Distribution
UC-400

SAND--89-0640

DE90 000927

Thermal Environmental Tests on Space Simulation Chamber

Ronald L. Akau
Fluid Mechanics and Heat Transfer Division III

J. Paul Freshour
Fusion Technology Division
Steve L. Wilde
Satellite Integration Division

Sandia National Laboratories
Albuquerque, NM 87185

Abstract

Thermal testing of space payloads at Sandia National Laboratories is conducted in a large cylindrical (7.0 feet in diameter) vacuum chamber with temperature controlled walls. The payload is generally attached to a baseplate with independent temperature controls. To establish well-defined boundary conditions during the tests, uniform wall temperatures are desired in the test chamber. Thermal-vacuum tests were conducted on this space simulation chamber to determine if temperature gradients existed on the chamber shroud and end-bells. Recorded temperature measurements indicated large temperature gradients on the chamber shroud and end-bells. Furthermore, it was difficult to manually control the flow of liquid to the end-bells in order to achieve equal end-bell temperatures. However, results from these tests were used in a computer program developed to predict locations on the shroud and end-bells where a thermocouple would measure the best area-weighted average temperature. These measurements provide necessary boundary temperatures that can be used in a thermal model of a satellite payload. Results were obtained for different shroud and baseplate temperature settings.

Contents

List of Tables

List of Figures

Nomenclature

A_{shroud}	total surface area of shroud section
$A_{end-bell}$	total surface area of end-bell
m	total number of tests
n	total number of thermocouples
r	radial coordinate
R	radius
SUM	sum of absolute temperature difference
T	temperature
z	longitudinal coordinate

Greek Symbols

θ	angular coordinate

Subscripts

ave	average temperature
$bottom$	bottom section of shroud
$east$	east end-bell
i	measured thermocouple temperature location
$north$	north section of shroud
$south$	south section of shroud
top	top section of shroud
$west$	west end-bell

1 Introduction

The space simulation chamber at Sandia National Laboratories is used extensively by a number of satellite payloads for thermal cycling and thermal balance tests. The purpose of a thermal balance test or steady-state test is to maintain constant boundary temperatures in order to validate a thermal model of the payload and/or to insure that the payload and components of the payload operate within allowable extreme temperatures. From several tests conducted on satellite payloads, it was observed that the inner wall of the chamber (shroud) and end-bells have a non-uniform temperature distribution. This result posed a problem when trying to determine a correct shroud boundary temperature from the thermal balance test for use in the thermal model. To resolve and quantify this problem, well-instrumented environmental tests were performed to determine temperature gradients that exist in the chamber for prescribed shroud and baseplate temperature settings. Copper-Constantan (Type-T) thermocouples were placed at different shroud and end-bell locations. From the measured temperatures, the shroud and end-bell thermocouple locations which represented the best area-weighted average temperature were determined.

2 Description of Vacuum Chamber

A photograph of the vacuum chamber is shown in Figure 1. The vacuum chamber is 7 feet (213.4 cm) in diameter and is approximately 10 feet (304.8 cm) long. A control unit is located to the left of the chamber and consists of a temperature set-point controller, a strip chart recorder which plots temperatures, and monitors which keep track of the vacuum chamber conditions. The inner wall of the chamber is called the shroud and is 6 feet (183 cm) in diameter, and 7.75 feet (236.2 cm) in length. A schematic diagram of the shroud is given in Figure 2. The shroud is made of 0.125 inches (0.32 cm) thick aluminum. The inner wall of the shroud is painted black. The temperature of the shroud and end-bells are controlled with liquid nitrogen cooling coils and rod heaters located at the outer surface of the shroud. Thermistors are located at the bottom-center of the shroud and the baseplate, and are used by the temperature set-point controller to maintain the shroud and baseplate at prescribed temperatures. However, these thermistors record local temperatures which are often different from other sections of the baseplate and shroud.

The liquid nitrogen enters and exits from the top of the chamber and the flow is controlled by a solenoid valve. The solenoid valve is activated by the temperature set-point controller and distributes liquid nitrogen through a manifold to the shroud and end-bells. For the shroud, the liquid nitrogen flows circumferentially through eight one-inch (2.54 cm) diameter tubes in a counter-clockwise direction (looking into the chamber at the west view, see Figure 2). The tubes are made of aluminum and are 12 inches

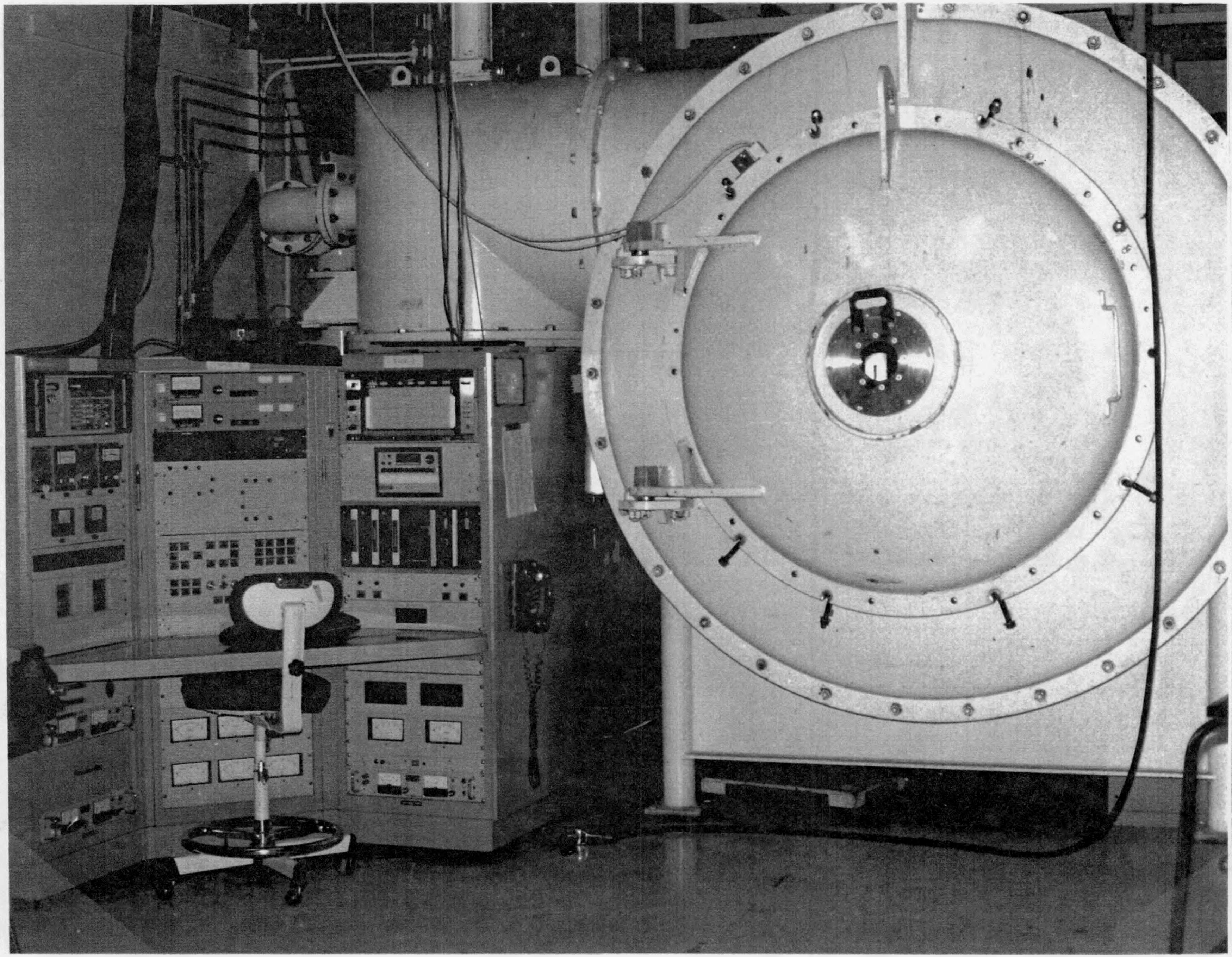
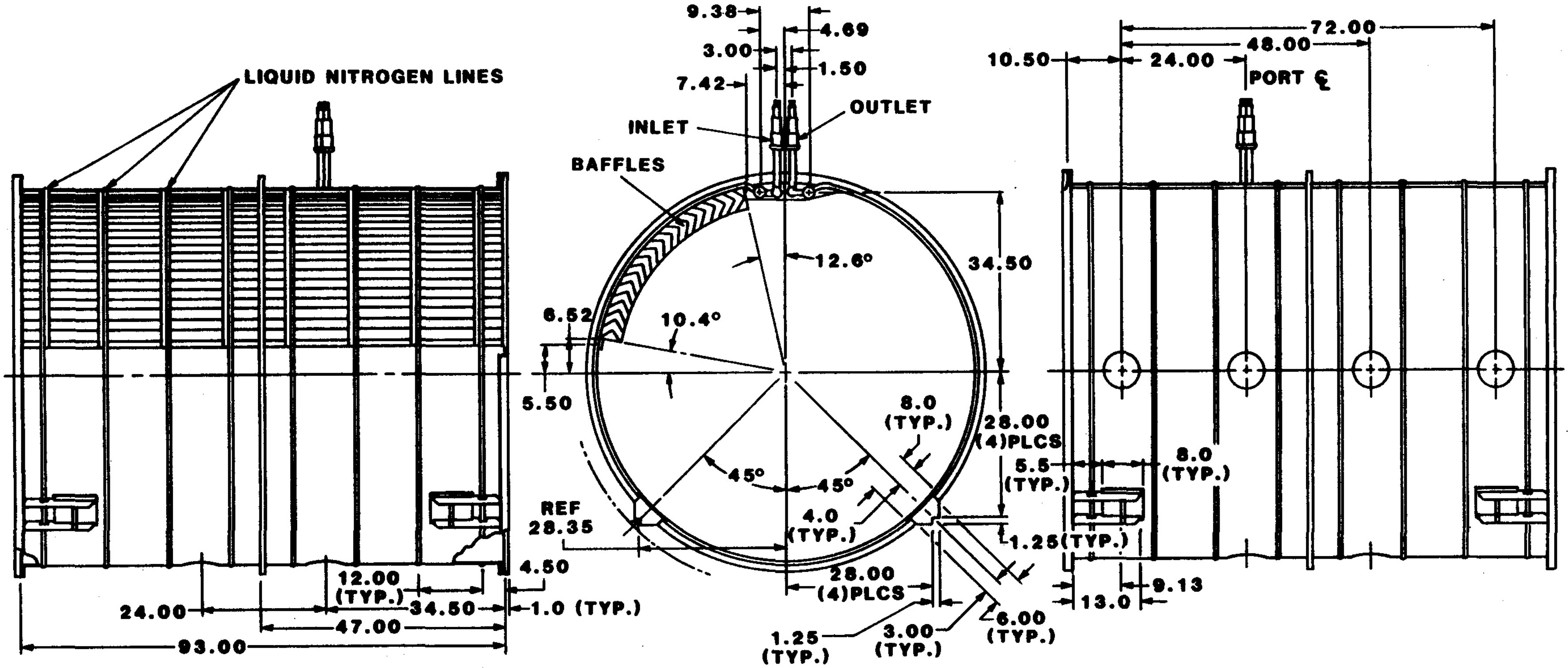


