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PHOTOELASTIC STUDY

KIWI-B PRESSURE VESSEL NOZZLE END

ACF-100

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TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
1	INTRODUCTION	1
2	OBJECTIVE	1
3	CONCLUSIONS	1
4	MATERIAL AND EQUIPMENT	2
5	DISCUSSION	2
5.1	Fabrication of Models	2
5.2	Assembly of Model	6
5.3	Loading Conditions	6
5.4	Slicing of Models	8
5.5	Machining of Slices	8
5.6	Analysis of Slices	9
5.7	Discussion of Results	13
<u>Appendix</u>		
Exhibit 1	SCALE MODEL TEST ASSEMBLY	
Exhibit 2	SCALE MODEL PRESSURE VESSEL	
Exhibit 3	SCALE MODEL TEST NOZZLE	
Exhibit 4	MOLD	
Exhibit 5	MOLD	
Exhibit 6	BASE	
Exhibit 7	KIWI-B CALIBRATION BEAM	
Exhibit 8	POURING PLASTIC INTO MOLDS	

TABLE OF CONTENTS (Continued)

Appendix

Exhibit 9	MODEL BLANKS AFTER CURING
Exhibit 10	MACHINING OUTSIDE OF MODEL
Exhibit 11	MACHINING INSIDE OF MODEL
Exhibit 12	COMPLETED KIWI-B MODEL PARTS
Exhibit 13	ASSEMBLED KIWI-B MODEL
Exhibit 14	CUTTING RADIAL SLICE FROM STRESS-FROZEN MODEL
Exhibit 15	MACHINING RADIAL SLICE
Exhibit 16	EXPLODED VIEW OF SLICED MODEL
Exhibit 17	RADIAL SLICE THROUGH BOLT HOLE
Exhibit 18	RADIAL SLICE BETWEEN BOLT HOLES
Exhibit 19	LONGITUDINAL STRESSES
Exhibit 20	TABULATION OF LONGITUDINAL STRESSES
Exhibit 21	GRAPH OF LONGITUDINAL STRESSES
Exhibit 22	CIRCUMFERENTIAL STRESSES
Exhibit 23	TABULATION OF CIRCUMFERENTIAL STRESSES
Exhibit 24	GRAPH OF CIRCUMFERENTIAL STRESSES

PHOTOELASTIC STUDY
KIWI-B PRESSURE VESSEL NOZZLE END

1. INTRODUCTION

The three-dimensional photoelastic study discussed in this report was undertaken to assist the Special Engineering Systems Analysis Group in the design and analysis of the KIWI-B pressure vessel. Areas of responsibility and proposed schedules were mutually agreed upon at the initial planning meeting held on February 14, 1961, attended by representatives of Development and Test, Special Engineering, and Product Engineering. It was agreed that Development and Test would furnish the blank casings for the model and do the stress freezing and analysis, Special Engineering would furnish required drawings of the model, and Product Engineering would supervise required tooling and manufacturing processing of the model.

2. OBJECTIVE

The objective of this study was to determine the distribution of stresses in the nozzle area of the KIWI-B pressure vessel under arbitrary internal pressure.

3. CONCLUSIONS

Model stresses and equivalent part stresses are presented in tabular form in Exhibits 20 and 23. Equivalent part stresses are presented in graphical form in Exhibits 21 and 24.

4. MATERIAL AND EQUIPMENT

- 4.1. The photoelastic models were made of epoxy ERL 2774 plastic catalyzed with phthalic anhydride and hexahydrophthalic anhydride.
- 4.2. A model 1225 Hotpack oven equipped with the stepless controller was used in the curing and stress freezing of the models.
- 4.3. The models were machined on a 25-inch American boring and turning lathe and a 46-inch Bullard vertical turret lathe.
- 4.4. All drilling and tapping on the nozzle and vessel models was done on a tape-controlled Burgmaster turret drilling and tapping machine.
- 4.5. The pressure vessel model was sliced on a DoAll Contourmatic band saw.
- 4.6. Machining of the slices was done on a Bridgeport milling machine.
- 4.7. A Jones and Lamson Model PC-30 20X optical comparator was used to measure the rotation of the flange on the stress-frozen model.
- 4.8. A diffused light polariscope equipped with a Polaroid camera with green filter attachment was used in the analysis of the slices.

