Thermal Analysis of the X-Band 34-Meter Antenna Feedcone

R. D. Hughes
Ground Facilities and Antenna Engineering Section

A thermal analysis was done to describe feedcone shell temperature profiles and induced thermal stresses in waveguide components. IMP-SS, a steady-state version of the thermal analysis computer program employing the implicit alternating-direction numerical technique documented in a previous report, was used to analyze the two-dimensional regions of the feedcone. This portion of the analysis determined the free relative displacement of the feedcone for a worst-case thermal condition.

I. Introduction

A newly developed X-band (8.4-GHz) feedcone configuration has been designed for the latest generation of 34-meter antennas to be installed at the Goldstone, Canberra, and Madrid Deep Space Communication Complexes. A potential problem of excessive stress due to environmental thermal effects was identified when the feedcone and inside waveguide component design was under review. To make an accurate estimate of the stress, a detailed thermal analysis depicting temperature distributions along the feedcone shell was necessary. The remaining portion of this analysis then involved computing the free relative displacement between the waveguide and the feedcone structure to which it is attached for a given worst-case condition. The free relative displacement is the displacement of the reference point shown in the feedcone configuration in Fig. 1 that would occur if the shell was unconstrained by connections to the waveguide components. The calculated value of displacement will be used by a separate analysis to calculate stresses in waveguide members.

The temperature distribution calculations were performed by using a general-purpose two-dimensional thermal analysis computer program developed by R. Hughes (Ref. 1). The program used the implicit alternating-direction finite difference technique to analyze systems represented in lumped parameter, electrical analog form. A program version, called IMP-SS, which models a region having steady-state boundary conditions, was developed to suit this particular problem.

II. Configuration Description and Assumptions

The thermal stability of the feedcone interior region is maintained within certain limits (18.3 to 25.6°C (65 to 78°F)) by an air-conditioning system, while the exterior is subject to environmental effects. This thermal analysis was based upon worst-case thermal conditions, assumed to be 54.4°C (130°F) average exterior ambient temperature and 26.7°C (80°F) interior ambient. Also, a "zero-stress" condition was assumed if both interior and exterior components are at 26.7°C. Thus, as the feedcone shell temperature increases above 26.7°C (80°F), thermally-induced stresses will occur by an amount δ_T, the vertical displacement of the reference location shown in Fig. 1. This is the displacement that would occur if the shell were free to expand (the maser/waveguide components were not connected to the feed horn). Therefore, the major portion of this analysis involved determining the temperature distribution of the shell. The feedcone shell consists of structural components covered by a thin aluminum skin insulated on the interior side.

The exterior ambient temperature was represented by the average of shell surface temperatures on the cone side facing the sun and the side away from the sun during peak solar levels. The temperature of a point on the shell surface facing furthest away from the sun was assumed to be 46.1°C (115°F), corresponding to the maximum expected air temperature at Goldstone, California. The temperature of a point on the surface facing most directly toward the sun was assumed to be 16.7°C (30°F) greater than the shady side, or 62.8°C (145°F). The assumption of a 16.7°C temperature difference was based upon field temperature measurements taken at the feedcone of the nearby 26-meter antenna located at Deep Space Station 13 (Venus), as well as from data in Ref. 2 pertaining to the instrument tower windshield of the 64-meter antenna located at Deep Space Station 14 (Mars).

The feedhorn component of the feedcone was assumed to also be exposed to an ambient exterior temperature of 54.4°C. Since the feedhorn is uninsulated, the representative horn wall temperature was assumed to be the average between the inside and outside ambient temperatures, T_{horn} = 40.6°C (105°F).

The feedcone shell thermal expansion was assumed to be characterized by a one-dimensional temperature profile in the axial direction. Thus, the representative shell temperature was computed as the integrated average of the composite temperature profile in the axial direction:

$$\overline{T}_{shell} = \frac{1}{L}\int_0^L T\,dy$$

III. Analysis

The IMP-SS computer program was used to determine the temperature distributions for three types of thermal regions of the feedcone shell (1) the intersection of the maser floor with the skin, (2) the intersection of a stiffening ring with the skin, and (3) the intersection of a vertical stiffener with the skin, as indicated in Fig. 1. The skin was represented as a one-dimensional thermal region in these analyses as shown in the thermal node networks of Figs. 2 through 4. These thermal networks are either horizontal (skin-stiffener intersection) or vertical (skin-floor and skin-ring intersections) cuts through the shell. In both cases, the curvature of the shell was neglected so that the analysis could be done in rectangular coordinates. Figs. 5 through 7 show the actual configurations before being transformed to the representative ones used in the model.