Figure 1. Photograph of vacuum chamber.



DIMENSIONS IN INCHES.

Figure 2: Schematic diagram of shroud.

(30.5 cm) apart. Directly adjacent and between the tubes are the rod heaters. Baffles are located on the upper left corner of the shroud (see west view in Figure 2) to allow a proper venting area for the two cryogenic pumps.

The ends of the chamber are called the east and west end-bells and are shown schematically in Figures 3 and 4. Both end-bells are made of 0.125 inch (0.32 cm) thick aluminum plates which are bolted to the chamber wall. The flowrate of liquid nitrogen to each end-bell is manually controlled with a valve which is located on top of the vacuum chamber. The west end-bell, as shown in Figure 3, has a single cooling coil at the outer surface while the east end-bell, as shown in Figure 4, has two sets of cooling coils. The liquid nitrogen flows through 1.50 inch (3.81 cm) outside diameter aluminum tubes. There is another cooling coil (not shown in Figure 3) on the west-end of the chamber similar in size to the outer cooling coil of the east end-bell. This coil is attached to the west-end of the shroud wall.

The west end-bell is also attached to a (5 feet (152.4 cm) diameter) door which provides easy access to the inside of the chamber. The inner surfaces of the end-bells are also painted black and have rod heaters.

3 Experimental Apparatus and Procedure

In order to determine the temperature gradients on the shroud and end-bells, 40 copper-constantan (Type-T) thermocouples (32 mil, 20 Gage wire diameter) were used. The thermocouples were taped to the inner walls of the shroud and end-bells and were centered half-way between the cooling coils. The other ends of the thermocouples were wired to electronic cards (10 thermocouples per card) which were plugged into the back end of the datalogger. Separate thermocouple reference temperature blocks are located on each card. A Biddle Versa-Cal calibrator system was used to calibrate the thermocouples at three different temperatures, -260°F (-162°C), 0°F (-18°C), and 100°F (38°C), respectively. The results showed that the accuracy of the thermocouples were card dependent and were within 2.1°F $\pm$ 0.1°F.

The thermocouples were interfaced with a Fluke 2240-B datalogger and an IBM personal computer. A data acquisition program, originally developed by D. M. Clark, 9223, and D. P. Holloway, 9224, recorded the temperature data, stored the data on a floppy disk, and displayed the results on the terminal screen.

The thermocouple locations for the shroud and end-bells are shown in Figures 5 and 6. A baseplate was placed inside the chamber and used as a heat source throughout the tests. The baseplate is made of aluminum and is 152.4 cm (5 feet) in length, 76.2 cm (2.5 feet) wide, and 2.54 cm thick. The baseplate temperature is controlled with rod heaters and liquid nitrogen lines. Two environmental tests were conducted in December

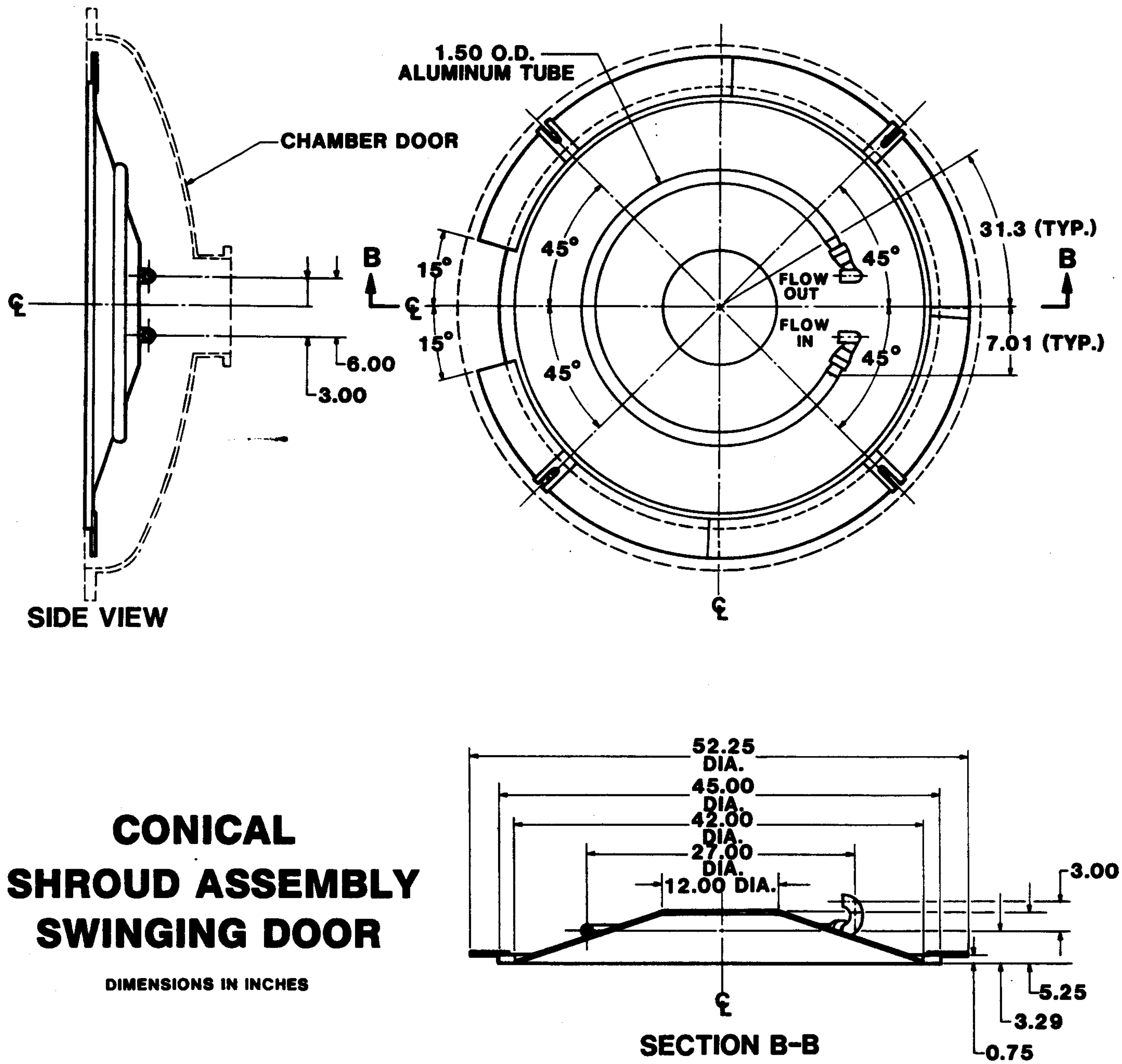


Figure 3: Schematic diagram of west end-bell.

