Development of a Lightweight Cryogenic Insulating System

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FINAL REPORT

30 JUNE 1964 THROUGH 31 MAY 1966

GER 12269

MAY 1966

CONTRACT NAS 8-11761

FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GOODYEAR AEROSPACE
CORPORATION

CODE IDENT NO. 25500

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CORPORATION

AKRON 15, OHIO

DEVELOPMENT OF A LIGHTWEIGHT CRYOGENIC INSULATING SYSTEM

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George C. Marshall Space Flight Center
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ABSTRACT

30857

This final report documents a 23-month effort to develop and perfect advanced lightweight panel insulation systems capable of providing efficient and highly reliable thermal protection when applied externally to cryogenic propellant tanks of launch vehicles.

The primary effort was expended on the development of materials and fabrication techniques associated with the MSFC dual-seal cryogenic insulation concept. Thermal and structural characteristics of selected panel constructions were defined by liquid hydrogen tankage tests on a large oval-shaped tank.

This report covers the work performed by Goodyear Aerospace Corporation on National Aeronautics and Space Administration Contract NAS 8-11761 during the period from 30 June 1964 through 31 May 1966. This contract was under the direct supervision of Dr. James M. Stuckey of the Non-Metallic Materials Branch, Materials Division, Propulsion and Vehicle Engineering Laboratory, NASA-MSFC.

Author

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SECTION I. INTRODUCTION

This program, sponsored by MSFC, was initiated under Contract NAS 8-11761 for the primary purpose of advancing the state of the art of improved lightweight external insulation systems for cryogenic liquid propellant tanks of launch vehicles. The concepts considered were lightweight sealed cell panel constructions having application to tanks 22 to 33 feet in diameter. A system was sought that could be bonded to a tank wall with room-temperature curing adhesives and that would maintain structural integrity and reliability when subjected to ground hold and launch operational conditions. The insulation system was to provide a thermal conductivity (K_a) of less than 0.15 BTU-in./ft^2-hr-^{o}F, and a weight limitation of 0.4 psf for the entire composite was specified.

At the offset of this research effort, it was generally known that only with a hermetically sealed concept would it be possible to obtain a thermal conductivity for the complete insulation system as low as 0.15 BTU-in./ft^2-hr-^{o}F. In addition, it was recognized that new materials and methods of application of these materials to the tank wall would need to be uncovered to realize the overall objectives. Through a program encompassing a literature survey, materials evaluation testing, and insulation system analysis, selected panel configurations were designed and methods of attachment to the tank wall were studied. The outgrowth of these initial efforts prompted a decision by MSFC to redirect the primary insulation systems development effort on this program to one system rather than several candidate systems. As a result of this decision, a concentrated effort was made to support MSFC interests in refining the dual-seal insulation system then under development at MSFC. Accordingly, all systems fabrication work and all liquid hydrogen tankage tests were designed to evaluate and to improve the performance and reliability of this system.

SECTION II. SUMMARY

NASA-MSFC's interest in upgrading the performance and lowering the weight of thermal insulation systems on boost vehicles, such as the S-II and S-IV stages of Saturn 5, has provided new insulation materials and concepts. Insulation systems are required for liquid hydrogen tanks of boost vehicles during ground-hold and for most of the launch phase to keep boil-off rates and tank pressure rise within reasonable limits. A number of insulation systems have been investigated (References 1, 2, and 3) for hydrogen-fueled launch vehicles. In general, it is agreed that adequate insulation effectiveness can be obtained for cryogenic tanks of launch vehicles by using a low-density material as a primary insulation medium. The main differences between various investigations and applications, however, are in the selection of materials and concepts used to (1) provide structural integrity to the insulation material, (2) provide an effective gas barrier to prevent cryopumping of liquified air into the insulation, and (3) provide effective means of attachment and compatibility between the tank and insulation. To gain acceptance as a flight-worthy concept, insulation systems must be capable of withstanding the ground-hold and launch environment without severe detriment to their thermal protection and structural requirements.

This program was conducted to provide the necessary engineering data to qualify new insulation materials and insulation system concepts to effect lower insulation weights and more reliable performance on future boost vehicles. The experimental investigation comprised the following tests:

(1) Mechanical and thermal property tests of new materials.

(2) Vibration and aerodynamic heating tests of composite panel constructions attached to oval-shaped tanks containing cryogenic fluid.

(3) Measurements of the apparent thermal conductivity of selected insulation panel constructions by means of flat plate calorimeter tests.

(4) Structural verification and heat-transfer measurements on a large oval-shaped guarded calorimeter tank filled with liquid hydrogen and cycled through multi-fill ground-hold conditions including a simulated ascent heating cycle.

The insulation system studied on this program was the dual-seal construction and consisted of a sealed-cell sublayer and a helium-purged heat-resistant outer layer. The sublayer was a Mylar honeycomb panel having a density of 2.1 pcf and each cell hermetically sealed within coverings of Mylar film and thin aluminum foil. The heat resistant outer layer of the composite consisted of a 0.2-inch thick, 3/8-inch cell, heat-resistant phenolic (HRP), perforated honeycomb panel bonded directly to the aluminum foil seal covering the sublayer and closed with an outer covering of bonded aluminum foil. The method of attachment used as the primary means of holding and sealing the insulation to the tank wall was adhesive bonding.

The results of the investigation indicated that the MSFC dual-seal concept is a fail-safe means of providing thermal protection to the exterior of liquid hydrogen tanks of large boost vehicles. The thermal effectiveness of the sealed cryopumped sublayer portion of the insulation system, when tested under liquid hydrogen tankage conditions, was demonstrated to be capable of approaching the theoretical predicted values. Under ambient test conditions, thermal conductivity values as low as 0.10 to 0.15 BTU-in./ft^2-hr-^{o}F were realized.

During the program, four sets of dual-seal insulation panels were evaluated on a large oval-shaped guarded calorimeter tank having an insulation surface area of approximately 100 square feet. Evaluation under multicycle ground-hold conditions did not significantly degrade the thermal effectiveness of the developed system.

Dual-seal insulation systems evaluated weighed approximately 0.43 to 0.50 psf as installed on the side wall of liquid hydrogen tanks. A potential reduction can be realized by bonding the Mylar honeycomb core directly to the tank wall, lowering the overall weight of the installed system by approximately 0.04 to 0.06 psf.

SECTION III. DESIGN STUDY

A. LITERATURE SURVEY

A comprehensive survey of accomplishments in the field of cryogenics and cryogenic engineering has been a continual part of the program. Specifically, literature on low density, low thermal conductivity insulating materials and systems has been the prime concern.

The following technical information services have been used:

(1) Technology Utilization Office
National Aeronautics and Space Administration
Marshall Space Flight Center

(2) Scientific and Technical Aerospace Reports
National Aeronautics and Space Administration

(3) Technical Abstracts Bulletin
Armed Services Technical Information Agency

(4) Papers from the 1964 Cryogenics Engineering Conference
held in Philadelphia, Pennsylvania

(5) Cryogenic Engineering Laboratory, National Bureau of Standards,
Boulder, Colorado

(6) In-house literature from the Goodyear Aerospace library.

Volumes 1 through 10 of "Advances In Cryogenic Engineering" contain many articles on the development of cryogenic insulations. Articles on the properties of liquid hydrogen were helpful in the calorimeter design.

B. THERMAL MODEL

1. General

A thermal model of a honeycomb panel was programmed and debugged for use on the IBM 1410 digital computer. This analytical tool was very helpful in determining what changes should result in significant insulation improvement of the panel. Different materials, thicknesses, surface coatings, adhesive, and gases were selected, and the steady-state heat transfer through the panel was calculated for the specific temperature differentials selected.

2. Theory

a. General. The modes of heat transfer considered are conduction and radiation. Convection was neglected because of cell restriction and gas density. The panel thicknesses and cell sizes applicable here are less than natural convective boundary layers and hence would greatly restrict this mode of heat transfer. The cold wall temperatures encountered here will also cause gas condensation and low pressures, which reduce the Grashopf number, and hence the natural convection will approach pure gas conduction.

The modes of heat transfer considered are conduction through the face sheets, glue line and cell walls and through the gas, along with radiation between the face sheets, cell walls, and cell walls to face sheets.

b. Basic Equations. The basic expression for heat transfer by conduction through the gas and the cell wall is

$$q_c = KA(\Delta T/\Delta x),$$

where

- q = heat flux through cell material - BTU/hr,
- K = thermal conductivity of cell material (or gas) - BTU-in./hr-ft^2-^{0}F,
- ΔT = temperature differential, face to face - ^{0}F,
- Δx = height of cell - inches,
- A = total cross-sectional area of all cell walls normal to direction of heat flux - ft^2.

The expression for heat transfer by radiation is

$$q_r = \epsilon\sigma A\bar{F}_{1-2}\left(T_1^4 - T_2^4\right),$$

where

ϵ = the emittance of the face sheets and cell walls,

σ = Stefan-Boltzman constant = $0.1713(10^{-8})$ BTU/hr-ft^2-$^oF^4$,

A = the radiating area - ft^2,

T_1, T_2 = the temperatures of the hot and cold face respectively - ^oF

$\bar{F}_{1-2}$ = the view factor.

The view factor is obtained for each node by the following relationship (see Reference 4):

$$\bar{F}_{1-2} = \frac{1}{2}\left[\frac{h^2+1}{r^2} + 1 - \sqrt{\left(\frac{h^2+1}{r^2}+1\right)^2 - \frac{4}{r^2}}\right],$$

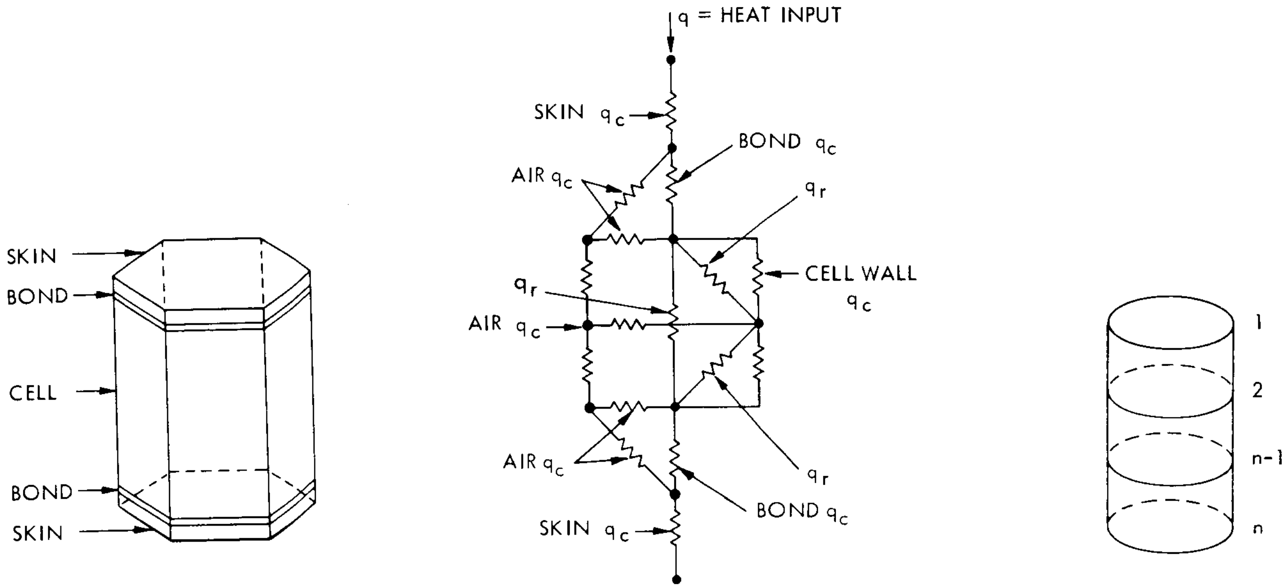
where

h = the distance from disc 1 to disc 2

r = the radius of disc 1 relative to disc 2 having a normalized radius of 1.

Subtracting the value of the view factor for disc 2 from disc 1, times the area ratio, gives value of the view factor for the cylindrical wall connecting discs to the discs.

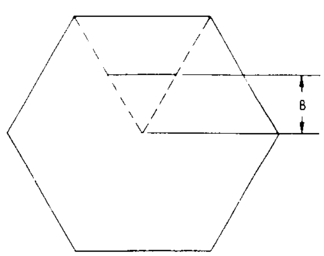
The following sketches show (a) the actual hexagonal cell from which the area calculations are determined, (b) the thermal circuit from which the heat transfer calculations are determined, and (c) the cylindrical cell for determination of view factors for radiation calculations.



a b c

Subtracting disc views results in view factors between a cylindrical wall section and the other wall sections.

The only remaining unknown is radial conduction that exists in the face sheets and in a gas layer, and this is obtained by assuming the average temperature exists at some distance (B) from the center.



The conductive term is then obtained by integrating from B out. This now enables the writing of a set of simultaneous equations. For example,

$$\left(\sum_{i=1,2,3} U_i + \sum \bar{F}_1 \sigma T_1^{3}\right) T_1 - U_2 T_2 - \left(U_3 + \bar{F}_{1,3}\sigma T_3^{3}\right) T_3$$

$$- \sum_{i=5,7,\ldots}^{2n-1} \bar{F}_{1,i}\sigma T_i^{4} = H_1$$

is for the first wall node, No. 1. For the first gas node, No. 2, the equation is

$$- U_2 T_1 + \Sigma U\, T_2 - U_4 T_4 = H_2$$

where

$\bar{F}_1 = 1 - \bar{F}_{1,1}$,

U = conductance - BTU/hr-sq ft-^{o}F,

H = a constant - BTU/hr-sq ft.

These are the first two nodes, and the remaining equations are similar, resulting in set of temperature coefficients, a, and column vector, H.

$$a_{1,1} + a_{2,2} + a_{3,3} + \cdots \cdots + a_{1,n} = H_1$$

$$a_{2,1} + a_{2,2} + \cdots \qquad \cdots \cdots + a_{2,n} = H_2$$

$$\vdots \qquad\qquad\qquad \vdots$$

$$a_{n,1} + a_{n,2} + \cdots \qquad \cdots \cdots + a_{n,n} = H_n$$

All terms of radiating nodes are linearized by retaining a temperature cubed in the coefficient. This requires the iteration technique of solving the set of equations, replacing old temperatures with new ones and repeating until the two temperatures agree within some tolerance.

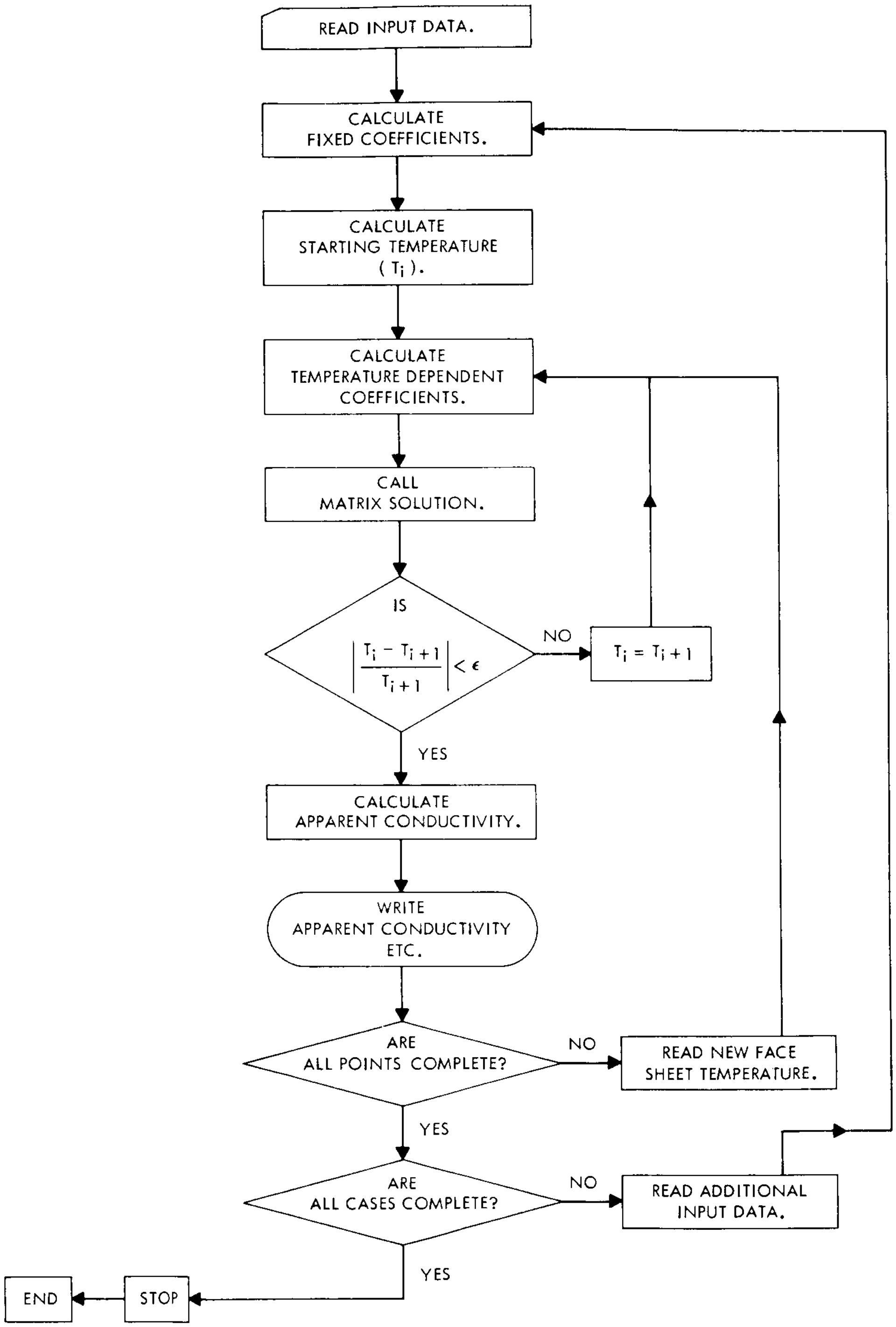


Figure 1. Data Flow Diagram

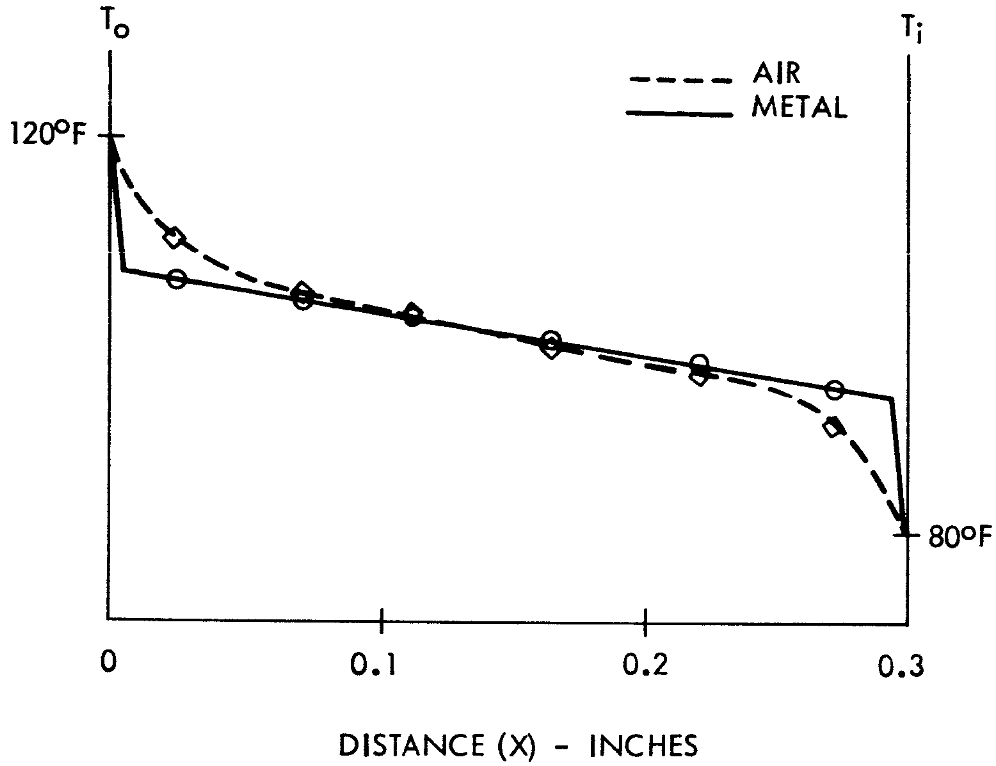


Figure 2. Temperature Profile

c. Computer Program. The data flow chart (Figure 1) describes generally the sequential usage of the above equations and input data.

The program was written along the lines of this flow chart, using the equations shown in the previous paragraphs. The results of the sample case used for debugging are shown in Figure 2.

3. Proposed Analysis

Utilizing the above thermal model and the testing schedule presented for the first 12 samples, the program was run to compare theoretical and test values. Correlating these two, the model was used to evaluate changing surface coatings, cell sizes, wall thicknesses, and gas pressures and to establish which way to go on remaining test panels.

C. THERMODYNAMIC ANALYSIS

1. General

Two areas of investigation are presented: testing and theoretical determination of apparent thermal conductivity in honeycomb panels. One test panel was tested using liquid nitrogen, and several panels were analyzed using the honeycomb thermal model.

2. Test Data

A 4/10-inch thick, sealed-cell, Mylar honeycomb sandwich was tested in the liquid nitrogen calorimeter with the hot surface held at 130°F. Under one atmosphere of pressure, the test panel was sealed and tested in an evacuated bell jar. The face sheet was then punctured, and the pressure in the bell jar was held at different levels at which the panel was again tested. Figures 3 and 4 present the test data as recorded. The corrected data is plotted in graph form in Figures 5 and 6, from which the line slopes were used to determine apparent thermal conductivity. These values were then plotted (see Figure 7) to show apparent thermal conductivity as a function of gas pressure in the cells.

The pressure that yields a mean free path equal to the cell size is about 3.2 microns of mercury. Figure 7 shows this point as an "x." The circled points are test points, and the effects of the gas conductivity, which should be pressure sensitive in this area can be seen around the "x" point. The test points at very low pressures are asymptotically approaching the apparent thermal conductivity of a no-gas panel.

