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Produced by the NASA Center for Aerospace Information (CASI)
LaRC DESIGN ANALYSIS REPORT
FOR
NATIONAL TRANSONIC FACILITY
FOR
304 STAINLESS STEEL TUNNEL SHELL
FINITE DIFFERENCE ANALYSIS OF CONE/CYLINDER JUNCTION (NASA) 137 p HC

BY
JAMES W. RAMSEY, JR., JOHN T. TAYLOR, JOHN F. WILSON, CARL E. GRAY, JR., ANNE D. LEATHERMAN, JAMES R. ROOKER, AND JOHNNY W. ALLRED
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<td>This report contains the results of extensive computer (finite element, finite difference and numerical integration), thermal, fatigue, and special analyses of critical portions of a large pressurized, cryogenic wind tunnel (National Transonic Facility). The computer models, loading and boundary conditions are described. Graphic capability was used to display model geometry, section properties, and stress results. A stress criteria is presented for evaluation of the results of the analyses. Thermal analyses were performed for major critical and typical areas. Fatigue analyses of the entire tunnel circuit is presented.</td>
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The major computer codes utilized are: SPAR - developed by Engineering Information Systems, Inc. under NASA Contracts NAS8-30536 and NAS1-13977; SALORS - developed by Langley Research Center and described in NASA TN D-7179; and SRA - developed by Structures Research Associates under NASA Contract NAS1-10091; "A General Transient Heat-Transfer Computer Program for Thermally Thick Walls" developed by Langley Research Center and described in NASA TM X-2058.

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UNCLASSIFIED - UNLIMITED
NATIONAL TRANSONIC FACILITY
TUNNEL SHELL
NASA - LARC

FINITE DIFFERENCE ANALYSIS
OF
CONE/CYLINDER JUNCTION

304 STAINLESS STEEL
SEPTEMBER 1976
VOLUME 1S
LaRC CALCULATIONS
FOR THE
NATIONAL TRANSONIC FACILITY
TUNNEL SHELL

DATE: SEPTEMBER, 1976

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This report is one volume of a Design Analysis Report prepared by LaRC on portions of the pressure shell for the National Transonic Facility. This report is to be used in conjunction with reports prepared under NASA Contract NAS1-13535(c) by the Ralph M. Parsons Company (Job Number 5409-3 dated September 1976) and Fluidyne Engineering Corporation (Job Number 1060 dated September 1976). The volumes prepared by LaRC are listed below:

NTF DESIGN CRITERIA
FOR 304 STAINLESS STEEL

GENERAL


MATERIAL

THE PRESSURE SHELL MATERIAL SHALL BE ASME, SA-240, GRADE 304 FOR PLATE AND SA-182, GRADE F304 FOR FORGINGS. THE MATERIAL PROPERTIES AT TEMPERATURES EQUAL TO OR BELOW 150°F ARE AS FOLLOWS:

(A) PLATE
YIELD = 30.0 KSI
ULTIMATE = 75.0 KSI

(B) WELDS (AUTOMATIC, SEMIAUTOMATIC, OR "STICK")
YIELD = 30.0 KSI
ULTIMATE = 75.0 KSI

OPERATING, DESIGN AND TEST CONDITIONS

THE OPERATING, DESIGN AND TEST CONDITIONS FOR THE TUNNEL PRESSURE SHELL AND ASSOCIATED SYSTEMS AND ELEMENTS ARE SUMMARIZED BELOW:
1. OPERATING MEDIUM
   ANY MIXTURE OF AIR AND NITROGEN

2. DESIGN TEMPERATURE RANGE
   MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT, EXCEPT IN THE REGION OF THE PLENUM BULKHEADS AND GATE VALVES INSIDE A 23-FOOT, 4-INCH DIAMETER, FOR WHICH THE TEMPERATURE RANGE IS MINUS 320 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT.

3. PRESSURE RANGE

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A. CONDITION I - PLENUM ISOLATION GATES OPEN AND TUNNEL OPERATING:
   - TUNNEL CIRCUIT EXCEPT PLENUM: 8.3 to 130
   - PLENUM (PLENUM PRESSURE IS LIMITED TO .4 TO 1 TIMES THE REMAINDER OF THE TUNNEL CIRCUIT):
     - BULKHEAD: 56 (EXTERNAL TO PLENUM)

B. CONDITION II - PLENUM ISOLATION GATES OPEN AND TUNNEL SHUTDOWN:
   - ENTIRE TUNNEL CIRCUIT: 8.3 to 130
   - BULKHEAD: 0

C. CONDITION III - PLENUM ISOLATION GATES AND ACCESS DOORS CLOSED:
   - TUNNEL CIRCUIT EXCEPT PLENUM: 8.3 to 130
PLENUM (PLENUM OPERATING PRESSURE CAN EXCEED THE PRESSURE IN THE REMAINDER OF THE TUNNEL CIRCUIT BY 24 PSI, BUT DOES NOT EXCEED THE 130 PSIA MAXIMUM OPERATING PRESSURE)

BULKHEAD

A. 25 (INTERNAL TO PLENUM)
B. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT

C. 115.7 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

D. CONDITION IV - PLENUM ISOLATION GATES CLOSED AND ACCESS DOORS OPEN:

TUNNEL CIRCUIT EXCEPT PLENUM 8.3 to 130 A. 8 EXTERNAL B. 119 INTERNAL

PLENUM 14.7 0

BULKHEAD

A. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT

B. 115.7 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.
4. HYDROSTATIC TEST DESIGN CONDITIONS

THE PRESSURE SHELL WAS DESIGNED FOR HYDROSTATIC TEST IN ACCORDANCE WITH THE REQUIREMENTS OF THE ASME CODE, SECTION VIII, DIVISION 1. THE TEST PRESSURES SHALL BE AS FOLLOWS. PRESSURE SHELL TEMPERATURE SHALL BE EQUAL TO OR BELOW 100°F DURING HYDROSTATIC TESTS.

CONDITION (1) - MAXIMUM INTERNAL PRESSURE CONDITION FOR THE ENTIRE TUNNEL CIRCUIT

\[ P_{H1} = 1.5 \left( \frac{18.7}{18.2} \right) + \text{HYDROSTATIC HEAD} \]

\[ = 183.4 \text{ PSI} + \text{HYDROSTATIC HEAD} \]

CONDITION (2) - MAXIMUM DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

\[ P_{H2} = 1.5 \left( \frac{18.7}{18.2} \right) (119) + \text{HYDROSTATIC HEAD} \]

\[ = 183.4 + \text{HYDROSTATIC HEAD} \]

\[ P_{H2} = 1.5 \left( \frac{18.7}{17.7} \right) + \text{HYDROSTATIC HEAD} \]

\[ = 183.4 + \text{HYDROSTATIC HEAD} \]

*TUNNEL OPERATION LIMITATIONS PRECLUDE PRESSURE DIFFERENTIALS ACROSS BULKHEADS IN EXCESS OF 115.7 PSI FOR BULKHEAD AND GATE TEMPERATURES IN EXCESS OF 150°F.

CONDITION (3) - MAXIMUM REVERSE DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

\[ P_{H3} = 1.5 \left( \frac{18.7}{18.2} \right) (25) = 38.5 \text{ PSI} \]

THE PRESSURE SHELL EXCEPT FOR THE PLENUM SHALL BE PRESSURIZED TO 144.9 PSIG. THE PLENUM SHALL BE PRESSURIZED TO 193.4 PSIG.

PRESSURE SHELL STRESS EVALUATION CRITERIA

THIS CRITERIA ESTABLISHES THE BASIS FOR ANALYSIS AND DESIGN OF THE PRESSURE SHELL SO IT WILL MEET OR EXCEED ALL OF THE REQUIREMENTS OF SECTION VIII, DIVISION 1 OF THE ASME BOILER AND PRESSURE VESSEL CODE AND CAN BE STAMPED WITH A DIVISION 1 "U" STAMP.

1. SECTION VIII, DIVISION 1, DIRECT APPLICATION
(A) THE MAXIMUM ALLOWABLE STRESS (S)

\[ S = 18.2 \text{ KSI} \quad (-320°F \text{ TO } +150°F) \]
\[ S = 17.7 \text{ KSI} \quad (-320°F \text{ TO } +200°F) \]

(B) PRIMARY BENDING PLUS PRIMARY MEMBRANE STRESSES

The local membrane stresses are not generally considered in Section VIII, Division 1 designs. However, for the purpose of designing local reinforcement at brackets, rings or penetrations not covered by design based on stress analysis, the local shell membrane stress shall be:

\[ P_b + P_m \leq 1.5 \text{ SE} \]

Note: E is joint efficiency.

2. In regions of the pressure shell where Division 1 does not contain rules to cover all details of design (Ref. U-2(g)), additional analyses were performed utilizing the guidelines of the ASME Code, Section VIII, Division 2, Appendix 4, "Design based on Stress Analysis." The basic stress criteria for Division 2 is represented in Figure 4-130.1 and restated below indicating any modifications or excess requirements applied to it to remain within the intent of Division 1 and to obtain a Division 1 stamp.