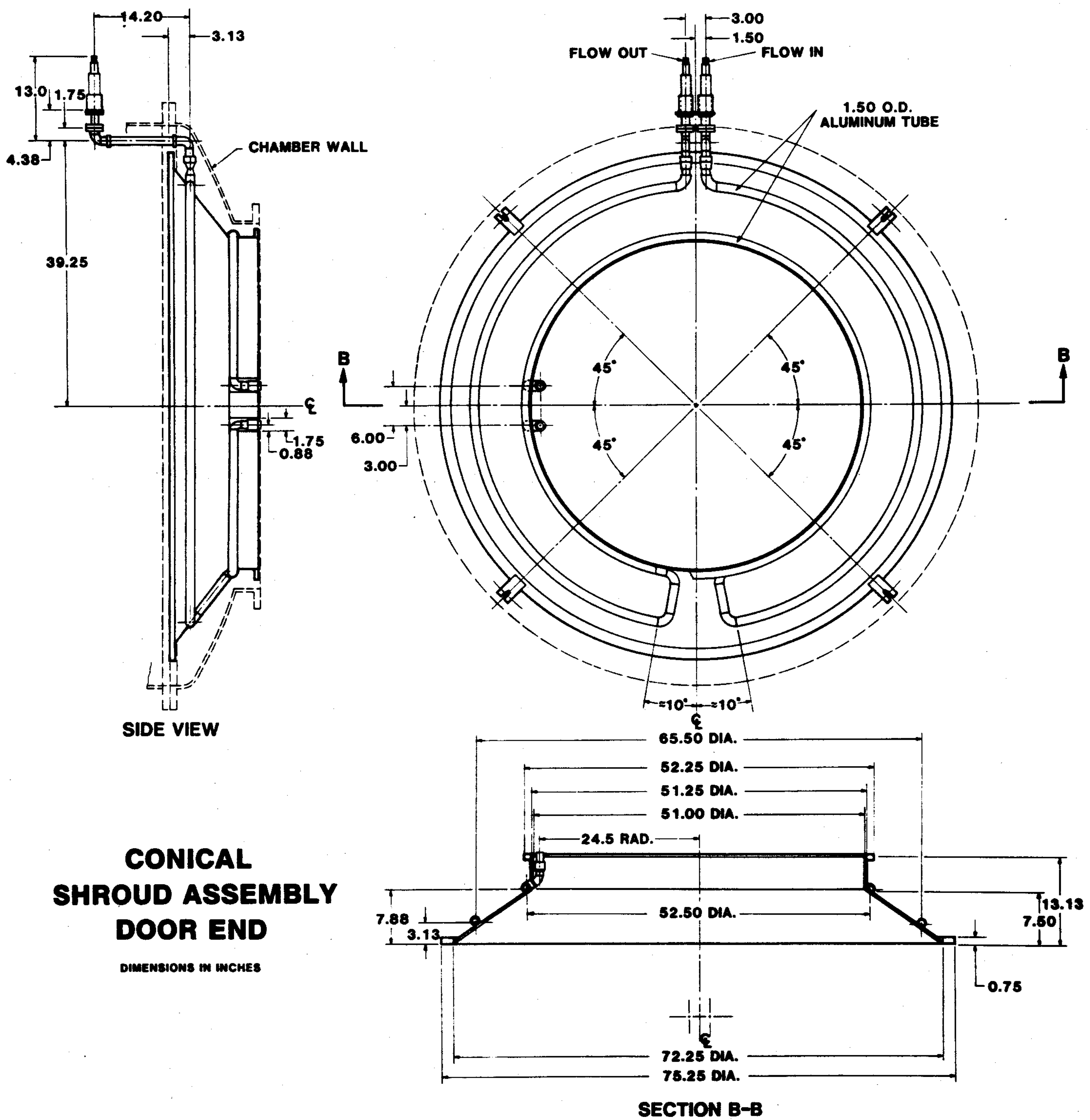


Figure 4: Schematic diagram of east end-bell.

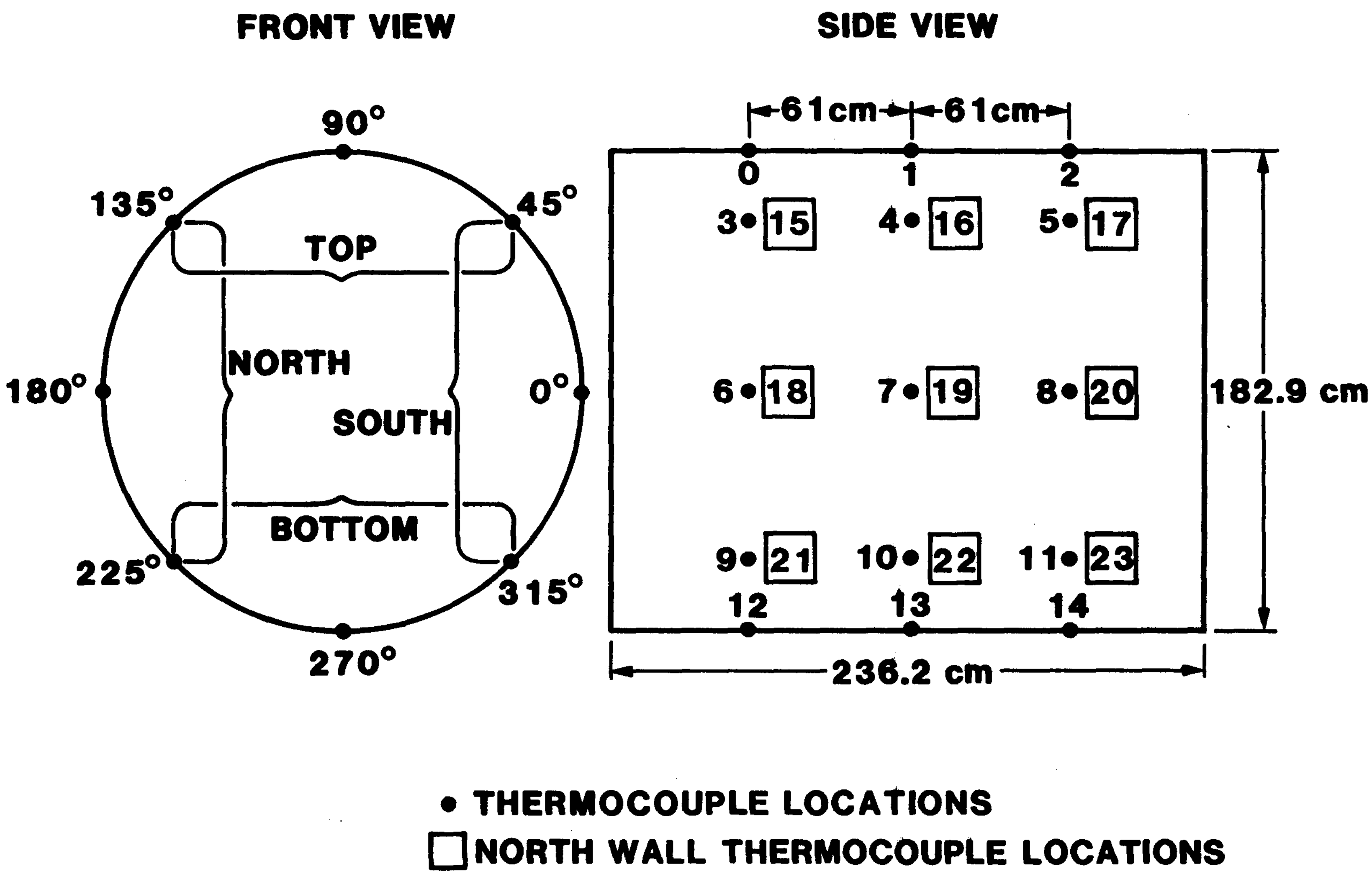


Figure 5: Shroud thermocouple locations.

