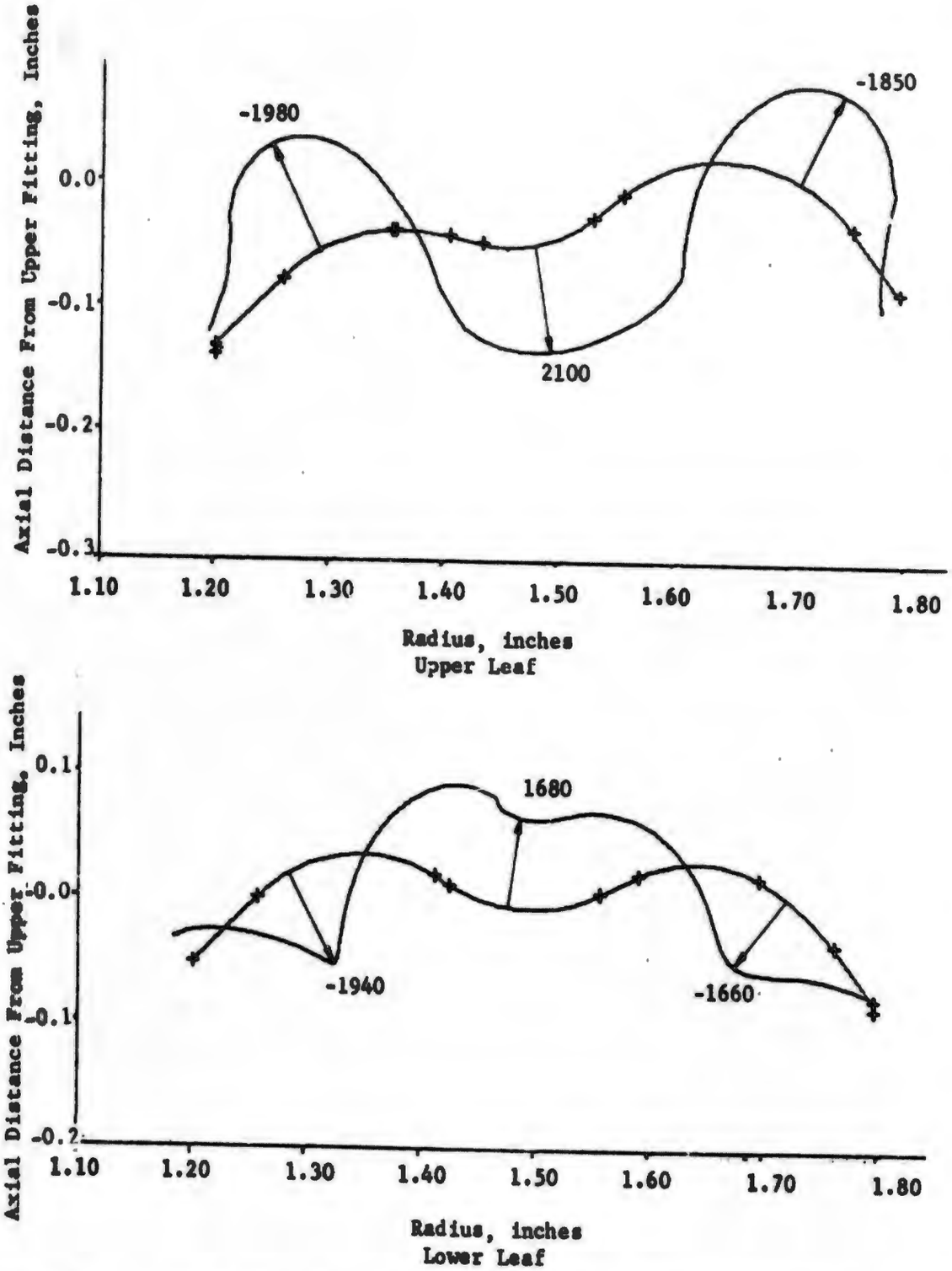
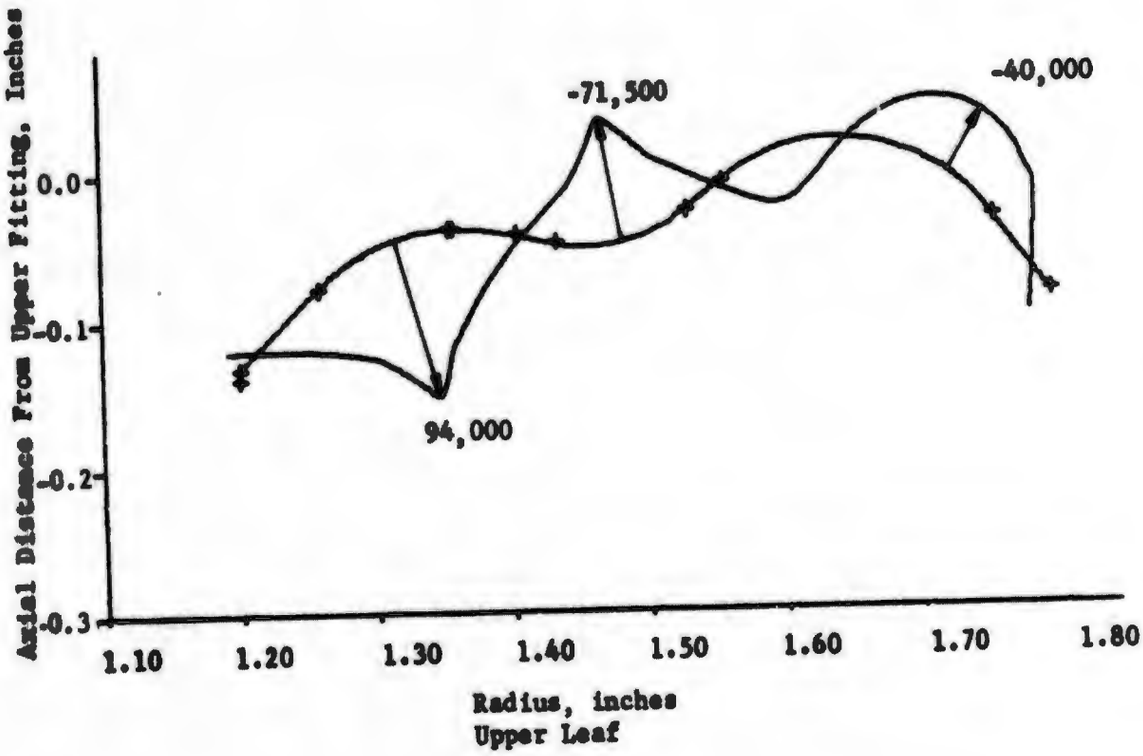


FIGURE 52. OUTER SURFACE MERIDIONAL STRESSES FOR INTERNAL PRESSURE IN AN EXACT MATHEMATICAL MODEL OF FABRICATED 3.5-INCH BELLOWS WITH 43° ID, 51.5° OD TILT ANGLES, 0.086-INCH PITCH AND 0.5950-INCH SPAN, (Pressure = 1 psi)



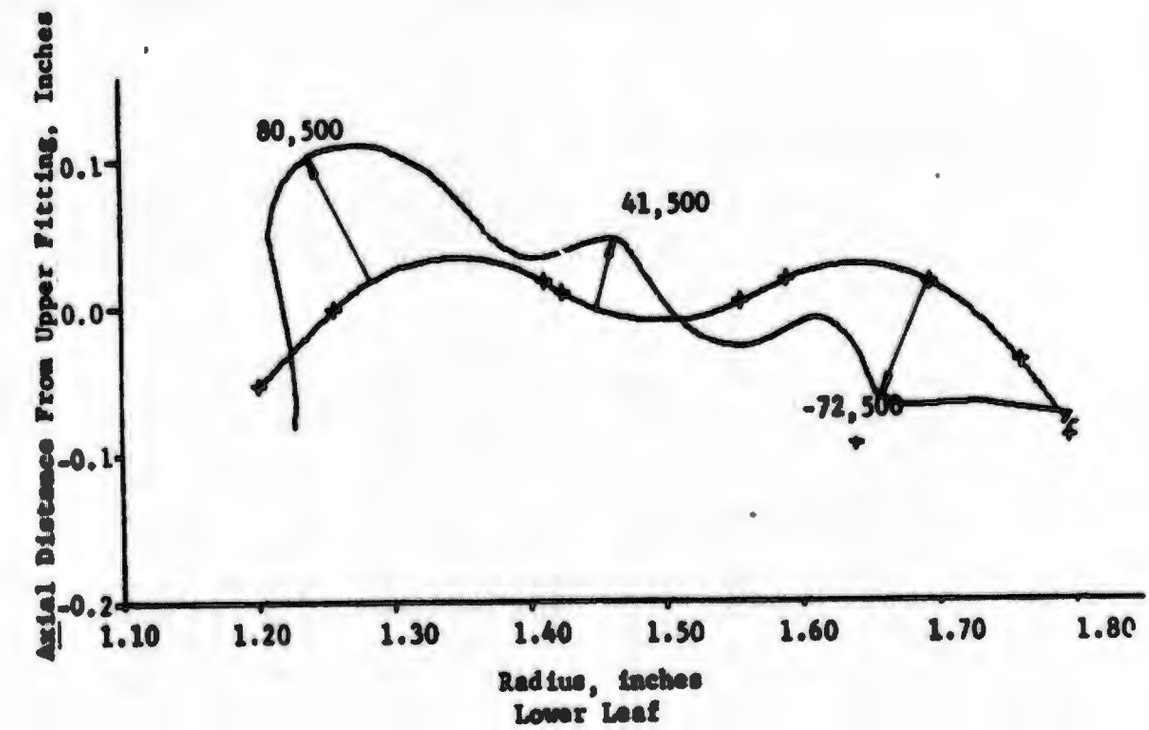


FIGURE 53. OUTER SURFACE MERIDIONAL STRESSES FOR AXIAL TENSION OF AN EXACT MATHEMATICAL MODEL OF FABRICATED 3.5-INCH BELLOWS WITH 43° ID, 51.5° OD TILT ANGLES, 0.086-INCH PITCH AND 0.5950-INCH SPAN, (Unit Deflection Per Unit Bellows Length)

TABLE 23. REVISED DIMENSIONS OF OPTIMIZED 3.5-INCH TILT-EDGE BELLOWS

Part No.	Shell Type	Outer Normal, degrees		Radii, inches	
		Initial	Final	a	b
		Upper Leaf			
1	Conical	230.000	---	1.7973	0.06000
2	Toroidal	230.000	138.150	1.64297	-0.15112
3	Toroidal	138.150	195.821	1.44132	0.15112
4	Toroidal	195.821	135.000	1.35892	-0.15112
5	Conical	135.000	---	1.25206	0.09000
		Lower Leaf			
7	Conical	-45.000	---	1.18902	0.08500
8	Toroidal	-45.000	30.600	1.3428	0.13250
9	Toroidal	30.600	-31.850	1.48661	-0.15000
10	Toroidal	-31.850	50.000	1.63621	0.13350
11	Conical	50.000	---	1.7385	0.09150

Optimized Bellows Inspection

The optimized bellows were given essentially the same inspection as the interim bellows. A variety of small blemishes were noted on several of the bellows, but these were judged to be typical of the state of the art in welded-bellows manufacture.

One exception was an end-fitting weld on one bellows. The weld had poor uniformity and a skipped region at one spot. This is shown in Figure 54. This bellows was returned for rewelding of the end fitting and subsequent inspection showed that the new weld was satisfactory.

Optimized Bellows Evaluation

Selected tests were conducted with the optimized bellows specimens to compare the optimized bellows with the selected standard welded bellows. The tests, which are described below, were selected as being most important for the application of tilt-edge welded bellows in typical rocket propulsion systems.

Primary tests included tests for leakage and measurements of spring rate, hysteresis, and fatigue life. In addition a test was made to determine the internal pressure that causes snap buckling of the bellows leaves.

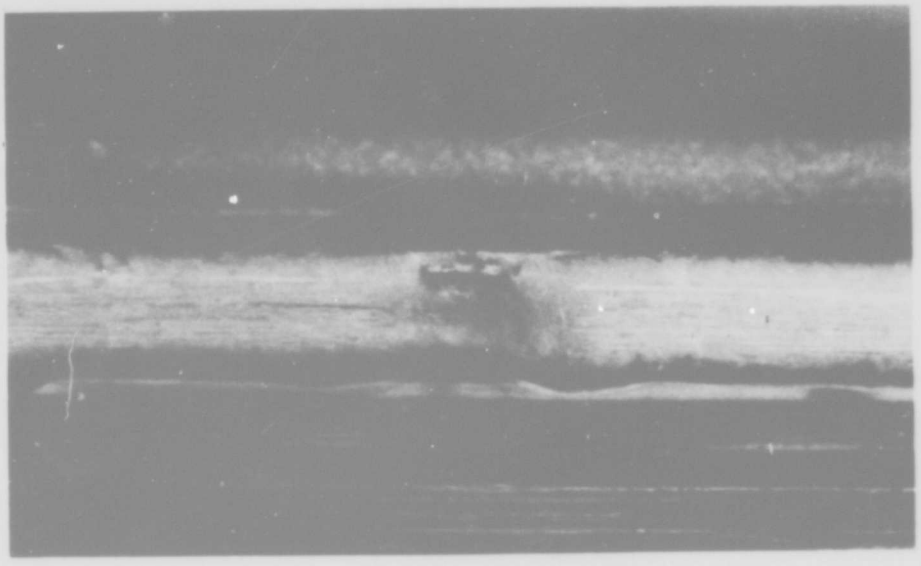


FIGURE 54. POOR END-FITTING WELD OF BELLOWS THAT WAS RETURNED FOR REWELDING

Leakage Analysis. Although inspection of the optimized bellows specimens showed a fabrication quality comparable to standard welded bellows, it was necessary to demonstrate that very low leakage assemblies had been produced. No leakage was measured with a helium mass spectrometer for any of the bellows specimens. These results were the same as those obtained with the standard bellows specimens and showed that any leaks in the bellows were less than 1×10^{-9} atm cc/sec of helium.

Spring Rate Analysis. As described previously for the interim bellows, it was important to compare the measured spring rates of the bellows specimens with the calculated spring rate. It was also important to compare the spring rates of the optimized configuration with the spring rates of the standard welded bellows measured during the previous program.

Table 24 shows the calculated (46 lb/in.) and measured spring rates for the optimized bellows specimens. It was concluded that the values were comparable in spread with those obtained during the previous program for standard welded bellows.

TABLE 24. EXPERIMENTAL AND THEORETICAL SPRING RATES FOR FINAL BELLOWS SPECIMENS

Bellows	Measured Compression Spring Rate (3/8-Inch Deflection), lb/in.	Measured Tension Spring Rate (3/8-Inch Deflection), lb/in.
KT-16	45.0	44.2
KT-17	43.9	45.2
KT-18	48.9	44.1
KT-19	44.1	45.3
KT-20	44.8	43.8
KT-21	44.2	44.8
KT-22	42.0	43.6
KT-23	39.5	42.7
KT-24	40.4	44.5
KT-25	42.9	45.7
KT-26	47.5	44.4
KT-27	47.6	45.3
KT-28	46.9	44.0
KT-29	43.6	43.8
KT-30	39.2	44.0
KT-31	45.2	44.3
KT-32	41.0	44.8
KT-33	41.4	45.0
KT-34	45.3	45.0
KT-35	40.6	42.7
KT-36	42.8	43.6
Theoretical Spring Rate (linear)	46.0	46.0

The calculated spring rate for the 3.5-inch standard welded bellows that the optimized configuration was to be compared with was 57 lb/in. This demonstrated that adequate flexibility can be achieved in a tilt-edge design despite the stiffening contributions of the conical diaphragm segments near the inner and outer weld beads.

Hysteresis Analysis. Hysteresis is the difference between the deflections of a bellows or diaphragm at a given load for increasing or decreasing loads. Table 25 shows the hysteresis for the optimized bellows specimens at 0 load after three compression cycles and after three tension cycles. Also shown are values for the "standard" 3.5-inch stainless steel bellows. The different deflections that were used corresponded to the full compression capability of each type of bellows. It can be seen that the amount of hysteresis in the tilt-edge bellows was significantly greater than in the standard bellows even when the difference in deflection is considered. Thus, the tilt-edge bellows configuration did not seem to be preferred over the standard bellows for those applications requiring low hysteresis.

TABLE 25. COMPARISON OF HYSTERESIS FOR STANDARD BELLOWS AND FINAL BELLOWS

Hysteresis in Standard Bellows for 0.240-Inch Deflection			Hysteresis in Final Bellows for 0.375-Inch Deflection		
Bellows No.	Compression Set, inch	Tension Set, inch	Bellows No.	Compression Set, inch	Tension Set, inch
JD-131	0.003	0.020	KT-16	0.007	0.044
JD-132	0.005	0.023	KT-17	0.009	0.044
JD-133	0.006	0.022	KT-18	0.010	0.040
JD-135	0.005	0.025	KT-19	0.008	0.043
JD-137	0.004	0.019	KT-20	0.016	0.037
JD-138	0.004	0.022	KT-21	0.014	0.037
JD-139	0.004	0.023	KT-22	0.011	0.049
JD-140	0.004	0.025	KT-23	0.011	0.052
JD-141	0.003	0.027	KT-24	0.010	0.046
JD-142	0.005	0.026	KT-25	0.011	0.035
			KT-26	0.012	0.039
			KT-27	0.010	0.039
			KT-28	0.012	0.040
			KT-29	0.008	0.049
			KT-30	0.009	0.045
			KT-31	0.023	0.035
			KT-32	0.008	0.048
			KT-33	0.008	0.047
			KT-34	0.010	0.044
			KT-35	0.023	0.076
			KT-36	0.020	0.058

(a) After 3 loadings each in compression and then in tension.

Buckling Pressure Analysis. The design of any bellows, whether welded or formed, requires a compromise between deflection capability and pressure capability. As the bellows is made more flexible to achieve greater deflection capability, its pressure capability decreases. As the bellows is made more pressure resistant, it becomes stiffer. As described earlier, it was decided that the bellows should be designed to give optimum deflection capability with pressure stresses comparable to the standard welded bellows. Although the fatigue behavior of the bellows under axial deflection was of primary interest in the program, it was also important to determine the pressure carrying capability of the optimized bellows.

Tests with the standard 3.5-inch welded bellows had shown a practical pressure limitation of about 40 psi. At an internal pressure of this magnitude, the diaphragms were sufficiently distorted that the fatigue life had been reduced to about 5000 cycles for a deflection of 0.480 inch. In contrast, the fatigue life of the same standard bellows with an internal pressure of 10 psi and a total deflection of 0.480 inch was about 150,000 cycles.

Although pressure reduced the fatigue life of the optimized configuration (see below), it was found that the tilt-edge design had a different pressure limitation from the standard bellows. This was oil-canning of a diaphragm; i.e., with a sufficiently high pressure, one of the bellows diaphragms would reverse. Although the bellows did not leak with this occurrence, its performance characteristics were altered sufficiently that it no longer functioned in an acceptable manner. For the optimized design it was found that the buckling (oil-canning) pressure with internal pressure was about 60 psi while the buckling pressure with external pressure was about 30 psi. Because of this buckling phenomena, it is believed that a bellows subjected to pressure or pressure surges up to 30 psi should be designed with decreased span to make it more resistant to pressure effects.

Fatigue Analysis. As with the interim bellows described earlier, three fatigue characteristics were of particular interest for the optimized bellows specimens (1) the location of the fatigue cracks, (2) the range of the fatigue life values for a given test condition and (3) the comparison of the fatigue lives with values estimated from calculated strains. It was shown in the previous study[1] that the fatigue failure of conventional welded bellows always occurred at the convolution welds. Because of the variable properties of the welds, large scatter was observed in the fatigue lives of the various conventional bellows tested. From the analytical results described earlier and from the results of the tests of the interim bellows, it was expected that fatigue failure at the welds could be prevented in the optimized tilt-edge bellows. It was believed that prevention of weld failures would not only improve welded-bellows fatigue life but also improve the reliability of the bellows.

It was believed that fatigue tests with the optimized bellows specimens would show that the design goals had been met:

(1) If the fatigue failure occurred in the parent metal of the convolution rather than in the weld beads

(2) If the range of fatigue failures for given test conditions was narrower than for standard welded bellows
(3) If the fatigue lives of the optimized tilt-edge bellows were greater for a given stroke than for the standard welded bellows selected for comparison.

It was also hoped that, with fatigue failure occurring in the parent metal of the bellows, the fatigue life of the tilt-edge bellows could be estimated using calculated maximum strains and coupon fatigue data from the literature.

Of the 14 bellows that failed in fatigue, 13 developed fatigue cracks in the parent metal of the diaphragms near the point of calculated maximum stress. One bellows failed prematurely at an end fitting when the diaphragm welded to the end fitting buckled. The cause of the buckling could not be determined, although the diaphragm may have been deformed during the welding operation. Because of the otherwise consistent failure in the parent metal, it was judged that the prevention of weld-bead fatigue failures had been amply demonstrated.

Table 26 duplicates Table N-8 which was included in Appendix N of Technical Report No. AFRPL-TR-68-22 to show the excessive variation in the fatigue life of standard welded bellows that were encountered during the previous program. It is important to note that bellows having early failures were not found to be poorly made either by the manufacturers nor during careful inspection at Battelle. In addition, cross sections of the bellows showed generally good welding practices.

TABLE 26. EXCESSIVE VARIATION IN THE FATIGUE LIFE OF STANDARD WELDED BELLOWS

Bellows	OD, inch	Bellows Material	Internal Pressure, psi	Stroke, inch	% Stroke in Tension	Fatigue Life, hr.
JD141	3-1/2	347 S.S.	20	0.240	0	453
JD135	3-1/2	347 S.S.	20	0.240	0	NF 1,747,069
JD132	3-1/2	347 S.S.	20	0.240	50	73,322
JD131	3-1/2	347 S.S.	20	0.240	50	NF 768,870
JD166	3	AM350	40	0.240	50	37,145
JD164	3	AM350	40	0.240	50	NF 1,000,000

Table 27 shows 9 different test conditions for the optimized tilt-edge bellows, each involving two or more test specimens. It has been shown that the fatigue failures of identical metal coupons can vary as much as 3 to 1 or more for identical test conditions. Only one bellows test condition produced a spread significantly greater than 3 to 1 (80,709 cycles vs. 10,935 cycles) and the early failure was caused by diaphragm buckling rather than fatigue cracking. These data, combined with the interim bellows data presented earlier, are believed to demonstrate clearly that the fatigue failure range for tilt-edge bellows is comparable to that obtained from coupon specimens. This spread is not only much better than that obtained with conventional welded bellows, but is better than that obtained with formed bellows, as shown in Figure 44.

Another aspect of the fatigue analysis of the optimum bellows specimens was a comparison of the deflection capability of the optimized bellows with the deflection capability of the standard welded bellows tested during the previous program. Figure 55 shows the comparison results. The largest deflection tested for the standard bellows was 0.240-inch compression and 0.240-inch extension. Four internal pressures were used, 4 psi, 10 psi, 20 psi, and 40 psi. Fatigue failure occurred in 158,115 and 158,570 cycles at 4 psi, 195,600 cycles at 10 psi, 11,382 cycles at 20 psi, and 4,219 cycles at 40 psi. Spring rate measurements showed that as the internal pressure of the standard bellows was increased above 15 psi, the spring rate of the bellows increased. This was thought to be caused by pressure-induced interference of the diaphragms. This, in turn, was believed to be the cause of the reduced fatigue life of the standard bellows at 20 and 40 psi.

For the optimized bellows, it can be seen that the fatigue life was far superior for a 0.240-inch compression and 0.240-inch extension. During the program it was not determined how many cycles could be obtained at internal pressures of 20 psi and below. Even with a 50 percent increase in stroke, the lives of the optimum bellows specimens were substantially greater than that of the standard welded bellows. Thus, in accordance with the design objective, the optimized tilt-edge bellows was shown to have substantially better deflection capabilities than the standard bellows selected for comparison.

The ability to estimate the fatigue life of an optimized bellows specimen was found to be good at low pressure. However, an increase in internal pressure caused a reduction in fatigue life and this effect was not predicted by a linear analysis. The analysis of this condition is summarized briefly.

A linear calculation for the optimized bellows configuration showed a strain range of 3200 μ in/in for 3/8-inch compression and 3/8-inch tension. From Figure 44, a fatigue life of from 1 to 2 million cycles was estimated for this test condition. As shown in Table 27, specimens KT-17, KT-25, and KT-28 gave 938,573 cycles, 2,066,147 cycles, and 2,433,778 cycles, respectively with an internal pressure of 2 psi. This was believed to be good correlation.

However, an increase in internal pressure to 10 psi decreased the fatigue life of KT-16 and KT-19 to 251,808 cycles and 382,710 cycles, respectively. An increase in internal pressure to 40 psi decreased the

TABLE 27. SIMILARITY OF FATIGUE CYCLES FOR OPTIMIZED BELLOWS SPECIMENS

Bellows No.	Total Stroke, in.	% Stroke in Tension	Internal Pressure, psi	Calculated Max. Strain Range, μ-in./in.	Cycles to Failure	Estimated Fatigue Life Range at Zero Pressure, hr.	
						Lower	Upper
KT-17	0.750	50	2	3200	938,573	8×10^{4}	1×10^{8}
KT-25	0.750	50	2	3200	2,066,147	8×10^{4}	1×10^{8}
KT-28	0.750	50	2	3200	2,433,778	8×10^{4}	1×10^{8}
KT-22	1.000	62	2	4266	51,375	2×10^{4}	2×10^{5}
KT-27	1.000	62	2	4266	42,600	2×10^{4}	2×10^{5}
KT-16	0.750	50	10	3200	251,808	8×10^{4}	1×10^{8}
KT-19	0.750	50	10	3200	382,710	8×10^{4}	1×10^{8}
KT-20	0.750	66	10	3200	272,252	8×10^{4}	1×10^{8}
KT-21	0.750	66	10	3200	81,873	8×10^{4}	1×10^{8}
KT-23	0.750	50	40	3200	47,500	8×10^{4}	1×10^{8}
KT-24	0.750	50	40	3200	58,191	8×10^{4}	1×10^{8}
KT-29	0.480	50	4	2050	2,962,300 NF	1×10^{7}	1×10^{10}
KT-30	0.480	50	4	2050	2,962,300 NF	1×10^{7}	1×10^{10}
KT-31	0.480	50	20	2050	2,046,222 NF	1×10^{7}	1×10^{10}
KT-32	0.480	50	20	2050	2,046,222 NF	1×10^{7}	1×10^{10}
KT-33	0.480	50	40	2050	1,418,086	1×10^{7}	1×10^{10}
KT-34	0.480	50	40	2050	2,345,678 NF	1×10^{7}	1×10^{10}
KT-35	0.620	50	40	2650	10,935 (Buckling Failure)	1×10^{6}	1×10^{9}
KT-36	0.620	50	40	2650	80,709	1×10^{6}	1×10^{9}

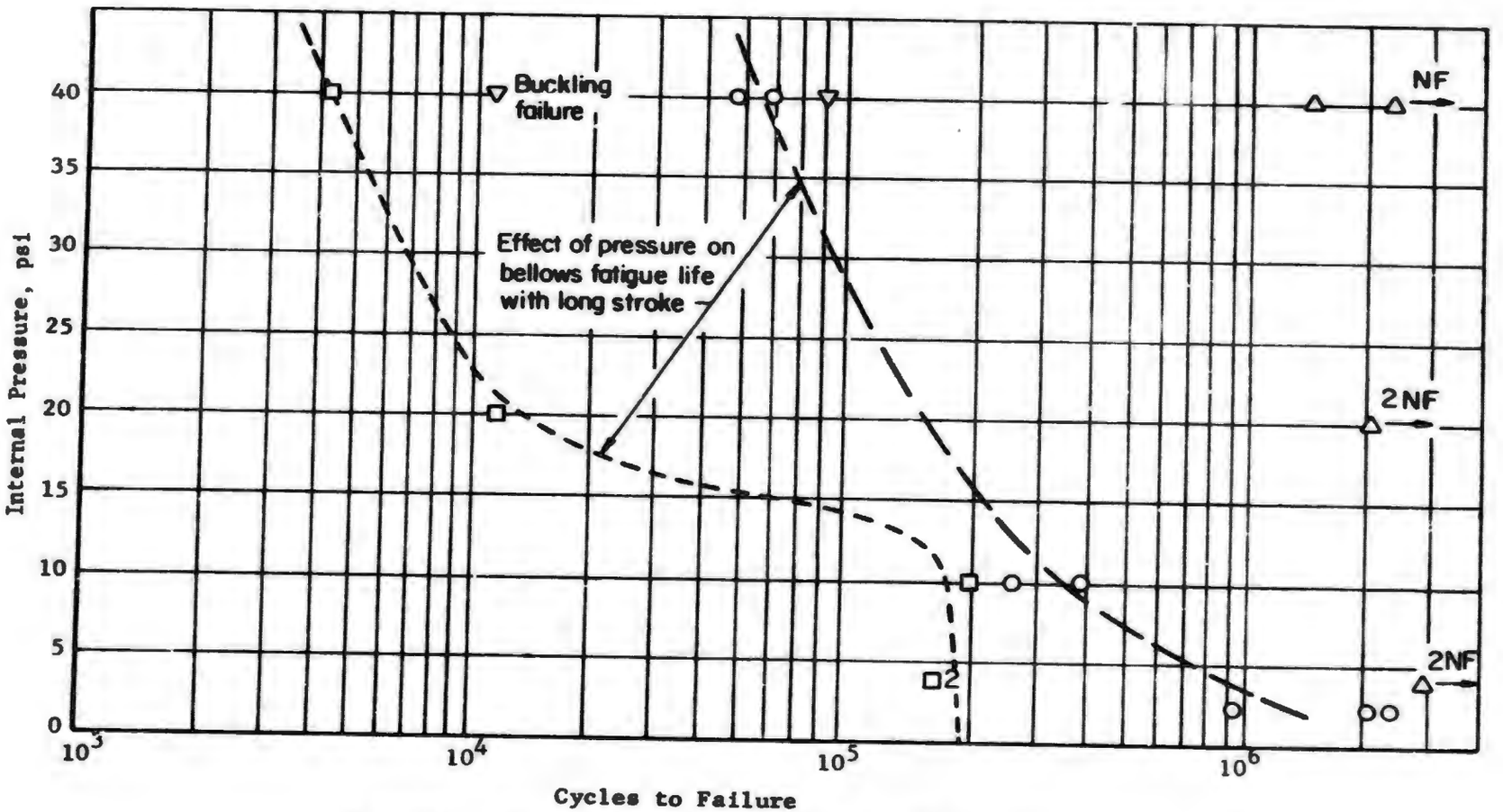


FIGURE 55. FATIGUE FAILURE COMPARISON OF OPTIMIZED TILT-EDGE BELLOWS WITH STANDARD BELLOWS

lives of KT-27 and KT-24 to 47,500 cycles and 58,191 cycles, respectively. An examination of a strain-gaged bellows subjected to 3/8-in compression and 3/8-inch extension with different amounts of internal pressure showed that the pressure was causing some parts of the diaphragms to press together or lock up. This reduced the effective length of the diaphragms and increased the strain in the diaphragms for given amounts of deflection of the bellows. Although it was believed that the computer analysis program could be modified to analyze this geometrically nonlinear condition, it was not possible to accomplish this in the current program.

SECTION V

CONCLUSIONS

As a result of the research study, it was concluded that tilt-edge bellows can be designed to give significantly better performance than conventional welded bellows. However, certain problems were identified with regard to the nonlinear effects of pressure on tilt-edge bellows. These problems should be studied further in order to develop a complete understanding of the behavior of tilt-edge bellows. Such an understanding will be required before tilt-edge bellows are generally used in place of conventional welded bellows.

The conclusions reached as a result of the theoretical design study and as a result of the fabrication and testing program are summarized in the following sections.

Theoretical Design Study

The theoretical design study was concerned with the effects of variations in tilt angle, span, sweep radius, and convolution pitch. The conclusions reached in studying these parameter effects are as follows:

Tilt Angle. It was found that properly selected tilt angles reduced the stresses at the root and crown welds to very nearly zero values under either pressure loading or axial deflection loading for all bellows sizes studied (1- to 3.5-inch OD). The optimum tilt angle for pressure loads was always higher than the optimum tilt angle for deflection loads. However, in all cases, tilt angles could be found (usually between the two optimum angles) that gave satisfactorily low stresses at the root and crown welds for either deflection or pressure loading.

Span. The effects of changes in the span were essentially the same for tilt-edge bellows as for conventional bellows. Increasing span lowered the maximum deflection stress almost in proportion to the change in span.

Convolution Pitch. Changing convolution pitch had little effect on the stresses due to pressure. The stresses due to axial deflection increased with pitch for an assumed unit deflection per unit length bellows. However, when an axial load of a 1-inch deflection per bellows convolution was considered, the maximum bellows stresses were relatively independent of pitch. This behavior was also similar to the behavior of conventional welded bellows.

Sweep Radius. The effects of sweep radius variations on the maximum stresses in tilt-edge bellows were found to be less pronounced than the effect of the above parameters. However, it was found that optimum sweep radii did exist that minimized the maximum convolution stresses. In the bellows considered, this sweep radius was approximately 25 percent of the bellows span.

End Fitting Stresses. End-fitting stresses were found to be satisfactorily low for many of the optimized convolution shapes with the end leaves identical to the optimum convolution leaf shapes. In those designs exhibiting unsatisfactorily high end-fitting stresses, it was found that the only reliable method of reducing these end-fitting stresses was to increase the thickness of the bellows end leaf that was welded to the fitting with high stresses.

As an overall result of the analytical design phase of the research study, it was found that theoretically optimized tilt-edge bellows designs could be found with very low stresses at the weld beads and at the end fittings.

Fabrication

Two different tilt-edge bellows models were fabricated. Based on this experience, the following conclusions were reached.

Formability of Bellows Diaphragms. It is possible to form the bellows diaphragms to precisely the shape required provided that appropriate allowance is made for spring back. Because of the greater overall curvature of the tilt-edge bellows diaphragms with respect to the standard welded bellows diaphragms, the spring back is greater. However, with a minimum amount of experience, this increased spring back can be anticipated in making the forming dies.

Weldability. The execution of the ID weld to join the upper and lower bellows diaphragms into a full convolution offers little difficulty. However, difficulties can be encountered in making the OD weld to join adjacent convolutions. The difficulties are primarily associated with fitting chill rings between the bellows leaves. It was found that the difficulty of using properly fitting chill rings increased as the OD tilt angle was increased and the convolution pitch was decreased. For very large tilt angles and small pitch it could become necessary to make the OD weld without using chill rings.

Experimental Program

The experimental program verified that the tilt-edge design did indeed have sufficiently low weld stresses to prevent fatigue failure in the welds. However, it was concluded that some problems still existed requiring further study. The following conclusions were reached as a result of the experimental program.

Spring Rate and Hysteresis. The spring rate of tilt-edge bellows can be calculated using NONLIN at least as accurately as for formed bellows. A tilt-edge bellows has about 10 percent to 20 percent higher spring rate than a conventional welded bellows with the same pitch, span, and thickness. However, this spring rate can easily be adjusted by changing the span.

When tested at their maximum stroke, the tilt-edge bellows exhibited more hysteresis than the standard bellows. However, since the maximum stroke given the tilt-edge bellows was much larger than the stroke given the standard bellows, it was concluded that both bellows exhibited sufficiently low hysteresis to meet Air Force standards.

Fatigue Life Under Cyclic Axial Loads. It was found that when cycled at moderate deflection ranges and at low pressures, the fatigue life of a tilt-edge bellows could be reliably estimated using the strain range calculated from the theoretical analysis and the appropriate coupon fatigue data. Further, it was found that the spread in fatigue life for sets of tilt-edge bellows tested at the same maximum strain range was almost as small as for coupon data. This low scatter was observed for a wide range of pressures and strain ranges and indicated that reproducible fatigue lives could be expected in tilt-edge bellows.

However, the experimental program showed that pressure had a significant effect on the performance of tilt-edge bellows. This pressure effect was manifested in two ways: (1) by a gradual reduction of the fatigue life under axial loading as the pressure was increased and (2) by snap-through buckling of an upper leaf at high internal pressure. Similar snap-through buckling of the lower leaf was observed for external pressure.

It was concluded that the first effect of pressure in reducing the fatigue life was similar to that observed in standard welded bellows. This effect was believed to be a combination of leaf interference caused by the pressure and the displacement of the mean stress point of the load cycle by the pressure stress.

The snap through buckling (oil canning) of the bellows leaves at higher pressures was not observed for standard bellows. However, it is a common phenomena with single-sweep bellows. It was concluded that the oil-canning was a result of the overall arch in the tilt-edge leaves that make them behave like a single sweep bellows with similarly arched leaves. The standard multi-sweep bellows leaves tended to be fairly flat and apparently deformed in response to the pressure from either side without buckling. It was concluded that the leaf buckling poses a definite limitation on the pressure capacity of a tilt-edge bellows.

SECTION VI

RECOMMENDATIONS

1. It is recommended that tooling arrangements and welding procedures be developed that would simplify the OD welding of bellows with relatively large tilt angles or with small values of pitch. This would be of considerable benefit for manufacturers who have not yet developed such techniques.

2. It is recommended that a theoretical and experimental investigation be carried out to develop procedures for predicting the effects of pressure on tilt-edge bellows. This investigation would involve extending NONLIN to account for leaf interaction and to predict the snap through buckling pressures. Further testing would also be needed, particularly to test for buckling loads. It is believed that such a research program would lead to the development of methods for predicting the performance of tilt-edge bellows under pressure with nearly the same reliability as was found for performance at low pressures.

APPENDIX A

ANALYSIS OF WELD AREA OF BELLOWS

APPENDIX A

ANALYSIS OF WELD AREA OF BELLOWS

An analysis of a welded bellows as a thin shell of revolution does not give a complete picture of the stresses in the area of the weld bead. A detailed analysis requires that this area be treated as an axisymmetric solid, in order that the local stress distributions can be calculated about the notch at which failures normally occur. This appendix describes such an analysis in which a single weld bead and short segments of the adjoining leaves were separated (for purposes of analysis) from the remainder of the bellows for detailed study. This removed portion was then analyzed with Battelle's computer program, AXISOL. AXISOL is applicable to such an axisymmetric solid of rather irregular cross section. Several representative cases were considered in this way: inner and outer welds, both small and large edge tilts, and both axial and pressure loading. The calculated stresses agreed with those of the thin shell analysis, except in the immediate area of the weld bead. In this area the effect of the notch on the level and distribution of stresses was determined.

The Finite Element Computer Program AXISOL

Battelle's computer program, AXISOL, was used to calculate the detailed stress distribution in the weld area. This computer program is well suited for this application, since it is capable of analyzing the stresses in axisymmetric bodies of general cross section. Only a brief description of the program will be given here, since it is rather widely used in the aerospace industry and is well documented (3).

The stresses in an elastic solid (such as that represented by the weld area of a bellows) can be described by the equations of the linear theory of elasticity. However, the geometry and loadings are far too complex in this case to allow an exact analytical solution of the problem. One must then consider numerical methods to obtain an approximate solution. One possible approach is to approximate the governing differential equations, as is done in the method of finite differences. In contrast, the approach on which the computing program AXISOL is based does not utilize the governing differential equations. It approximates the solid with an appropriate structural model and then calculates the exact response of this model. This approach is described as the finite element method.

In the program AXISOL, the solid is modeled as an assembly of ring elements which can be of either quadrilateral or triangular cross section. It is assumed that the stresses and strains within each element are constant, but that they change from one element to the next. Thus, in areas where the stresses change rapidly, closely spaced elements are required for accurate results. The elements are interconnected at their mutual corners, which are designated nodal points. Equilibrium equations in terms of the unknown nodal point displacements and the known elemental stiffnesses are formulated. The solution of these equations describes the deformation of the finite element approximation of the continuous solid. There is no restriction in

AXISOL on the shape of the solid provided that it is a body of revolution. However, the number of elements required to accurately model the solid is restricted by the computer storage capacity. Over 2000 elements are permitted, which is far more than the approximately 300 elements needed in this study to describe the bellows weld area. The stresses in the solid may be calculated for either arbitrarily prescribed boundary deformations or boundary stresses, as well as thermal loadings. Computation times of between 1 and 2 minutes on Battelle's CDC-6400 digital computer were experienced in the weld area analysis.

Procedure of Analysis

For study of the bellows weld area it was assumed that the results of the thin shell analyses were accurate, except very near the welds. Thus, only a very limited portion of the bellows near a weld had to be considered in each finite element calculation. This portion consisted of the weld and short lengths of the two adjoining shell leaves, which were considered to be cut from the bellows a few shell thicknesses from the weld. On these imaginary cuts the action of the remainder of the bellows on the weld area was represented as external loads. The appropriate force and moment values were obtained from a separate shell calculation.

The basic finite element pattern that was used for all the calculations is shown in Figure A-1. This figure was produced by the computer plotting facility on the basis of input data describing the finite element model. The conception and specification of the precise number and arrangement of the elements is a key step in each problem and rests largely on the judgment of the analyst. With a well-constructed pattern one can obtain accurate stress results with a reasonable number of elements and thereby minimize the effort required to prepare the input data and the machine computation time. In the modeling of the bellows weld area, a minimum of six elements through the leaf thickness was believed necessary to represent the bending stress variation between the inner and outer surfaces. Elements of excessively elongated cross section were avoided in this area. Increasingly smaller elements were taken near the tip of the notch to represent the stress peak there. In contrast, relatively large elements were used in the outer portion of the weld. A total of 288 elements were utilized for the analysis. Figure A-1 represents but one of four weld geometries considered. It is a model of an outer weld with an edge tilt of 35 degrees. Since considerable time and effort were required to produce this mesh, this basic configuration was used as data to produce the meshes for the other three cases. A simple computer program was written to transform the coordinate data by applying appropriate rigid body translations and rotations while maintaining the element pattern. In this way, the mesh could be positioned to represent either an inner or outer weld with the required tilt angle.