3. Thermal Model

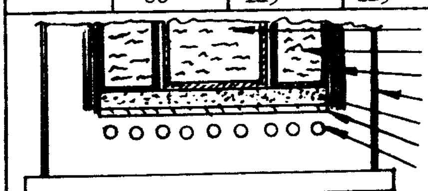
The thermal model was utilized to obtain apparent thermal conductivities for this same panel, and these points are shown as triangles in Figure 7. A temperature-dependent gas conductance was used for the high point, and a free molecular flow

Project	TEST DATA RECORD	Test No.	Sheet	Of
CRYOGENIC INSULATION	ADVANCED MATERIALS LABORATORY	V-277	1	1
RFT Or EI No.		Date Test Recd	Date of Test 10-28-64	

Type Test	Requested by:	Charge No.
THERMAL CONDUCTIVITY	R. FRENCH	808021

Specimen Description	Test Procedure	
Material: CLEAR HONEYCOMB SOLID FACES	Temperature: +130°F	Heating Or Cooling Device
Coating: SOLID OUTER SURFACES	Exposure Conditions	

Clock Time	Elapsed Time Min	Temperature °F #1	Temperature °F #2	Temperature °F #3	Boil Off	Gas Temp. °F	Gas Pressure " H_2O	Bell Jar Press. x 10^{-5}
1300	0	129	129		0	78.5	.2	1.6
	5	129	129		.2350	78.5	.2	1.6
	10	129	129		.4540	78.5	.2	1.6
	15	129	129		.6750	78.5	.2	1.6
	20	129	129		.9000	78.5	.2	1.6
	25	127	127		1.1200	78.5	.2	1.5
	30	126	126		1.3850	79.0	.2	1.5
	37	128	128		1.670	79.0	.2	1.5
	40	128	128		1.795	79.0	.2	1.5
	45	130	130		2.015	79.0	.2	1.5
	50	130	130		2.2390	79.0	.2	1.4
	55	129	129		2.4755	79.0	.2	1.4
	60	129	129		2.7400	79.0	.2	1.4



Thermocouple #1, #2, #3

Specimen Description

Weight ________ gms

Thickness 0.4 in

Calorimeter Surfaces (Black X
(Shiny ____

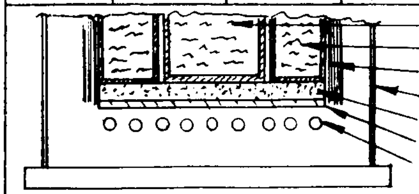
Tested By B. Brescia			Witness		Apparent K $\frac{BTU\text{-}In}{Sq\ Ft\text{-}Hour\text{-}°F}$ ______	
Dept 417	Ext 5336	Date 10-28-64	Dept	Date	Dept	Date

Figure 3. Recorded Test Data - Test No. V-277

Project CRYOGENIC INSULATION	TEST DATA RECORD ADVANCED MATERIALS LABORATORY	Test No. V-278	Sheet 1	Of 4
RFT Or EI No.		Date Test Recd	Date of Test 10-30-64	
Type Test THERMAL CONDUCTIVITY	Requested by: R. BURKLEY		Charge No. 807841	

Specimen Description		Test Procedure	
Material MYLAR HONEYCOMB (CLEAR)		Temperature +130°F	Heating Or Cooling Device
Coating PUNCTURED CELLS ON HOT FACE		Exposure Conditions	

Clock Time	Elapsed Time Min	Temperature °F #1	Temperature °F #2	Temperature °F #3	Boil Off Ft^3	Gas Temp. °F	Gas Pressure " H_2O	Bell Jar Press. x 10^{-5}
0900	0	128	128		0	0.0	.2	1.5
	5	125	125		.1400		.2	1.5
	10	132	132		.2100		.2	1.3
	15	135	135		.2985		.2	1.4
	20	138	138		.3880		.2	1.4
	25	136	136		.4870		.2	1.4
	30	134	134		.5750		.2	1.3
	35	130	130		.6660		.2	1.2
	40	128	128		.7570		.2	1.2
	45	129	129		.8460		.2	1.2
	50	130	130		.9385		.2	1.2
	55	130	130		1.024		.2	1.2
	60	130	130		1.113		.2	1.2



Measuring Vessel(Dia)
Guard Vessel(Dia)
Super-Insulation
Bell Jar
Specimen
Hot Plate (Aluminum)
Quartz Lamps

Thermocouple #1, #2, #3

Calorimeter Surfaces (Black X
(Shiny ____

Specimen Description

Weight ________ gms

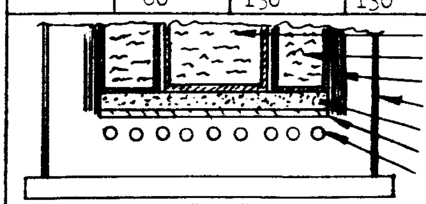
Thickness 0.4 in

Tested By B. Brescia			Witness		Apparent K $\frac{\text{BTU-In}}{\text{Sq Ft-Hour-°F}}$ ______	
Dept 417	Ext 5336	Date 10-29-64	Dept	Date	Dept	Date

Figure 4. Recorded Test Data - Test No. V-278 (Sheet 1)

Project CRYOGENIC INSULATION	TEST DATA RECORD	Test No. V-278	Sheet 2	Of 4	
RFT Or EI No.	ADVANCED MATERIALS LABORATORY	Date Test Rec'd	Date of Test 10-30-64		
Type Test THERMAL CONDUCTIVITY		Requested by: R. BURKLEY	Charge No. 507841		
Specimen Description		Test Procedure			
Material MYLAR HONEYCOMB (CLEAR)		Temperature +130°F	Heating Or Cooling Device		
Coating PUNCTURED CELLS ON HOT FACE		Exposure Conditions			

Clock Time	Elapsed Time Min	Temperature °F #1	#2	#3	Boil Off Cu Ft	Gas Temp. °F	Gas Pressure " H_2O	Bell Jar Press.
1500	0	130	130		0	72	.2	1 micron
	5	126	126		.1160	72	.2	"
	10	128	128		.2345	72	.2	"
	15	128	128		.3530	72	.2	"
	20	130	130		.4700	72	.2	"
	25	130	130		.5905	72	.2	"
	30	130	130		.7100	72	.2	"
	35	129	129		.8300	72	.2	"
	40	129	129		.9480	72	.2	"
	45	129	129		1.0675	72	.2	"
	50	130	130		1.1855	72	.2	"
	55	131	131		1.3075	72	.2	"
	60	130	130		1.4260	72	.2	"



Measuring Vessel(Dia)
Guard Vessel(Dia)
Super-Insulation
Bell Jar
Specimen
Hot Plate (Aluminum)
Quartz Lamps

Specimen Description
Weight ______ gms
Thickness 0.4 in

Thermocouple #1, #2, #3

Calorimeter Surfaces (Black X
(Shiny ____

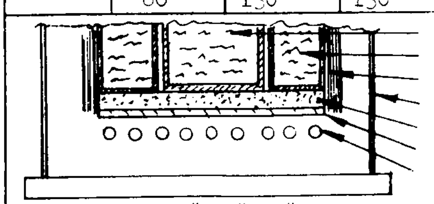
Tested By B. Brescia			Witness		Apparent K $\frac{\text{BTU-In}}{\text{Sq Ft-Hour-°F}}$ ______	
Dept 417	Ext 5336	Date 10-30-64	Dept	Date	Dept	Date

Figure 4. Recorded Test Data - Test No. V-278 (Sheet 2)

Project CRYOGENIC INSULATION	TEST DATA RECORD	Test No. V-278	Sheet 3	Of 4
RFT Or EI No.	ADVANCED MATERIALS LABORATORY	Date Test Recd	Date of Test 11-2-64	
Type Test THERMAL CONDUCTIVITY		Requested by: R. BURKLEY	Charge No. 807841	

Specimen Description	Test Procedure	
Material MYLAR HONEYCOMB (CLEAR)	Temperature +130°F	Heating Or Cooling Device
Coating	Exposure Conditions	

Clock Time	Elapsed Time Min	Temperature °F #1	#2	#3	Boil Off Cu Ft	Gas Temp. °F	Gas Pressure " H_2O	Bell Jar Press.
1045	0	128	128		0	75	.2	100 microns
	5	128	128		.1435	75	.2	"
	10	126	12[illegible]		.2820	75	.2	"
	15	126	12[illegible]		.[illegible]45	75	.2	"
	20	128	128		.[illegible]715	75	.2	"
	25	133	[illegible]		.8500	75	.2	"
	30	133	[illegible]		1.050	75	.2	"
	35	132	132		1.2150	75	.2	"
	40	131	131		1.3[illegible]50	75	.2	"
	45	131	131		1.5[illegible]	75	.2	"
	50	131	131		1.7570	75	.2	"
	55	130	130		1.[illegible]65	75.5	.2	"
	60	130	130		2.2300	75.5	12	"



Measuring Vessel(Dia)
Guard Vessel(Dia)
Super-Insulation
Bell Jar
Specimen
Hot Plate (Aluminum)
Quartz Lamps

Thermocouple #1, #2, #3

Specimen Description

Weight ______ gms

Thickness 0.4 in

Calorimeter Surfaces (Black X
(Shiny ____

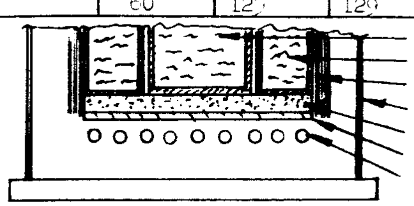
Tested By B. Brescia			Witness		Apparent K $\frac{\text{BTU-In}}{\text{Sq Ft-Hour-}^{\circ}\text{F}}$	
Dept 417	Ext 5336	Date 11-2-64	Dept	Date	Dept	Date

Figure 4. Recorded Test Data - Test No. V-278 (Sheet 3)

Project: CRYOGENIC INSULATION	TEST DATA RECORD	Test No. V-278	Sheet 4	Of 4
RFT Or EI No.	ADVANCED MATERIALS LABORATORY	Date Test Rec'd	Date of Test 11-2-64	
Type Test: THERMAL CONDUCTIVITY		Requested by: R. BURKLEY	Charge No. 807841	

Specimen Description		Test Procedure	
Material: MYLAR HONEYCOMB (CLEAR)		Temperature: +130°F	Heating Or Cooling Device
Coating		Exposure Conditions	

Clock Time	Elapsed Time Min	Temperature °F #1	Temperature °F #2	Temperature °F #3	Boil Off Cu Ft	Gas Temp. °F	Gas Pressure " H_2O	Bell Jar Press.
1415	0	132	132		0	77.5	.2	1000 microns
	5	131	131		.2[illegible]	77.5	.2	"
	10	127	127		.[illegible]7[illegible]	77.[illegible]	.2	"
	15	12[illegible]	12[illegible]		.7[illegible]0	77.5	.2	"
	22	12[illegible]	126		1.0[illegible]	77.5	.2	"
	25	127	1[illegible]7		1.[illegible]	77.5	.2	"
	30	132	132		1.4[illegible]	77.5	.2	"
	35	132	132		1.[illegible]480	77.5	.2	"
	40	130	1[illegible]0		1.88[illegible]	77.5	.2	"
	45	130	130		2.1[illegible]	77.5	.2	"
	50	127	127		2.[illegible]00	77.5	.2	"
	55	128	128		2.5[illegible]0	77.5	.2	"
	60	129	129		2.8280	77.5	.2	"



Thermocouple #1, #2, #3

Calorimeter Surfaces (Black X
(Shiny ____

Specimen Description
Weight ________ gms
Thickness 0.4 in

Tested By B. Brescia			Witness		Apparent K $\frac{\text{BTU-In}}{\text{Sq Ft-Hour-°F}}$ ______	
Dept 417	Ext 5336	Date 11-2-64	Dept	Date	Dept	Date

Figure 4. Recorded Test Data - Test No. V-278 (Sheet 4)

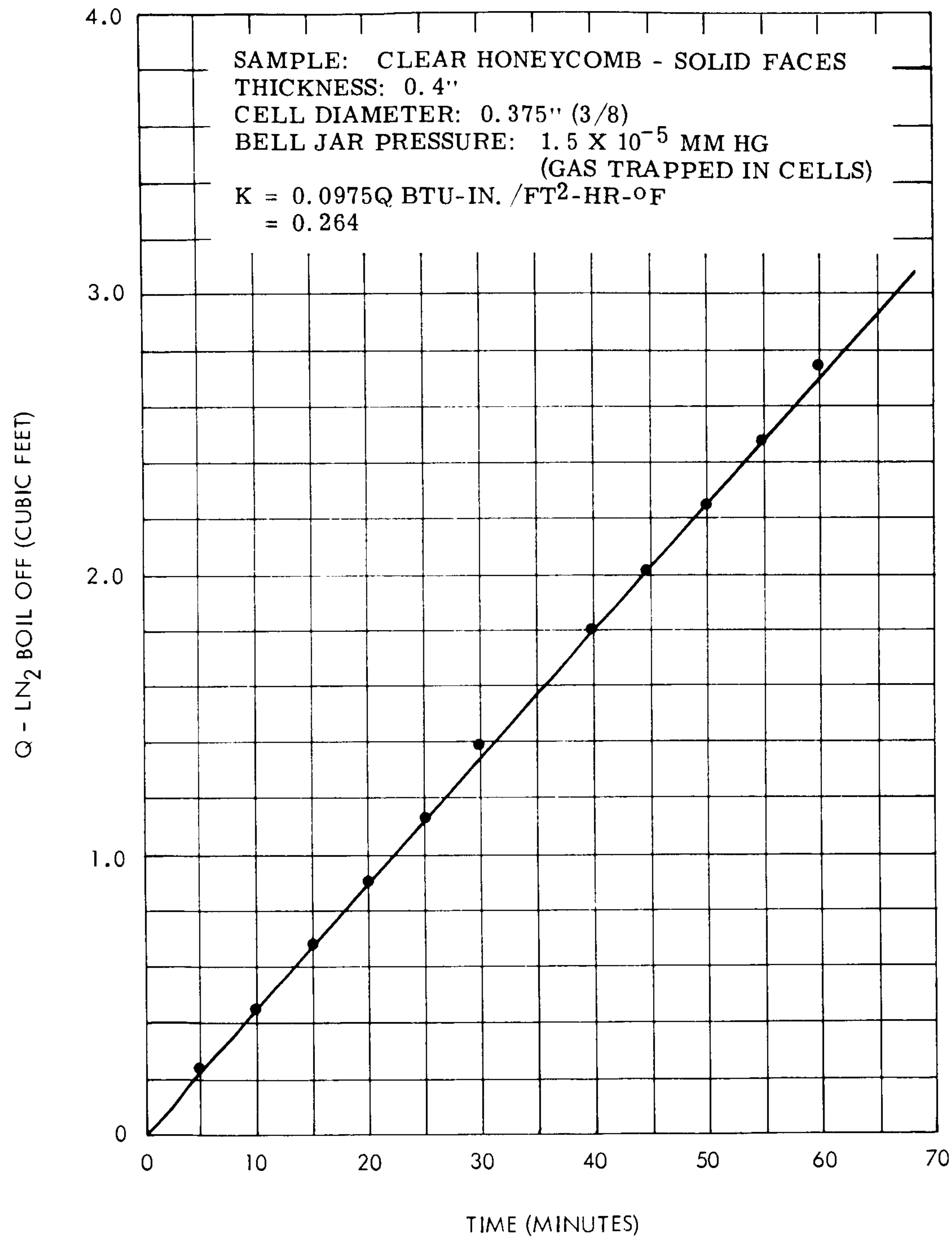


Figure 5. Corrected Test Data - Test No. V-277

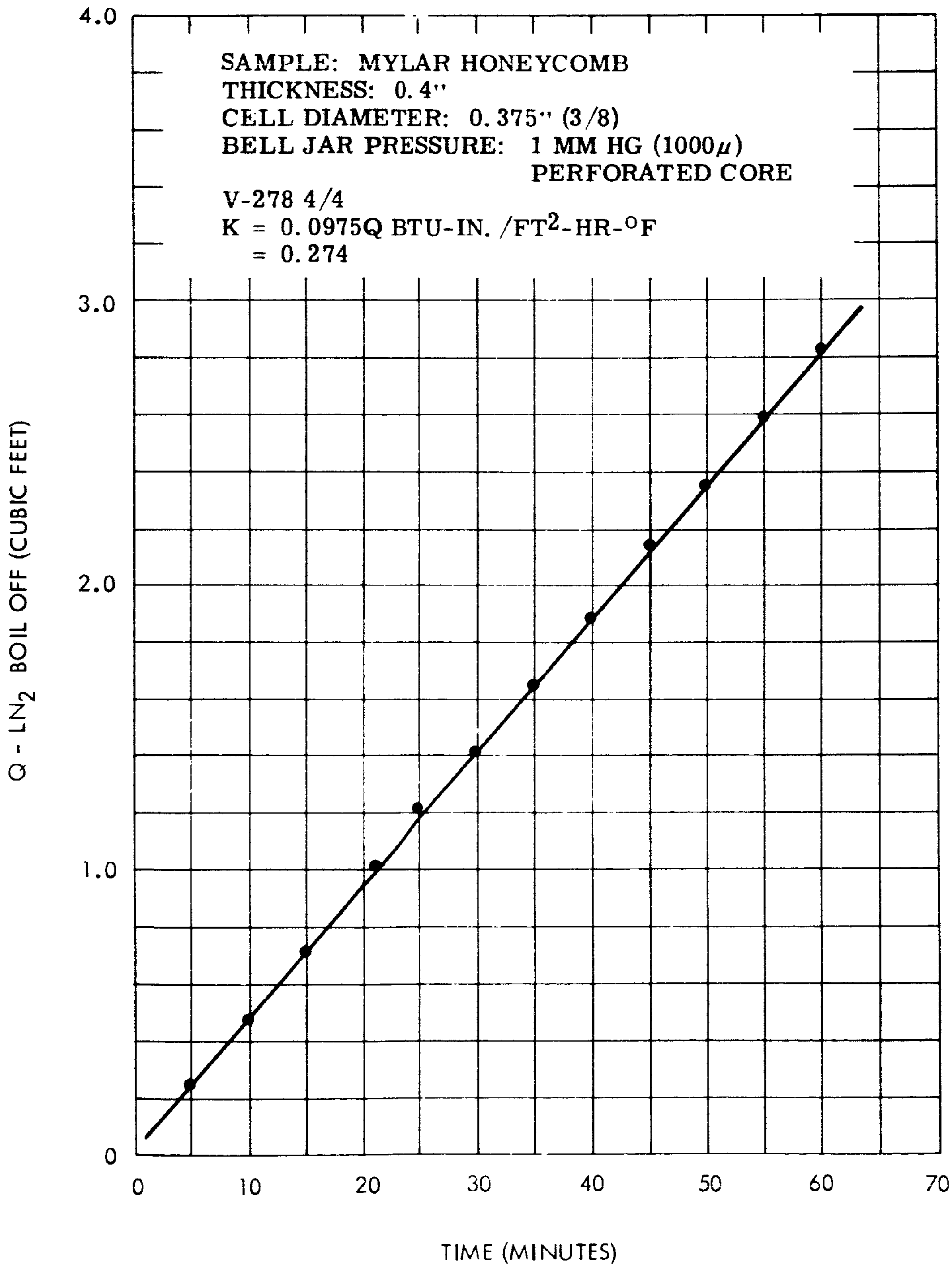


Figure 6. Corrected Test Data - Test No. V-278 (Sheet 1)

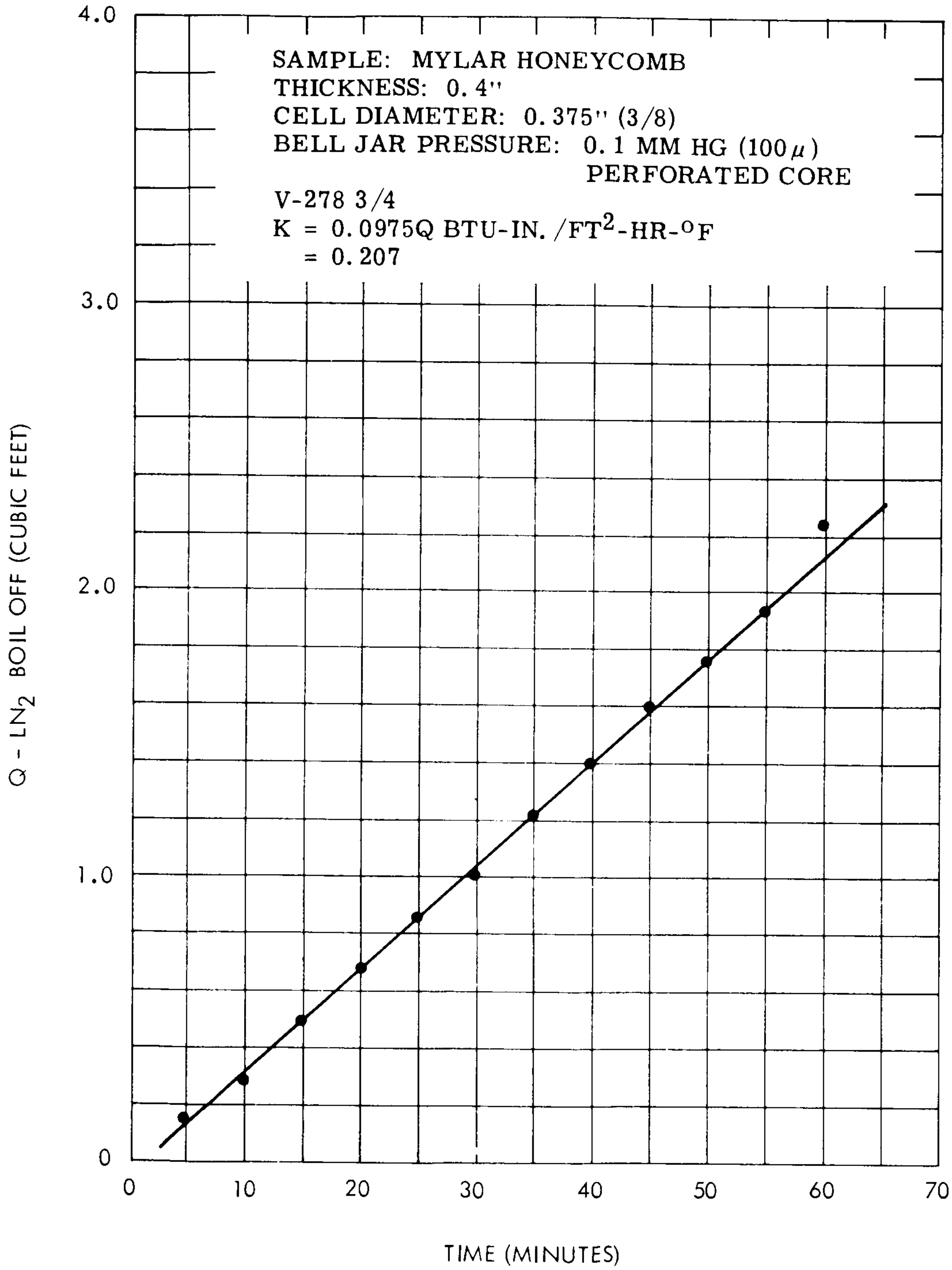


Figure 6. Corrected Test Data - Test No. V-278 (Sheet 2)