The following four boundary conditions were applied to each of the three thermal networks in Figs. 2 through 4: (1) a line of symmetry, (2) an interior ambient temperature of 26.7°C, (3) an exterior ambient temperature of 54.4°C, and (4) a prescribed temperature profile at a sufficient distance from a "thermal disturbance" (i.e., the intersection of ring and skin) so that the temperature distribution from the inside to the outside across the wall thickness, including insulation, becomes one dimensional and may be predicted analytically for a composite wall. This analytical composite wall result is shown in Fig. 8 for two inside and outside temperatures. The computations and material properties are described in the Appendix.

IV. Results

The resulting temperature distributions for pertinent nodes of the three thermal region types are shown in Tables 1 through 3. The parts of the tables enclosed in solid lines indicate temperatures in the skin and the attached structural component (ring, stiffener, and floor). The vertical stiffeners appear to have an influence on the skin temperature of only about 0.5°C (1°F) and therefore the effect of stiffeners on skin temperature was neglected. The skin temperature profiles for the skin-ring and skin-floor intersection regions are shown in Fig. 9. These profiles indicate a significant thermal influence upon skin temperature. Note that both are asymptotic to the undisturbed skin temperature, and are reasonably close to it at the boundary of the thermal network modeled.

These profiles were mapped onto appropriate regions of the feedcone skin, resulting in an overall skin temperature profile that is a composite of the individual profiles. Although the various stiffening rings differ in dimension, it was felt that the ring configuration modeled was typical, and the use of one profile for all ring regions provided an acceptable level of detail for this analysis. The skin temperature profile was integrated along the axial length of the feed cone surface to determine an integrated average skin temperature of 48.6°C (119.4°F).

The average temperature of the stiffener cross section was estimated from Table 1 to be 51.4°C (124.5°F). This temperature was combined with the average skin temperature to give a weighted average shell temperature based on cross-sectional area:

$$\overline{T}_{shell} = 49.7^\circ\text{C}\ (121.3^\circ\text{F})$$

The resulting shell expansion in the axial direction was 0.196 cm (0.077 in.). This expansion would be directed upward in Fig. 1. The axial thermal expansion of the feedhorn was calculated to be 0.038 cm (0.015 in.), directed downward. Thus, the net displacement of the reference location is:

$$\delta_T = 0.157 \text{ cm } (0.062 \text{ in.})$$

based on the assumptions made in this analysis. Calculation details regarding the skin temperature profile and deflections are given in the appendix.

References

1. Hughes, R. D., "The Application of the Implicit Alternating Direction Numerical Technique to Thermal Analysis Involving Conduction and Convection," *Telecommunications and Data Acquisition Progress Report 42-73*, Jet Propulsion Laboratory, Pasadena, Calif., May 1983.

2. McGinness, H. D., "210-Ft. Antenna Tower Positional Stability," *DSN Space Programs Summary No. 37-50*, Vol. II, Jet Propulsion Laboratory, Pasadena, Calif., March 1968.

Table 1. Skin-stiffener region temperature distribution, °C

Vertical node, I	Horizontal nodes, J[a]											
	1	2	3	4	5	6	7	8	9	10	11	12
1	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
2	47.5	51.3	47.5									
3	49.5	51.4	49.6									
4	50.3	51.4	50.3									
5	50.6	51.4	50.6									
6	50.9	51.4	50.9									
7	51.1	51.5	51.1									
8	51.2	51.5	51.2									
9	51.4	51.5	51.4									
10	51.5	51.6	51.5	51.4	51.2	50.8	50.0					
11	51.6	51.6	51.6	51.6	51.6	51.6	51.1	50.9	50.9	50.9	50.9	51.0
12	51.6	51.6	51.6	51.6	51.6	51.6	51.7	51.8	51.9	52.0	52.0	52.2
13	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4

[a]Refer to Fig. 2 for node network configuration.