The notches in actual welded bellows show considerable geometrical variation as can be seen in cross-sectioned bellows. The particular notch configuration that was assumed for this study was believed to be reasonably representative. For analysis purposes the notch tip was taken as perfectly sharp with no radius. A realistic value for this radius would have been

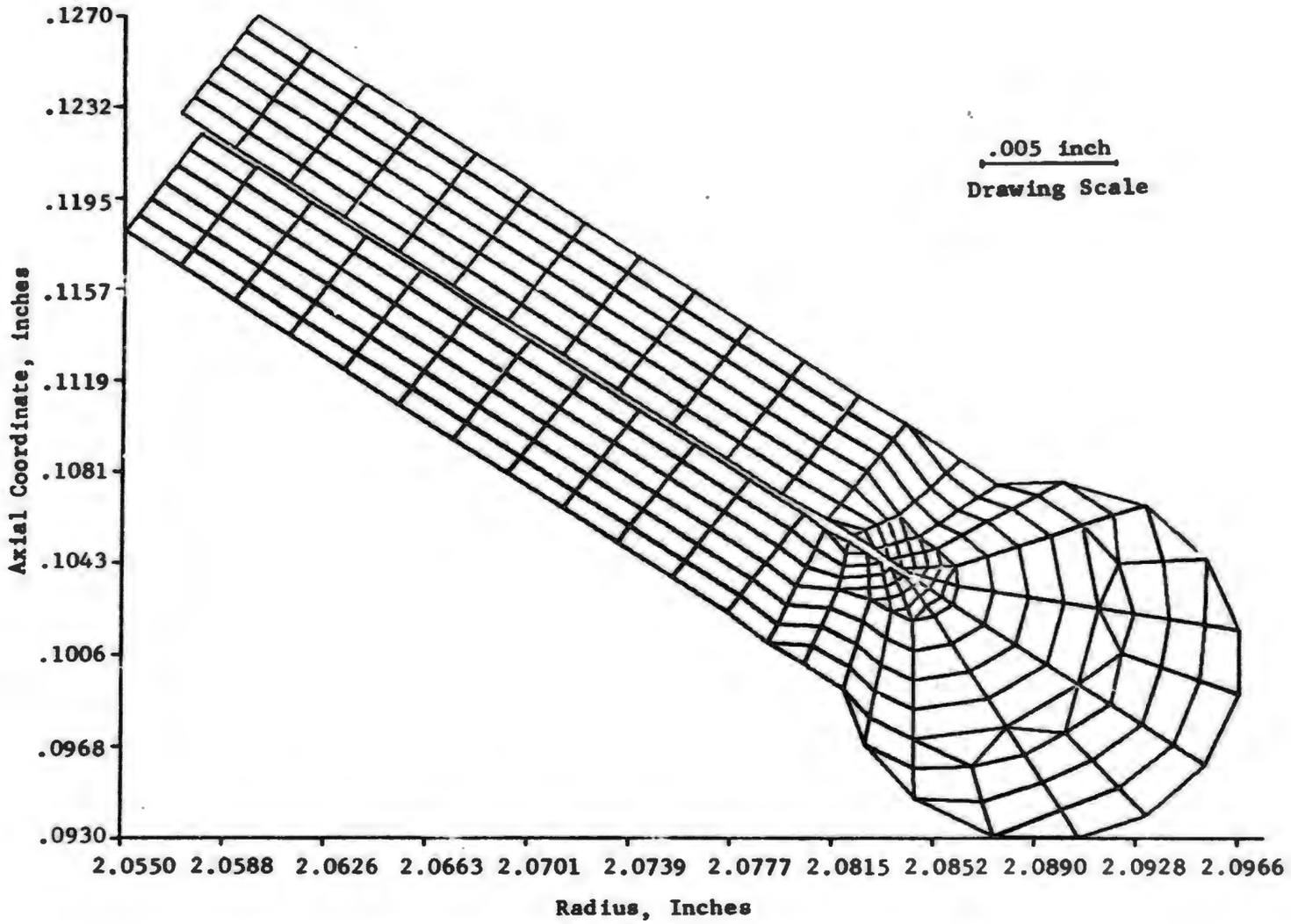


FIGURE A-1. MESH CONFIGURATION FOR MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT

smaller than could have been conveniently represented with the finite element mesh. No attempt was therefore made in this study to model a rounded notch tip. Another factor of potential importance was the distance that the notch extended into the weld material. The effect of variation of this distance on the stress distribution in the weld could have been explored by changing the finite element model of the notch area. However, this was beyond the scope of the study.

Precise application of the force and moment loads to the edges of the leaf segments as equivalent sets of nodal point forces was an important step in the analysis. To ensure accuracy and to eliminate hand calculations, a Fortran IV subroutine was written for AXISOL to allow the resultant moment and the normal and shear force resultants obtained by the thin shell calculation to be specified directly as input data for AXISOL. Particular care was taken to calculate a nodal point load pattern that had the precise force and moment resultants. The exact distribution was believed to be of lesser importance. Such a procedure was considered important, since it was anticipated that the calculated stresses (in particular, the hoop stress component) would be quite sensitive to even small variations in the net applied loads.

In thin-shell analysis of welded bellows it had not been the practice to include separation of the midsurfaces of the two leaves joined at the weld. These were taken to be coincident, with the midsurface separation corresponding to the leaf thickness being ignored. In the detailed analysis of the weld area as a solid of revolution, this separation was, of course, included. During the study it became apparent that this separation had a local effect near the weld. It was concluded that this effect must be included in the shell calculation in order to obtain a consistent set of edge loadings for the finite element analyses. This local effect could be explained by the fact that the membrane forces in the two adjacent leaves (which are nearly equal and opposite in direction) had their lines of action separated by a distance of about one shell thickness. This produced a couple of the same order of magnitude as the shell bending moments. This had a local effect on the shell equilibrium. Thus, to determine the correct shell resultants for application as external loads in the finite element analysis, the weld beads were represented in the shell calculations as short segments of cylindrical shells. Numerical values of stresses, calculated with and without separation provided in this manner, are tabulated in Table A-1. At the weld there were fairly large differences in the stresses calculated with the thin shell program. A few shell thicknesses away these differences were significantly smaller. The results of the finite element calculation showed a more dramatic effect, however. In one case the edge loads were based on shell calculations with no midsurface separation. In the other case, separation was included. It is seen that the calculated meridional stresses (SPHI) for both cases were similar, but that the circumferential stresses differed by an order of magnitude. When separation of the leaves at the weld is included, the shell and finite element calculations gave consistent results for the circumferential stresses.

TABLE A-1. STRESS AT OUTER WELD OF 4-INCH BELLOWS WITH 35° EDGE TILT DUE TO AXIAL LOADING -- WITH AND WITHOUT SEPARATION OF MIDSURFACES OF ADJOINING LEAVES

		Upper Leaf				Lower Leaf			
		At Cut		At Weld		At Cut		At Weld	
		SPHI	STHETA	SPHI	STHETA	SPHI	STHETA	SPHI	STHETA
Shell Calculation	Membrane	-1,156 / -1,213	1,257 / 1,665	-1,151 / -1,194	-3,349 / -1,794	1,196 / 1,190	2,484 / 4,161	1,161 / 1,194	-4,269 / -1,079
	Bending	23,757 / 19,560	7,439 / 6,100	10,264 / 4,694	3,612 / 1,797	17,297 / 20,581	4,607 / 5,592	2,050 / 4,694	68 / 1,019
Finite Element Calculation	Membrane	-1,150 / -1,180	1,692 / 37,700			1,190 / 1,190	2,418 / 27,450		
	Bending	20,500 / 16,800	6,500 / 9,950			15,000 / 17,200	3,900 / 18		

SPHI = Meridional stress
STHETA = Circumferential stress

With separation / Without separation

Description of Cases Considered

Calculations were performed for a total of eight cases to explore the importance of weld position (inner or outer weld), edge tilt angle, and type of loading (axial load or internal pressure). All the cases considered were for a nominal bellows with an outside diameter of 4.0 inches and a leaf thickness of 0.005 inch. The basic bellows configurations were the same as the 35° tilt-edge bellows that was described in Appendix D of the final report AFRPL-TR-68-22. A list of the cases is given in Table A-2. Included are the values of the loadings that were applied along the edges where the weld areas were assumed (for purposes of analysis) to have been cut from the remainder of the bellows. These loadings were obtained from thin-shell analysis as explained previously. Each of the cases represented a separate finite element calculation.

Two tilt angles were selected: 15° and 35°. With the 15° tilt angle, the bellows leaves were subjected to considerable bending in the weld area, as is characteristic for small edge tilts. The 35° tilt angle was intended to represent a more favorable edge tilt. For this angle, little bending was observed and the applied axial load was carried mainly as membrane and shearing forces in the weld area.

For the cases of axial loading, the stresses were calculated for an imposed axial deflection of 0.09838 inch per convolution. The pressure loadings corresponded to an internal pressure of 10.0 psi. Pressure and axial loadings were treated separately. Thus, the effects of combined loadings were not considered.

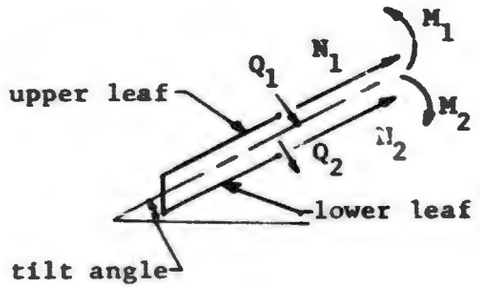
Results and Discussion

The results of the stress calculations are shown in Figures A-2 through A-11 in the form of stress contours. Contours of principal (or maximum) stress are shown for all cases, while contours of circumferential (or hoop) stress (which are of less interest) are shown for only two cases. The principal stress contours are based only on the two principal stress components acting in the r-z plane. The third principal stress is the circumferential stress. In the finite element solutions the stress states in the bellows leaves (away from the weld bead) correspond to the meridional membrane and bending stresses of the shell calculations. However, about the notch the stress pattern becomes more complex and the stresses increase rapidly. In this area, there are two nonzero components of principal stress. This complicated the plotting of the stress contours. A convention was thus adopted to indicate, at a given point, that component that was largest in absolute value. No such difficulty was encountered in plotting the principal stresses in the bellows leaves where the characteristic thin shell stress distribution existed. Here the stress normal to the shell surface is always one of the two principal stresses and was nominally zero. The principal stress of interest was composed of the meridional membrane and bending stresses.

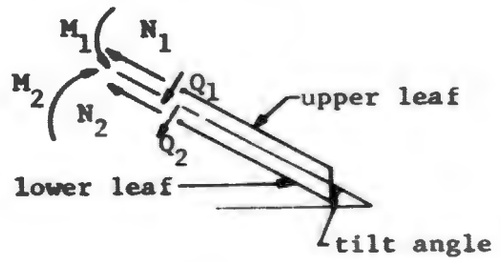
The character of the stress in the weld area is apparent from the contours of Figures A-2 through A-11. In all cases there was a concentration of stress at the tip of the notch, while the outer portions of the weld bead

TABLE A-2. DESCRIPTION OF CASES TREATED IN STUDY OF STRESSES IN WELD AREA OF BELLOWS WITH APPLIED EDGE LOADINGS

Configuration				Prescribed Edge Loads					
Case	Inner or Outer Weld	Tilt Angle	Type of Loading	N_1 lb/in.	M_1 in.-lb/in.	Q_1 lb/in.	N_2 lb/in.	M_2 in-lb/in.	Q_2 in-lb/in.
1	outer	35°	axial	-5.77897	.098978	-1.49099	5.9765	.073735	1.6265
2	outer	15°	axial	-5.61011	.19635	.268798	4.2286	.16456	-.63306
3	inner	35°	axial	-8.24315	-.093082	2.0467	8.8936	-.068648	-2.5124
4	inner	15°	axial	-9.67209	-.21614	.035447	8.0923	-.16301	.383622
5	outer	35°	pressure	5.22403	-.052849	.13205	-5.8155	-.036324	-.56815
6	outer	15°	pressure	6.2029	-.14796	-1.2834	-6.3734	-.11951	1.2350
7	inner	35°	pressure	7.254	-.052163	.51718	8.2343	-.033546	-1.2623
8	inner	15°	pressure	9.8931	-.166965	-1.12896	10.4271	-.11920	.95444



Notation - Inner Weld



Notation - Outer Weld

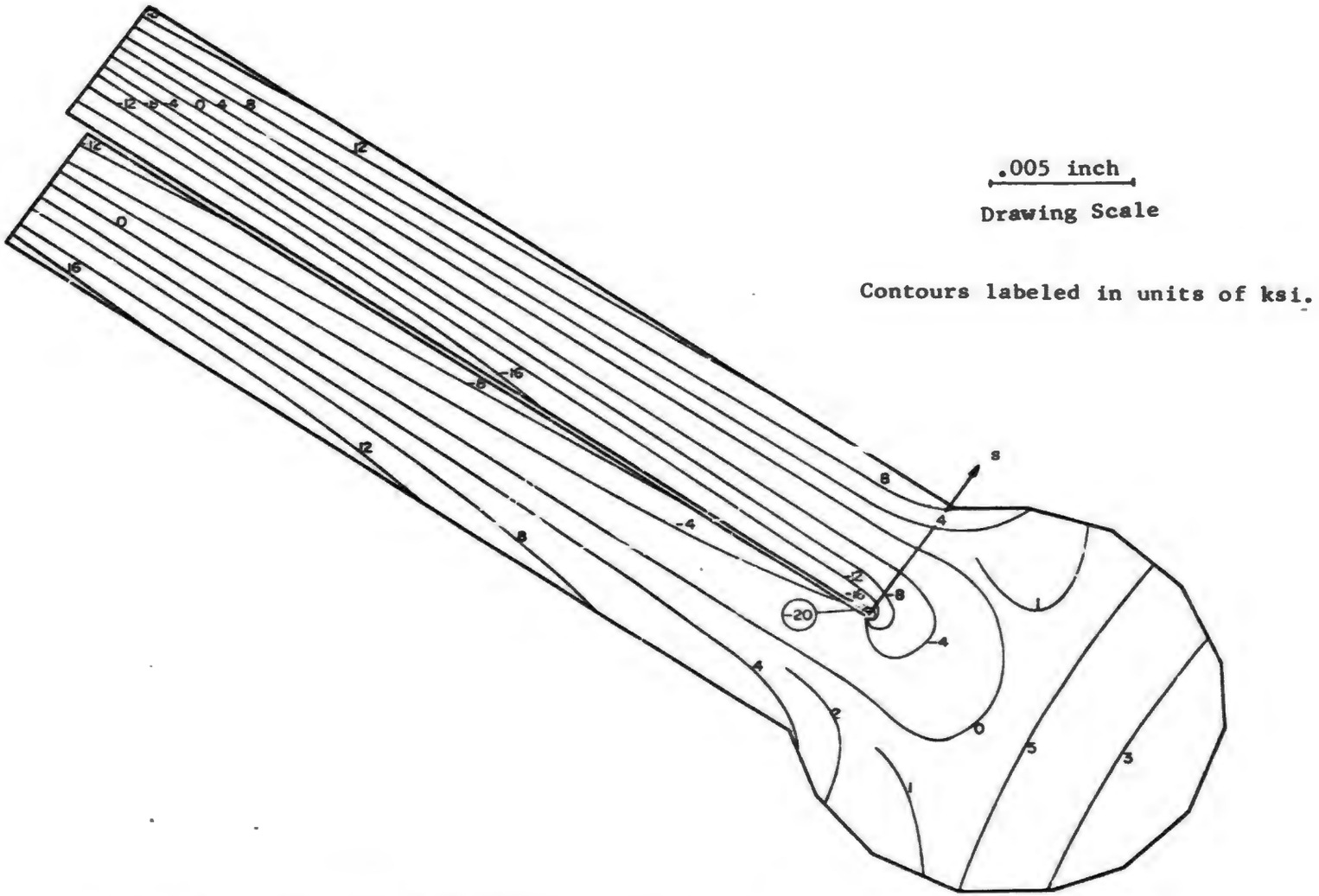


FIGURE A-2. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT DUE TO AN AXIAL DEFLECTION OF $\delta = 0.09838$ INCH PER CONVOLUTION

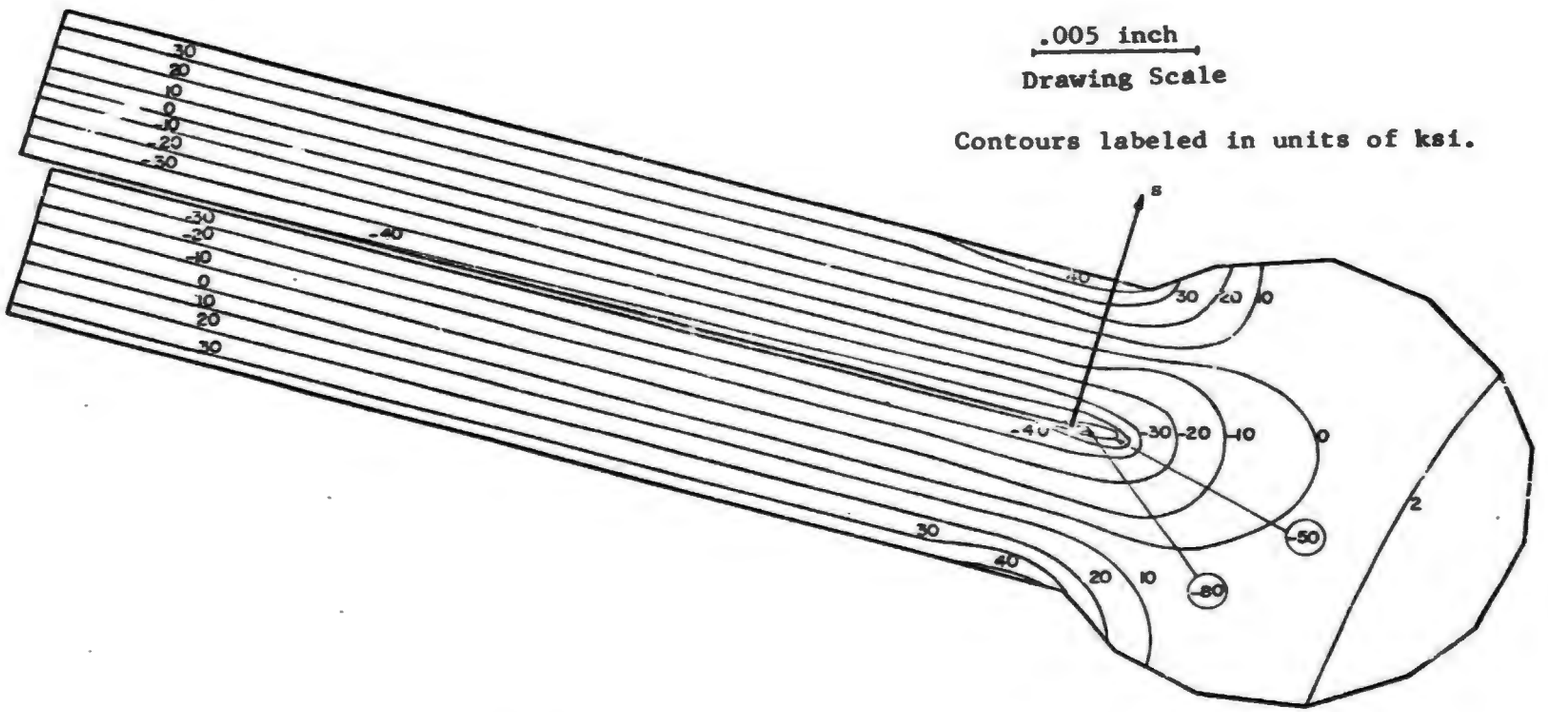


FIGURE A-3. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 15° EDGE TILT DUE TO AN AXIAL DEFLECTION OF δ = 0.09838 INCH PER CONVOLUTION

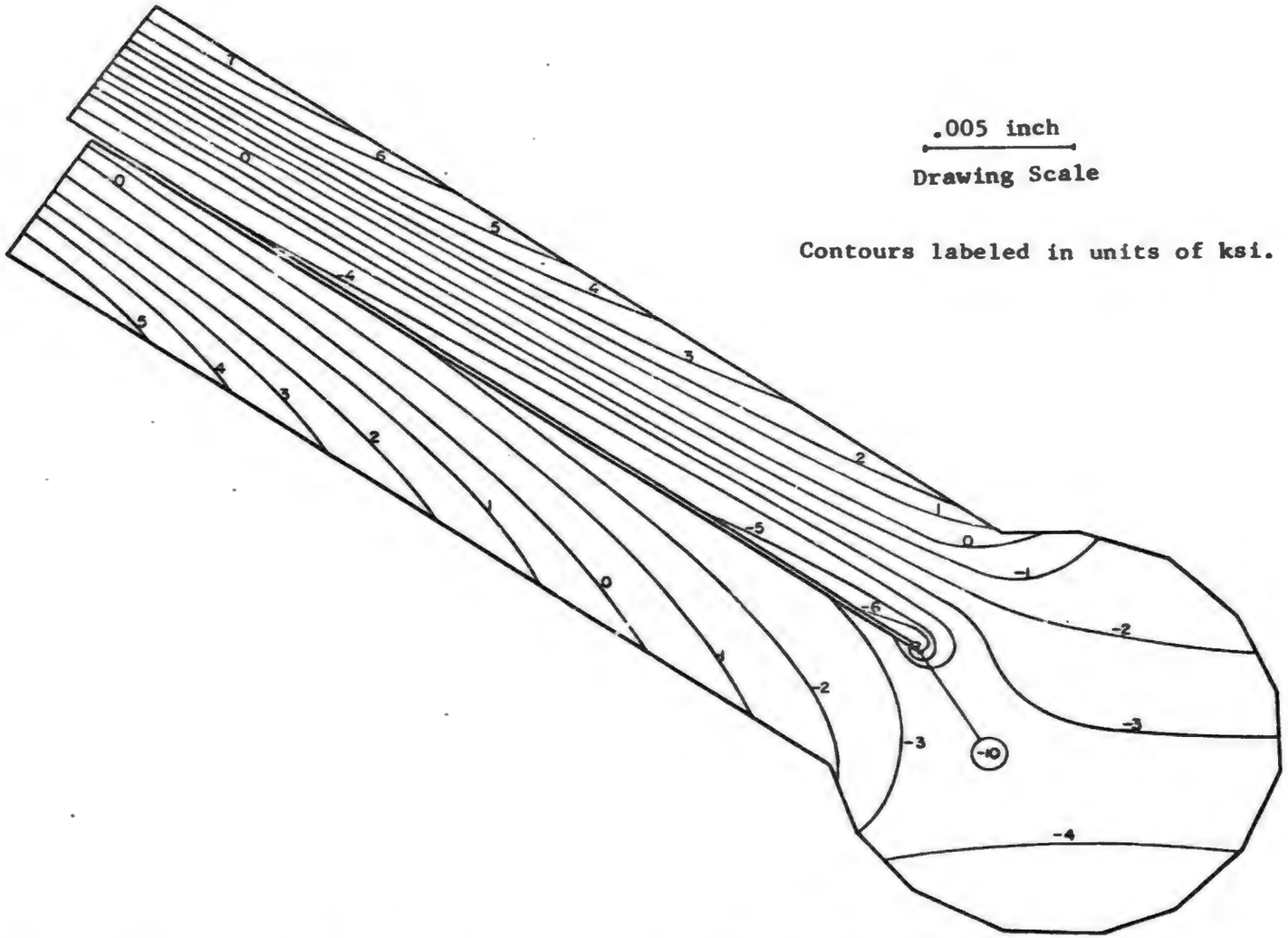


FIGURE A-4. CONTOURS OF HOOP STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT DUE TO AN AXIAL DEFLECTION OF δ = 0.09838 INCH PER CONVOLUTION

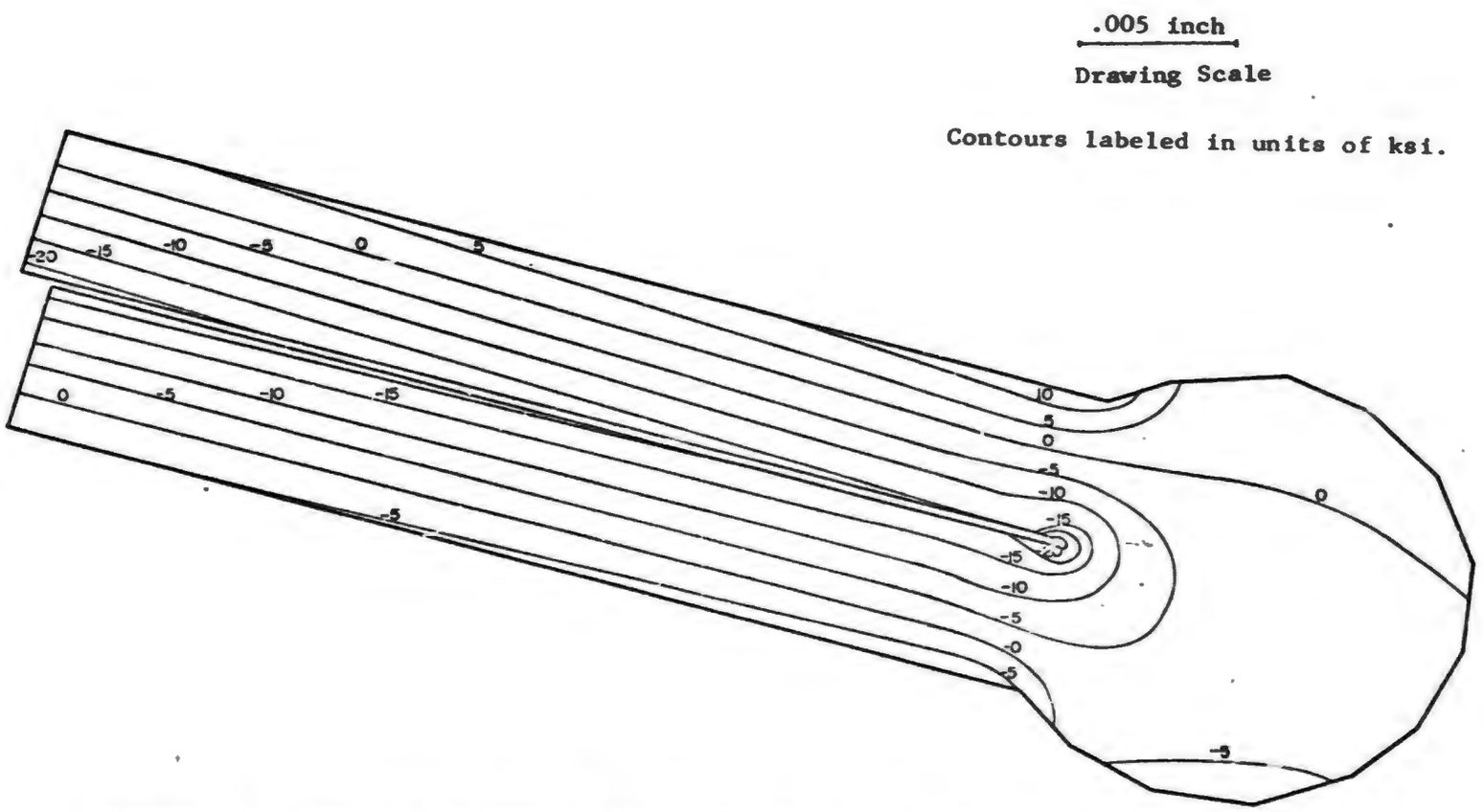


FIGURE A-5. CONTOURS OF HOOP STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 15° EDGE TILT DUE TO AN AXIAL DEFLECTION OF δ = 0.09838 INCH PER CONVOLUTION

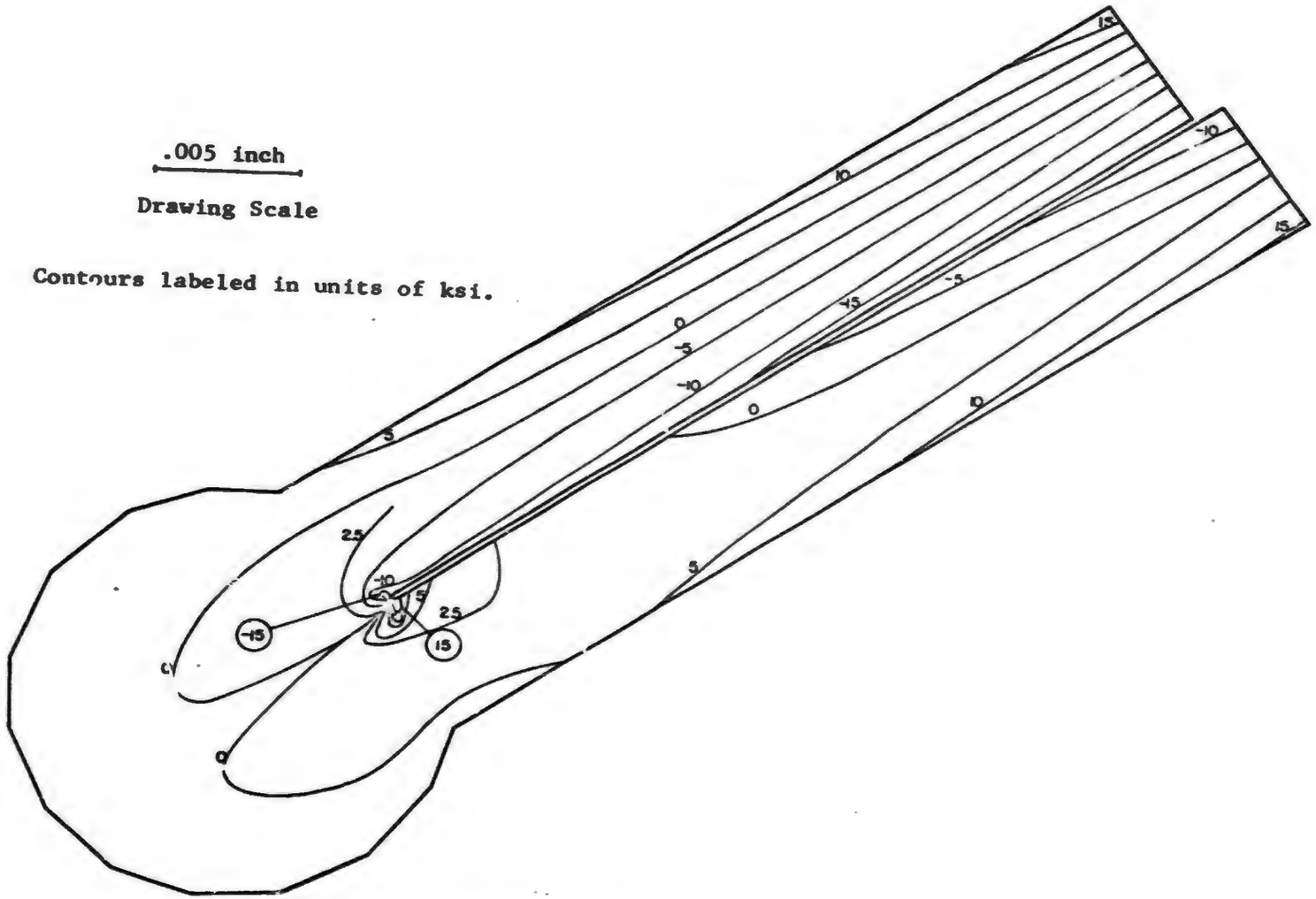


FIGURE A-6. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF ID WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT DUE TO AN AXIAL DEFLECTION OF δ = 0.09838 INCH PER CONVOLUTION

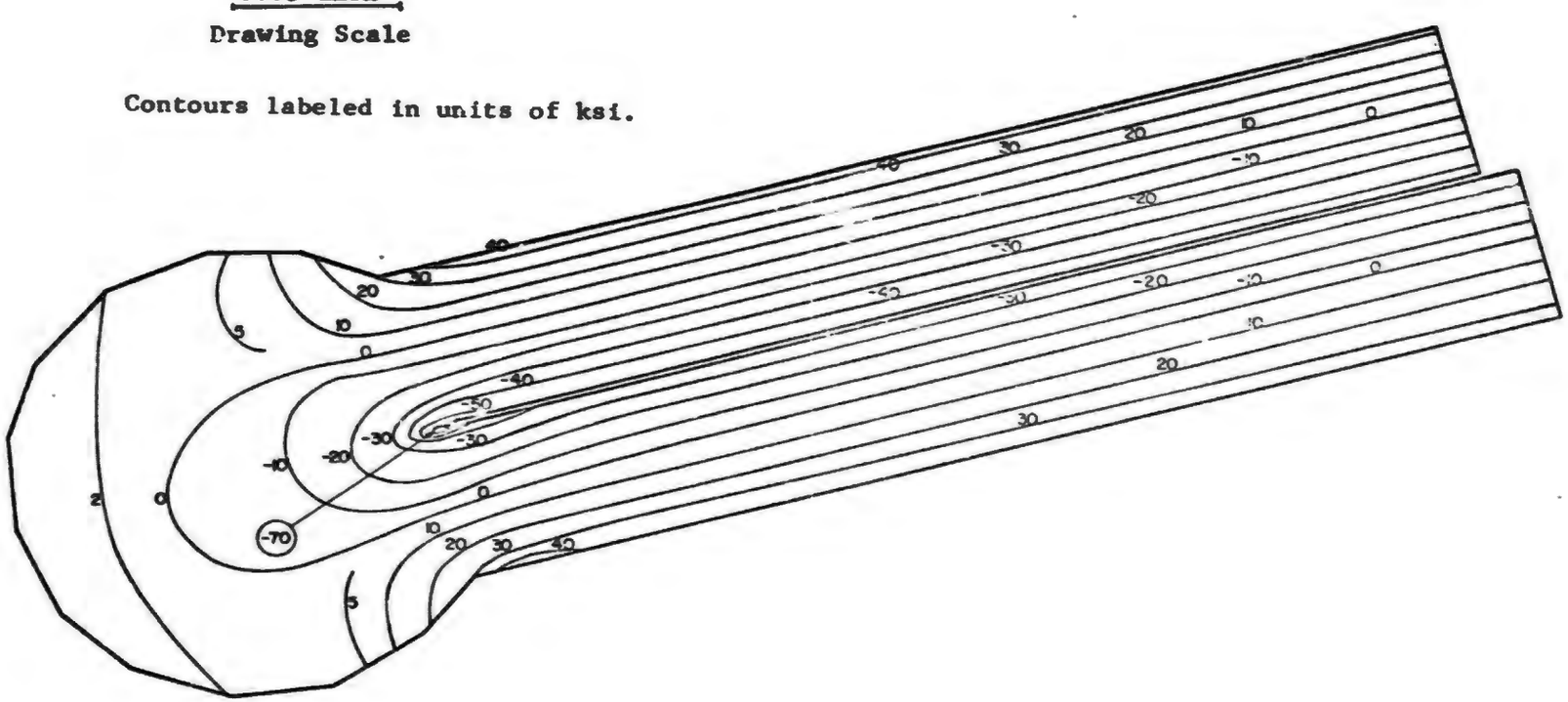


FIGURE A-7. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF ID WELD OF 4-INCH WELDED BELLOWS WITH 15° EDGE TILT DUE TO AN AXIAL DEFLECTION OF δ = 0.09838 INCH PER CONVOLUTION

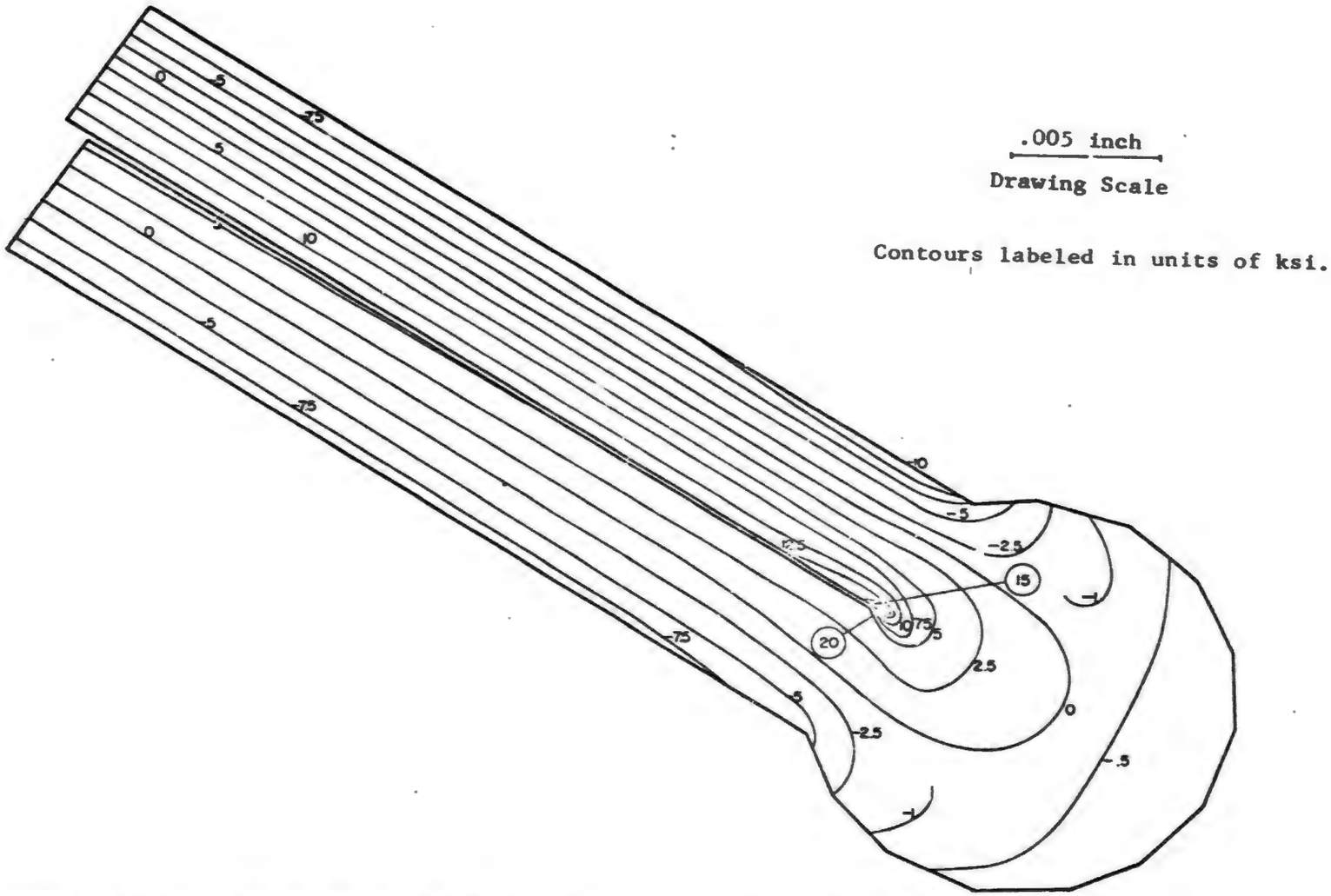


FIGURE A-8. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT DUE TO AN INTERNAL PRESSURE OF 10.0 PSI

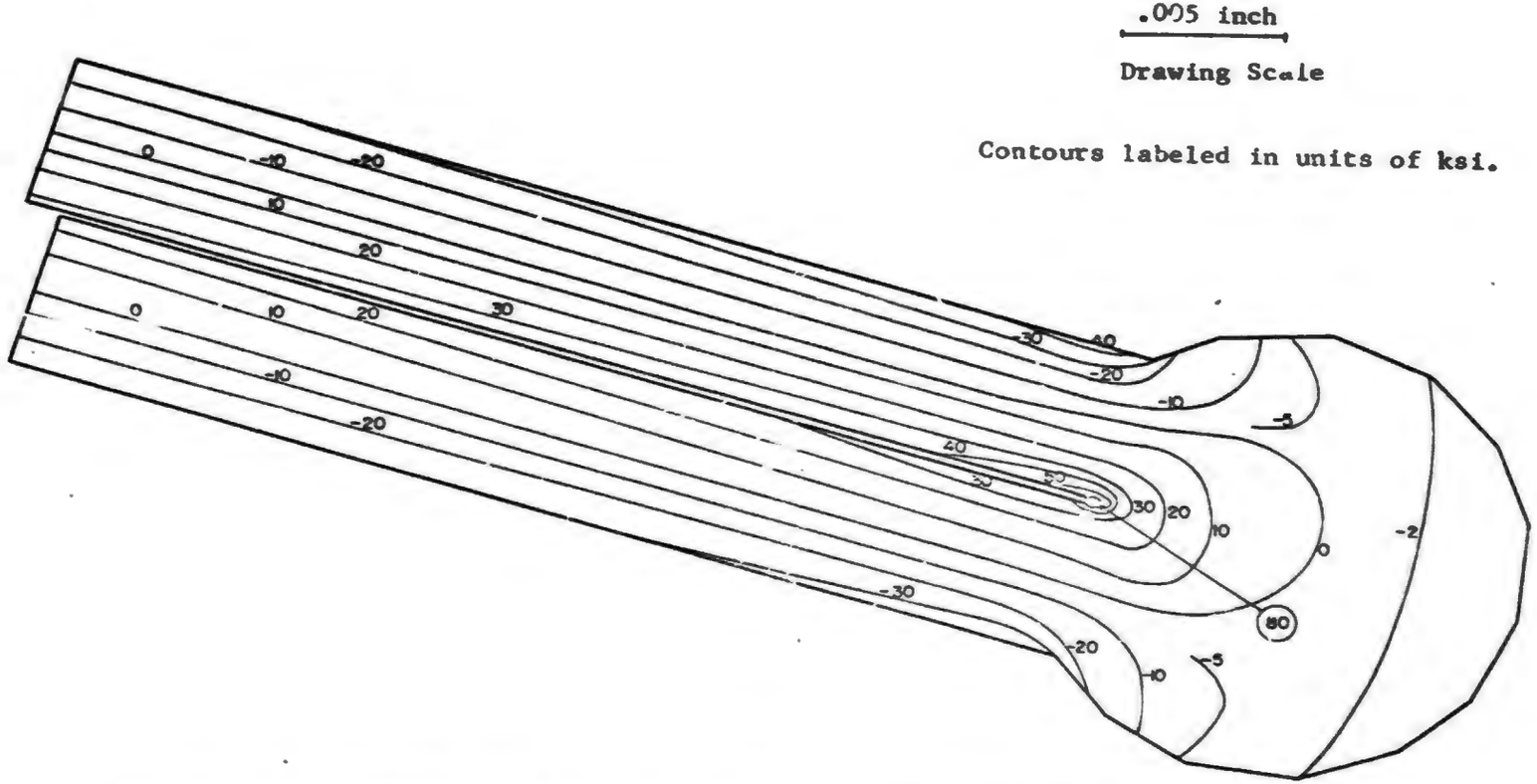


FIGURE A-9. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF OD WELD OF 4-INCH WELDED BELLOWS WITH 15° EDGE TILT DUE TO AN INTERNAL PRESSURE OF 10.0 PSI

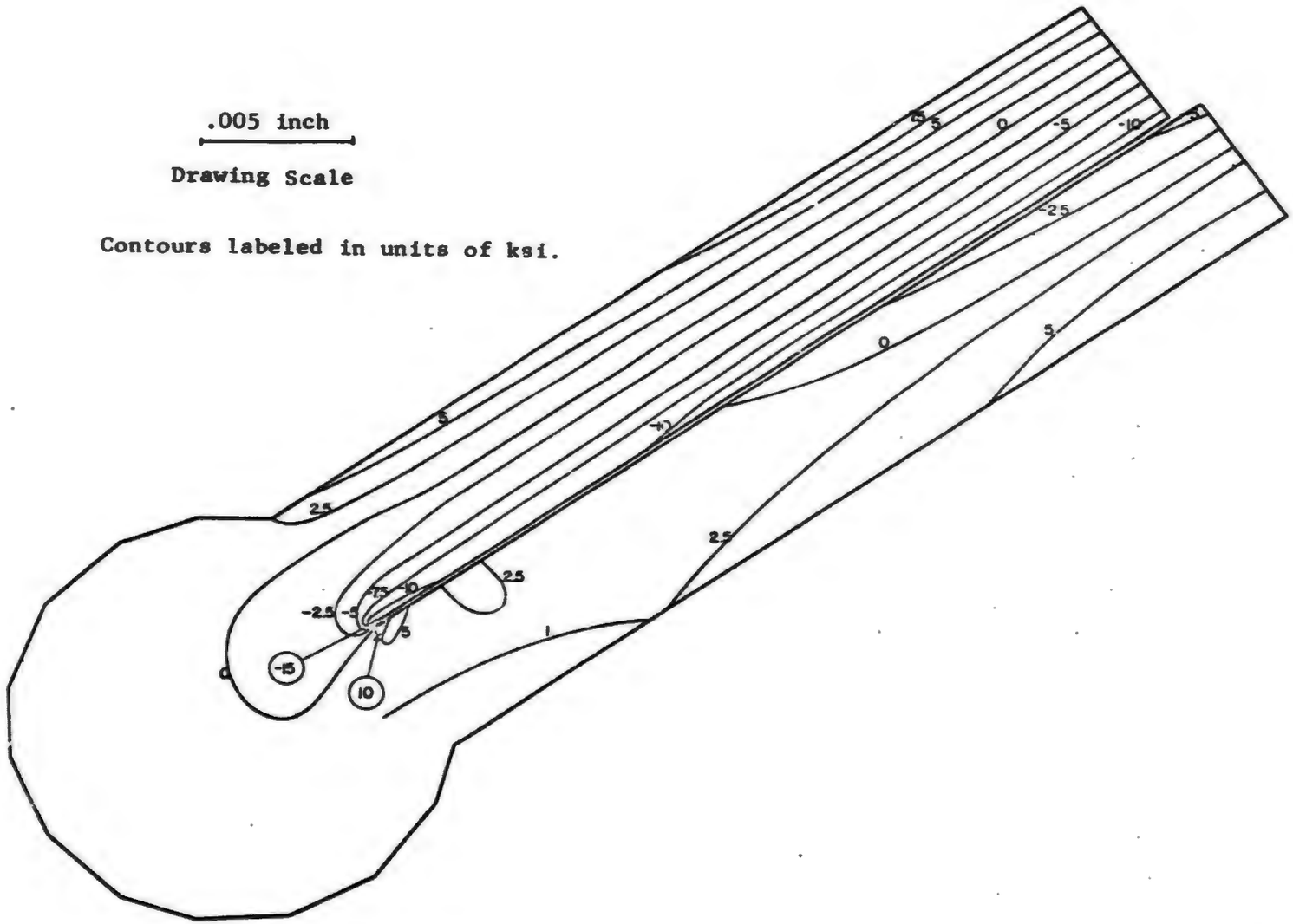


FIGURE A-10. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF ID WELD OF 4-INCH WELDED BELLOWS WITH 35° EDGE TILT DUE TO AN INTERNAL PRESSURE OF 10.0 PSI

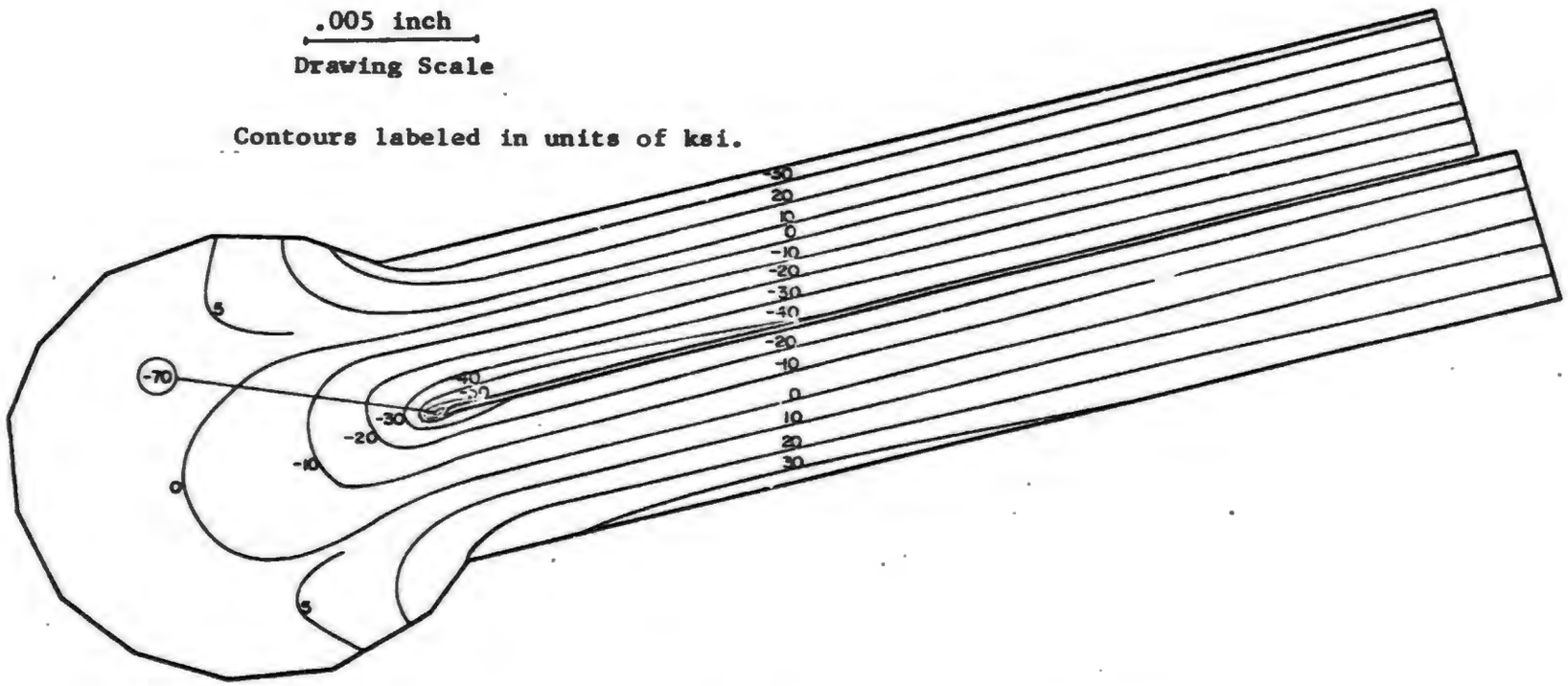


FIGURE A-11. CONTOURS OF PRINCIPAL STRESS IN MATHEMATICAL MODEL OF ID WELD OF 4-INCH WELDED BELLOWS WITH 15° EDGE TILT DUE TO AN INTERNAL PRESSURE OF 10.0 PSI

were only slightly stressed. The peak stress values that were calculated near the notch tip require special interpretation. The finite element results represented an approximation of the stress peak (infinite stress for a perfectly sharp notch) that an exact, analytical solution for the elastic stress field would show. If the mesh of finite elements were made much finer near the notch, the calculated stresses would more closely approximate such a closed-form solution. However, continued refinement of the element representation would be of little practical value, since in an actual bellows a small zone of plastic deformation will relieve these high stresses at the notch tip. For this reason, no effort was made in this study to increase the number of elements over that shown in Figure A-1. Thus, in viewing the plotted stress contours in the notch area, one should not attach much importance to the exact numerical values shown at the tip. For plotting purposes the numerical value of the innermost contour was based on the value for the element at the tip with the highest calculated stress.