5. DISCUSSION

5.1. Fabrication of Models.

- 5.1.1. The molds used in casting the plastic blanks from which the

models were machined as shown in Exhibits 4 and 5. A collapsible layer of cardboard was wrapped around the inner cone of the vessel mold shown in Exhibit 4 to allow for shrinkage of the plastic during the gelling cycle. This wrapping was then sealed with a room-temperature-curing resin consisting of 50 parts ERL 2774 and 50 parts Versamid 120. The molds were then coated with a generous amount of DC-4 mold release compound to eliminate sticking of the castings and the molds.

- 5.1.2. The castings were made from a mix consisting of 100 parts ERL 2774, 42 parts phthalic anhydride, and 20 parts hexahydrophthalic anhydride. After the ERL 2774 and the hexahydrophthalic anhydride had been pre-heated to 100° C, the hexahydrophthalic anhydride was poured into the ERL 2774 through a cheesecloth filter. Phthalic anhydride was then added and the mixture heated to 115° C and stirred until all the phthalic anhydride was in solution. The solution was then poured into the molds, which had been pre-heated to 95° C, and put in the oven to gel. After the plastic was poured into the molds, a leak was noticed at the juncture of the vessel mold and its base plate. It was necessary to remove the plastic from the vessel mold and construct a putty dam around the juncture where the leak had occurred. Before the plastic was poured back into the mold, it had to be re-heated and mixed to put the phthalic anhydride back into solution. Since this procedure was not followed in regards to the calibration beam and nozzle simulator blanks, it is pos-

sible that these parts could have slightly different optical and physical properties than the vessel part.

- 5.1.3. Gelling of the plastic was accomplished by leaving the filled molds in the oven for approximately three days at 92° C. As soon as the plastic gelled, the oven was cycled to 100° C at the rate of 1° C per hour and back to room temperature at a rate of 3° C per hour. At this time the plastic blanks were removed from the molds and the mold release compound cleaned off the blanks in preparation for the curing cycle.
- 5.1.4. All three plastic blanks, calibration beam, vessel, and nozzle were then put in the oven for final curing. The oven temperature was raised to 100° C at 2° C per hour and then to 150° C at 1/2° C per hour, at which temperature the blanks were allowed to soak for eight days. The temperature was then lowered to 100° C at 1/2° C per hour and on to room temperature at 1° C per hour. A crusty composition was observed on the outside nose surface of the nozzle blank. This was probably caused by mixing of mold release compound with the plastic during pour. This encrustation was no problem, however, since it was removed when the nozzle blank was machined.
- 5.1.5. The calibration beam was machined in the Development and Test Model Shop to the dimensions shown in Exhibit 7. This machining was done on a Bridgeport milling machine and required finishing cuts of three mils to prevent chipping of the edges of the beam.
- 5.1.6. The model vessel and nozzle were machined in the Production

Shop according to the prints shown in Exhibits 2 and 3. The vessel simulates only the nozzle end of the prototype. All dimensions, including tolerances, were scaled to one-quarter prototype part size. The nozzle was machined on a 25-inch American boring and turning lathe and the vessel was machined on a 46-inch Bullard turret lathe. All required drilling and tapping was done on a tape-controlled Burgmaster turret drilling and tapping machine. Since the epoxy plastic used in making the blanks is extremely brittle and abrasive, it was necessary to keep the cutting tool flooded at all times with a coolant consisting of one part Prestone and two parts water, and to use sharp-grade carbide turning tools. Cutting speeds ranged from 200 to 400 surface feet per minute depending on the depth of cut. Maximum roughing cuts taken were .125-inch deep with .005-inch tool advance per revolution. Maximum semi-finish cuts were .030-inch deep with .005-inch tool advance per revolution. Maximum finish cuts were .005-inch deep with .003-inch tool advance per revolution. Parts were never allowed to stand horizontally in the lathe for any extended period of time because the plastic tends to sag when in this unsymmetrical position. Whenever it was necessary to leave parts in the horizontal lathe overnight or over a weekend, the machine was kept rotating at 40 revolutions per minute. When the parts were not in a machine, they were placed flange-end down on a horizontal surface to prevent warpage and sag.