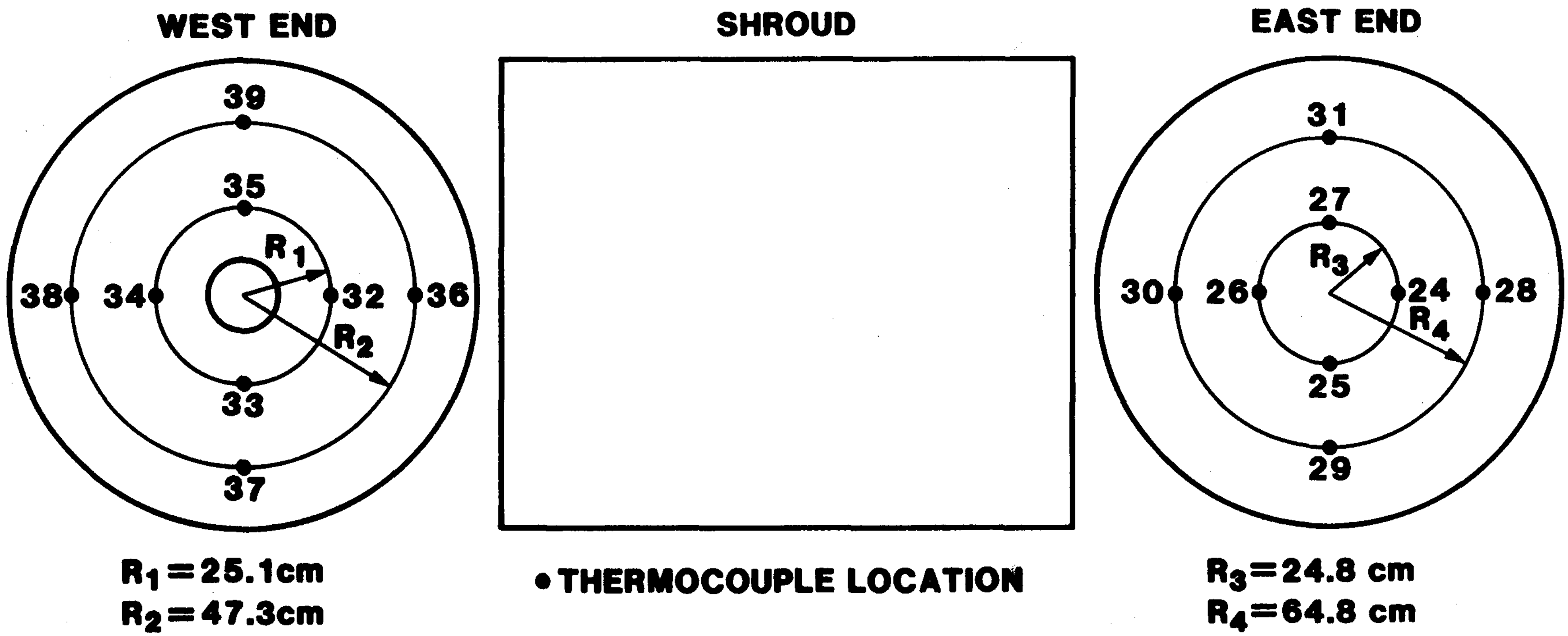


Figure 6: Thermocouple locations for end-bells.

1986 (Test 1), and in September 1987 (Test 2). The objective of Test 1 was to attempt to equate the end-bell temperatures manually by adjusting the liquid nitrogen valves at the top of the vacuum chamber and to determine the shroud and end-bell temperature distributions for different shroud and baseplate temperature settings. For Test 2 the end-bell control valves were replaced with special cryogenic valves, and the diameter of the manifold pipes located at the top of the vacuum chamber was increased.

The test procedure involved keeping the shroud thermistor temperature setting fixed and changing the baseplate thermistor to different temperature settings as shown in Tables 1 and 2. The baseplate temperature setting was held constant until the shroud and baseplate temperatures were at steady-state (approximately 24 hours). All the tests were conducted at a chamber pressure of approximately 10^{-6} torr.

4 Average Shroud and End-Bell Temperatures

The thermocouples located on the shroud and end-bells are assumed to represent the temperature of a particular finite area. Thus, the shroud and end-bells can be divided into area zones as shown in Figures 7 and 8. The shroud can be further divided into top, bottom, north, and south sections as shown previously in Figure 5. The top region goes from 45° to 135°, bottom region from 225° to 315°, north region from 135° to 225°, and the south region from 315° to 45°. An average temperature based on an area-weighted average for each shroud section and the end-bells can be obtained according to the relation,

$$T_{shroud} = \frac{\sum_i A_i T_i}{A_{shroud}} \quad (1)$$

for the shroud where A_{shroud} is the total surface area of a shroud section (either north, south, top, or bottom) and

$$T_{end-bell} = \frac{\sum_i A_i T_i}{A_{end-bell}} \quad (2)$$

for the end-bells, where $A_{end-bell}$ is the total surface area of either the east end-bell or west end-bell. The areas for the four shroud regions (top, bottom, north, and south) are equal. Equations (1) and (2) yield the average temperature for the shroud sections

$$T_{top} = 0.19\,[T_0 + T_2 + 0.5\,(T_{15} + T_3 + T_{17} + T_5)] + 0.12\,[T_1 + 0.5\,(T_{16} + T_4)] \quad (3)$$

Table 1: Shroud and Baseplate Thermistor Temperature Settings for Test 1.

Test No.	Temperature (°C)	
	Shroud	Baseplate
1-1	-100 (-148°F)	-50 (-58°F)
1-2	-100 (-148°F)	-50 (-58°F)
1-3	-100 (-148°F)	-50 (-58°F)
1-4	-100 (-148°F)	-50 (-58°F)
1-5	-100 (-148°F)	-25 (-13°F)
1-6	-100 (-148°F)	0 (32°F)
1-7	-100 (-148°F)	25 (77°F)
1-8	-100 (-148°F)	50 (122°F)
1-9	-100 (-148°F)	50 (122°F)
1-10	-50 (-58°F)	-50 (-58°F)
1-11	-50 (-58°F)	-25 (-13°F)
1-12	-50 (-58°F)	0 (32°F)
1-13	-50 (-58°F)	25 (77°F)
1-14	-25 (-13°F)	-25 (-13°F)
1-15	-25 (-13°F)	0 (32°F)
1-16	-25 (-13°F)	25 (77°F)
1-17	-25 (-13°F)	50 (122°F)
1-18	-100 (-148°F)	-50 (-58°F)

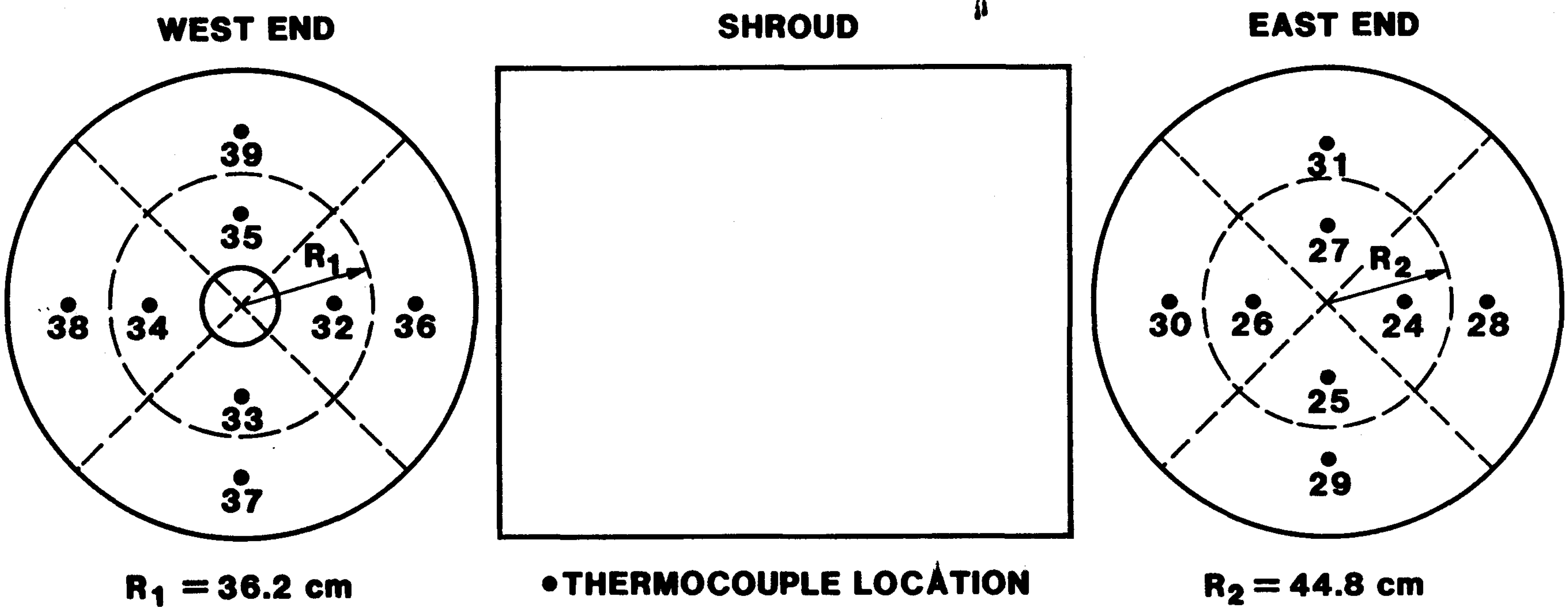


Figure 7: Area zones for end-bells.