Figures A-12 and A-13 show more clearly the rise in stress near the notch. The curves show the variations in principal stress for Cases 1 and 2 along the direction of the line labeled "s" in Figures A-2 and A-3. This line is approximately in the direction of the maximum stress gradient for both cases. This line cuts normal to the surface of the upper leaf at the notch tip. The linear variation of the stress, as predicted by the shell calculation, is shown for comparison purposes. As indicated, the stresses calculated by the finite element method were in reasonable agreement with the shell results, at distances greater than .0005 inch from the notch tip. For distances less than .0005 inch, the results diverged rapidly. The curve passed through the finite element data points appears to rise asymptomatically. In this zone, the elastic stresses would be very high and plastic deformation is indicated. The results suggest that the plastic zone was relatively small, on the order of one-tenth the shell thickness.

The rising nature of the curves in Figures A-12 and A-13 also suggested that larger stress could be calulated if one had added additional elements nearer the notch tip. However, the element representation used in this analysis appeared to have been sufficient to detect the stress peak. Thus, the stresses calculated for the elements adjacent to the notch tip should give some indication of the elastic stress level at the distance from the notch tip corresponding to the centers of these elements. Also, since identical element patterns were used for all eight cases, element-by-element comparison between the cases should provide a basis for determination of the effect of the notch on the relative stress levels corresponding to different tilt angles and loadings. Table A-3 gives the values of the stresses at the notch from both the shell and finite element calculations. Results for both the upper and lower leaves are shown for each of the eight cases. A stress intensification due to the notch was calculated for each case. This was defined as the ratio of the maximum stress as calculated by the shell analysis to the maximum stress as calculated by the finite element analysis. Values ranging from 1.3 to 1.9 were obtained. These values are of qualitative value since much larger values could have been obtained had more elements been taken near the notch tip. Referring to Figure A-1, the tabulated stresses correspond to the two elements closest to the notch, whose centers are about .00015 inch from the tip.

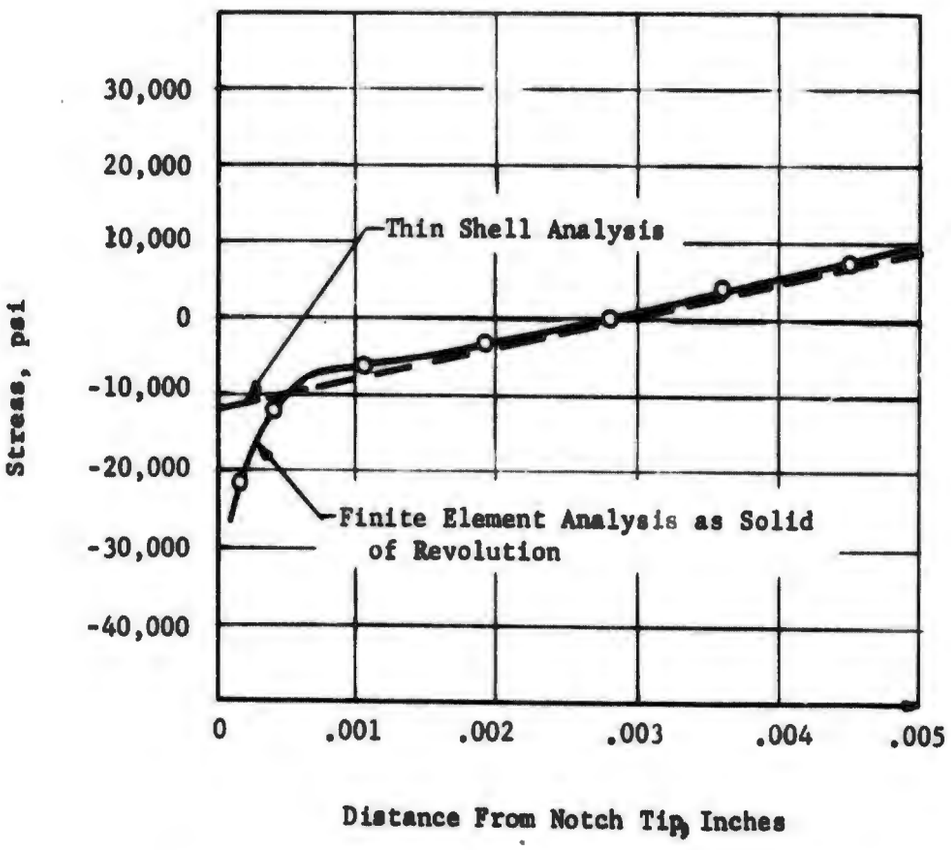


FIGURE A-12. VARIATION OF MAXIMUM STRESS WITH DISTANCE (s) MEASURED ALONG THE OUTER NORMAL FROM THE NOTCH TIP (Fig. 3); CASE 1; 35° TILT ANGLE, OUTER WELD, AXIAL LOADING

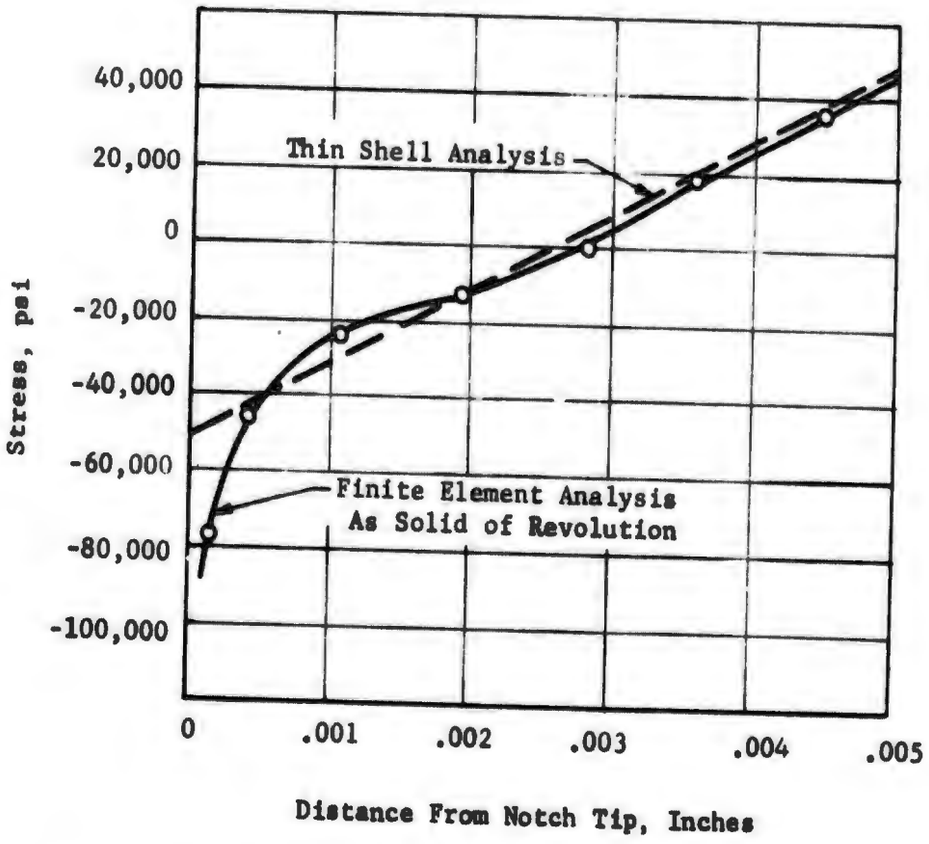


FIGURE A-13. VARIATION OF MAXIMUM STRESS WITH DISTANCE (s) MEASURED ALONG THE OUTER NORMAL FROM THE NOTCH TIP (FIG. 3); CASE 1; 15° TILT ANGLE, OUTER WELD, AXIAL LOADING

TABLE A-3. CALCULATED STRESSES AT NOTCH

Case	Inner or Outer Weld	Tilt Angle	Type of Loading		Maximum Stress Shell Analysis psi	Maximum Stress Finite Element Analysis psi	Stress Intensification*
1	Outer	35°	Axial	Upper Leaf	-11,415	-21,860	1.9
				Lower Leaf	-889	-3,864	
2	Outer	15°	Axial	Upper Leaf	-50,610	-54,800	1.6
				Lower Leaf	-49,958	-81,050	
3	Inner	35°	Axial	Upper Leaf	-6,229	-14,310	1.5
				Lower Leaf	9,361	14,410	
4	Inner	15°	Axial	Upper Leaf	-55,210	-78,370	1.4
				Lower Leaf	-40,696	-59,600	
5	Outer	35°	Pressure	Upper Leaf	13,362	23,610	1.8
				Lower Leaf	4,681	5,473	
6	Outer	15°	Pressure	Upper Leaf	49,578	78,780	1.6
				Lower Leaf	40,136	48,850	
7	Inner	35°	Pressure	Upper Leaf	-10,394	-14,280	1.4
				Lower Leaf	2,461	11,530	
8	Inner	15°	Pressure	Upper Leaf	-54,701	-73,020	1.3
				Lower Leaf	-38,609	-49,070	

*Stress Intensification = $\left(\frac{\text{maximum stress from finite element analysis}}{\text{maximum stress from shell analysis}} \right)$

The thin shell analysis of the welded bellows indicated that large reductions in stress at the welds could be achieved by tilting the edges of the bellows. However, the shell calculations did not include any stress-intensification effects of the notch. It was not known how such effects might interact with the effect of tilting the bellows edge. The more detailed, finite element analyses of the weld area provide valuable support to previous conclusions that were based on the shell calculations. Table A-4 shows the effect of changing the edge tilt from 15 to 35 degrees. Ratios of the maximum stress at the weld for 35 degrees tilt to the maximum stress for 15 degrees tilt are given. The ratios were calculated from the stress values given in Table A-3. Remarkable agreement was found between the ratios calculated based in one case on the results of shell analysis and in the other case on the results of the finite element analysis. Considering the conventions used to calculate these ratios, no significance should be attached to the fact that slightly smaller reductions in stress due to increasing the edge tilt were predicted in each case by the finite element calculation.

Conclusions

The results of the weld area analysis can be summarized with the following conclusions:

(1) Except for an intense stress peak at the tip of the notch, the stresses in the weld bead material were low compared to the stresses in the adjacent leaves.

(2) The peak stresses at the notch were much greater than the nominal stresses predicted by thin shell calculations However these peak stresses were very localized and decayed to the shell stress distribution within a distance of about one tenth of a leaf thickness from the notch tip.

(3) Optimization of the edge tilt angle on the basis of the nominal stresses calculated with thin shell theory was valid, since variation of the edge tilt angle had a comparable effect on both nominal and peak stress in the weld area.

(4) In the analysis of welded bellows with thin shell theory, separation of the midsurfaces of the joined bellows leaves should be included in the shell model. The representation of the weld bead as a short, cylindrical, shell part had a significant local effect on the calculated shell stresses. It yielded nominal stress values that are consistent with the more exact analysis of the weld area as a solid of revolution.

TABLE A-4. DECREASE IN STRESS AT WELD DUE TO CHANGE IN EDGE TILT ANGLE FROM 15° TO 35°

Cases	Stress Reduction Shell Analysis	Stress Reduction Finite Element Analysis
Outer Weld, Axial Load Case No. 1 vs. Case No. 2	.23	.27
Inner Weld, Axial Load Case No. 3 vs. Case No. 4	.17	.18
Outer Weld, Pressure Case No. 5 vs. Case No. 6	.27	.30
Inner Weld, Pressure Case No. 7 vs. Case No. 8	.19	.20

$$\text{Stress Reduction} = \left(\frac{\text{maximum stress } 35^\circ \text{ tilt}}{\text{maximum stress } 15^\circ \text{ tilt}}\right)$$

APPENDIX B

ADDITIONAL SUBROUTINES TO AID IN THE INVESTIGATION OF WELDED BELLOWS

APPENDIX B

ADDITIONAL SUBROUTINES TO AID IN THE INVESTIGATION OF WELDED BELLOWS

During the course of the investigation of improved welded bellows configurations, two major subroutines to aid in the analyses have been developed, namely subroutines FIT and PLT. The subroutine FIT uses the x-y coordinates of the bellows to be analyzed and automatically prepares the shell-parameter input data as required by program NONLIN. PLT was developed so that plots of preselected variables (deflections, stresses, etc.) could be made and superimposed on the shape of the bellows model being analyzed.

These additional subroutines required that certain changes be made in the original versions of NONLIN, INPUT, and PRINT. They were described in Appendix B of the "Final Report on the development of Analytical Techniques for Bellows and Diaphragm Design", Technical Report No. AFRPL-TR-68-22[1]. Also, several, smaller subroutines were developed for use with the program FIT. This appendix describes the changes required in the original program versions reported previously and the new subroutines developed for use with FIT. It presents the FORTRAN listings of all the new programs developed, along with detailed instructions on their proper usage.

Description of Subroutine PLT

This portion of the appendix describes the new subroutine called "PLT" which has been incorporated into the computer program NONLIN. NONLIN has been presented in Appendix B of the "Final Report on the Development of Analytical Techniques for Bellows and Diaphragm Design", Technical Report No. AFRPL-TR-68-22.

PLT is written in FORTRAN IV and is operational on the CDC 6400 at Battelle-Columbus. It makes use of CALCOMP 565 plotter and various plotting subroutines developed at Battelle. These routines are QIKPLT, QLINE, PLOT, SYMBOL, and ENCODE. These routines are on the System Library tape at Battelle-Columbus. The purpose of PLT is:

(1) To define the Input Mathematical Model in an x-y coordinate system, to select a proper scale such that the model fits in an 8-1/2 by 11-inch plotting area, and then to draw the shape of the model. It also identifies the first and last points on each shell part by point (+) plots on the model already drawn.

(2) To superimpose on the shape of the model the value of a preselected variable (deflection, stress, etc.) so that the model cross section corresponds to zero "variable" level. The variable is plotted along the normal to the shell and on a suitable scale automatically determined by PLT.

The incorporation of PLT in NONLIN involved an extension of "Input Data Preparation" (Appendix B, Paragraph B-II-d of Technical Report No. AFRPL-TR-68-22). The program now includes 15 data sets. A previously coded variable in Data Set 5 was activated; this variable initiates the call to PLT and also specifies the number of variables to be plotted. Revised Data Set 5 and Data Sets 13, 14, and 15 are described below.

In order to make PLT operational, a minimum number of changes were made in NONLIN, PRINT, and INPUT. These changes consist of only activating those portions on NONLIN, PRINT, and INPUT which had previously been coded for use in a plot subroutine. The particular changes in portions of the program NONLIN and the subroutines INPUT and PRINT required for the incorporation of PLT are presented at the end of this section together with a complete FORTRAN listing of the new subroutine PLT.

It should be mentioned that since it has been found that toroidal, conical, and cylindrical parts are sufficient to represent even the most irregular bellows, the present plot routine PLT does not accept a model with either ellipsoidal, paraboloidal, or spheroidal shell parts. Also, for welded bellows analysis, PLT has the capability of plotting up to two convolutions or four leaves of the mathematical model. Each leaf cross section, together with the desired superimposed curve of stress or deformation variable, is plotted automatically on a separate sheet.

New Data Sets Required for Use with PLT

Data Set 5

```
READ (5,561)  IBRM, ITER, NDUMMY, PLØT, INTPRN, INTVAL, LEVEL 1, LEVEL 2,
              ERP, CØNVER, NUMHAR, (NFØURA (1), I = 1, 8)

561 FØRMAT (8I5, 2E10.3 , 10I2)
```

IBRM = number of parts in composite shell
ITER = number of iterations at a load level for nonlinear calculations
ITER = 0 for linear analysis

NDUMMY = not presently used

PLØT = number of variables to be plotted; maximum number that can be specified is 10. If PLØT is other than 0, then Data Sets 13, 14, and 15 are to be read in.

Use PLØT = 0 for no plot.

INTPRN = 0 indicates that intermediate results from the nonlinear analysis, i.e., values of parameters and slopes will not be printed out. Use 1 to obtain values.

INTVAL = 0 indicates that the intermediate results from the initial value integrations will not be printed out. Use 1 to obtain values.

LEVEL 1 = number of increments into which the loading is divided for nonlinear analysis.

LEVEL 2 = not presently used.

ERP = accuracy for integration subroutine. If left blank, it is internally set to 1.0 E - 05.

CØNVER = convergence criteria for use in nonlinear analysis.

NUMHAR = number of FØURIER harmonics in the analysis. For a nonlinear analysis, NUMHAR = 1. For a linear analysis, NUMHAR must not be greater than 8. If the shell is axisymmetrically loaded, NUMHAR = 1. For a nonsymmetrically loaded shell which has the same boundary conditions for all harmonics, NUMHAR can have any value up to 8.

NFØURA (I) = FOURIER harmonic value.
For an axisymmetric deformation NFØURA (1) = 0.

Data Set 13

READ (5,525) (IPLØT (I), I = 1, PLØT)
READ (5,526) (JØBPLT (I), I = 1, PLØT)

525 FØRMAT (10I5)

526 FØRMAT (10A8)

IPLØT (I) is the code number for the variable to be plotted against the geometry of the shell parts. See left-hand side of the table given after JØBPLOT (I)

JØBPLØT (I) is the variable name. See right-hand side of the table below.

Code Number	Variable Name
1	W
2	Q PHI
3	U PHI
4	N PHI
5	BETA PHI
6	M PHI
7	N THETA
8	M THETA
9	EPS THET
10	EPS PHI
11	SIG NPHI
12	SIG MPHI
13	SIG PHII
14	SIG PHIØ
15	SIG NTHT
16	SIG MTHT
17	SIG THTI
18	SIG THTØ
19	TAU PHI

Data Set 14

READ (5,2001) (YTITLE (I,J), I=1, 8), J = 1, PLØ1)

2001 FØRMAT (8A10)

YTITLE is full title of the variable. For each plot a separate card is needed. Each title takes 42 columns. An * is required in column's 1 and 42. (PLØ1) is the name for PLØT local to the subroutine PLT.)

Data Set 15

READ (5, 2002) NLS

2002 FORMAT (I5)

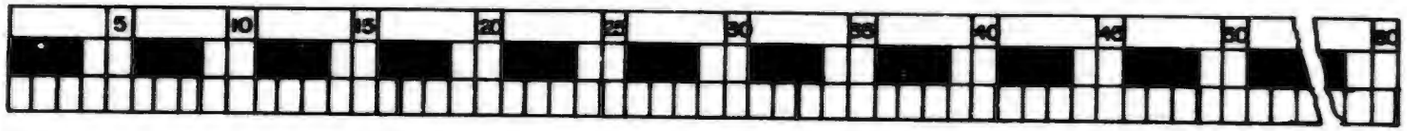
READ (5,2003) (INLS (I), I = 1, NLS)

2003 FORMAT (4I5)

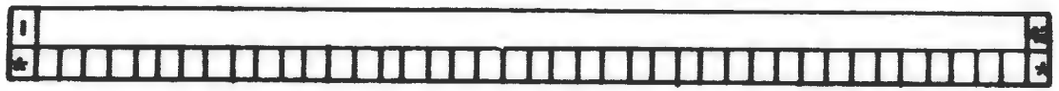
NLS is the number of leaves in the mathematical model. NLS can be either 1, 2, 3, or 4.

INLS (I) is the last part number (IBRM) of each leaf.

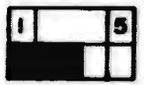
Data sheets showing the proper format for Data Sets 13, 14, and 15, described above are shown in Figure B-1.

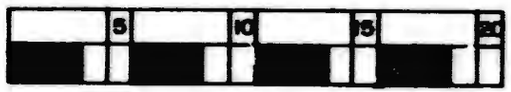


DATA SET 13 (PLOT CODE AND VARIABLE NAME)



DATA SET 14 (TITLE OF PLOT)





DATA SET 15 (NO. OF LEAVES AND LAST PART NO.)

FIGURE B-1. INPUT SHEET FOR DATA SETS 13, 14, and 15

Required Changes in NONLIN, INPUT, and PRINT

The following FORTRAN IV listings indicate the changes made in NONLIN, INPUT, and PRINT which were required for the incorporation of the new subroutine PLT. Only those parts of the listings which differ from the original versions given in Battelle's earlier report on analytical techniques for bellows and diaphragm design are presented. The particular changes are clearly marked.

```
      PROGRAM NONLIN(INPUT,OUTPUT,PLOT,TAPE5=INPUT,TAPE6=OUTPUT,PUNCH,TA
     1PE7=PUNCH)
      DIMENSION       IA(8)           , SI(60)          , IPAR(60)      ,
     *                IB(8)           , SX(60)          , INT(60)       ,
     *                GA(8)           , PRNT(8)         , ISS(60)       ,
     *                GB(8)           , ERR(8)          , PSR(60)       ,
     *                Y(8)            , DM(8,61)        , EYM(60)       ,
     *                DY(8)           , TL(8,8)         , A(8,9)        ,
     *                TR(8,8)         , TLI(8,8)        , JOBPLT(10)    ,
     *                TRI(8,8)        , TRY(8,61)       , TR2(8,8)      ,
     *                SOUT(275)       , D(8,9,60)       , P(5,275)      ,
     *                SLOPE(5,275)    , TRI(8,8)        , E(9,60)
      DIMENSION       V3(8)           , VM(7,60)        , YAM(72)       ,
     *                DYAM(72)        , AMC(21)         , FAM(10)       ,
     *                BACK(60)        , YSAVE(8)        , DETERM(10)    ,
     *                IPLOT(10)       , XPLOT(350)      , YPLOT(350,10),
     *                STROUT(350)     , SIGNPH(350)     , SIGNPH(350)   ,
     *                SIGPHT(350)     , SIGPHB(350)     , SIGNTH(350)   ,
     *                SIGNTH(350)     , SIGTHT(350)     , SIGTHB(350)   ,
     *                TAUPHI(350)     , VARTIK(60)      , POINT(60)     ,
     *                DMSAVE(6,61)
      DIMENSION       XPLT(350),YPLT(350,10)
      COMMON / BLOCKA / NU, PI, RLD, NTYPE, INDEX, IBR, PN, NPOINT,
     1                  ISM, TT, T1, T2, MTT, INTC
      COMMON / BLOCKB / H, H1, H2, H3, SXN, CKS
      COMMON / BLOCKC / DM, GA, GB, NF, NFP, NPL, NM, NN, TRY
      COMMON / BLOCKD / TL, TR, TLI, TRI, ALFL, ALFR
      COMMON / BLOCKF / NFF, SMXX, SZERO, GO, ERP, ISS, E,
     *                  MAX, INTPRN, INTVAL, NPP
      COMMON / BLOCKG / NPARTS, PHI, V3, KIND, NT, MT, SPRINT, VN, EYM,
     1                  BACK, NBACK
      COMMON / BLOCKH / MDE
      COMMON / BLOCKJ / DELX, PDELX, ABC, EAM
      COMMON / BLOCKK / PIN, PHIN, HO, XO, EMIN, EMAX
      COMMON / BLOCKL / YAM, DYAM
      COMMON / BLOCKM / YSAVE
      COMMON / BLOCKN / DETERM
      COMMON / BLOCKP / PLOT, PLTIME, SPLOT, PLOTPT, IPLOT, YMOD, KST,
     *                  HGAMMA, DEAD, NFH
      COMMON / BLOCKQ / TIME, VARTIK, NVARTK
      COMMON / BLOCKS / JOBPLT, ALXL, ALXR, IA, IB, NOPUNC, INPUN,
     *                  CONVER, SI, SX, INT, IPAR, PSR, ITER, NTRY,
     *                  NERROR, IBRM, TRYIN, IBRMAX
      COMMON / BLOCKX / LEVEL1, LEVEL2
      COMMON / PLXY1C / IEX(8), DUM(4)
      COMMON /PLXY2C / XPLT,YPLT,NCC
      COMMON          SLOPE, P, SOUT, D, A
      EQUIVALENCE   (Y(1), PRNT(1)), (Y(1), YAM(2)), (DY(1), DYAM(2)),
     1              (S, YAM(1)), (VARTIK(1), POINT(1))
      EQUIVALENCE    (SLOPE(1) ,  YPLOT(1)    ),
     *               (D(476)   ,  XPLOT(1)    ),
     *               (D(826)   ,  STROUT(1)   ),
     *               (D(1176)  ,  SIGNPH(1)   ),
     *               (D(1526)  ,  SIGMPH(1)   ),
     *               (D(1876)  ,  SIGPHT(1)   ),
     *               (D(2226)  ,  SIGPHB(1)   ),
```

```
     *                (D(2576)  ,  SIGNTH(1)  ),
     *                (D(2926)  ,  SIGNTH(1)  ),
     *                (D(3276)  ,  SIGTMT(1)  ),
     *                (D(3626)  ,  SIGTMB(1)  ),
     *                (D(3976)  ,  TAUPHI(1)  )
      INTEGER  GO, TRYIN, PASS, SPACE, ADMSCT, FINIS, PLOT,
     *         PLOTPT, PLTIME, TIME, VARTIK, POINT
      DATA(RPD = 0.17453292552E-01)
      REAL     NU, NT, MT, NBACK, NFM
C
C        ***************************************************
C        *                                                 *
C        *              SUMMARY OF COMMON                  *
C        *                                                 *
C        ***************************************************
C        * PROGRAM *A*B*C*D*E*F*G*H*J*K*L*M*N*O*P*Q*S*X*1* *
C        ***************************************************
C        * ADMINT  * * * * * * * *Y*Y*Y*Y* * *Y* * * * * * *
C        ***************************************************
C        * ADMRES  * * * * * * * *Y*Y*Y*Y* * *Y* * * * * * *
C        ***************************************************
C        * BCOND   * * * *Y* * * *Y* * * * * * * * * * * * *
C        ***************************************************
C        * CALCUL  *Y*Y*Y*Y* *Y*Y*Y*Y*Y*Y*Y*Y* *Y*Y*Y* *Y*Y*
C        ***************************************************
C        * DIFFEQ  *Y*Y* * * * * *Y* * *Y* * * *Y* * * * *Y*
C        ***************************************************
C        * GOMTRY  *Y*Y*Y* * *Y*Y* * * *Y* * * *Y*Y* * * *Y*
C        ***************************************************
C        * INPUT   *Y* *Y* *Y*Y*Y*Y* * * * *Y* *Y*Y*Y*Y* * *
C        ***************************************************
C        * INTEG   *Y*Y*Y* * *Y* *Y*Y*Y*Y* * * *Y* * * * *Y*
C        ***************************************************
C        * INVERT  * * * * * * * * * * * * * * * * * * * * *
C        ***************************************************
C        * MATML   * * * * * * * * * * * * * * * * * * * * *
C        ***************************************************
C        * NONLIN  *Y*Y*Y*Y* *Y*Y*Y*Y*Y*Y*Y*Y* *Y*Y*Y*Y*Y*Y*
C        ***************************************************
C        * PLTXY1  * * * * * * * * * * * * * * * * * * *Y* *
C        ***************************************************
C        * PRINT   *Y*Y*Y*Y* *Y*Y*Y*Y*Y*Y*Y*Y* *Y*Y*Y* *Y*Y*
C        ***************************************************
C        * THICK   *Y*Y* * *Y* *Y* * * *Y* * * * *Y* * * * *
C        ***************************************************
C        * TRIANG  * * *Y* * *Y* *Y* * * * *Y* * * * * * *Y*
C        ***************************************************
C
999   CALL INPUT
      IF(PLOT .EQ. 0)1,2
    1 PLTIME=0
      GO TO 3
    2 PLTIME=1
    3 CONTINUE
      IF(INTVAL .EQ. 0) GO TO 415
```

```
      WRITE  (6,483)
415   ALFL = ALXL*RPD
      ALFR = ALXR*RPD
      CALL BCOND
      DO 250 I = 1, 8
      DO 250 J = 1, 8
      TLI(I,J) = 0.0
      TRI(I,J) = 0.0
250   CONTINUE
      DO 20 J=1,NDE
      DO 20 I=1,NDE
      K=IA(I)
      L=IB(I)
      DM(I,J)=TL(K,J)
   20 A (I,J)=TR(L,J)
      DO 23 I=1,NDE
      DO 23 J=1,NDE
      TL(I,J)=DM(I,J)
   23 TR(I,J)=A (I,J)
      DO 21 I=1,NDE
      DO 21 J=1,NDE
      TLI(I,J)=TL(I,J)
   21 TRI(I,J)=TR(I,J)
      CALL INVERT (TLI,NDE,8,DET,ISCAL)
      CALL INVERT (TRI,NDE,8,DET,ISCAL)
      IF(INTVAL .EQ. 0) GO TO 410
      WRITE(6,22)  ((TL(I,J), J = 1, 8),   (TR(I,J), J = 1, 8),
     1             I = 1, NDE)
      WRITE  (6,24 )
      WRITE(6,22)  ((TLI(I,J), J = 1, 8),   (TRI(I,J), J = 1, 8),
     1             I = 1, NDE)
410   NFP = NPARTS + 1
      DO 859 I = 1, IBRN
      BACK(I) = 1.0
859   CONTINUE
      DO 770 IBR = 1, IBRN
      ISM = ISS(IBR)
      GO TO (770, 770, 7703, 7703, 7703, 770, 7703, 770),  ISM
7703  IF(SX(IBR) .GT. SI(IBR))  GO TO 7710
      BACK(IBR) = -1.0
      SI(IBR) = 180.0 - SI(IBR)
      SX(IBR) = 180.0 - SX(IBR)
7710  SX(IBR) = SX(IBR)*RPD
      SI(IBR) = SI(IBR)*RPD
770   CONTINUE
      IF(ISS(IBRN) .EQ. 1) GO TO 855
      IBRMAX = IBRN
      GO TO 856
855   IBRMAX = IBRN - 1
856   DO 1100 J = 1, NFP
      DO 1100 I = 1, 8
      TRY(I,J) = 0.0
1100  CONTINUE
      DO 1103 L = 1, IBRMAX
      DO 1103 I = 1, 8
      DM(I,L) = 0.0
```

```
1103  CONTINUE
      NN = 1
      NTYPE = 1
      CALL CALCUL
      CALL PRINT
      MCC=2
      CALL PLI
      WRITE(6,693)  DETERM(1)
      IF(ITER .EQ. 0)  GO TO 999
      WRITE(6,601)  PN, GA(1), GA(2), GB(4), GB(5)
      FACTOR = 1.0/FLOAT(LEVEL1)
      DO 420 L = 1, NFP
      DO 420 I = 1, 6
      TRY(I,L) = BM(I,L)*FACTOR
  420 CONTINUE
      NN = 0
      NFAIL = 0
      NTYPE = 2
      NNNMAX = LEVEL1
      PNMAX = VN(5,1)
      DEMAX1 = GA(1)
      DEMAX2 = GA(2)
      DEMAX3 = GB(4)
      DEMAX4 = GB(5)
      GA(1) = 0.0
      GA(2) = 0.0
      GB(4) = 0.0
      GB(5) = 0.0
      PNINCR = PNMAX/FLOAT(NNNMAX)
      DEINC1 = DEMAX1/FLOAT(NNNMAX)
      DEINC2 = DEMAX2/FLOAT(NNNMAX)
      DEINC3 = DEMAX3/FLOAT(NNNMAX)
      DEINC4 = DEMAX4/FLOAT(NNNMAX)
      TEMP = 0.0
      DO 105 L = 1, NFP
      DO 105 I = 1, 6
      DNSAVE(I,L) = 0.0
  105 CONTINUE
      DO 400 NNN = 1, NNNMAX
      TEMP = TEMP + PNINCR
      DO 397 L = 1, IBMM
      VN(5,L) = TEMP
  397 CONTINUE
      GA(1) = GA(1) + DEINC1
      GA(2) = GA(2) + DEINC2
      GB(4) = GB(4) + DEINC3
      GB(5) = GB(5) + DEINC4
      ITERCT = 0
  810 NN = NN + 1
      CALL CALCUL

C COMMENT   CHECK CONVERGENCE

      ITERCT = ITERCT + 1
      MAXXX = NPARTS - 1
      DO 811 L = 2, MAXXX
```

```
      DO 811 I = 1, 6
      IF(TRY(I,L) .EQ. 0.0)  GO TO 811
      IF(DM(I,L) .EQ. 0.0)  GO TO 811
      IF(ABS((DM(I,L) - TRY(I,L))/DM(I,L)) .GT. CONVER)  GO TO 850
  811 CONTINUE
      DO 110 L = 1, NFP
      DO 110 I = 1, 6
      TRY(I,L) = 2.0*DM(I,L) - DMSAVE(I,L)
  110 CONTINUE
      DO 112 L = 1, NFP
      DO 112 I = 1, 6
      DMSAVE(I,L) = DM(I,L)
  112 CONTINUE
      GO TO 815
  850 IF(ITERCT .EQ. ITER)  GO TO 8115
      DO 100 L = 1, NPARTS
      DO 100 I = 1, 6
      TRY(I,L) = DM(I,L)
  100 CONTINUE
      GO TO 810
 8115 NFAIL = 1
  815 CALL PRINT
      NCC=2
      CALL PLI
      WRITE(6,681)  PN, GA(1), GA(2), GB(4), GB(5)
      IF(NFAIL .EQ. 0)  GO TO 3951
      WRITE(6,692) ITER
      GO TO 396
 3951 WRITE(6,689)  ITERCT
      ITERCT = 0
  396 WRITE(6,690)
      DO 425 I = 1, NN
      WRITE(6,691)  I, DETERM(I)
  425 CONTINUE
      IF(NFAIL .EQ. 1)  GO TO 999
      NN = 0
  400 CONTINUE
      GO TO 999
  403 FORMAT (1H0,22X, 28HT MATRIX AT LEFT END,44X, 21HT MATRIX AT RIGHT
     1 END)
   22 FORMAT(1H , 8F8.4, 2X, 8F8.4)
   24 FORMAT(1H0)
  693 FORMAT(1H0, 58HDETERMINANT OF FLEXIBILITY MATRIX FOR LINEAR ANALYS
     1IS WAS E15.8)
  681 FORMAT(1H0, 32HLOADINGS FOR THIS ANALYSIS WERE /
     $              6H PN = E14.7 /
     $              9H GA(1) = E14.7 /
     $              9H GA(2) = E14.7 /
     $              9H GB(4) = E14.7 /
     $              9H GB(5) = E14.7 )
  692 FORMAT(1H0, 28HCONVERGENCE NOT OBTAINED IN I1, 11H ITERATIONS)
  689 FORMAT(1H0, 34HCONVERGENCE OBTAINED ON ITERATION I1)
  690 FORMAT(1H0, 57HDETERMINANTS OF FLEXIBILITY MATRIX FOR THIS LOADING
     S WERE    )
  691 FORMAT(1H , 10HITERATION I1, 3X, E15.8)
      END
```