Table 2. Skin-floor region temperature distribution, °C

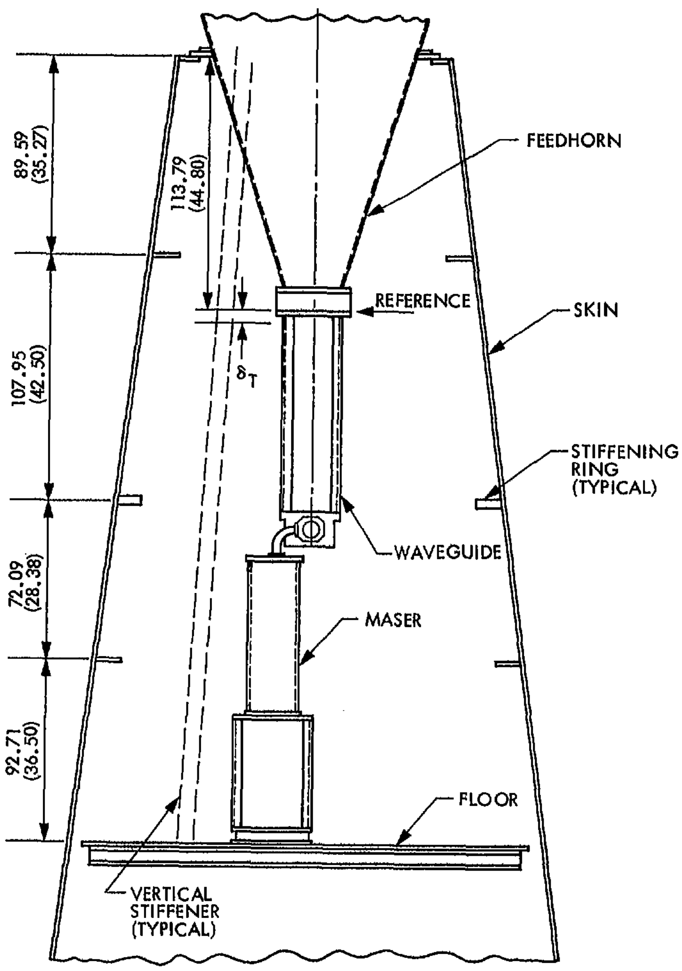
Vertical node, I	Horizontal nodes, J[a]												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
2	26.7	27.8	26.7										
3	26.7	29.0	26.7										
4	26.7	30.3	26.7										
5	26.8	31.9	26.8										
6	26.8	34.1	26.8										
7	31.2	36.0	31.2										
8	36.1	36.9	36.1										
9	39.6	37.5	39.6	42.8	45.0	46.5	47.5	48.2	49.0	49.4	49.6	49.7	49.9
10	40.8	37.8	40.8	44.4	46.8	48.5	49.7	50.4	51.2	51.7	52.0	52.1	52.2
11	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4

[a]Refer to Fig. 3 for node network configuration.