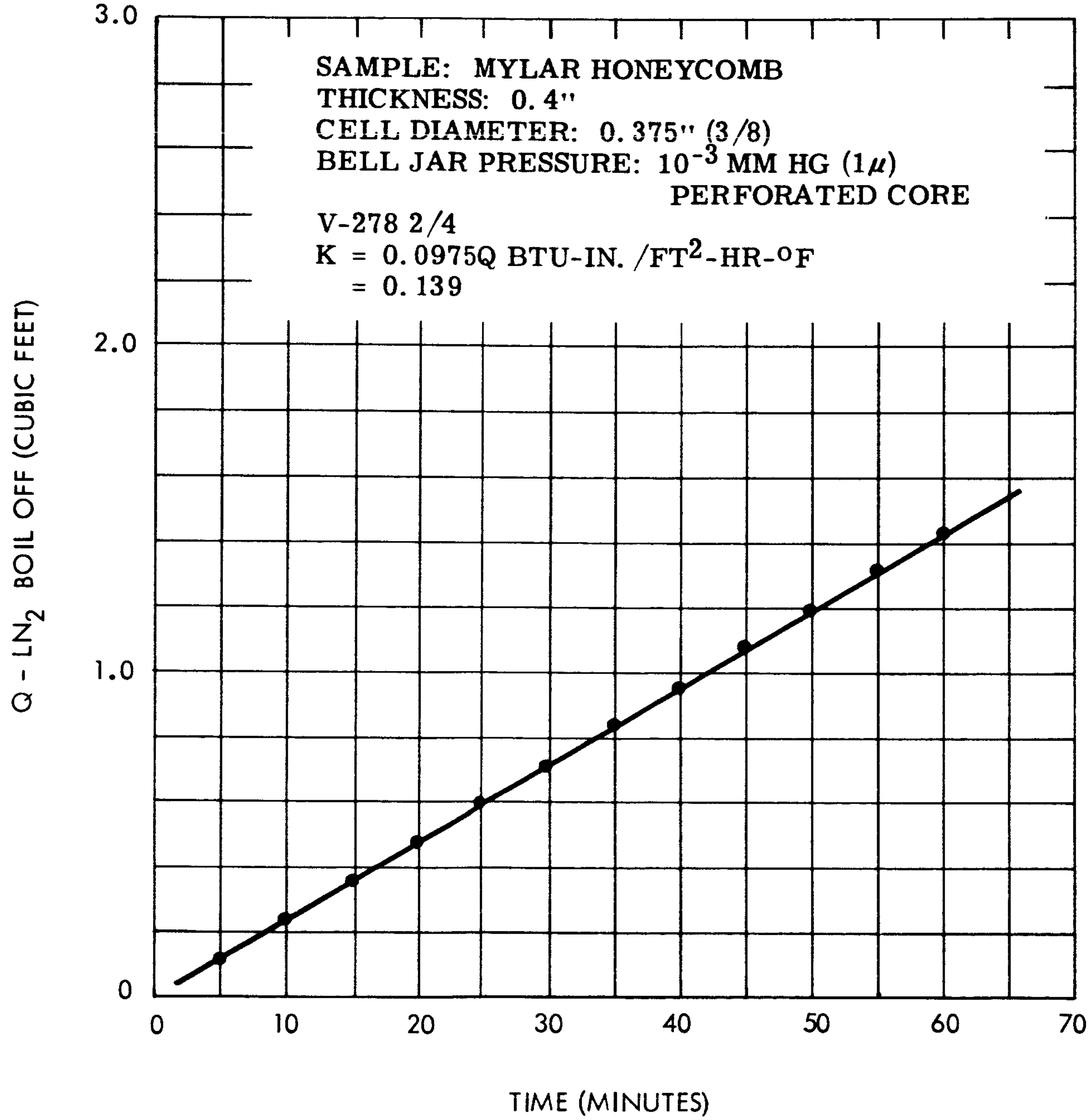


Figure 6. Corrected Test Data - Test No. V-278 (Sheet 3)

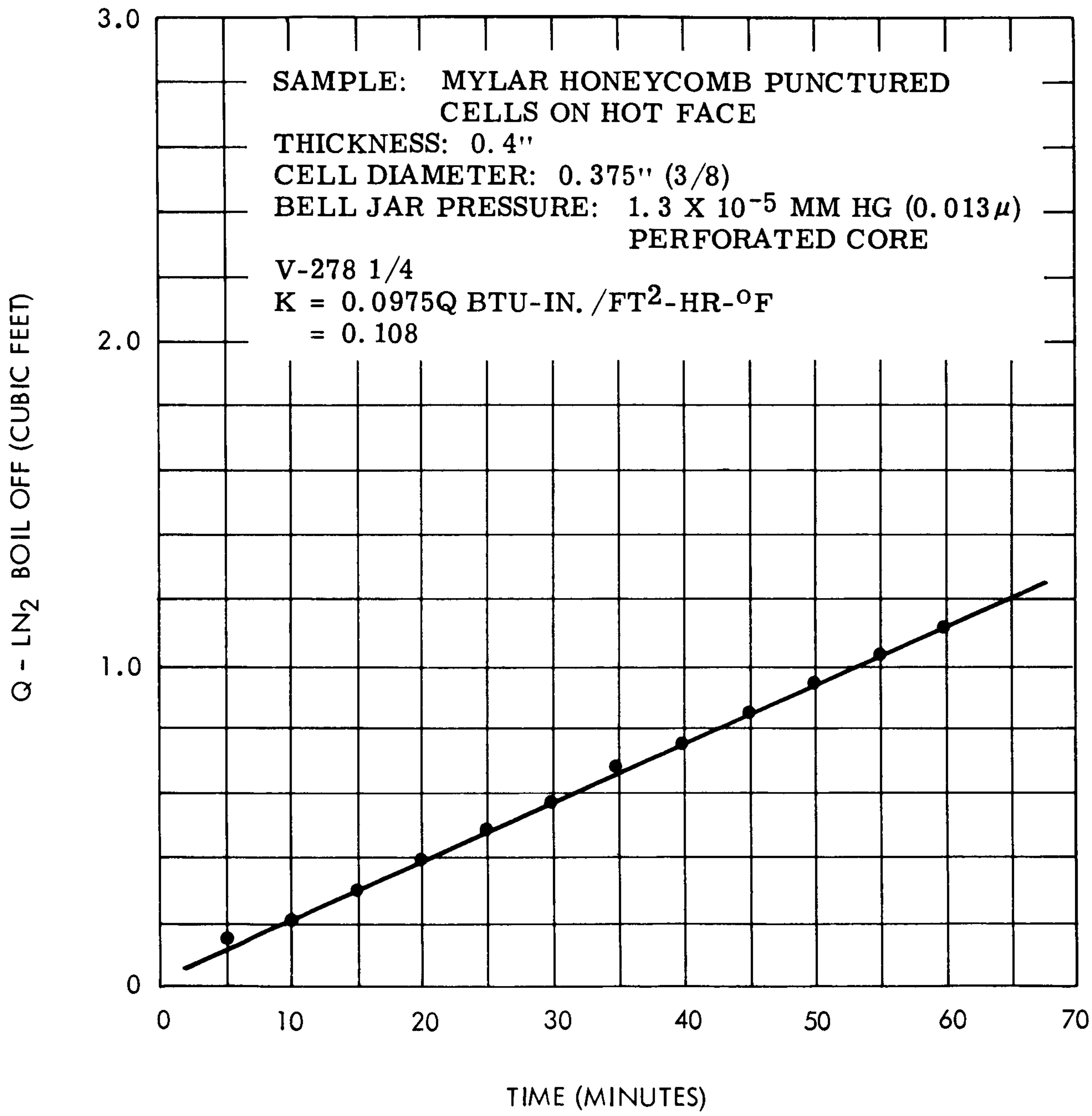


Figure 6. Corrected Test Data - Test No. V-278 (Sheet 4)

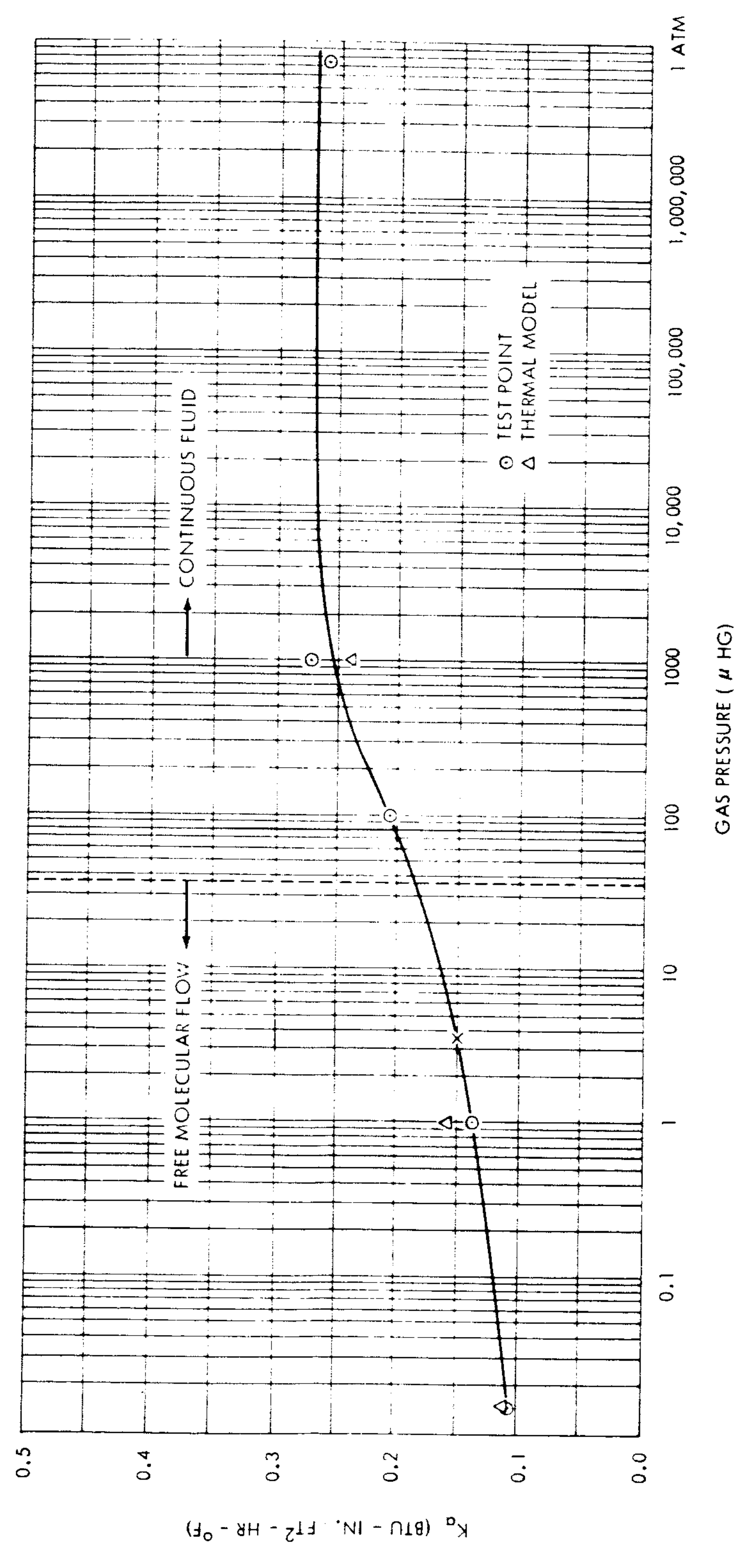
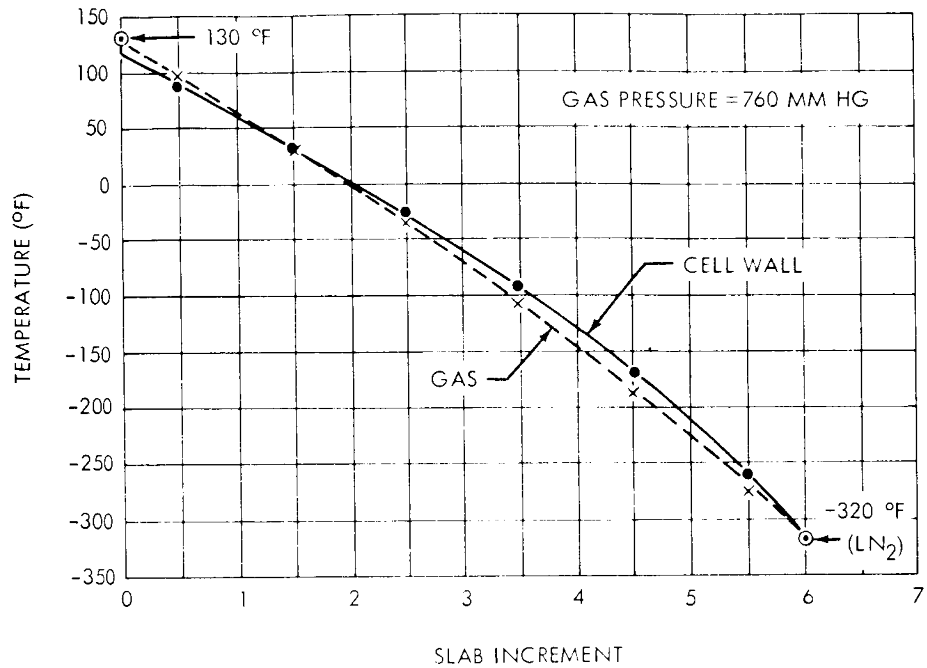


Figure 7. Thermal Conductivity versus Pressure



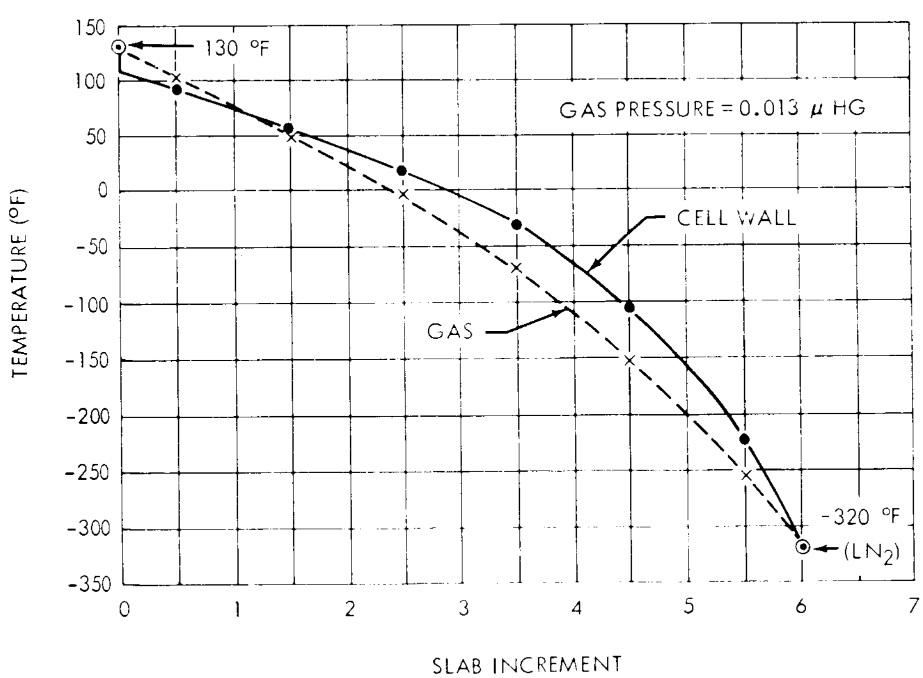


Figure 8. Temperature Profiles (Gas and No-Gas Conditions)

thermal conductivity was used for the two lower points. The test data and thermal model seem to be in good agreement; however, one thing should be noted. The no-gas apparent thermal conductivity was a little low, using an emittance of 0.5 in the thermal model for the plastic honeycomb material. Since the plastic honeycomb panel had transparent face sheets and the calorimeter surfaces were black, it was assumed that the effective emittance could be higher. A value of 0.9 matched the no-gas condition. The gas and no-gas temperature profiles are shown in Figure 8.

SECTION IV. MATERIAL AND PROCESS STUDY

A. RESEARCH AND DEVELOPMENT

1. General

Throughout this program GAC has maintained a materials and process study effort toward improving the properties of the basic MSFC dual-seal design (see Figure 9). Emphasis was placed on the development and evaluation of material treatments and process methods for making the cold face bond between the Mylar honeycomb core and Mylar face sheet. In addition, various bonding adhesives were considered for hot-face and center-face bonds.

2. Cold Face Bonding

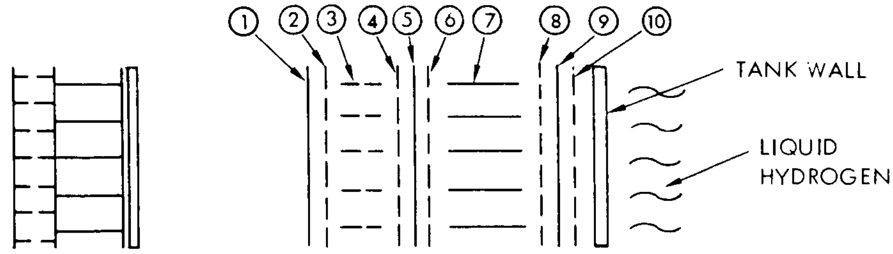
For the dual-seal panel insulation to function efficiently, the cold-face bond must meet the following requirements:

(1) The adhesive system must be capable of developing a high-strength, low-permeability (gas) bond between the Mylar core and Mylar face sheet.

(2) The adhesive system must not require a cure temperature above 225-250^{o}F, using moderate pressure.

(3) The adhesive system must possess a sufficient degree of flexibility at liquid hydrogen temperature so that it will not crack within itself or delaminate from the Mylar and cause gas leaks between core cells.

(4) The adhesive system must be low in voltatile materials and must liberate a minimum quantity of gases in the curing process.



Components	Description - Material	Weight (lb/sq ft)
(1) Hot Face	0.003 inch aluminum foil	0.047
(2) Bond Line	Hot face to HRP core Bloomingdale HT-424 adhesive	0.090
(3) HRP Core	Perforated honeycomb core 3/8 inch cell size, 0.20 inch thick	0.037
(4) Bond Line	HRP core to inner face Bloomingdale HT-424 adhesive	0.090
(5) Inner Face	0.0015 inch aluminum foil	0.024
(6) Bond Line	Inner face to Mylar honeycomb core 3M, AF-111 adhesive	0.050
(7) Mylar Honeycomb Core	3/8 inch cell size, 0.40 inch thick 0.003 inch Mylar	0.070
(8) Bond Line	Mylar honeycomb core to cold face. Narmco 7343/7139 adhesive or DuPont Adiprene L100/Moca. Both mixed to 100/12.5 parts by weight.	0.020
(9) Cold Face	0.002 Mylar	0.014
(10) Tank Cold Face Bond Line	Cold face to tank wall. Narmco 7343/7139 adhesive or DuPont Adiprene L100/Moca adhesive. Both mixed to 100/12.5 parts by weight.	0.060
	Total Weight	0.492

Figure 9. MSFC Dual-Seal Design

On the basis of screening tests by MSFC, GAC, and others, it was generally agreed that the most promising adhesive for effecting the desired cold face bond was an elastomeric polyurethane material, namely, DuPont Adiprene L100/ Moca or its equivalent Narmco 7343/7139. Based on their experience, MSFC recommended a formulation of 100/12.5 parts by weight of the two component adhesives and a cure cycle of 48 hours at room temperature, followed by a 24-hour cure at $160^{\circ}F$.

Using this adhesive formulation and the test panel fabrication process given in Table 1, a series of panels was fabricated. Specimens were prepared per Table 2 and evaluated on the basis of flatwise tensile strengths (see Section V). In fabricating these test panels, certain process parameters, such as Mylar pretreatments, method of adhesive application, and cure cycle were varied in an effort to determine their effect on bond strengths. These parameters are discussed in the following paragraphs.

3. Mylar Pretreatments

Two Mylar pretreatments were investigated: vacuum condition and surface priming.

a. Vacuum Conditioning. Previous experience in bonding Mylar to itself or other materials has shown that it is beneficial to precondition the Mylar in a vacuum chamber prior to bonding. Using this pretreatment in making up test panels, both the Mylar core and Mylar film were exposed. This was accomplished by placing the test panel materials in a vacuum bell jar for 36 hours at a measured pressure of 2×10^{-5} mm Hg. From actual weight loss measurements, Mylar film loses approximately 0.2 percent when exposed to a vacuum. This loss is believed to be effected by out-gassing of residual low-molecular weight materials on the surface of the material. As a general rule, adhesive bonds between high-molecular weight materials, such as Mylar and polyurethane, can

Table 1. Test Panel Fabrication Process

Step No.	Procedure
1	Cut two 12 x 12 inch sheets from roll of 0.002-inch Mylar film face sheet.
2	Visually inspect face sheets for flaws, foreign inclusions, and pinholes.
3	Wipe bond side of face sheets with methylethyl ketone solvent to assure a clean surface for bonding purposes.
4	Cut 12 x 12 inch slab of Mylar honeycomb core (3/8" cell size, 0.40" thick and 0.071 psf).
5	Visually inspect Mylar honeycomb core for imperfections and non-uniformity. (Compare with minimum acceptable panel selected by GAC engineering.)
6	Materials pretreatment (option, see text) a. Condition core and face sheets in vacuum bell jar. b. Prime core and face sheets.
7	Adhesive applications (option, see text) a. Adhesive to core b. Adhesive to face sheet
8	Place face sheet on flat table and core on top with adhesive applied between as accomplished in step 7.
9	Cover top of core with a sheet of FEP fluorocarbon film and a rubber-padded caul plate.
10	Apply a positive pressure of 1/2 to 1 psi, using lead shot placed on top of caul plate.
11	Cure adhesive (option, see text) Cure Cycle A. 48 hours at room temperature and 24 hours in a 160°F oven. Cure Cycle B. 24 hours in a 160°F oven Cure Cycle C. 4 hours in a 160°F oven

Table 1. Test Panel Fabrication Process (Continued)

Step No.	Procedure
12	Remove from oven and let cool to room temperature. Inspect bond lines for any flaws, voids, and non-uniformities.
13	Repeat process for bonding second face sheet.
14	Identify test panel.

Table 2. Flatwise Tensile Specimen Fabrication Process

Step No.	Procedure
1	Cut specimens (2-1/2 x 2-1/2 inches) from fabricated panel.
2	Clean surfaces of specimen and bonding surface of aluminum test blocks with methylethyl ketone solvent.
3	Brush prime all bonding surfaces (4) with G-207 adhesive.
4	Allow primer to air dry four hours prior to polyurethane adhesive application.
5	Apply polyurethane adhesive to Mylar faces and aluminum block bonding faces.
6	Assemble blocks and specimen in jig with holes in blocks at 90 degrees to each other.
7	Cure bond between blocks and outer faces of Mylar for 4 hours at a temperature of 160°F.
8	Remove flatwise tensile specimens after cure and trim excess material from blocks.
9	Code specimens prior to testing.

best be accomplished by minimizing the interference of low molecular weight materials at their interface.

b. Surface Priming. The best material appeared to be a Goodyear G-207 adhesive, a linear polyester solution resin developed for heat sealing polyester films. G-207 adhesive is described in Table 3. In this program, G-207 is used as a primer coat on the Mylar core and face sheet to create a cohesive bond with the polyurethane adhesive, thereby improving the bond strength between the Mylar face sheet materials. Mylar to Mylar bonds made with this resin demonstrate excellent adhesion and toughness at cryogenic temperatures. It has been developed to be applied as a brush coat, roller coat, or spray coat. G-207 is a two-part adhesive system with good solution stability. The adhesive resin (G-207B) is prepared as a 28 percent solids solution that can be reduced to thinner solutions by simply adding a dual solvent such as a 70/30 ratio of toluene and methylethyl ketone. Uncatalyzed G-207B will remain permanently tacky as a coating after solvent evaporation and could be used similar to a contact adhesive. When properly catalyzed with G-207C, the adhesive coating will polymerize to a tack-free state having moderate temperature capabilities.