CHANGES IN INPUT:

```
      SUBROUTINE INPUT
      DIMENSION       TITLE1(20)    , BOUNDI(8)     , GA(8)         ,
     *                TITLE2(20)    , BOUNDF(8)     , GB(8)         ,
     *                TITLE3(20)    , SI(60)        , IA(8)         ,
     *                NAMEBI(6)     , SX(60)        , IB(8)         ,
     *                NAME2(60)     , IPAR(60)      , INT(60)       ,
     *                TDIST(60)     , VN(7,60)      , VARTIK(60)    ,
     *                NAMES1(8)     , EYM(60)       , XP(10,60)     ,
     *                NAMES2(8)     , PSR(60)       , YP(10,60)     ,
     *                ISS(60)       , IPLOT(10)     , TRY(8,61)     ,
     *                SL(9,60)      , DM(8,61)      , V3(8)         ,
     *                BACK(60)      , POINT(60)     , UNITI(2)      ,
     *                UNITD(2)      , JOBPLT(10)    , DETERM(10)    ,
     *                E(9,60)       , NFOURA(9)
      DIMENSION       XPLT(350),YPLT(350,10)
      COMMON / BLOCKA / MU, PI, ALD, NTYPE, INDEX, IBR, PN, NPOINT,
     1                  ISH, TT, T1, T2, NTT, INTC
      COMMON / BLOCKC / DM, GA, GB, NF, NFP, NPL, NM, NN, TRY
      COMMON / BLOCKE / XP, YP, SL
      COMMON / BLOCKF / NFF, SMXX, SZERO, GO, ERP, ISS, E,
     *                  MAX, INTPHN, INTVAL, NPP
      COMMON / BLOCKG / NPAHTS, PHI1, V3, KIND, NT, MT, SPRINT, VN, EYM,
     1                  BACK, NBACK
      COMMON / BLOCKH / NDE
      COMMON / BLOCKN / DETERM
      COMMON / BLOCKP / PLOT, PLTIME, SPLOT, PLOTPT, IPLOT, YMOD, KST,
     1                  NGAMMA, DEAD, NFM
      COMMON / BLOCKU / TIME, VARTIK, NVARTK
      COMMON / BLOCKS / JOBPLT, ALXL, ALXR, IA, IB, NOPUNC, INPUN,
     *                  CONVER, SI, SX, INT, IPAR, PSR, ITER, NTRY,
     *                  NERROR, IBRN, TRYIN, IBRMAX
      COMMON / BLOCKX / LEVEL1, LEVEL2
      COMMON /PLXY2C / XPLT,YPLT,NGC
      EQUIVALENCE  (VARTIK(1), POINT(1))
      DATA( RPD = 0.1745329252E-01 )
      DATA  (NAMEBI(1) = 6HDISPLA) , (NAMEBI(5) = 6HCEMENT) ,
     *      (NAMEBI(2) = 6HFORCE  ) ,
     *      (NAMEBI(3) = 6HSLOPE  ) , (NAMEBI(6) = 6H      ) ,
     *      (NAMEBI(4) = 6HMOMENT)
      DATA  (MARKC = 2HYE), (MARKD = 2HNO), (MARKE = 1HS),
     *      (MARKN = 3HNO ), (MARKY = 3HYES)
      DATA ((NAMES1(I), I = 1, 8) = 6HCROWN , 6HCYLIND, 6HSPHERO,
     *                              6HPARABO, 6HELLIPS, 6HCONICA,
     *                              6HTOROID, 6HVARCYL),
     *     ((NAMES2(I), I = 1, 8) = 6H      , 6HHICAL , 6HIDAL  ,
     *                              6HLOIDAL, 6HOIDAL , 6HL     ,
     *                              6HAL    , 6HINDER )
      DATA    (UNITI(1) = 6HINCHES),
     *        (UNITI(2) = 1H      ),
     *        (UNITD(1) = 6HDEGREE),
     *        (UNITD(2) = 1HS     )
      INTEGER  VARTIK, POINT, GO, TRYIN, PLOT, PLTIME, TIME, BOUNDI,
     *         BOUNDF, TDIST
      REAL           MU, NT, MT, NBACK, NFM
```

```
C     FOR PLOTTING USE THE FOLLOWING CODE NUMBERS TO INDICATE THE VARIABLE
C     DESIRED.
C
C                          CODE NUMBER        VARIABLE
C                                1            W
C                                2            Q PHI
C                                3            U PHI
C                                4            N PHI
C                                5            BETA PHI
C                                6            M PHI
C                                7            N THETA
C                                8            M THETA
C                                9            EPSILON THETA
C                               10            EPSILON PHI
C                               11            SIGMA N PHI
C                               12            SIGMA M PHI
C                               13            SIGMA PHI [illegible] INNER
C                               14            SIGMA PHI [illegible] OUTER
C                               15            SIGMA N THETA
C                               16            SIGMA M THETA
C                               17            SIGMA THETA [illegible] INNER
C                               18            SIGMA THETA [illegible] OUTER
C                               19            TAU PHI
C
C     TRYIN = 0 INDICATES THAT LINEAR PROBLEM WILL BE SOLVED.
C     TRYIN = 1 INDICATES THAT LINEAR PROBLEM AND POSSIBLY ONE OR MORE
C     ITERATIONS HAVE BEEN DONE AND THE LAST RESULT IS TO BE READ IN.
C
C     INTPRN = 0 INDICATES THAT INTERMEDIATE RESULTS FROM THE NONLINEAR
C     ANALYSIS, I.E., VALUES OF PARAMETERS AND SLOPES, WILL NOT BE
C     PRINTED OUT.
C
C     INTVAL = 0 INDICATES THAT INTERMEDIATE RESULTS FROM INITIAL VALUE
C     INTEGRATIONS WILL NOT BE PRINTED OUT.
C
C      NOPUNC = 0 INDICATES THAT SOLUTIONS, DM(I,NF) AND E(I,JJ) WILL
C     NOT BE PUNCHED.
C     NOPUNCH = 1 INDICATES THAT THEY WILL BE PUNCHED.
C
C     PLOT = NUMBER OF COLUMNS OF VARIABLES TO BE PUT ON PLOT TAPE TO
C     BE MACHINE PLOTTED AT LATER TIME.

COMMENT   SET NUMBER 1        ( CARDS = 3 )
      READ(5,500)  TITLE1
      IF(EOF,5) 998, 997
997   CONTINUE
      READ(5,500)  TITLE2, TITLE3
```

```
      GO TO 402
400   DO 401 L = 1, IBRM
      EYM(L) = YOUNG
      PSR(L) = POISON
401   CONTINUE

COMMENT   SET NUMBER 11
COMMENT   READ IN PRESSURE LOADING, DENSITY OF MATERIAL, AND DEAD WEIGHT ONLY IF
COMMENT   THEY ARE NOT THE SAME FOR EACH PART.

402   IF(NPRES .EQ. MARKC)  GO TO 4025
      READ(5,566)  (VN(5,L), VN(6,L), VN(7,L), L = 1, IBRM)
      GO TO 4026
4025  DO 963 L = 1, IBRM
      VN(5,L) = PRESS
      VN(6,L) = DENSTY
      VN(7,L) = DEAD
963   CONTINUE
COMMENT   SET NUMBER 12
COMMENT   READ IN VARIABLE THICKNESSES

4026  DO 403 L = 1, IBRM
      IF(VARTIK(L) .EQ. 0)  GO TO 403
      NPNT = VARTIK(L)
      READ(5,565)  (AP(I,L), I = 1, NPNT)
      READ(5,565)  (TP(I,L), I = 1, NPNT)
403   CONTINUE
      IF(ISS(IBRM) .GT. 1) GO TO 86
      STRT = NPARTS + 1
      NSTOP = NPARTS + 1
      GO TO 87
86    STRT = NPARTS
      NSTOP = NPARTS
COMMENT   SET NUMBER 13

87    IF(PLO .EQ. 0) GO TO 1238
      READ(5,402) (IPLOT(I), I = 1, PLOT)
      READ(5,404) (JOBPLT(I), I = 1, PLOT)
1238  CONTINUE
      REWIND
      CALL PLT
      IA(1) = 1
      IA(2) = 3
      IA(3) = 5
      IA(4) = 7
      IB(5) = 1
      IB(6) = 3
      IB(7) = 5
      IB(8) = 7
      IF(IBOUND(1) .NE. NAME(4))  IA(1) = 2
      IF(IBOUND(2) .NE. NAME(1))  IA(2) = 4
      IF(IBOUND(3) .NE. NAME(3))  IA(3) = 6
      IF(IBOUND(4) .NE. NAME(7))  IA(4) = 8
      IF(IBOUND(5) .NE. NAME(1))  IB(5) = 2
      IF(IBOUND(6) .NE. NAME(1))  IB(6) = 4
      IF(IBOUND(7) .NE. NAME(1))  IB(7) = 6
```

CHANGES IN PRINT:

```
      SUBROUTINE PRINT
      DIMENSION       IA(8)          , SI(60)         , IPAR(60)      ,
     *                IB(8)          , SX(60)         , INT(60)       ,
     *                GA(8)          , PRNT(8)        , ISS(60)       ,
     *                GB(8)          , ERR(8)         , PSR(60)       ,
     *                Y(8)           , DM(8,61)       , EYM(60)       ,
     *                DY(8)          , TL(8,8)        , A(8,9)        ,
     *                TR(8,8)        , TLI(8,8)       , JOBPLT(10)    ,
     *                TRI(8,8)       , TRY(8,61)      , TR2(8,8)      ,
     *                SOUT(275)      , D(8,9,60)      , P(5,275)      ,
     *                SLOPE(5,275)   , TRI(8,8)       , E(9,60)
      DIMENSION       V3(8)          , VN(7,60)       , YAM(72)       ,
     *                DYAM(72)       , ABC(21)        , EAM(10)       ,
     *                BACK(60)       , YSAVE(8)       , DETERM(10)    ,
     *                IPLOT(10)      , XPLOT(350)     , YPLOT(350,10),
     *                STROUT(350)    , SIGNPM(350)    , SIGMPM(350)   ,
     *                SIGPMT(350)    , SIGPMB(350)    , SIGNTM(350)   ,
     *                SIGMTM(350)    , SIGTMT(350)    , SIGTMB(350)   ,
     *                TAUPMI(350)    , VARTIK(60)     , POINT(60)
      DIMENSION       XPLT(350),YPLT(350,10)
      COMMON / BLOCKA / NU, PI, XLD, NTYPE, INDEX, IBR, PN, NPOINT,
     1                  ISM, TT, T1, T2, MTT, INTC
      COMMON / BLOCKB / N, R1, R2, R3, SXN, CXS
      COMMON / BLOCKC / DM, GA, GB, NF, NFP, NPL, MM, NN, TRY
      COMMON / BLOCKD / TL, TR, TLI, TRI, ALFL, ALFR
      COMMON / BLOCKF / NFF, SMXX, SZERO, GO, ERP, ISS, E,
     *                  MAX, INTPRN, INTVAL, NPP
      COMMON / BLOCKG / NPARTS, PMII, V3, KIND, MT, MT, SPRINT, VN, EYM,
     1                  BACK, NBACK
      COMMON / BLOCKM / MDE
      COMMON / BLOCKJ / DELX, PDELX, ABC, EAM
      COMMON / BLOCKK / PIN, PMIN, MO, XO, EMIN, EMAX
      COMMON / BLOCKL / YAM, DYAM
      COMMON / BLOCKM / YSAVE
      COMMON / BLOCKN / DETERM
      COMMON / BLOCKP / PLOT, PLTIME, SPLOT, PLOTPT, IPLOT, YMOD, KST,
     1                  NGAMMA, DEAD, NFN
      COMMON / BLOCKQ / TIME, VARTIK, NVARTK
      COMMON / BLOCKS / JOBPLT, ALXL, ALXR, IA, IB, NOPUNC, INPMIN,
     *                  CONVER, SI, SX, INT, IPAR, PSR, ITER, NTRY,
     *                  NERROR, IBRM, TRYIN, IBRMAX
      COMMON            SLOPE, P, SOUT, D, A
      COMMON / PLXY1C / IEX(8), DUM(4)
      COMMON /PLXY2C / XPLT,YPLT,NCC
      EQUIVALENCE   (Y(1), PRNT(1)), (Y(1), YAM(2)), (DY(1), DYAM(2)),
     1              (5, YAM(1)), (VARTIK(1), POINT(1))
      EQUIVALENCE    (SLOPE(1)  ,  YPLOT(1)    ),
     *               (D(476)    ,  XPLOT(1)    ),
     *               (D(826)    ,  STROUT(1)   ),
     *               (D(1176)   ,  SIGNPM(1)   ),
     *               (D(1526)   ,  SIGMPM(1)   ),
     *               (D(1876)   ,  SIGPMT(1)   ),
     *               (D(2226)   ,  SIGPMB(1)   ),
     *               (D(2576)   ,  SIGNTM(1)   ),
     *               (D(2926)   ,  SIGMTM(1)   ),
     *               (D(3276)   ,  SIGTMT(1)   ),
```

```
      SIGPHT(KST) = TERM1 - TERM2
      SIGPHB(KST) = TERM1 + TERM2
      SIGNTH(KST) = TERM3
      SIGNTH(KST) = TERM4
      SIGTHT(KST) = TERM3 - TERM4
      SIGTHB(KST) = TERM3 + TERM4
      TAUPHI(KST) = 1.5*V3(2)/H
      IF(PLTIME .EQ. 0)  GO TO 666
      XPLOT(PLOTPT) = SPLOT
      XPLT(PLOTPT)=XPLOT(PLOTPT)
      DO 665 I = 1, PLOT
      COLUMN = IPLOT(I)
      IF(COLUMN .GT. 6) GO TO 595
      YPLOT(PLOTPT,I) = V3(COLUMN)
      YPLT(KST,I)=V3(COLUMN)
      GO TO 665
595   KOLUMN = COLUMN - 6
      GO TO (600, 605, 610, 615, 620, 625,
     1       630, 635, 640, 645, 650, 655, 660), KOLUMN
600   YPLOT(PLOTPT,I) = NT
      YPLT(KST,I)=NT
      GO TO 665
605   YPLOT(PLOTPT,I) = NT
      YPLT(KST,I)=NT
      GO TO 665
610   YPLOT(PLOTPT,I) = EPT
      YPLT(KST,I)=EPT
      GO TO 665
615   YPLOT(PLOTPT,I) = EPP
      YPLT(KST,I)=EPP
      GO TO 665
620   YPLOT(PLOTPT,I) = SIGNPH(KST)
      YPLT(KST,I)=SIGNPH(KST)
      GO TO 665
625   YPLOT(PLOTPT,I) = SIGNPH(KST)
      YPLT(KST,I)=SIGNPH(KST)
      GO TO 665
630   YPLOT(PLOTPT,I) = SIGPHT(KST)
      YPLT(KST,I)=SIGPHT(KST)
      GO TO 665
635   YPLOT(PLOTPT,I) = SIGPHB(KST)
      YPLT(KST,I)=SIGPHB(KST)
      GO TO 665
640   YPLOT(PLOTPT,I) = SIGNTH(KST)
      YPLT(KST,I)=SIGNTH(KST)
      GO TO 665
645   YPLOT(PLOTPT,I) = SIGNTH(KST)
      YPLT(KST,I)=SIGNTH(KST)
      GO TO 665
650   YPLOT(PLOTPT,I) = SIGTHT(KST)
      YPLT(KST,I)=SIGTHT(KST)
      GO TO 665
655   YPLOT(PLOTPT,I) = SIGTHB(KST)
      YPLT(KST,I)=SIGTHB(KST)
      GO TO 665
660   YPLOT(PLOTPT,I) = TAUPHI(KST)
```

FORTRAN Listing of Subroutine PLT

Given below is a complete listing of the FORTRAN IV version of the subroutine PLT currently operational on the CDC 6400 at Battelle-Columbus. This subroutine together with the modified versions of NONLIN, INPUT, and PRINT presented above provides the user with an improved tool for the analytical study of bellows and diaphragms.

```
      SUBROUTINE PLT
      DIMENSION INLS(4)
      DIMENSION  X(900),Y(900),JOBPLT(10),IA(8),IB(8)   ,
     *           SI(60),SX(60),INT(60),IPAR(60),PSR(60),
     *           V3(8),VN(7,60),EVN(60),BACK(60),ISS(60),
     *           E(9,60),X1(900),Y1(900)
      DIMENSION  XPLT(350),YPLT(350,10),IPLOT(10),RT(60),
     *           XM(350),YM(350),XS(350),YS(350)
      DIMENSION YTITLE(8,10),XX(100),YY(100),XX1(100),YY1(100)
      COMMON / BLOCKF / NFF, SNXX, SZERO, GO, ERP, ISS, E,
     *                  MAX, INTPAN, INTVAL, NPP
      COMMON / BLOCKP / PLOI, PLTIME, SPLOT, PLOTPT, IPLOT, YMOD, KST,
     *                  HGAMMA, DEAD, NFH
      COMMON / BLOCK6 / NPARTS, PHI1, V3, KIND, NT, MT, SPRINT, VN, EVN,
     1                  BACK, NBACK
      COMMON / BLOCKS / JOBPLT, ALXL, ALXR, IA, IB, NOPUNC, IMPUN,
     *                  CONVER, SI, SX, INT, IPAR, PSR, ITER, NTRY,
     *                  NERROR, IBRN, TRYIN, IBRMAX
      COMMON /PLXY2C / XPLT,YPLT,NCC
      DATA (RPO =0.1745329252E-01)
      INTEGER PLOI,PLOTPT,PLTIME
      REAL JSCALE,MAXX1,MINX1,MAXY1,MINY1
      IF(PLOI .EQ. 0)RETURN
      GO TO (1000,1001)NCC
C     XY ARE COORDINATES OF POINTS ON SHELL PARTS
C     XX,YY ARE COORDINATES OF INTIAL AND FINAL POINTS ON SHELL PARTS
C     AND ALSO INCLUDE CENTRES OF TOROIDAL SHELLS
C     BETWEEN 1000 AND 1001 XY VALUES ARE COMPUTED AFTER INPUT
C     OBTAIN  XY SYSTEM FOR MODEL AND STORE
 1000 NBRC=0
C      DATA SET NUMBER 14
C     READ TITLES FOR DESIRED PLOTS
      READ(5,2001)((YTITLE(I,J),I=1,8),J=1,PLOI)
 2001 FORMAT(8A10)
C     DATA SET NUMBER 15
C     READ NUMBER OF LEAF AND NO.OF PART AT END OF EACH LEAF
      READ(5,2002)NLS
 2002 FORMAT(I5)
      READ(5,2003) (INLS(I),I=1,NLS)
 2003 FORMAT(4I5)
      NBR=1
      JBR=1
      DO 1 I=1,IBRN
      K=ISS(I)
      GO TO (999,99,999,999,999,100,101,99)K
C     OBTAIN XY SYSTEM FOR CYLINDRICAL PARTS
   99 IF(I .EQ. 1)410,411
  410 Y(NBR)=0.0
      GO TO 412
  411 Y(NBR)=Y(NBR-1)
  412 X(NBR)=VN(2,I)
      XX(JBR)=X(NBR)
      YY(JBR)=Y(NBR)
      JBR=JBR+1
      NBR=NBR+1
      X(NBR)=X(NBR-1)
```

```
      Y(NBR)=Y(NBR-1)-VN(3,I)
      XX(JBR)=X(NBR)
      YY(JBR)=Y(NBR)
      NBR=NBR+1
      JBR=JBR+1
      GO TO 11
C     OBTAIN XY SYSTEM FOR CONICAL PARTS.
  100 IF(I .EQ.1)102,103
  102 Y(NBR)=0.0
      GO TO 104
  103 Y(NBR)=Y(NBR-1)
  104 X(NBR)=VN(2,I)
      XX(JBR)=X(NBR)
      YY(JBR)=Y(NBR)
      JBR=JBR+1
      NBR=NBR+1
      X(NBR)=X(NBR-1)+VN(3,I)*COS(SI(I)*RPD)
      Y(NBR)=Y(NBR-1)-VN(3,I)*SIN(SI(I)*RPD)
      XX(JBR)=X(NBR)
      YY(JBR)=Y(NBR)
   20 NBR=NBR+1
      JBR=JBR+1
      GO TO 11
C     OBTAIN XY SYSTEM FORR CIRCLE PARTS
  101 CX=VN(2,I)
      ALPHAI=90.0-SI(I)
      ALPHAF=90.0-SX(I)
      IF(I .EQ. 1)400,401
  400 CY=0.0
      GO TO 402
  401 CY=Y(NBR-1)-VN(3,I)*SIN(ALPHAI*RPD)
      XX(JBR)=XX(JBR-1)
      YY(JBR)=YY(JBR-1)
      JBR=JBR+1
  402 A1=ABS(SX(I)-SI(I))/2.0
      NPPP=2.0*A1+1.
      NPPP=NPPP/2
      DO 2 JJ=1,NPPP
      IF(JJ .EQ. 1)3,4
    4 IF(JJ .EQ.NPPP)5,6
    5 ALPHAI=ALPHAF
      GO TO 3
    6 IF(VN(3,I))200,999,201
  200 ALPHAI=ALPHAI+2.0
      GO TO 3
  201 ALPHAI=ALPHAI-2.0
    3 X(NBR)=CX+VN(3,I)*COS(ALPHAI*RPD)
      Y(NBR)=CY+VN(3,I)*SIN(ALPHAI*RPD)
      NBR=NBR+1
      IF(I .EQ. 1 .AND. JJ .EQ. 1)403,2
  403 XX(JBR)=X(NBR-1)
      YY(JBR)=Y(NBR-1)
      JBR=JBR+1
    2 CONTINUE
      XX(JBR)=CX
      YY(JBR)=CY
```

```
      JBR=JBR+1
      XX(JBR)=X(NBR-1)
      YY(JBR)=Y(NBR-1)
      JBR=JBR+1
   11 IF(NBR .EQ. 991)GO TO 999
      IF( NLS .EQ. 1)GO TO 1
      IF(NLS .EQ. 4)7,8
    7 NLS1=NLS-1
      GO TO 9
    8 NLS1=NLS
    9 CONTINUE
      DO 2004 INN=1,NLS1
      IF(I .EQ. INLS(INN))22,2004
   22 NBRC=NBRC+1
      GO TO (23,24,25)NBRC
   23 NBR1=NBR-1
      JBR1=JBR-1
      GO TO 1
   24 NBR2=NBR-1
      JBR2=JBR-1
      GO TO 1
   25 NBR3=NBR-1
      JBR3=JBR-1
      GO TO 1
 2004 CONTINUE
    1 CONTINUE
      NBR=NBR-1
      JBR=JBR-1
      RETURN
C     XY VALUES HERE AFTER ARE COMPUTED AFTER PRINT
C     OBTAIN  XS,YS,XN,YN WHERE
C     XN=X-COORDINATE OF MODEL AT PRINT POINT
C     YN=Y-COORDINATE OF MODEL AT PRINT POINT
C     XS AND YS ARE CORRESPONDING COORDINATES WITH VARIABLE SUPERIMPOSED
 1001 DO 2000 KLN=1,PLOI
      NBRC=0
      NBR=1
      NPNPT=0
      DO 1002 I=1,IBNN
      NPNPT=NPNPT+IPAR(I)*INT(I)
 1002 CONTINUE
C     FIND MAXIMUM NUMERICAL VALUE OF THE VARIABLE FROM YPLT(NPNPT,KLN)
C     YPLT IS THE VALUE OF VARIABLE
C     XPLT IS THE MERIDIONAL COORDINATE
C     KLN NO OF PLOTS,MAXIMUM OF 10
C     DETERMINE BEST POSSIBLE SCALE
      IJK=1
      NOR=1
      DO 600 I=1,IBNN
      KIND=IBS(I)
      GO TO (999,601,999,999,999,601,602,601)KIND
  601 IJK=IJK+IPAR(I)*INT(I)
      GO TO 600
  602 IJKP=IJK-1+IPAR(I)*INT(I)
      DO 603 JK=IJK,IJKP
      IF(JK .EQ.IJK)604,605
```

```
  604 YMAX=ABS(YPLT(JK,KLM))
      GO TO 603
  605 IF(ABS(YPLT(JK,KLM)) .GT. YMAX) YMAX=ABS(YPLT(JK,KLM))
  603 CONTINUE
      IJK=IJKP+1
      RT(NOR)=0.75*ABS(VN(3,I))/YMAX
      NOR=NOR+1
  600 CONTINUE
      NOR=NOR-1
      SCALE=RT(1)
      DO 606 NO=2,NOR
      IF(RT(NO) .LT. SCALE) SCALE=RT(NO)
  606 CONTINUE
      DO 1009 J=1,NPNPT
      YPLT(J,KLM)=YPLT(J,KLM)*SCALE
 1009 CONTINUE
      DO 1010 I=1,IBMM
      KIND=ISS(I)
      GO TO (999,998,999,999,999,1011,1012,999)KIND
C     CYLINDRICAL PART
  998 LLL=IPAR(I)
      KKK=INT(I)
      DO 420 LL=1,LLL
      IF(I .EQ. 1 .AND. LL .EQ. 1)421,422
  421 YN(MBR)=0.0
      XN(MBR)=VN(2,I)
      XS(MBR)=XN(MBR)+YPLT(MBR,KLM)*SIN(VN(3,I)*RPD)
      YS(MBR)=YN(MBR)
      MBR=MBR+1
  422 DO 420 KK=1,KKK
      IF(I .EQ. 1 .AND. LL .EQ. 1 .AND. KK .EQ. 1)GO TO 420
      IF(KK .EQ. 1)423,424
  423 XN(MBR)=XN(MBR-1)
      YN(MBR)=YN(MBR-1)
      GO TO 425
  424 XN(MBR)=XN(MBR-1)
      YN(MBR)=YN(MBR-1)-SI(I)/(LLL*(KKK-1))
  425 XS(MBR)=XN(MBR)+YPLT(MBR,KLM)*SIN(VN(3,I)*RPD)
      YS(MBR)=YN(MBR)
      MBR=MBR+1
  420 CONTINUE
      GO TO 2020
C     CONICAL PART
 1011 LLL=IPAR(I)
      KKK=INT(I)
      DO 1013 LL=1,LLL
      IF(I.EQ.1 .AND. LL .EQ. 1)1014,1015
 1014 YN(MBR)=0.0
      XN(MBR)=VN(3,I)
      XS(MBR)=XN(MBR)+YPLT(MBR,KLM)*SIN(VN(2,I)*RPD)
      YS(MBR)=YN(MBR)+YPLT(MBR,KLM)*COS(VN(2,I)*RPD)
      MBR=MBR+1
 1015 DO 1013 KK=1,KKK
      IF(I .EQ. 1 .AND. LL .EQ. 1 .AND. KK .EQ. 1)GO TO 1013
      IF(KK .EQ. 1)51,52
   51 XN(MBR)=XN(MBR-1)
```

```
      YN(NBR)=YN(NBR-1)
      GO TO 53
   52 XN(NBR)=XN(NBR-1)+SX(I)*COS(VN(2,I)*RPD)/(LLL*(KKK-1))
      YN(NBR)=YN(NBR-1)-SX(I)*SIN(VN(2,I)*RPD)/(LLL*(KKK-1))
   53 XS(NBR)=XN(NBR)+YPLT(NBR,KLN)*SIN(VN(2,I)*RPD)
      YS(NBR)=YN(NBR)+YPLT(NBR,KLN)*COS(VN(2,I)*RPD)
      NBR=NBR+1
 1013 CONTINUE
      GO TO 2020
C     CIRCULAR PARTS
 1012 CX=VN(2,I)
      IF(BACK(I))300,999,301
  300 ALPHAI=90.0+SI(I)/RPD-180.0
      ALPHAF=90.0+SX(I)/RPD-180.0
      GO TO 302
  301 ALPHAI=90.0-SI(I)/RPD
      ALPHAF=90.0-SX(I)/RPD
  302 ALPHAD=ABS(ALPHAF-ALPHAI)
      IF(I .EQ. 1)404,405
  404 CY=0.0
      GO TO 406
  405 CY=YN(NBR-1)-VN(3,I)*SIN(ALPHAI*RPD)
  406 CONTINUE
      LLL=IPAR(I)
      KKK=INT(I)
      DO 1016  LL=1,LLL
      DO 1016  KK=1,KKK
      IF(KK .EQ. 1) GO TO 1020
      IF(VN(3,I))1017,999,1018
 1017 ALPHAI=ALPHAI+ALPHAD/(LLL*(KKK-1))
      GO TO 1020
 1018 ALPHAI=ALPHAI-ALPHAD/(LLL*(KKK-1))
 1020 XN(NBR)=CX+VN(3,I)*COS(ALPHAI*RPD)
      YN(NBR)=CY+VN(3,I)*SIN(ALPHAI*RPD)
      XS(NBR)=XN(NBR)+YPLT(NBR,KLN)*COS(ALPHAI*RPD)
      YS(NBR)=YN(NBR)+YPLT(NBR,KLN)*SIN(ALPHAI*RPD)
      NBR=NBR+1
 1016 CONTINUE
 2020 CONTINUE
      IF(NLS .EQ. 1) GO TO 1010
      DO 2005 INN=1,NLS1
      IF(I .EQ. INLS(INN))305,2005
  305 NBRC=NBRC+1
      GO TO (306,307,308) NBRC
  306 NBR1=NBR-1
      GO TO 1010
  307 NBR2=NBR-1
      GO TO 1010
  308 NBR3=NBR-1
      GO TO 1010
 2005 CONTINUE
 1010 CONTINUE
      NBR=NBR-1
      IF(NBRC .EQ. 0)40,31
   40 NNN=NBR
      NNN=NBR
```

```
      JJJJ=JBR
      DO 92 MM=1,MMM
      X1(MM)=X(MM)
      Y1(MM)=Y(MM)
   92 CONTINUE
      DO 93 JJ=1,JJJJ
      XX1(JJ)=XX(JJ)
      YY1(JJ)=YY(JJ)
   93 CONTINUE
      GO TO 41
   31 IF(MLS .EQ. 4 .AND. KLM .EQ. 1) NBRC=NBRC+1
      IF (NBRC .GE. 5) NBRC=4
      DO 26 JJJ=1,NBRC
      GO TO (27,28,29,30)JJJ
   27 NB=0
      MB=0
      JB=0
      MMM=NBR1
      NNN=NBR1
      JJJJ=JBR1
      GO TO 32
   28 NB=NBR1
      MB=MBR1
      JB=JBR1
      MMM=NBR2-NBR1
      NNN=NBR2-NBR1
      JJJJ=JBR2-JBR1
      GO TO 32
   29 NB=NBR2
      MB=MBR2
      JB=JBR2
      MMM=NBR3-NBR2
      NNN=NBR3-NBR2
      JJJJ=JBR3-JBR2
      GO TO 32
   30 NB=NBR3
      MB=MBR3
      JB=JBR3
      MMM=NBR-NBR3
      NNN=NBR-NBR3
      JJJJ=JBR-JBR3
   32 DO 90 MM=1,MMM
      X1(MM)=X(MM+NB)
      Y1(MM)=Y(MM+NB)
   90 CONTINUE
      DO 91 MM=1,NNN
      XS(MM)=XS(MM+NB)
      YS(MM)=YS(MM+NB)
   91 CONTINUE
      DO 94 JJ=1,JJJJ
      XX1(JJ)=XX(JJ+JB)
      YY1(JJ)=YY(JJ+JB)
   94 CONTINUE
   41 IF(NBRC .EQ. 0  .OR. JJJ .EQ. 1)42,43
   42 MAXX1=X1(1)
      MINX1=X1(1)
```

```
      MAXY1=Y1(1)
      MINY1=Y1(1)
      DO 500 MM=2,MMM
      IF(X1(MM) .GT. MAXX1)MAXX1=X1(MM)
      IF(X1(MM) .LT. MINX1)MINX1=X1(MM)
      IF(Y1(MM) .GT. MAXY1)MAXY1=Y1(MM)
      IF(Y1(MM) .LT. MINY1)MINY1=Y1(MM)
  500 CONTINUE
      DIFFX=MAXX1-MINX1
      DIFFY=MAXY1-MINY1
      IF(DIFFX .GT. DIFFY)501,502
  501 DIFF=DIFFX
      JSCALE=8.0
      GO TO 503
  502 DIFF=DIFFY
      JSCALE=6.0
  503 KON=2
      FACE=20.0
   72 DIFF1=DIFF*FACE
      IF(DIFF1 .LE. JSCALE)70,71
   70 DX=1.0/FACE
      GO TO 69
   71 KON=KON+1
      IF(KON .EQ. 7)GO TO 70
      FACE=FACE/2.0
      IF(KON .EQ. 4)FACE=4.0
      GO TO 72
   69 CONTINUE
      DDX=MINX1-DX
      DDY1=-4.0*DX
      DDY2=MINY1-DX
      IF(DDY1 .LT. DDY2)80,81
   80 DDY=DDY1
      GO TO 82
   81 DDY=DDY2
   82 CONTINUE
      SCALE=DX/SCALE
      DDYC=DDY+7.0*DX
   43 DO 83 JJ=2,JJJJ
      IF(YY1(JJ) .LT. DDY .OR. YY1(JJ) .GT. DDYC) 84,83
   84 XX1(JJ)=XX1(JJ-1)
      YY1(JJ)=YY1(JJ-1)
   83 CONTINUE
C     SPECIFY LENGTH AND SCALE OF XY AXES AND VALUES OF XY AT INTESECT.
      CALL GIKSET(10.0,DDX,DX,7.0,DDY,DX)
C     DRAW MODEL
      CALL GIKPLT(X1,Y1,MMM,3H*X*,3H*Y*,YTITLE(1,KLM))
      CALL PLOT(-11.0,1.0,-3)
C     SUPERIMPOSE VARIABLE COORDINATES AND FIRST-LAST PTS. OF SHELLS
      CALL GLINE(XS,YS,MMM,0)
      CALL GLINE(XX1,YY1,-JJJJ,3)
      CALL SYMBOL(6.5,1.5,0.14,14HSCALE- 1IN . = ,0.0,14)
      ENCODE(13,60,XSCALE)SCALE
   60 FORMAT(E13.5)
      CALL SYMBOL(8.1,1.5,0.14,XSCALE,0.0,13)
      CALL PLOT(12.0,-1.0,-3)
```

```
   26 CONTINUE
 2000 CONTINUE
      RETURN
  999 CALL EXIT
      END
```

Description of Computing Program FIT

In order to ease the burden of preparing the data required by program NONLIN[1], a computing program (called FIT) has been developed which computes a mathematical model of a shell midsurface from a set of (x,y) coordinates. This appendix is intended for those who plan to use FIT for the preparation of data for NONLIN.

While NONLIN is capable of analyzing shells composed of parts having several different shapes (cylindrical, spheroidal, ellipsoidal, paraboloidal, conical, or toroidal), FIT has been designed to describe the shell in terms of cylindrical, conical, and toroidal parts only. In addition to a mathematical model of a shell midsurface, program FIT generates variable thickness data, variable elastic parameter data, and variable loading data. The information generated by FIT is punched onto cards in the sequence and format required by NONLIN. This allows the user to change the boundary conditions or make other minor changes in the data without rerunning the entire problem through FIT.

Input Preparation

The information required by FIT to produce a complete set of data for NONLIN will now be described. Although some of the following is a duplication of input data described elsewhere for NONLIN[1], for the sake of self-containment it is included here. In terms of "data-sets", FIT requires a total of eleven which are listed below:

1. Title cards (3 cards)
2. Boundary-value data at initial edge of shell (1 card)
3. Boundary-value data at final edge of shell (1 card)
4. Rotation angle between shell supports and shell centerline at initial and final edges of shell (1 card)
5. NONLIN control card (1 card)
6. Young's modulus and Poisson's ratio (1 card)
7. Loading parameters-pressure, unit weight, and dead weight (1 card)
8. FIT control card (1 card)
9. Tolerance and coordinate transformation card (1 card)
10. Pointwise description of shell (1 card for each point)
11. Vertex information (1 card).

Data Sets 1-7

With the exception of data set five, the first seven data sets are prepared exactly as described in Appendix B of Reference (1). The exception, the NONLIN control card, must have the first five columns blank. These locations are for IBRM, the number of parts in the composite shell, which is not known until the model has been developed. The other entries on data set five are as they have been.

Data Set 8 Fit Control Card

This card contains the number of points which will be used to describe the shell shape, the number of vertices in the shell (points through which the tangent is not required to turn continuously), and the total number of print points desired for the entire shell. The number of print points refers to the points at which the values of stress resultants and moments, the displacements and strains, and the surface stresses computed by NONLIN are printed out. This information was previously read in for each part. FIT computes the number of print points per segment for each part by taking the appropriate fraction of the total number of print points requested according to each parts proportion of the total arc length. Clearly this procedure does not allow the user to obtain detailed information in regions of interest on the first pass. However, the number of print points per segment for a particular region of interest can be changed on the data deck obtained from FIT.

Data Set 9 Tolerance and Coordinate Transformation Card

The first entry on this card is the tolerance which is the maximum distance any point can lie from the model. If the tolerance is set too small it may be that no model will be obtained, while too large a tolerance will yield a model which does not adequately describe the shell. A suggested tolerance is 1/10 of the average thickness, although reasonably good results have been obtained with a tolerance of 1/2 the average thickness.

The remaining entries on this card deal with transforming the arbitrary set of coordinate axes (used to measure the (x,y) coordinates of the shell midsurface) to the coordinate system needed to describe the mathematical model. In order to obtain the correct descriptions of the shell parts, the origin of coordinates must be translated so as to lie on the centerline of the shell. This also implies that the x-coordinates must all be positive. To ensure all of these conditions it may be necessary to translate and reflect in the coordinate axes.

To illustrate this point consider Figure B-2, depicting a simple encapsulated shape with a set of axes superimposed. These axes are used to measure (x,y) coordinates of the points. Table B-1 lists a set of (x,y) values which might be obtained.

TABLE B-1. COORDINATES FOR SHELL OF FIGURE B-1

Reading	Coordinates	
	x	y
1	0	0
2	0.5	0.5
3	1.0	1.0
4	1.5	1.25
5	2.0	1.4
6	2.5	1.4

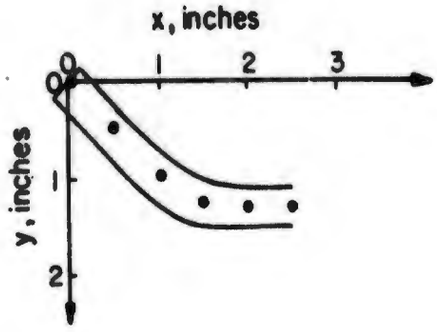


FIGURE B-2. ACTUAL ENCAPSULATED SHAPE

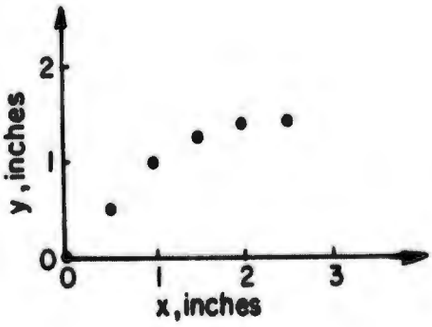


FIGURE B-3. INTERPRETATION OF MEASURED POINTS

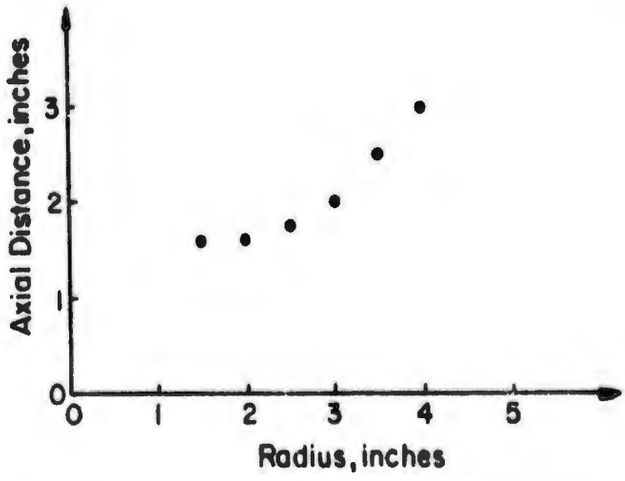


FIGURE B-4. TRANSFORMED COORDINATES

When read into FIT in the indicated order, the interpretation is as shown in Figure B-3, with the y-axis being used as the centerline of the shell. The desired interpretation is shown in Figure B-4. To transform the (x,y) coordinate system to the desired (r,z) coordinate system it is necessary to: (a) reflect in the y-axis, (b) reflect in the x-axis, and (c) translate in the positive x direction. There is no need to have the y-coordinates positive, except to enhance the appearance of any plot of the final model.

Data Set 10 Pointwise Description of the Shell

This set of data has one card for each point describing the shell midsurface. In general, each card will contain the x and y coordinates of a point and the thickness of the shell at that point. If only the first card of this set has a thickness specified, the resulting model will have constant thickness. If the thickness is not specified at a point, the last thickness value read in is assigned as the shell thickness at that point. Thus, the first card must always contain a thickness specification.

When the elastic and loading parameters are constant for a particular problem no other information need be supplied on these cards. However, if they vary along the shell, the variations are prescribed on these cards. It is anticipated that these parameters will be constant over large portions of the shell. Therefore, their values are allowed to be prescribed only at the first point and at points which are vertices. The user is allowed, however, to label as vertices points which are not "geometric" vertices when variable loading and elastic parameters require this to be done. The resulting model will probably be suitable. But, the tangent is not required to turn continuously through points which are labeled as vertices.

Data Set 11 Vertex Information

This card contains the indices (in the order of their appearance) of the points which the user calls vertices. Generally speaking, these are points on the shell generator at which the tangent is not required to turn continuously. However, if variable loading or elastic parameters change value at points which are not "geometric" vertices, the user can specify such points as vertices if he is willing to accept the loss of the continuity of the first derivative at that point.

Item-by-Item Description of Input Data

Data Set 1 Job Identification

```
READ (5,500) TITLE 1, TITLE 2, TITLE 3

500 FØRMAT (80A1)
```

Any information can be placed on these three cards. It is necessary to have three cards, although any can be left blank.

Data Set 2 Boundary Data at Initial Edge

READ (5,530) (BOUNDI(I), GA(I), I = 1,4)

530 FØRMAT (4 (A6, 6X, F8.2))

BØUNDI (1) is either DISPLACEMENT or FØRCE in normal or 1 direction

GA (1) is its value

BØUNDI (2) is either DISPLACEMENT or FØRCE in meridional or 2 direction

GA (2) is its value

BØUNDI (3) is either SLOPE or MØMENT

GA (3) is its value

BØUNDI (4) is either DISPLACEMENT or FØRCE in circumferential direction

GA (4) is its value

For an axisymmetrically loaded shell BØUNDI (4) and GA (4) need not be specified.

Data Set 3 Boundary Data at Final Edge

READ (5,530) (BØUNDF (I), GB (I), I = 5,8)

530 FØRMAT (4 (A6, 6X, F8.2))

BØUNDF (5) is either DISPLACEMENT or FØRCE in normal or 1 direction

GB (5) is its value

BØUNDF (6) is either DISPLACEMENT or FORCE in meridional or 2 direction

GB (6) is its value

BØUNDF (7) is either SLØPE or MØMENT

GB (7) is its value

BØUNDF (8) is either DISPLACEMENT or FØRCE in circumferential direction

GB (8) is its value

For an axisymmetrically loaded shell BØUNDF (8) and GB (8) need not be specified.

Data Set 4 Boundary Rotation Angles

READ (5,565) ALXL, ALXR

565 FØRMAT (8F10.5)

ALXL is the boundary rotation angle at the initial edge of the shell

ALXR is the boundary rotation angle at the final edge of the shell

Data Set 5 Control Card

READ (5,561) IBRM, ITER, NDUMMY, PLØT, INTPRN, INTVAL, LEVELI, LEVEL2, ERP, CØNVER, NUMHAR, (NFØURA (I), I = 1,8)

561 FØRMAT (815, 2E10.3, 10I2)

IBRM = Set IBRM = 0 to use fitting subroutine. Fit determines the number of shell parts.

ITER = number of iterations at a load level for nonlinear calculations. ITER = 0 for linear analysis.

NDUMMY = not presently used

INTPRN = 0 indicates that intermediate results from the nonlinear analysis, i.e., values of parameters and slopes, will not be printed out. Use 1 to obtain values.

INTVAL = 0 indicates that intermediate results from the initial value integrations will not be printed out. Use 1 to obtain values.

LEVEL1 = number of increments into which the loading is divided for nonlinear analysis.

LEVEL2 = not presently used

ERP = accuracy for integration subroutine. If left blank, it is internally set to 1.0 E-05.

CØNVER = convergence criteria for use in nonlinear analysis.

NUMHAR = number of FØURIER harmonics in the anlysis. For a nonlinear analysis, NUMHAR = 1. For a linear analysis, NUMHAR must not be greater than 8. If the shell is axisymmetrically loaded, NUMHAR = 1. For a nonsymetrically loaded shell which has the same boundary conditions for all harmonics, NUMHAR can have any value up to 8.

NFOURA(I) = FØURIER harmonic value. For an axisymmetric deformation, NFOURA (1) = 0.

Data Set 6 Elastic Parameters

READ (5,563) NELAS, YØUNG, PØISØN

563 FØRMAT (2X, A2, 4X, E11.4, 4X, F6.4)

NELAS is either YES or NØ. YES indicates that the elastic parameters are the same for each part in the composite shell. If YES, then the values of Young's modulus and Poisson's ratio are read in on the same card. If NØ, the values for each part are read in as Data Set 10.

YOUNG = Young's modulus ($lb/in.^2$)

POISSON = Poisson's ratio (in./in.)

Data Set 7 Loading Parameters

READ (5,680) NPRES, PRESS, DENSTY, DEAD

680 FØRMAT (2X, A2, 4X, 3F 14.5)

NPRES is either YES or NØ. YES indicates that the distributed loadings are the same for each part in the composite shell. If YES, then the values of the normal pressure, the weight density of the material, and the dead loading on the shell are given on the same card. If NØ, then the values for each part are read in as Data Set 11.

Data Set 8 Control Card For Fit (One Card)

READ (5,5010) NPTS, NV, ITNT

5010 FØRMAT (3I5)

NPTS = Number of points used to describe shell midsurface.

NV = Number of vertices

ITNT = Total number of print points.

Data Set 9 Tolerance and Transformation

READ (5,5020) EPS1, XTRANS, YTRANS, XRFLCT, YRFLCT

5020 FØRMAT (3F10.5, 2X, A2, 3X, A2)

EPS1 = User prescribed tolerance. No point will be more than EPS1 from the resulting model. EPS1 is a positive quantity, usually between 1/2 and 1/10 the average thickness of the shell.

XTRANS = Distance the given points are to be translated in the x direction.

YTRANS = Distance the given points are to be translated in the y direction.

XRFLCT = YES or NO; if YES then the given points will be reflected in the x-axis. If NO the points will be unchanged.

YRFLCT = YES or NO. If YES then the given points will be reflected in the y-axis. If NO, the points will be unchanged.

Data Set 10 Pointwise Description of the Shell (One card is needed for each point)

READ (5,5070) X1, Y1, T1, PR, YM, PRS, DW, DNS

5070 FORMAT (8F10.5)

X1 = x-coordinate of the point.*

Y1 = y-coordinate of the point.*

T1 = thickness of the shell at (X1, Y1).*

PR = Poisson's ratio (in./in.)

YM = Young's modulus ($lb/in.^2$)

PRS = Pressure loading ($lb/in.^2$)

DW = Dead weight loading ($lb/in.^2$)

DNS = Density ($lb/in.^3$)

Data Set 11 Vertex Information

READ (5,5060) (IV(I + 1), I = 1, NV)

5060 FORMAT (16I5)

IV(I) = index of the I-th vertex.