Table 3. Skin-ring region temperature distribution, °C

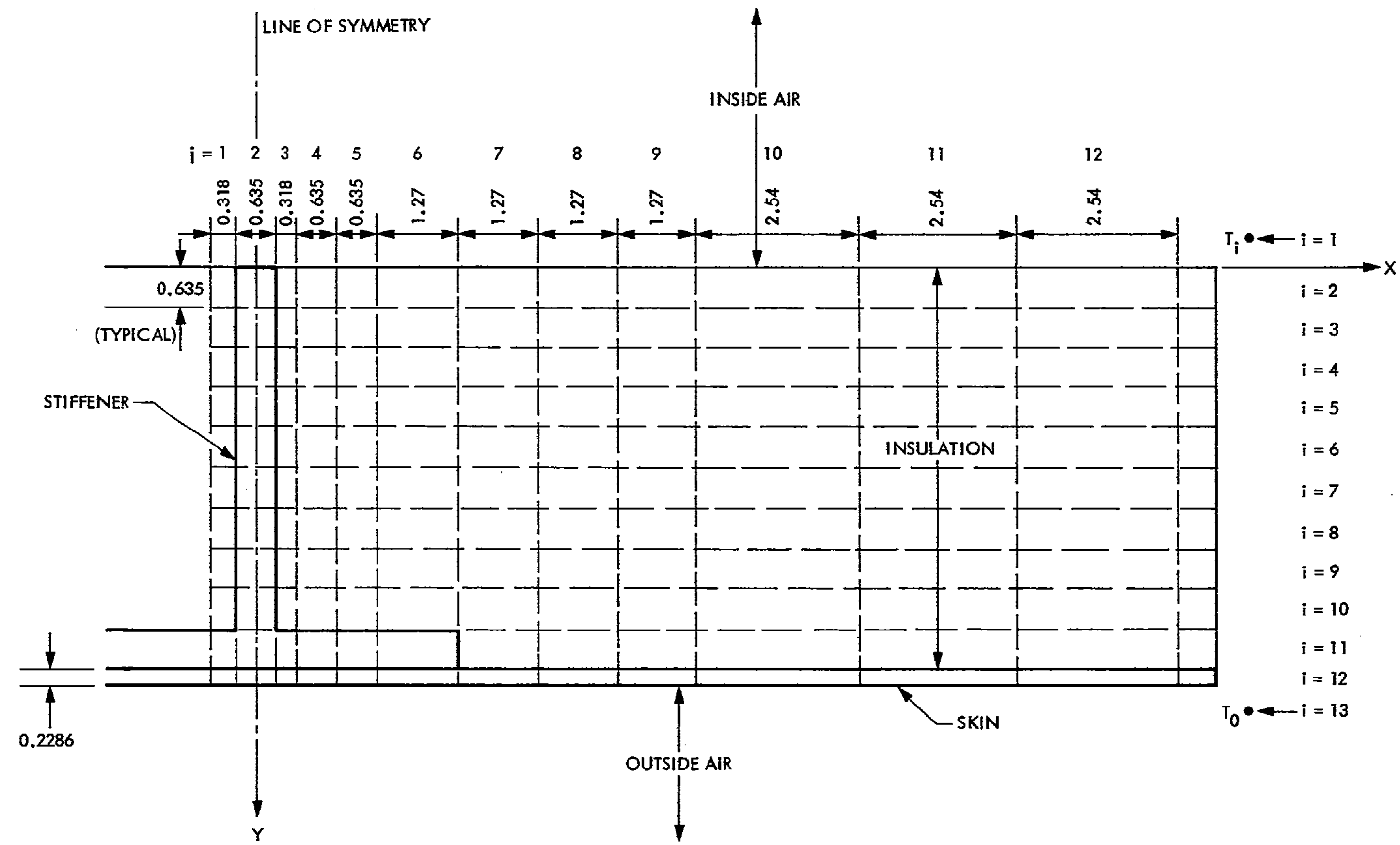
Vertical node, I	Horizontal nodes, J[a]												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
2	26.7	43.6	26.7										
3	26.7	43.7	26.7										
4	26.7	43.8	26.7										
5	33.4	43.9	33.4										
6	40.1	44.2	40.1										
7	44.6	44.3	44.6	46.0	47.2	48.0	48.5	48.9	49.3	49.6	49.7	49.8	49.9
8	46.1	44.4	46.1	48.0	49.3	50.1	50.8	51.2	51.6	51.9	52.0	52.1	52.2
9	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4

[a]Refer to Fig. 4 for node network configuration.



DIMENSIONS IN CENTIMETERS (INCHES)