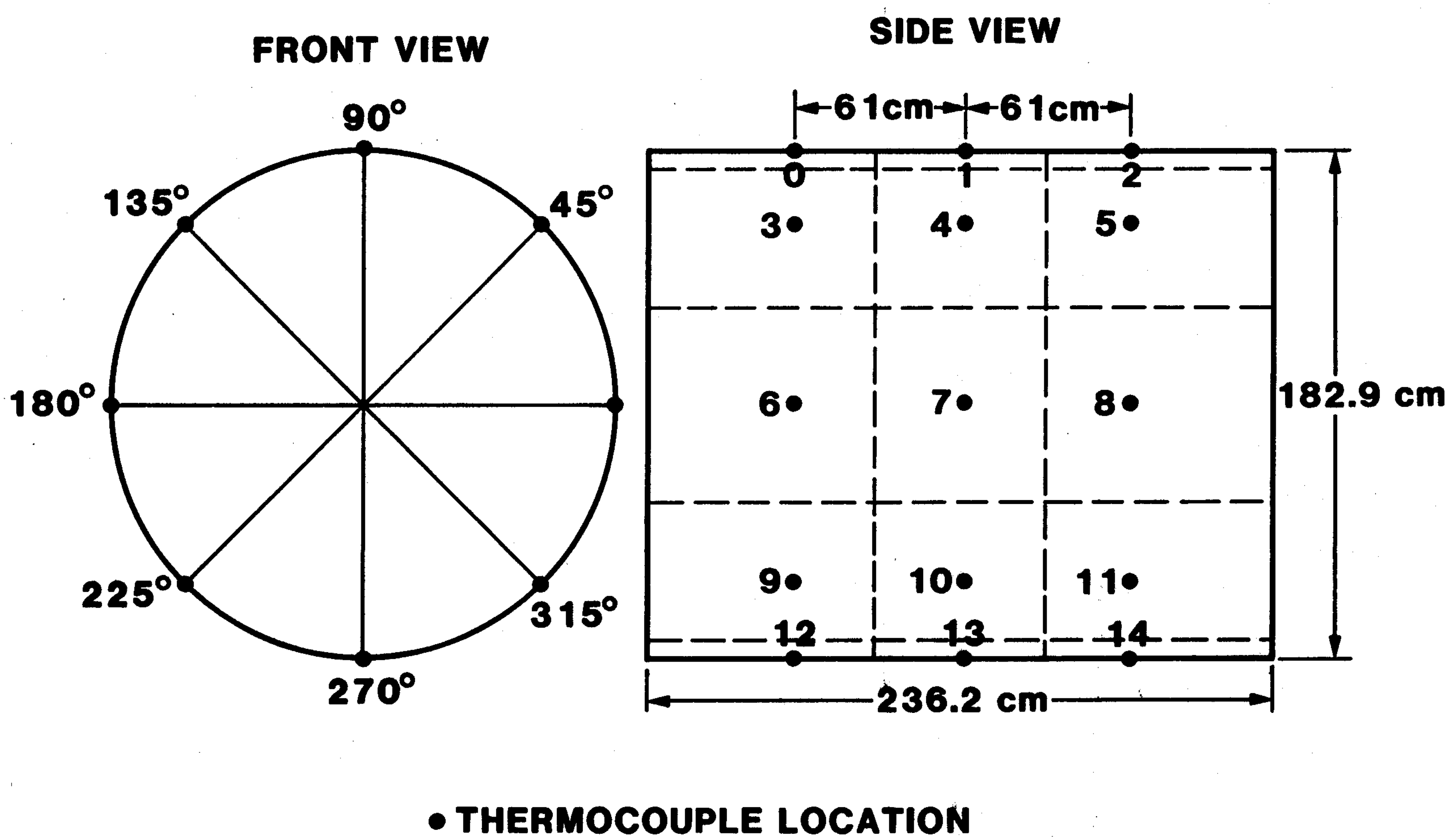


Figure 8: Area zones for shroud.

Table 2: Shroud and Baseplate Thermistor Temperature Settings for Test 2.

Test No.	Temperature (°C)	
	Shroud	Baseplate
2-1	-100 (-148°F)	-100 (-148°F)
2-2	-100 (-148°F)	-50 (-58°F)
2-3	-50 (-58°F)	-25 (-13°F)
2-4	-50 (-58°F)	0 (32°F)
2-5	-50 (-58°F)	25 (77°F)
2-6	-25 (-13°F)	-25 (-13°F)
2-7	-25 (-13°F)	0 (32°F)
2-8	-25 (-13°F)	25 (77°F)
2-9	-100 (-148°F)	-50 (-58°F)

$$T_{bottom} = 0.19\,[T_{12} + T_{14} + 0.5\,(T_{21} + T_9 + T_{23} + T_{11})] + 0.12\,[T_{13} + 0.5\,(T_{22} + T_{10})] \quad (4)$$

$$T_{north} = 0.19\,[T_{18} + T_{20} + 0.5\,(T_{15} + T_{17} + T_{21} + T_{23})] + 0.12\,[T_{19} + 0.5\,(T_{16} + T_{22})] \quad (5)$$

$$T_{south} = 0.19\,[T_6 + T_8 + 0.5\,(T_3 + T_5 + T_9 + T_{11})] + 0.12\,[T_7 + 0.5\,(T_{10} + T_4)] \quad (6)$$

and for the end-bells

$$T_{east} = 0.06\,[T_{24} + T_{25} + T_{26} + T_{27}] + 0.19\,[T_{28} + T_{29} + T_{30} + T_{31}] \quad (7)$$

$$T_{west} = 0.05\,[T_{32} + T_{33} + T_{34} + T_{35}] + 0.2\,[T_{36} + T_{37} + T_{38} + T_{39}] \quad (8)$$

Thus, Equations 3 to 8 determine the average shroud and end-bell steady-state temperatures for a particular test.

The location of the thermocouple in each section which best represents the average temperature can be obtained by performing an absolute temperature difference summation

$$SUM_i = \sum_{j=1}^{m} ABS(T_{ave,j} - T_i) \quad (9)$$

where m is the total number of tests (i.e. 18 for Test 1 (Table 1) and 9 for Test 2 (Table 2)) and n is the total number of thermocouples for each section. T_i is the local thermocouple temperature. For example, the east end-bell has thermocouples 24 to 31 (i = 24 through 31). The average east end-bell temperature for each test (i.e. 1-1 through 1-18 from Table 1) is calculated from Equation (7). Next, the absolute temperature difference between T_{ave} and T_i is calculated for each test and this value is added over the total number of tests, $m = 18$ for Test 1.

The thermocouple that has the smallest value of SUM is at the desired location. A simple computer program was written to calculate the average temperature and the value of SUM for each thermocouple.

5 Discussion of Results

5.1 Test 1

A detailed summary of the steady-state temperatures for Test 1 are shown in Appendix A. Each test lasted for approximately 24 hours. It should be mentioned that the temperature of thermocouple 13 should be close to the shroud thermistor temperature. However, an inspection of their location after Test 1 showed that the shroud thermistor was close to a cooling coil which resulted in a lower temperature than thermocouple 13. For Test 2, thermocouple 13 was placed near the shroud thermistor and measured temperatures were in very good agreement, as shown in Appendix B. The average temperatures calculated from Equations 3 thru 8 are given in Table 3. The first three tests of Test 1 (Test 1-1 thru Test 1-3) were devoted to trying to balance the end-bell temperatures. On the first day (Test 1-1) the average east end-bell temperature was 36°F higher than the west end-bell and increased to 81°F and 60°F higher for Tests 1-2 and 1-3, respectively. Because of this large temperature difference a liquid nitrogen valve on top of the shroud was manually adjusted to reduce the average temperature difference between the east and west end-bells. After four days the average temperature of the end-bells were almost the same (Test 1-4). From these tests it was apparent that the end-bell temperatures were very sensitive to the valve adjustment since it required 4 days to balance the end-bell temperatures. However, for Test 1-6 the average end-bell temperature difference increased to 13°F which further increased to 46°F for Test 1-7.

The results in Table 3 show that the north section of the shroud had the coldest shroud temperatures since the liquid nitrogen flows circumferentially from the north to the south section. The average temperature of the north section was 16°F to 20°F colder than the south section. The average end-bell temperatures were the same for Tests 1-4 and 1-5, but the east end-bell became colder thereafter. For shroud temperature settings of -58°F (-50°C) and -13°F (-25°C) the east end-bell was colder than the west end-bell. The average shroud temperatures were much higher than the shroud temperature recorded from the shroud temperature monitor (thermistor) located close to thermocouple 13 (see Appendix A). For a shroud temperature setting of -58°F (-50°C) and -13°F (-25°C), the end-bell temperature differences were smaller than for the colder settings. In Test 1-18, both the shroud and baseplate were cooled back down to the temperature settings of Test 1-4 and the results indicated an end-bell average temperature difference of 30°F.

From the tests conducted for Test 1-1 thru Test 1-18 , the thermocouple locations which best represented the average temperatures from the SUM calculation from Equation (9) were located at thermocouples 1, 10, and 19 for the top, bottom, and north shroud regions, respectively. For the south section of the shroud, the smallest SUM values were calculated for thermocouples 4 and 5, depending on the test, and thermocouple locations 28 and 34 were most representative for the east and west end-bells, respectively.