Internally, the first and last points are required to be vertices. The user, However, must not enter these indices as vertices. IV(I) and IV(NV + 2) are set internally to 1 and NPTS, respectively.

---

* Note - The units used for thicknesses and coordinates should be actual dimensions in inches.

Description of Output

The main output from FIT is in the form of a punched set of data ready to be read into NONLIN. A plot of x-y coordinate and shape of model is also obtained. Since all of this standard input is described in detail in Appendix B of Reference (1), nothing more need be said about this part of the output.

In addition to the input for NONLIN, certain intermediate results which describe the fitting process are printed out. An understanding of these results is important to the user if trouble is encountered by the program in obtaining a model. Before describing these results it will be necessary to consider briefly the fitting procedure.

The fitting procedure begins by grouping the points according to whether the tangent to the fitting curve will rotate clockwise, counterclockwise, or not turn (a line), as the group of points is traversed in the positive direction. The positive direction along the curve is defined by the order in which the points are read in. This grouping of points accomplishes several important tasks. It isolates inflection points, gives a lower bound to the number of parts required in the final model, and provides an easy check on whether a given circular arc has the proper curvature. It must be emphasized here that the way in which this grouping is done requires that lines be described by at least three points. This is brought out since it may, on occasion, be necessary to add points to those obtained from the encapsulating procedure to ensure obtaining conical parts where they are desired.

Basically the fitting procedure requires the joining of two curves so that they have a common tangent and are within the prescribed tolerance of the given points. The requirement that the first derivative be continuous determines a line on which the center of a fitting circle must lie. In the case of a fitting line segment, this requirement demands that the line be tangent to any circles adjacent to it.

There are essentially four different problems associated with the fitting procedure. These are starting the fitting curve with a circle or a line and extending the fitting curve with a circle or a line.

If the fitting curve is being extended with a circle, then a line is known on which the center must lie. This line is either the normal through the last point of the preceding line or the extended diameter through the last point of the preceding circle. The next circle is then completely determined by requiring it to pass through one additional point. To fit as many points as possible the circle through the last point of the group of points being fit is tested for suitability. This test includes a check on the curvature and a check on whether or not all of the points being fit lie within the tolerance of the curve. If any point does not satisfy the tolerance the circle is judged unacceptable and the circle through the next to the last point is tested. This process is continued until a suitable circle is found. The acceptable circle is then extended as far as possible by testing successive points past the last point on the circle until one is found which exceeds the tolerance.

When the fitting curve is being extended by a line, the procedure is simply to find the appropriate line which contains the last point of the group of collinear points and is tangent to the preceding circle.

A fitting curve is begun at vertices and at the first point of the set of data points. If the first group of points being fit is not collinear, the fitting procedure requires a line on which the center of the fitting circle must lie. This line is taken to be the extended radius of the circle through the first three points.

There is one further procedure which is carried out as a matter of course when the fitting curve is extended by joining two circles of opposite curvature. This procedure is to search for a better inflection point than is offered by the last point of the preceding circle. Nine trial inflection points are created on the preceding circle between the last two points fit. Each trail point is tried and the best one is chosen according to a measure of the goodness of fit the curve from each trial point achieves.

Several things can happen to the fitting curve extended from a given trial point: (a) it can be extended from the trial point to the last point of the present group of points with one or more circular arcs, (b) it can be extended so as to fit all but a few of the points before the curvature reverses, or (c) it can only be extended one point before curvature reversal occurs. The last two cases are distinguished, because, when curvature reversal occurs, nine trial points are created between the last two points successfully fit and each is tried to obtain the best point from which to continue the fitting procedure. While this strategy is satisfactory for case (b), it will lead to uncontrolled looping in case (c).

Corresponding to each of the three cases, a number indicative of the trial points suitability is computed. For case (a), the number of circular arcs required plus the sum of the absolute values of the distances the points are from the curve is computed. This number is computed for each trial point and is placed in a vector called BSTFIT. If the fitting procedure could not go from the k^{th} trial point to the last point of the group, BSTFIT(K) is set equal to 100. In case (b), the index of the last point properly fit in extending the curve from the k^{th} trial point is stored in a vector called IFIT. Thus, if BSTFIT(K) = 100 for all nine trial points, the best trial point is chosen according to the largest entry in IFIT.

In order to discuss case (c), let us suppose that the nine trial points were created between the j^{th} and $j + 1^{st}$ points. Then IFIT(K) = j + 1 for all nine trial points. So that the fitting procedure may continue, the vector EP(K) is computed for each trial point. EP(K) contains the distance of the $j + 1^{st}$ point from the circle through the $j + 2^{nd}$ point, provided this circle has the proper curvature. In case the curvature does reverse, EP(K) is set equal to 100. The best trial point is chosen according to the smallest value in EP, which of course will be larger than the tolerance. A message indicating that the tolerance has been exceeded is printed out and the user can decide whether or not to accept the model.

With this brief explanation of the curve fitting procedure, the output description should now be clear. The first few pages of output are

self-explanatory, consisting of job identification, tolerance, and the translated and reflected (x,y) coordinates together with the thickness at these points.

The results of the preliminary grouping are then displaced. Each row of this output corresponds to one group of points and contains the type of the grouping and the first and last points of the grouping. The type of the grouping is a number which indicates the direction of rotation of the tangent as follows:

a)	ITYPE(I) = 1	Clockwise
b)	ITYPE(I) = 2	Counterclockwise
c)	ITYPE(I) = 3	Line segment

The remaining output will vary from problem to problem, but will always consist of the same type of information. The information is geared to indicate how the set of points was fit. The fitting information for each group of points is started at the top of a new page. If a group of points is collinear, no information other than the first and last points of the line is given.

For circles there are several pieces of information printed out. Whenever a set of trial points is created and tested the values of BSTFIT, IFIT, and EP are printed out for each trial point. The index of the best trial point is identified and its coordinates given. The next line gives the indices of the points the circle must pass through, the index of the last point of the group of points being fit, and the center coordinates and radius of the fitting circle. If there are any points which the circle does not contain, their coordinates and distances from the circle are then listed. The distance is a signed quantity which is positive when the point is inside the circle. When this information pertains to points fit by extending a circle, it is distinguished by the words "Following Point Check", as compared to "Intermediate Point Check".

The output described above is useful when a smaller tolerance is desired or when trouble developes during the fitting procedure. A different, better fitting model will not necessarily result from changing the tolerance. However, a glance at the actual distances the points are from the model will indicate how small the tolerance must be set to achieve a change in the model. The vectors BSTFIT, IFIT, and EP are often useful when the fitting procedure fails; as they give a good indication of what caused the failure and help in correcting the trouble.

When the fitting procedure is completed the set of (x,y) coordinates, including the various trial points used, is listed. The familiar output from NONLIN is then printed out, starting with the boundary data and followed by the geometry generated by FIT. Finally, a plot of the model versus the original set of data points is provided for visual acceptance or rejection of the model.

Sample Problem

To illustrate the preceding remarks we consider an example problem taken from Reference (2). A step-by-step explanation of input preparation and output interpretation will be given.

Table B-2 lists the (x,y) coordinates and thicknesses measured for two leafs of the 3-1/2-inch single-ply stainless steel bellows JN 136. The incapsulated bellows is shown photographed and enlarged 20X in Figure B-5. We observe that when the coordinates were measured, the positive y direction was down on the photograph. This implied that a reflection and translation about the x-axis will be required.

A decision must be made on how the weld should be modeled. It can be modeled as a short cylinder by adding one point between points 33 and 34 (three points are needed to determine a line) or it can be modeled as a sharp point (a vertex) by omitting point 34 and shifting points 35 through 65 a distance of 0.005 inch in the y direction. The second way of modeling will be used in this example, although it is not necessarily the best way.

The input data are shown prepared on coding sheets in Figure B-6. The first three cards contain the job identification desired by the user. The next three data sets contain the boundary data which are described adequately in Reference (2). Data Set 5 has the first five columns blank, since we desire to obtain a model by means of program FIT. For this problem, Young's modulus, Poisson's ratio, and the loading parameters are constant for the entire shell.

Data Set 8 is the beginning of the data for program FIT. The number of points being fit is 65. There is one vertex and we shall request 200 print points. The next card contains the tolerance, which we will specify as 0.0025 inches for a first try. We need to translate the points so that the x-coordinate represents the distance from the centerline to the point. Moreover, the points need to be reflected in x-axis. In order that the plot of the model will lie in the first quadrant, we must, also, translate the points in the y direction. From Reference (2) we find that the points need to be translated 1.4264 inches in x. To place the points in the first quadrant, a translation of 0.08 in y after reflection will suffice.

The next 65 cards comprise Data Set 10. From Figure B-5 it is clear that the first and last parts of the shell should be described by lines. To ensure this, the y-coordinate of points 2 and 64 have been changed. Each card in this set contains the coordinates and thickness of one point. The last data set contains the index of the vertices. For this problem the only vertex is the 33rd point.

The results obtained from FIT for this problem are shown in Figures B-10 to B-16. An item-by-item description is outlined below:

(a) Header page, which gives name of company. Any title appropriate to a given company can be obtained by modifying FORMAT statement Numbers 534, 535, 536, 537, 539 in subroutine input.

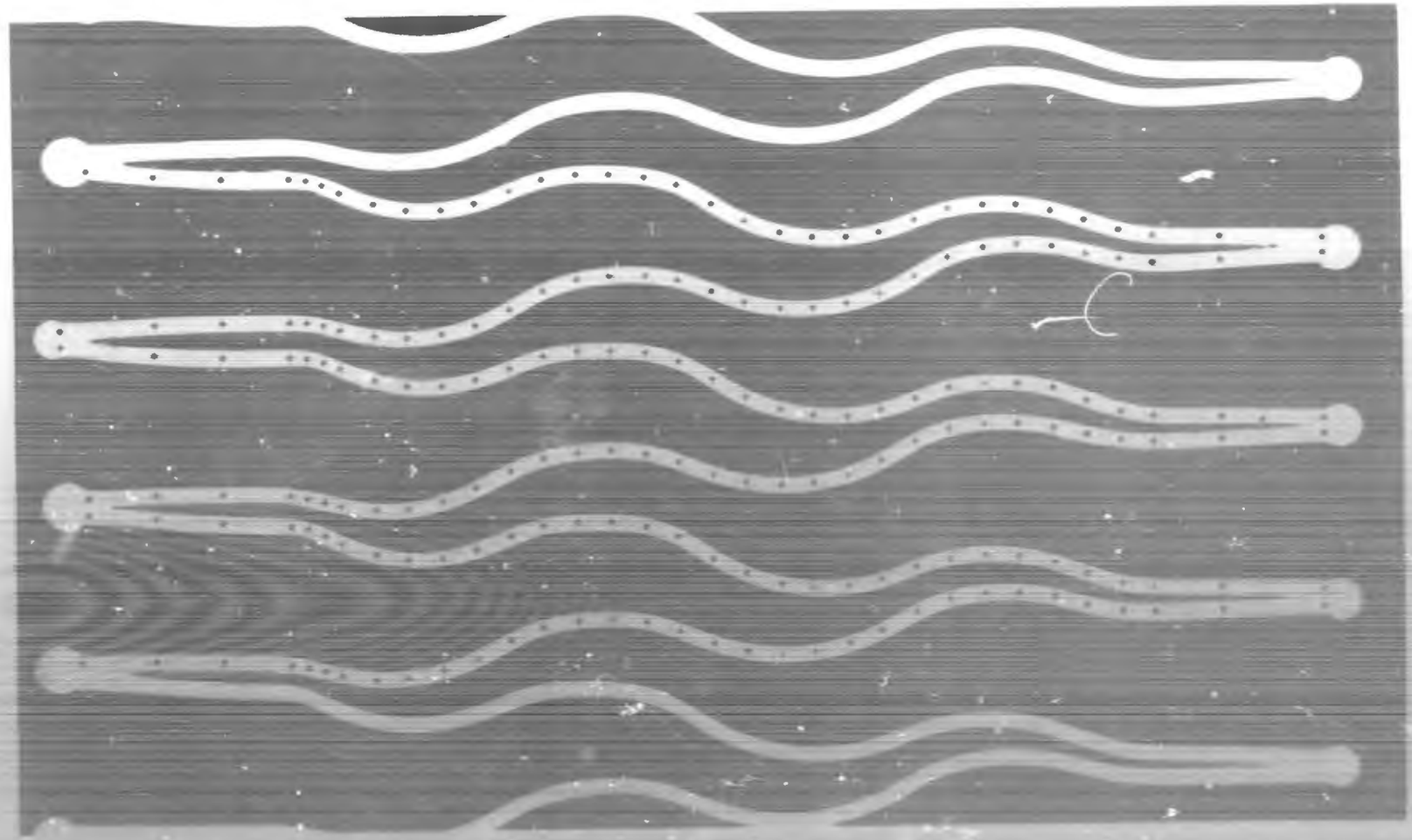


FIGURE 9-5. ENLARGED CROSS SECTIONAL VIEW OF A CONVENTIONAL 3.5-INCH WELDED BELLOWS JB-136

TABLE B-2. COORDINATES AND THICKNESS MEASUREMENTS FOR 3-1/2 INCH BELLOWS JN 136

(Nominal Thickness = 0.005 in.; 1 Unit = 0.001 in.)

Reading	Coordinates x	Coordinates y	Thickness, Inch	Reading	Coordinates x	Coordinates y	Thickness, Inch
1	0	0	0.00527	34	365	26.5	0.00520
2	20	1.5	0.00523	35	365	29	0.00518
3	40	3	0.00535	36	335	31	0.00503
4	60	3	0.00506	37	315	31	0.00527
5	65	3.5	0.00462	38	305	30	0.00523
6	70	5	0.00466	39	295	28.5	0.00518
7	75	7.5	0.00510	40	285	26	0.00507
8	85	11	0.00503	41	275	25	0.00503
9	95	13	0.00503	42	265	26	0.00507
10	105	13	0.00494	43	255	29	0.00503
11	115	11	0.00510	44	245	34.5	0.00507
12	125	7	0.00503	45	235	40	0.00503
13	135	3.5	0.00499	46	225	43	0.00503
14	145	2	0.00523	47	215	44.5	0.00499
15	155	2	0.00527	48	205	45	0.00507
16	165	3	0.00515	49	195	42.5	0.00503
17	175	5.5	0.00499	50	185	39	0.00494
18	185	11.5	0.00515	51	175	35.5	0.00490
19	195	17	0.00523	52	165	34	0.00514
20	205	21	0.00523	53	155	34	0.00518
21	215	22.5	0.00507	54	145	35	0.00510
22	225	22.5	0.00510	55	135	38.5	0.00507
23	235	21	0.00503	56	125	44.5	0.00507
24	245	17	0.00494	57	115	49.5	0.00499
25	255	13.5	0.00494	58	105	52	0.00490
26	265	12.5	0.00503	59	95	53	0.00486
27	275	12.5	0.00494	60	85	52.5	0.00490
28	285	14.5	0.00490	61	75	50.5	0.00490
29	295	17.5	0.00503	62	70	49	0.00474
30	305	21	0.00503	63	65	48	0.00490
31	315	23	0.00523	64	60	48	0.00499
32	335	23.5	0.00510	65	40	48	0.00518
33	365	24	0.00523	66	20	49	0.00507
				67	0	50	0.00518

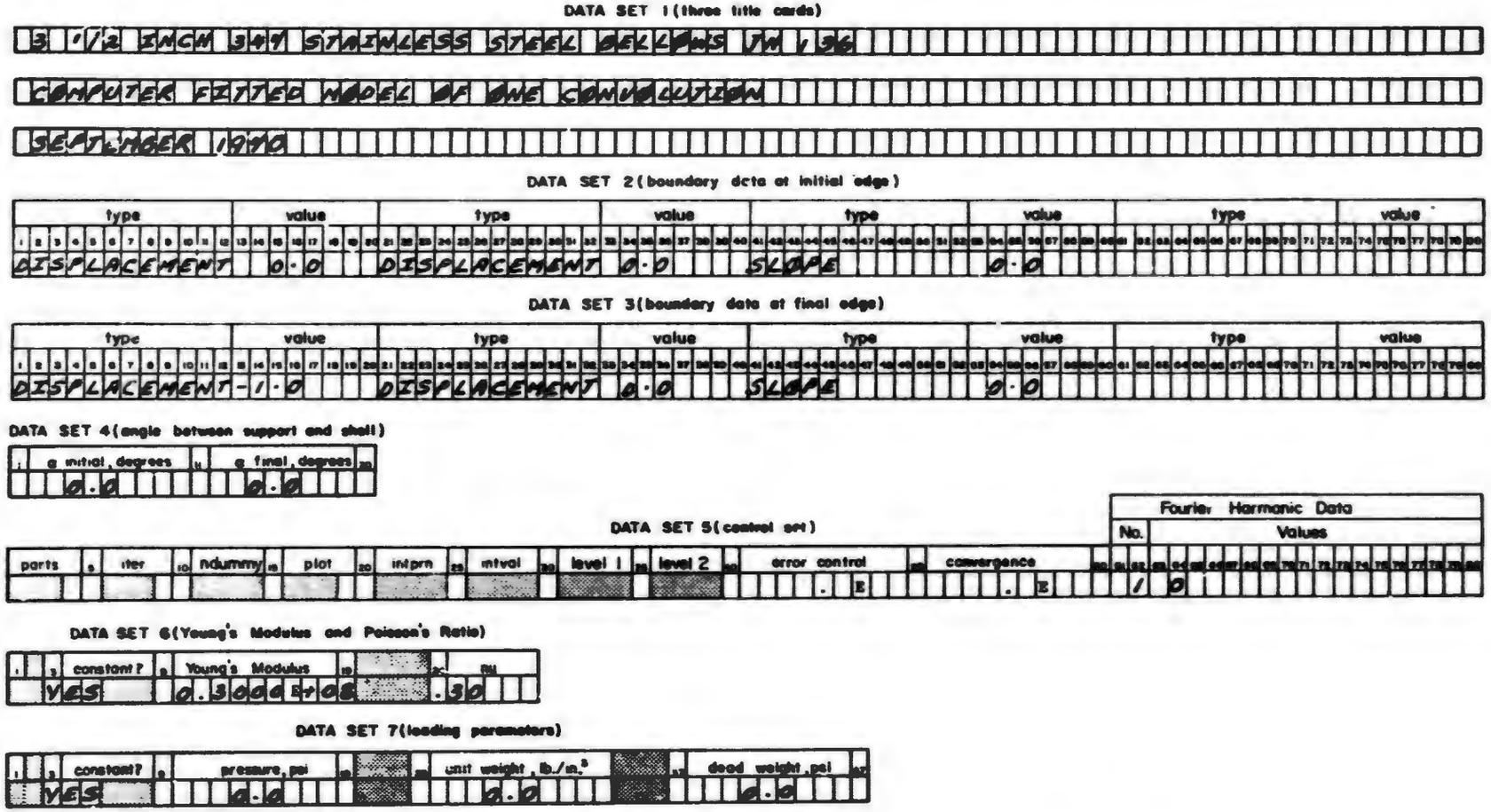


FIGURE B-6. INPUT DATA FOR SAMPLE PROBLEM FOR COMPUTING PROGRAM FIT

DATA SET 8 (control card)

NPTS					NV					ITNT				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			6	7					1			2	0	0

DATA SET 9 (tolerance and transformation)

EPSI										XTRANS										YTRANS										XR FLCT				YR FLCT			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		33	34	35		38	39	40
			0	.	0	0	2	5					1	.	4	2	6	4					0	.	0	8					N	O			Y	E	S

FIGURE B-6. (Continued)

PROGRAM FIT DATA SET 10 (pointwise description of shell)

x-coordinate	y-coordinate	thickness	Poisson's ratio	Young's modulus	pressure	dead weight	density
0.000	0.00000	0.00523					
0.020	0.00115	0.00523					
0.040	0.00310	0.00535					
0.060	0.00530	0.00506					
0.065	0.00635	0.00466					
0.070	0.00750	0.00446					
0.075	0.00975	0.00510					
0.085	0.01110	0.00503					
0.095	0.01330	0.00503					
0.105	0.01530	0.00499					
0.115	0.01710	0.00510					
0.125	0.01870	0.00503					
0.135	0.02035	0.00499					
0.145	0.02220	0.00523					
0.155	0.02420	0.00527					
0.165	0.02630	0.00515					
0.175	0.02855	0.00499					
0.185	0.03115	0.00515					
0.195	0.03370	0.00523					
0.205	0.03610	0.00513					
0.215	0.03835	0.00507					
0.225	0.04035	0.00510					
0.235	0.04210	0.00503					
0.245	0.04370	0.00499					
0.255	0.04535	0.00499					
0.265	0.04695	0.00503					
0.275	0.04845	0.00499					
0.285	0.04985	0.00490					
0.295	0.05115	0.00503					
0.305	0.05210	0.00503					

FIGURE B-6. (Continued)

PROGRAM FIT DATA SET 10 (pointwise description of shell)

radius	z coordinate	thickness	Poisson's ratio	Young's modulus	pressure	dead weight	density
0.315	0.02830	0.00513					
0.335	0.02835	0.00510					
0.365	0.02840	0.00513					
0.365	0.02865	0.00520					
0.365	0.02890	0.00518					
0.335	0.03110	0.00503					
0.315	0.03110	0.00527					
0.305	0.03000	0.00523					
0.295	0.02885	0.00516					
0.285	0.02860	0.00507					
0.275	0.02850	0.00503					
0.265	0.02860	0.00507					
0.255	0.02890	0.00503					
0.245	0.02945	0.00507					
0.235	0.03000	0.00503					
0.225	0.03030	0.00503					
0.215	0.03045	0.00497					
0.205	0.03050	0.00507					
0.195	0.03085	0.00503					
0.185	0.03090	0.00494					
0.175	0.03055	0.00490					
0.165	0.03040	0.00514					
0.155	0.03040	0.00515					
0.145	0.03050	0.00510					
0.135	0.03085	0.00507					
0.125	0.03145	0.00507					
0.115	0.03195	0.00499					
0.105	0.03230	0.00490					
0.095	0.03230	0.00496					
0.085	0.03233	0.00510					

FIGURE B-6. (Continued)

PROGRAM FIT DATA SET 10 (pointwise description of shell)

x-coordinate	y-coordinate	thickness	Poisson's ratio	Young's modulus	pressure	dead weight	density
0.075	0.0505	0.00490					
0.070	0.0490	0.00474					
0.065	0.0480	0.00490					
0.060	0.0480	0.00499					
0.040	0.0480	0.00518					
0.020	0.0490	0.00507					
0.000	0.0500	0.00518					

PROGRAM FIT DATA SET 11 (vertex point numbers)

1	31	35

FIGURE B-6. (Concluded)

BATTELLE MEMORIAL INSTITUTE

COLUMBUS, OHIO

STRESS ANALYSIS OF A SHELL OF REVOLUTION

ADVANCED SOLID MECHANICS DIVISION

MECHANICAL ENGINEERING DEPARTMENT

FIGURE B-7. OUTPUT DATA FROM COMPUTING PROGRAM FIT

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

COORDINATES AS READ IN

I	X(I)	Y(I)
1	0.00000	0.00000
2	.02000	.00150
3	.04000	.00300
4	.06000	.00300
5	.06500	.00350
6	.07000	.00500
7	.07500	.00750
8	.08500	.01100
9	.09500	.01300
10	.10500	.01300
11	.11500	.01100
12	.12500	.00700
13	.13500	.00350
14	.14500	.00200
15	.15500	.00200
16	.16500	.00300
17	.17500	.00550
18	.18500	.01150
19	.19500	.01700
20	.20500	.02100

FIGURE B-7. (Continued)

21	.21500	.02250
22	.22500	.02250
23	.23500	.02100
24	.24500	.01700
25	.25500	.01350
26	.26500	.01250
27	.27500	.01250
28	.28500	.01450
29	.29500	.01750
30	.30500	.02100
31	.31500	.02300
32	.32500	.02350
33	.33500	.02400
34	.34500	.02650
35	.35500	.02900
36	.33500	.03100
37	.31500	.03100
38	.30500	.03000
39	.29500	.02850
40	.28500	.02650
41	.27500	.02500
42	.26500	.02650
43	.25500	.02900
44	.26500	.03450
45	.23500	.04000
46	.22500	.04300
47	.21500	.04450
48	.20500	.04500

FIGURE B-7. (Continued

49	.19500	.06250
50	.18500	.03900
51	.17500	.03550
52	.16500	.03400
53	.15500	.03400
54	.14500	.03500
55	.13500	.03850
56	.12500	.04450
57	.11500	.04950
58	.10500	.05200
59	.09500	.05300
60	.08500	.05250
61	.07500	.05050
62	.07000	.04900
63	.06500	.04800
64	.06000	.04800
65	.04000	.04800
66	.02000	.04900
67	0.00000	.05000

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

NO. OF POINTS	NO. OF VERTICES	TOLERANCE
67	2	.2500E-02

COORDINATES AS MODIFIED BY DATA SET 9.

I	X(I)	Y(I)	RTHICK(I)
1	1.42640	.06900	.00527
2	1.40640	.08150	.00523
3	1.38640	.08300	.00535
4	1.36640	.08300	.00506
5	1.34140	.08350	.00462
6	1.32640	.08500	.00466
7	1.30140	.08750	.00510
8	1.28140	.09100	.00503
9	1.26140	.09300	.00503
10	1.24140	.09300	.00494
11	1.22140	.09100	.00510
12	1.20140	.08700	.00503
13	1.18140	.08050	.00499
14	1.16140	.08200	.00523
15	1.14140	.08200	.00527

FIGURE B-7. (Continued)

16	1.26140	.04300	.00515	
17	1.25140	.08550	.00499	
18	1.24140	.09150	.00515	
19	1.23140	.09700	.00523	
20	1.22140	.10100	.00523	
21	1.21140	.10250	.00507	
22	1.20140	.10250	.00510	
23	1.19140	.10100	.00503	
24	1.18140	.09700	.00496	
25	1.17140	.09350	.00496	
26	1.16140	.09250	.00503	
27	1.15140	.09250	.00496	
28	1.14140	.09450	.00498	
29	1.13140	.09750	.00503	
30	1.12140	.10100	.00503	
31	1.11140	.10300	.00523	
32	1.09140	.10350	.00510	
33	1.08140	.10400	.00523	THIS POINT IS A VERTEX
34	1.06140	.10450	.00520	
35	1.05140	.10500	.00525	THIS POINT IS A VERTEX
36	1.04140	.11100	.00563	
37	1.03140	.11100	.00527	
38	1.02140	.11000	.00523	
39	1.01140	.10950	.00510	
40	1.00140	.10800	.00507	
41	.99140	.10500	.00503	
42	.98140	.10400	.00507	
43	.97140	.10050	.00543	

FIGURE B-7. (Continued)

44	1.14140	.11450	.00507
45	1.19140	.12000	.00503
46	1.20140	.12300	.00503
47	1.21140	.12450	.00499
48	1.22140	.12500	.00507
49	1.23140	.12750	.00503
50	1.24140	.11900	.00494
51	1.25140	.11550	.00490
52	1.26140	.11400	.00514
53	1.27140	.11490	.00519
54	1.28140	.11500	.00510
55	1.29140	.11850	.00507
56	1.30140	.12450	.00507
57	1.31140	.12950	.00499
58	1.32140	.13200	.00490
59	1.33140	.13300	.00486
60	1.34140	.13250	.00490
61	1.35140	.13050	.00490
62	1.35640	.12900	.00474
63	1.36140	.12800	.00490
64	1.36640	.12890	.00499
65	1.37640	.12800	.00518
66	1.40640	.12900	.00507
67	1.42000	.13000	.00518

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JH 136

COMPUTED FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

PRELIMINARY GROUPING OF POINTS

I	ITYPE(I)	FIRST POINT X	FIRST POINT Y	LAST POINT X	LAST POINT Y
1	3	1.4264	.0800	1.3864	.0830
2	2	1.3864	.0830	1.3664	.0830
3	1	1.3464	.0830	1.3514	.0875
4	2	1.3514	.0875	1.3014	.0870
5	1	1.3014	.0870	1.2414	.0915
6	2	1.2414	.0915	1.1814	.0970
7	1	1.1414	.0970	1.1214	.1010
8	2	1.1214	.1010	1.0614	.1040
9	3	1.0614	.1040	1.0614	.1090
10	1	1.0414	.1090	1.1414	.1060
11	2	1.1414	.1060	1.1714	.1090
12	3	1.1714	.1090	1.1914	.1200
13	1	1.1914	.1200	1.2314	.1225
14	3	1.2314	.1225	1.2514	.1155
15	2	1.2514	.1155	1.3014	.1245
16	1	1.3014	.1245	1.3564	.1290
17	2	1.3564	.1290	1.3614	.1280
18	3	1.3614	.1280	1.3864	.1280
19	3	1.3864	.1280	1.4264	.1300

FIGURE B-7. (Continued)

3 [illegible]-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

FITTING DATA FOR GROUP OF POINTS NO. 1

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 1 TO POINT 3.

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1978

FITTING DATA FOR GROUP OF POINTS NO. 2

L1 = 2 L2 = 4 L = 4 X3 = 1.37664 Y3 = -.05033 K = .13371

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JH 136
COMPUTED FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1978
          FITTING DATA FOR GROUP OF POINTS NO.   3
                              RSTFIT    IFIT           FP
                              1.00017     8        0.E+00
                              1.00099     8        0.E+00
                              1.00181     8        0.E+00
                              1.00257     8        0.E+00
                              1.00324     8        0.E+00
                              1.00392     8        0.E+00
                              1.00451     8        0.E+00
                              1.00505     8        0.E+00
                              1.00554     8        0.E+00
LL =   1 IS THE BEST TRIAL POINT.
   L1 =  4  L2 =  8  L =  8  X3 =   1.36668  Y3 =   .11179  H =   .02865
   J =  1  NP =  3  X4 =   1.36640  Y4 =   .08307  EPS =   -.84799312E-04 INTERMEDIATE POINT CHECK
   J =  2  NP =  3  X4 =   1.34140  Y4 =   .04357  EPS =   -.73309372E-04 INTERMEDIATE POINT CHECK
   J =  3  NP =  3  X4 =   1.35640  Y4 =   .08500  EPS =    .72032705E-05 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.   4
                          ASTFIT    IFIT          EP
                          1.00330    14        0.E+00
                          1.00205    14        0.E+00
                          1.00074    14        0.E+00
                          1.00087    14        0.E+00
                          1.00214    14        0.E+00
                          1.00357    14        0.E+00
                          1.00495    14        0.E+00
                          1.00633    14        0.E+00
                          1.00771    14        0.E+00
LL =   3 IS THE BEST TRIAL POINT.
  L1 =  8  L2 = 14  L = 14  X3 =   1.32640  Y3 =    .03942  H =    .05394
  J =  1  NP =  5  X4 =   1.35140  Y4 =   .08750  EPS =   -.75341058E-04 INTERMEDIATE POINT CHECK
  J =  2  NP =  5  X4 =   1.34140  Y4 =   .09109  EPS =    .32621726E-03 INTERMEDIATE POINT CHECK
  J =  3  NP =  5  X4 =   1.33140  Y4 =   .09309  EPS =    .15601557E-03 INTERMEDIATE POINT CHECK
  J =  4  NP =  5  X4 =   1.32140  Y4 =   .09300  EPS =    .82246084E-04 INTERMEDIATE POINT CHECK
  J =  5  NP =  5  X4 =   1.31140  Y4 =   .09100  EPS =    .10451478E-03 INTERMEDIATE POINT CHECK
```

(FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JM 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.   5
                          RSTFIT   IFIT          EP
                         1.00261     21       0.E+00
                         1.00154     21       0.E+00
                         1.00333     21       0.E+00
                         1.00586     21       0.E+00
                         1.00437     21       0.E+00
                         1.01188     21       0.E+00
                       100.00000     14        .10000000E+03
                       100.00000     14        .10000000E+03
                       100.00000     14        .10000000E+03
LL =   2 IS THE BEST TRIAL POINT.
  L1 = 14  L2 = 21  L = 21  X3 =    1.27553  Y3 =    .14540  H =    .06387
  J =  1  NP =  6  X4 =   1.30140  Y4 =    .08700  EPS =    -.79690099E-04 INTERMEDIATE POINT CHECK
  J =  2  NP =  6  X4 =   1.29140  Y4 =    .08350  EPS =    -.11304624E-03 INTERMEDIATE POINT CHECK
  J =  3  NP =  6  X4 =   1.28140  Y4 =    .08200  EPS =     .11522462E-03 INTERMEDIATE POINT CHECK
  J =  4  NP =  6  X4 =   1.27140  Y4 =    .08200  EPS =     .25145160E-03 INTERMEDIATE POINT CHECK
  J =  5  NP =  6  X4 =   1.26140  Y4 =    .08390  EPS =    -.19254162E-03 INTERMEDIATE POINT CHECK
  J =  6  NP =  6  X4 =   1.25140  Y4 =    .08550  EPS =    -.70603469E-03 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JM 135
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1979
          FITTING DATA FOR GROUP OF POINTS NO.   6
                                   HSTFIT    IFIT          EP
                                  1.00631     28        0.E+00
                                  1.00956     29        0.E+00
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
                                100.00000     21         .10000000E+03
LL =    1 IS THE BEST TRIAL POINT.
   L1 = 21  L2 = 28  L = 28  X3 =    1.29550  Y3 =    .03015  R =    .07107
   J =  1  NP =  6  X4 =   1.24140  Y4 =   .09151  EPS =    -.19930095E-04 INTERMEDIATE POINT CHECK
   J =  2  NP =  6  X4 =   1.23140  Y4 =   .09709  EPS =    -.63028145E-03 INTERMEDIATE POINT CHECK
   J =  3  NP =  6  X4 =   1.22140  Y4 =   .10100  EPS =    -.15507552E-02 INTERMEDIATE POINT CHECK
   J =  4  NP =  6  X4 =   1.21140  Y4 =   .10259  EPS =    -.15284257E-02 INTERMEDIATE POINT CHECK
   J =  5  NP =  6  X4 =   1.20140  Y4 =   .10250  EPS =    -.14047709E-02 INTERMEDIATE POINT CHECK
   J =  6  NP =  6  X4 =   1.19140  Y4 =   .10109  EPS =    -.11180647E-02 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1979
          FITTING DATA FOR GROUP OF POINTS NO.   7
                              HSTFIT   IFIT          EP
                              1.00283   35     0.E+00
                              1.00394   35     0.E+00
                              1.00527   35     0.E+00
                              1.00704   35     0.E+00
                              1.00885   35     0.E+00
                            100.00000   28      .10000000E+03
                            100.00000   28      .10000000E+03
                            100.00000   28      .10000000E+03
                            100.00000   28      .10000000E+03
LL =    1 IS THE BEST TRIAL POINT.
   L1 = 28  L2 = 35  L = 35  X3 =   1.15633  Y3 =    .17322  R =     .00022
   J =  1  NP =  6  X4 =   1.14140  Y4 =   .09703  EPS =   -.14985422E-04 INTERMEDIATE POINT CHECK
   J =  2  NP =  6  X4 =   1.17140  Y4 =   .09350  EPS =   -.99954708E-03 INTERMEDIATE POINT CHECK
   J =  3  NP =  6  X4 =   1.16140  Y4 =   .09250  EPS =   -.65649715E-03 INTERMEDIATE POINT CHECK
   J =  4  NP =  6  X4 =   1.15140  Y4 =   .09250  EPS =   -.64759772E-03 INTERMEDIATE POINT CHECK
   J =  5  NP =  6  X4 =   1.14140  Y4 =   .09451  EPS =    .99774708E-04 INTERMEDIATE POINT CHECK
   J =  6  NP =  6  X4 =   1.13140  Y4 =   .09759  EPS =    .50495598E-03 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.   9
                                    RSTFIT   IFIT             EP
                                 100.00000     35        .10000000E+03
                                 100.00000     35        .10000000E+03
                                 100.00001     35        .10000000E+03
                                 100.00309     35        .10000000E+03
                                 100.00003     35        .10000000E+03
                                 100.00000     35        .10000000E+03
                                   1.00297     39      0.E+00
                                   1.00291     39      0.E+00
                                   1.00301     39      0.E+00
LL =   9 IS THE BEST TOTAL POINT.
    L1 = 38  L2 = 39  L = 39  X3 =    1.04311  Y3 =    -.03003  R =    .13057
    J =  1  NP =  3  X4 =    1.12140  Y4 =    .10100  EPS =    -.71216693E-03 INTERMEDIATE POINT CHECK
    J =  2  NP =  3  X4 =    1.11149  Y4 =    .10300  EPS =    -.22135743E-03 INTERMEDIATE POINT CHECK
    J =  3  NP =  3  X4 =    1.09140  Y4 =    .10350  EPS =     .19807305E-02 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

FITTING DATA FOR GROUP OF POINTS NO. 9

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 39 TO POINT 61.

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1974
          FITTING DATA FOR GROUP OF POINTS NO.  19
    L1 = 41  L2 = 46  L = 46  X3 =    1.09146  Y3 =    -.14838  R =     .27884
    J =  1  NP =  4  X4 =    1.09140  Y4 =     .11189  EPS =      -.41875342E-03 INTERMEDIATE POINT CHECK
    J =  2  NP =  4  X4 =    1.11140  Y4 =     .11100  EPS =      -.11563750E-02 INTERMEDIATE POINT CHECK
    J =  3  NP =  4  X4 =    1.12140  Y4 =     .11000  EPS =      -.10677516E-02 INTERMEDIATE POINT CHECK
    J =  4  NP =  4  X4 =    1.13140  Y4 =     .10950  EPS =      -.84294334E-03 INTERMEDIATE POINT CHECK
```


FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 134
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.  11
                                    RSTFIT   IFIT              EP
                                   1.00051     50        0.E+00
                                   1.00082     50        0.E+00
                                   1.00116     50        0.E+00
                                   1.00149     50        0.E+00
                                   1.00183     50        0.E+00
                                   1.00217     50        0.E+00
                                   1.00251     50        0.E+00
                                   1.00285     50        0.E+00
                                   1.00319     50        0.E+00
LL =   1 IS THE BEST TRIAL POINT.
    L1 = 44   2 = 50  L = 98  X3 =    1.15078  Y3 =     .16394  R =     .05870
    J =  1  NP =  3  X4 =    1.14148  Y4 =     .10604  EPS =       -.10848838E-04 INTERMEDIATE POINT CHECK
    J =  2  NP =  3  X4 =    1.15148  Y4 =     .10509  EPS =       -.20004148E-03 INTERMEDIATE POINT CHECK
    J =  3  NP =  3  X4 =    1.16148  Y4 =     .10608  EPS =       -.22331008E-03 INTERMEDIATE POINT CHECK
```


FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JH 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

FITTING DATA FOR GROUP OF POINTS NO. 12

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 58 TO POINT 82.

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.  13
   L1 = 52  L2 = 56  L = 56  X3 =    1.21376  Y3 =     .00347  H =     .04283
   J =  1  NP =  3  X4 =    1.20140  Y4 =     .12300  EPS =        .141206766-02 INTERMEDIATE POINT CHECK
   J =  2  NP =  3  X4 =    1.21140  Y4 =     .12450  EPS =        .173257366-02 INTERMEDIATE POINT CHECK
   J =  3  NP =  3  X4 =    1.22140  Y4 =     .12500  EPS =        .603840226-03 INTERMEDIATE POINT CHECK
```


FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1978

FITTING DATA FOR GROUP OF POINTS NO. 14

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 56 TO POINT 58.