Pretreating the Mylar core and Mylar face sheet by surface priming was accomplished by spraying the core and brush coating the face sheet with a 10 percent solids solution of Goodyear G-207 adhesive (see Figure 10). To ensure a uniform and complete coating, the resin solution was colored. Following the adhesive application, the Mylar core and Mylar face sheet were allowed to air dry for at least four hours prior to panel fabrication. Test samples were fabricated using different cure times both at room temperature and at different elevated cure temperatures. Based on results of the sample testing, the process selected for the large test panels was a 6-hour cure of the primer at $200^{\circ}F$.

Table 3. Goodyear G-207 Adhesive Physical Properties and Recommended Formulations

Physical properties

Color	Light straw colored
Odor	Odorless
Specific gravity (100 % solids)	1.215
Melting point	250 - 325°F
Bonding temperature	200 - 300°F
Thermal stability	Excellent
Moisture absorption	0.4% at 100°F at 100% relative humidity
Hydroxyl number	2.5 - 3.0

Recommended formulations:

Spray solution (10% solids)

G-207B	100 g (pbw)
Toluene	126 g (pbw)
Methylethyl ketone	54 g (pbw)
G-207C	4 g (pbw)

Brush solution (14.7% solids)

G-207B	100 g (pbw)
Toluene	63 g (pbw)
Methylethyl ketone	27 g (pbw)
G-207C	4 g (pbw)

Roller-coat solution (28% solids)

G-207B	100 g (pbw)
G-207C	4 g (pbw)

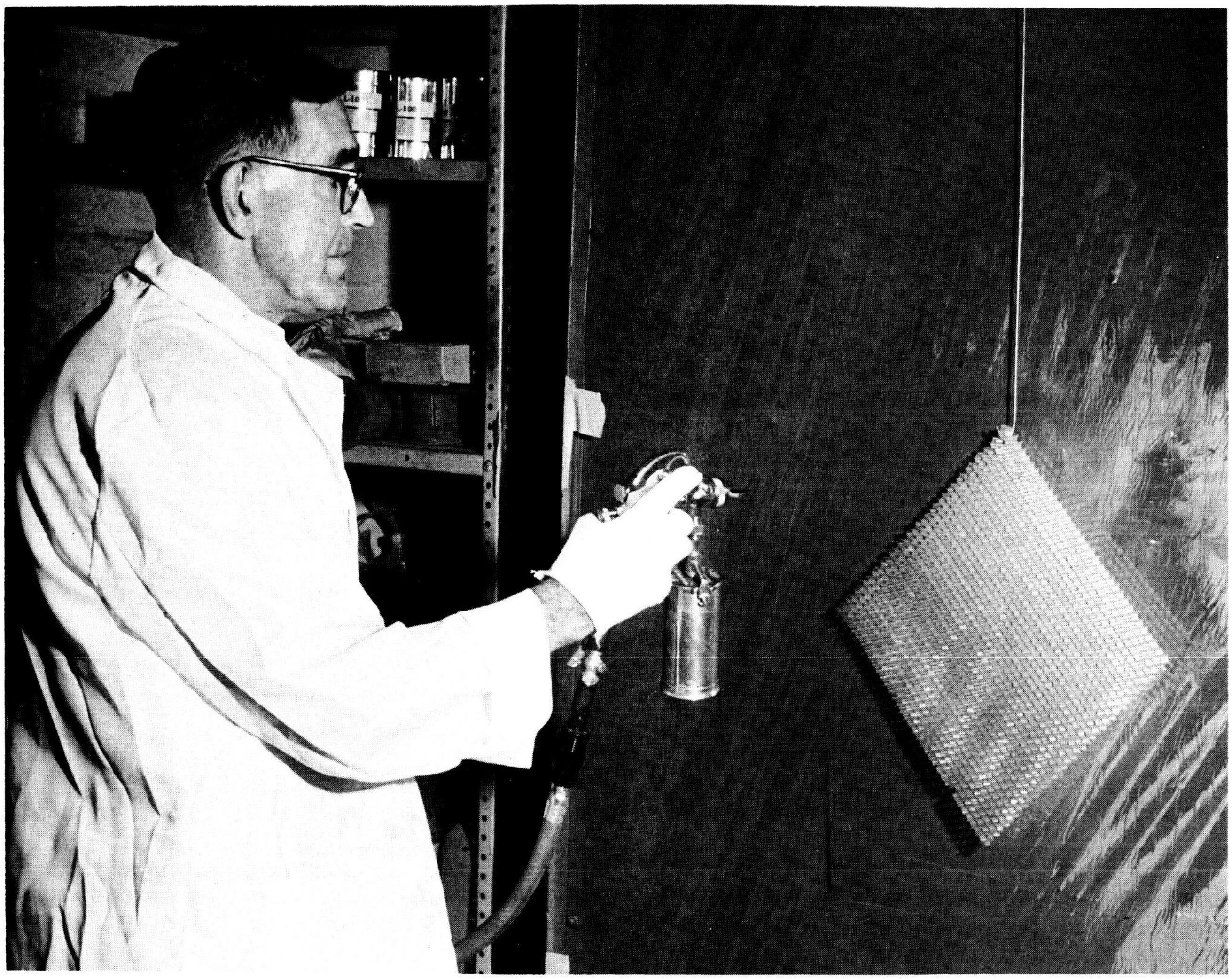


Figure 10. Mylar Core Pretreatment

4. Adhesive Applications

Since weight is a primary consideration in the selection and application of materials making up the insulation panels under development, methods of applying the polyurethane adhesive to the Mylar core and face sheet materials were investigated.

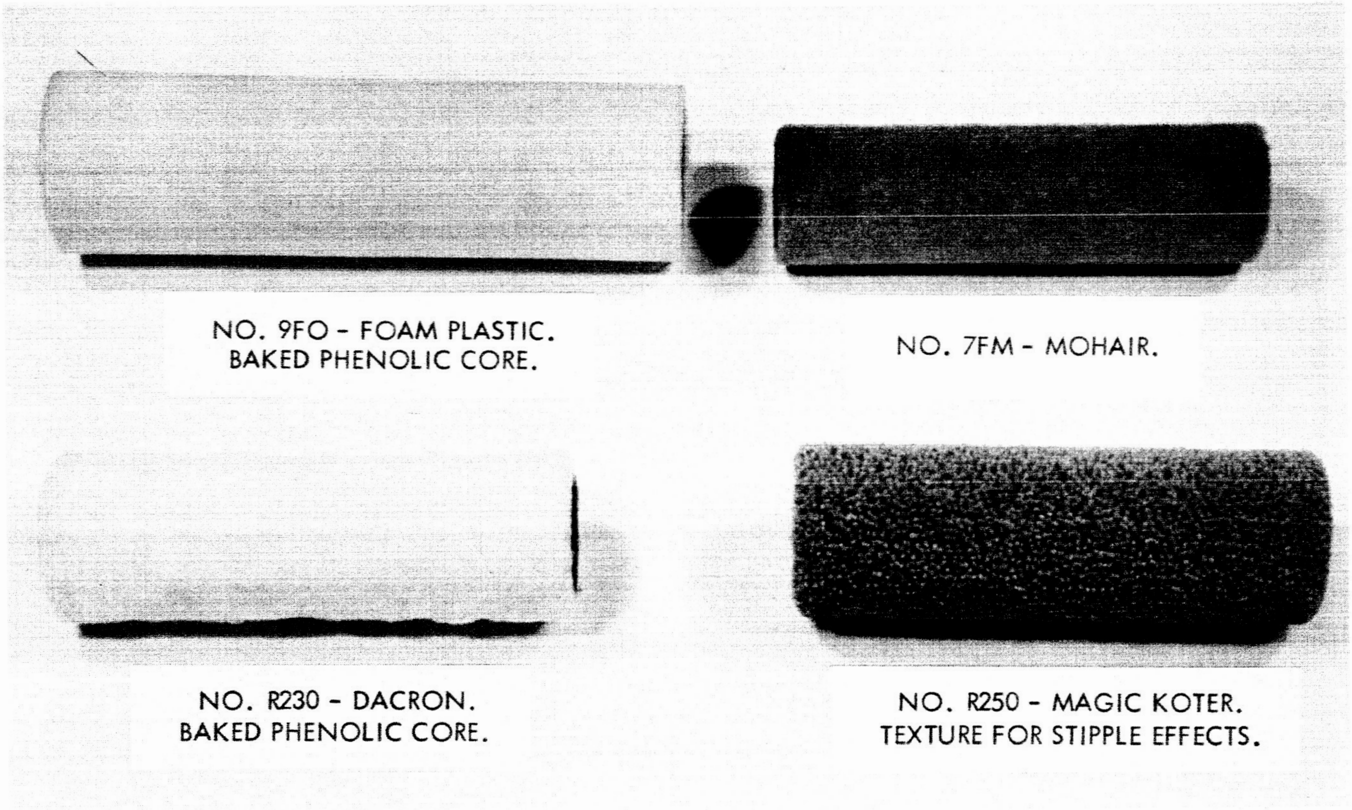


Figure 11. Adhesive Rollers Investigated

a. Roller Coating Core. Four different rollers (Figure 11) were used in making polyurethane core to face sheet bonds. In all cases, the rollers deposited approximately 0.01 pound of adhesive per square foot of core. The roller textures were different, and the resultant bond lines developed showed distinct variations in fillet radius and uniformity of adhesive coverage to the core. Visual inspection of the test bond lines indicated that the Dacron felt roller and the spongy foam roller gave the preferred adhesive bond line. The spongy foam roller was selected for test panel fabrication.

b. Roller Coating Face Sheets. The panel fabrication process developed by MSFC employs a face sheet adhesive coating method wherein an adhesive layer weighing approximately 0.02 psf is applied to the face sheet. To simulate this bonding method, roller coating the face sheets with polyurethane adhesive was investigated. It was determined that two passes of the coated spongy foam roller would deposit the required amount of adhesive. This method was then used in fabricating test panels.

5. Cure Cycle

Tests have indicated that crushing of the Mylar core will result if cure temperatures of 275°F or higher are used in processing and with assembly cure pressures greater than 5 psi. Therefore, it was decided to limit the pressure to 1 - 3 psi.

Pressure was obtained by using weights, a vacuum bag with controlled vacuum pressure, or an autoclave. Test samples were fabricated using room temperature and/or elevated temperature cures. While it appears possible to develop sufficient strength in bond at room temperature over several days, it is more practical in production to use a faster elevated temperature cure, such as 160°F, which also gives higher bond strength (see test data, Section V).

6. Panel Joints

Some work was done on the panel joints, mainly in connection with the LH_2 test tank installation. On the vibration tank, shown in Figure 12A, the gap between the panels was open, giving no support to the aluminum foil. During the filling operation, the tank contracted and the foil wrinkled. After several cycles, the foil cracked at the wrinkles. Several materials and methods were investigated. It was found that Mylar-aluminum-Mylar (MAM) does not fatigue crack like aluminum foil when wrinkled. Reinforcing the MAM with stretched nylon (see Figure 12D) reduced its tendency to wrinkle. The use of polyurethane foam filler

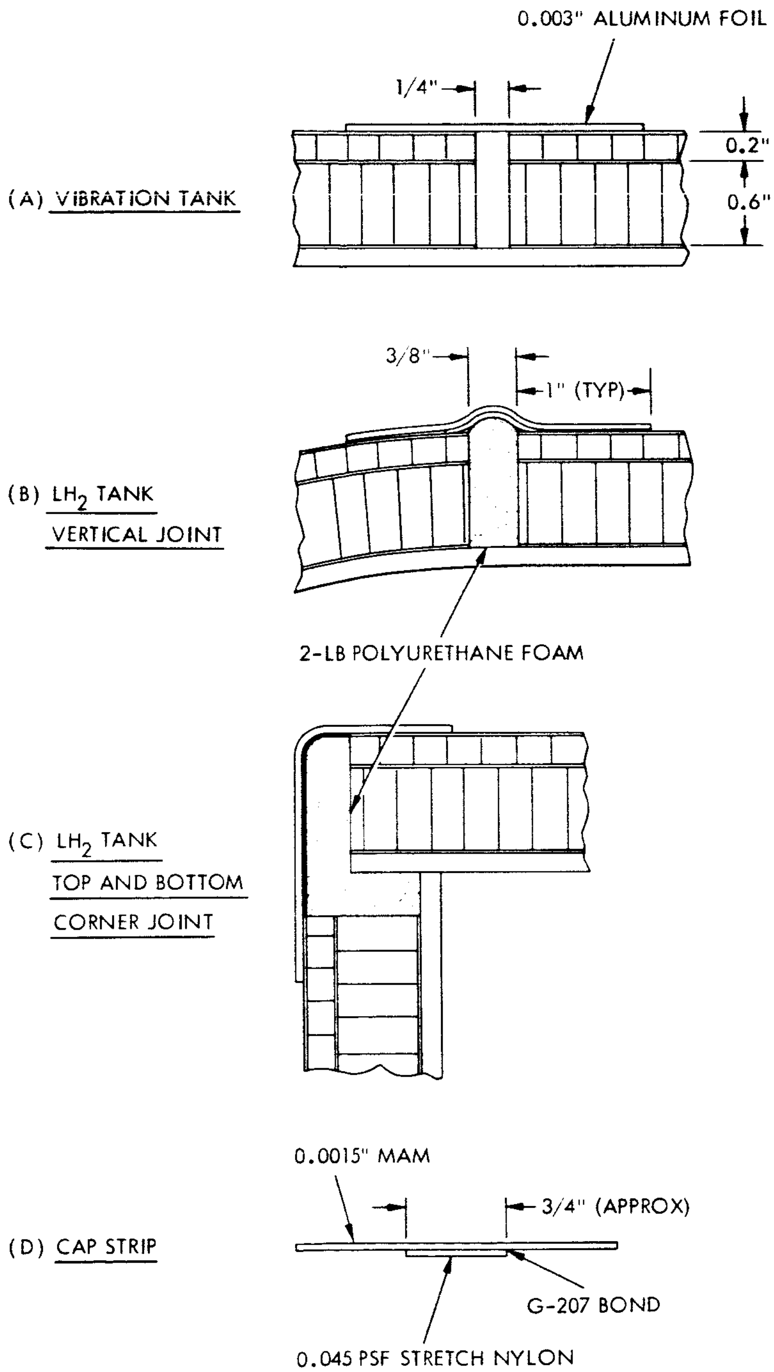


Figure 12. Panel Joints

prevented reverse wrinkling. Figure 12B shows the raised foam filler. Tests run where the foam was flush with the surface also worked satisfactorily. LH_2 tank test No. 1 had raised foam joints (see Figure 12B), and LH_2 tank test No. 2 had flush joints. Neither showed any indication of degradation during testing.

B. PROCESSING METHODS FOR INDIVIDUAL TEST PANELS

The processing methods for the individual test panels are discussed in the following paragraphs.

1. Calorimeter Panel No. 1

This panel was fabricated as shown in Figure 9. The aluminum face sheets were not primed, and HT-424 adhesive film was used in bonding the foils to HRP core. The Mylar core and film were primed with G-207 adhesive. The cure cycles were the same as for the final fabrication process (see page 41), except that a weighted plate was used instead of a vacuum bag to obtain pressure. This panel used 0.4-inch-thick Mylar core.

2. Calorimeter Panel No. 2

This panel was similar to the final fabrication process (page 41) except that the HRP core was roller coated with HT-424F adhesive for bonding to both aluminum face sheets. The panel was satisfactory; however, the HT-424F adhesive is difficult to apply. On larger panels, maintaining even distribution and adequate fillets could be a problem. This panel used 0.6-inch-thick Mylar core.

3. Calorimeter Panel No. 3

This panel was fabricated the same as panel No. 1 except that the Mylar core sealed cells were filled with CO_2 instead of air. This was accomplished using a pressure bag, alternately filling with CO_2, then evacuating until the air was purged out of the cells.

4. Calorimeter Panel No. 4

This panel was fabricated in accordance with the final fabrication process, (page 41), except that only the core, not the Mylar film, was roller coated with urethane. The panel was fabricated satisfactorily and the weight was reduced, but on larger panels there could be areas of insufficient fillets between the core and the skin.

5. Calorimeter Panel No. 5

This panel was fabricated in accordance with the final fabrication process (page 41).

6. Calorimeter Panel No. 6

An effort was made to improve the bond between the Mylar core and the center skin. The goal was to find a system that would be more flexible and more impervious to helium leakage than the AF-111 adhesive. An experimental adhesive system called G-208, a modification of G-207, was considered. Initial testing looked encouraging, and the adhesive was used on calorimeter panel No. 6. For this sample, the 0.0015-inch aluminum was replaced by MMA supplied by MFSC. The adhesive as formulated for this panel did not live up to expectations. It was decided that more basic formula study was required but that there was insufficient time to include it in this program.

7. Calorimeter Panel No. 7

This panel varied from the final fabrication process as follows. The center skin was 0.002-inch MAAM instead of 0.0015-inch aluminum. Both faces of MAAM were primed with G-207 adhesive. Polyurethane adhesive was used to bond Mylar core to the MAAM. This change in material required making three lay-ups instead of two. The lay-ups were made as follows:

Lay-Up No. 1. Assemble MAAM and Mylar core (roller coat with polyurethane for skin and core), then cure for 4 hours at 160°F under vacuum.

Lay-Up No. 2. Add HRP core and 0.003-inch aluminum outer skin to first lay-up, then bag and cure.

Lay-Up No. 3. Same as final fabrication process.

8. Vibration Panel No. 1

This panel was fabricated using 0.4-inch Mylar core, CO_2 purged. The process was the same as the process for calorimeter panel No. 3.

9. Vibration Panel No. 2

This panel was fabricated using 0.4-inch Mylar core, air filled. The adhesives and processing were the same as the final fabrication processing.

10. LH_2 Test No. 1 Panels

Both panel A and panel B were fabricated full size, in accordance with the final fabrication process. During the fabrication, a weight check was made to determine the amount of weight of the bond line component 8 where both the core and film were roller coated. The weight of component 10 bond line was also determined. The overall panel weighed 21 pounds, 5 ounces, and measured 94-7/8 x 73-3/4 inches. Based on this information, the following weight data was calculated:

Component	Wt/Sq Ft
1 - 9	0.4386 lb
8	0.0189 lb
10	0.0251 lb

11. LH_2 Test No. 2 Panels

These panels were fabricated at the same time and are identical with calorimeter panel No. 7. On the initial trial of this configuration, the outer sandwich, comprising the 0.003-inch aluminum skin, HRP core, and MAAM, was fabricated in the first lay-up. This caused dimpling in the MAAM, so that when bonding the Mylar core, the fillets between the MAAM and Mylar core were not sufficient to bridge the gaps and seal the cells. By reversing the operation and bonding the MAAM and Mylar core first, this problem was overcome. Panel A was a full size panel, but panel B was split in two along the horizontal centerline.

C. FINAL FABRICATION PROCEDURE

The procedure developed to produce the MSFC dual-seal insulation panel configuration (see Figure 13) is described in the following paragraphs. Various completed panels are shown in Figure 14. Figure 15 shows the panel on the male lay-up mold. Figure 16 shows the panel in the female cradle used during the core roller-coating operation.

(1) All materials must be clean prior to bonding. Wipe with methylethyl ketone and clean cloth.

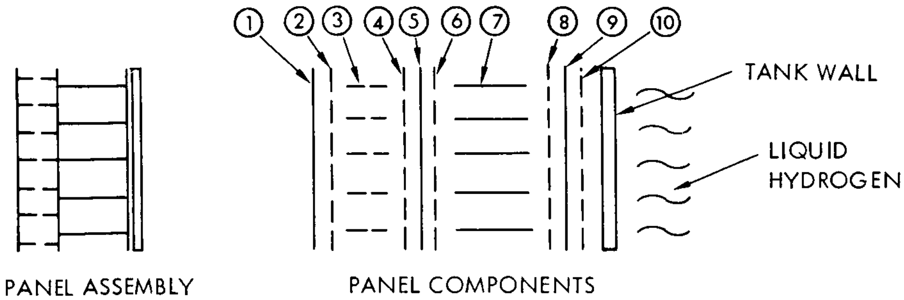
(2) Priming is accomplished as follows:

(a) To prime Mylar core, mount core on curtain stretcher type of frame. Using 10 percent solids solution of G-207 adhesive primer, apply a spray coat to each side, making certain to get complete coverage. Cure in oven for 6 hours at 200°F.

(b) To prime Mylar film, mount film in suitable "picture" frame. Apply spray coat of G-207 to both sides and cure as in step "a".

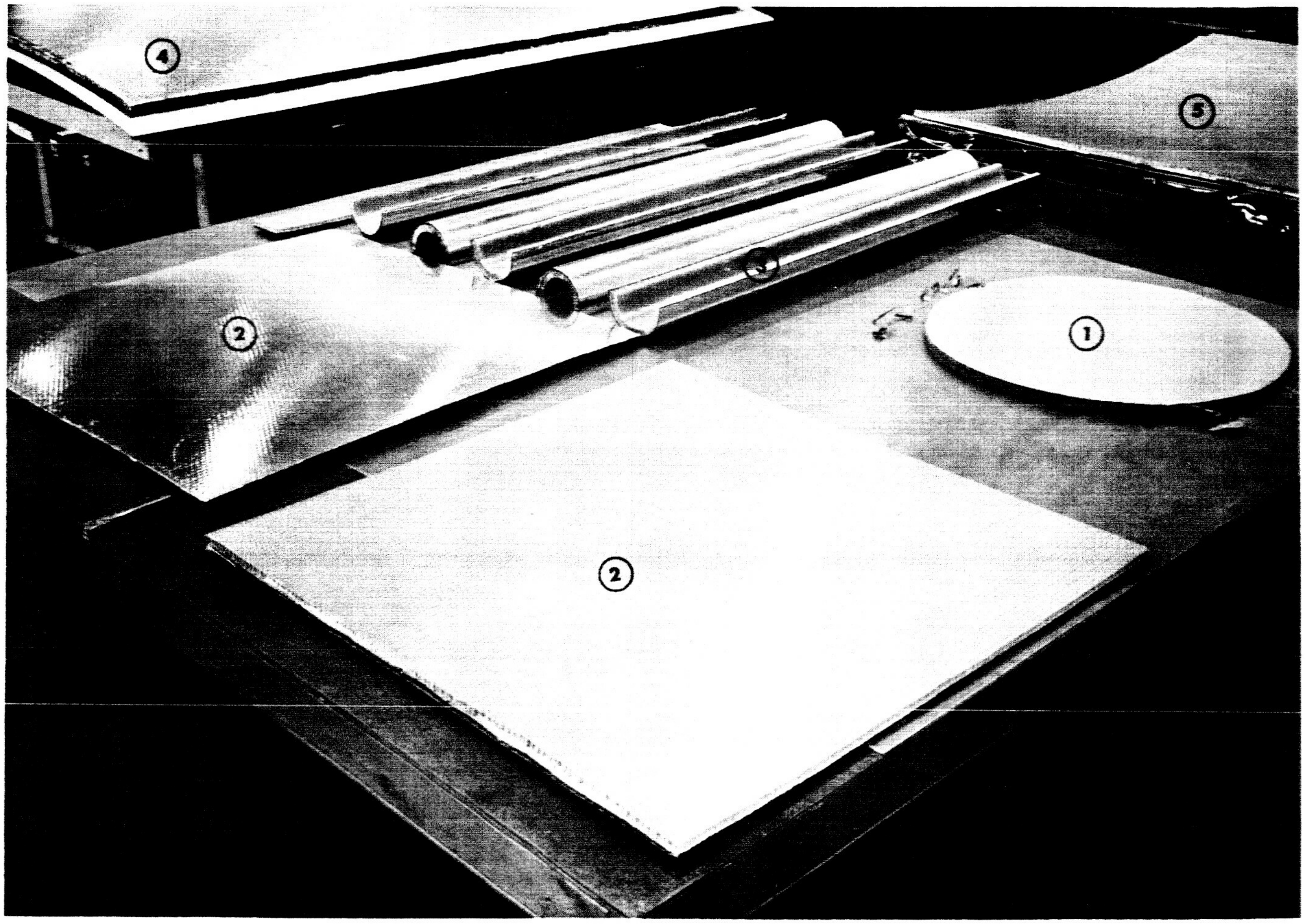
(c) To prime aluminum foil, mount in picture frame. Apply spray coat of HT-424 A/B primer. Cure in oven for 1 hour at 150°F after 0.5 hour minimum at room temperature. On 0.003-inch foil prime one side; on 0.00015-inch foil prime both sides.