5.2. Assembly of Model.

- 5.2.1. The model parts were assembled as shown in Exhibits 1 and 13. Fillister head NF-632-1 nylon screws cut off to seven-eighths inch length were used to fasten the nozzle to the vessel. Due to the tight fit between screws and tapped holes and the high friction developed, it was necessary to lubricate the screws with Kel-F grease in order to insert them. The nylon screws tended to "wind-up" when they were screwed into place, making it impossible to apply a pre-determined torque. It was necessary to tighten the screws three times with prolonged intervals between each torquing application to allow for relaxation of the screws. Kel-F grease was also used as a sealant between mating surfaces of the nozzle and vessel.
- 5.2.2. Exhibit 6 shows the aluminum base plate to which the plastic model was fastened with steel bolts. Kel-F grease was again used as a sealant between mating surfaces of the model and base plate.

5.3. Loading Conditions.

- 5.3.1. The pressurizing system used to load the model during the stress-freezing cycle consisted of a high-pressure nitrogen bottle pressure source, a cartesian manostat controller, a pressure bleed valve, a pressure gauge, and a permanent pass-through fixture installed in the side of the oven. Quarter-inch stainless steel tubing was used as a pressure line outside the oven. An adjustable loop of eighth-inch stainless steel tubing

was used as a pressure line between the pass-through and the model base plate inside the oven. The pressure bleed valve was inserted between the manostat and the pressure gauge to permit adjustment of line pressure during the stress-freezing cycle.

5.3.2. The stress-freezing cycle consisted of heating the models to 170° C at a rate of 4° C per hour. At this temperature, the models were soaked for two hours, during which time a gauge pressure of one pound per square inch was applied through the pressurizing system. The model was kept under pressure while the oven was cycled to 140° C at 4° C per hour. At this temperature the stress fringes were frozen in the model. The pressure in the system was released and the oven allowed to drop to room temperature at 4° C per hour. Due to variations in pressure through the manostat, it was necessary to monitor the pressurizing system throughout the test and to make adjustments in line pressure with the pressure bleed valve. After the test was completed, the pressure gauge was checked and found to be in error. Instead of one pound per square inch pressure, it was determined that the true line pressure had been between 0.8 and 0.9 psi. It is recommended that in any future three-dimensional photoelastic tests, a more dependable pressure control system be utilized.

5.3.3. A constant moment load as shown in Exhibit 7 was applied to the calibration beam during the stress-freezing cycle described

in the previous paragraph. Since the static load was applied using the standard loading pan technique, it was decided to apply the load throughout the entire cycle.

5.4. Slicing of Models.

5.4.1. To facilitate slicing procedures, the model was first cut normal to its axis of rotation through the cylindrical section. Radial slices were then cut from the sectioned model on a DoAll saw, as shown in Exhibit 14. Two radial slices were cut between bolt holes, one for analysis of longitudinal stresses and one for subslicing to determine circumferential stresses. Another radial slice was cut through a bolt hole to determine the effect of localized bolt loads. Exhibits 17 and 18 present photographs of these radial slices as they are seen through the polariscope.

5.4.2. One circumferential slice was cut from the cylindrical portion of the model. This slice was approximately a 40° sector of the cylinder and was used in the determination of actual pressure applied to the model during the test.

5.4.3. One radial slice was subsliced as shown in Exhibits 22 and 23. A jeweler's saw was used for this operation because of the accuracy required.

5.5. Machining of Slices.

5.5.1. All of the slices and subslices were machined in the Development and Test Model Shop on a Bridgeport milling machine. Wooden holding fixtures cut to the shape of the radial slices

were used in machining the radial slices in order to lessen the resulting vibration.

5.5.2. An M-2 high-speed steel Shell End Mill cutter three inches in diameter was used in the machining operations. In order to reduce chipping of the edge of the slices, the cutter was turned at 1750 RPM and finishing cuts were held to three mils. Because of the high cutter speed, the small cuts, and the slow feeds which were used, it was not necessary to use coolant in this machining operation.

5.6. Analysis of Slices.

5.6.1. Boundary effects confused the first attempts at analyzing the slices. The particular plastic formulation used in the models was found to be very susceptible to moisture. Compression fringes formed on the slices after only several hours of exposure to the high humidity of the photoelasticity laboratory. It was thus necessary to keep the slices in the oven overnight at 80° C before analysis. Analysis time on any one slice was limited to about three hours.