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 144
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970

          FITTING DATA FOR GROUP OF POINTS NO.  14

   L1 = 50  L2 = 43  L = 43  X3 =    1.26057  Y3 =     .14752  H =     .05100

   J =  1  NP =  4  X4 =    1.26148  Y4 =     .11408  EPS =      .96822352E-03 INTERMEDIATE POINT CHECK
   J =  2  NP =  4  X4 =    1.27164  Y4 =     .11408  EPS =      .13950575E-02 INTERMEDIATE POINT CHECK
   J =  3  NP =  4  X4 =    1.28148  Y4 =     .11508  EPS =      .80749878E-03 INTERMEDIATE POINT CHECK
   J =  4  NP =  4  X4 =    1.29148  Y4 =     .11454  EPS =      .51604402E-03 INTERMEDIATE POINT CHECK
```


FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTED FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.  16
                                    HSTFIT    IFIT              EP
                                   1.00704      70         0.E+00
                                   1.00454      70         0.E+00
                                   1.00232      70         0.E+00
                                   1.00104      70         0.E+00
                                   1.00054      70         0.E+00
                                   1.00014      70         0.E+00
                                   1.00071      70         0.E+00
                                 100.00000      63          .10000000E+03
                                 100.00000      63          .10000000E+03
LL =   4 IS THE BEST TRIAL POINT.
   L1 = 63  L2 = 70  L = 70  X3 =    1.33005  Y3 =     .04937  R =     .06373
   J =  1  NP =  6  X4 =    1.30140  Y4 =     .12450  EPS =       -.38750122E-03 INTERMEDIATE POINT CHECK
   J =  2  NP =  6  X4 =    1.31140  Y4 =     .12450  EPS =       -.57301171E-03 INTERMEDIATE POINT CHECK
   J =  3  NP =  6  X4 =    1.32140  Y4 =     .13200  EPS =       -.21500402E-03 INTERMEDIATE POINT CHECK
   J =  4  NP =  6  X4 =    1.33140  Y4 =     .13300  EPS =       -.71240726E-05 INTERMEDIATE POINT CHECK
   J =  5  NP =  6  X4 =    1.34140  Y4 =     .13250  EPS =        .12178153E-03 INTERMEDIATE POINT CHECK
   J =  6  NP =  6  X4 =    1.35140  Y4 =     .13050  EPS =        .13520959E-03 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

```
3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970
          FITTING DATA FOR GROUP OF POINTS NO.  17
                              WSTFIT   IFIT            EP
                              1.00001    72        0.E+00
                              1.00003    72        0.E+00
                              1.00006    72        0.E+00
                              1.00009    72        0.E+00
                              1.00012    72        0.E+00
                              1.00015    72        0.E+00
                              1.00018    72        0.E+00
                              1.00021    72        0.E+00
                              1.00024    72        0.E+00
LL =   1 IS THE BEST TRIAL POINT.
   L1 = 70  L2 = 72  L = 72  X3 =    1.36240  Y3 =    .14833  H =    .02030
   J =  1  NP =  1  X4 =    1.35640  Y4 =    .12909  EPS =     -.00300523E-05 INTERMEDIATE POINT CHECK
```

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL HELLOS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

FITTING DATA FOR GROUP OF POINTS NO. 1N

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 72 TO POINT 74.

FIGURE B-7. (Continued)

J 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136
COMPUTER FITTED MODEL OF ONE CONVOLUTION
SEPTEMBER 1970

FITTING DATA FOR GROUP OF POINTS NO. 10

THIS GROUP OF POINTS IS COLINEAR. IT EXTENDS FROM POINT 74 TO POINT 76.

FIGURE B-7. (Continued)

```
• • •  PRINTOUT OF INPUT DATA  • • •

• BOUNDARY DATA •

          INITIAL EDGE                          FINAL EDGE

DISPLACEMENT =    0.00000          DISPLACEMENT =   -1.00000
DISPLACEMENT =    0.00000          DISPLACEMENT =    0.00000
       SLOPE =    0.00000                 SLOPE =    0.00000
BOUNDARY ANGLE =  0.00000       BOUNDARY ANGLE =    0.00000

ELASTIC PARAMETERS ARE THE SAME FOR EVERY PART IN THIS SHELL. THEIR VALUES ARE
        YOUNGS MODULUS =  .30000E+08 POUNDS PER SQUARE INCH
        POISSONS RATIO =  .30000

LOADING PARAMETERS ARE THE SAME FOR EVERY PART IN THIS SHELL. THEIR VALUES ARE
        PRESSURE =      0.00000 POUNDS PER SQUARE INCH
        UNIT WEIGHT OF MATERIAL =     0.00000 POUNDS PER CUBIC INCH
        DEAD WEIGHT =     0.00000 POUNDS PER SQUARE INCH
```

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1979

			• GEOMETRY •							
			COORDINATES							
PART	TYPE	NO. OF SEGMENTS	INITIAL	FINAL	DIMENSIONS	A, INCHES	R, INCHES	C, INCHES	THICKNESS, CONSTANT	INCHES VALUE
1	CONICAL	1	-175.71045		DEGREES	1.42640	.04011		NO	
2	TOROIDAL	1	-175.71045	-183.43132	DEGREES	1.37640	-.13371		NO	
3	TOROIDAL	1	-183.43132	-191.12167	DEGREES	1.36669	.02865		NO	
4	TOROIDAL	1	-191.12167	-205.79579	DEGREES	1.32680	-.05396		NO	
5	TOROIDAL	1	-205.79579	-148.73357	DEGREES	1.27553	.04387		NO	
6	TOROIDAL	1	-148.73357	-194.96491	DEGREES	1.20550	-.07107		NO	
7	TOROIDAL	1	-194.96491	-188.20745	DEGREES	1.15633	.08022		NO	
8	TOROIDAL	1	-188.20745	-189.16642	DEGREES	1.08311	-.13657		NO	
9	VARCYLINDER	1	270.00000		DEGREES	1.06140	.00500		NO	
10	TOROIDAL	1	-6.10468	10.19019	DEGREES	1.09106	.27888		NO	
11	TOROIDAL	1	10.19019	-31.47108	DEGREES	1.15078	-.05878		NO	
12	CONICAL	1	-31.47108		DEGREES	1.18142	.01170		NO	
13	TOROIDAL	1	-31.47108	19.47086	DEGREES	1.21376	.04283		NO	
14	CONICAL	1	19.47086		DEGREES	1.22814	.02466		NO	
15	TOROIDAL	1	19.47086	-34.48464	DEGREES	1.26857	-.05100		NO	
16	TOROIDAL	1	-34.48464	28.06138	DEGREES	1.33405	.06373		NO	
17	TOROIDAL	1	28.06138	-.13512	DEGREES	1.36298	-.02038		NO	
18	CONICAL	1	-.13512		DEGREES	1.36295	.02345		NO	
19	CONICAL	1	-2.46241		DEGREES	1.38640	.04005		NO	

FIGURE B-7. (Continued)

3 1/2-INCH 347 STAINLESS STEEL BELLOWS JN 136

COMPUTER FITTED MODEL OF ONE CONVOLUTION

SEPTEMBER 1970

* VARIABLE THICKNESS *

PART 1								
COORDINATE	0.00000	.02904	.06011					
THICKNESS	.00527	.00523	.00535					
PART 2								
COORDINATE	-175.71095	-183.43132						
THICKNESS	.00535	.00509						
PART 3								
COORDINATE	-183.43132	-179.43450	-169.40197	-158.96095	-151.12167			
THICKNESS	.00509	.00506	.00462	.00486	.00497			
PART 4								
COORDINATE	-151.12167	-152.07296	-164.19381	-175.09027	-185.75161	-196.61936	-205.79579	
THICKNESS	.00497	.00510	.00503	.00503	.00494	.00510	.00504	
PART 5								
COORDINATE	-205.79579	-203.06090	-194.35966	-185.20983	-176.27545	-167.29487	-158.08340	-148.73357
THICKNESS	.00504	.00503	.00499	.00523	.00527	.00515	.00499	.00513
PART 6								
COORDINATE	-148.73357	-149.66694	-158.02317	-167.35219	-175.33837	-183.29341	-191.25506	-198.96491
THICKNESS	.00513	.00515	.00523	.00523	.00507	.00510	.00503	.00495
PART 7								
COORDINATE	-198.96491	-190.20900	-190.70593	-183.59536	-176.50662	-169.26238	-161.77799	-160.26045
THICKNESS	.00495	.00494	.00494	.00503	.00494	.00490	.00503	.00503
PART 8								
COORDINATE	-160.26045	-163.40338	-168.00340	-176.46782	-189.14662			
THICKNESS	.00503	.00503	.00523	.00518	.00523			
PART 9								
COORDINATE	0.00000	.00250	.00590					
THICKNESS	.00523	.00520	.00518					
PART 10								
COORDINATE	-6.10460	.07025	4.16573	6.22229	8.29229	10.10910		
THICKNESS	.00514	.00503	.00527	.00523	.00518	.00500		
PART 11								
COORDINATE	10.10910	9.10803	-.00718	-1[illegible].38761	-31.07100			
THICKNESS	.00536	.00507	.00513	.00507	.00503			

FIGURE B-7. (Continued)

PART 12								
COORDINATE.	0.00003	.00061	.01202					
THICKNESS	.00503	.00507	.00503					
PART 13								
COORDINATE	-31.47160	-17.36416	-3.29371	10.42152	19.67006			
THICKNESS	.00593	.00503	.00499	.00507	.00503			
PART 14								
COORDINATE	0.00000	.01407	.02446					
THICKNESS	.00503	.00494	.00490					
PART 15								
COORDINATE	19.67006	8.23432	-3.27505	-14.81947	-26.89339	-34.00064		
THICKNESS	.00490	.00516	.00518	.00514	.00507	.00507		
PART 16								
COORDINATE	-34.00064	-30.61106	-20.02400	-11.40930	-2.34224	6.63623	15.83324	20.06130
THICKNESS	.00597	.00507	.00499	.00490	.00486	.00490	.00498	.00476
PART 17								
COORDINATE	20.06130	19.59791	-.13512					
THICKNESS	.00476	.00474	.00490					
PART 18								
COORDINATE	0.00000	.06345	.02345					
THICKNESS	.00494	.00499	.00518					
PART 19								
COORDINATE	0.00000	.02402	.04095					
THICKNESS	.00518	.00507	.00518					

FIGURE B-7. (Concluded)

(b) (1) First three printed lines are the job identification cards supplied by the user.

(2) The number of points, vertices, and the tolerance are then listed.

(3) The coordinates and thicknesses read in are then given. Vertices, if any are specified, are identified.

(c) (1) First three lines are the job identification cards supplied by the user.

(2) The preliminary grouping of points is given. This includes the type and first and last point of each group.

The following information is provided for each group of points.

(d) (1) First three lines are the job identification cards supplied by the user.

(2) If trial inflection points are tested for a group of points, the vectors BSTFIT, IFIT, and EP are printed out and the best trial point identified.

(3) The indices of the two points which determine a fitting circle (L1 and L) are identified along with the index of the last point of the group of points (L2) and the center coordinates and radius of the circle.

(4) Intermediate point checks are given for each point between K(L1) and K(L). The distance each point is from the circle is also given.

(5) Following point checks are given if the circle is extended.

The input data for NONLIN generated by FIT is then given.

(e) (1) First three printed lines are the job identification cards supplied by user.

(2) Boundary conditions are then listed along with boundary rotation angles.

(3) If elastic parameters are the same for every part in the shell, their values are given.

(4) If loading parameters are the same for every part in the shell, their values are given.

(f) (1) First three printed lines are the job identification cards.

(2) Geometry of shell is now listed. The following items are given: part number, type of part, number of segments,

coordinates, radii a, b, and c, and thickness data. If thickness is constant, a YES is printed along with the value. If thickness is variable, a NØ is printed and entry under value is left blank. If there are more than 40 parts in the composite shell, the numbers over 40 are listed on the next page.

(g) If Young's modulus and Poisson's ratio are not constant for the shell, then the following is printed out. Otherwise go to (h).

(1) First three printed lines are the job identification cards.

(2) The part number, type, Young's modulus, and Poisson's ratio are then given.

If there are more than 40 parts in the composite shell, the numbers over 40 are listed on the next page.

(h) If the heading parameters are not constant then the following is printed out. Otherwise go to (i).

(1) First three printed lines are the job identification cards.

(2) The part number, type, normal pressure, weight density, and dead loading are then given.

If there are more than 40 parts in the composite shell, the numbers over 40 are listed on the next page.

(i) If at least one of the parts has variable thickness, then the following is printed out.

(1) First three printed lines are the job identification cards.

(2) The part number, independent coordinates, and thickness for each part which has variable thickness are then listed.

Listings of FIT and Associated Program and Subroutines

The basic total computational package associated with the subroutine FIT consists of the program DATA and the subroutines FIT, EXITD, and ANGLE. DATA is the name given to a version of the program NONLIN modified for use with FIT. EXITD and ANGLE are smaller subroutines called from FIT to facilitate numerous routine calculations required during the fitting process described above. This set of programs, the FORTRAN IV listings of which follow, allows the user to generate a complete and accurate set of input data which can in turn be used with NONLIN (and/or the PLT version of NONLIN) to obtain a detailed theoretical analysis of a bellows or diaphragm.

```
         PROGRAM DATA(INPUT,OUTPUT,PLOT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,
        .TAPE99=PLOT)
000003   DIMENSION          TITLE1(20)    , HOUNDI(8)     , GA(8)        ,
        .                   TITLE2(20)    , HOUNDF(8)     , AA(8)        ,
        .                   TITLE3(20)    , SI(60)        , IA(8)        ,
        .                   NAMER1(8)     , SX(60)        , IB(8)        ,
        .                   NAME2(60)     , IPAH(60)      , INT(60)      ,
        .                   TUIST(60)     , VN(7,60)      , VARTIK(60)   ,
        .                   NAMES1(8)     , EYM(60)       , XP(10,60)    ,
        .                   NAMES2(8)     , PSR(60)       , YP(10,60)    ,
        .                   ISS(60)       , IPLOT(10)     , TRY(4,61)    ,
        .                   SL(9,60)      , AA(4,61)      , V3(8)        ,
        .                   BACK(60)      , POINT(60)     , UNITI(2)     ,
        .                   UNITO(2)      , JOHPLT(10)    , DETERM(10)   ,
        .                   E(9,60)       , NFOURA(9)
000003   DIMENSION          IFMT(6)       , L1(8)
000003   COMMON / BLOCKA / NU, PI, XLD, NTYPE, INDEX, IBR, PN, NPOINT,
        1                  ISM, TT, T1, T2, NTT, INTC
000003   COMMON / BLOCKC / UM, GA, GM, NF, NFP, NPL, NM, NN, TNY
000003   COMMON / BLOCKE / XP, YP, SL
000003   COMMON / BLOCKF / NFF, SMXX, SZERO, GO, EMP, ISS, E,
        .                  MAX, INTPRN, INTVAL, NPP
000003   COMMON / BLOCKG / NPARTS, PHI1, V3, KIND, NT, MT, SPRINT, VN, EYM,
        1                  BACK, NBACK
000003   COMMON / BLOCKM / NNE
000003   COMMON / BLOCKN / DETERM
000003   COMMON / BLOCKP / PLOT, PLTIME, SPLOT, PLOTPT, IPLOT, YMOD, KST,
        1                  NGAMMA, DEAD, NFM
000003   COMMON / BLOCKQ / TIME, VARTIK, NVARTK
000003   COMMON / BLOCKS / JOHPLT, ALXL, ALAR, IA, IB, NOPUNC, INPUN,
        .                  CONVER, SI, SX, INT, IPAH, PSR, ITER, NTRY,
        .                  NERROR, IURN, TRYIN, IBRMAX
000003   COMMON / BLOCKX / LEVEL1, LEVEL2
000003   EQUIVALENCE    (VARTIK(1), POINT(1))
000003   DATA( RPD = 0.1745329252E-01 )
000003   DATA  (NAMER1(1) = 6HDISPLA) , (NAMEB1(5) = 6HCEMENT) ,
        .      (NAMER1(2) = 6HFORCE ) ,
        .      (NAMER1(3) = 6HSLOPE ) , (NAMER1(6) = 6H      ) ,
        .      (NAMER1(4) = 6HMOMENT)
000003   DATA  (MARKC = 2HYE), (MARKD = 2HNO), (MARKE = 1HS),
        .      (MARKM = 3HNO ), (MARKY = 3HYES)
000003   DATA ((NAMES1(I), I = 1, 8) = 6HCROWN , 6HCYLIND, 6HSPHERO,
        .                             6HPARABO, 6HELLIPS, 6HCONICA,
        .                             6HTOROID, 6HVARCYL),
        .     ((NAMES2(I), I = 1, 8) = 6H      , 6HRICAL , 6HIDAL  ,
        .                             6HLOIDAL, 6HOIDAL , 6HL     ,
        .                             6HAL    , 6HINDER )
000003   DATA  (UNITI(1) = 6HINCHES),
        .      (UNITI(2) = 1H     ),
        .      (UNITO(1) = 6HDEGREE),
        .      (UNITO(2) = 1HS    )
000003   INTEGER  VARTIK, POINT, GO, TRYIN, PLOT, PLTIME, TIME, HOUNDI,
        .         HOUNDF, TDIST
000003   REAL         NU, NT, MT, NBACK, NFM
```

```
C
C
C     FOR PLOTTING USE THE FOLLOWING CODE NUMBERS TO INDICATE THE VARIABLE
C     DESIRED.
C
C                          CODE NUMBER        VARIABLE
C
C                              1              W
C                              2              Q PHI
C                              3              U PHI
C                              4              N PHI
C                              5              BETA PHI
C                              6              M PHI
C                              7              N THETA
C                              8              M THETA
C                              9              EPSILON THETA
C                             10              EPSILON PHI
C                             11              SIGMA N PHI
C                             12              SIGMA M PHI
C                             13              SIGMA PHI OUTER
C                             14              SIGMA PHI INNER
C                             15              SIGMA N THETA
C                             16              SIGMA M THETA
C                             17              SIGMA THETA OUTER
C                             18              SIGMA THETA INNER
C                             19              TAU PHI
C
C     TRYIN = 0 INDICATES THAT LINEAR PROBLEM WILL BE SOLVED.
C     TRYIN = 1 INDICATES THAT LINEAR PROBLEM AND POSSIBLY ONE OR MORE
C     ITERATIONS HAVE BEEN DONE AND THE LAST RESULT IS TO BE READ IN.
C
C
C     INTPRN = 0 INDICATES THAT INTERMEDIATE RESULTS FROM THE NONLINEAR
C     ANALYSIS. I.E., VALUES OF PARAMETERS AND SLOPES, WILL NOT BE
C     PRINTED OUT.
C
C
C     INTVAL = 0 INDICATES THAT INTERMEDIATE RESULTS FROM INITIAL VALUE
C     INTEGRATIONS WILL NOT BE PRINTED OUT.
C
C
C      NOPUNC = 0 INDICATES THAT SOLUTIONS, DM(I,NF) AND E(I,JJ) WILL
C     NOT BE PUNCHED.
C     NOPUNCH = 1 INDICATES THAT THEY WILL BE PUNCHED.
C
C
C     PLOT = NUMBER OF COLUMNS OF VARIABLES TO BE PUT ON PLOT TAPE TO
C     BE MACHINE PLOTTED AT LATER TIME.
C
C
C
C     COMMENT   SET NUMBER 1        ( CARDS = 3 )
C
000003      999 READ(5,504)  TITLE1
```

```
000011          IF(EOF,5) 994, 947
000014    947   CONTINUE
000014          KFIT = 0
000015          READ(5,500)  TITLE2, TITLE3
000025          WRITE(6,534)
000031          WRITE(6,535)
000035          WRITE(6,536)
000041          WRITE(6,537)
000045          WRITE(6,539)
000051          NTIME = 1
000052    354   WRITE(6,541)  TITLE1, TITLE2, TITLE3
000064          GO TO (354, 360, 365, 370,375), NTIME
                C
                COMMENT   SET NUMBER 2          ( CARDS = 1 )
                COMMENT   BOUNDARY DATA AT INITIAL EDGE
                C
000075    355   READ(5,530)  (NBOUND(I), BA(I), I = 1, 4)
                C
                COMMENT   SET NUMBER 3          ( CARDS = 1 )
                COMMENT   BOUNDARY DATA AT FINAL EDGE
                C
000111          READ(5,530)  (NBOUNDF(I), BA(I), I = 5, 8)
                C
                COMMENT   SET NUMBER 4          ( CARDS = 1 )
                COMMENT   ANGLE IN DEGREES AT INITIAL AND FINAL BOUNDARIES
                C
000125          READ(5,565)  ALXL, ALXR
000135          IF(NBOUND(1) .EQ. NAMEBI(1) .OR. BOUND(1) .EQ. NAMEBI(2)) B15,800
000145    B15   IF(BOUND(2) .EQ. NAMEAI(1) .OR. BOUND(2) .EQ. NAMEBI(2)) B16,800
000155    B16   IF(BOUND(3) .EQ. NAMEBI(3) .OR. BOUND(3) .EQ. NAMEAI(4)) B17,800
000165    B17   IF(NBOUND(4) .EQ. NAMEAI(1) .OR. NBOUND(4) .EQ. NAMEBI(2)
                .
00020U    B18   IF(BOUNDF(5) .EQ. NAMEBI(1)                .OR. BOUND(4) .EQ. NAMES2(1)) B18,800
000210    B19   IF(BOUNDF(6) .EQ. NAMEAI(1)                .OR. BOUNDF(5) .EQ. NAMEBI(2)) B19,800
000220    B20   IF(BOUNDF(7) .EQ. NAMEBI(3)                .OR. BOUNDF(6) .EQ. NAMEAI(2)) B20,800
000730    B21   IF(BOUNDF(8) .EQ. NAMEBI(1)                .OR. BOUNDF(7) .EQ. NAMEBI(4)) B21,800
                .                                          .OR. BOUNDF(8) .EQ. NAMEAI(2)
000744    B22   CONTINUE                                   .OR. BOUNDF(8) .EQ. NAMES2(1)) B22,800
                C
                COMMENT   CONTROL CARD
                COMMENT   SET NUMBER 5          ( CARDS = 1 )
                C
000244          READ(5,561)  IRRM, ITER, NDUMMY, PLOT, INTPRN, INTVAL,
                .            LEVEL1, LEVEL2, ERP, CONVER, NUMBAR, (NFOURA(I),
                .            I = 1, 8)
000304          IF(IRRM .EQ. 0) KFIT =5
000306          NOPUNC = 0
000307          INPUN = 0
000310          TPYIN = 0
000311          NDE = 6
000312          IF(NFOURA(1) .GT. 0)  NDE = 8
000314          NPL = NDE + 1
000316          NFM = FLOAT(NFOURA(1))
000320          IF(ABS(ERP) .EQ. 0.0)  ERP = 1.E - 05
000323          IF(PLOT .GT. 10)  GO TO 803
```

```
C
C      SET NUMBER 6          ( CARDS = 1 )
C      INDICATE BY YES OR NO WHETHER ELASTIC PARAMETERS ARE SAME FOR EACH
C      PART. IF YES, ON SAME CARD, GIVE VALUES. IF NO, READ THEM IN AFTER SET
C      NUMBER 9.
C
000327       READ(5,562) NELAS, YOUNG, POISON
000340       IF(NELAS .EQ. MARKC .OR. NELAS .EQ. MARKD)  A215, 809
000350  A215 CONTINUE
C
C      SET NUMBER 7          ( CARDS = 1 )
C      INDICATE BY YES OR NO WHETHER PRESSURE LOADING, DENSITY OF MATERIAL,
C      OR DEAD LOAD ON SHELL IS THE SAME FOR EACH PART. IF YES, ON SAME
C      CARD, GIVE VALUES. IF NO, READ THEM IN AFTER SET NUMBER 10.
C
000350       READ(5,566) NPRES, PRESS, DENSTY, DEAD
000364       IF(NPRES .EQ. MARKC .OR. NPRES .EQ. MARKD)  A225, 810
000374  A225 CONTINUE
C
C      SET NUMBER 8          ( CARDS = NUMBER OF PARTS )
C      TYPE OF SHELL, INITIAL AND FINAL COORDINATES, NUMBER OF SEGMENTS,
C      NUMBER OF PRINT POINTS, YES OR NO FOR THICKNESS DISTRIBUTION, IF
C      YES, THEN SPECIFY VALUE, IF NO, SPECIFY NUMBER OF POINTS WHICH
C      SPECIFIES DISTRIBUTION.
C
C      FOR CYLINDER SI(L) IS EITHER 90.0 DEGREES (NORMAL OUT) OR
C      270.0 DEGREES (NORMAL IN), SX(L) IS LEFT BLANK.
C
C      FOR CONE SI(L) IS THE ANGLE (DEGREES) WHICH THE NORMAL MAKES WITH
C      THE AXIS OF THE SHELL, SX(L) IS LEFT BLANK.
C
000374       IF(KFIT .EQ. 0) GO TO 88999
000375       CALL FIT (VN,IPAR,SI,SX,ISS,INT,VARTIK,TDIST,XP,YP,EYM,PSR,IBRM,
     *              NPRES,NELAS,TITLE1,TITLE2,TITLE3)
000417  88999 CONTINUE
000417       IF(IBRM) 802, 802, 990
000421  990  IF(IBRM .GT. 60)  GO TO 802
000425       IF(KFIT .GT. 0) GO TO 89000
000427       READ(5,512) (NAME2(L), SI(L), SX(L), IPAR(L), INT(L),
     *                  TDIST(L), VN(I,L), VARTIK(L), L = 1, IBRM)
C
C      DETERMINE IF SPELLING OF SHELL PARTS IS CORRECT.
C
000460       DO 325 L = 1, IBRM
000462       IF(NAME2(L) .EQ. NAMES1(1) .OR.
     *    *    NAME2(L) .EQ. NAMES1(2) .OR.
     *    *    NAME2(L) .EQ. NAMES1(3) .OR.
     *    *    NAME2(L) .EQ. NAMES1(4) .OR.
     *    *    NAME2(L) .EQ. NAMES1(5) .OR.
     *    *    NAME2(L) .EQ. NAMES1(6) .OR.
     *    *    NAME2(L) .EQ. NAMES1(7) .OR.
     *    *    NAME2(L) .EQ. NAMES1(8))   325, 801
000522  325  CONTINUE
000525  89000 CONTINUE
C
```

```
      COMMENT   DETERMINE IF IDIST(L) CONTAINS CORRECT SPELLING.
      C
000525            DO 326 L = 1, IHRM
000527            IF(IDIST(L) .EQ. MARKC .OR. IDIST(L) .EQ. MARKU)  326, 804
000537      324   CONTINUE
000542            PLOTPT = 0
000543            DO 1234 I = 1, IHRM
000544            PLOTPT = PLOTPT + IPAN(I)*INT(I)
000550      1234  CONTINUE
000552            IF(PLOTPT .GT. 380)  GO TO 805
000556            NPARTS = 0
000560            DO 45 I = 1, IHRM
000562      45    NPARTS = NPARTS + IPAN(I)
000564            IF(NPARTS .GT. 60)  GO TO 806
000567            DO 327 L = 1, IHRM
000570            VARTIK(L) = IABS(VARTIK(L))
000572      327   CONTINUE
000575            DO 300 L = 1, IHRM
000576            IF(IDIST(L) .EQ. MARKC)  GO TO 329
000600            IF(VARTIK(L) .LT. 2 .OR. VARTIK(L) .GT. 10)  GO TO 807
000610            GO TO 300
000610      329   IF(VARTIK(L) .NE. 0)  GO TO 808
000612      300   CONTINUE
      C
      COMMENT   SET ISS(L) MATRIX. THIS SPECIFES CODE NUMBER FOR SHELL TYPES.
      C
      COMMENT   CROWN          = 1
      COMMENT   CYLINDRICAL    = 2
      COMMENT   SPHEROIDAL     = 3
      COMMENT   PARAHYPOTOIDAL = 4
      COMMENT   ELLIPSOIDAL    = 5
      COMMENT   CONICAL        = 6
      COMMENT   TOROIDAL       = 7
      COMMENT   VARCYLINDER    = 8
      C
000615            IF(KFIT .GT. 0) GO TO 89010
000617            DO 150 L = 1, IHRM
000620            DO 150 I = 1, 8
000621            IF(NAME2(L) .NE. NAMES1(I))  GO TO 150
000624            ISS(L) = I
000625      150   CONTINUE
000632      89010 CONTINUE
      C
      COMMENT   DETERMINE IF CYLINDRICAL SHELL 2 HAS VARTIK(L) .EQ. 0 AND IF
      COMMENT   VARCYLINDER SHELL 8 HAS VARTIK(L) .NE. 0.
      C
000632            DO 994 L = 1, IHRM
000634            ISH = ISS(L)
000636            GO TO (994, 995, 994, 994, 994, 994, 994, 996), ISH
000652      995   IF(VARTIK(L) .NE. 0)  GO TO 808
000654            GO TO 994
000654      996   IF(VARTIK(L) .EQ. 0)  GO TO 807
000656      994   CONTINUE
      C
```

```
C
COMMENT   SET NUMBER 9        ( CARDS = NUMBER OF PARTS )
COMMENT   READ IN A, B, C
C
COMMENT   FOR SPHERE AND SPHERE ONLY SPECIFY A
C
COMMENT   FOR CYLINDER A IS RADIUS, B IS LENGTH
C
COMMENT   FOR CONE A IS RADIUS AT INITIAL, B IS SLANT LENGTH
C
COMMENT   FOR ELLIPSE C .GT. 0.0 INDICATES TORUIDAL SHELL OF ELLIPTICAL CROSS
COMMENT        SECTION PROVIDED A .NE. B.
C
000661          IF(KFIT .GT. 0) GO TO 89020
000663          READ(5,562)  (VN(2,L), VN(3,L), VN(4,L), L = 1, IBRM)
000704    89020 CONTINUE
C
COMMENT   SET NUMBER 10
COMMENT   READ IN YOUNGS MODULUS AND POISSONS RATIO ONLY IF NOT THE SAME FOR
COMMENT   EACH PART.
C
000704          IF(NPLAS .EQ. MARKC)  GO TO 400
000706          IF(KFIT .GT. 0) GO TO 89030
000711          READ(5,564)  (EYM(L), PSR(L), L = 1, IBRM)
001725    89030 CONTINUE
000725          GO TO 402
000726    400   DO 401 L = 1, IBRM
000730          EYM(L) = YOUNG
000732          PSR(L) = POISON
000735    401   CONTINUE
C
COMMENT   SET NUMBER 11
COMMENT   READ IN PRESSURE LOADING, DENSITY OF MATERIAL, AND DEAD WEIGHT ONLY IF
COMMENT   THEY ARE NOT THE SAME FOR EACH PART.
C
000735    402   IF(NPRES .EQ. MARKC)  GO TO 4025
000737          IF(KFIT .GT. 0) GO TO 89040
000742          READ(5,564)  (VN(5,L), VN(6,L), VN(7,L), L = 1, IBRM)
000763    89040 CONTINUE
000763          GO TO 4026
000764    4025  DO 963 L = 1, IBRM
000766          VN(5,L) = PRESS
000771          VN(6,L) = DENSTY
000773          VN(7,L) = DEAD
000776    963   CONTINUE
C
COMMENT   SET NUMBER 12
COMMENT   READ IN VARIABLE THICKNESSES
C
001000    4026  CONTINUE
001000          IF(KFIT .GT. 0) GO TO 89050
001003          DO 403 L = 1, IBRM
001004          IF(VARTIK(L) .EQ. 0)  GO TO 403
001005          NPNT = VARTIK(L)
001007          READ(5,565)  (XP(I,L), I = 1, NPNT)
```

```
001025          READ(5,565)  (YY(I,L), I = 1, NPNT)
001040    459   CONTINUE
001043    4995) CONTINUE
001043          IF(ISS(IMPN) .GT. 1) GO TO 46
001047          NTRY = NPARTS + 1
001050          NERROR = NPARTS - 1
001051          GO TO 47
001051    46    NTRY = NPARTS
001053          NERROR = NPARTS
                C
                COMMENT   SET NUMBER 13
                C
001054       47 IF(PLOT .EQ. 0) GO TO 1238
001055          READ(5,525) (IPLOT(I), I = 1, PLOT)
001070          READ(5,52A) (JUNPLT(I), I = 1, PLOT)
001103    1238  CONTINUE
001103          IA(1) = 1
001104          IA(2) = 3
001105          IA(3) = 5
001106          IA(4) = 7
001107          IB(5) = 1
001110          IB(6) = 3
001111          IB(7) = 5
001112          IB(8) = 7
001113          IF(BOUND1(1) .NE. NAMEH1(1))  IA(1) = 2
001116          IF(BOUND1(2) .NE. NAMEB1(1))  IA(2) = 4
001121          IF(BOUND1(3) .NE. NAMEH1(3))  IA(3) = 6
001124          IF(BOUND1(4) .NE. NAMEB1(1))  IA(4) = 8
001127          IF(BOUNDF(5) .NE. NAMEB1(1))  IB(5) = 2
001132          IF(BOUNDF(6) .NE. NAMEA1(1))  IB(6) = 4
001135          IF(BOUNDF(7) .NE. NAMEH1(3))  IB(7) = 6
001140          IF(BOUNDF(8) .NE. NAMEB1(1))  IB(8) = 8
001143          WRITE(6,543)
001147          WRITE(6,544)
001153          WRITE(6,565)
001157          IF(IA(1) .EQ. 1 .AND. IB(5) .EQ. 1)  GO TO 121
001166          IF(IA(1) .EQ. 1 .AND. IB(5) .EQ. 2)  GO TO 122
001174          IF(IA(1) .EQ. 2 .AND. IB(5) .EQ. 1)  GO TO 123
001203          IF(IA(1) .EQ. 2 .AND. IB(5) .EQ. 2)  GO TO 124
001211    121   WRITE(6,551)   GA(1), GB(5)
001221          GO TO 125
001222    122   WRITE(6,542)   GA(1), GB(5)
001232          GO TO 125
001233    123   WRITE(6,543)   GA(1), GB(5)
001243          GO TO 125
001244    124   WRITE(6,544)   GA(1), GB(5)
001254    125   IF(IA(2) .EQ. 3 .AND. IB(6) .EQ. 3)  GO TO 126
001263          IF(IA(2) .EQ. 3 .AND. IB(6) .EQ. 4)  GO TO 127
001271          IF(IA(2) .EQ. 4 .AND. IB(6) .EQ. 3)  GO TO 128
001300          IF(IA(2) .EQ. 4 .AND. IB(6) .EQ. 4)  GO TO 129
001306    126   WRITE(6,551)   GA(2), GB(6)
001316          GO TO 130
001317    127   WRITE(6,542)   GA(2), GB(6)
001327          GO TO 130
001330    128   WRITE(6,553)   GA(2), GB(6)
```