(3) Make skin splices as shown in Figure 17A.



Components	Description - Material
(1) Hot Face	0.003 inch aluminum foil. Prime with HT-424 A/B.
(2) Bond Line	Hot Face to HRP core. 3M, AF-111 adhesive.
(3) HRP Core	Perforated honeycomb core. 3/8 inch cell size, 0.20 inch thick.
(4) Bond Line	HRP core to inner face. 3M, AF-111 adhesive.
(5) Inner Face	0.0015 inch aluminum foil. Prime with HT-424 A/B.
(6) Bond Line	Inner face to Mylar honeycomb core. 3M, AF-111 adhesive.
(7) Mylar Honeycomb Core	3/8 inch cell size, 0.60 inch thick 0.003 inch Mylar. Prime with G-207.
(8) Bond Line	Mylar honeycomb core to cold face. Narmco 7343/7139 adhesive or DuPont Adiprene L100/ Moca. Both mixed to 100/12.5 parts by weight.
(9) Cold Face	0.002 Mylar. Prime with G-207.
(10) Tank Cold Face Bond Line	Cold face to tank wall. Narmco 7343/7139 adhesive or DuPont Adiprene L100/Moca adhesive. Both mixed to 100/12.5 parts by weight.

Figure 13. MFSC Dual-Seal Panel Configuration



1. CALORIMETER PANEL
2. VIBRATION TEST PANEL
3. LH_2 TANK RADIUS INSULATION
4. LH_2 TANK TEST PANEL ON MALE MOLD
5. LH_2 TANK TEST PANEL IN FEMALE CRADLE

Figure 14. Radius Insulation, Vibration Test Panels, and Calorimeter Panel

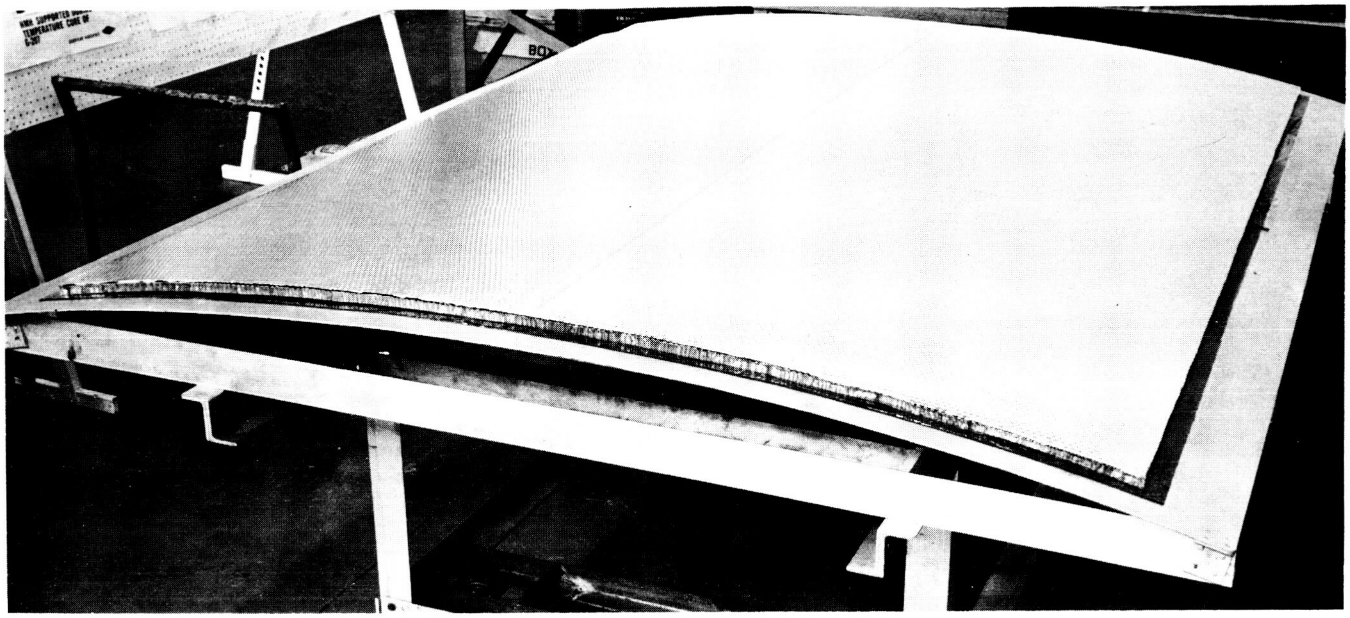


Figure 15. Male Mold Used To Lay Up Panel

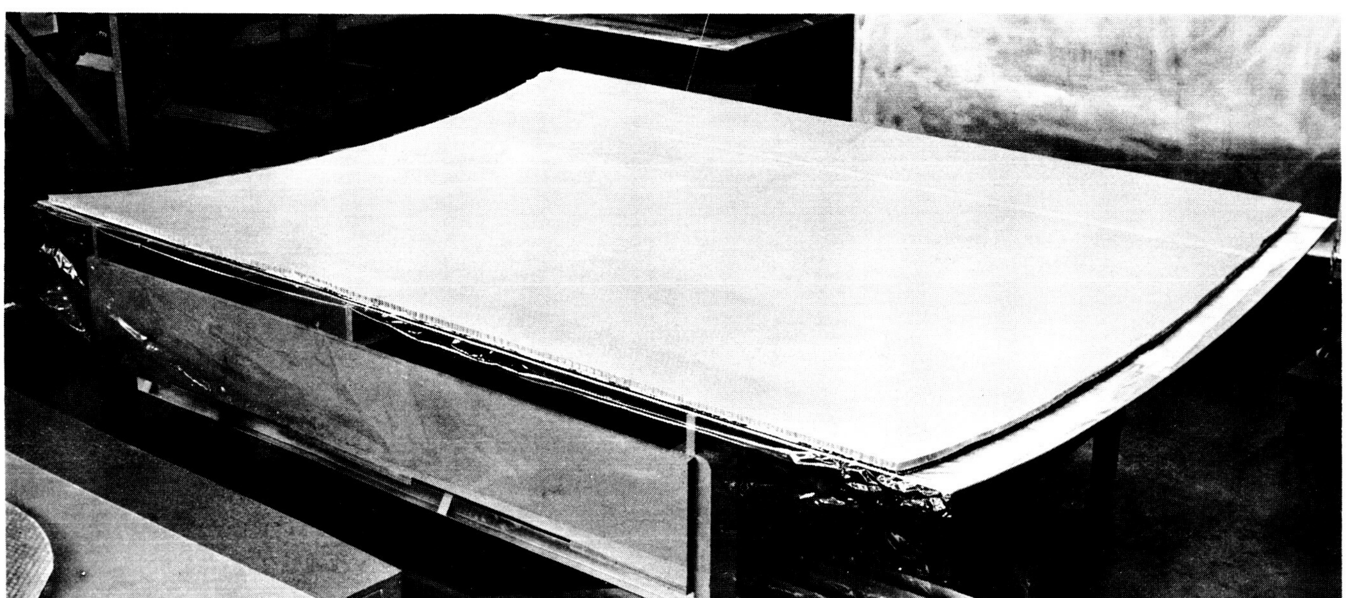


Figure 16. Panel in Cradle Used To Roller Coat Core and Used in Assembly of Panels to Tank

(4) Make Mylar core joint splice as shown in Figure 17B.

(5) Clean the mold and cover with FEP film.

(6) The first sandwich lay-up is accomplished as follows:

(a) Position Mylar core (preprimed and jointed) on mold.

(b) Apply layer of AF-111 adhesive film.

(c) Place 0.0015-inch aluminum film (preprimed and spliced) over adhesive; smooth out all wrinkles.

(d) Add another layer of AF-111 adhesive film.

(e) Position HRP core, butt splicing the sections.

(f) Cover with layer of AF-111 adhesive film.

(g) Lay down 0.003-inch aluminum foil with primed face toward adhesive.

(h) Cover lay-up with FEP film, a bleeder ply such as TG-30, and a PVA vacuum bag.

(i) Use a vacuum pressure of 2 to 3 psi and cure in oven for 6 hours at 250°F.

(7) The second sandwich lay-up is accomplished as follows:

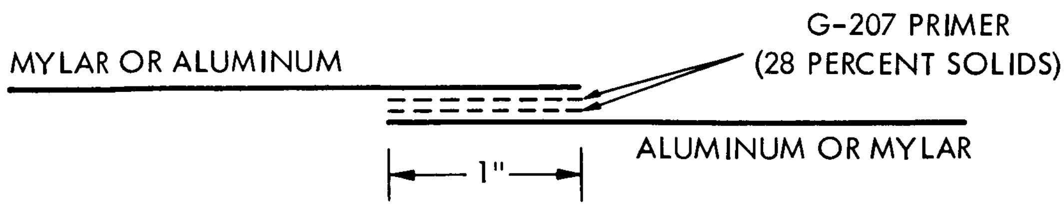
(a) Remove first lay-up from mold and inspect.

(b) Cover mold surface with thin sheet of rubber and FEP film.

(c) Lay down (preprimed and spliced) Mylar sheet and apply roller coat of polyurethane adhesive per Table 4.

(d) Place lay-up No. 1 in cradle and apply roller coat of polyurethane adhesive to Mylar core per Table 4.

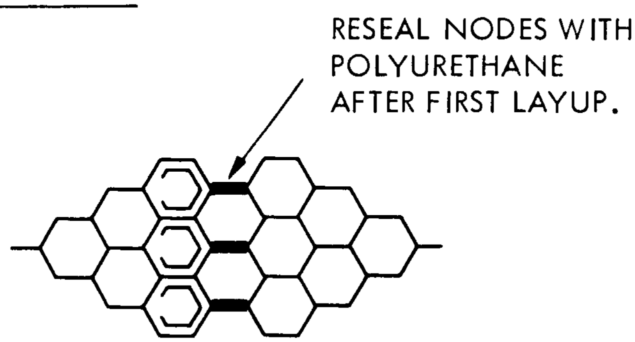
(A) ALUMINUM OR MYLAR FOIL JOINTS



IRON JOINT WITH IRON AT 300 (± 20)°F.

LET G-207 AIR DRY TO TACK-FREE CONDITION (15 - 20 MIN) TO OBTAIN SOLVENT-FREE ADHESIVE.

(B) MYLAR HONEYCOMB JOINT



NODE BOND MUST BE SPLIT TO INTERMESH THE HONEYCOMB.

Figure 17. Aluminum or Mylar Foil Joints and Mylar Honeycomb Joints

Table 4. Polyurethane Adhesive - Roller Application

1. Spread adhesive out on flat table covered with cellophane.

2. Saturate foam roller with adhesive by rolling back and forth in adhesive, until a uniform coverage is visually evident.

3. Roll adhesive on face sheet.
   a. Tape face sheet down to table.
   b. Roll across and back on face sheet with saturated roller.
   c. Resaturate roller.
   d. Roll across and back on face sheet at 90-degree direction to that in step 3(b).
   e. Visually check for uniformity of adhesive application.
   f. Reroll where required.

4. Roll adhesive on Mylar honeycomb core.
   a. Saturate roller.
   b. Roll across core in one direction.
   c. Resaturate roller.
   d. Roll across core at 90 degrees to that of step 4(b).
   e. Visually check for uniformity of adhesive application.
   f. Reroll where required.

Approximate Weight

(1) .020 - .030 lb/sq ft of adhesive on face sheet.

(2) .010 - .015 lb/sq ft of adhesive on core.

(e) Position coated core face on top of coated skin.

(f) Cover with FEP film, a bleeder ply, and a PVA vacuum bag.

(g) Cure in autoclave under positive pressure of 2 to 3 psi (bag vented to atmosphere) for 12 hours at 80 to 100°F plus 24 hours at 160°F.

(h) Remove from mold, trim to size, and inspect.

(8) The following procedure is used to bond the insulation panel to the tank:

(a) Clean tank surface. Prime with spray coat of G-207, and cure for 6 hours at 200^{o}F.

(b) Apply roller coat of polyurethane adhesive to tank surface and to Mylar skin of panel per Table 4.

(c) Position panel on tank, and cover with bleeder ply and vacuum bag.

(d) Cure under full vacuum at 160^{o}F for 12 hours.

(9) Splice the panel joints as follows:

(a) Cut foam strips to fit and insert in gap between panels as shown in Figure 12. This may be done at same time panels are bonded to tank.

(b) Prepare cap strips. Bond stretch nylon to 0.0015-inch MAM (pre-primed) as shown in Figure 12D, using G-207 (28 percent) adhesive and heat seal with iron.

(c) Coat face of cap strip and edge of panel with G-207 (28 percent). Allow to air dry. Position cap strip and seal with a 300^{o}F iron over a Dacron cloth.

SECTION V. MECHANICAL PROPERTIES TESTS

A. TEST METHODS AND SETUP

The mechanical property tests that were performed on candidate insulation panel components are discussed in the following paragraphs.

1. Flatwise Compression

The flatwise compression tests were conducted in a compression cage test fixture (Figure 18) in accordance with ASTM test C-365-57 and Method 5.1.3 of MIL STD 401. These tests provided stress-strain data for the composite materials across their thickness.

2. Edgewise Compression

The edgewise compression tests were also conducted in a compression cage test fixture (Figure 19) in accordance with ASTM test C-364-57 and Method 5.1.2 of MIL STD 401. The edges of the test specimens (Figure 20) were reinforced to eliminate localized failure of the skin materials. These tests provided stress-strain data as well as the buckling strength of the skin materials. For the honeycomb materials, the load was applied to the specimen in the direction parallel to the ribbon of the core.

3. Flatwise Tensile

The flatwise tensile tests were conducted as shown in Figure 21(A) to determine the tensile bond strength between the skin and core. The test specimens were bonded to metal blocks to provide uniform load distribution across the skin surfaces (see Figures 21 and 22). Face sheet to tank wall tests were made as shown in Figure 21(B) in accordance with ASTM test C-297-55 and

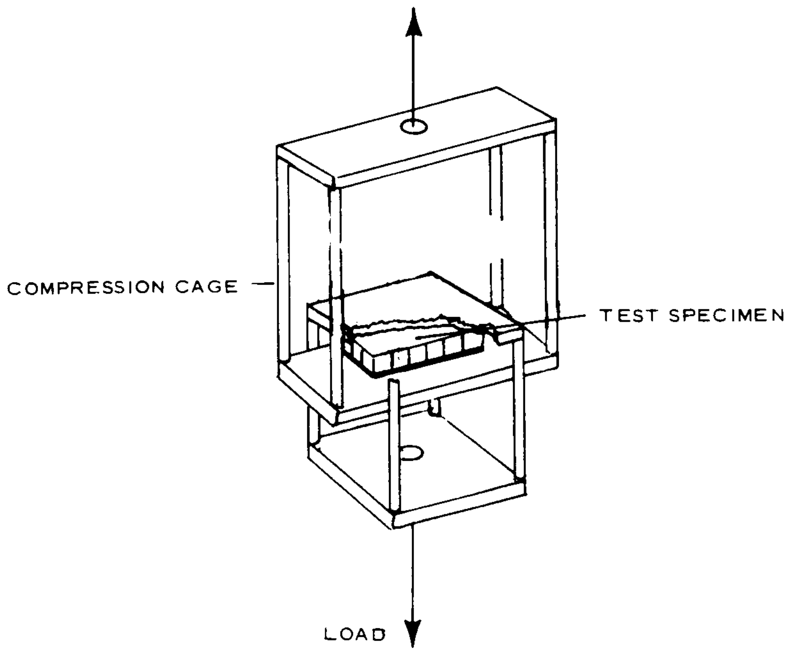


Figure 18. Flatwise Compression Test

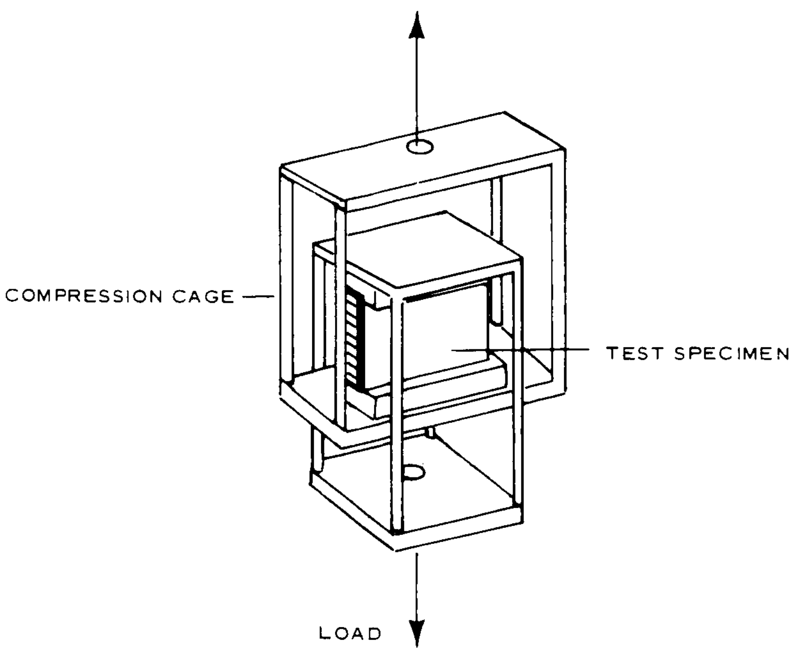


Figure 19. Edgewise Compression Test

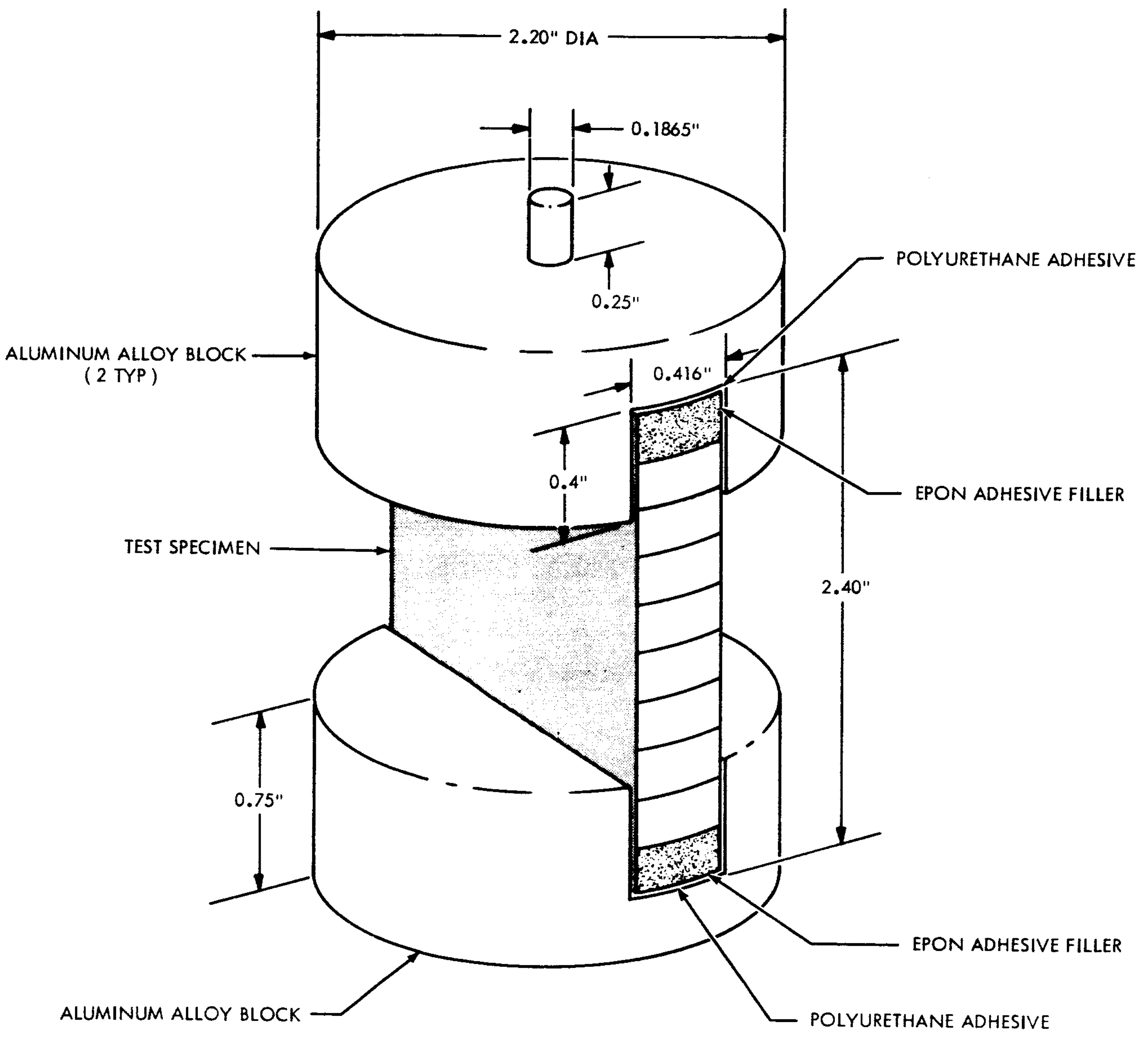


Figure 20. Edgewise Compression Test Specimen

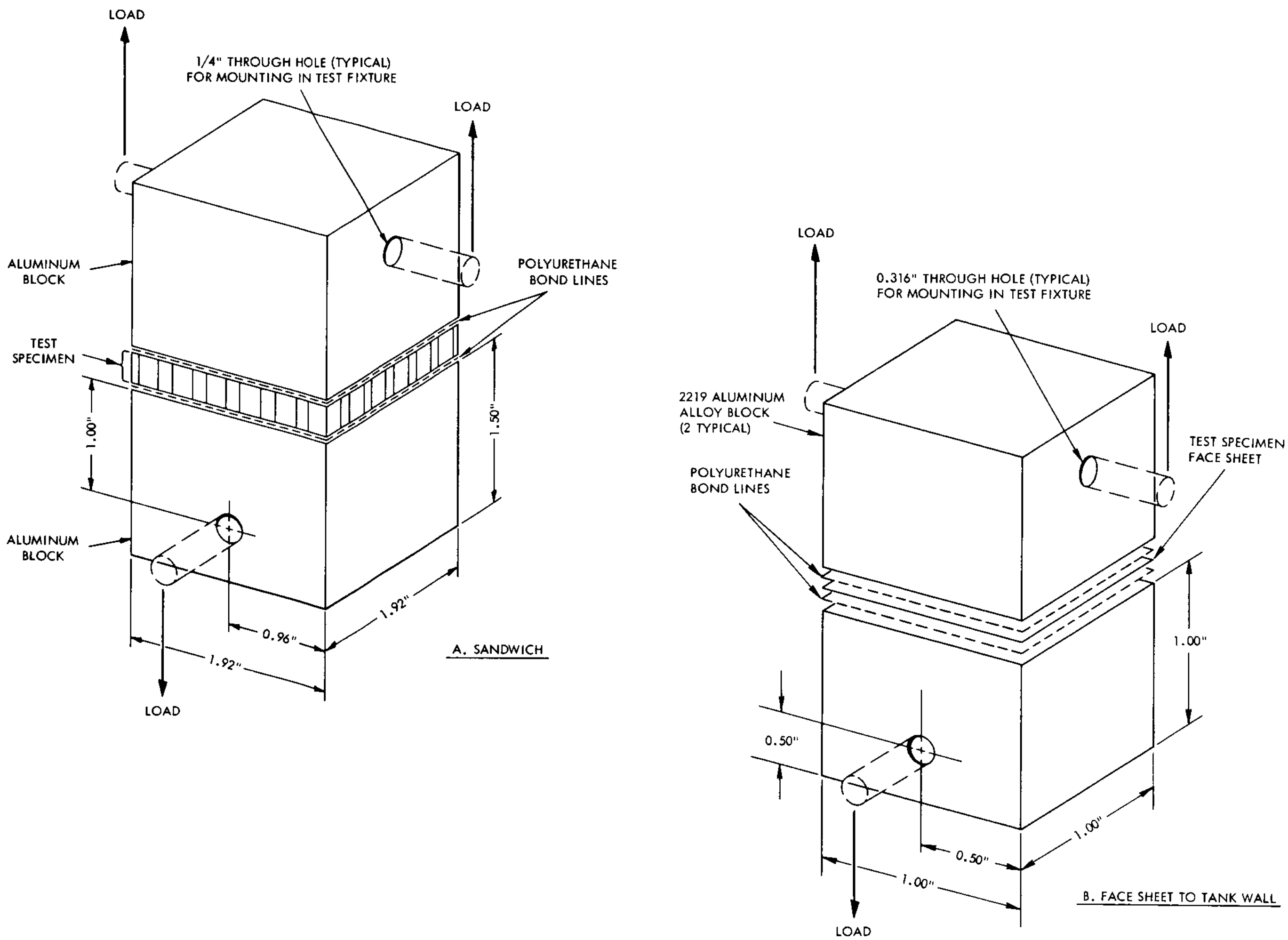


Figure 21. Flatwise Tensile Tests

Method 5.2 of MIL STD 401. Figure 23 shows the setup in the Baldwin testing machine using special adapter yokes.