A. GENERAL PRINCIPAL MEMBRANE STRESS

MAXIMUM ALLOWABLE STRESS

\[ S = 18.2 \text{ KSI} \quad (-320°F \text{ TO } +150°F) \]
\[ S = 17.7 \text{ KSI} \quad (-320°F \text{ TO } +200°F) \]

MAXIMUM ALLOWABLE STRESS INTENSITY

\[ S_m = 20.0 \text{ KSI} \quad (-320°F \text{ TO } +300°F) \]

B. PRIMARY GENERAL MEMBRANE STRESS INTENSITY

\[ P_m \leq S_m \]

And in order to comply with Division 1, the maximum principal membrane stress must be:

\[ P_m^* \leq S \]

Note: The * is used to denote that maximum principal stresses are to be computed for the given loading condition. The intent is to determine the stresses which represent the hoop stresses and meridional stresses which are the stresses used in Division 1 computations.
C. DESIGN LOADS, PRIMARY LOCAL MEMBRANE STRESS INTENSITY

\[ P_L \leq 1.5 S_m \]

NOTE: LOCAL MEMBRANE STRESS INTENSITY IS DEFINED IN ACCORDANCE WITH DIVISION 2, APPENDIX 4-112(1). THE TOTAL MERIDIONAL LENGTH IS CONSIDERED TO BE 1.0 \( \sqrt{RT} \).

D. DESIGN LOADS, PRIMARY LOCAL MEMBRANE PLUS PRIMARY BENDING STRESS INTENSITY

\[ P_L + P_b \leq 1.5 S_m \]

E. OPERATING LOADS, PRIMARY PLUS SECONDARY STRESS INTENSITY

\[ P_L + P_b + Q \leq 3 S_m \]

3. A FATIGUE ANALYSIS WAS CONDUCTED IN ACCORDANCE WITH SECTION VIII, DIVISION 2 WITHOUT MODIFICATION.

4. HYDROSTATIC TEST CONDITION DESIGN CONSIDERATIONS

A. PRESSURE SHELL

IN ACCORDANCE WITH DIVISION 1 OF THE ASME CODE, DESIGN ANALYSIS OF THE PRESSURE SHELL FOR THE HYDROSTATIC TEST CONDITION IS NOT REQUIRED. HOWEVER, IN ORDER TO PROVIDE A SATISFACTORY ENGINEERING DESIGN FOR THE PRESSURE SHELL SPECIAL EMPHASIS WAS GIVEN, AS PROMPTED BY NOTE (1) OF SECTION VIII, DIVISION 1 OF THE ASME CODE, TO FLANGES OF GASKETED JOINTS OR OTHER APPLICATIONS WHERE SLIGHT AMOUNTS OF DISTORTION CAN CAUSE LEAKAGE OR MALFUNCTION. EXAMPLES OF THESE AREAS ARE THE PLENUM, PLENUM ACCESS DOORS, PLENUM ACCESS DOOR REINFORCEMENT, THE BULKHEADS, AND BULKHEAD FLANGES.

B. SUPPORT RINGS

DESIGN OF THE PRESSURE SHELL SUPPORT RINGS, INCLUDING
THE CORNER RINGS, FOR THE HYDROSTATIC TEST CONDITION, COMPLIES WITH THE FOLLOWING:

(A) THE COMBINED VALUE OF THE SHELL CIRCUMFERENTIAL PRESSURE STRESS, \( S_1 \) AND SHELL BENDING STRESS \( S_2 \), RESULTING FROM ACTION OF A PORTION OF THE SHELL AS AN INNER FLANGE OF THE RING, SHALL NOT EXCEED 0.8 WELD YIELD STRESS:

\[ S_1 + S_2 \leq 0.8 \text{ WELD YIELD STRESS}, \]

WHERE, FOR SUPPORT RINGS NOT ANALYZED BY FINITE ELEMENT TECHNIQUES,

\[ S_1 = P_H \left( \frac{R}{T} \right) + 0.6 P_H; P_H \text{ INCLUDES HYDROSTATIC HEAD CORRECTION, AND} \]

\[ S_2 = \text{RING BENDING STRESS AT INNER FLANGE, BASED ON AN EFFECTIVE WIDTH OF THE PRESSURE SHELL ACTING AS AN INNER FLANGE OF THE RING OF } 1.1 \text{ MULTIPLIED BY THE SQUARE ROOT OF } D_0 T. \]

(B) THE BENDING STRESS, \( S_{2F} \) ON THE OUTSIDE FLANGE SHALL NOT EXCEED 0.9 WELD YIELD STRESS. (IN THE COMPUTER ANALYSIS ALL LOADING CONDITIONS ARE LIMITED TO 0.9 \( S_Y \) ON THE OUTER FLANGE.)

(C) BRACKETS AND SUPPORT PAD WELDMENTS

THE DESIGN FOR ALL LOADING CONDITIONS INCLUDING THE HYDROSTATIC TEST CONDITION OF THOSE PORTIONS OF BRACKETS AND SUPPORT PAD WELDMENTS WHICH ARE ATTACHED TO THE PRESSURE SHELL BUT NOT ON THE SURFACE OF THE SHELL SHALL COMPLY WITH THE REQUIREMENTS OF THE AISC CODE, I.E. MAXIMUM STRESS IN TENSION EQUALS 0.6 \( S_Y \), ETC.
Vol 15

Finite Difference Analyses of Cone/Cylinder Junctions

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## PART 2

Hydro Test Pressure

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## PART 3

Effect of Insulation Tee Bungs on Shell Stresses

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Reference Drawing No 9443835 & 9443905

The cone/cylinder junctions were analyzed utilizing a shell of revolution computer code.

Computer Code

SALORS - Structural Analysis of
  Layered Orthotropic Ring - Stiffened
  Shell-of-Revolution - is a
  finite-difference code

Reference NASA TN D-7179
A typical cone/cylinder is shown below.

---

**Loading**

Internal pressure = 119 psig for design condition

Internal pressure = 1.5(119) + water head for hydro test condition
All pressure loadings remain normal to the deformed surface.

Boundary Conditions

Symmetric B.C. were applied to each end of the model.

End 1 was fixed in the axial direction. A boundary force of \( \frac{1}{2} \)PR (lb/m of circ.) was applied to end 2.

\[
\text{END 1} \quad \text{END 2} \quad \frac{1}{2} \text{PR}
\]
Fig 1  Computer plot of geometry

Fig 2  Average net-section hoop stress  
P = 119 psi

Fig 3  Inside surface stress  
longitudinal & hoop  
P = 119 psi

Fig 4  Outside surface stress  
longitudinal & hoop  
P = 119 psi

Fig 5  Radial displacement  
P = 119 psi
Knuckle region at small dia cylinder

This model did not include the influence from corner #4 (elliptical ring R1). This region was considered in detail in the analyses of corner #4. See corner #4 (Vol 45) analyses of this region.
Knuckle region of large dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity
(Fig. 2, 3, 4, 4) \( P = 119 \text{psi} \)

\[ \sigma_1 = -14.5 \text{ KSI} \]

\[ \sigma_2 = \frac{28 + (-14.8)}{2} = 6.6 \text{ KSI} \]

\[ \sigma_3 = \frac{-119}{2} = -59.5 \text{ KSI} \]

\[ S_{12} = \sigma_1 - \sigma_2 = -14.5 - 6.6 = -21.1 \text{ KSI} \]

\[ S_{23} = 6.6 - (-59.5) = 66.1 \text{ KSI} \]

\[ S_{31} = -59.5 - (-14.5) = 45 \text{ KSI} \]

\[ P_L = | -21.1 | = 21.1 \text{ KSI} \]

\[ P_L \leq 1.5 \text{Sm} \]

21.1 \( \leq 1.5(20) \times 0 \) O.K.
The meridional length at a stress intensity of 1.1 Sm (1.1 x 20 = 22 ksi) is 0. The peak stress intensity is less than 1.1 Sm

\[ 0 < \sqrt{RT} \]

:: This stress intensity in this region is a local membrane stress intensity

**General Membrane Stress Intensity**

\[ R_1 = 18.0 \text{ KSI} \]
\[ S_2 = \frac{9+9}{2} = 9 \text{ KSI} \]
\[ T_3 = -\frac{119}{2} = -0.06 \text{ KSI} \]

\[ S_{12} = 18.0 - 9 = 9.0 \text{ KSI} \]
\[ S_{23} = 9 - (-0.06) = 9.06 \text{ KSI} \]
\[ S_{31} = -0.06 - 18 = -18.06 \text{ KSI} \]

\[ P_m = | -18.06 | = 18.06 \text{ KSI} \]
\[ P_m \leq S_m \]

18.00 \leq 20 \text{ ksi} \quad \text{O.K.}

General principal membrane stress

\[ S = 18.0 \text{ ksi} \]

\[ S < 23.7 \text{ ksi} \]

18.0 \leq 23.7 \text{ ksi} \quad \text{O.K.}

The membrane stress (intensity) for the region meets the stress evaluation criteria.
Primary Plus Secondary Stress