```
001340          GO TO 130
001341    129   WRITE(6,546)   GA(2), GB(6)
001351    130   IF(IA(3) .EQ. 5 .AND. IB(7) .EQ. 5)  GO TO 131
001360          IF(IA(3) .EQ. 5 .AND. IB(7) .EQ. 6)  GO TO 132
001366          IF(IA(3) .EQ. 6 .AND. IB(7) .EQ. 5)  GO TO 133
001375          IF(IA(3) .EQ. 6 .AND. IB(7) .EQ. 6)  GO TO 134
001404    131   WRITE(6,555)   GA(3), GB(7)
001413          GO TO 135
001414    132   WRITE(6,546)   GA(3), GB(7)
001424          GO TO 135
001425    133   WRITE(6,547)   GA(3), GB(7)
001435          GO TO 135
001436    134   WRITE(6,548)   GA(3), GB(7)
001446    135   IF(NDE .EQ. 4)  GO TO 140
001450          IF(IA(4) .EQ. 7 .AND. IB(8) .EQ. 7)  GO TO 136
001457          IF(IA(4) .EQ. 7 .AND. IB(8) .EQ. 8)  GO TO 137
001465          IF(IA(4) .EQ. 8 .AND. IB(8) .EQ. 7)  GO TO 138
001474          IF(IA(4) .EQ. 8 .AND. IB(8) .EQ. 8)  GO TO 139
001504    136   WRITE(6,541)   GA(4), GB(8)
001514          GO TO 140
001513    137   WRITE(6,542)   GA(4), GB(8)
001523          GO TO 140
001524    138   WRITE(6,543)   GA(4), GB(8)
001534          GO TO 140
001535    139   WRITE(6,544)   GA(4), GB(8)
001545    140   WRITE(6,549)   ALAL, ALAN
001555          IF(NUE .EQ. 8)  GO TO 100
001557          IN(4) = IA(5)
001561          IN(5) = IA(6)
001562          IN(6) = IA(7)
001563          GA(4) = GA(5)
001564          GA(5) = GA(6)
001565          GA(6) = GA(7)
001566    100   NM = NUE/2
              C
              COMMENT   THIS LOOP SETS UP IA(4), IA(5), IA(6) FOR NDE = 6 AND
              COMMENT   IA(5), IA(6), IA(7), IA(8) FOR NDE = 8.
              C
001570          M = NM + 1
001574          L = 1
001573          DO 104 IK = M, NDE
001575          DO 102 N = L, NDE
001577          DO 101 J = 1, NM
001600          IF(IA(J) .EQ. N)  GO TO 102
001602    101   CONTINUE
001604          GO TO 103
001605    102   CONTINUE
001610    103   L = N + 1
001612          IA(IK) = N
001614    104   CONTINUE
              C
              COMMENT   THIS LOOP SETS UP IB(4), IB(5), IB(6) FOR NDE = 6 AND
              COMMENT   IB(5), IB(6), IB(7), IB(8) FOR NDE = 8.
              C
001616          L = 1
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001417          DO 104 IN = 1, NN
001421          DO 106 N = L, NDF
001423          DO 105 J = M, NDF
001425          IF(IN(J) .EQ. N)  GO TO 106
001427   105    CONTINUE
001431          GO TO 107
001433   106    CONTINUE
001435   107    L = N + 1
001437          IA(IN) = N
001441   108    CONTINUE
               C
               COMMENT   IF ELASTIC PARAMETERS ARE SAME FOR EACH PART, THEN WRITE THEM RIGHT
               COMMENT         UNDER BOUNDARY DATA. IF THEY ARE NOT THE SAME FOR EACH PART,
               COMMENT         THEN SKIP TO NEXT PAGE & WRITE GEOMETRY, SKIP PAGE, WRITE
               COMMENT         ELASTIC PARAMETERS, SKIP PAGE, WRITE VARIABLE THICKNESSES.
               C
001603          IF(NELAS .EQ. MARKD)  GO TO 475
001645          WRITE(6,575)    YOUNG, POISON
001655   475    IF(NPRES .EQ. MARKD)  GO TO 4755
001657          WRITE(6,602)  PRESS, DENSTY, DEAD
001671   4755   DO 478 II = 1, 2
001673          IF(II .EQ. 1)  GO TO 476
001675          IF(IMAX .LT. 41)  GO TO 479
001677   476    NTIME = 2
001700          GO TO 350
001701   350    WRITE(6,513)
001705          WRITE(6,514)
001711          GO TO (3504, 3504), II
001717   3504   IMIN = 1
001720          IMAX = IBAN
001722          IF(IBAN .GT. 40)  IMAX = 40
001725          GO TO 3507
001726   3506   IMIN = 41
001727          IMAX = IBAN
001731   3507   DO 385 L = IMIN, IMAX
001733          ISH = ISS(L)
001735          GO TO (881, 882, 881, 883, 884, 882, 883, 882), ISH
001751   881    IF(VARTIK(L) .EQ. 0)  GO TO 8815
001753          WRITE(6,776) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITD(1), UNITD(2), VN(2,L), MARKN
002003          GO TO 385
002004   8815   WRITE(6,777) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITD(1), UNITD(2), VN(2,L), MARKY, VN(1,L)
002041          GO TO 385
002042   882    IF(VARTIK(L) .EQ. 0)  GO TO 8825
002044          WRITE(6,778) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L),
              *                UNITD(1), UNITD(2), VN(2,L), VN(3,L), MARKN
002076          GO TO 385
002077   8825   WRITE(6,779) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L),
              *                UNITD(1), UNITD(2), VN(2,L), VN(3,L), MARKY, VN(1,L)
002135          GO TO 385
002136   883    IF(VARTIK(L) .EQ. 0)  GO TO 8835
002140          WRITE(6,780) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITD(1), UNITD(2), VN(2,L), VN(3,L), MARKN
002174          GO TO 385
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002173   8835  WRITE(6,7831) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITU(1), UNITU(2), VN(2,L), VN(3,L), MANKY, VN(1,L)
002235         GO TO 385
002236   884   IF(VARTIK(L) .EQ. 0)  GO TO 8845
002240         WRITE(6,7832) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITU(1), UNITU(2), VN(2,L), VN(3,L), VN(4,L),
              *                MANKY
002277         GO TO 385
002300   8845  WRITE(6,7833) L, NAMES1(ISH), NAMES2(ISH), IPAR(L), SI(L), SX(L),
              *                UNITD(1), UNITU(2), VN(2,L), VN(3,L), VN(4,L),
              *                MANKY, VN(L,1)
002342   385   CONTINUE
002345   478   CONTINUE
002347    479  CONTINUE
         C
         COMMENT   DETERMINE IF SHELL PARTS ARE CONTINUOUS.
         C
002347         NTIME=0
002350         L=0
002351       3 L=L+1
002353         IF(L.GT.IARM) GO TO 13
002356         ISH=ISS(L)
002357         ALFAI = SI(L)*RPD
002361         ALFAF = SX(L)*RPD
002362         A = VN(2,L)
002365         B = VN(3,L)
002367         GO TO (3, 4, 5, 6, 7, 8, 9, 4), ISH
002403       4 RI = A
002405         RF = RI
002406         GO TO 10
002406       5 RI = A*SIN(ALFAI)
002412         RF = A*SIN(ALFAF)
002415         GO TO 10
002415       6 RI = A
002417         RF = A*TAN(ALFAF)/TAN(ALFAI)
002425         GO TO 10
002425       7 DO 75 I = 1, 2
002427         IF(I .EQ. 2)  GO TO 76
002431         SXN = SIN(ALFAI)
002433         GO TO 77
002433      76 SXN = SIN(ALFAF)
002436      77 R = VN(4,L) + B*SXN/((A/B)**2 + (1.0 - (A/B)**2)*SXN*SXN)
002451         IF(I .EQ. 2)  GO TO 78
002453         RI = R
002455         GO TO 75
002455      78 RF = R
002457      75 CONTINUE
002461         GO TO 10
002462       8 RI = A
002464         RF = A + B*COS(ALFAI)
002470         GO TO 10
002471       9 RI = A + B*SIN(ALFAI)
002476         RF = A + B*SIN(ALFAF)
002503      10 IF (NTIME.EQ.1) GO TO 11
002505         RI1=RI
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002507            RF1=RF
002510            ATIME=1
002511            GO TO 3
002512         11 RI2=RI
002514            RF2=RF
002515            IF(ABS(RF1 - RI2) .GT. 0.0025)  GO TO 812
002523            RF1=RF2
002524            RI1=RI2
002524            GO TO 3
002525         13 CONTINUE
002525            IF(NELAS .EQ. MARKC)GO TO 488
002527            DO 442 II = 1, 2
002531            IF(II .EQ. 1)  GO TO 483
002533            IF(IARR .LT. 41)  GO TO 488
002535   483      NTIME = 3
002536            GO TO 350
002537   364      WRITE(6,568)
002543            WRITE(4,577)
002547            GO TO (3648, 3649), II
002555   3648     IMIN = 1
002556            IMAX = IARR
002560            IF(IARR .GT. 40)  IMAX = 40
002563            GO TO 3618
002564   3649     IMIN = 41
002565            IMAX = IARR
002567   3618     DO 386 L = IMIN, IMAX
002571            ISM = ISS(L)
002573            WRITE(6,576)  L, NAMES1(ISM), NAMES2(ISM), EVN(L), PSR(L)
002610   386      CONTINUE
002613   482      CONTINUE
002615   488      IF(NPRES .EQ. MARKC)  GO TO 4885
002617            DO 1782 II = 1, 2
002621            IF(II .EQ. 1)  GO TO 1783
002623            IF(IARR .LT. 41)  GO TO 4885
002625   1783     NTIME = 4
002626            GO TO 350
002627   379      WRITE(6,683)
002633            WRITE(4,684)
002637            GO TO (7838, 7831), II
002645   7838     IMIN = 1
002646            IMAX = IARR
002650            IF(IARR .GT. 40)  IMAX = 40
002653            GO TO 7832
002654   7831     IMIN = 41
002655            IMAX = IARR
002657   7832     DO 786 L = IMIN, IMAX
002661            ISM = ISS(L)
002663            WRITE(6,685)  L, NAMES1(ISM), NAMES2(ISM), (VN(I,L), I = 5, 7)
002703     786    CONTINUE
002706   1782     CONTINUE
         C
         COMMENT   PUT YP(1,L) IN VA(1,L)
         C
002710   4885     DO 955 L = 1, IARR
002712            IF(VARFIX(L) .EQ. 0)  GO TO 950
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002713          VN(I,L) = VP(I,L)
002717    950   CONTINUE
              C
              COMMENT   NVARC = INDICATES NO VARIABLE THICKNESS
              C
002722          NVARC = 0
002723          DO 974 L = 1, IBHM
002724          NVARC = NVARC + VARTIK(L)
002726    974   CONTINUE
002730          IF(NVARC .EQ. 0)  GO TO 48600
              C
              COMMENT   WRITE OUT VARIABLE THICKNESS DATA
              C
002731          NTIME = 5
002732          GO TO 350
002732    975   WRITE(6,976)
002736          DO 975 L = 1, IBHM
002740          NPNT = VARTIK(L)
002742          IF(NPNT .EQ. 0)  GO TO 975
002743          WRITE(6,977)  L
002750          WRITE(6,978) (XP(I,L), I = 1, NPNT)
002765          WRITE(6,979) (YP(I,L), I = 1, NPNT)
003002          WRITE(6,980)
003006    975   CONTINUE
003011    48600 IF(KFIT .EQ. 0) GO TO 48500
003012          PUNCH 500,TITLE1
003020          PUNCH 500,TITLE2
003026          PUNCH 500,TITLE3
003034          DO 86051 I=1,4
003036          L1(I) = 0
003037          IF(GA(I) .NE. 0.0)L1(I)=ALOG10(ABS(GA(I)))
003047          L1(I) = 6-L1(I)
003052          IF(L1(I) .GT. 6) L1(I) = 6
003056          IF(GA(I) .LT. 0.0)L1(I)=L1(I)+1
003062          IF(L1(I) .LT. 0) L1(I) = 0
003065    86051 CONTINUE
003067          K1 = L1(1)
003071          K2 = L1(2)
003072          K3 = L1(3)
003074          K4 = L1(4)
003075          ENCODE(56,53000,IFMT) K1,K2,K3,K4
003113          PUNCH IFMT, (GAMMA(I),GA(I),I=1,4)
003127          DO 86052 I=5,8
003131          L1(I) = 0
003132          IF(GB(I) .NE. 0.0)L1(I)=ALOG10(ABS(GB(I)))
003142          L1(I) = 6-L1(I)
003145          IF(L1(I) .GT. 6) L1(I) = 6
003151          IF(GB(I) .LT. 0.0)L1(I)=L1(I)+1
003155          IF(L1(I) .LT. 0) L1(I) = 0
003160    86052 CONTINUE
003162          K1 = L1(5)
003164          K2 = L1(6)
003165          K3 = L1(7)
003167          K4 = L1(8)
003170          ENCODE(56,53000,IFMT) K1,K2,K3,K4
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003206          PUNCH IFMT,(HONNOF(I),GH(I),I=5,8)
003222   53000 FORMAT(12H(A6, 6X, F8..I1,13H, A6, 6X, F8..I1,13H, A6, 6X, F8..I1,
               *13H, A6, 6X, F8..I1,1H))
003222          PUNCH 565,ALEL,ALER
003232          PUNCH 561,INMM,ITER,ADUMMY,PLOT,INTPRN,INTVAL,LEVEL1,LEVEL2,ENP,
               *CONVER,NNMMAN, (MMMUMA(I), I=1,8)
003272          PUNCH 563,NELAS,YOUNG,POISON
003304          PUNCH 886,NPHES,HHESS,DENSTY,HEAD
003320          DO 86099 L=1,INMM
003322          K=ISS(L)
003324          PUNCH 876,NAMES1(K),NAMES2(K),SI(L),SX(L),IPAR(L),INT(L),
               * TDIST(L),VM(1,L),VARTIK(L)
003352   86099 CONTINUE
003355          PUNCH 562,(VN(2,L),VN(3,L),L=1,INMM)
003373          IF(NELAS .EQ. MARKC) GO TO 86000
003375          PUNCH 566,(FVM(L), PSN(L) ,L=1,INMM)
003412   86000 IF(NPHES .EQ. MARKC) GO TO 87000
003414          PUNCH 566,(VN(5,L), VN(6,L),VN(7,L),L=1,INMM)
003430   87000 CONTINUE
003430          DO 86001 L=1,INMM
003440          IF(TDIST(L) .EQ. MARKC) GO TO 86001
003442          NPNT = VARTIK(L)
003444          PUNCH 565,(XP(I,L),I=1,NPNT)
003460          PUNCH 565,(YP(I,L),I=1,NPNT)
003475   86001 CONTINUE
003500   88003 CONTINUE
         C
         COMMENT   FOLLOWING REPLACEMENTS MUST BE MADE TO MAKE ARRAYS COMPATIBLE FOR USE
         COMMENT   IN GOMTRY
         C
003500   970    DO 955 L = 1, INMM
003502          ISM = ISS(L)
003504          GO TO (955, 953, 955, 955, 955, 954, 955, 953), ISM
003520   953    SX(L) = VN(3,L)
003523          VN(3,L) = SI(L)
003526          SI(L) =  0.0
003527          GO TO 955
003527   954    SX(L) = VN(3,L)
003532          VN(3,L) = VN(2,L)
003536          VN(2,L) = SI(L)
003540          SI(L) = 0.0
003541   955    CONTINUE
         C
         COMMENT   CHANGE XP(I,L) TO RADIANS AND ADJUST IF FINAL COORDINATE IS
         COMMENT          LESS THAN INITIAL COORDINATE
         C
003544          DO 404 L = 1, INMM
003545          IF(VARTIK(L) .EQ. 0)  GO TO 404
003546          NPNT = VARTIK(L)
003550          ISM  = ISS(L)
003551          GO TO (404, 404, 2505, 2505, 2505, 404, 2505, 404), ISM
003564   2505   IF(XP(NPNT,L) .GT. XP(1,L))  GO TO 2605
003574          DO 255 I = 1, NPNT
003575          XP(I,L) = 180.0 - XP(I,L)
003602   255    CONTINUE
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004005   544   FORMAT(8X, E11.4, 4X, F8.4)
004005     446 FORMAT(5X, 3F15.5)
004005   525   FORMAT(1H1)
004005   524   FORMAT(1HA8)
004005   549   FORMAT(    ///// 49X, 34H0 * *  PRINTOUT OF INPUT DATA  * * *///// )
004005   554   FORMAT(1H0, 57X, 19H0  BOUNDARY DATA  * /// )
004005   546   FORMAT(1H , 94X, 12HINITIAL EDGE, 30X, 10HFINAL EDGE, / )
004005   551   FORMAT(1H , 27X, 15HDISPLACEMENT = F10.5,
                      20X, 15HDISPLACEMENT = F10.5)
004005   552   FORMAT(1H , 27X, 15HDISPLACEMENT = F10.5,
                      20X, 15H       FORCE = F10.5)
004005   553   FORMAT(1H , 27X, 15H       FORCE = F10.5,
                      20X, 15HDISPLACEMENT = F10.5)
004005   554   FORMAT(1H , 27X, 15H       FORCE = F10.5,
                      20X, 15H       FORCE = F10.5)
004005   555   FORMAT(1H , 27X, 15H       SLOPE = F10.5,
                      20X, 15H       SLOPE = F10.5)
004005   556   FORMAT(1H , 27X, 15H       SLOPE = F10.5,
                      20X, 15H      MOMENT = F10.5)
004005   557   FORMAT(1H , 27X, 15H      MOMENT = F10.5,
                      20X, 15H    ROTATION = F10.5)
004005   558   FORMAT(1H , 27X, 15H      MOMENT = F10.5,
                      20X, 15H      MOMENT = F10.5)
004005   559   FORMAT(1H0, 25X, 17HBOUNDARY ANGLE = F10.5,
                      10X, 17HBOUNDARY ANGLE = F10.5)
004005   575   FORMAT(1H0, /// 24X, 42HELASTIC PARAMETERS ARE THE SAME FOR EVERY
                      36HPART IN THIS SHELL. THEIR VALUES ARE , /
             1H ,     38X, 16HYOUNGS MODULUS = E12.5,
                       1X, 22HPOUNDS PER SQUARE INCH,  /
             1H ,     38X, 16HPOISSONS RATIO = F8.5)
004005   482   FORMAT(1H0, ///  24X, 42HLOADING PARAMETERS ARE THE SAME FOR EVERY
                       ,   36HPART IN THIS SHELL. THEIR VALUES ARE , /
             1H , 38X, 11HPRESSURE = F11.5,
                       1X, 22HPOUNDS PER SQUARE INCH,  /
             1H ,      38X, 25HUNIT WEIGHT OF MATERIAL = F11.5,
                       1X, 21HPOUNDS PER CUBIC INCH  /
             1H , 38X, 13HHEAD WEIGHT = F11.5,
                       1X, 22HPOUNDS PER SQUARE INCH)
004005   513   FORMAT(//// 42X, 14H0  GEOMETRY  * ///,
             1H , 25X, 6HNO. OF, 10X, 21HC O O R D I N A T E S, 40X,
             17HTHICKNESS, INCHES)
004005   514   FORMAT(1H , 5X,
                      4HPART, 6X, 4HTYPE, 5X, 8HSEGMENTS, 4X, 7HINITIAL, 54X,
                      5HFINAL, 4X, 10HDIMENSIONS, 3X, 8HA,INCHES, 5X,
                      8HB,INCHES, 5X, 8HC,INCHES, 4X, 17HCONSTANT    VALUE)
004005   774   FORMAT(1H , I8, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1,  F13.5,
                       32X, A3                 )
004005   777   FORMAT(1H , I8, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1,  F13.5,
                       32X, A3, F13.5  )
004005   778   FORMAT(1H , I8, 3X, 2A6, I5, 4X,  F12.5,14X, A6, A1, 2F13.5,
                       19X, A3                 )
004005   779   FORMAT(1H , I8, 3X, 2A6, I5, 4X,  F12.5,14X, A6, A1, 2F13.5,
                       19X, A3, F13.5 )
004005   780   FORMAT(1H , I8, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1, 2F13.5,
                       19X, A3                 )
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004005    781   FORMAT(1H , 1H, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1, 2F13.5,
     *                     19X, A3, F13.5 )
004005    782   FORMAT(1H , 18, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1, 2F13.5,
     *                     F13.5, 6X, A3      )
004005    783   FORMAT(1H , 1H, 3X, 2A6, I5, 4X, 2F12.5, 2X, A6, A1, 2F13.5,
     *                     F13.5, 6X, A3, F13.5 )
004005    500   FORMAT(/////, 50X, 16H*  PROPERTIES  * ///,
     *       1H , 44X, 43HE = YOUNG'S MODULUS (POUNDS PER SQUARE INCH), /
     *       1H , 44X, 19HNU = POISSONS RATIO   / )
004005    577   FORMAT(1H , 44X, 4HPART, 6X, 4HTYPE, 13X, 1HE, 12X, 2HNU)
004005    574   FORMAT(1H , 45X, I2, 3X, 2A6, 3X, E12.5, 3X, F8.5)
004005    600   FORMAT(/////, 57X, 16H*   LOADINGS   *///,
     *       1H , 46X, 39HP = PRESSURE (POUNDS PER SQUARE INCH)   */
     *       1H , 44X, 39HW = UNIT WEIGHT (POUNDS PER CUBIC INCH) */
     *       1H , 46X, 40HD = DEAD WEIGHT (POUNDS PER SQUARE INCH)  )
004005    494   FORMAT(1H0, 34X, 4HPART, 6X, 4HTYPE, 13X, 1HP, 13X, 1HW, 13X, 1HD)
004005    495   FORMAT(1H , 35X, I2, 3X, 2A6, 3F14.5)
004005    484   FORMAT(/////, 50X, 22H* VARIABLE THICKNESS * ///)
004005    687   FORMAT(1H , 4HPART I3)
004005    688   FORMAT(1H , 10HCOORDINATE 10F12.5)
004005    489   FORMAT(1H , 10HTHICKNESS  10F12.5)
004005    690   FORMAT(1H )
004005    670   FORMAT(1H0, 39HSPELLING ON BOUNDARY CARD IS INCORRECT.)
004005    671   FORMAT(1H0, 17HSPELLING OF PART I2, 14H IS INCORRECT.)
004005    644   FORMAT(1H0, 50HNUMBER OF PARTS IS EITHER ZERO OR GREATER THAN 60.)
004005    664   FORMAT(1H0, 30HNUMBER OF PLOTS REQUESTED WAS I4,
     *                     26H. ONLY 10 CAN BE OBTAINED.)
004005    672   FORMAT(1H0, 44HSPELLING OF YES OR NO IS INCORRECT FOR PART I2.1H.)
004005    663   FORMAT(1H0, 37HNUMBER OF PRINT POINTS REQUESTED WAS I5,
     *                     34H. ONLY 300 POINTS CAN BE OBTAINED.)
004005    665   FORMAT(1H0, 22HNUMBER OF SEGMENTS IS I3,
     *                     35H. ONLY 60 SEGMENTS CAN BE ANALYZED.)
004005    673   FORMAT(1H0,  5HPART I2, 24H HAS VARIABLE THICKNESS,
     *                     29HNUMBER OF POINTS READ IN WAS I3,
     *                     48H. THIS CANNOT BE LESS THAN 2 OR GREATER THAN 10.)
004005    674   FORMAT(1H0,  5HPART I2, 24H HAS CONSTANT THICKNESS,
     *                     29HNUMBER OF POINTS READ IN WAS I3,
     *                     19H. THIS SHOULD BE 0.)
004005    675   FORMAT(1H0, 45HSPELLING INCORRECT ON ELASTIC PARAMETER CARD.)
004005    676   FORMAT(1H0, 44HSPELLING INCORRECT ON DISTRIBUTED LOAD CARD.)
004005    677   FORMAT(1H0, 34HSPELLING INCORRECT ON CONTROL CARD.)
004005      601 FORMAT(1H0, 35HTWO SHELL PARTS ARE NOT CONTINUOUS.
     $                     47H CHECK INITIAL AND FINAL COORDINATES AND RADII
     $                     9HFOR PART I2, 19H AND PREVIOUS PART.)
004005    660   FORMAT(1H0, 33HPROCESSING OF INPUT DATA STOPPED.)
004005      876 FORMAT(4X,2A6,F11.5,F12.5,2I5,2X,A2,1X,F10.5,I5)
004005    999   CALL EXIT
004006          END
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              SUBROUTINE FIT (VN,IPAR,SI,SX,ISS,INT,VARTIK,TDIST,XP,YP,ETM,PSR,I
             1NRM,NPRES,NFLAS,TITLE1,TITLE2,TITLE3)
000025        DIMENSION        INT(60)        , VARTIK(60)     , TDIST(60)     ,
             1                 XP(10,60)      , YP(10,60)      , ETM(40)       ,
             2                 YMOD(10)       , PRAT(10)       , JFLAS(60)     ,
             3                 JPRES(10)      , PRES(10)       , DFD(10)       ,
             4                 DFNS(10)       , FP(4)          , ZT(20)        ,
             5                 WT(20)         , IFIT(9)        , XTRY(9)       , PSR(40)       ,
             6                 XTHICK(400)    , XTRY(9)        , YTRY(9)       ,
             7                 RSTFIT(9)      , LPC(3)         , LPH(3)        ,
             8                 TITLE1(20)     , TITLE2(20)     , TITLF3(20)    ,
             9                 KPOINT(62)     , A(3,3)         , R(3)          ,
             $                 LTEMP(3)       , IPAR(60)       , X(400)        ,
             $                 Y(400)         , IV(20)         , IPNT(400)     ,
             $                 ITYPE(60)      , ISI(62)        , ISF(62)       ,
             $                 UNITD(2)       , VN(7,60)       , SI(60)        ,
             $                 SX(60)         , ISS(60)        , NAMES1(8)     ,
             $                 NAMES2(8)      , XX(400)        , YY(400)       ,
             $                 XO(400)        , YO(400)        , ITITLE(10)
000025        DATA      ( MARKC = 2HYE ), ( MARKD = 2HNO )
000025        DATA      ( RPD = 0.1745329252E-01 ), ( DPR = 57.29577951 )
000025        DATA      ( PI = 3.14159265 )
000025        REAL NI,NP
000025        INTEGER VARTIK,TDIST,XRFLCT,YRFLCT, TITLE1, TITLE2, TITLE3
        C
        COMMENT   INPUT OF DATA
        C
000025        READ (5,2430) NPTS,NV,ITNT
000036        READ (5,2440) EPS1,XTRANS,YTRANS,XRFLCT,YRFLCT
000054        READ (5,2450) X1,Y1,T1,PR,YM,PRS,DW,DNS
000100        X(1)=X1
000102        Y(1)=Y1
000103        XTHICK(1)=T1
000105        JFLAS(1)=1
000106        YMOD(1)=YM
000107        PRAT(1)=PR
000111        JPRES(1)=1
000112        PRES(1)=PRS
000113        DFD(1)=DW
000115        DFNS(1)=DNS
000116        L=2
000117        K=2
000120        DO 40 I=2,NPTS
000125        READ (5,2450) X1,Y1,T1,PR,YM,PRS,DW,DNS
000150        X(I)=X1
000152        Y(I)=Y1
000154        XTHICK(I)=XTHICK(I-1)
000156        IF (T1.NE.0.0) XTHICK(I)=T1
000163        IF (NFLAS.EQ.MARKC) GO TO 20
000166        IF (PR.EQ.0.0) GO TO 20
000167        JFLAS(L)=I
000171        YMOD(L)=YM
000172        PRAT(L)=PR
000173        L=L+1
```

```
003600   265   DO 265 I = 1, NPNT
003600         XP(I,L) = XP(I,L)*RAD
003613   265   CONTINUE
003615   404   CONTINUE
003620         DO 405 L = 1, IMAX
003621         IF(VARTIK(L) .EQ. 0)  GO TO 405
003622         NPNT = VARTIK(L)
003625         DO 384 I = 2, NPNT
003625         SL(I - 1,L) = (YP(I,L) - YP(I - 1,L))/
     *                       (XP(I,L) - XP(I - 1,L))
003640         YP(I - 1,L) = YP(I - 1,L) - SL(I - 1,L)*XP(I - 1,L)
003647   384   CONTINUE
003651   405   CONTINUE
003654         GO TO 999
003654   800   WRITE(6,670)
003660         GO TO 9000
003661   801   WRITE(6,671)  L
003667         GO TO 9000
003670   802   WRITE(6,646)
003674         GO TO 9000
003675   803   WRITE(6,644)  PLOT
003703         GO TO 9000
003704   804   WRITE(6,672)  L
003712         GO TO 9000
003713   805   WRITE(6,663)  PLOTPT
003721         GO TO 9000
003722   806   WRITE(6,665)  NPARTS
003730         GO TO 9000
003731   807   WRITE(6,673)  L, VARTIK(L)
003741         GO TO 9000
003742   808   WRITE(6,674)  L, VARTIK(L)
003752         GO TO 9000
003753   809   WRITE(6,675)
003757         GO TO 9000
003760   810   WRITE(6,676)
003764         GO TO 9000
003765   811   WRITE(6,677)
003771         GO TO 9000
003772   812   WRITE(6,641)  L
004000   9000  WRITE(6,649)
004004         GO TO 998
004005   500   FORMAT(20A4)
004005   534   FORMAT(1H1, ////////////////////54X, 27HBATTELLE MEMORIAL INSTITUTE)
004005   535   FORMAT(//40X, 14HCOLUMBUS, OHIO)
004005   536   FORMAT(// 47X, 44HSTRESS ANALYSIS OF A SHELL OF REVOLUTION)
004005   537   FORMAT(// 50X, 33HADVANCED SOLID MECHANICS DIVISION)
004005   538   FORMAT(// 50X, 33HMECHANICAL ENGINEERING DEPARTMENT)
004005   501   FORMAT(1H1, 20A4/(1H0, 20A4))
004005   502   FORMAT(A6, 4X, F9.2, A6, 6X, F8.2, A6, 6X, F8.2, A6, 6X, F8.2)
004005   504   FORMAT(8F10.6)
004005   541   FORMAT(8I5, 2E10.3, 10I2)
004005   549   FORMAT(2X, A2, 4X, E11.4, 4X, F6.4)
004005   481   FORMAT(2X, A2, 4X, 3F14.5)
004005   517   FORMAT(4X, A4, 6X, F11.5, F12.5, 2I5, 2X, A2, 1X, F10.5, I9)
004005   542   FORMAT(3X, 2F12.5)
```

```
000175    20    CONTINUE                                                  275
000175          IF (NPRES.EQ.MARKC) GO TO 30                              280
000200          IFST=PWS+PW+NWS                                           285
000203          IF (A4>(IFST).L  .),AE-12) GO TO 30                       290
000204          JPRFS(K)=I                                                295
000210          PRES(K)=PWS                                               300
000211          NFO(K)=DW                                                 305
000213          NFWS(K)=JWS                                               310
000214          K=K+1                                                     315
000216    30    CONTINUE                                                  320
000216    40    CONTINUE                                                  325
000221          WRITE (6,2440)                                            330
000224          WRITE (6,2470) (I,X(I),Y(I),I=1,NPTS)                     335
000242          KELAS=L-1                                                 340
000244          KPRES=K-1                                                 345
000246          READ (5,2480) (IV(I+1),I=1,NV)                            350
000260          IV(1)=1                                                   355
000261          IV(NV+2)=NPTS                                             360
000263          NV=NV+2                                                   365
000265          IF (XREFLCT.EQ.MARKD) GO TO 60                            370
000272          DO 50 I=1,NPTS                                            375
000274          Y(I)=-Y(I)                                                380
000276    50    CONTINUE                                                  385
000300    60    IF (YREFLCT.EQ.MARKD) GO TO 80                            390
000302          DO 70 I=1,NPTS                                            395
000304          X(I)=-X(I).                                               400
000306    70    CONTINUE                                                  405
000310    80    CONTINUE                                                  410
000310          IF (NELAS.EQ.MARKC) GO TO 110                             415
000313          DO 100 J=1,KELAS                                          420
000314          IFLAG=1                                                   425
000315          DO 90 L=1,NV                                              430
000317          IF (IV(L).NE.JELAS(J)) GO TO 90                           435
000322          IFLAG=2                                                   440
000323    90    CONTINUE                                                  445
000326          IF (IFLAG.EQ.2) GO TO 100                                 450
000330          CALL EXIT0 (12,J)                                         455
000332          GO TO 2420                                                460
000336    100   CONTINUE                                                  465
000341    110   CONTINUE                                                  470
000341          IF (NPRES.EQ.MARKC) GO TO 140                             475
000344          DO 130 J=1,KPRES                                          480
000345          IFLAG=1                                                   485
000346          DO 120 L=1,NV                                             490
000350          IF (IV(L).NE.JPRES(J)) GO TO 120                          495
000353          IFLAG=2                                                   500
000354    120   CONTINUE                                                  505
000357          IF (IFLAG.EQ.2) GO TO 130                                 510
000361          CALL EXIT0 (13,J)                                         515
000363          GO TO 2420                                                520
000367    130   CONTINUE                                                  525
000372    140   CONTINUE                                                  530
          C                                                             535
          COMMENT   PRINT OF INPUT                                      540
          C                                                             545
```

```
000374          NV2=NV-2                                                        550
000374          EPSL=EPSI                                                       555
000376          H=.01                                                           560
000377          ITEST=2                                                         565
000400          NPTS=NPTS                                                       570
000406          WRITE (6,2400) TITLE1,TITLE2,TITLE3                             575
000416          WRITE (6,2500) NPTS,NV2,EPSI                                    580
000430          WRITE (6,2510)                                                  585
000434          DO 190 I=1,NPTS                                                 590
000441          X(I)=X(I)+XTRANS                                                595
000446          Y(I)=Y(I)+YTRANS                                                600
000446          IF (X(I).GE.0.0) GO TO 150                                      605
000447          CALL EXITO (0,I)                                                610
000451          GO TO 2420                                                      615
000455    150   CONTINUE                                                        620
          C                                                                     625
          COMMENT   STORE XY VALUES FOR LATER PLOT                            630
          C                                                                     635
000455          XO(I)=X(I)                                                      640
000460    *     YO(I)=Y(I)                                                      645
000462          IF (I.EQ.NPTS) GO TO 180                                        650
000463          K=IV(ITEST)                                                     655
000465          IF (K-I) 160,170,180                                            660
000467    160   WRITE (6,2520) K                                                665
000475          CALL EXIT                                                       670
000476    170   WRITE (6,2530) I,X(I),Y(I),XTHICK(I)                            675
000512          ITEST=ITEST+1                                                   680
000514          GO TO 190                                                       685
000520    180   WRITE (6,2540) I,X(I),Y(I),XTHICK(I)                            690
000534    190   CONTINUE                                                        695
000542          XMIN=X(1)                                                       700
000544          DO 200 I=2,NPTS                                                 705
000545          IF (X(I).LT.XMIN) XMIN=X(I)                                     710
000552    200   CONTINUE                                                        715
000555          XTRANS=XMIN-.01                                                 720
000557          DO 210 I=1,NPTS                                                 725
000560          XO(I)=XO(I)-XTRANS                                              730
000563    210   CONTINUE                                                        735
000565          WRITE (6,2400) TITLE1,TITLE2,TITLE3                             740
          C                                                                     745
          COMMENT   COMPUTE THE DIRECTION OF ROTATION OF THE TANGENT FOR      750
          COMMENT   CONSECUTIVE TRIPLES OF POINTS                             755
          C                                                                     760
          C          IPHI(I) DESIGNATES ROTATION DIRECTION AS FOLLOWS         765
          C                                                                     770
          C               IPHI(I) = 1    CLOCKWISE                            775
          C               IPHI(I) = 2    COUNTER-CLOCKWISE                    780
          C               IPHI(I) = 3    NO ROTATION  ( STRAIGHT LINE )       785
          C               IPHI(I) = 4    (X(I+1),Y(I+1)) IS A VERTEX          790
000601          NBR=1                                                           795
000602          L1=1                                                            800
000603          DO 420 L=2,NV                                                   805
000610          L2=IV(L)-2                                                      810
000613          DX1=X(L1+1)-X(L1)                                               815
                                                                                820
```

```
000410          DY1=Y(L1+1)-Y(L1)                                                   825
000420          DO 410 I=L1,L2                                                      830
000424          DX2=X(I+2)-X(I+1)                                                   835
000428          DY2=Y(I+2)-Y(I+1)                                                   840
000427          IF (ABS(DX1).LT.1.0E-05) 220,210                                    845
000430    220   IF (ABS(DX2).LT.1.0E-05) 230,240                                    850
000440    230   IF (DY1.LT.0.0) 250,270                                             855
000447    240   IF (DY2.LT.0.0) 250,260                                             860
000450    250   P=3.0                                                               865
000454          GO TO 340                                                           870
000455    260   CALL EXITD (1,I)                                                    875
000457          GO TO 2420                                                          880
000460    270   IF (DY2.GT.0.0) 250,280                                             885
000470    280   IF (ABS(DY2).LT.1.0E-05) 290,300                                    890
000476    290   CALL EXITD (2,I)                                                    895
000500          GO TO 2420                                                          900
000504    300   P=-DX2/DY2                                                          905
000506          GO TO 344                                                           910
000507    310   M1=DY1/DX1                                                          915
000511          IF (ABS(DX2).LT.1.0E-05) 320,340                                    920
000517    320   IF (ABS(DY1).LT.1.0E-05) 290,330                                    925
000525    330   P=1/M1                                                              930
000530          GO TO 360                                                           935
000534    340   M2=DY2/DX2                                                          940
000536          IF (ABS(M1*M2+1.0).LT.1.0E-05) 290,350                              945
000542    350   P=(M2-M1)/(1.0+M1*M2)                                               950
000551          IF (ABS(M1-M2).LT.1.0E-12) P=0.0                                    955
000554    360   IF (P) 370,380,390                                                  960
000560    370   IPHI(I)=1                                                           965
000564          GO TO 400                                                           970
000567    380   IPHI(I)=3                                                           975
000573          GO TO 400                                                           980
000574    390   IPHI(I)=2                                                           985
000600    400   DX1=DX2                                                             990
000604          DY1=DY2                                                             995
000611    410   CONTINUE                                                           1000
000614          L3=IV(L)-1                                                         1005
000617          IPHI(L3)=4                                                         1010
001001          L1=L2+2                                                            1015
001002    420   CONTINUE                                                           1020
          C                                                                        1025
          COMMENT   SEGMENT CURVE ACCORDING TO DIRECTION OF ROTATION OF TANGENT   1030
          C                                                                        1035
          C              ITYPE(I) DESIGNATES THE DIRECTION OF ROTATION AS FOLLOWS  1040
          C                                                                        1045
          C                   ITYPE(I) = 1   CLOCKWISE                           1050
          C                   ITYPE(I) = 2   COUNTER-CLOCKWISE                   1055
          C                   ITYPE(I) = 3   NO ROTATION  ( STRAIGHT LINE )      1060
          C                                                                        1065
001004          NS=1                                                             1070
001005          ISI(1)=1                                                         1075
001006          ITYPE(1)=IPHI(1)                                                 1080
001010          NPT=NPTS-2                                                       1085
001012          DO 500 I=2,NPT                                                   1090
001013          IF (IPHI(I).EQ.ITYPE(NS)) 460,430                                1095
```

```
001021   430    IF (IPHI(I).EQ.4) 440,450
         C
         C      OMMENT   THIS IS A VERTEX
         C
001026   440    ISF(NS)=I+1
001031          NS=NS+1
001032          ISI(NS)=I+1
001033          ITYPE(NS)=IPHI(I+1)
001035          GO TO 460
001036   450    ISF(NS)=I+1
001041          NS=NS+1
001042          ISI(NS)=I+1
001043          ITYPE(NS)=IPHI(I)
001045   460    IF (NS.GT.60) 470,480
001052   470    CALL EXITA (3+1)
001054          GO TO 2420
001060   480    IF (I.EQ.NPT) 490,500
001065   490    ISF(NS)=NPTS
001067   500    CONTINUE
001072          IF (NS.EQ.1) GO TO 520
001074          LS=1
001075   510    LS=LS+1
001077          IF (LS.EQ.NS+1) GO TO 520
001101          IF (ITYPE(LS).NE.3) GO TO 510
001104          K=ISI(LS)-1
001105          K=IPHI(K)
001107          IF (K.EQ.4) GO TO 510
001111          ISI(LS)=ISI(LS)-1
001114          ISF(LS-1)=ISI(LS)
001116          GO TO 510
001116   520    CONTINUE
001116          LS=1
001117   530    LS=LS+1
001121          IF (LS.EQ.NS+1) GO TO 550
001123          JTEST=ISF(LS)-ISF(LS-1)
001126          IF (JTEST.NE.0) GO TO 530
001127          IF(ITYPE(LS-1) .EQ. 3 .AND. ITYPE(LS+1) .EQ. 3)3001,3002
001136   3001 NV1=0
001137   3003 NV1=NV1+1
001141          IF(ISF(LS) .GT. IV(NV1))GO TO 3003
001146          NV=NV+1
001147          DO 3004 I=1,NV
001151          J=NV+1-I
001153          IF(J .EQ. NV1)GO TO 3005
001155          IV(J)=IV(J-1)
001157   3004 CONTINUE
001161   3005 IV(NV1)=ISF(LS)
001164   3002 CONTINUE
001164          NS=NS-1
001166          DO 540 I=LS,NS
001170          ITYPE(I)=ITYPE(I+1)
001172          ISI(I)=ISI(I+1)
001174   540    ISF(I)=ISF(I+1)
001200          GO TO 530
001201   550    CONTINUE
```

```
        C
        COMMENT   PRINT OF PRELIMINARY GROUPING OF POINTS
        C
001201            WRITE (6,2550)
001205            DO 560 L=1,NS
001212            K=ISI(L)
001214            M=ISF(L)
001215            WRITE (6,2560) L,ITYPE(L),X(K),Y(K),X(M),Y(M)
001235    560     CONTINUE
        C
        COMMENT   FIT GIVEN SET OF POINTS WITH CIRCLES AND STRAIGHT LINES
        C
001243            PCX=0.0
001244            PCY=0.0
001245            KPOINT(1)=1
001246            SUM1=0.0
001247            NSEG=0
001250            IP=1
001251            IIV=1
001252            DO 2210 I=1,NS
001253            DO 570 J=1,9
001254            EP(J)=0.0
001255    570     CONTINUE
001257            WRITE (6,2490) TITLE1,TITLE2,TITLE3
001273            WRITE (6,2570) I
001301            IADJST=0
001302            IF (I.EQ.1) 580,610
        C
        COMMENT   IS THE FIRST SEGMENT A LINE OR A CIRCLE
        C
001312    580     IF (ITYPE(I).EQ.3) 630,590
001317    590     J=ISI(I)
        C
        COMMENT   OBTAIN THE LINE ON WHICH THE CENTER OF THE STARTING CIRCLE
        COMMENT   IS TO LIE
        C
        COMMENT   SOLVE THE SYSTEM
001321            DO 600 M=1,3
001323            LTEMP(M)=1
001325            A(M,1)=X(J)
001327            A(M,2)=Y(J)
001331            A(M,3)=1.0
001333            B(M)=X(J)**2+Y(J)**2
001337            J=J+1
001340    600     CONTINUE
001342            CALL LIN2 (A,3,3,B,0,0,1,3,LTEMP,IERR,DET,NPIV,PIV,LPR,LPC)
001357            D=B(1)
001361            E=B(2)
001362            F=B(3)
001364            CX=-D/2.0
001366            CY=-E/2.0
001367            CR=(SQRT(D**2+E**2-4.0*F))/2.
001377            L1=ISI(I)
001401            L2=ISF(I)
001402            GO TO 660
```

```
        C
        COMMENT   IS (X(L1),Y(L1)) A VERTEX OR AN INFLECTION POINT
        C
001406  610   IF (IV(IIV).EQ.L1) 620,640
        C
        COMMENT   IS CURVE FROM VERTEX (X(L1),Y(L1)) A LINE OR A CIRCLE
        C
001413  620   IF (ITYPE(I).EQ.3) 630,590
001420  630   L1=ISI(I)
001422        L2=ISF(I)
001424        WRITE (6,2581) L1,L2
001433        L=L2
001435        GO TO 1410
001441  640   IF (ITYPE(I).EQ.3) 620,650
001446  650   IF (ITYPE(I-1).EQ.3) 660,1200
001453  660   L2=ISF(I)
001455        L=L2
001456  670   X1=X(L1)
001460        Y1=Y(L1)
001462        X2=X(L)
001464        Y2=Y(L)
001465        DX1=X1-CX
001467        DY1=Y1-CY
001471        SUM=0.0
        C
        COMMENT   PASS CIRCLE THROUGH (X1,Y1), (X2,Y2) WITH CENTER ON
        COMMENT   (X1,Y1)-(CX,CY)
        C
001472        IF (ABS(DY1).LT.1.0E-05) 680,690
001500  680   E=-2.0*Y1
001502        D=((X2**2-X1**2)+(Y2-Y1)**2)/(X1-X2)
001511        F=Y1**2-X1**2-D*X1
001515        GO TO 720
001516  690   IF (ABS(DX1).LT.1.0E-05) 700,710
001524  700   D=-2.0*X1
001526        E=((X1-X2)**2+(Y2**2-Y1**2))/(Y1-Y2)
001536        F=X1**2-Y1**2-E*Y1
001542        GO TO 720
001543  710   SL=DY1/DX1
        C
        COMMENT   SOLVE THE SYSTEM
        C
001545        A(1,1)=X1
001547        A(1,2)=Y1
001550        A(1,3)=1.0
001552        A(2,1)=X2
001553        A(2,2)=Y2
001555        A(2,3)=1.0
001556        A(3,1)=SL/2.0
001560        A(3,2)=-1.0/2.0
001561        A(3,3)=0.0
001562        B(1)=X1**2+Y1**2
001564        B(2)=X2**2+Y2**2
001567        B(3)=SL*X1-Y1
001571        CALL LIN2 (A,3,3,0,0,0,1,3,LTEMP,IERR,DET,NPIV,PIV,LPR,LPC)
```