5.2 Test 2

Results from Test 1 indicated that it was difficult to control the flow of liquid nitrogen to the end-bells. As a result, the end-bell valves were removed and replaced with two vacuum approved cryogenic valves. The liquid nitrogen pipes on the manifold were also removed and replaced with larger diameter pipes. The valves have an outside pipe diameter of 0.75 inches (1.9 cm) and an operating range of -400°F (-240°C) to 150°F (65°C). In order to test the effectiveness of these new valves, a series of environmental tests were again conducted at different shroud and end-bell temperature settings as shown previously in Table 2. A summary of temperature results for Test 2 are given in Appendix B. The average temperatures for the shroud and end-bells are given in Table 4. The results illustrate that the end-bells were balanced within 11°F at shroud and baseplate temperature settings of -148°F (-100°C). This procedure took a few hours as compared to four days for Test 1. However, when the shroud temperature setting was increased to -58°F (-50°C), Tests 2-3 thru 2-5 indicated end-bell average temperature differences that ranged from 17°F to 21°F. Further increasing the shroud temperature to -13°F (-25°C) showed an improved comparison (maximum difference of 8°F for Test 2-8). These variations indicate that balancing the end-bells at the coldest shroud and baseplate temperature settings does

Table 3: Measured Average Temperatures from Equations (3) through (8) for Shroud Sections and End-Bells for Test 1.

Test No.	Shroud Thermistor Temp. (°F)	Baseplate Thermistor Temp. (°F)	Temperature (°F) Shroud				End-Bells	
			Top	South	Bottom	North	East	West
1-1	-137	-72	-122.4	-109.9	-112.6	-128.9	-127.4	-163.3
1-2	-150	-56	-125.3	-113.0	-119.8	-134.7	-119.2	-200.4
1-3	-150	-56	-124.6	-112.3	-119.3	-134.7	-118.1	-178.3
1-4	-148	-58	-122.1	-110.6	-118.4	-133.9	-118.0	-118.6
1-5	-148	-13	-121.1	-109.9	-117.2	-133.5	-117.9	-120.6
1-6	-148	32	-123.1	-110.9	-116.7	-134.0	-119.3	-132.4
1-7	-148	77	-123.1	-109.8	-115.5	-133.8	-114.6	-160.6
1-8	-148	122	-119.6	-107.3	-110.7	-130.8	-114.7	-133.4
1-9	-148	122	-119.5	-107.1	-110.8	-130.6	-115.9	-128.6
1-10	-58	-58	-63.0	-40.4	-46.9	-64.1	-35.7	-28.5
1-11	-58	-13	-55.8	-34.6	-42.5	-60.8	-32.5	-23.8
1-12	-58	32	-58.4	-36.6	-43.1	-62.2	-32.8	-26.5
1-13	-58	77	-56.6	-34.2	-41.6	-61.5	-31.1	-24.3
1-14	-13	-13	-18.2	-1.5	-4.9	-17.7	-3.4	4.9
1-15	-13	32	-13.7	0.5	-3.3	-16.4	-2.5	7.1
1-16	-13	77	-23.6	-2.2	-6.3	-24.3	-5.1	3.9
1-17	-13	122	-17.2	-0.1	-3.9	-22.0	-4.7	5.8
1-18	-148	-58	-125.0	-107.2	-114.2	-127.4	-75.0	-105.9

not imply that the end-bell temperatures will remain close to each other at other shroud and baseplate temperature settings. To obtain equal end-bell temperatures would require balancing the end-bells at each shroud and baseplate temperature setting, a process that could be very time consuming.

Table 4: Measured Average Temperatures from Equations (3) through (8) for Shroud Sections and End-Bells for Test 2.

Test No.	Shroud Thermistor Temp. (°F)	Baseplate Thermistor Temp. (°F)	Temperature (°F)					
			Shroud				End-Bells	
			Top	South	Bottom	North	East	West
2-1	-148	-148	-132.7	-120.8	-124.5	-137.9	-237.9	-226.7
2-2	-148	-58	-129.5	-117.7	-122.1	-136.9	-237.3	-223.7
2-3	-58	-13	-58.8	-44.9	-47.3	-61.4	-74.0	-54.9
2-4	-58	32	-61.8	-46.3	-49.9	-64.4	-82.9	-62.0
2-5	-58	77	-59.0	-42.5	-46.7	-64.2	-77.7	-61.4
2-6	-13	-13	-17.1	-7.2	-9.1	-18.4	-16.2	-10.3
2-7	-13	32	-16.9	-5.2	-7.8	-18.5	-16.5	-10.1
2-8	-13	77	-18.0	-4.4	-7.9	-20.2	-19.8	-12.0
2-9	-148	-58	-131.2	-120.7	-123.7	-139.1	-237.6	-229.1

As the shroud and baseplate temperature settings were increased, the average temperatures for the end-bells were closer to those on the shroud (see Table 4). For Test 2-9, the shroud and baseplate temperature settings were decreased to -148°F (-100°C) and -58°F (-50°C) and the end-bell temperature difference was 9°F which is close to the 13°F difference obtained for Test 2-2. It should also be mentioned that the end-bell temperatures for Test 2 were much colder than that measured for Test 1 because the end-bell control valves permitted more liquid nitrogen to flow to the end-bells.

Similar to Test 1, the north section average temperature of the shroud was 9°F to 18°F colder than the south section (Test 2-5). From the SUM calculations, the thermocouple locations which had the smallest SUM values were at 2, 10, 19, and 4, for the top, bottom, north, and south regions, respectively, and at 27 and 38 for the east and west end-bells. A comparison of thermocouple locations which were most representative of the average temperature for Tests 1 and 2 are shown in Table 5. The results showed good agreement for the shroud with the only difference for the top section (thermocouple location 1 for Test 1 and location 2 for Test 2). The best thermocouple locations for the east and west end-bells were different for the two test series. Locations 34 and 38 for the west end-bell are adjacent to each other (see Figure 6). This difference could be attributed to the end-bells being at much colder temperatures for Test 2. However, in future tests the end-bell thermocouples will be placed at the locations specified by Test 2 since this test was conducted for the modified chamber design (adding new valves and pipes).

Table 5: Comparison of Best Thermocouple Locations for Tests 1 and 2 from SUM Results.

Location	Thermocouple Number	
	Test 1	Test 2
Shroud:		
North	19	19
South	4,5	4
Top	1	2
Bottom	10	10
End-Bells:		
East	28	27
West	34	38

6 Summary and Conclusions

Thermal vacuum tests were conducted on the 7-foot diameter space simulation chamber. The results indicated large temperature gradients exist on the shroud and end-bells. Because of the design of the vacuum chamber, no attempt was made to reduce the temperature gradients on the shroud. However, modifications were made to the manifold on the top of the chamber by replacing the end-bell control valves and increasing the diameter of the pipes. This resulted in the two end-bells being closer in temperature at the lowest shroud and baseplate temperature settings as shown in Test 2. However, the end-bell temperatures did not closely match the shroud temperature, particularly at the coldest settings. In addition, the average end-bell temperatures showed a larger difference at other shroud and baseplate temperature settings. In fact, results from Test

1 showed better agreement between end-bell temperatures than Test 2 as the shroud and baseplate temperatures were increased.

Even though the results from the two test series did not produce equal end-bell temperatures at every shroud and baseplate temperature setting, the tests did characterize the thermal behavior of the chamber. The recorded temperature data also provided enough information to determine locations on the shroud and end-bells where a thermocouple should be placed which represented the best estimate of the average temperature. These locations provide more appropriate temperature boundary conditions for input into a thermal model of a satellite payload.

Since these tests were conducted, several modifications to the chamber and control system were made by Division 9214 Vacuum Lab personnel. Temperature set-point controllers were added to control the temperature of each end-bell separately with end-bell thermistors placed near the locations shown in Table 5 for Test 2. The two cryogenic valves which manually controlled the flow of liquid nitrogen to the end-bells were removed and replaced with solenoid valves. Tests were conducted at different shroud temperature settings as low as -100°C and the shroud and end-bell thermistors consistently recorded temperatures within 5°C of each other. This automated approach represents a significant improvement.

Appendix A

Steady-State Temperatures for Test 1

Table A.1: Steady-State Temperatures for Tests 1-1 to 1-4.