Inside Surface

\[ \sigma_1 = 28 \text{ KSI} \]
\[ \sigma_2 = -14.2 \text{ KSI} \]
\[ \sigma_3 = -\frac{14.2}{2} = -0.6 \text{ KSI} \]

\[ S_{11} = 28.0 - (-14.2) = 42.2 \text{ KSI} \]
\[ S_{21} = -14.2 - (-0.6) = -14.14 \text{ KSI} \]
\[ S_{31} = -0.6 - 28.0 = -28.06 \text{ KSI} \]

\[ S = |42.2| = 42.2 \text{ KSI} \]

\[ P_L + P_b + \phi \leq 3S_m \]

\[ 42.2 \leq 3(60) = 60 \text{ kSI} \]
Outside Surface

\[ \sigma_1 = -20.5 \text{ ksi} \]
\[ \sigma_2 = -13.8 \text{ ksi} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = -20.5 - (-13.8) = -6.7 \text{ ksi} \]
\[ S_{23} = -13.8 - 0 = -13.8 \text{ ksi} \]
\[ S_{31} = 0 - 20.5 = -20.5 \text{ ksi} \]

\[ S = |20.5| = 20.5 \text{ ksi} \]

\[ P_L + P_b + Q \leq 35 \text{ ksi} \]

\[ 20.5 \leq 3 \times 20 = 60 \text{ ksi} \quad \text{OK} \]

The primary plus secondary stress intensity meets the stress evaluation criteria.
Fig 6. Computed Pi3 -- Geometry

Fig 7. Average nodal circumferential hoop stress

Fig 8. Inside circumferential hoop longitudinal hoop
12 - 117 psi

Fig 9. Outside surface stress
longitudinal / hoop
P = 119 psi

Fig 10. Radial displacement
P = 119 psi
Knuckle region of the small dia cylinder

Membrane Stress (Intensity)

Primary local membrane stress intensity

see Fig

\[ \sigma_1 = -20 \text{ ksi} \]

\[ \sigma_2 = \frac{20 + (-10)}{2} = 5 \text{ ksi} \]

\[ \sigma_3 = \frac{-0.9}{2} = -0.45 \text{ ksi} \]

\[ S_{12} = 25 - 5 = 20 \text{ ksi} \]

\[ S_{23} = 5 - (-0.06) = 5.06 \text{ ksi} \]

\[ S_{31} = 0.2 - 25 = -24.8 \text{ ksi} \]

\[ S = |25.06| = 25.06 \text{ ksi} \]

\[ P_L \leq 1.5 \times S_m \]

\[ 25.06 \leq 1.5 \times (20) = 30 \text{ ksi} \]

O.K.
Since the stress intensity (25.06 ksi) is equal to (within reading accuracy of the stress plots) the stress (25.0 ksi), the meridional distance vs. stress intensity is taken in fig 7.

The meridional distance at a stress intensity of 1.15m (1.1x10^-2 ksi) is 18.5.

\[ 18.5 \leq \sqrt{\frac{17}{1160.75 \times 2.09}} = 18.78" \quad \text{O.K.} \]

The stress intensity in the region is a local membrane stress intensity.

**General Membrane Stress Intensity**

\[ \sigma_1 = 15.5 \text{ ksi} \]

\[ \sigma_2 = \frac{20.0 + (-10)}{2} = 5 \text{ ksi} \]

\[ \tau_c = \frac{-119}{2} = -0.6 \text{ ksi} \]
\[ S_{12} = 15.5 - 5 = 10.5 \text{ KSI} \]
\[ S_{23} = 5 - 0.06 = 4.94 \text{ KSI} \]
\[ S_{31} = -0.06 - 15.5 = -15.56 \text{ KSI} \]

\[ S = | -15.56 | = 15.56 \text{ KSI} \]

\[ P_n \leq S_m \]

\[ 15.56 \leq 20.0 \text{ KSI} \quad \text{O.K.} \]

General principle membrane stress

\[ \sigma = 15.5 \text{ KSI} \]

\[ \sigma \leq S \]

\[ 15.5 \leq 23.7 \text{ KSI} \]

The membrane stress (intensity) meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

Inside Surface (Fig)

\[
G_1 = 20.3 \text{ksi}
\]

\[
G_2 = -10.0 \text{ksi}
\]

\[
G_3 = -0.119
\]

\[
S_{12} = 20.3 - (-10.0) = 30.3 \text{ksi}
\]

\[
S_{23} = -10.0 - (-0.119) = -9.881 \text{ksi}
\]

\[
S_{31} = -0.119 - 20.3 = -20.419 \text{ksi}
\]

\[
S = \sqrt{30.3^2} = 30.3 \text{ ksi}
\]

\[
P_L + P_b + q \leq 35 \text{ksi}
\]

\[
30.3 < 3(20) = 60 \text{ksi} \quad \text{O.K.}
\]
Outside Surface

\[ \sigma_1 = 20.0 \text{ ksi} \]
\[ \sigma_2 = 29.0 \text{ ksi} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = 20.0 - 29.0 = -9.0 \text{ ksi} \]
\[ S_{23} = 29.0 - 0 = 29.0 \text{ ksi} \]
\[ S_{31} = 0 - 20.0 = -20.0 \text{ ksi} \]

\[ S = 29.0 \text{ ksi} \]

\[ P_L + P_b + Q \leq 3S_m \]

\[ 29.0 \leq 3(20) = 60 \text{ ksi} \quad \text{O.K.} \]

The primary plus secondary stress intensity meets the stress evaluation criteria.
Knuckle region at the large dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity

see Fig

\[ \sigma_1 = -10.2 \text{ KSI} \]

\[ \sigma_2 = \frac{-15 + 3.60}{2} = 8 \text{ KSI} \]

\[ \sigma_3 = \frac{-119}{2} = -59.5 \text{ KSI} \]

\[ s_{12} = -10.2 - 8.0 = -18.2 \text{ KSI} \]

\[ s_{23} = 8 - (-10.2) = 18.06 \text{ KSI} \]

\[ s_{31} = -0.06 - (-10.2) = 10.14 \text{ KSI} \]

\[ s = |-18.2| = 18.2 \text{ KSI} \]

\[ P_L \leq 1.5 s_m \]

\[ 18.2 \leq 1.5(30) = 30 \text{ KSI}, \text{ O.K.} \]
Since the stress intensity is also < S_m (20 ksi), the stress intensity meets the stress evaluation criteria.

General Membrane Stress

S = -10.2 KSI (largest negative stress)

or

S = 17.0 KSI positive stress on cone

S ≤ 18.2 KSI

17 ≤ 18.2 KSI O.K.

The membrane stress (intensity) meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 31.0 \text{ ksi} \]

\[ \sigma_2 = -3.5 \text{ ksi} \]

\[ \sigma_3 = -0.119 \text{ ksi} \]

\[ S_{12} = 31.0 - (-3.5) = 34.5 \text{ ksi} \]

\[ S_{23} = -3.5 - (-0.119) = -3.381 \text{ ksi} \]

\[ S_{31} = -0.119 - 31.0 = -31.119 \text{ ksi} \]

\[ S = |34.5| = 34.5 \text{ ksi} \]

\[ P_L + P_b + \sigma \leq 35 \text{ ksi} \]

\[ 34.5 \leq 3(20) = 60 \text{ ksi} \text{ OK.} \]
Outside Surface

\[ \sigma_1 = -17.0 \text{ ksi} \]
\[ \sigma_2 = -15.0 \text{ ksi} \]
\[ \sigma_3 = 0 \]
\[ S_{12} = -17.0 - (-15.0) = -2.0 \text{ ksi} \]
\[ S_{23} = -15.0 - 0 = -15.0 \text{ ksi} \]
\[ S_{31} = 0 - (-17.0) = 17.0 \text{ ksi} \]
\[ S = |17.0| = 17.0 \text{ ksi} \]
\[ P_c + P_b + \Delta \leq 1.5 S_m \]
\[ 17.0 < 1.5(20) = 30 \text{ ksi} \]

\[ \text{O.K.} \]

\[ \therefore \text{The primary plus secondary stress intensity meets the stress evaluation criteria.} \]
Fig 11  Computer plot of geometry

Fig 12  Average net-section hoop stress
        \( P = 119 \text{ psi} \)

Fig 13  Inside surface stress
        Longitudinal & hoop
        \( P = 119 \text{ psi} \)

Fig 14  Outside surface stress
        Longitudinal & hoop
        \( P = 119 \text{ psi} \)

Fig 15  Radial displacement
        \( P = 119 \text{ psi} \)
Junction region at the small dia cylinder

Membrane Stress (intensity)

Primary general membrane stress intensity

\[
\sigma_1 = 14.0 \text{ ksi}
\]

\[
\sigma_2 = \frac{1 + \frac{t}{2}}{2} = 7.5 \text{ ksi}
\]

\[
\sigma_3 = -\frac{11\rho}{2} = -0.06 \text{ ksi}
\]

\[
S_{12} = 14.0 - 7.5 = 6.5 \text{ ksi}
\]

\[
S_{23} = 7.5 - (-0.06) = 7.56 \text{ ksi}
\]

\[
S_{31} = -0.06 - 14.0 = -14.06 \text{ ksi}
\]

\[
S = \left| -14.06 \right| = 14.06 \text{ ksi}
\]
This model did not consider the influence of corner #1.