```
001407          D=Q(1)                                                          1860
001611          E=Q(2)                                                          1865
001612          F=Q(3)                                                          1870
001614    72    X3=-D/2.0                                                       1875
001620          Y3=-E/2.0                                                       1880
001627          R=(SQRT((D**2+E**2-4.0*F))/2.                                   1885
001635          IF (IADJST.NE.0) GO TO 730                                      1890
001645          WRITE (6,2504) L1,L2,L,X3,Y3,R                                  1895
001653    73    CONTINUE                                                        1900
001661          IF (L1.EQ.IV(IIV)) GO TO 800                                    1905
001664          T1=X(L1)-X3                                                     1910
001666          T2=Y(L1)-Y3                                                     1915
001671          T3=X(L1)-PCX                                                    1920
001673          T4=Y(L1)-PCY                                                    1925
001675          T1=T1**T3                                                       1930
001676          T2=T2**T4                                                       1935
001700          PCX=X3                                                          1940
001701          PCY=Y3                                                          1945
001706    74    IF (L1.EQ.ISI(I)) 770,740                                       1950
001712    75    IF (T1.EQ.0.0) 750,760                                          1955
001717    76    IF (T2.GT.0.0) 800,1200                                         1960
001724    77    IF (T1.GT.0.0) 800,1200                                         1965
001730          IF (ITYPE(I-1).EQ.3) GO TO 800                                  1970
001731          IF (T1.EQ.0.0) 780,790                                          1975
001735    78    IF (T2.GT.0.0) 1200,800                                         1980
001742    79    IF (T1.GT.0.0) 1200,800                                         1985
001747    800   IF ((L-L1).EQ.1) 810,940                                        1990
001754    810   EPS=0.0                                                         1995
001755          GO TO 980                                                       2000
                C                                                             2005
                C   COMMENT   OBTAIN LINE TANGENT TO CIRCLE AND THROUGH LAST POINT OF LINE   2010
                C                                                             2015
001756    82    L1=ISI(I)                                                       2020
001760          L=ISF(I)                                                        2025
001762          WRITE (6,2504) L1,L                                             2030
001771          XT=X(L1)                                                        2035
001773          YT=Y(L1)                                                        2040
001775          R=X(L)                                                          2045
001777          S=Y(L)                                                          2050
002000          X3=CX                                                           2055
002002          Y3=CY                                                           2060
002004          R3=CR                                                           2065
002005          IF (S.EQ.Y3) 830,840                                            2070
002014    83    X1=R3**2/(R-X3)+X3                                              2075
002020          X2=X1                                                           2080
002021          T=SQRT(R3**2-(X1-X3)**2)                                        2085
002026          Y1=Y3+T                                                         2090
002030          Y2=Y3-T                                                         2095
002031          GO TO 880                                                       2100
002035    84    IF (R.EQ.X3) 850,860                                            2105
002042    85    Y1=R3**2/(S-Y3)+Y3                                              2110
002046          Y2=Y1                                                           2115
002047          T=SQRT(R3**2-(Y1-Y3)**2)                                        2120
002054          X1=X3+T                                                         2125
                                                                              2130
```

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002056          X2=X3-T
002057          GO TO 880
002063    940   Z=X3**2+Y3**2-R3**2-R*X3-S*Y3
002073          T=(X3-R)/(Y3-S)
002075          TD=Y3-S
002077          U=1.0+T**2
002102          V=2.0*T*(Y3-Z/TD)-2.0*X3
002107          W=Z**2/TD**2-2.0*Y3*Z/TD+Y3**2+X3**2-R3**2
002123          W1=V**2-4.0*U*W
002130          IF (W1.GE.0.) GO TO 870
002131          CALL EXITD (10,I)
002133          GO TO 2420
002137    870   CONTINUE
002137          R=SQRT(V**2-4.0*U*W)
002146          X1=(-V+R)/(2.0*U)
002152          X2=(-V-R)/(2.0*U)
002156          Y1=Z/TD-T*X1
002161          Y2=Z/TD-T*X2
          C
          COMMENT   CHOOSE THE POINT OF TANGENCY CLOSEST TO POINT (X(L1),Y(L1))
          C
002164    880   D1=SQRT((X1-X(L1))**2+(Y1-Y(L1))**2)
002175          D2=SQRT((X2-X(L1))**2+(Y2-Y(L1))**2)
002205          IF (D1.LT.D2) 890,900
002214    890   X(L1)=X1
002216          Y(L1)=Y1
002220          L2=L
002221          GO TO 910
002222    900   X(L1)=X2
002224          Y(L1)=Y2
002226          L2=L
          C
          COMMENT   ADJUST FINAL ANGLE OF PRECEEDING PART
          C
002227    910   T1=XT-X(L1)
002232          T2=XT-X(L1+1)
002234          T1=T1*T2
002236          DX1=XT-CX
002237          DY1=YT-CY
002241          CA=DX1/CR
002243          SA=DY1/CR
002245          DX2=X(L1)-CX
002250          DY2=Y(L1)-CY
002252          XT=DX2*SA-DY2*CA
002256          YT=DX2*CA+DY2*SA
002260          CALL ANGLE (1,XT,YT,0.,0.,ANGLEN,ANGLED,IFIND,SL)
002271          DTHETA=ABS(ANGLED)
002273          JD=2
002274          ID=2
002275          IF (T1.LT.0.0) JD=3
002303          IF (ITYPE(I-1).EQ.2) ID=3
002307          JD=JD+ID
002311          GO TO (2420,2420,2420,930,920,930), JD
002322    920   DTHETA=-DTHETA
002323    930   SX(IP-1)=SX(IP-1)+DTHETA
```

```
002324          GO TO 1010                                                      2410
002327    940   J=1                                                             2415
002330          NP=L-L1+1                                                       2420
          C                                                                     2425
          COMMENT   CHECK TO SEE WHETHER POINTS BETWEEN (X1,Y1) AND (X2,Y2) ARE 2430
          COMMENT   CLOSE ENOUGH TO THE CIRCLE                                  2435
          C                                                                     2440
002333          ETEMP=EPS1                                                      2445
002334          IFLAG=1                                                         2450
002335          DO 960 J=1,NP                                                   2455
002337          X4=X(L1+J)                                                      2460
002342          Y4=Y(L1+J)                                                      2465
002344          EPS=R-SQRT((X3-X4)**2+(Y3-Y4)**2)                               2470
002354          SUM=SUM+ABS(EPS)                                                2475
002357          IF (IADJST.NE.0) GO TO 950                                      2480
002363          WRITE (6,9000) J,NP,X4,Y4,EPS                                   2485
002401    950   CONTINUE                                                        2490
002401          IF (ABS(EPS).LE.EPS1) GO TO 960                                 2495
002410          IFLAG=10                                                        2500
002411          IF (ETEMP.LT.ABS(EPS)) ETEMP=ABS(EPS)                           2505
002415    960   CONTINUE                                                        2510
002420          IF (IFLAG.EQ.1) GO TO 980                                       2515
002422          IF (IADJST.EQ.0) GO TO 970                                      2520
002425          IF (L-L1.EQ.2) E(IADJST)=ETEMP                                  2525
002427    970   L=L-1                                                           2530
002431          IF (L.NE.L1+1) GO TO 670                                        2535
002433          IF (I.EQ.1) GO TO 670                                           2540
002435          IF (ITYPE(I-1).EQ.3.AND.IADJST.NE.0) GO TO 980                  2545
002443          GO TO 670                                                       2550
002443    980   IF (L.EQ.L2) 1190,990                                           2555
002450    990   J=1                                                             2560
          C                                                                     2565
          COMMENT   EXTEND CIRCLE AS FAR AS POSSIBLE                            2570
          C                                                                     2575
002451    1000  X4=X(L+J)                                                       2580
002454          Y4=Y(L+J)                                                       2585
002456          EPS2=R-SQRT((X3-X4)**2+(Y3-Y4)**2)                              2590
002466          IF (IADJST.NE.0) GO TO 1010                                     2595
002473          WRITE (6,9010) J,X4,Y4,EPS2                                     2600
002506    1010  CONTINUE                                                        2605
002506          IF (EPS2.LT.0.0) 1020,1070                                      2610
002515    1020  IF (J.EQ.1) 1030,1060                                           2615
002522    1030  IF (EPS.LT.0.0) 1190,1040                                       2620
002526    1040  IF ((L-L1).EQ.1) 1110,1050                                      2625
002533    1050  L=L-1                                                           2630
002535          GO TO 1110                                                      2635
002535    1060  L=L+J-2                                                         2640
002540          IF (J.EQ.1) L=L+1                                               2645
002542          GO TO 1110                                                      2650
002543    1070  IF (ABS(EPS2).LT.EPS1) 1080,1060                                2655
002551    1080  SUM=SUM+ABS(EPS2)                                               2660
002554          IF ((L+J).EQ.L2) 1100,1090                                      2665
002561    1090  J=J+1                                                           2670
002563          GO TO 1000                                                      2675
002563    1100  L=L2                                                            2680
```

```
                                                                                2685
002545    1114  DX=X3-X(L)                                                      2690
002570          DY=Y3-Y(L)                                                      2695
          C                                                                     2700
          COMMENT   PLACE LAST POINT ON CONTAINED CIRCLE                        2705
          C                                                                     2710
002573          IF (ABS(DX).LT.1.0E-05) 1120,1130                               2715
002601    1129  X1=X3                                                           2720
002603          X2=X3                                                           2725
002604          Y1=Y3+R                                                         2730
002606          Y2=Y3-R                                                         2735
002607          GO TO 1164                                                      2740
002610    1130  IF (ABS(DY).LT.1.0E-05) 1140,1150                               2745
002616    1140  Y1=Y3                                                           2750
002620          Y2=Y3                                                           2755
002621          X1=X3+R                                                         2760
002625          X2=X3-R                                                         2765
002626          GO TO 1164                                                      2770
002625    1150  SL=DY/DX                                                        2775
002627          T=R/SQRT(1.+SL**2)                                              2780
002635          X1=X3+T                                                         2785
002637          X2=X3-T                                                         2790
002643          Y1=Y3+SL*T                                                      2795
002643          Y2=Y3-SL*T                                                      2800
002645    1160  D1=SQRT((X1-X(L))**2+(Y1-Y(L))**2)                              2805
002656          D2=SQRT((X2-X(L))**2+(Y2-Y(L))**2)                              2810
002660          IF (D1.LT.D2) 1170,1180                                         2815
002675    1170  X(L)=X1                                                        2820
002677          Y(L)=Y1                                                         2825
002701          GO TO 1194                                                      2830
002701    1180  X(L)=X2                                                        2835
002703          Y(L)=Y2                                                         2840
          C                                                                     2845
          COMMENT   CHECK CURVATURE TO SEE IF IT IS CORRECT I.E., IF TWO CIRCLES 2850
          COMMENT   JOIN AND BOTH HAVE A TANGENT TURNING IN THE SAME DIRECTION. 2855
          C                                                                     2860
002705    1194  GO TO 1414                                                      2865
002706    1200  IF (IADJST.EQ.0) GO TO 1230                                     2870
002707          ESTFIT(IADJST)=100.0                                            2875
002711          IFIT(IADJST)=L1                                                 2880
002712          IF (EPS.EQ.0.0) GO TO 1210                                      2885
002713          EP(IADJST)=100.                                                 2890
002715    1210  CONTINUE                                                        2895
002715          IF (IADJST.EQ.9) GO TO 1440                                     2900
002717          IADJST=IADJST+1                                                 2905
002720          L1=JJ                                                           2910
002722          X(L1)=XTRY(IADJST)                                              2915
002725          Y(L1)=YTRY(IADJST)                                              2920
002727          L=L2                                                            2925
002730          K=1                                                             2930
002731          NIN=L1+1                                                        2935
002733          DO 1220 J=NIN,L                                                 2940
002734          X(J)=ZT(K)                                                      2945
002737          Y(J)=ZT(K)                                                      2950
002741          K=K+1                                                           2955
002742    1220  CONTINUE
```

```
002744          X2=X(L)                                                         2960
002745          Y2=Y(L)                                                         2965
002747          C=VN(2,JP2)-(ADJST*COSC                                         2970
002754          CY=VN(4,JP2)-(ADJST*CYC                                         2975
002761          JPP=JP1
002762          PCX=CX                                                          2985
002763          PCY=CY                                                          2990
002765          GO TO 670                                                       2995
                C                                                               3000
                COMMENT   IF THE CURVATURE REVERSES WITHIN AN ARC OF CONSTANT CURVATURE,  3005
                COMMENT   CREATE NINE TRIAL POINTS BETWEEN THE LAST TWO POINTS OF THE     3010
                COMMENT   LAST KNOWN PART                                       3015
                C                                                               3020
002765  1230    JP2=IP-1                                                        3025
002767          JJ=KPOINT(IP)                                                   3030
                C                                                               3035
                COMMENT   STORE POINTS IN PART 1 PRIOR TO THE SEARCH FOR THE NEXT        3040
                COMMENT   INFLECTION POINT                                      3045
                C                                                               3050
002771          K=1                                                             3055
002772          MAX1=ISF(1)                                                     3060
002774          DO 1240 J=1,MAX1                                                3065
002776          ZT(K)=X(J)                                                      3070
003001          WT(K)=Y(J)                                                      3075
003003          K=K+1                                                           3080
003004  1240    CONTINUE                                                        3085
003006          IF (ISS(JP2).EQ.7) GO TO 1299                                   3090
003011          DEL1=.9                                                         3095
003012          IF (ISS(JP2).EQ.2) GO TO 1270                                   3100
003016          XT1=X(JJ)                                                       3105
003017          YT1=Y(JJ)                                                       3110
003020          KT=JJ-1                                                         3115
003022          XT2=X(KT)                                                       3120
003024          YT2=Y(KT)                                                       3125
003025          DXC=(XT1-XT2)/10.0                                              3130
003030          DYC=(YT1-YT2)/10.0                                              3135
003032  1250    DO 1260 J=1,9                                                   3140
003035          XTRY(J)=X(JJ)-J*DXC                                             3145
003042  1260    YTRY(J)=Y(JJ)-J*DYC                                             3150
003050          GO TO 1280                                                      3155
003054  1270    YT1=Y(JJ)                                                       3160
003056          YT2=Y(JJ-1)                                                     3165
003060          DXC=0.0                                                         3170
003065          DYC=(YT1-YT2)/10.0                                              3175
003069          GO TO 1250                                                      3180
003071  1280    YT2=VN(2,JP2)                                                   3185
003075          YT4=VN(4,JP2)                                                   3190
003100          VN(2,JP2)=CX                                                    3195
003104          VN(4,JP2)=CY                                                    3200
003110          GO TO 1310                                                      3205
003113  1290    DXC=0.0                                                         3210
003116          DYC=1.0                                                         3215
003119          P=AMS(VN(3,JP2))                                                3220
003121          DXI=X(JJ)-VN(2,JP2)                                             3225
003125          DY1=Y(JJ)-VN(4,JP2)                                             3230
```

```
003111          CA=DX1/R
003114          SA=DY1/R
003116          DX2=X(JJ-1)-VN(2,JP2)
003121          DY2=Y(JJ-1)-VN(4,JP2)
003124          XT=DX2*SA-DY2*CA
003130          YT=DX2*CA+DY2*SA
003132          CALL ANGLF (1,XT,YT,0.,0.,ANGLER,ANGLFD,IFIND,S( )
003143          DELTH=.1*ABS(ANGLER)
003146          CT=COS(DELTH)
003150          ST=SIN(DELTH)
003152          I6=1
003153          IF (VN(3,JP2).GT.0.0) GO TO 1300
003163          I6=2
003164          ST=-ST
003165    1300  CONTINUE
003165          DO 1310 J=1,9
003167          CD=CA*CT-SA*ST
003173          SD=SA*CT+CA*ST
003175          XTRY(J)=R*CD+VN(2,JP2)
003203          YTRY(J)=R*SD+VN(4,JP2)
003207          CA=CD
003210          SA=SD
003211    1310  CONTINUE
C
COMMENT   UPDATE VECTORS X, Y, IV, ISI, ISF, KPOINT
C
003213          KT=NPTS+1
003215          NPTS=KT
003216          JK=JJ+1
003217          DO 1320 J=JK,NPTS
003220          X(KT)=X(KT-1)
003223          Y(KT)=Y(KT-1)
003225          KTHICK(KT)=KTHICK(KT-1)
003227    1320  KT=KT-1
003232          J=1
003233          J1=1
003234          J2=1
003235    1330  KT=IV(J)
003237          IF (KT.NE.JJ) GO TO 1350
003241    1340  J=J+1
003243          GO TO 1330
003243    1350  IV(J)=IV(J)+1
003246          IF (J.NE.NV) GO TO 1340
003250          IF (IV(J).NE.JPRES(J1)) GO TO 1360
003253          JPRES(J1)=JPRES(J)+1
003255          J1=J1+1
003256    1360  IF (IV(J).NE.JELAS(J2)) GO TO 1370
003262          JFLAS(J2)=JFLAS(J2)+1
003264          J2=J2+1
003265    1370  CONTINUE
003265          GO TO 1340
003266    1390  CONTINUE
003266          DO 1390 J=I,NS
003270    1390  ISF(J)=ISF(J)+1
003275          KT=I+1
```

```
003276          DO 1400 J=KT,NS                                                 3510
003277   1400   IS1(J)=IS(J-1)                                                  3515
003303          IS1(1)=IS(1-1)                                                  3520
                C                                                               3525
                COMMENT   INITIALIZE THE VARIOUS COUNTERS FOR TRIAL OF FIRST TRIAL POINT  3530
                C                                                               3535
                C              NPPA      NO. OF PARTS TO GET TO THE END OF THE ARC  3540
                C              IADJST    INDEX OF CURRENT TRIAL POINT            3545
                C              L2        INDEX OF THE LAST POINT OF THE PRESENT ARC  3550
                C              I1 AND L  INDICES OF THE FIRST AND LAST POINTS OF THE  3555
                C                        PRESENT CIRCLE BEING TESTED FOR SUITABILITY  3560
                C              CX AND CY COORDINATES OF THE CENTER OF THE PRECEEDING  3565
                C                        CIRCLE                                 3570
                C                                                               3575
003306          NPPA=1                                                          3580
003307          IADJST=1                                                        3585
003310          L2=IS(1)                                                        3590
003311          L=L2                                                            3595
003312          L1=JJ                                                           3600
003314          X(L1)=XTRY(1)                                                   3605
003316          Y(L1)=YTRY(1)                                                   3610
003317          CX=VN(2,JP2)-IADJST*DXC                                         3615
003325          CY=VN(4,JP2)-IADJST*DYC                                         3620
003331          PCX=CX                                                          3625
003333          PCY=CY                                                          3630
003334          GO TO 670                                                       3635
003335   1410   CONTINUE                                                        3640
003335          IF (IADJST.EQ.0) GO TO 1490                                     3645
003336          IF (L.EQ.L2) GO TO 1420                                         3650
003340          CX=X3                                                           3655
003342          CY=Y3                                                           3660
003345          L1=L                                                            3665
003346          L=L2                                                            3670
003346          NPPA=NPPA+1                                                     3675
003346          SUM1=SUM1+SUM                                                   3680
003350          GO TO 670                                                       3685
003350   1420   HSTF1((IADJST)*NPPA+SUM1+SUM                                    3690
003355          IF(IADJST)=L2                                                   3695
003356          NPPA=1                                                          3700
003357          IF (IADJST.EQ.0) GO TO 1440                                     3705
003361          IADJST=IADJST-1                                                 3710
003362          SUM1=0.0                                                        3715
003365          L1=JJ                                                           3720
003366          L=L2                                                            3725
003366          X(L1)=XTRY(IADJST)                                              3730
003371          Y(L1)=YTRY(IADJST)                                              3735
003375          K=1                                                             3740
003376          MIN=L1+1                                                        3745
003376          DO 1430 J=MIN,L                                                 3750
003377          X(J)=ZT(K)                                                      3755
003402          Y(J)=ZT(K)                                                      3760
003404          K=K+1                                                           3765
003405   1440   CONTINUE                                                        3770
003407          CX=VN(2,JP2)-IADJST*DXC                                         3775
003416          CY=VN(4,JP2)-IADJST*DYC                                         3780
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003421          PC4=CX                                                          3760
003422          PCY=CY                                                          3790
003424          GO TO 670                                                       3795
                C                                                               3800
                COMMENT   THE BEST OF THE NINE TRIAL POINTS IS CHOSEN ACCORDING TO THE  3805
                COMMENT   VECTORS BSTFIT, FIT, AND EP                           3810
                C                                                               3815
                C               BSTFIT(IADJST)      THE NUMBER OF PAIRS PLUS THE SUM OF  3820
                C                       THE ABSOLUTE VALUES OF THE DISTANCES OF THE  3825
                C                       POINTS FROM THE OBTAINED CIRCLES.  IF NO  3830
                C                       SEQUENCE OF CIRCLES CAN BE FOUND WHICH GO FROM  3835
                C                       THE INITIAL VALUE OF L1 TO L2, THEN  3840
                C                       BSTFIT IS SET EQUAL TO 100          3845
                C               IFIT(IADJST)        TESTED ONLY IF ALL ENTRIES OF BSTFIT  3850
                C                       ARE 100.  IT CONTAINS THE INDEX OF THE LAST  3855
                C                       POINT SUCCESSFULLY FOUND, STARTING FROM  3860
                C                       (X(IADJST),Y(IADJST)                3865
                C               EP                  SEARCHED FOR THE BEST TRIAL POINT  3870
                C                       ONLY IF THE MAXIMUM VALUE IN IFIT IS L1+1.  3875
                C                       THAT IS, NONE OF THE TRIAL POINTS ENABLED THE  3880
                C                       PROGRAM TO DO CALCULATIONS ANY FURTHER THAN IT  3885
                C                       DID BEFORE THE CREATION OF THE TRIAL POINTS.  3890
                C                       IN THIS CASE, EP(IADJST) CONTAINS THE DISTANCE  3895
                C                       FROM THE CIRCLE THROUGH POINTS INDEXED BY L1  3900
                C                       AND L1+2 OF POINT WITH INDEX L1+1.  THE BEST  3905
                C                       TRIAL POINT IS THEN THE POINT WITH THE SMALLEST  3910
                C                       EP VALUE                            3915
                C                                                           3920
003424  1440    J=0                                                         3925
003425          PRINT 2624                                                  3930
003431          DO 1450 K=1,9                                               3935
003436          PRINT 2634, BSTFIT(K),IFIT(K),EP(K)                         3940
003447  1450    CONTINUE                                                    3945
003455          TEST1=50.                                                   3950
003456          LL=50                                                       3955
003457  1460    J=J+1                                                       3960
003461          IF (J.GT.9) GO TO 1480                                      3965
003464          TEST2=BSTFIT(J)                                             3970
003465          IF (TEST2.LT.TEST1) GO TO 1470                              3975
003467          GO TO 1460                                                  3980
003470  1470    LL=J                                                        3985
003472          TEST1=TEST2                                                 3990
003473          GO TO 1460                                                  3995
003474  1480    IF (LL.LT.50) GO TO 1530                                    4000
003477          J=0                                                         4005
003500          ITST1=1                                                     4010
003501          LL=101                                                      4015
003502  1490    J=J+1                                                       4020
003504          IF (J.GT.9) GO TO 1510                                      4025
003507          ITST2=IFIT(J)                                               4030
003510          IF (ITST1.LT.ITST2) GO TO 1500                              4035
003512          GO TO 1490                                                  4040
003513  1500    LL=J                                                        4045
003515          ITST1=ITST2                                                 4050
003516          GO TO 1490                                                  4055
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003517   1510  IF (LL.LT.100) GO TO 153:                                        4060
003522   1520  CALL EXITD (7,1)                                                 4065
003526         GO TO 2020                                                       4070
003530   1530  CONTINUE                                                         4075
003530         IF (IFIT(LL).GT.JJ+1) GO TO 1570                                 4080
003536         TEST1=50.                                                        4085
003537         DO 1550 J=1,9                                                    4090
003540         IF (EP(J).LT.TEST1) GO TO 1540                                   4095
003543         GO TO 1550                                                       4100
003544   1540  LL=J                                                             4105
003546         TEST1=EP(J)                                                      4110
003547   1550  CONTINUE                                                         4115
003551         IF (EP(LL).EQ.100.) GO TO 1520                                   4120
003554         IF (LL.EQ.9) GO TO 1560                                          4125
003556         LL=LL+1                                                          4130
003557   1560  EPS1=EP(LL)*.000000001                                           4135
003562         CALL EXITD (9,JJ)                                                4140
003564         PRINT 2640, EPS1                                                 4145
003572   1570  XTEST=1                                                          4150
003573         PRINT 2650, LL                                                   4155
003601         IADJST=0                                                         4160
003602         L1=JJ                                                            4165
003604         X(L1)=XTHV(LL)                                                   4170
003607         Y(L1)=YTHV(LL)                                                   4175
003611         XTHICK(L1)=XTHICK(L1-1)+.1*((1.-LL)*(XTHICK(L)+1)-XTHICK(L1-1))  4180
003623         CX=VN(2,JP2)-LL*DC                                               4185
003634         CY=VN(1,JP2)-LL*DYC                                              4190
003641         PCX=CX                                                           4195
003642         PCY=CY                                                           4200
003644         SX(JP2)=SU(JP2)+((-1)**IS)*UPW*DELTW*LL                          4205
003650         L2=ISF(I)                                                        4210
003660         L=L2                                                             4215
003661         K=1                                                              4220
003662         M[K=L]=1                                                         4225
003664         DO 1580 J=1,L                                                    4230
003665         X(J)=ZI(K)                                                       4235
003670         Y(J)=WI(K)                                                       4240
003672         K=K+1                                                            4245
003673   1580  CONTINUE                                                         4250
003675         IF (ISS(JP2).EQ.7) GO TO 670                                     4255
003700         VP(2,JP2)=VT2                                                    4260
003702         VN(4,JP2)=VT4                                                    4265
003705         DAPC=SQRT(DXC**2+DYC**2)                                         4270
003712         VN(3,JP2)=VP(3,JP2)-LL*DAPC                                      4275
003722         GO TO 670                                                        4280
               C                                                                4285
               COMMENT   PARTS DESCRIBED BY STRAIGHT LINES                      4290
               C                                                                4295
003725   1590  IF (ITYPE(I).NE.3) GO TO 1770                                    4300
003726         DX1=X(L)-X(L1)                                                   4305
003731         DY1=Y(L)-Y(L1)                                                   4310
003734         ISS(IP)=6                                                        4315
003736         IF (ABS(DX1).LT.1.0E-05) 1600,1610                               4320
               C                                                                4325
               COMMENT   PARTS DESCRIBED BY CYLINDERS                           4330
```

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                C
003744   1600   S=DY1/(3.0*SQRT(H*X(L)))
003753          IPAR(IP)=1+ABS(S)
003763          ISS(IP)=2
003765          VN(2,IP)=X(L))
003771          VN(3,IP)=ABS(DY1)
003774          SI(IP)=90.0
003776          IF (DY1.LT.0.0) 1620,1610
004001   1610   SI(IP)=270.0
004004   1620   Y3=Y(L)
004006          X3=2.0*X(L)+1.0
004011          SX(IP)=SI(IP)
004014          IF (IV(IIV).EQ.L1) IIV=IIV+1
004020          GO TO 2020
004021   1630   IF (ABS(DY1/DX1).LT.1.0E-05) 1640,1690
                C
                COMMENT   PARTS DESCRIBED BY FLAT PLATES
                C
004030   1640   VN(2,IP)=X(L))
004034          VN(3,IP)=ABS(DX1)
004040          SI(IP)=0.0
004041          IPAR(IP)=1
004042          RATIO=X(L)/X(L1)
004046          IF (DX1.LT.0.0) 1650,1660
004052   1650   SI(IP)=180.0
004055          RATIO=1.0/RATIO
004056   1660   IF (RATIO.GT.2.0) 1670,1680
004064   1670   IPAR(IP)=2
004066   1680   X3=X(L)
004070          Y3=2.0*Y(L)+1.0
004073          SX(IP)=SI(IP)
004076          IF (IV(IIV).EQ.L1) IIV=IIV+1
004102          GO TO 2120
                C
                COMMENT   PARTS DESCRIBED BY CONES
                C
004103   1690   XM=(X(L)+X(L1))/2.0
004110          APCL=SQRT(DX1**2+DY1**2)
004115          SM=DY1/DX1
004117          R2=SQRT(XM**2+XM**2/SM**2)
004125          S=SQRT((X(L1)**2)*(1.0+SM**2))
004134          TEST=S*SM/H
004136          IF (TEST.GE.30.) 1700,1710
004140   1700   HS=1.0*APCL/(3.0*SQRT(R2*H))
004157          GO TO 1720
004163   1710   ST=S/(30.0*H)
004166          RT=SQRT((XM**2)*(1.0+ST**2))
004173          HS=1.0*APCL/(3.0*SQRT(RT*H))
004203   1720   RINC=APCL/HS
004206          RATIO=RINC/X(L1)
004210          VN(2,IP)=X(L1)
004220          IF (RATIO.LT.1.0) 1750,1730
004225   1730   HS=2*HS
004226          IF (HS.GE.60) 1740,1720
004233   1740   CALL EXITA (5,IP)
```

```
004235          GO TO 2420                                                      4610
004241   1750   IPAR(IP)=5                                                      4615
004244          VN(3,IP)=ARCL                                                   4620
004246          X3=P.AOS(L)                                                     4625
004251          Y3=Y(L)-X(L)/SM                                                 4630
004254          IF (IV(IIV).EQ.L1) GO TO 1760                                   4635
004257          SI(IP)=SX(IP-1)                                                 4640
004262          SX(IP)=SI(IP)                                                   4645
004266          GO TO 2920                                                      4650
004265   1760   XT=X(L)                                                         4655
004267          YT=Y(L)                                                         4660
004271          IIV=IIV+1                                                       4665
004272          K=1                                                             4670
004273          TEST=SM*DY1                                                     4675
004275          IF (TEST.LT.P.0) K=2                                            4680
004277          CALL ANGLE (K,XT,YT,X3,Y3,ANGLEN,ANGLE1,IP(NN),SL)              4685
004310          SI(IP)=ANGLEN                                                   4690
004316          SX(IP)=SI(IP)                                                   4695
004321          GO TO 2920                                                      4700
          C                                                                     4705
          COMMENT   PARTS DESCRIBED BY CIRCLES                                  4710
          C                                                                     4715
004321   1770   VN(2,IP)=X3                                                     4720
004324          VN(4,IP)=Y3                                                     4725
004327          DX1=X(L1)-X3                                                    4730
004332          DY1=Y(L1)-Y3                                                    4735
004336          DX2=X(L)-X3                                                     4740
004341          DY2=Y(L)-Y3                                                     4745
004344          DP=X(L1)-X(L)                                                   4750
004346          DZ=Y(L1)-Y(L)                                                   4755
004350          ISS(IP)=7                                                       4760
004350          IF (ABS(DX1).LT.1.0E-05) 1780,1790                              4765
004356   1780   M1=1.0E+10                                                      4770
004360          GO TO 1820                                                      4775
004360   1790   IF (ABS(DY1).LT.1.0E-05) 1800,1810                              4780
004366   1800   M1=0.0                                                          4785
004367          GO TO 1820                                                      4790
004370   1810   M1=DY1/DX1                                                      4795
004372   1820   IF (ABS(DX2).LT.1.0E-05) 1830,1840                              4800
004400   1830   M2=1.0E+10                                                      4805
004402          GO TO 1870                                                      4810
004402   1840   IF (ABS(DY2).LT.1.0E-05) 1850,1860                              4815
004410   1850   M2=0.0                                                          4820
004411          GO TO 1870                                                      4825
004412   1860   M2=DY2/DX2                                                      4830
004414   1870   IF (IV(IIV).EQ.L1) 1880,1900                                    4835
004421   1880   SI(IP)=SX(IP-1)                                                 4840
004426          GO TO 1940                                                      4845
004425   1890   IIV=IIV+1                                                       4850
004427          IF (M1.EQ.0.0) 1900,1930                                        4855
004434   1900   IF (DP.GT.0) 1910,1920                                          4860
004440   1910   SI(IP)=-90.0                                                    4865
004443          GO TO 1940                                                      4870
004443   1920   SI(IP)=90.0                                                     4875
004446          GO TO 1940
```

```
004440   1930  IF (M1.EQ.1.0E+10) 1940,1970
004453   1940  IF (DZ.GT.0.0) 1950,1960
004460   1950  SI(IP)=0.0
004462         GO TO 1980
004463   1960  SI(IP)=180.0
004466         GO TO 1980
004466   1970  K=ITYPE(I)
004470         XT=X(L1)
004472         YT=Y(L1)
004474         CALL ANGLE (K,XT,YT,X3,Y3,ANGLER,ANGLED,IFIND,SL)
004504         SI(IP)=ANGLED
       C
       COMMENT   COMPUTATION OF FINAL ANGLE FOR CIRCLES
       C
004512   1980  CONTINUE
004512         K=ITYPE(I)
004514         CA=DX1/R
004516         SA=DY1/R
004520         XT=DX2*SA-DY2*CA
004523         YT=DX2*CA+DY2*SA
004526         CALL ANGLE (1,XT,YT,0.,0.,0.,ANGLER,ANGLED,IFIND,SL)
004537         IF (ITYPE(I).EQ.2) GO TO 1990
004546         GO TO (2010,2000,2000,2010), IFIND
004555   1990  ANGLED=-ANGLED
004557         GO TO (2000,2010,2010,2000), IFIND
004567   2000  ANGLED=360.+ANGLED
004571   2010  SF(IP)=SI(IP)+((-1)**(K+1))*ANGLED
004604         VN(3,IP)=((-1)**(K+1))*R
004616         NS=1+ABS((R*ANGLER)/3/SQRT(HOH))
004631         IPAR(IP)=NS
004636   2020  NSEG=NSEG+IPAR(IP)
       C
       COMMENT   STORE XY VALUES FOR LATER PLOT
       C
004641         IF (ITYPE(I).EQ.3) 2030,2040
       C
       COMMENT   OBTAIN FIRST AND LAST (X,Y) FOR STRAIGHT LINE PARTS
       C
004646   2030  XX(NRR)=X(L1)-XTRANS
004652         YY(NRR)=Y(L1)
004654         NRR=NRR+1
004655         XX(NRR)=X(L)-XTRANS
004660         YY(NRR)=Y(L)
004662         NRR=NRR+1
004663         GO TO 2170
004663   2040  IF (ITYPE(I).EQ.1) 2050,2110
       C       OBTAIN XY FOR CIRCLE PARTS
004670   2050  THETAI=SI(IP)-90.0
004673         THETAF=SF(IP)-90.0
004675         ALPHI=(THETAF-THETAI)/4.
004700         NPP=2.*ALPHI+1.
004703         NPP=NPP/2
004705         DO 2100 JJ=1,NPP
004706         IF (JJ.EQ.1) 2090,2060
004712   2060  IF (JJ.EQ.NPP) 2070,2080
```

```
004717    2070    THETA1=THETAF                                                 5145
004721            GO TO 2090                                                    5150
004721    2080    THETA1=THETA1+4.*                                             5155
004723    2090    XX(NNN)=XX+ABS(VN(3,IP))*COS(THETA1*RPD)-XINANS               5160
004744            YY(NNN)=YY-VN(3,IP)*SIN(THETA1*RPD)                           5165
004761            NNN=NNN+1                                                     5170
004762    2100    CONTINUE                                                      5175
004765            GO TO 2174                                                    5180
004765    2110    THETA1=SI(IP)+90.0                                            5185
004770            THETAF=S4(IP)+90.0                                            5190
004772            ALPHA=(THETA1-THETAF)/4.0                                     5195
004775            NPP=2.*ALPHA+1.                                               5200
005000            NPP=NPP/2                                                     5205
005002            DO 2140 K=1,NPP                                               5210
005003            IF (KK.EQ.1) 2150,2120                                        5215
005007    2120    IF (KK.EQ.NPP) 2130,2140                                      5220
005010    2130    THETA1=THETAF                                                 5225
005016            GO TO 2150                                                    5230
005016    2140    THETA1=THETA1-4.0                                             5235
005020    2150    XX(NNN)=XX+ABS(VN(3,IP))*COS(THETA1*RPD)-XINANS               5240
005041            YY(NNN)=YY+VN(3,IP)*SIN(THETA1*RPD)                           5245
005056            NNN=NNN+1                                                     5250
005057    2160    CONTINUE                                                      5255
005062    2170    CONTINUE                                                      5260
005062            IP=IP+1                                                       5265
005066            IF (N.EQ.NT.40) 2220,2180                                     5270
005071    2180    RPD(NT(IP)=L                                                  5275
005074            PC1=X3                                                        5280
005076            PC1=Y3                                                        5285
005076            EPSI=EPSL                                                     5290
005100            KP=IP-1                                                       5295
005101            IF (L.EQ.L2) 2200,2190                                        5300
005105    2190    L1=L                                                          5305
005107            L=L2                                                          5310
005110            X2=X(L2)                                                      5315
005111            Y2=Y(L2)                                                      5320
005113            CX=X3                                                         5325
005114            CY=Y3                                                         5330
005116            CW=0                                                          5335
005117            GO TO 670                                                     5340
005120    2200    CX=X3                                                         5345
005122            CY=Y3                                                         5350
005124            CW=W                                                          5355
005125            L1=L2                                                         5360
005126    2210    CONTINUE                                                      5365
005131    2220    IN=NP=IP-1                                                    5370
005133            SUM=0.0                                                       5375
005134            DO 2240 J=1,NPP                                               5380
005136            IF (ISS(J).EQ.7) GO TO 2230                                   5385
005141            SUM=SUM+ABS(VN(3,J))                                          5390
005145            GO TO 2240                                                    5395
005145    2230    S=VN(3,J)*(SY(J)-SI(J))*RPD                                   5400
005154            SUM=SUM+ABS(S)                                                5405
005156    2240    CONTINUE                                                      5410
005161            DO 2260 J=1,NPP                                               5415
```

```
005162          IF (ISS(J).EQ.7) GO TO 2250
005165          S=ABS(VN(3,J))
005170          RAT=S/SUM
005172          AMPP=RAT*TINT
005174          IF (AMPP.LT.1.0) AMPP=1.0
005200          INT(J)=1+AMPP/IPAR(J)
005207          GO TO 2260
005210   2250   S=VN(3,J)*(SX(J)-SI(J))*HPU
005217          RAT=ABS(S)/SUM
005221          AMPP=RAT*TINT
005223          IF (AMPP.LT.1.0) AMPP=1.0
005227          INT(J)=1+AMPP/IPAR(J)
005230   2260   CONTINUE
005241          DO 2330 I=1,IORN
005242          K=ISS(I)
005244          J1=KPOINT(I)
005246          J2=KPOINT(I+1)
005247          IVAR=1
005250          TH1=THICK(J1)
005252          J11=J1+1
005254          DO 2270 J=J11,J2
005255          TH2=THICK(J)
005257          IF (TH1.EQ.TH2) GO TO 2270
005261          IVAR=2
005262          J=J2
005263   2270   CONTINUE
005266          IF (IVAR.EQ.2) GO TO 2280
005270          TDIST(I)=DAVE
005273          VH(1,I)=TH1
005275          VARTIK(I)=0
005277          GO TO 2330
005300   2280   CONTINUE
005306          IF (J2-J1+1.GT.10) CALL EXITO (11,1)
005312          IF (K.EQ.7) GO TO 2310
005316          XP(1,I)=0.0
005320          YP(1,I)=THICK(J1)
005324          TDIST(I)=DMMD
005327          VARTIK(I)=J2-J1+1
005333          KK=1
005334          DO 2290 J=J11,J2
005336          DX=X(J)-X(J-1)
005341          DY=Y(J)-Y(J-1)
005343          DS=SQRT(DX**2+DY**2)
005351          KK=KK+1
005352          XP(KK,I)=DS+XP(KK-1,I)
005361          YP(KK,I)=THICK(J)
005365   2290   CONTINUE
005373   2300   IF (K.EQ.7) ISS(I)=0
005377          GO TO 2330
005400   2310   XP(1,I)=SI(I)
005405          YP(1,I)=THICK(J1)
005411          TDIST(I)=DMMD
005414          VARTIK(I)=J2-J1+1
005420          KK=1
005421          X3=VN(2,I)
```

```
005423          V3=VN(4,I)                                                      5705
005426          CR=ABS(VN(3,I))                                                 5710
005431          X1=X(J1)                                                        5715
005433          Y1=Y(J1)                                                        5720
005436          CA=(X1-X3)/CR                                                   5725
005437          SA=(Y1-Y3)/CR                                                   5730
005442          DO 2320 J=J1,J2                                                 5735
005446          DX2=X(J)-X3                                                     5740
005447          DY2=Y(J)-Y3                                                     5745
005451          XT=DX2*SA-DY2*CA                                                5750
005455          YT=DX2*CA+DY2*SA                                                5755
005457          CALL ANGLE (1,XT,YT,0.,0.,ANGLER,ANGLED,IND,SL)                 5760
005470          DTHETA=ABS(ANGLED)                                              5765
005476          IFLL=SA(I)-SI(I)                                                5770
005502          IF=1                                                            5775
005503          IF (IFLL.GT.0.0) IF=2                                           5780
005505          KK=K+1                                                          5785
005507          XP(KK,I)=XP(KK-1,I)+((-1)**IF(I))*DTHETA                        5790
005522          YP(KK,I)=YTHICK(J)                                              5795
005527          CO=U2/CN                                                        5800
005531          SA=DY2/CR                                                       5805
005533  2320    CONTINUE                                                        5810
005535  2330    CONTINUE                                                        5815
005540          IF (NELAS.EQ.NAMED) GO TO 2340                                  5820
005542          VNOD(I)=0.0                                                     5825
005543          PRAT(I)=0.0                                                     5830
005544  2340    IF (NPRES.EQ.NAMED) GO TO 2350                                  5835
005547          DCPS(I)=0.0                                                     5840
005550          QFD(I)=6.0                                                      5845
005551          PRES(I)=0.0                                                     5850
005552  2350    CONTINUE                                                        5855
005556          IF (NELAS.EQ.NAMEC.AND.NPRES.EQ.NAMEC) GO TO 2390               5860
005562          J=1                                                             5865
005563          K=1                                                             5870
005564          PPS=PRES(K)                                                     5875
005566          DD=JEV(K)                                                       5880
005567          VNO=VNOD(J)                                                     5885
005571          PRT=PRAT(J)                                                     5890
005573          DEN=DENS(K)                                                     5895
005576          II=2                                                            5900
005575          DO 2360 I=1,IMAX                                                5905
005577          VI(5,I)=PPS                                                     5910
005602          VN(7,I)=VNO                                                     5915
005604          VN(6,I)=DEN                                                     5920
005607          EVN(I)=VNO                                                      5925
005611          PSR(I)=PRT                                                      5930
005616          IF (NPJNT(I+1).NE.IV(II+1)) GO TO 2340                          5935
005617          IF (JFLAS(J).NE.NPOINT(I+1)) GO TO 2340                         5940
005622          IF (NELAS.EQ.NAMEC) GO TO 2360                                  5945
005626          J=J+1                                                           5950
005627          VNO=VNOD(J)                                                     5955
005631          PRT=PRAT(J)                                                     5960
005631  2340    IF (NPRES.EQ.NAMEC) GO TO 2370                                  5965
005634          IF (JPRES(K).NE.NPOINT(I+1)) GO TO 2370                         5970
005637          K=K+1                                                           5975
```

```
005640          PPS=PRES(K)
005642          DD=DED(K)
005644          UE=DUENS(K)
005645   2370   CONTINUE
005645          IIV=IIV+1
005647   2380   CONTINUE
005652   2390   CONTINUE
005652          NP=NN-1
005654          WRITE(6,4501)
005657          CALL SCALE1(XX,10.0,NNR,1,10.0)
005663          CALL SCALE1(YY,0.0,NNR,1,10.0)
005667          XX1=XX(NNR+1)
005671          XXD=XX(NNR+2)
005673          YY1=YY(NNR+1)
005674          YYD=YY(NNR+2)
005676          IF (YYD.GT.XXD) GO TO 2400
005705          YY1=-XXD
005705          YYD=XXD
005705          GO TO 2410
005707   2400   XX1=-YYD
005711          XXD=YYD
005712   2410   CONTINUE
005712          CALL DIKSET (10.0,XX1,XXD,0.0,YY1,YYD)
005716          CALL DIKPLT (XX,YY,NNR,3HOX0,3HOY0,7HOSOUR.L0)
005722          CALL PLOT (-11.0,1.0,-3)
005725          CALL DLINE (X0,Y0,-NPTS,3)
005732          CALL PLOT (-2.5,-1.0,-3)
005735          ENCODE (80,2600,ITITLE) TITLE1
005751          CALL SYMBOL (0.5,2.0,0.14,ITITLE,90.0,80)
005755          ENCODE (80,2600,ITITLE) TITLE2
005771          CALL SYMBOL (1.0,2.0,0.14,ITITLE,90.0,80)
005775          ENCODE (80,2600,ITITLE) TITLE3
006011          CALL SYMBOL (1.5,2.0,0.14,ITITLE,90.0,80)
006015          CALL PLOT (15.0,0.0,-3)
006020          CALL ENDPLT
006021          RETURN
006022   2420   CALL EXIT
         C
006023   2430   FORMAT (3I5)
006023   2440   FORMAT (3F10.5,2X,A2,3X,A2)
006023   2450   FORMAT (8F10.5)
006023   2460   FORMAT (////50X,22HCOORDINATES AS READ IN/////47X,1HI10X,4HX(I)8X,
               14HY(I))
006023   2470   FORMAT ((1H0,63X,I4,4X,2(F14.5,2X)))
006023   2480   FORMAT (16I5)
006023   2490   FORMAT (1H1,20A4/(1H0,20A4))
006023   2500   FORMAT (/////25X,13HNO. OF POINTS15X,15HNO. OF VERTICES20X,9HTOLER
               1ANCE//30X,I5,25X,I5,17X,E12.4////)
006023   2510   FORMAT (///45X,34HCOORDINATES AS MODIFIED BY DATA SET 9.////29X,1H
               1I16X,4HX(I)14X,4HY(I)11X,9HAT=I(K(I)/)
006023   2520   FORMAT (1H0,10X,25HFAILED TO FIND VERTEX NO.,I4)
006023   2530   FORMAT (1H025X,I4,3(10X,F19.5),5X,22HTHIS POINT IS A VERTEX)
006023   2540   FORMAT (1H025X,I4,3(19X,F10.5))
006023   2550   FORMAT (/////49X,31HPRELIMINARY GROUPING OF POINTS///51X,11HFIRST
               1POINT25X,10HLAST POINT/11X,1H16X,4HTYPE(I)1/X,1HX11X,1HY23X,1HX11
```

```
                  2X,1HY)
006023    2560  FORMAT (1H0I5X,I4,I4X,I4,6X,2F12.4,12X,2F12.4)
006023    2570  FORMAT (1H0I1X,3AHFITTING DATA FOR GROUP OF POINTS NO.I4)
006023    2580  FORMAT (////////////1OX,33HTHIS GROUP OF POINTS IS COLINEAR.
                1 22H IT EXTENDS FROM POINT  I3, 9H TO POINT  I3, 1H. )
006023    2590  FORMAT (1H0,5X,5HL1 = ,I2,7H  L2 = ,I2,6H  L = ,I2,7H  X3 = ,F10.5
                1,7H  Y3 = ,F10.5,6H  R = ,F10.5)
006023    2600  FORMAT (1H0,5X,4HJ = ,I2,7H  NP = ,I2,7H  X4 = ,F10.5,7H  Y4 = ,F1
                10.5,9H  EPS = ,E20.8,25H INTERMEDIATE POINT CHECK)
006023    2610  FORMAT (1H0,5X,4HJ = ,I3,7H  X4 = ,F10.5,7H  Y4 = ,F10.5,8H  EPS =
                1 ,E20.8,25H  FOLLOWING POINT CHECK)
006023    2620  FORMAT (1H0,30X,6HRSIF(I,3X,6HIF(IT,14X,2HEP)
006023    2630  FORMAT (1H0,30X,F10.5,2X,I5,2X,E20.8)
006023    2640  FORMAT (1H0,1X,E20.8,13HOF THE CURVE.)
006023    2650  FORMAT (1H0,1X,5HLL = ,I3,25H IS THE BEST TRIAL POINT.)
006023    2660  FORMAT (2A4)
006023    4001  FORMAT(1H1)
006023          END
```

```
                 SUBROUTINE EXITD (IEXIT,I)
000005           GO TO (20,30,40,50,60,70,80,90,100,110,120,130,140), IEXIT
000025     20    PRINT 160, I
000033           GO TO 150
000035     30    PRINT 170, I,I,I
000047           GO TO 150
000051     40    PRINT 180
000055           GO TO 150
000057     50    PRINT 190, I
000065           GO TO 150
000067     60    PRINT 200, I
000075           GO TO 150
000077     70    PRINT 210, I
000105           GO TO 150
000107     80    PRINT 220, I
000115           GO TO 150
000117     90    PRINT 230, I
000125    100    I=I+1
000130           PRINT 240, I
000135           I=I-1
000140           GO TO 150
000140    110    PRINT 250
000144           GO TO 150
000146    120    PRINT 260, I
000154           GO TO 150
000156    130    PRINT 270, I
000164           GO TO 150
000166    140    PRINT 280, I
000174    150    RETURN
           C
000175    160     FORMAT (1H0,5HPOINT,I5,3X,61HIS OUT OF ORDER.CHECK DATA. DID YOU F
                1ORGET TO LABEL A VERTEX.)
000175    170     FORMAT (1H0,6HPOINTS,I5,1H,,I5,2H ,,1H,,3HAND,I5,2H ,2,94HFORM A RI
                1GHT ANGLE. EITHER THE MIDDLE POINT IS A VERTEX OR MORE POINTS ARER
                2EQUIRED IN THISREGION.)
000175    180     FORMAT (1H0,45HTOO MANY PARTS. THE TANGENT HAS CHANGED DIRECTION M
                1ORE THAN 40 TIMES.)
000175    190     FORMAT (1H0,37HTHE CURVATURE HAS REVERSED IN SECTION,I2,1H.)
000175    200     FORMAT (1H0,42HMORE THAN 40 SEGMENTS ARE REQUIRED IN PARTS,I2,1H.)
000175    210     FORMAT (1H0,4HPART,I2,1X,10HHAS ZERO AREALENGTH)
000175    220     FORMAT (1H0,42HNO SUITABLE INFLECTION POINT STARTING PART,I5,10HWA
                1S FOUND.)
000175    230     FORMAT (1H0,5HPOINT,I3,2X,91HHAS NEGATIVE VALUE AFTER TRANSLATION.
                1CHECK THE VALUE OF XTRANS READ IN ON SECOND DATA CARD.)
000175    240     FORMAT (1H0,5HPOINT,I3,1X,16HIS NOW ONLY WITHIN)
000175    250     FORMAT (1H0,44HLAST POINT OF LINE LIES INSIDE PRECEEDING CIRCLE.)
000175    260     FORMAT (1H0,5HPART ,I1,1X,91HHAS MORE THAN 10 THICKNESS VARIATIONS
                1. REDUCE NO. OF THICKNESS SPECIFICATIONS IN THIS PART.)
000175    270     FORMAT (1H0,4HJELAS(,I3,44H) DOES NOT CORRESPOND TO A VERTEX INDEX
                1.)
000175    280     FORMAT (1H0,4HJPRES(,I3,44H) DOES NOT CORRESPOND TO A VERTEX INDEX
                1.)
000175            END
```

```
                SUBROUTINE ANGLE (I,X1,Y1,XC,YC,ANGLER,ANGLED,IFIND,SL)                  5
000010          DPR=57.29577951                                                         10
000015          PI=3.1415926                                                            15
000016          X=X1-XC                                                                 20
000020          Y=Y1-YC                                                                 25
000021          IF (I.EQ.1) GO TO 10                                                    30
000024          X=-X                                                                    35
000025          Y=-Y                                                                    40
000026    10    IF (ABS(X).LT.1.0E-05.OR.ABS(Y).LT.1.0E-05) GO TO 20                    45
000042    20    I1=2                                                                    50
000043          I2=2                                                                    55
000044          IF (X.LT.0.0) I1=3                                                      60
000047          IF (Y.LT.0.0) I2=3                                                      65
000052          IFIND=I1*I2                                                             70
000055          IF (IFIND.EQ.4) IFINC=1                                                 75
000061          IF (IFIND.EQ.3) IFINC=4                                                 80
000064          IF (IFIND.EQ.6) IFINC=2                                                 85
000067          IF (IFIND.EQ.27) IFINC=3                                                90
000072          SL=ABS(Y/X)                                                             95
000074          SL=(PI/2.)-ATAN(SL)                                                     100
000102          GO TO (30,40,50,60), IFIND                                              105
000116    30    ANGL=SL                                                                 110
000120          GO TO 70                                                                115
000120    40    ANGL=-SL                                                                120
000122          GO TO 70                                                                125
000122    50    ANGL=SL-PI                                                              130
000125          GO TO 70                                                                135
000125    60    ANGL=PI-SL                                                              140
000130    70    ANGLER=ANGL                                                             145
000131          ANGLED=ANGL*DPR                                                         150
000133          GO TO 150                                                               155
000136    80    CONTINUE                                                                160
000136          IF (ABS(X).LT.1.0E-05) 90,100                                           165
000142    90    ANGL=PI                                                                 170
000144          GO TO 140                                                               175
000146    100   IF (X) 120,130,110                                                      180
000150    110   ANGL=PI/2.                                                              185
000150          GO TO 140                                                               190
000151    120   ANGL=3.*PI/2.                                                           195
000154          GO TO 140                                                               200
000154    130   CALL EXIT0 (4,1)                                                        205
000156          CALL EXIT                                                               210
000157    140   IFIND=1                                                                 215
000161          GO TO 70                                                                220
000163    150   RETURN                                                                  225
000166          END                                                                     230
```

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13. ABSTRACT

A two and one-half year program was conducted to investigate the tilt-edge bellows concept. This involved the idea that the stresses at the convolution root and crown welds of a welded bellows could be minimized by appropriately tilting the convolution mid surfaces near the root and crown. The research program involved an extensive theoretical analysis of various convolution cross-sectional shapes to optimize the shape with respect to the maximum stress as well as the weld bead stresses. A particular optimized bellows with a 3.5-inch OD was fabricated and tested. The results of the tests verified that the tilt-edge bellows had superior fatigue resistance. Further, the fatigue failures occurred at positions away from the welds which verified that the weld bead stresses were small. Elimination of fatigue failures at the convolution and end fitting welds also resulted in reduced scatter in bellows fatigue life. This should allow fatigue life predictions to be made with greater confidence for tilt-edge bellows than for conventional welded bellows designs.

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Elastic Analysis						
Linear Shell Analysis						
Metallic Bellows						
Nonlinear Shell Analysis						
Stress Analysis						
Welded Bellows						