4. Panel Shear

Panel shear tests were conducted as shown in Figure 24. These tests provided data for evaluation of the shear strength of the composite materials as well as bond strength of the core to skin. The method of testing differs from ASTM or MIL Specifications in that a symmetrical specimen comprised of two pieces of composite material was used.

B. COLD FACE ADHESIVE SCREENING TESTS

Flatwise tensile tests were conducted in an effort to perfect an optimum method of processing the polyurethane adhesive close-out bond between the Mylar core and face sheet. Processing parameters included Mylar pretreatments, different cure cycles, and several adhesive weights. The tests presented in Table 5 were conducted at room temperature (75^{o}F) and liquid nitrogen temperature (-320^{o}F) using the test method described in paragraph A.

On the basis of the data presented in Table 5 and the comparison shown in Figure 25, pretreatment of the core and face sheet tends to substantially improve the polyurethane bond between the core and face sheet materials. Of the two types of Mylar pretreatments investigated, surface priming enhanced the polyurethane adhesive tensile bond strengths by a factor greater than 5 over that obtained with untreated materials.

The longer elevated cure cycle recommended by MSFC was shown to produce the highest strength bonds.

Application of the adhesive to the core as compared to its application to the face sheet produced the higher strength bonds.

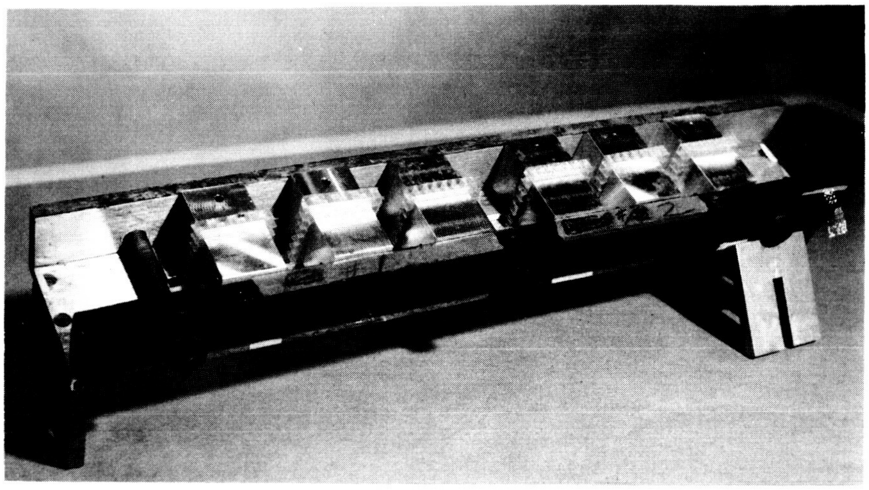


Figure 22. Flatwise Tensile Specimen Bonding Fixture

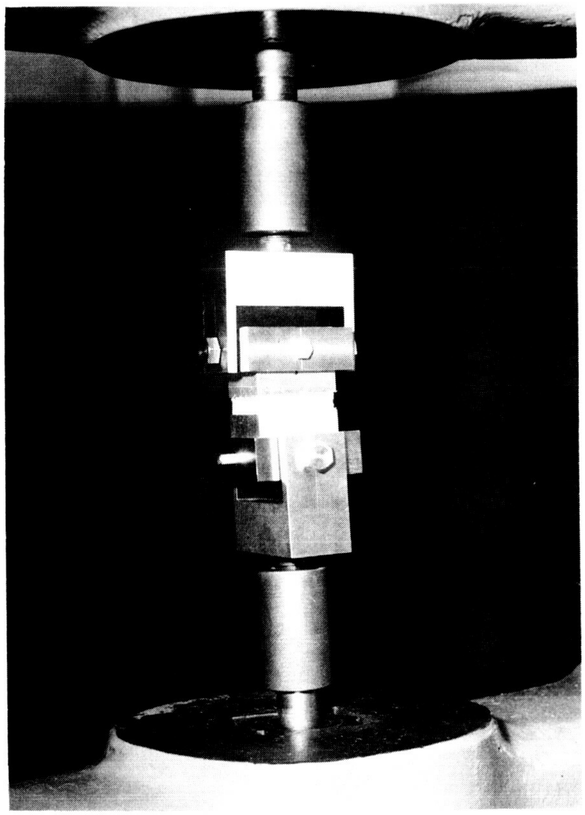


Figure 23. Flatwise Tensile Specimen in Test Fixture

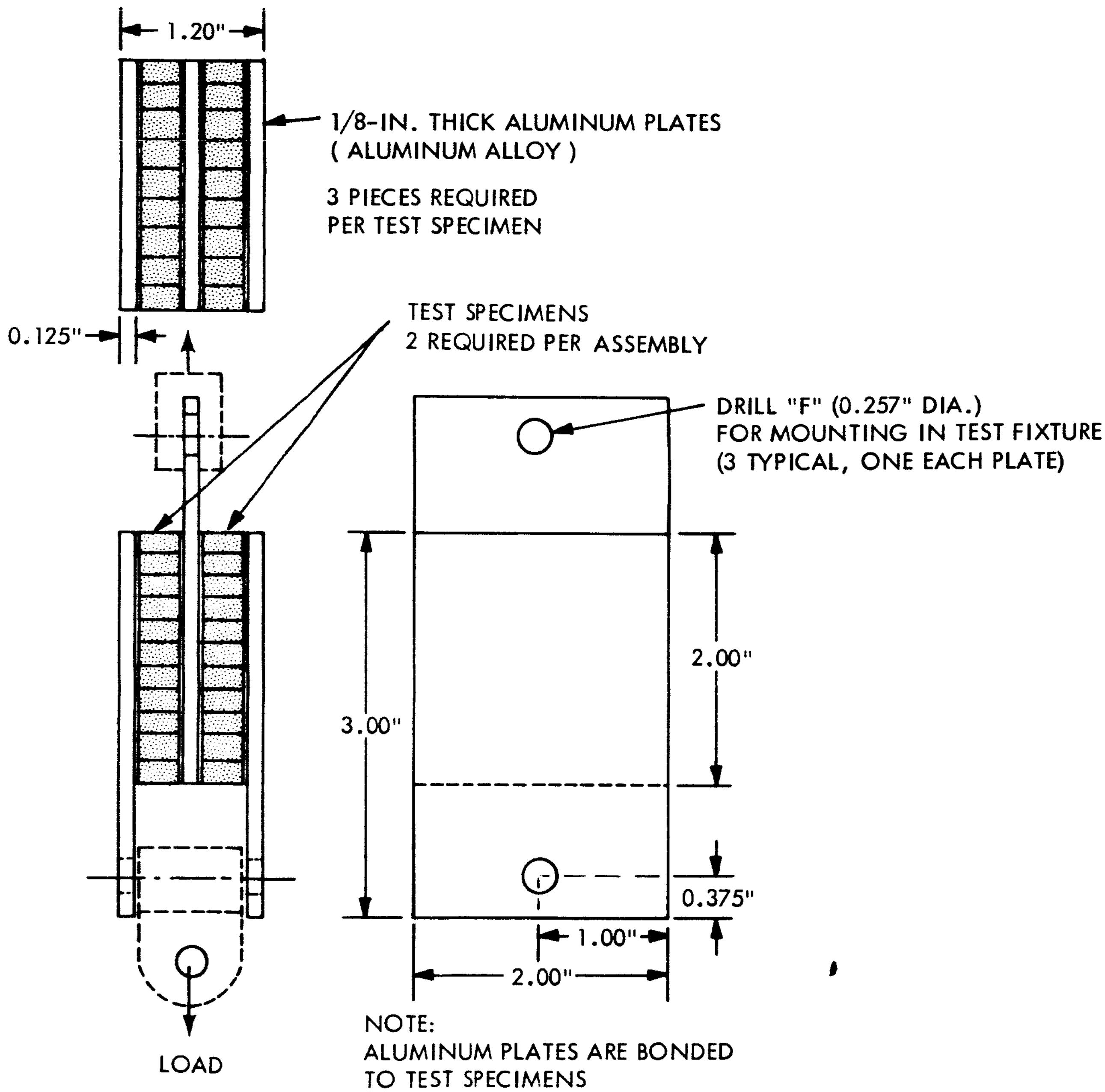


Figure 24. Panel Shear Test

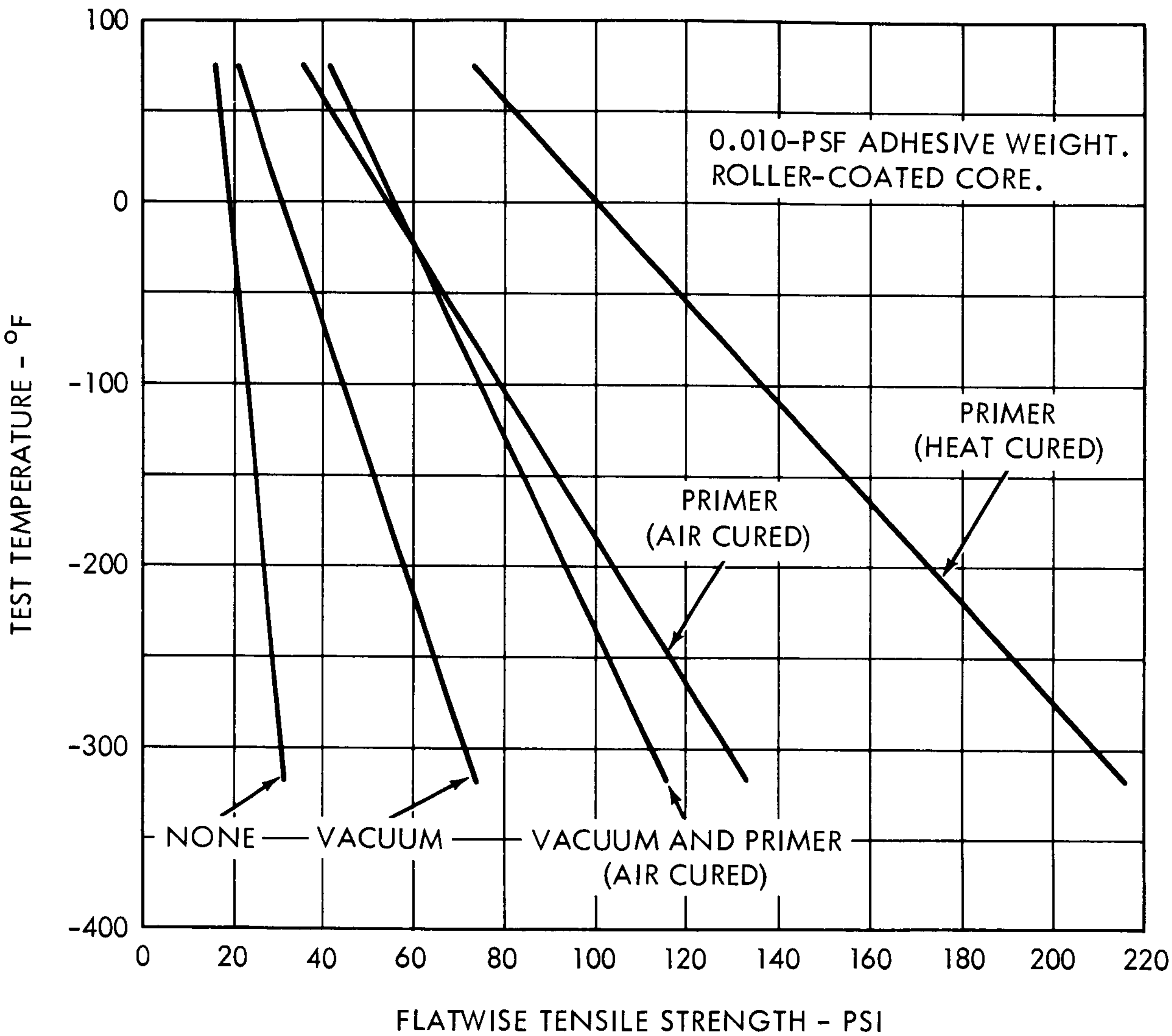


Figure 25. Cold Face Adhesive Tests for Various Mylar Pretreatments

Table 5. Cold Face Adhesive Screening Test Results
Mylar Film and Mylar Core

Polyurethane Adhesive Application(1)	Mylar Pretreatment	Cure Cycle (A) 48 hr at RT & 24 hr at 160°F (B) 24 hr at 160°F (C) 4 hr at 160°F	Flatwise Tensile Strength 75°F Specimen No.	75°F psi	75°F Avg psi	(LN$_2$) -320°F Specimen No.	-320°F psi	-320°F Avg psi
Roller Coated Core (Adhesive Wt - 0.010 psf)	None	A	25 26 27	9 14 20	14	28 29 30	34 30 34	33
	Exposed to Vacuum(2)	A	31 32 33	29 19 16	21	34 35 36	57 86 79	74
	Primed(3)	C	37 38 39	27 32 26	28	40 41 42	193 119 137	150
		B	43 44 45	37 34 36	36	46 47 48	143 124 133	133
		A	49 50 51	28 38 43	36	52 53 54	125 158 132	138
	Exposed to Vacuum(2) and Primed(3)	C	55 56 57	36 37 37	37	58 59 60	193 96 144	144
		B	61 62 63	42 37 44	41	64 65 66	113 97 113	108
		A	67 68 69	39 43 42	41	70 71 72	129 112 131	124
	Primed(3) & Heat Set at 250°F (1 hr)	B	171 172 173	68 83 69	73	174 175 176	240 182 228	217

(1) Resin Formulation: Narmco 7343 100 parts by weight and Narmco 7139 12.5 parts by weight.
(2) Mylar cores and face sheets placed in bell jar under vacuum of 2 x 10^{-5} mm of Hg for 36 hr.
(3) Core sprayed and face sheet brushed with G-207 10 percent solids and given a 4-hour air dry.

Table 5. Cold Face Adhesive Screening Test Results Mylar Film and Mylar Core (Continued)

Polyurethane Adhesive Application(1)	Mylar Pretreatment	Cure Cycle (A) 48 hr at RT & 24 hr at 160°F (B) 24 hr at 160°F (C) 4 hr at 160°F	Flatwise Tensile Strength 75°F Specimen No.	75°F psi	75°F Avg psi	(LN_2) -320°F Specimen No.	-320°F psi	-320°F Avg psi
Roller Coated Core (Adhesive Wt - 0.020 psf)	Primed (3) & Heat Set at 200°F (2 hr)	B	207 208 209 210 211 212	80 81 90 95 76 83	84			
		C and B(4)	225 226 227 228 229 230	78 84 83 79 82 95	84			
	Primed(3) & Heat Set at 200°F (6 hr)	B	216 217 218 219 220	95 116 91 94 78	95			
		C and B(4)	234 235 236 237 238 239	90 102 95 87 100 79	92			
Roller Coated Face Sheet (Adhesive Wt - 0.020 psf)	None	A	1 2 3	20 34 16	23	4 5 6	69 39 52	53
	Primed(3)	C	7 8 9	46 48 45	46	10 11 12	102 143 112	119
		C	117 118 119	43 53 50	49	120 121 122	104 105 93	101

(1) Resin Formulation: Narmco 7343 100 parts by weight and Narmco 7139 12.5 parts by weight.
(3) Core sprayed and face sheet brushed with G-207 10 percent solids and given a 4-hour air dry.
(4) Initial face sheet to core made with cure cycle C, and opposite face sheet to core made with cure cycle B.

Table 5. Cold Face Adhesive Screening Test Results Mylar Film and Mylar Core (Continued)

Polyurethane Adhesive Application(1)	Mylar Pretreatment	Cure Cycle (A) 48 hr at RT & 24 hr at 160°F (B) 24 hr at 160°F (C) 4 hr at 160°F	Flatwise Tensile Strength 75°F Specimen No.	75°F psi	75°F Avg psi	(LN$_2$) -320°F Specimen No.	(LN$_2$) -320°F psi	(LN$_2$) -320°F Avg psi
Roller Coated Face Sheet (Adhesive Wt - 0.020 psf)	Primed(3)	B	13 14 15	59 15 58	59	16 17 18	161 174 136	157
		B	123 124 125	52 58 54	55	126 127 128	149 198 197	181
		A	19 20 21	59 64 58	60	22 23 24	164 152 164	160
		A	129 130 131	51 45 54	50	132 133 134	183 149 209	180
	Primed(3) & Heat Set at 250°F (1 hr)	B	147 148 149	61 67 62	63	150 151 152	185 147 189	174
		B	153 154 155	70 42 68	60	156 157 158	233 217 187	212
		B	159 160 161	60 64 53	59	162 163 164	160 181 169	170
Core Dipped (Adhesive Wt 0.060 psf)	None	A	189 190 191	88 92 84	88	192 193 194	204 194 163	187
	Primed(3) & Heat Set at 250°F (1 hr)	A	183 184 185	137 132 136	132	186 187 188	311 316 322	316

(1) Resin Formulation: Narmco 7343 100 parts by weight and Narmco 7139 12.5 parts by weight.
(3) Core sprayed and face sheet brushed with G-207 10 percent solids and given a 4-hour air dry.

Table 5. Cold Face Adhesive Screening Test Results
Mylar Film and Mylar Core (Continued)

Polyurethane Adhesive Application(1)	Mylar Pretreatment	Cure Cycle (A) 48 hr at RT & 24 hr at 160°F (B) 24 hr at 160°F (C) 4 hr at 160°F	Flatwise Tensile Strength					
			75°F			(LN_2) -320°F		
			Specimen No.	psi	Avg psi	Specimen No.	psi	Avg psi
Roller Coated Core & Face Sheet (Adhesive Wt 0.060 psf)	None	A	195 196 197	82 72 81	78	198 199 200	284 265 218	256
	Primed(3) & Heat Set at 250°F (1 hr)	A	201 202 203	111 105 89	102	204 205 206	333 350 305	329
MSFC Specimen (Adhesive Wt 0.060 psf)	None	A	MSFC specimen	65 72 81	67			

(1) Resin Formulation: Narmco 7343 100 parts by weight and Narmco 7139 12.5 parts by weight.
(3) Core sprayed and face sheet brushed with G-207 10 percent solids and given a 4-hour air dry.

C. MYLAR HONEYCOMB SANDWICH TESTS

A 36 x 36 inch test panel was fabricated comprised of 2-mil Mylar skins and 0.4-inch-thick Mylar honeycomb core. Mylar skins and core were primed with G-207 and bonded with polyurethane adhesive (roller coat both skins and core), in accordance with processing, Section IV-C. Samples were prepared and tested as described in paragraph A of this section. Test results are summarized in Table 6.

D. FACE SHEET TO TANK WALL BOND TESTS

To test the adhesive bond strength between the insulation panel and the tank wall, Mylar face sheet specimens were prepared, bonded to a simulated tank surface, and tested in flatwise tension.

A series of specimens was run to check variations in primer cure, using a standard cure of two days minimum at room temperature on polyurethane

Table 6. Mylar Honeycomb Sandwich Test Results

Type of Test	TEST TEMPERATURES							
	+75°F		-100°F		-320°F		-423°F	
	No.	PSI	No.	PSI	No.	PSI	No.	PSI
Flatwise Tensile Test	1 2 3 avg	113 107 116 112	1 2 3 avg		1 2 3 avg	371 349 328 350	1 2 3 avg	331 274 - 303
Flatwise Compression Test	1 2 3 avg	92 95 105 97	1 2 3 avg	138 123 138 133	1 2 3 avg	205 143 178 175	1 2 3 avg	195 191 177 188
Edgewise Compression Test	1 2 3 avg	3220 5000 3660 3960	1 2 3 avg	9050 8280 9600 8930	1 2 3 avg	16, 550 9, 590 13, 100 13, 100	1 2 3 avg	9, 700 9, 350 21, 100 13, 383
Panel Shear Test in Longitudinal Direction	1 2 3 avg	75 80. 1 75. 1 76. 7	1 2 3 avg	89. 4 123. 5 137. 5 116. 8	1 2 3 avg	174 170 155 166	1 2 3 avg	144 145 167 152
Panel Shear Test in Transverse Direction			1 2 3 avg	58. 4 62. 5 62. 0 63. 0	1 2 3 avg	70 59 68 66	1 2 3 avg	69 70 - 70

adhesive. Specimens included no primer, 4 hours at room temperature, 6 hours at 200°F, and 12 hours at 150°F cures. The data given in Table 7 indicates that the elevated temperature cure is superior.