The approximately influence for corner #1 can be determined by noting the influence of corner #4 on the cone/cylinder junction.

From corner #4 analyses, the max. membrane stress was 24.10 KSI.

From the solar analyses, the max. membrane stress intensity was 20.8 KSI.

% increase due to corner influence

\[
\frac{24.10 - 20.8}{24.10} = 13.7\% 
\]
From frame #4 analyses, the primary plus secondary stress intensity was

\[ S = 29.44 \text{ KSI} \quad \text{outside surface} \]

\[ S = 29.46 \text{ KSI} \quad \text{inside surface} \]

For SALOR analyses

Outside Surface

\[ \sigma_1 = 24.0 \text{ KSI} \]

\[ \tau_2 = 14.4 \text{ KSI} \]

\[ \tau_3 = 0 \]

\[ S_{12} = 24.0 - 14.4 = 9.6 \text{ KSI} \]

\[ S_{23} = 14.2 - 0 = 14.2 \text{ KSI} \]

\[ S_{31} = 0 - 24.0 = -24.0 \text{ KSI} \]

\[ S = \left| -24.0 \right| = 24.0 \text{ KSI} \]
Inside surface

\[ \tau_1 = 17.5 \text{ KSI} \]
\[ \tau_2 = -7.0 \text{ KSI} \]
\[ \tau_3 = -\frac{119}{2} = -59.5 \text{ KSI} \]

\[ S_{12} = 17.3 - (-7.0) = 24.3 \text{ KSI} \]
\[ S_{23} = -7.0 - (-0.06) = -6.94 \text{ KSI} \]
\[ S_{31} = -0.06 - 17.3 = 17.2 \text{ KSI} \]

\[ S = |24.3| = 24.3 \text{ KSI} \]

% increase due to corner influence

outside surface

\[ \frac{29.44 - 24.0}{29.44} = 18.47\% \]

inside surface

\[ \frac{29.46 - 24.3}{29.46} = 17.57\% \]
Increase membrane stress intensity at cone/cylinder junction near R9 by 13.7%.

\[ S = 1.137 \times 14.06 = 15.99 \text{ KSI} \]

\[ P_m \leq S_m \]

15.99 < 20.0 KSI  O.K.

General Principal membrane stress

\[ \sigma = 13.0 \]

Increase by 13.7% due to corner influence

\[ \sigma = 1.137 \times 13.0 = 14.78 \text{ KSI} \]

\[ \sigma \leq 18.2 \text{ KSI} \]

14.78 < 18.2 KSI  O.K.

The membrane stress (intensity) for this region meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 13.5 \text{ ksi} \]
\[ \sigma_2 = 1 \text{ ksi} \]
\[ \sigma_3 = -11.9 \text{ ksi} \]

\[ S_{xx} = 13.5 - 1 = 12.5 \text{ ksi} \]
\[ S_{x3} = +1 - (-1.12) = 1.12 \text{ ksi} \]
\[ S_{x1} = -1.12 - 13.5 = -13.65 \text{ ksi} \]

\[ S = \sqrt{13.65} = 13.65 \text{ ksi} \]

Increase \( S \) by 17.5% (see p. ___)

\[ S = 1.175 \times 13.65 = 16.04 \text{ ksi} \]

\[ P_L + P_R + \phi \leq 3.5 \text{ in} \]

\[ 16.04 \leq 3(20) = 60.0 \text{ ksi} \] O.K.
Outside Surface

\[ \sigma_1 = 16.0 \text{ ksi} \]
\[ \sigma_2 = 14.0 \text{ ksi} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = 16.0 - 14.0 = 2.0 \text{ ksi} \]
\[ S_{22} = 14.0 - 0 = 14.0 \text{ ksi} \]
\[ S_{31} = 0 - 16.0 = -16.0 \text{ ksi} \]

\[ S = |-16.0| = 16.0 \text{ ksi} \]

Increase \( S \) by 18.4% (see p.

\[ S = 1.184 \times 16.0 = 18.94 \text{ ksi} \]

\[ P_L + P_b + Q \leq 3S_m \]

\[ 18.94 < 3(20) = 60.0 \text{ ksi} \]

\[ \therefore \text{The primary plus secondary stress intensity for this region meets the stress evaluation criteria.} \]
Junction region at the large dia. cylinder

Membrane stress (intensity)

General membrane stress

\[
\sigma_1 = 8.0 \text{ KSI} \\
\sigma_2 = -\frac{9 + 27}{2} = 9 \text{ KSI} \\
\sigma_3 = -\frac{-119}{2} = -0.06 \text{ KSI}
\]

\[
S_{12} = 8.0 - 9 = -1 \text{ KSI} \\
S_{23} = 9 - (-0.06) = 9.06 \text{ KSI} \\
S_{31} = -0.06 - 8.0 = -8.06 \text{ KSI}
\]

\[
S = |9.06| = 9.06 \text{ KSI}
\]

\[
P_m \leq S_m \\
9.06 < 20.0 \text{ KSI} \quad \text{O.K.}
\]

This region meets the criteria for general membrane stress intensity.
General Membrane stress

\( \sigma = 8.0 \) at junction

\( \sigma = 14.0 \) on large cylinder

\( \sigma \leq 5 \)

\( 16 < 18.2 \text{ ksi} \)

The region meets the stress criteria for the general membrane stress.
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 27.6 \text{ KSI} \]
\[ \sigma_2 = 14.0 \text{ KSI} \]
\[ \sigma_3 = -0.119 = -0.12 \text{ KSI} \]

\[ S_{12} = 27.6 - 13.0 = 14.0 \text{ KSI} \]
\[ S_{23} = 14.0 - (-0.12) = 14.12 \text{ KSI} \]
\[ S_{31} = -0.12 - 27.0 = -27.12 \text{ KSI} \]

\[ S = \left| -27.12 \right| = 27.12 \text{ KSI} \]

\[ \sigma_L + \sigma_b + \sigma_t \leq 3S_m \]

\[ 27.12 \leq 3(20) = 60.0 \text{ KSI} \quad \text{O.K.} \]
Outside Surface

\[ \sigma_1 = -9.0 \text{ KSI} \]
\[ \sigma_2 = 3.5 \text{ KSI} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = -9.0 - 3.5 = 12.5 \text{ KSI} \]
\[ S_{23} = 3.5 - 0 = 3.5 \text{ KSI} \]
\[ S_{31} = 0 - (-9.0) = +9.0 \text{ KSI} \]

\[ S = |12.5| = 12.5 \text{ KSI} \]

\[ P_c + P_b + Q \leq 35 \text{in} \]
\[ 12.5 \geq 3(20) = 60 \text{ KSI} \]

The primary plus secondary stress intensity meets the stress evaluation criteria.
The stresses in the region of R7 to R8 are approximately the same as the junction regions. Since the stresses in the junction meet the criteria by a large margin, a detail summary of the stresses at R7 and R8 is not given in this stress evaluation.
R10 to R12

Fig 16  Computer plot of geometry

Fig 17  Average net-section hoop stress
         P = 119 psi

Fig 18  Inside surface stress
         longitudinal + hoop
         P = 119 psi

Fig 19  Outside surface stress
         longitudinal + hoop
         P = 119 psi

Fig 20  Radial displacement
         P = 119 psi
This model did not consider the influence from corner #1 and corner #2.

% increase due to corner influence for membrane
see p.

% increase 13.7%

Primary plus secondary stress intensity
(see p.

% increase

Outside surface 18.4%

Inside surface 17.5%
Junction region at the small dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity

\[ \sigma_1 = 17.0 \, \text{ksi} \]
\[ \sigma_2 = \left[ \frac{17.0 + 0}{2} \right] = 8.5 \, \text{ksi} \]
\[ \frac{17.0}{2} = -0.06 \, \text{ksi} \]

\[ S_{12} = 17.0 - 8.5 = 8.5 \, \text{ksi} \]
\[ S_{23} = 8.5 - (-0.06) = 8.56 \, \text{ksi} \]
\[ S_{31} = -0.06 - 17.0 = -17.06 \, \text{ksi} \]

\[ S = \left| -17.06 \right| = 17.06 \, \text{ksi} \]
\[ S = 1.137(17.06) = 19.39 \]

\[ P_m \leq S_m \]
\[ 19.39 \leq 20.0 \, \text{ksi} \]

O.K.