Fig. 1. 34-meter antenna feedcone configuration



DIMENSIONS IN CENTIMETERS

Fig. 2. Thermal cells: skin with vertical stiffener

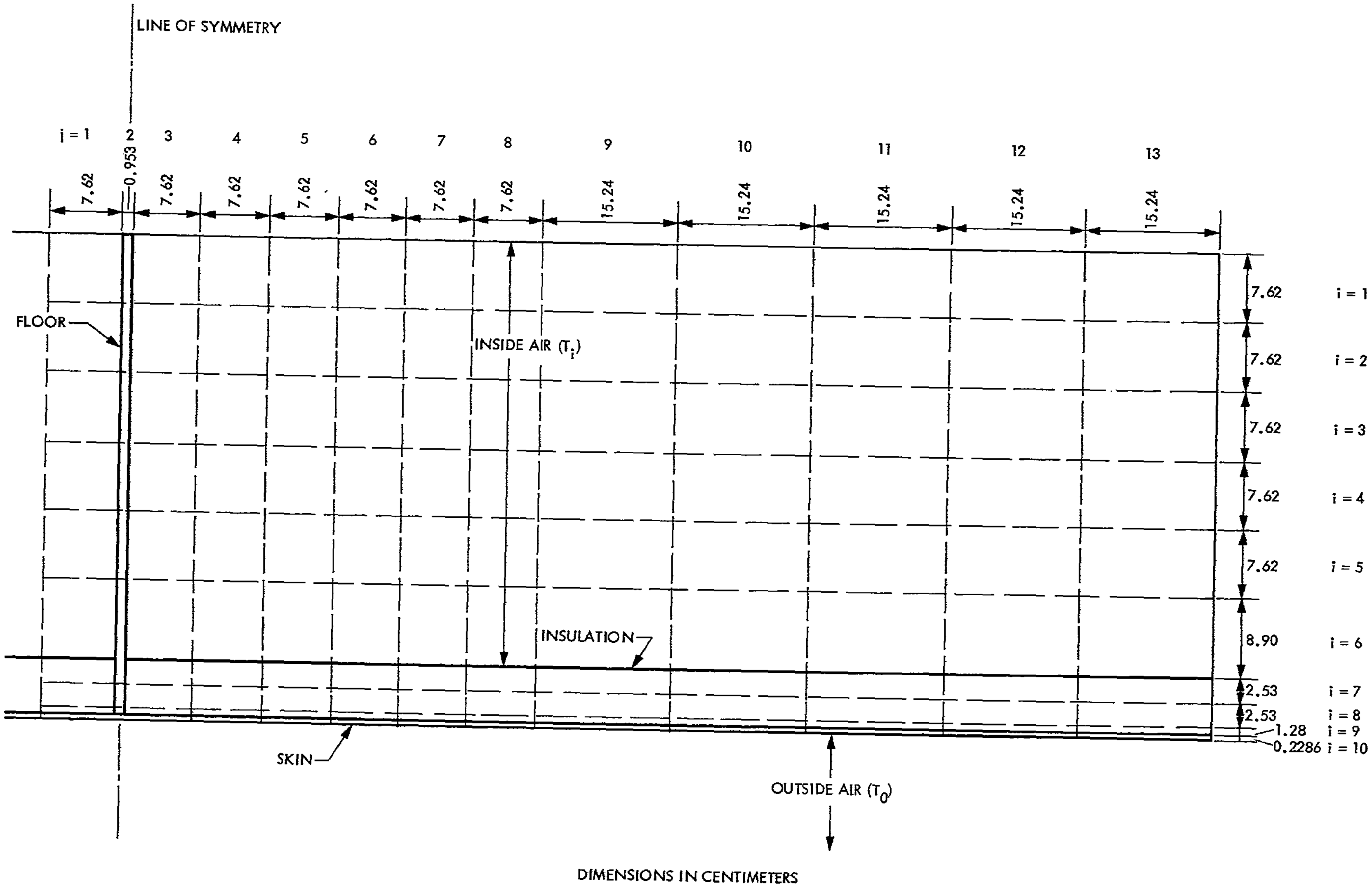


Fig. 3. Thermal cells: skin and floor intersection

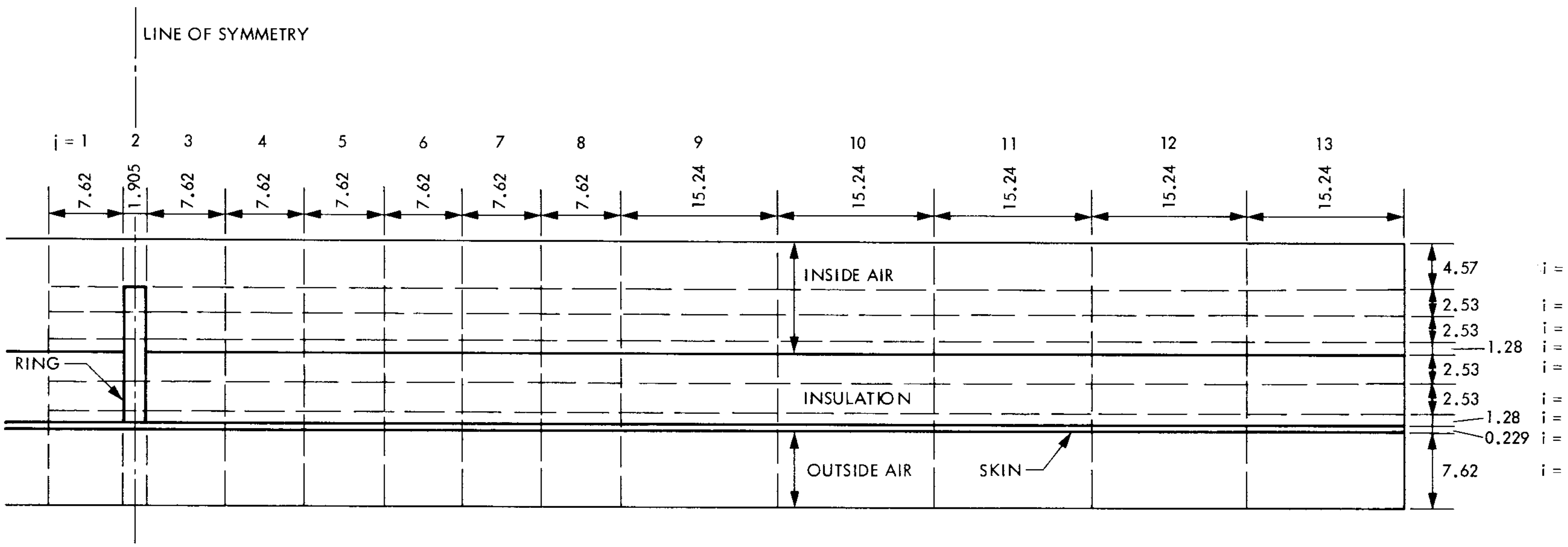


Fig. 4. Thermal cells: skin and ring intersection

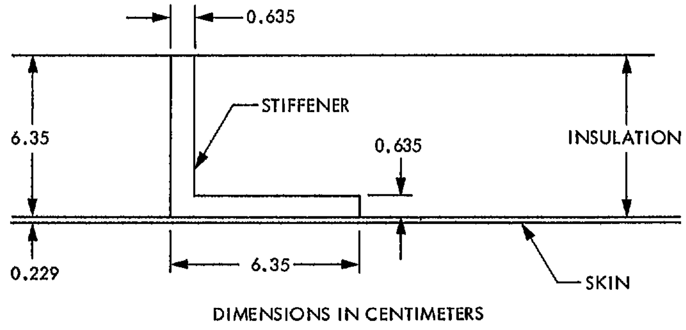


Fig. 5. Vertical stiffener actual configuration

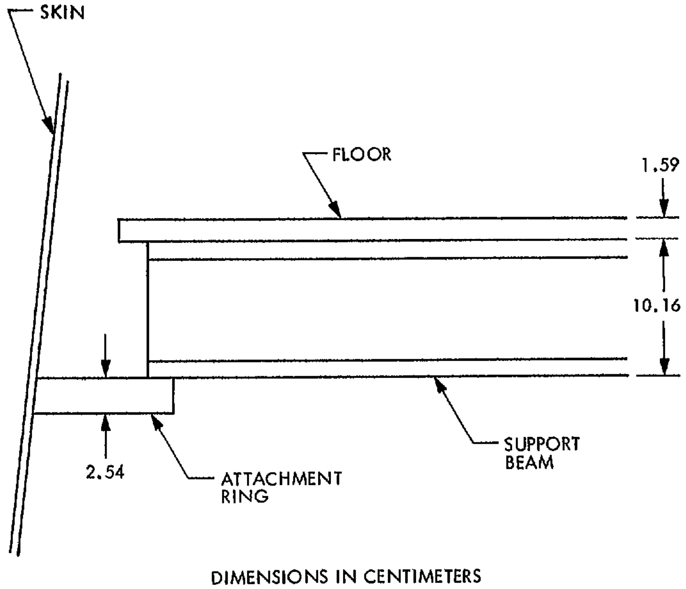


Fig. 6. Skin: floor region actual configuration

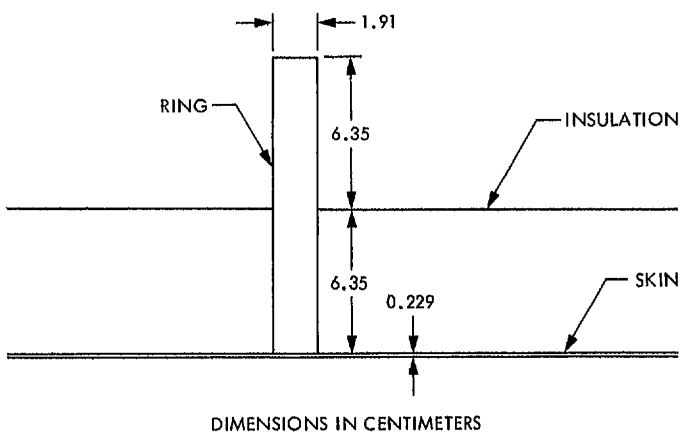


Fig. 7. Skin: ring region actual configuration

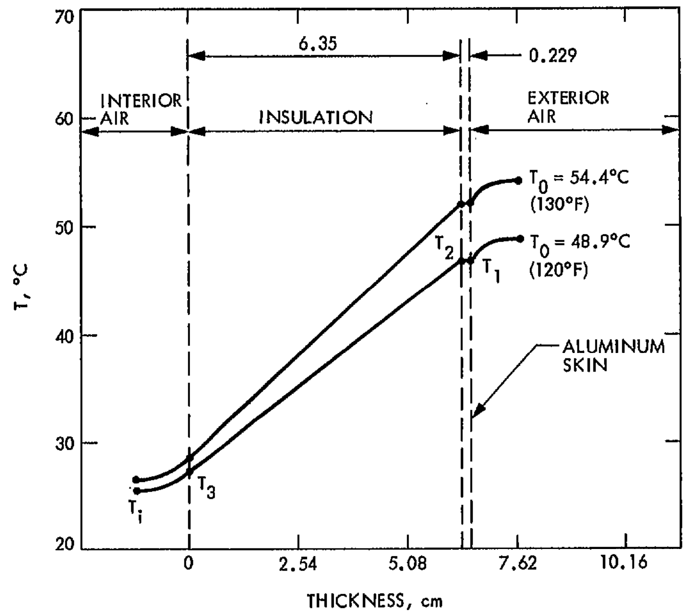


Fig. 8. One-dimensional wall temperature profiles

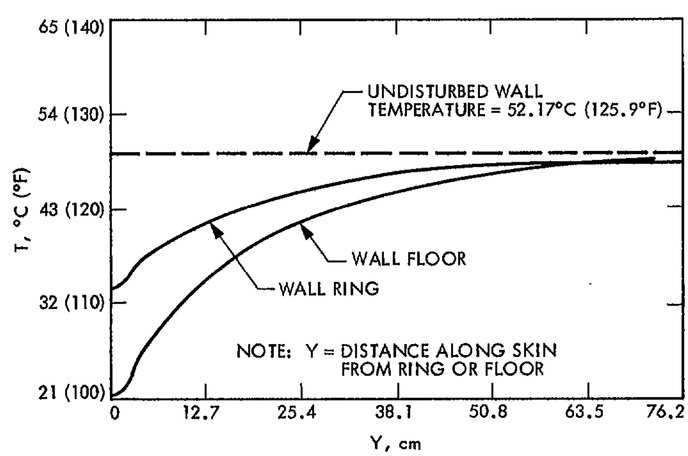


Fig. 9. Skin temperature profiles

Appendix

Computational Procedure

I. One-Dimensional Wall Temperature Profile