Using a primer cure of six hours at 200°F, a series of specimens was run to check the length of time required for optimum room temperature cure. The

Table 7. Face Sheet to Tank Wall Test Results
Variation in Primer Cure

Primer cure	Test Temperature (°F)					
	+75		-320		-423	
	No.	psi	No.	psi	No.	psi
No primer	A-1	--	--	--	--	--
	A-2	667	--	--	--	--
	A-3	428	--	--	--	--
	avg	544	--	--	--	--
4 hr at RT	B-4	1300	B-1	1953	--	--
	B-5	1340	B-2	1400	--	--
	B-6	1220	B-3	1760	--	--
	avg	1287	avg	1704	--	--
6 hr at 200°F	C-7	1740	A-1	2800	S6-1	2500
	C-8	1790	A-2	2810	S6-2	2250
	C-9	1800	A-3	2880	S6-3	2700
	avg	1770	avg	2830	avg	2483
12 hr at 150°F	C-4	1950	C-1	2570	S12-1	1850
	C-5	1900	C-2	2620	S12-2	2180
	C-6	1880	C-3	2090	--	--
	avg	1910	avg	2430	avg	2015

Note: Polyurethane adhesive was cured for two days minimum at room temperature.

data given in Table 8 indicates that a minimum cure of 2 days at room temperature is sufficient to obtain good strength properties.

A series of tests was run to determine the effect of time variation between the priming operation and bonding operation. The data is given in Table 9.

Table 8. Face Sheet to Tank Wall Bond Test Results
Variation in Adhesive Cure

Adhesive Cure	Specimen No.	PSI at Room Temp
2 days at RT	U2-1	1704
	U2-2	1686
	U2-3	1698
	avg	1696
7 days at RT	U7-1	1720
	U7-2	1880
	U7-3	1880
	avg	1827
14 days at RT	U14-1	1820
	U14-2	1920
	U14-3	1900
	avg	1880
28 days at RT	U28-1	1610
	U28-2	1680
	U28-3	1720
	avg	1670
56 days at RT	U56-1	1950
	U56-2	2010
	U56-3	1650
	avg	1870

Note: G-207 primer was cured for six hours at 200°F.

Table 9. Face Sheet to Tank Wall Bond Test Results
Variation in Time between Priming and Bonding

Time in Days between Priming and Bonding	Test Temperature (°F)			
	+75		-320	
	No.	psi	No.	psi
Same day	P-1	1850	PA-4	1728
	P-2	1680	PA-5	1973
	P-3	1790	PA-6	2152
	avg	1773	avg	1951
2 days	P2-1	1430	P2-4	1912
	P2-2	2000	P2-5	1800
	P2-3	1700	P2-6	--
	avg	1710	avg	1856
12 days	P3-1	1780	P3-4	1980
	P3-2	1530	P3-5	2040
	P3-3	1810	P3-6	1930
	avg	1707	avg	1983
16 days	P4-1	2120	P4-4	1920
	P4-2	1500	P4-5	1900
	P4-3	2000	P4-6	1800
	avg	1877	avg	1873
28 days	P5-1	1840	P5-4	2650
	P5-2	1840	P5-5	2025
	P5-3	--	P5-6	2300
	avg	1840	avg	2325

Notes: 1. G-207 primer was cured for six hours at 200°F.
2. Polyurethane adhesive was cured for 48 hours at room temp and for 24 hours at 160°F.

SECTION VI. VIBRATION TESTS

A. TANK AND TEST PANEL CONFIGURATION

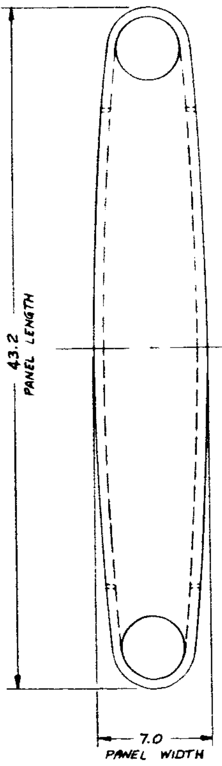
A wing-shaped vibration test tank (Figure 26) was fabricated of 2219 aluminum. The tank sides have a curvature of 16-1/2 foot radius.

Panel No. 1 was fabricated using 0.4-inch-thick, CO_2- purged Mylar core as described in Section IV-B. The outer and center aluminum foil skins were bonded to the HRP core with HT-424 film adhesive. Panel No. 2 was fabricated using 0.4-inch-thick, air-filled Mylar core. The outer and center aluminum foil skins were primed with HT-424 A/B primer and bonded to the cores with AF-111 film adhesive. The 30 x 30 inch test panels and the tank were primed with G-207 and cured for 6 hours at 200°F. Both tank surface and test panels were roller-coated with Adiprene L-100 adhesive. The panels were vacuum bagged at 3 psi to the tank, using a spot bag, and cured for 48 hours at room temperature, plus 24 hours at 160°F. Additional pieces of insulation were used to cover the rest of the tank as shown in Figures 27 and 28. Figure 28 shows the installation of one of the helium purge tubes and the aluminum foil cap strips. These were bonded to the skin using G-207 adhesive. The G-207 was applied to both surfaces and allowed to air dry. Then the two surfaces were ironed together, using a 300°F iron over a Dacron cloth.

Thermocouple leads were built into the panels to check internal temperatures, and thermocouple wires were bonded to the outside surface of the test panels. A coating of black epoxy paint was applied to facilitate panel heating.

B. TEST SETUP

The overall test setup including instrumentation is shown in Figure 29. The tank


43.2
PANEL LENGTH
7.0
PANEL WIDTH

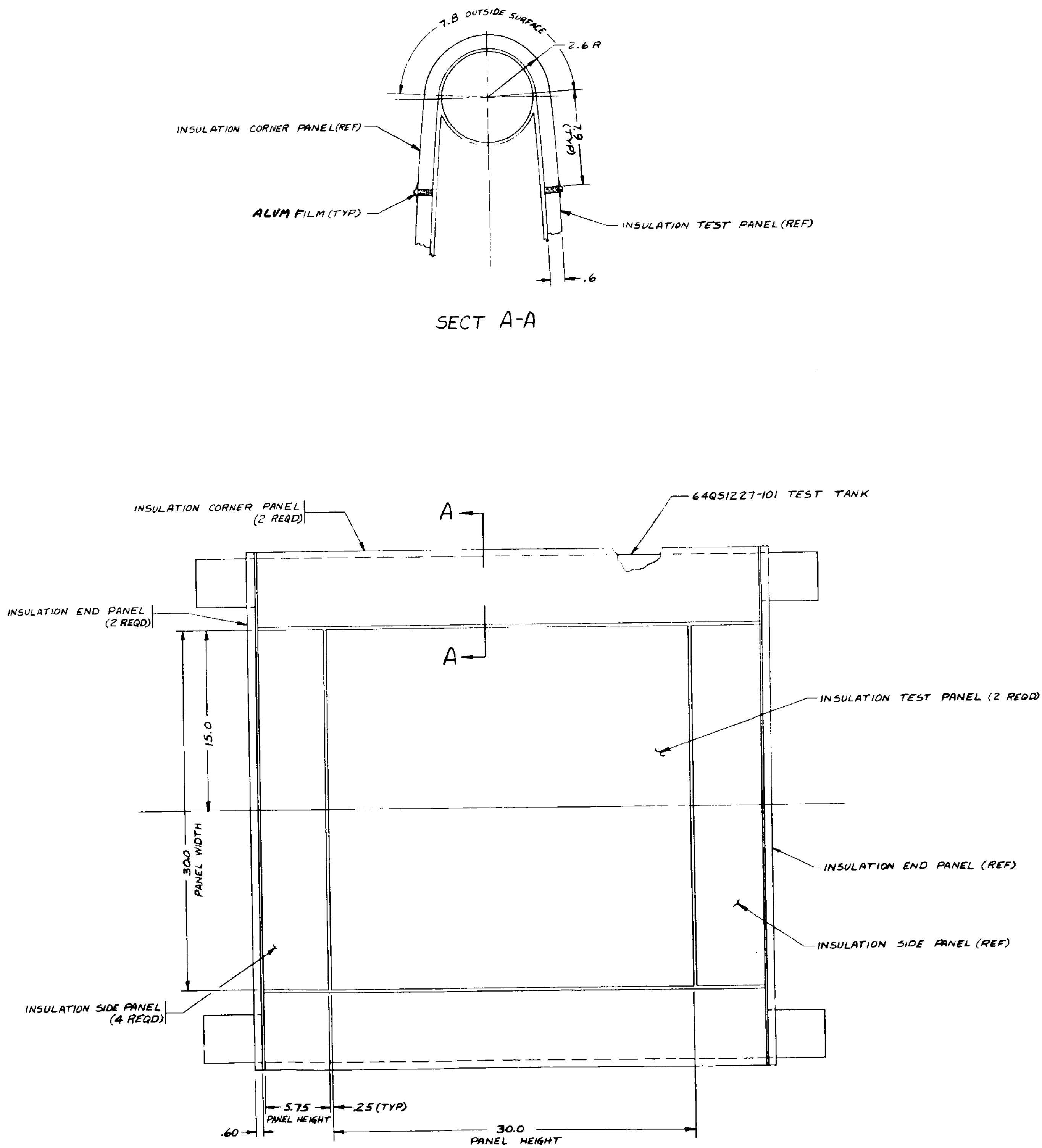


Figure 26. Vibration Tank and Insulation Test Panels

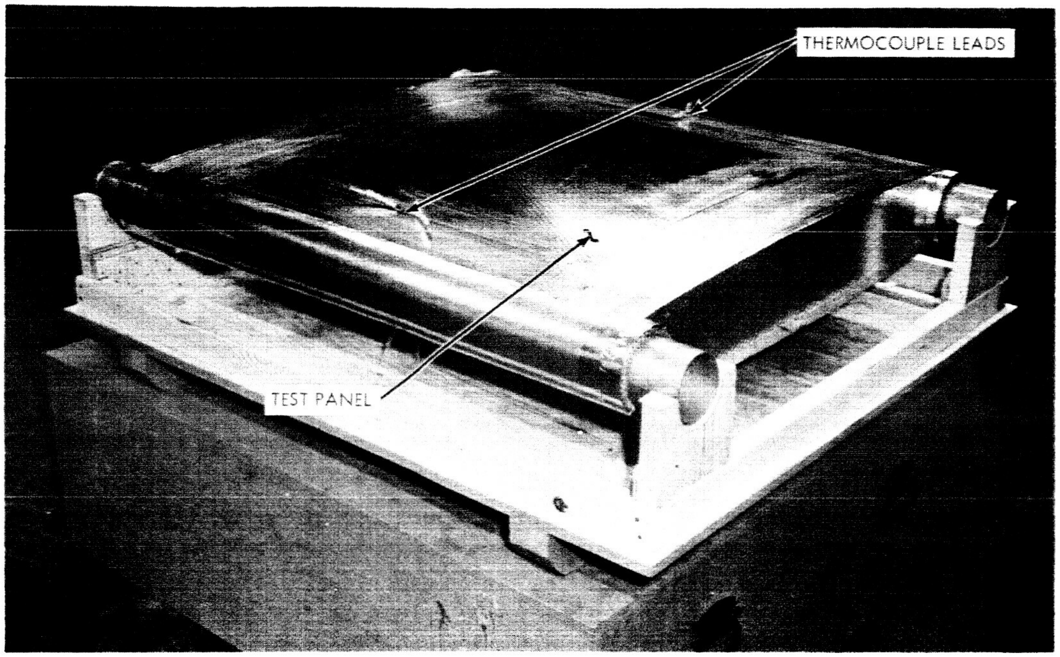


Figure 27. Vibration Tank Insulation

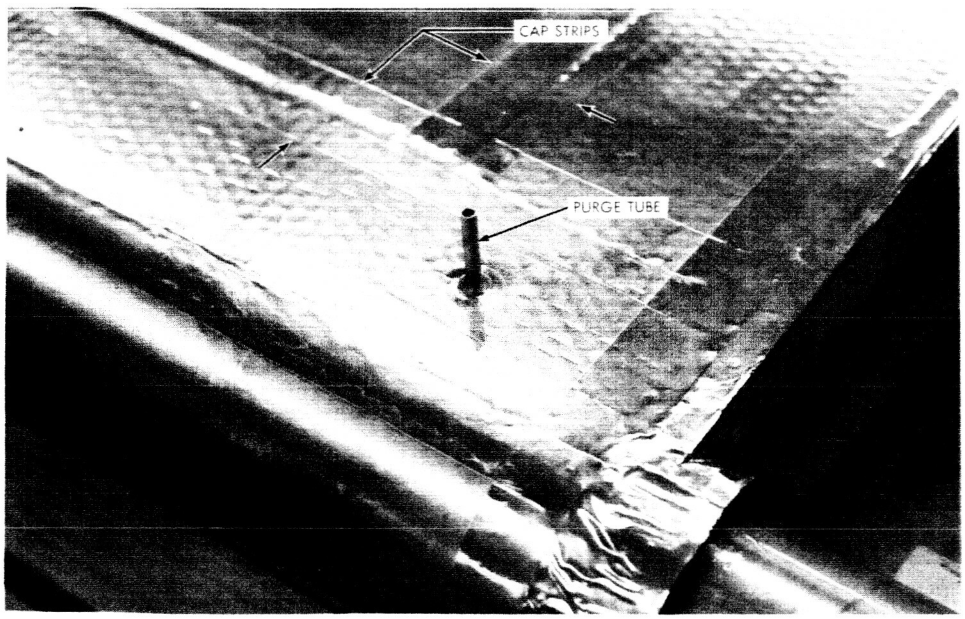


Figure 28. Vibration Tank Insulation - Detail of Cap Strips and Purging Tube

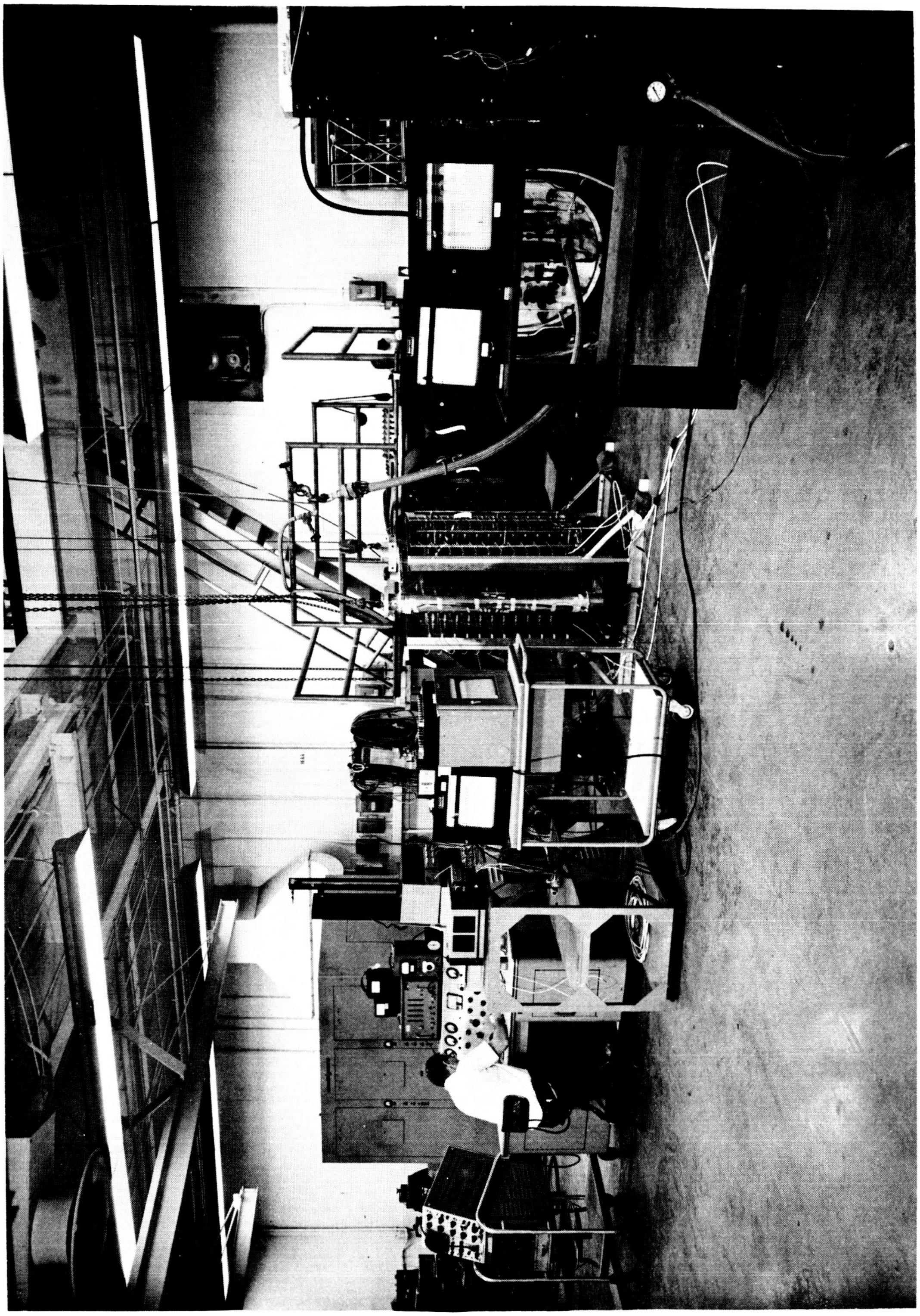


Figure 29. Vibration Test Setup - Circumferential Axis Test

is attached to an MB-C100 vibrator with adapter clamps. Figures 29 and 30 show the tank mounted for the circumferential axis test. Figures 31 and 32 show the tank mounted for the normal axis test. Quartz lamp heaters were used to maintain the outer surface temperature and to run the temperature profile. The tank was filled with liquid nitrogen just prior to the test, and LN_2 was continually added during the test to compensate for boil-off. Figure 33 shows frost caused by LN_2 and wrinkles in the cap strip caused by tank shrinkage.

C. TESTING

The circumferential axis test was run first. A resonant survey was conducted by vibrating from 20 to 500 cps and back to 20 cps over 15 minutes. The outer surface panel was maintained at 70 to 75°F. The resonant frequency was determined to be 185 cps. The tank was vibrated for four minutes at this frequency with the outer surface maintained at 75°F. Then the tank was subjected to the temperature profile (Figure 34) while at resonant frequency. The pressure profile was not run at this time. There was no visible evidence of damage after test.

The tank was reset for the normal axis test and refilled with LN_2. The sweep to 500 cps and back to 20 cps was conducted, and the resonant frequency was determined to be 90 cps. The tank was vibrated at resonant frequency at 75°F for four minutes, followed by exposure to the temperature profile per Figure 34. The final run was a combined temperature and pressure profile. The maximum pressure obtained was 5 psi. At this time it was noticed that the cap strips (shown by arrow X in Figures 35 and 36) had fractured. The test terminated at the end of the day. The next morning the tank was removed from the test jig, and it was noted that panel No. 2 had a vertical centerline break as shown by arrow Z in Figure 36.