The general membrane stress intensity for this region meets the stress evaluation criteria.
General principal stress

\[ \sigma = 1.137(16) = 18.19 \text{ KSI} \]

\[ \sigma \leq S \]

\[ 18.19 < 18.2 \text{ KSI} \quad \text{O.K.} \]

This region meets the criteria for membrane stress (intensity).
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 16.5 \text{ KSI} \]
\[ \sigma_2 = 7.0 \text{ KSI} \]
\[ \sigma_3 = -1.14 \text{ KSI} \]

\[ S_{12} = 16.5 - 7.0 = 9.5 \text{ KSI} \]
\[ S_{23} = 7.0 - (-0.12) = 7.12 \text{ KSI} \]
\[ S_{31} = -0.12 - 16.5 = -16.62 \text{ KSI} \]

\[ S = | -16.62 | = 16.62 \text{ KSI} \]

Increase due to Corner: 17.5%

\[ S = 1.175(16.62) = 19.53 \text{ KSI} \]

\[ P_c + P_b + Q \leq 3.5 \text{ ksi} \]

\[ 19.53 \leq 3(20) = 60.0 \text{ KSI} \]

O.K.
Outside Surface

\[ \sigma_1 = 19.0 \text{ ksi} \]
\[ \sigma_2 = 12.0 \text{ ksi} \]
\[ \sigma_3 = 0 \]
\[ S_{12} = 19.0 - 12.0 = 7.0 \text{ ksi} \]
\[ S_{23} = 12.0 - 0 = 12.0 \text{ ksi} \]
\[ S_{31} = 0 - 19.0 = -19.0 \text{ ksi} \]

\[ S = \left| -19.0 \right| = 19.0 \text{ ksi} \]

increase due to corner 18.4 %

\[ S = 1.184 \times 19.0 = 22.50 \text{ ksi} \]

\[ P_a + P_b + Q \leq 3S_m \]
\[ 22.50 \leq 3(20) = 60.0 \text{ ksi} \]

O.K.

The primary plus secondary stress intensity for this region meet the evaluation criteria.
Junction at the large dia cylinder

Membrane Stress (Intensity)

\[ \sigma_1 = 18.2 \text{ KSI} \]
\[ \sigma_2 = \frac{12.2 + 6}{2} = 9.1 \text{ KSI} \]
\[ \sigma_3 = -\frac{119}{2} = -10.6 \text{ KSI} \]

\[ S_{12} = 18.2 - 9.1 = 9.1 \text{ KSI} \]
\[ S_{23} = 9.1 - (-0.06) = 9.06 \text{ KSI} \]
\[ S_{31} = -0.06 - 18.2 = -18.26 \text{ KSI} \]

\[ S = | -18.26 | = 18.26 \text{ KSI} \]

Assume the same % increase for this region as the small dia region (13.7 %)

\[ S = 1.137 (18.26) = 20.76 \text{ KSI} \]

\[ P_L \leq 1.5 \text{ Sm} \]

\[ 20.76 < 1.5(20) = 30.0 \text{ KSI} \quad O.K. \]
The stress intensity (26.76 KSI) <
1.15m (1.1 x 20 = 22.0 KSI)

The meridional length over which
the stress intensity exists is 0

This stress is a local membrane
stress intensity

General Membrane Stress intensity

\[
\sigma_1 = 18.0 \text{ KSI}
\]

\[
\sigma_2 = \frac{9.0}{2} = 9.0 \text{ KSI}
\]

\[
\sigma_3 = -\frac{119}{2} = -0.06 \text{ KSI}
\]

\[
S_{12} = 18.0 - 9.0 = 9.0 \text{ KSI}
\]

\[
S_{22} = 9.0 - (-0.06) = 9.06 \text{ KSI}
\]

\[
S_{31} = -0.06 - 18.06 = -18.06 \text{ KSI}
\]

\[
S = |\text{-}18.06| = 18.06 \text{ KSI}
\]
\[ P_m \leq S_m \]

18.06 \leq 20.0 \text{ kSi} \quad \text{O.K.}

General membrane stress

\[ \sigma = 18.0 \text{ kSi} \]
\[ \sigma \leq S \]
18.0 \leq 18.2 \text{ kSi} \quad \text{O.K.}

The membrane stress (intensity) meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 18.0 \text{ KSI} \]
\[ \sigma_2 = 11.0 \text{ KSI} \]
\[ \sigma_3 = -119 \text{ KSI} \]

\[ S_{12} = 18.0 - 11.0 = 7.0 \text{ KSI} \]
\[ S_{23} = 11.0 - (-119) = 111.12 \text{ KSI} \]
\[ S_{31} = -12 - 18.0 = -18.12 \text{ KSI} \]

\[ S = \{ -18.12 \} = 18.12 \text{ KSI} \]

Increase due to corner influence

\[ S = 1.175 (18.12) = 21.29 \text{ KSI} \]

\[ P_1 + P_6 + G \leq 35 \text{m} \]

\[ 21.29 \leq 3(20) = 60 \text{ KSI} \quad \text{O.K.} \]
Outside Surface

\[ \sigma_1 = 18.0 \text{ KSI} \]
\[ \sigma_2 = 12.0 \text{ KSI} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = 18.0 - 12.0 = 6.0 \text{ KSI} \]
\[ S_{23} = 12 - 0 = 12.0 \text{ KSI} \]
\[ S_{31} = 0 - 18.0 = -18.0 \text{ KSI} \]

\[ S = |-18.0| = 18.0 \text{ KSI} \]

Increase due to corner

\[ S = 1.184 (18.0) = 21.31 \text{ KSI} \]

\[ P_6 + P_6 + Q \leq 3S_m \]

\[ 21.31 \leq 3(20) = 60 \text{ KSI} \quad \text{O.K.} \]

The primary plus secondary stress intensity meets the criteria.
The analysis of this section includes a ring (R11) located on the cone section. This ring has subsequently been removed and ring R12 renumbered as R11. This analysis was not redone with this ring removed since the effects of it were negligible.
R134 to S8

Fig 21  Computer plot of geometry

Fig 22  Average net-section hoop stress
        $P = 119$ psi

Fig 23  Inside surface stress
        $P = 119$ psi

Fig 24  Outside surface stress
        $P = 119$ psi

Fig 25  Radial displacement
        $P = 119$ psi
Knuckle region at the small dia cylinder

Membrane stress (intensity)

Primary local membrane stress intensity see Fig 22

\[ \sigma_1 = 24.0 \text{ ksi} \]
\[ \sigma_2 = \frac{-9.0 + 17.5}{2} = 4.25 \text{ ksi} \]
\[ \sigma_3 = \frac{-119}{2} = -59.5 \text{ ksi} \]
\[ S_{12} = 24.0 - 4.25 = 19.75 \text{ ksi} \]
\[ S_{23} = 4.25 - (-0.6) = 4.31 \text{ ksi} \]
\[ S_{31} = -0.6 - 24.0 = -24.6 \text{ ksi} \]

\[ S = | -24.0 | = 24.06 \text{ ksi} \]

\[ P_L = 1.5 S_m \]

24.06 < 1.5(30) = 30 ksi
Since the stress intensity (24.06 ksi) is equal to (within reading accuracy of the stress plots) the stress (24.0 ksi), the meridional distance vs. stress intensity is taken from Fig.

The meridional distance at a stress intensity of 1.15 m (1.1 x 20 = 22 ksi) is 13.5".

\[ 13.5" < \sqrt{RT} = \sqrt{132(1.75)} = 15.20" \text{ O.K.} \]

\[ \therefore \text{The stress intensity in the region is a local membrane stress intensity.} \]

**General Membrane Stress Intensity**

\[ \sigma_1 = 12.3 \text{ ksi} \]

\[ \sigma_2 = \frac{1.2 + 12.8}{2} = 7.0 \text{ ksi} \]

\[ \sigma_3 = \frac{-1.19}{2} = -0.06 \text{ ksi} \]
\[ S_{12} = 12.3 - 7.0 = 5.3 \text{kSI} \]

\[ S_{23} = 7.0 - (-0.6) = 7.06 \text{kSI} \]

\[ S_{31} = -0.6 - 12.3 = -12.36 \]

\[ S = |-12.36| = 12.36 \text{kSI} \]

\[ P_m \leq S_m \]

\[ 12.36 < 20.0 \text{kSI} \]

**General principle membrane stress**

\[ \sigma = 12.3 \]

\[ \sigma \leq S \]

\[ 12.3 < 23.7 \text{kSI} \]

*The membrane stress (intensity) meets the stress evaluation criteria.*
Primary Plus Secondary Stress Intensity

Inside surface (Fig

\[ \sigma_1 = 20.0 \text{ KSI} \]
\[ \sigma_2 = -9.0 \text{ KSI} \]
\[ \sigma_3 = -119 \text{ KSI} \]

\[ S_{12} = 20.0 - (-9.0) = 29.0 \text{ KSI} \]
\[ S_{23} = -9.0 - (-119) = 881 \text{ KSI} \]
\[ S_{31} = -119 - 20.0 = -20119 \text{ KSI} \]

\[ S = |29.0| = 29.0 \text{ KSI} \]

\[ P_l + P_b + G \leq 3S_m \]

\[ 29.0 < 3(20) = 60 \text{ KSI} \]

0.K.
Outside surface

\[ \sigma_1 = 27.5 \text{ ksi} \]
\[ \sigma_2 = 17.5 \text{ ksi} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = 27.5 - 17.5 = 10.0 \text{ ksi} \]
\[ S_{23} = 17.5 - 0 = 17.5 \text{ ksi} \]
\[ S_{31} = 0 - 27.5 = -27.5 \text{ ksi} \]

\[ S = | -27.5 | = 27.5 \text{ ksi} \]

\[ P_L + P_b + Q \leq 3 \cdot S_m \]
\[ 27.5 \leq 3(20) = 60 \text{ ksi} \]

\[ \therefore \text{ The primary plus secondary stress intensity meets the stress evaluation criteria.} \]
Knuckle region at the large dia cy linder

Membrane stress (intensity)

Primary local membrane stress intensity, see Fig 22

\[
\sigma_1 = -8.3 \text{ KSI}
\]
\[
\sigma_2 = \frac{32.6 + (-16.5)}{2} = 8.2 \text{ KSI}
\]
\[
\sigma_3 = -119 \frac{2}{2} = -106 \text{ KSI}
\]
\[
S_{12} = -8.3 - 8.2 = -16.5 \text{ KSI}
\]
\[
S_{23} = 8.2 - (-1.06) = 8.06 \text{ KSI}
\]
\[
S_{31} = -1.06 - (-8.3) = 8.24 \text{ KSI}
\]
\[
S = \left| -16.5 \right| = 16.5 \text{ KSI}
\]

\[
P_L \leq 1.5 \times S_m
\]

\[
16.5 < 1.5(30) = 45 \text{ KSI}
\]
Since the stress intensity is also $S_m$ (20 ksi), the stress intensity meets the stress evaluation criteria.