Test No.	1-1	1-2	1-3	1-4
Pressure (torr)	2.4×10^{-6}	2.5×10^{-6}	2.5×10^{-6}	2.8×10^{-6}
Payload (°C)	-60 (-76°F)	-51 (-60°F)	-51 (-60°F)	-51 (-60°F)
Shroud (°C)	-94 (-137°F)	-101 (-150°F)	-101 (-150°F)	-100 (-148°F)
Baseplate (°C)	-58 (-72°F)	-49 (-56°F)	-49 (-56°F)	-49 (-56°F)
T/C No.	Temperature (°F)			
Shroud				
0	-136	-139	-133	-130
1	-117	-117	-115	-115
2	-113	-109	-108	-107
3	-110	-119	-116	-112
4	-106	-113	-111	-110
5				
6	-111	-120	-117	-113
7	-101	-107	-108	-109
8	-99	-104	-105	-106
9	-106	-117	-114	-112
10	-107	-116	-115	-115
11	-106	-113	-112	-112
12	-116	-126	-122	-118
13	-107	-114	-114	-114
14	-107	-109	-112	-113
15	-144	-150	-150	-150
16	-138	-144	-144	-145
17	-128	-131	-131	-131
18	-134	-142	-140	-137
19	-127	-133	-133	-132
20	-121	-125	-126	-126
21	-128	-137	-135	-131
22	-123	-130	-130	-130
23	-121	-125	-127	-128

Table A.1: (Continued)

Test No.	1-1	1-2	1-3	1-4
Pressure (torr)	2.4×10^{-6}	2.5×10^{-6}	2.5×10^{-6}	2.8×10^{-6}
Payload (°C)	-60 (-76°F)	-51 (-60°F)	-51 (-60°F)	-51 (-60°F)
Shroud (°C)	-94 (-137°F)	-101 (-150°F)	-101 (-150°F)	-100 (-148°F)
Baseplate (°C)	-58 (-72°F)	-49 (-56°F)	-49 (-56°F)	-49 (-56°F)
T/C No.	Temperature (°F)			
East End-Bell				
24	-123	-114	-116	-113
25	-121	-115	-117	-114
26	-123	-116	-117	-114
27	-125	-116	-117	-115
28	-129	-117	-120	-118
29	-130	-125	-127	-122
30	-130	-123	-126	-121
31	-127	-117	-119	-116
West End-Bell				
32	-164	-196	-154	-117
33	-163	-189	-154	-121
34	-164	-205	-154	-112
35	-158	-190	-150	-121
36	-157	-178	-151	-122
37	-160	-184	-150	-121
38	-170	-219	-156	-116
39	-169	-227	-155	-115

Table A.2: Steady-State Temperatures for Tests 1-5 to 1-8.

Test No.	1-5	1-6	1-7	1-8
Pressure (torr)	3.0×10^{-6}	3.4×10^{-6}	3.5×10^{-6}	3.8×10^{-6}
Payload (°C)	-28 (-18°F)	-5 (23°F)	17 (63°F)	39 (102°F)
Shroud (°C)	-100 (-148°F)	-101 (-150°F)	-101 (-150°F)	-99 (-146°F)
Baseplate (°C)	-25 (-13°F)	0 (32°F)	25 (77°F)	50 (122°F)
T/C No.	Temperature (°F)			
Shroud				
0	-128	-134	-138	-133
1	-113	-114	-113	-109
2	-106	-108	-106	-103
3	-112	-114	-111	-112
4	-108	-108	-108	-103
5				
6	-112	-115	-117	-112
7	-109	-109	-107	-105
8	-106	-106	-103	-101
9	-112	-114	-116	-113
10	-114	-114	-114	-110
11	-111	-111	-110	-106
12	-111	-115	-115	-115
13	-112	-108	-104	-96
14	-112	-111	-106	-103
15	-150	-151	-152	-150
16	-145	-146	-145	-143
17	-131	-132	-130	-128
18	-137	-138	-141	-136
19	-131	-130	-129	-125
20	-126	-126	-123	-121
21	-131	-132	-136	-131
22	-129	-129	-129	-126
23	-128	-129	-127	-126

Table A.2: (Continued.)

Test No.	1-5	1-6	1-7	1-8
Pressure (torr)	3.0×10^{-6}	3.4×10^{-6}	3.5×10^{-6}	3.8×10^{-6}
Payload (°C)	-28 (-18°F)	-5 (23°F)	17 (63°F)	39 (102°F)
Shroud (°C)	-100 (-148°F)	-101 (-150°F)	-101 (-150°F)	-99 (-146°F)
Baseplate (°C)	-25 (-13°F)	0 (32°F)	25 (77°F)	50 (122°F)
T/C No.	Temperature (°F)			
East End-Bell				
24	-114	-114	-109	-108
25	-113	-115	-110	-111
26	-114	-116	-111	-111
27	-116	-116	-111	-110
28	-121	-119	-113	-112
29	-119	-123	-120	-121
30	-118	-122	-119	-120
31	-117	-117	-112	-111
West End-Bell				
32	-119	-132	-160	-132
33	-123	-135	-163	-137
34	-120	-132	-163	-134
35	-122	-132	-155	-130
36	-124	-133	-156	-135
37	-122	-132	-156	-134
38	-119	-133	-166	-133
39	-118	-131	-165	-134

Table A.3: Steady-State Temperatures for Tests 1-9 to 1-12.

Test No.	1-9	1-10	1-11	1-12
Pressure (torr)	3.9×10^{-6}	4.2×10^{-6}	4.6×10^{-6}	4.6×10^{-6}
Payload (°C)	39 (102°F)	-52 (-62°F)	-26 (-15°F)	-2 (28°F)
Shroud (°C)	-99 (-146°F)	-52 (-62°F)	-49 (-56°F)	-50 (-58°F)
Baseplate (°C)	50 (122°F)	-53 (-63°F)	-25 (-13°F)	0 (32°F)
T/C No.	Temperature (°F)			
Shroud				
0	-134	-78	-65	-70
1	-109	-62	-50	-56
2	-102	-56	-50	-51
3	-112	-41	-32	-36
4	-103	-42	-36	-38
5				
6	-112	-39	-32	-36
7	-105	-40	-36	-37
8	-102	-39	-34	-35
9	-112	-39	-33	-36
10	-110	-44	-39	-41
11	-106	-43	-38	-39
12	-106	-43	-37	-38
13	-96	-46	-41	-40
14	-104	-44	-41	-40
15	-150	-86	-82	-86
16	-143	-83	-80	-81
17	-129	-69	-67	-68
18	-136	-63	-59	-61
19	-124	-61	-57	-58
20	-121	-57	-54	-54
21	-131	-56	-52	-55
22	-126	-60	-56	-57
23	-126	-57	-55	-56

Table A.3: (Continued.)

Test No.	1-9	1-10	1-11	1-12
Pressure (torr)	3.9×10^{-6}	4.2×10^{-6}	4.6×10^{-6}	4.6×10^{-6}
Payload (°C)	39 (102°F)	-52 (-62°F)	-26 (-15°F)	-2 (28°F)
Shroud (°C)	-99 (-146°F)	-52 (-62°F)	-49 (-56°F)	-50 (-58°F)
Baseplate (°C)	50 (122°F)	-53 (-63°F)	-25 (-13°F)	0 (32°F)
T/C No.	Temperature (°F)			
East End-Bell				
24	-110	-34	-30	-31
25	-112	-35	-32	-32
26	-112	-38	-35	-35
27	-112	-37	-33	-34
28	-114	-34	-30	-30
29	-120	-34	-31	-31
30	-122	-37	-34	-34
31	-113	-39	-35	-36
West End-Bell				
32	-127	-27	-22	-25
33	-132	-30	-25	-28
34	-128	-29	-24	-26
35	-126	-31	-26	-28
36	-131	-33	-28	-31
37	-129	-29	-24	-27
38	-127	-26	-22	-24
39	-128	-25	-21	-24

Table A.4: Steady-State Temperatures for Tests 1-13 to 1-15.

Test No.	1-13	1-14	1-15
Pressure (torr)	4.6×10^{-6}	5.0×10^{-6}	Order 10^{-6}
Payload (°C)	20 (68°F)	-21 (-6°F)	Data not recorded
Shroud (°C)	-49 (-56°F)	-24 (-11°F)	-25 (-13°F)
Baseplate (°C)	25 (77°F)	-21 (-6°F)	0 (32°F)
T/C No.	Temperature (°F)		
Shroud			
0	-69	-24	-16
1	-53	-22	-13
2	-49	-17	-12
3	-33	1	3
4	-34	-4	-1
5			
6	-33	1	3
7	-35	-2	-1
8	-33	-2	-1
9	-34	2	4
10	-38	-4	-2
11	-36	-4	-2
12	-34	0	3
13	-36	-4	-1
14	-38	-5	-4
15	-87	-31	-28
16	-82	-32	-30
17	-68	-27	-27
18	-60	-13	-11
19	-56	-15	-13
20	-53	-15	-15
21	-54	-10	-8
22	-57	-14	-13
23	-56	-15	-15

Table A.4: (Continued.)