The temperature profiles shown in Fig. 8 are derived by first calculating the steady-state heat flux according to the relationship for a composite wall:

$$q = \frac{T_0 - T_i}{\frac{1}{h_0} + \frac{X_1}{k_{sk}} + \frac{X_2}{k_{ins}} + \frac{1}{h_i}}$$

where:

q = heat flux into the wall, W/m^2

h_0 = outside heat transfer coefficient = 8.29 W/m^2 - C

k_{sk} = conductivity of skin = 154.9 W/m - C

k_{ins} = conductivity of insulation = 0.052 W/m - C

X_1 = thickness of skin = 0.00229 m

X_2 = thickness of insulation = 0.0635 m

h_i = inside heat transfer coefficient = 8.29 W/m^2 - C

T_0 = outside air temperature = 54.4°C (130°F)

T_i = inside air temperature = 26.7°C (80°F)

which gives:

$$q = 18.94 \text{ W/m}^2.$$

Local temperatures, as depicted in Fig. 8, are calculated from the relations:

$$T_1 = t_0 - \frac{q}{h_0}$$

$$T_2 = T_1 - \frac{q X_1}{k_{sk}}$$

$$T_3 = T_2 - \frac{q X_2}{k_{ins}}$$

which give:

$$T_1 = 52.2°\text{C}, T_2 = 52.2°\text{C}, T_3 = 29.06°\text{C}.$$

II. Skin Temperature Profile Calculation

The feedcone skin was divided into regions as shown in Fig. A-1. The appropriate temperature profile (Fig. 9) was applied to each region, and the integrated average in each region was determined by:

$$\overline{T}_i = \frac{1}{L} \int_0^L T\, dy$$

The results are as follows:

Region	L, cm	T, °C
1	46.36	46.50
2	46.36	48.89
3	36.04	48.39
4	36.04	48.39
5	53.98	49.22
6	53.98	49.22
7	44.96	48.83
8	44.96	48.83

Although this procedure involved "cutting off" the profiles to conform to the distances between rings, the temperatures at the locations on the skin furthest from the rings differed from the "undisturbed wall temperature" (52.17°C) by only a maximum of 1°C. Thus, no attempt was made to refine the model to take this condition into account, since any error would be well within the scope of accuracy already incorporated.