**General Membrane Stress**

$$S = 17.0 \text{ ksi}$$

$$S \leq 18.2 \text{ ksi}$$

$$17.0 < 18.2 \text{ ksi} \quad \text{O.K.}$$

The membrane stress (intensity) meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

**Inside Surface**

\[ \sigma_1 = 32.8 \text{ KSI} \]
\[ \sigma_2 = -1.0 \text{ KSI} \]
\[ \sigma_3 = -1.119 \text{ KSI} \]

\[ S_{12} = 32.8 - (-1.0) = 33.8 \text{ KSI} \]
\[ S_{23} = -1.0 - (-1.119) = -.881 \text{ KSI} \]
\[ S_{31} = -1.119 - 32.8 = -32.919 \text{ KSI} \]

\[ S = \sqrt{33.8} = 33.8 \text{ KSI} \]

\[ P_L + P_b + Q \leq 3S_m \]

\[ 33.8 \leq 3(60) = 180 \text{ KSI} \]
Outside surface

\[ \sigma_1 = -16.5 \text{ KSI} \]
\[ \sigma_2 = -15.8 \text{ KSI} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = -16.5 - (-15.8) = 0.7 \text{ KSI} \]
\[ S_{23} = -15.8 - 0 = -15.8 \text{ KSI} \]
\[ S_{31} = 0 - (-16.5) = 16.5 \text{ KSI} \]

\[ S = |16.5| = 16.5 \text{ KSI} \]

\[ P_e + P_b + Q \leq 1.5 S_{31} \]

\[ 16.5 < 1.5(20) - 20 \text{ KSI} \]
Fig 26  Computer plot of geometry

Fig 27  Average net-section hoop stress
        $P = 119$ psi

Fig 28  Inside surface stress
        longitudinal & hoop
        $P = 119$ psi

Fig 29  Outside surface stress
        longitudinal & hoop
        $P = 119$ psi

Fig 30  Radial displacement
        $P = 119$ psi
Knuckle region at the small dia cylinder

Membrane Stress (Intensify)

Primary local membrane stress intensity

see Fig 27

\[
\sigma_1 = 24.4 \text{ ksi}
\]

\[
\sigma_2 = 18.0 + \frac{(-8.0)}{2} = 5.0 \text{ ksi}
\]

\[
\sigma_3 = -\frac{-11.9}{2} = -0.6 \text{ ksi}
\]

\[
\sigma_{12} = 24.4 - 5.0 = 19.4 \text{ ksi}
\]

\[
\sigma_{23} = 5.0 - (-0.06) = 5.06 \text{ ksi}
\]

\[
\sigma_{31} = -0.6 - 24.4 = -24.46
\]

\[
S = \left| -24.46 \right| = 24.46 \text{ ksi}
\]

\[
P_L \leq 1.5 S_m
\]

\[
24.46 \leq 1.5(20) = 30 \text{ ksi}
\]
Since the stress intensity (24.46 ksi) is equal to (within reading accuracy of the stress plots) the stress (24.4 ksi), the meridional distance vs. stress intensity is taken from Fig 27.

The meridional distance at a stress intensity of 11.5 m (1.1 x 20 = 22 ksi) is 12".

\[ 12" < \sqrt{RT} = \sqrt{110(1.40)} = 12.5" \]

\[ \therefore \text{The stress intensity in the region is a local membrane stress intensity.} \]

**General Membrane Stress Intensity**

\[ \sigma_1 = 15.0 \text{ KSI} \]

\[ \sigma_2 = \frac{6.0 + 8.6}{2} = 7.3 \text{ KSI} \]

\[ \sigma_3 = \frac{-1.19}{2} = -0.6 \text{ KSI} \]
\[ S_{12} = 15.0 - 7.3 = 7.7 \text{ ksi} \]

\[ S_{23} = 7.3 - (-0.6) = 7.36 \text{ ksi} \]

\[ S_{31} = -0.6 - 15.0 = -15.06 \text{ ksi} \]

\[ S = | -15.06 | = 15.06 \text{ ksi} \]

\[ P_m \leq S_m \]

\[ 15.06 < 20.0 \text{ ksi} \]

**General principal membrane stress**

\[ \sigma = 15.0 \text{ ksi} \]

\[ \sigma \leq S \]

\[ 15.0 < 23.7 \text{ ksi} \]

The membrane stress (intensity) meets the stress evaluation criteria.
Primary plus Secondary Stress Intensity

Inside Surface (Fig 28)

\[ \sigma_1 = 20.5 \text{ ksi} \]
\[ \sigma_2 = -8.0 \text{ ksi} \]
\[ \sigma_3 = -1.119 \]
\[ S_{12} = 20.5 - (-8.0) = 28.5 \text{ ksi} \]
\[ S_{23} = -8.0 - (-1.119) = -6.881 \text{ ksi} \]
\[ S_{31} = -1.119 - 20.5 = -21.619 \text{ ksi} \]
\[ S = |28.5| = 28.5 \text{ ksi} \]

\[ P_L + P_b + G \leq 3 S_m \]

\[ 28.5 < 3(20) = 60 \text{ ksi} \quad \text{O.K.} \]
Outside Surface

\[ \sigma_1 = 28.5 \text{ ksi} \]
\[ \sigma_2 = 18.0 \text{ ksi} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = 28.5 - 18.0 = 10.5 \text{ ksi} \]
\[ S_{23} = 18.0 - 0 = 18.0 \text{ ksi} \]
\[ S_{31} = 0 - 28.5 = -28.5 \text{ ksi} \]

\[ S = \left| -28.5 \right| = 28.5 \text{ ksi} \]

\[ P_L + P_b + Q \leq 3S_m \]
\[ 28.5 < 3(20) = 60 \text{ ksi} \]

\[ \therefore \text{The primary plus secondary stress intensity meets the stress evaluation criteria.} \]
Knuckle region at large dia cylinder

Membrane Stress (intensity)

Primary local membrane stress intensity. See Fig 27.

\[ \sigma_1 = -9.1 \text{ ksi} \]
\[ \sigma_2 = -14.0 + \frac{32.2}{2} = 8.1 \text{ ksi} \]
\[ \sigma_3 = -\frac{119}{2} = -59 \text{ ksi} \]

\[ S_{12} = -9.1 - 8.1 = -17.2 \text{ ksi} \]
\[ S_{23} = 8.1 - (-0.6) = 8.16 \text{ ksi} \]
\[ S_{31} = -0.6 - (-9.1) = 9.04 \text{ ksi} \]

\[ S = | -17.2 | = 17.2 \text{ ksi} \]

\[ P_L \leq 1.5 \cdot S_m \]

\[ 17.2 \leq 1.5 \cdot (30) = 30 \text{ ksi} \]
Since the stress intensity is also $S_m (20$ ksi), the stress intensity meets the stress evaluation criteria.