5.6.2. The Tardy method of determining fractional fringe orders was used exclusively in analyzing the slices. With polarizer and analyzer crossed (dark field) and coinciding with the principal stress directions at a point on the boundary of a slice, the analyzer was rotated through an angle of ϕ until extinction occurs at the point in question. Then

$$n = r + \phi/180$$

where r is the order of the last visible fringe and n is the final fringe order at the point. If extinction is obtained by rotation in the opposite direction, the equation becomes

$$n = r - \phi/180.$$

The direction of rotation was determined by the desirability of moving a lower order fringe up to the point (first equation) or moving a higher order fringe down to the point (second equation). The nearest integral fringe order, r , was determined at each point by flexing the slices in the polariscope and observing the relationship of the nearest fringe to the easily-distinguishable zero fringe. After a little practice, the determination of final fringe orders proved to be no problem.

5.6.3. The material fringe constant, f , was determined from analysis of the stress-frozen calibration beam using the following equation:

$$f = \frac{12M}{h^3} \frac{Y}{n}$$

where

M = constant moment applied to beam - 2.5-inch pounds

h = depth of beam - 0.963-inches

Y = distance from neutral axis of beam to fringe under consideration

n = fringe under consideration

The average value of Y/n for the calibration beam was found to be 0.0694. Thus the fringe constant was computed to be 2.33 psi/fringe/inch.

SEE
page 156-163
of Enock's Vol I
for derivation

5.6.4. Since a faulty pressure gauge was used in the stress-freezing portion of the test, it was necessary to determine the model test pressure from analysis of radial and circumferential slices taken from the cylindrical portion of the model. A value for model pressure was obtained from analysis of longitudinal stress at the outside boundary of the cylindrical portion of the radial slices. The equations used for this analysis are

$$\frac{Pr}{2t_v} = \frac{nf}{t_s}$$

$$P = \frac{2nft_v}{rt_s}$$

where

P = pressure in model

n = fringe order on outside boundary of slice

f = material fringe constant

t_v = wall thickness of vessel

r = radius of vessel

t_s = thickness of slice

Model pressure was also computed using the stress in the circumferential slice described in paragraph 5.4.2. The equation used in determining model pressure from circumferential stress on the outside boundary is

$$P = \frac{nft_v}{rt_s}$$

The average value of model pressure computed from the slices using these equations was 0.84 psi.

5.6.5. Longitudinal stresses were determined at model locations as shown in Exhibits 19 and 20. Analysis was made of the shoulder area only because this was the area of interest to Special Engineering. The Tardy method, as described in paragraph 5.6.2., was used to determine the fringe order at desired locations on the boundary of the slice. Longitudinal stresses on the boundaries of the slice were determined from the equation

$$p - q = \frac{nf}{t}$$

where

P = maximum principal stress

q = minimum principal stress

Since $q = 0$ on the outside boundary, the equation for longitudinal stress on the outside boundary reduces to

$$p = \frac{nf}{t}$$

On the inside boundary, $q = -P$ and the equation for longitudinal stress on the inside boundary is

$$p = \frac{nf}{t} - P$$

5.6.6. Circumferential stresses were determined at model locations as shown in Exhibits 22 and 23. Equations presented in the previous paragraph were also used for computing the circumferential stresses. Thus, circumferential stress on the outside boundary is expressed by

$$p = \frac{nf}{t}$$

and on the inside boundary by

$$p = \frac{nf}{t} - P$$

5.6.7. Conversion of model stresses to equivalent part stresses

was accomplished by using the equation

$$S_p = S_m \frac{P_p}{P_m}$$

where

S_m = model stress at a point

S_p = equivalent ^{prototype} part stress

P_p = internal pressure in part ^{type}

P_m = internal pressure in model

The angle of rotation of the flange on the model due to the strain level was measured on an optical comparitor and found to be $42\frac{1}{2}$ minutes. Structural tests on the prototype part at various pressures in the Special Engineering Test Cell have indicated that an internal part pressure of 232 psi causes this same flange rotation of $42\frac{1}{2}$ minutes. In order to better simulate the structural tests, it was decided to convert all model stresses to equivalent part stresses at a part pressure of 232 psi. At this pressure, the loaded geometries of the model and prototype are similar. Model stresses and equivalent part stresses are tabulated in Exhibits 20 and 23. Equivalent part stresses are shown in graphical form in Exhibits 21 and 24.