Note also that the cone angle (~ 7 deg) was neglected in mapping the temperature profiles onto the skin; the profiles were integrated in terms of axial length. This represents an error of less than 1%.

The overall integrated average skin temperature was then calculated by:

$$\overline{T}_{skin} = \sum_i (\overline{T}_i L_i) / \sum_i L_i$$

which gives:

$$\overline{T}_{skin} = 48.6°\text{C}$$

The average stiffener temperature, as given in the text was 51.4°C. The representative shell temperature was taken to be the weighted average of the skin and stiffener temperatures according to cross-sectional area. Representative areas were taken at midheight of the cone where: diameter = 197.9 cm, the cross-sectional area of the skin between two stiffeners = 11.85 cm^2, and the cross-sectional area of a stiffener = 7.66 cm^2.

The resulting weighted average shell temperature is $\overline{T}_{shell}$ = 49.7°C.

III. Free Relative Displacement

The axial expansion of the shell is given by:

$$\delta_s = \mu L \Delta T$$

where:

μ = coefficient of thermal expansion = 0.0000234/°C for 6061-T6 aluminum

L = axial length (height) of cone section from floor to top of feed horn = 362.7 cm

ΔT = temperature differential = 49.7°C - 26.7°C = 23°C

which gives:

$$\delta_s = 0.195 \text{ cm}$$

Note that this displacement would be upward in Fig. A-1.

The axial displacement of the feedhorn is determined according to the conditions:

$$L = 113.8 \text{ cm}$$

$$\Delta T = 40.6°\text{C} - 26.7°\text{C} = 13.9°\text{C}$$

which gives: δ_h = 0.0381 cm downward. The net free relative displacement of the reference location at the bottom of the feed horn is:

$$\delta_T = 0.195 \text{ cm} - 0.0381 \text{ cm}$$

or

$$\delta_T = 0.157 \text{ cm}$$

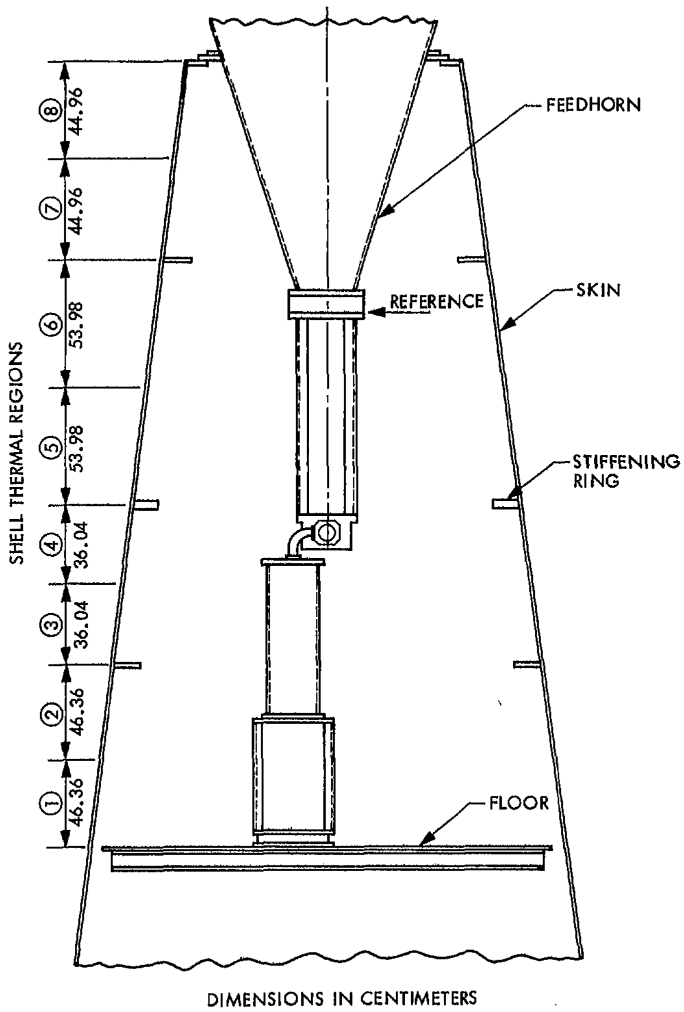


Fig. A-1. Feed cone thermal regions