**General Membrane Stress**

$$S = -9.1 \text{ KSI} \quad \text{(largest negative stress)}$$

or

$$S = 17.0 \text{ KSI} \quad \text{(positive stress on cone)}$$

$$S \leq 18.2 \text{ KSI}$$

$$17.0 < 18.2 \text{ KSI} \quad \text{O.K.}$$

::: The membrane stress (intensity) meets the stress evaluation criteria.
Primary Plus Secondary Stress Intensity

Inside Surface

\[ \sigma_1 = 32.5 \text{ KSI} \]
\[ \sigma_2 = -2.0 \text{ KSI} \]
\[ \sigma_3 = -1.19 \text{ KSI} \]

\[ S_{12} = 32.5 - (-2.0) = 34.5 \text{ KSI} \]
\[ S_{23} = -2.0 - (-1.19) = -1.81 \text{ KSI} \]
\[ S_{31} = -1.19 - 32.5 = -33.69 \text{ KSI} \]

\[ S = \left| 34.5 \right| = 34.5 \text{ KSI} \]

\[ P_L + P_b + Q \leq 35 \text{mp} \]

\[ 34.5 < 3(20) = 60 \text{ KSI} \]
Outside Surface

\[ \sigma_1 = -16.0 \text{ KSI} \]
\[ \sigma_2 = -15.8 \text{ KSI} \]
\[ \sigma_3 = 0 \]

\[ S_{12} = -16.0 - (-15.8) = -0.2 \text{ KSI} \]
\[ S_{23} = -15.8 - 0 = -15.8 \text{ KSI} \]
\[ S_{31} = 0 - (-16.0) = 16.0 \text{ KSI} \]

\[ S = \left| 16.0 \right| = 16.0 \text{ KSI} \]

\[ P_L + P_b + Q \leq 1.5 \cdot S_m \]
\[ 16.0 \leq 1.5(20) = 30 \text{ KSI} \]

\[ \text{PRODUCIBILITY OF THE ORIGINAL PAGE IS POOR} \]

The primary plus secondary stress intensity meets the stress evaluation criteria.
59 to R21

This region of the tunnel is a long shallow cone. The cone angle for the cone is shallower than the cone angle for the region between R6 + R9. Due to the fact shallow cone angles do not produce high stresses at the knuckles (Ref. Fig 11-14 and the evaluation of R6 to R9 cone p. 20 thru 32) the area was not analyzed by finite difference methods.
GEOMETRY PLOT -
SECTION R1 - 52

FIGURE 1
FIGURE 2

AVERAGE HOOP STRESS

P = 119 W/KNUCKLES
Figure 4

OUTSIDE SURFACE

- = LONGITUDINAL
- = HOOP

P = 119 W/KNUCKLES

NOTE: PRODUCIBILITY OF THE ORIGINAL PAGE IS POOR
Figure 6

Geometry plot - section S3-R3

Reproducibility of the original page is poor
INSIDE SURFACE

- = LONGITUDINAL
- = HOOP

P = 119 W/KNUCKLES

FIGURE 8

MERIDIONAL DISTANCE, S, IN

STRESS, KSI
GEOMETRY PLOT
SECTION R6 - R9

FIGURE II
FIGURE 13

INSIDE SURFACE

- LONGITUDINAL
- HOOP

P = 119 W/O KNUCKLES

STRESS, KSI

MERIDIONAL DISTANCE, 5 IN

1.30

R6

R7

R8

R9

1.92
Figure 14

Reproducibility of the original page is poor.
GEOMETRY PLOT
SECTION R10-R12

Figure 16
AVERAGE HOOP STRESS

P = 119 w/o KNUCKLES

FIGURE 17
Figure 18

Reproducibility of the original page is poor.
Figure 19

Outside Surface

- \( R_{10} = 1.92 \)
- \( R_{11} = 0.87 \)
- \( R_{12} = 2.08 \)

- \( \bigcirc \) Longitudinal
- \( \square \) Hoop

\( P = 119 \) w/o Knuckles

Meridional Distance, S, in
Figure 20

Reproducibility of the original page is poor.
GEOMETRY PLOT
SECTION R18A-58

FIGURE 21
13.5" < \sqrt{RT} = 15.20°

AVERAGE HOOP STRESS

P = 119 W/NUCKLES

FIGURE 22

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR
OUTSIDE SURFACE

○ = LONGITUDINAL
□ = HOOP

P = 119, W/KNUCKLES

REPRODUCIBILITY OF
ORIGINAL PAGE IS POOR
GEOMETRY PLOT
SECTION 59-R16

FIGURE 26
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR
AVERAGE HOOPT STRESS

\[ p = 119 \text{ W/KNUCKLES} \]
FIGURE 28

INSIDE SURFACE

○ = LONGITUDINAL
□ = HOOP

P = 119 W/KNUCKLES

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR
Figure 29

Stress, KSI

Outside Surface

○ = Longitudinal
□ = Hoop

P = 119 W/Knuckles
Figure 30: Reproducibility of the original page is poor.
The following section of the tunnel was modeled using Nastran.

Note:
This is not a detailed analysis of this section of the tunnel. The following computer results and hand calculations are used only to verify stress calculations due to hydro test conditions.
Nas-tran (NASA Structural Analysis) is a general purpose digital computer program for the analysis of large complex structures. 

NASA SP-222(01)
Vaspan model description

This section of the tunnel was modeled using homogenous quadrilateral membrane and bending elements, except for E1 & E2, which were modeled using beam elements. Due to the need of modeling a variable pressure, a half model using 31 elements around the circumference was generated.

See Figure 1 for a joint location sketch of this area.
Constraints.

The RZ plane was modeled as a plane of symmetry.

On the R1 end of the model the Z displacement and rotations were removed.

On the R3 end of the model all rotations were removed.

The rotation normal to the shell elements was removed.

Nodes on the flange of the support tee 52 and 53 located at θ = 90° were fixed in the vertical direction. (fig 2)
Boundary Conditions

Cooling Coil Section
Model geometry

as previously mentioned a half model with 31 elements around the circumference and 1117 nodes, was generated.
The model ran from ring location R1 to ring location R3.

All shell thickness were 1.24" except for the down stream shell past the second cone cylinder junction. This thickness was 1.00".

<table>
<thead>
<tr>
<th>Material Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E = 30 \times 10^6 \text{ PSI}$</td>
</tr>
<tr>
<td>$v = 0.3$</td>
</tr>
<tr>
<td>$\rho = 0.283 \text{ lbs/in}^3$</td>
</tr>
</tbody>
</table>
Loading

A uniform element pressure of 119 psi was applied to all shell elements. In addition to this uniform pressure, a variable pressure due to the water head was added on.

\[
Y = \frac{62.4 \text{ lbs/ft}^3}{0.0361 \frac{\text{lb}}{\text{in.}^2}}
\]

\[
\begin{align*}
\Delta P_x &= Y [2R - (R + R \cos \theta)] \\
\Delta P_y &= Y (R - R \cos \theta) \\
P_{\text{test}} &= 1.5 \times \Delta P_{\text{opp}} = 1.5 \times 119 = 173.5
\end{align*}
\]

The variable pressure at any point \( x \) around the circumference was defined by

\[
\Delta P_x = Y (R - R \cos \theta) + P_{\text{test}}
\]

Note: all pressures are in psi.
With 31 elements around the circumference
The enclosure angle between elements
$180^\circ / 30$ spaces = $6^\circ$

Theta to the first element is $3^\circ$.

Pressure at $\theta = 3^\circ$

$$p_c = 119 \times 1.5 + 0.361 \left(20.5 \times 12 - 20.5 \times 12 \times \cos(3^\circ)\right)$$

$$p_c = 178.55 \text{ psi}$$

Pressure at $\theta = 180^\circ$

$$p_b = 119 \times 1.5 + 0.361 \left(20.5 \times 12 - 20.5 \times 12 \times \cos(180^\circ)\right)$$

$$p_b = 196.23 \text{ psi}$$

Where $(119 \times 1.5) = 178.5 \text{ psi}$ is the Hydro test pressure.

$\gamma R(1 - \cos\theta)$ is the additional pressure at any point due to the water head.
A linear variable end force was applied to the R3 end of the model given by

\[ P = \left( \frac{P_b - P_a}{Z_R} \right) x + P_a \]

\[ P = \frac{\Delta P}{Z_R} \left[ R \left( 1 - \cos \theta \right) \right] + P_a \]

\[ P = \Delta P \left[ 1 - \cos \theta \right] + P_a \]

Pressure \[ x = \Delta P \left[ 1 - \cos \theta \right] + P_a \]
Results

The primary purpose for this model was to verify that scaling of operating stresses to hydro stresses wouldn't generate any incorrect stresses results.

Also, note that this section of the tunnel has the highest and lowest elevation. Therefore, the highest pressure due to the water head.
Water weights - from computer run GT 78007

<table>
<thead>
<tr>
<th>Node</th>
<th>Constraint Reaction lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>264</td>
<td>-5.59934 x10^3</td>
</tr>
<tr>
<td>295</td>
<td>-4.44728 x10^5</td>
</tr>
<tr>
<td>362</td>
<td>-5.115345 x10^4</td>
</tr>
<tr>
<td>729</td>
<td>-5.441023 x10^4</td>
</tr>
<tr>
<td>760</td>
<td>-4.59041 x10^5</td>
</tr>
<tr>
<td>791</td>
<td>-5.556915 x10^4</td>
</tr>
<tr>
<td>3016</td>
<td>-4.098632 x10^5</td>
</tr>
<tr>
<td>1039</td>
<td>-3.277161 x10^5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1858475.165</td>
</tr>
</tbody>
</table>

Calculated weight of water in this section of the tunnel: 1851719.0 lbs.