5.7. Discussion of Results.

5.7.1. Comparison of part stresses determined in this study to part stresses measured on the prototype showed the photoelas-

tically determined part stresses to be somewhat lower. Maximum longitudinal stresses determined photoelastically are 12,584 psi tension and 4,972 psi compression. Corresponding maximum longitudinal stresses determined in prototype tests are 17,300 psi tension and 11,000 psi compression. Maximum circumferential shoulder stresses determined photoelastically are 4,461 psi tension and 3,601 psi compression. Corresponding maximum circumferential stresses determined in prototype tests are 2,500 psi tension and 4,500 psi compression.

5.7.2. The lower stresses evaluated in the photoelastic test result from lower equivalent bending in the shoulder area of the photoelastic model. Two theories have been presented to explain the excessive restraint exhibited by the flange area of the photoelastic model. One explanation holds that the joint between the vessel and nozzle was too tight, thereby reducing the rotation of the flange area. The other possible explanation is that the load in the nylon bolts holding the nozzle to the head was greater than it should have been to simulate the prototype test. This condition would also restrain the flange of the model from rotating and thereby reduce the bending moment developed in the shoulder area of the model. Investigation of these two possibilities is underway. A later report will present the results of these studies along with results of the next model test.

To a point where the material is not allowed to rotate. This is a restraint. The joint between the vessel and nozzle was too tight, thereby reducing the rotation of the flange area. The other possible explanation is that the load in the nylon bolts holding the nozzle to the head was greater than it should have been to simulate the prototype test. This condition would also restrain the flange of the model from rotating and thereby reduce the bending moment developed in the shoulder area of the model. Investigation of these two possibilities is underway. A later report will present the results of these studies along with results of the next model test.

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2	WA. HEN. A. S. SE. D. *S. S. D.	9	
3	BO. T. H. E. X. H. O. S. T. E. *S. S. O. N. B. A. S. S. L. O.	10	
4	3 50599 00 BASE	11	
5	3 50599 00 SCALE MODEL PRE. USE. VE. a	12	
6	3 50599 00 SCALE MODEL TEST ASSEMBLY	13	
7	3 50599 00	14	
8	PART NO. DESCRIPTION & MATERIAL	15	
9	LIST OF MATERIAL	16	
10		17	
11		18	
12		19	
13		20	
14		21	
15		22	
16		23	
17		24	
18		25	
19		26	
20		27	
21		28	
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[illegible]

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EXHIBIT 3

NOTES -
 1. BREAK ALL CORNERS & SHARP EDGES
 2. STRETCH THE STCH TOOL AT ALL LONG PARTS
 3. STRETCH ON COULD FOR TOOL
 4. NEW "NEW" TO
 5. ALL P. SHEN CLIPPING TO BE

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2	400	1000	1000
3	400	1000	1000
4	400	1000	1000
5	400	1000	1000
6	400	1000	1000
7	400	1000	1000
8	400	1000	1000
9	400	1000	1000
10	400	1000	1000
11	400	1000	1000
12	400	1000	1000
13	400	1000	1000
14	400	1000	1000
15	400	1000	1000
16	400	1000	1000
17	400	1000	1000
18	400	1000	1000
19	400	1000	1000
20	400	1000	1000

EXHIBIT 4

Thickness of Beam = 0.214"