Test No.	1-13	1-14	1-15
Pressure (torr)	4.6×10^{-6}	5.0×10^{-6}	Order 10^{-6}
Payload (°C)	20 (68°F)	-21 (-6°F)	Data not recorded
Shroud (°C)	-49 (-56°F)	-24 (-11°F)	-25 (-13°F)
Baseplate (°C)	25 (77°F)	-21 (-6°F)	0 (32°F)
T/C No.	Temperature (°F)		
East End-Bell			
24	-29	-1	0
25	-31	-3	-2
26	-34	-5	-4
27	-32	-5	-4
28	-28	-2	-1
29	-30	-1	-1
30	-33	-3	-2
31	-34	-7	-6
West End-Bell			
32	-22	5	8
33	-26	4	6
34	-24	7	9
35	-26	4	6
36	-29	2	4
37	-25	5	7
38	-22	6	9
39	-22	7	8

Table A.5: Steady-State Temperatures for Tests 1-16 to 1-18.

Test No.	1-16	1-17	1-18
Pressure (torr)	4.9×10^{-6}	Order 10^{-6}	Order 10^{-6}
Payload (°C)	22 (72°F)	Data not recorded	Data not recorded
Shroud (°C)	-25 (-13°F)	-25 (-13°F)	-100 (-148°F)
Baseplate (°C)	26 (79°F)	50 (122°F)	-50 (-58°F)
T/C No.	Temperature (°F)		
Shroud			
0	-37	-22	-155
1	-20	-14	-121
2	-20	-13	-104
3	1	4	-118
4	-3	0	-107
5			
6	0	3	-115
7	-4	-3	-98
8	-3	-2	-96
9	0	2	-115
10	-5	-3	-111
11	-5	-2	-109
12	1	5	-120
13	-2	2	-111
14	-6	-5	-102
15	-43	-38	-149
16	-42	-39	-141
17	-35	-34	-119
18	-20	-16	-136
19	-20	-16	-126
20	-20	-19	-114
21	-15	-13	-130
22	-19	-17	-125
23	-20	-20	-118

Table A.5: (Continued.)

Test No.	1-16	1-17	1-18
Pressure (torr)	4.9×10^{-6}	Order 10^{-6}	Order 10^{-6}
Payload (°C)	22 (72°F)	Data not recorded	Data not recorded
Shroud (°C)	-25 (-13°F)	-25 (-13°F)	-100 (-148°F)
Baseplate (°C)	26 (79°F)	50 (122°F)	-50 (-58°F)
T/C No.	Temperature (°F)		
East End-Bell			
24	-3	-2	-73
25	-5	-4	-75
26	-7	-7	-78
27	-7	-6	-76
28	-3	-3	-73
29	-3	-3	-75
30	-5	-5	-75
31	-9	-9	-76
West End-Bell			
32	5	7	-103
33	3	5	-109
34	6	8	-105
35	3	5	-109
36	0	3	-110
37	4	6	-109
38	6	8	-102
39	6	7	-102

Appendix B

Steady-State Temperatures for Test 2

Table B.1: Steady-State Temperatures for Tests 2-1 thru 2-4.

Test No.	2-1	2-2	2-3	2-4
Pressure (torr)	9.5×10^{-7}	9.9×10^{-7}	1.3×10^{-6}	1.3×10^{-6}
Payload (°C)	-114 (-173°F)	-111 (-168°F)	-53 (-63°F)	-49 (-56°F)
Shroud (°C)	-100 (-148°F)	-99 (-146°F)	-50 (-58°F)	-49 (-56°F)
Baseplate (°C)	-101 (-150°F)	-52 (-62°F)	-24 (-11°F)	-1 (30°F)
T/C No.	Temperature (°F)			
Shroud				
0	-140	-135	-66	-70
1	-124	-120	-54	-57
2	-131	-126	-59	-62
3	-126	-123	-44	-45
4	-120	-117	-45	-45
5	-116	-114	-44	-45
6	-131	-126	-46	-45
7	-126	-121	-46	-45
8	-112	-110	-42	-43
9	-117	-115	-40	-40
10	-118	-116	-44	-44
11	-118	-116	-44	-44
12	-123	-119	-42	-44
13	-148	-142	-53	-53
14	-110	-109	-45	-45
15	-146	-144	-67	-72
16	-144	-144	-73	-77
17	-144	-143	-74	-77
18	-141	-139	-58	-61
19	-138	-136	-60	-62
20	-135	-134	-61	-63
21	-137	-136	-55	-58
22	-131	-130	-56	-58
23	-127	-127	-56	-58

Table B.1: (continued.)

Test No.	2-1	2-2	2-3	2-4
Pressure (torr)	9.5×10^{-7}	9.9×10^{-7}	1.3×10^{-6}	1.3×10^{-6}
Payload (°C)	-114 (-173°F)	-111 (-168°F)	-53 (-63°F)	-49 (-56°F)
Shroud (°C)	-100 (-148°F)	-99 (-146°F)	-50 (-58°F)	-49 (-56°F)
Baseplate (°C)	-101 (-150°F)	-52 (-62°F)	-24 (-11°F)	-1 (30°F)
T/C No.	Temperature (°F)			
East End-Bell				
24	-225	-224	-69	-77
25	-230	-229	-70	-79
26	-229	-228	-69	-78
27	-238	-237	-72	-80
28	-227	-226	-73	-79
29	-234	-234	-75	-85
30	-244	-244	-74	-84
31	-256	-256	-80	-89
West End-Bell				
32	-208	-204	-54	-61
33	-212	-209	-56	-63
34	-234	-232	-56	-63
35	-236	-233	-57	-65
36	-218	-214	-55	-62
37	-237	-235	-53	-60
38	-226	-224	-54	-61
39	-231	-227	-57	-65

Table B.2: Steady-State Temperatures for Tests 2-5 thru 2-9.

Test No.	2-5	2-6	2-7	2-8	2-9
Pressure (torr)	1.4×10^{-6}	1.4×10^{-6}	1.9×10^{-6}	2.0×10^{-6}	1.0×10^{-6}
Shroud (°C)	-49 (-56°F)	-25 (-13°F)	-25 (-13°F)	-25 (-13°F)	-100 (-148°F)
Baseplate (°C)	-49 (-56°F)	-25 (-13°F)	0 (32°F)	25 (77°F)	-50 (-58°F)
T/C No.	Temperature (°F)				
Shroud					
0	-65	-22	-21	-21	-135
1	-52	-14	-18	-19	-124
2	-58	-17	-15	-17	-128
3	-42	-8	-6	-6	-125
4	-43	-8	-6	-6	-119
5	-43	-6	-5	-6	-116
6	-40	-9	-5	-2	-126
7	-40	-9	-5	-2	-126
8	-42	-6	-5	-6	-113
9	-39	-5	-3	-2	-116
10	-43	-7	-6	-6	-118
11	-43	-7	-6	-6	-118
12	-39	-5	-3	-2	-119
13	-50	-12	-10	-9	-140
14	-44	-8	-7	-7	-113
15	-70	-20	-20	-21	-145
16	-76	-26	-26	-28	-145
17	-78	-30	-31	-34	-146
18	-60	-15	-15	-16	-141
19	-62	-18	-17	-18	-138
20	-64	-18	-19	-22	-137
21	-57	-13	-13	-14	-138
22	-57	-15	-14	-16	-133
23	-59	-15	-16	-18	-130

Table B.2: (Continued.)

Test No.	2-5	2-6	2-7	2-8	2-9
Pressure (torr)	1.4×10^{-6}	1.4×10^{-6}	1.9×10^{-6}	2.0×10^{-6}	1.0×10^{-6}
Shroud (°C)	-49 (-56°F)	-25 (-13°F)	-25 (-13°F)	-25 (-13°F)	-100 (-148°F)
Baseplate (°C)	-49 (-56°F)	-25 (-13°F)	0 (32°F)	25 (77°F)	-50 (-58°F)
T/C No.	Temperature (°F)				
East End-Bell					
24	-73	-15	-14	-17	-229
25	-73	-13	-12	-15	-229
26	-73	-14	-13	-16	-228
27	-76	-16	-16	-19	-238
28	-76	-18	-18	-22	-225
29	-78	-14	-15	-18	-234
30	-78	-15	-15	-18	-243
31	-84	-21	-21	-25	-257
West End-Bell					
32	-60	-9	-10	-12	-227
33	-62	-11	-12	-13	-217
34	-63	-11	-9	-11	-234
35	-63	-11	-10	-12	-206
36	-61	-10	-9	-11	-206
37	-60	-10	-12	-14	-262
38	-60	-11	-10	-12	-224
39	-64	-11	-9	-12	-233

Internal Distribution:
1510 J. W. Nunziato
1511 D. W. Gartling
1512 J. C. Cummings
1513 D. W. Larson
1513 R. L. Akau (5)
1520 L. W. Davison
1530 D. B. Hayes
1550 C. W. Peterson
3151 W. L. Garner (3)
3154-1 C. H. Dalin (8) for DOE/OSTI
6510 W. B. Gauser
6514 J. B. Whitley
6514 J. P. Freshour (5)
8524 P. W. Dean
9210 H. M. Dumas
9211 T. G. Taylor
9214 L. E. Anderson
9216 S. Ortiz
9216 S. L. Wilde (5)
9220 G. H. Mauth
9222 L. S. Walker
9222 D. E. Lee