Calculated | 1851719.0 | lbs
Model generated | 1858475.0 | lbs
Δ Water weight | -6756.0 | lbs.
.36% diff.
Operating pressure \( P = 119.00 \)

(Top) Hydro pressure at element 2001 = \( 0.0483 + 178.5 = 178.55 \) psi

(Bottom) Hydro pressure at element 2030 = \( 17.73 + 178.5 = 196.23 \) psi

Scale factor for top of tunnel:
\[
\frac{178.55}{119} = 1.5004
\]

Scale factor for bottom of tunnel:
\[
\frac{196.23}{119} = 1.649
\]

From Nastran run GT 78007 w/ \( P = 119 \)
(Peak stresses)

<table>
<thead>
<tr>
<th>Element</th>
<th>Hoop Inside KSI</th>
<th>Hoop Outside KSI</th>
<th>Axial Inside KSI</th>
<th>Axial Outside KSI</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>-4.43</td>
<td>-13.9</td>
<td>+27.59</td>
<td>-3.71</td>
<td>( \theta = 0^\circ )</td>
</tr>
<tr>
<td>2030</td>
<td>-4.44</td>
<td>-13.9</td>
<td>+27.59</td>
<td>-3.71</td>
<td>( \theta = 180^\circ )</td>
</tr>
</tbody>
</table>

Scaled Stresses from above

<table>
<thead>
<tr>
<th>Element</th>
<th>Hoop Inside KSI</th>
<th>Hoop Outside KSI</th>
<th>Axial Inside KSI</th>
<th>Axial Outside KSI</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>-6.647</td>
<td>-20.86</td>
<td>+41.336</td>
<td>-5.57</td>
<td>1.5</td>
</tr>
<tr>
<td>2030</td>
<td>-7.32</td>
<td>-22.92</td>
<td>+45.50</td>
<td>-6.12</td>
<td>1.649</td>
</tr>
</tbody>
</table>

Stresses from Hydro run \( P = 178.5 + \text{H}_2\text{O head} \)

<table>
<thead>
<tr>
<th>Element</th>
<th>Hoop KSI Inside</th>
<th>Hoop KSI Outside</th>
<th>Axial KSI Inside</th>
<th>Axial KSI Outside</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>-7.14</td>
<td>-21.6</td>
<td>42.0</td>
<td>-5.71</td>
<td>( \theta = 0^\circ )</td>
</tr>
<tr>
<td>2030</td>
<td>-7.15</td>
<td>-22.6</td>
<td>45.23</td>
<td>-6.03</td>
<td>( \theta = 180^\circ )</td>
</tr>
</tbody>
</table>
As can be seen from the last two tables, scaling of operating stresses does not generate any erroneous stresses.

To add additional verification to the above procedure, some hand calculations to predict stresses in the region between support ring were made.

\[ P_a = 178.55 \]
\[ P_b = 196.73 \]
For Hydro Conditions.

At point A.  element no. 528
\[ R = 246.62 \quad \theta = 0^\circ \quad P = 178.55 \text{ PSI} \]

\[ \sigma_{\text{hoop}} = (178.55 \times 246.62) / 1.24 = 35511 \text{ PSI} \]

at point B  element no. 557
\[ R = 246.62 \quad \theta = 180^\circ \quad P = 196.23 \]

\[ \sigma_{\text{hoop}} = (196.23 \times 246.62) / 1.24 = 39027 \text{ PSI} \]

From Nastran run no. GT 78007:

at element no. 528
\[ \sigma_{\text{hoop (inside)}} = 355089 \quad \sigma_{\text{hoop (outside)}} = 35405.8 \]

at element no. 557
\[ \sigma_{\text{hoop (inside)}} = 39929 \quad \sigma_{\text{hoop (outside)}} = 39025 \]

\[ \text{Jaw} = 35457 \text{ PSI} \]

Reproducibility of the original page is poor.

<table>
<thead>
<tr>
<th>Element</th>
<th>Hand Calculation</th>
<th>Computer results</th>
<th>( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>528</td>
<td>35.5 KSI</td>
<td>35.5 KSI</td>
<td>0(^\circ)</td>
</tr>
<tr>
<td>557</td>
<td>39.0 KSI</td>
<td>39.0 KSI</td>
<td>180(^\circ)</td>
</tr>
</tbody>
</table>
In conclusion the following method was used in predicting hydro test stresses from operating conditions.

**Upper Center line**

\[ P_{\text{hydro}} = 1.19 \times 1.5 + \gamma \left( 4.1 \times \frac{1}{2} + D_L \times \frac{1}{2} \right) \]

\[ \gamma = 0.036 \text{ lb/ft}^3 \]

\[ D_L = \text{Local Diameter} \]

**Lower Center line**

\[ P_{\text{hydro}} = 1.19 \times 1.5 + \gamma \left( 4.1 \times \frac{1}{2} + D_L \times \frac{1}{2} + 81.75 \right) \]

Therefore,

\[ \sigma_{\text{(hydro)}} = \left( \sigma_{\text{(operating)}} \right) \left( \frac{P_{\text{hydro}}}{119.0} \right) \]
Assume a cylinder with no structural support and design in accordance with Div I of Code

\[ t = \frac{PR}{SE - 0.6P} \]

\[ P = 119 \text{ psig} \]
\[ R = 120'' \]
\[ S = 25.0 \text{ ksi} \]
\[ E = 1 \]

\[ t = \frac{(119 \times 120)}{(25000 \times 1) - 0.6(119)} \]

\[ t = 0.573 \text{ in.} \]

\[ \sigma = \frac{PR}{t} = \frac{(119 \times 120 \times 286)}{0.573} = 24,980 \text{ psi} \]
Cylinder with insulation rings Model 1

\[ R = 1.7865 \]

Cylinder w/ K insulation rings Model 2

\[ L = 0.573 \]

48" 48" 48" 48"
Cylinder with insulation rings. Model B

Same as model 2 except ring is as follows:

Boundary Forces

\[ F = \frac{(119 \times 100.2865)}{2} \]

\[ F = 715.7 \text{ lb/ft} \]
<table>
<thead>
<tr>
<th>T-SECTION PROPERTIES</th>
<th>T-SECTION PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>B= 2.500&quot;</td>
<td>B= 2.500&quot;</td>
</tr>
<tr>
<td>D= 5.000&quot;</td>
<td>D= 5.000&quot;</td>
</tr>
<tr>
<td>S= 0.250&quot;</td>
<td>S= 0.250&quot;</td>
</tr>
<tr>
<td>T= 0.250&quot;</td>
<td>T= 0.250&quot;</td>
</tr>
<tr>
<td>H= 4.875</td>
<td>H= 4.535</td>
</tr>
<tr>
<td>AREA= 1.844</td>
<td>AREA= 1.675</td>
</tr>
<tr>
<td>y= 3.267</td>
<td>y= 3.087</td>
</tr>
<tr>
<td>I y= 4.797</td>
<td>I y= 3.360</td>
</tr>
<tr>
<td>I y= 0.332</td>
<td>I y= 0.088</td>
</tr>
</tbody>
</table>
Results: (From SALORS)

Cylinder with Insulation Rings - Study

**CASE 1 NO RINGS**

(76/03/01 14.00.05)

Hoop Stress = 25,003 psi
Long. Stress = 17,490 psi

Rad. disp. = 0.0887 in.

**Case 2. With Insulation Rings  t = 0.25**

(76/03/01 14.21.26)

<table>
<thead>
<tr>
<th>%</th>
<th>Smax</th>
<th>0.245</th>
<th>0.490</th>
<th>0.735</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>Smax</td>
<td>Long. Stress (Psi)</td>
<td>Hoop Stress (Psi)</td>
<td>Rad. St. (in)</td>
<td>Net section Hoop</td>
</tr>
<tr>
<td>1.470</td>
<td>Inside</td>
<td>4792.8</td>
<td>23.605.8</td>
<td>0.0701</td>
<td>20.447</td>
</tr>
<tr>
<td></td>
<td>Outside</td>
<td>4,601.9</td>
<td>18,287.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.611</td>
<td>1</td>
<td>12,360.6</td>
<td>25,761.1</td>
<td>0.0894</td>
<td>25.475</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>12,583.1</td>
<td>25,329.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Case 3 With Insulation Rings $t = 0.50$

<table>
<thead>
<tr>
<th>$\frac{1}{2} \text{in}$</th>
<th>Long Stress (psi)</th>
<th>Hoop Stress (psi)</th>
<th>Rod. dell. (in)</th>
<th>Net Ext. Hook</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.366</td>
<td>INSIDE</td>
<td>12.77</td>
<td>25.426</td>
<td>25.434</td>
</tr>
<tr>
<td></td>
<td>OUTSIDE</td>
<td>12.650</td>
<td>25.538</td>
<td></td>
</tr>
<tr>
<td>0.490</td>
<td>INSIDE</td>
<td>25.353</td>
<td>21.725</td>
<td>17.324</td>
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<tr>
<td></td>
<td>OUTSIDE</td>
<td>4.535</td>
<td>13.783</td>
<td></td>
</tr>
<tr>
<td>0.611</td>
<td>INSIDE</td>
<td>12.77</td>
<td>25.426</td>
<td>25.482</td>
</tr>
<tr>
<td></td>
<td>12.650</td>
<td>25.538</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For 0.25 in thick Rings

\[
\frac{2595 - 25003}{2595} = 0.11
\]

Insulation rings result in 1.1% net section stress in hoop direction

---

For 0.50 in thick Rings

\[
\frac{25480 - 25003}{25003} = 0.019
\]

Insulation results in 0.9% net section stress in hoop direction
Fig. 2

Inside Surface

P = 119 psi

Hoop Stress (Inside Surface) with No Internal Rings

Long Stress (Inside Surface) with Internal Rings

Rad. Deflection