KIWI-B CALIBRATION BEAM

EXHIBIT 7

POURING PLASTIC INTO MOLDS

EXHIBIT 8

MODEL BLANKS AFTER CURING

EXHIBIT 9

MACHINING OUTSIDE OF MODEL
EXHIBIT 10

MACHINING INSIDE OF MODEL
EXHIBIT 11

COMPLETED KIWI-B MODEL PARTS

EXHIBIT 12

ASSEMBLED KIWI-B MODEL

EXHIBIT 13

CUTTING RADIAL SLICE FROM STRESS-FROZEN MODEL

EXHIBIT 14

MACHINING RADIAL SLICE

EXHIBIT 15

EXPLODED VIEW OF SLICED MODEL
EXHIBIT 16

RADIAL SLICE THROUGH BOLT HOLE

EXHIBIT 17

RADIAL SLICE BETWEEN BOLT HOLES

EXHIBIT 18

LONGITUDINAL STRESSES

NOTES: n = Fringe order

f = 2.33 psi/fringe/inch Material fringe constant

t = 0.251" Average thickness of slice

S_{mo} = $\frac{nf}{t}$ Stress on outside boundary of model

S_{mi} = $\frac{nf}{t} - P_m$ Stress on inside boundary of model

P_m = 0.84 psi Internal pressure in model

P_p = Internal pressure in ^{prototype}part

S_p = $\frac{S_m P_p}{P_m} = \frac{232 S_m}{.84} = 276 S_m$ Equivalent ^{prototype}part stress with 232 psi internal pressure

TABULATION OF LONGITUDINAL STRESSES

Point	X	Y	n	S _m	S _p
Inside Boundary					
a _i	-.49	.98	2.92	26.26	7252
b _i	-.37	.84	3.73	33.77	9326
c _i	-.25	.70	4.39	39.90	11020
d _i	-.14	.54	4.94	45.00	12428
e _i	-.06	.37	5.00	45.56	12584
f _i	-.02	.18	4.50	40.92	11301
g _i	0	0	3.50	31.64	8739
h _i	0	-.25	1.89	16.70	4612
i _i	0	-.50	1.11	9.46	2612
j _i	0	-.75	0.56	4.36	1204
k _i	0	-1.02	0.30	1.94	536
Outside Boundary					
a _o	-.33	1.16	-0.06	.56	-155
b _o	-.18	1.00	-0.94	8.72	-2408
c _o	-.05	.84	-1.56	14.48	-4000
d _o	.06	.66	-1.89	17.54	-4844
e _o	.16	.46	-1.94	18.00	-4972
f _o	.24	.22	-1.61	14.94	-4127
g _o	.25	0	-0.78	7.24	-2000
h _o	.25	-.25	0.50	4.62	1276
i _o	.25	-.50	1.17	10.86	3000
j _o	.25	-.75	1.73	16.05	4434
k _o	.25	-1.02	1.84	17.07	4714

NOTE: For description of terms and location of coordinate axes see Exhibit 19.

GRAPH OF LONGITUDINAL STRESSES

CIRCUMFERENTIAL STRESSES

NOTES: n = Fringe order

f = 2.33 psi/fringe/inch Material fringe constant

t = Thickness of subslice

$S_{mo} = \frac{nf}{t}$ Stress on outside boundary of model

$S_{mi} = \frac{nf}{t} - P_m$ Stress on inside boundary of model

P_m = 0.84 psi Internal pressure in model

P_p = Internal pressure in part

$S_p = \frac{S_m P_p}{P_m} = \frac{232 S_m}{.84} = 276 S_m$ Equivalent part stress with 232 psi internal pressure

TABULATION OF CIRCUMFERENTIAL STRESSES

Point	X	Y	t	n	S _m	S _p
Inside Boundary						
n _i	-.41	.895	.1855	1.11	13.10	3619
o _i	-.255	.705	.2044	1.44	15.57	4301
p _i	-.11	.49	.1893	1.38	16.15	4461
q _i	-.025	.26	.1911	1.33	15.38	4248
r _i	0	0	.1696	.95	12.21	3373
s _i	0	-.19	.0995	.38	8.06	2227
t _i	0	-.45	.1886	.50	5.34	1476
u _i	0	-.705	.1890	.39	3.97	1097
v _i	0	-.96	.1883	.28	2.62	724
Outside Boundary						
n _o	-.25	1.055	.1855	-.16	2.01	-554
o _o	-.065	.845	.1993	-.73	8.53	-2355
p _o	.095	.605	.1890	-1.05	12.94	-3573
q _o	.22	.31	.1875	-1.05	13.04	-3601
r _o	.25	0	.1690	-.62	8.55	-2362
s _o	.375	-.19	.1019	-.11	2.52	-696
t _o	.25	-.45	.1840	.50	6.33	1749
u _o	.25	-.705	.1864	1.08	13.50	3728
v _o	.25	-.96	.1851	1.61	20.27	5598

NOTE: For description of terms and location of coordinate axes, see Exhibit 22.

GRAPH OF CIRCUMFERENTIAL STRESSES