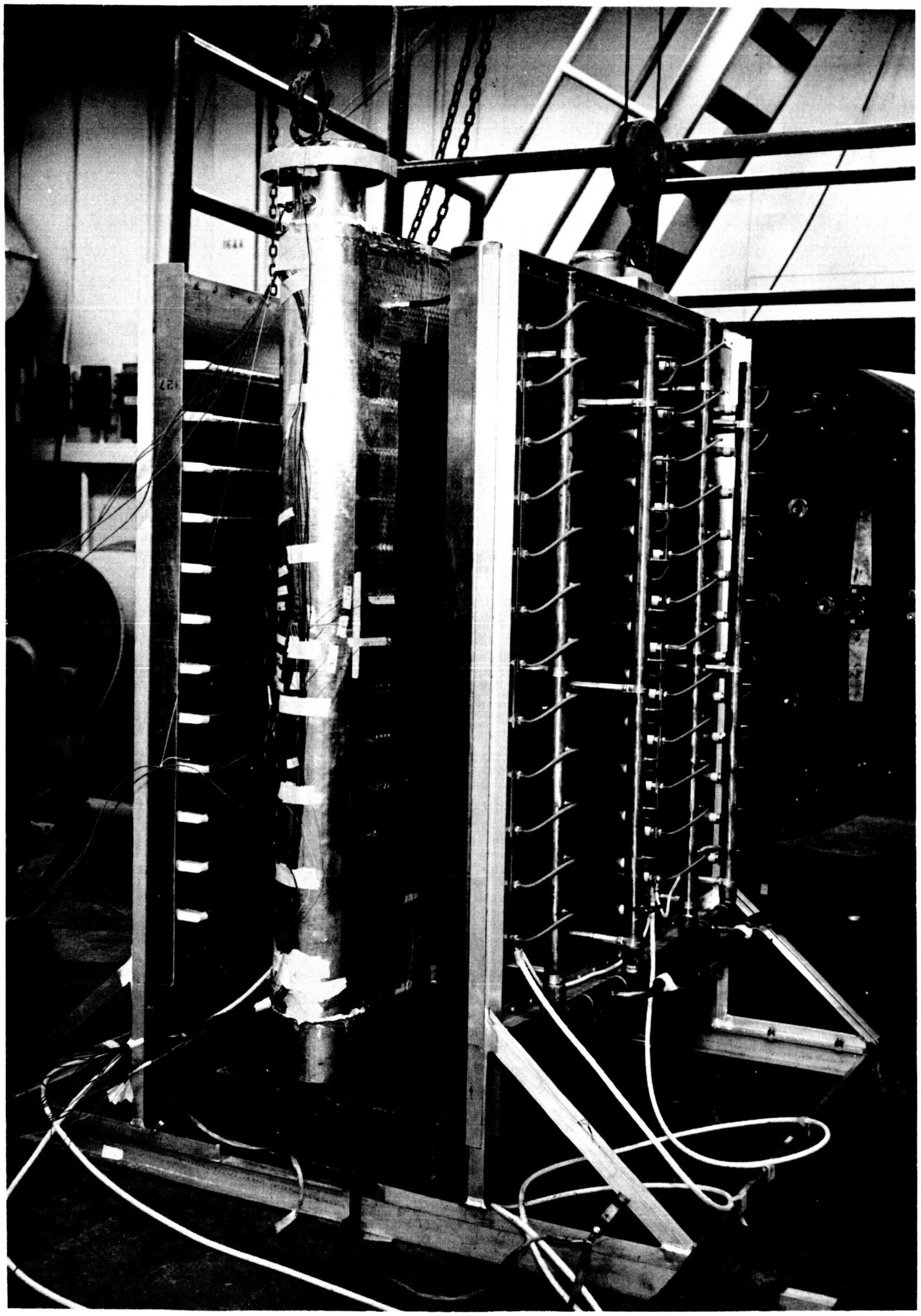


Figure 30. Vibration Tank - Circumferential Axis Test Setup

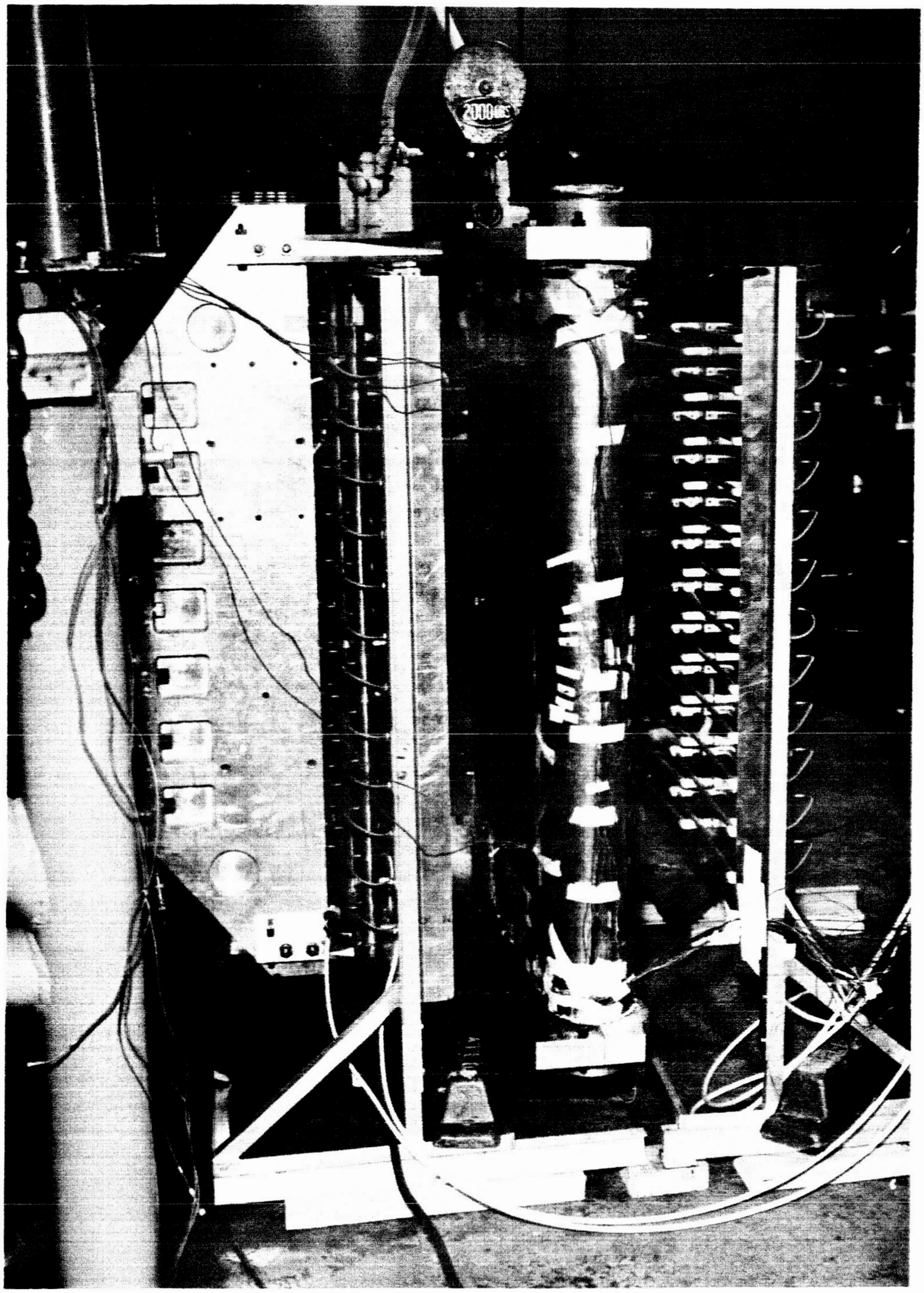


Figure 31. Vibration Test - Normal Axis Setup

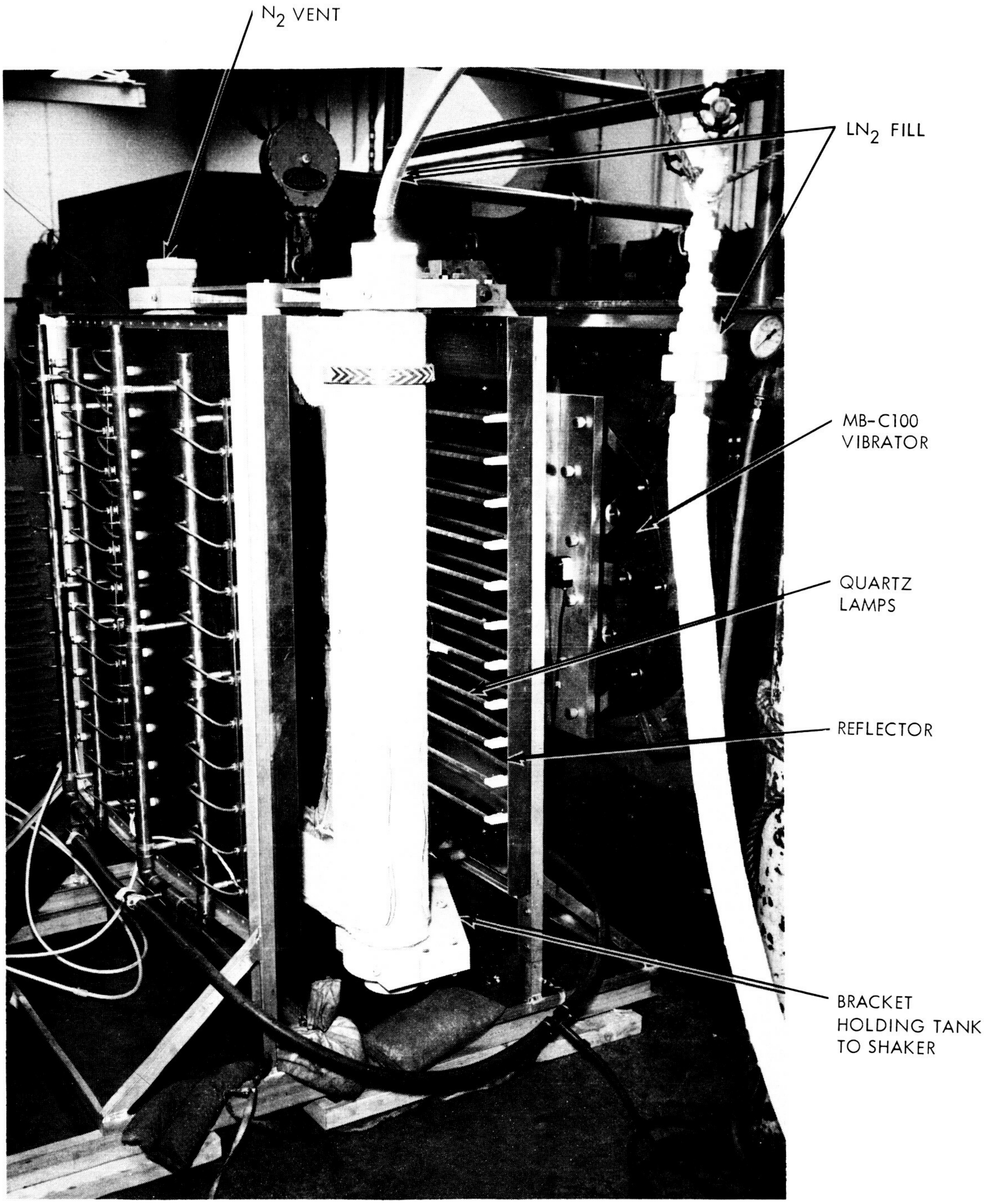


Figure 32. Vibration Test - Normal Axis Setup - Filling Tank with LN_2

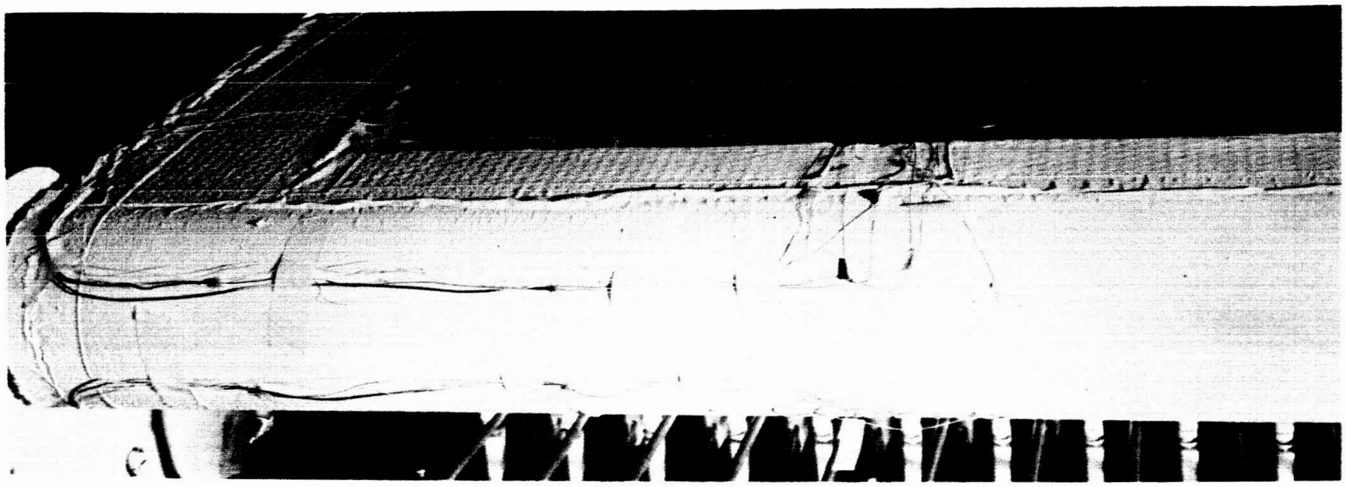


Figure 33. Vibration Test - Normal Axis - Cap Strip Wrinkles

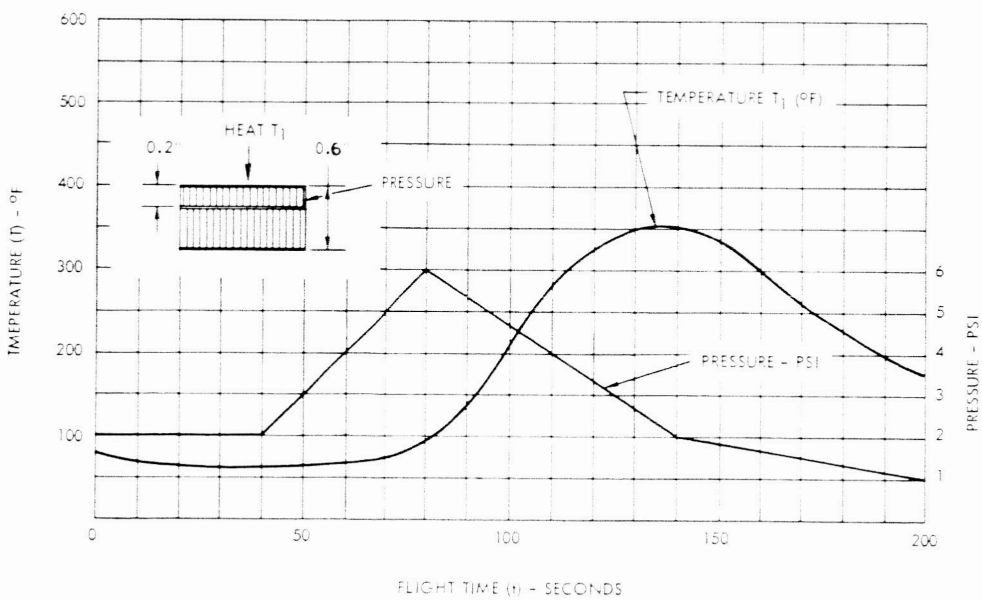
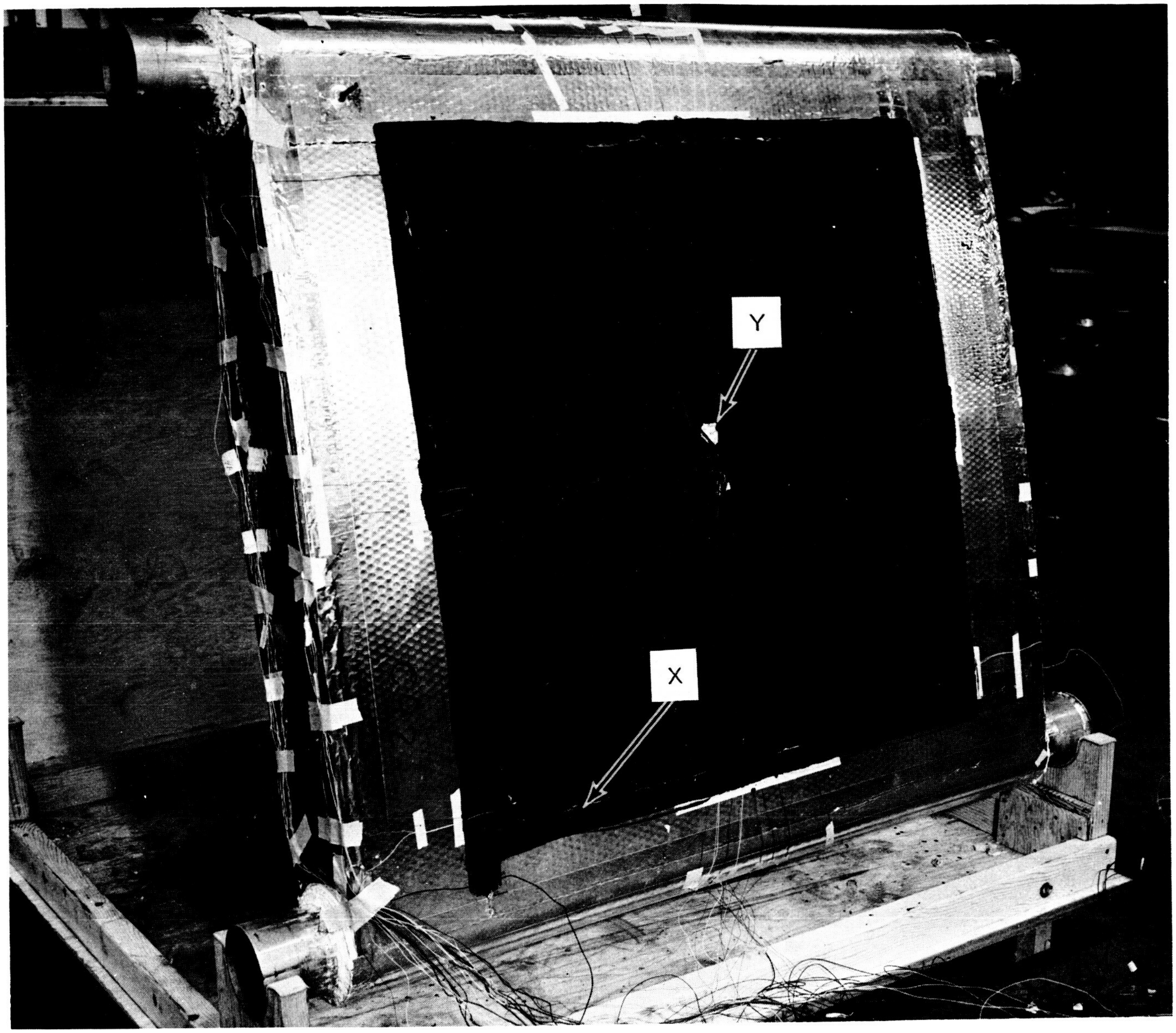
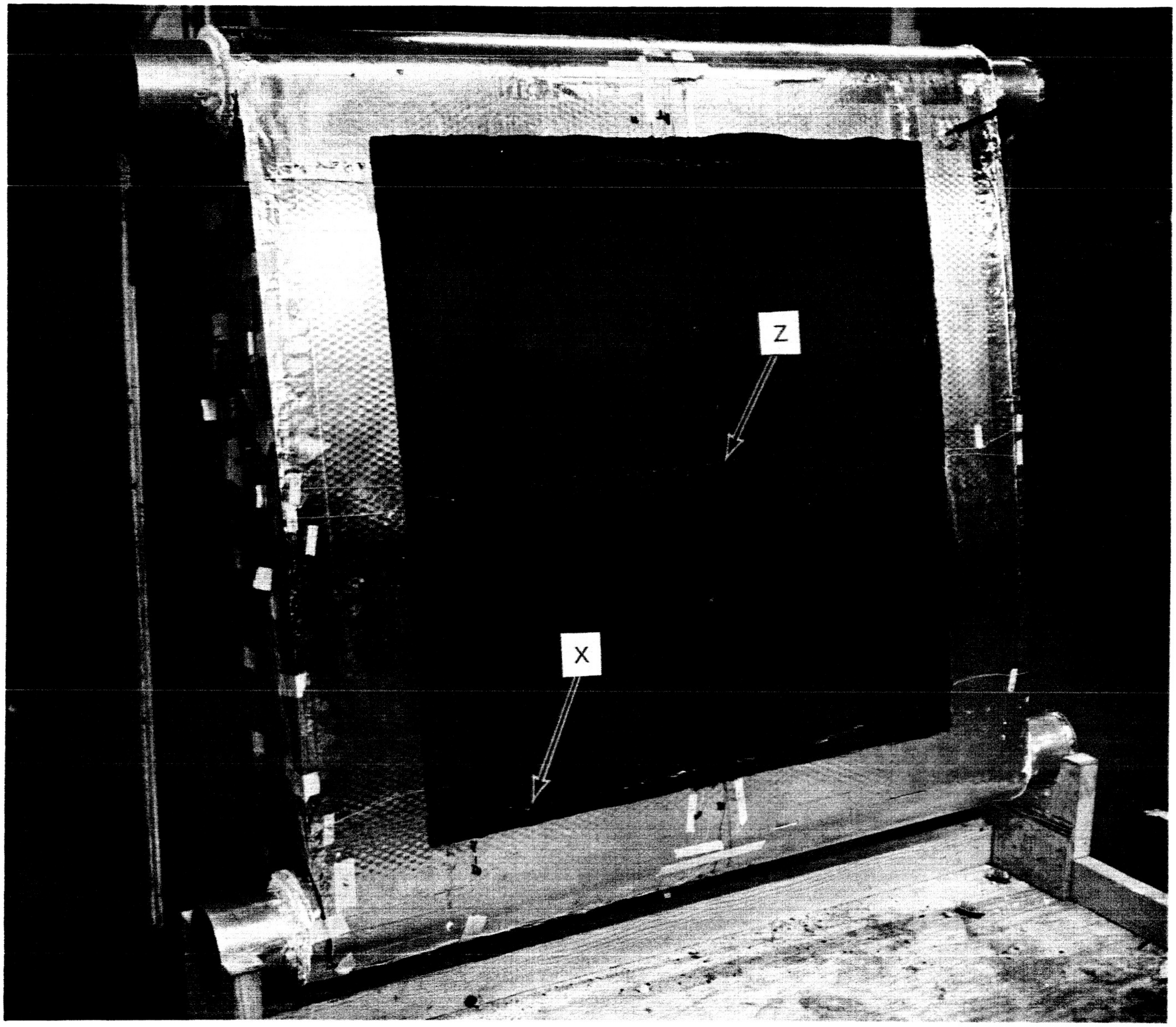


Figure 34. Time, Temperature, and Pressure Profile



X = FAILURE IN CAP STRIP
Y = HAIRLINE CRACKS IN ALUM FACE SHEET
PARALLEL TO VERTICAL CENTER LINE

Figure 35. Vibration Tank Panel No. 1 after Test



X = FAILURE IN CAP STRIP
Z = CENTER LINE CRACK

Figure 36. Vibration Tank Panel No. 2 after Test

D. DISCUSSION OF TEST RESULTS

The purpose of the test was to subject the test panels to very adverse vibration loads to determine the adequacy of the adhesive bond between the tank and the panel. Several significant facts were learned from this test. First, the panel to tank adhesive bonds showed no sign of failure as a result of the vibration test. In addition, there was no visual evidence to indicate a degradation of any kind of the bond lines making up the test panels. Secondly, the center-line splitting of the outer and middle aluminum skins on test panel No. 2, which is an indication of the severity of the test, points out the need to further investigate the fatigue characteristics of the composite insulation. Finally, the biaxial wrinkling and failure of the aluminum foil cap strips between test panels indicate that the panel close-out design should be carefully reviewed.

It is believed that panel No. 2 fractured (see arrow Z, Figure 36), whereas panel No. 1 did not fracture because of the difference in adhesive. Panel No. 2 used AF-111, an unsupported adhesive film, whereas panel No. 1 used HT-424, which added support to the aluminum skin. In Figure 35, arrow Y, the aluminum skin of panel No. 1 showed results of strain in that the surface appeared crystalline and showed numerous hairline cracks.

It was planned to fabricate and test a second set of panels after the first LH_2 tank test. Since the aluminum foil cap strips failed because of wrinkling, it was decided to use MAM reinforced with stretch nylon. It was also decided to use foam strips to fill the gap at the joints (refer to Section IV). Because of the limited time left, it was not possible to run a second vibration test after completion of the LH_2 tank test.

SECTION VII. CALORIMETER TESTS

A. COLD GUARD CALORIMETER

1. Design

The design specifications for the calorimeter were set by the thermal characteristics of the components that make up the calorimeter. Each component that allows heat flux into the measuring vessel was analyzed to determine the magnitude of the heat flux and, where necessary, the means by which this heat flux could be made negligible.

The heat fluxes into the measuring vessel are as follows (see Figure 37):

q_1 = conductive heat flux normal to test specimen
q_2 = conductive heat flux through edge of test specimen
q_3 = conductive heat flux from guard vessel to measuring vessel
q_4 = conductive heat flux down vent tube
q_5 = radiation heat flux down vent tube

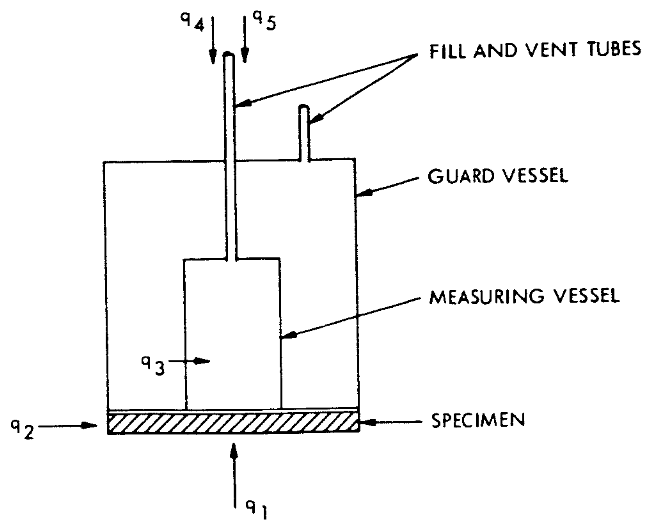


Figure 37. Heat Flux Diagram

The first step in the thermal analysis of the calorimeter was to determine the width of the guard required for a test area of 100 square inches. A computer program that determines the percent error due to heat flux through the edge of the sample was written for the IBM 1410 digital computer. The program determines the heat flux into the measuring vessel, with and without edge effects, and the temperature distribution along the specimen, for varying specimen thicknesses and thermal conductivities. The basic heat transfer equations for the steady state two-dimensional analysis are

$$q = \frac{2\pi k_x (\Delta T)}{\ln(r_2/r_1)}$$

for radial heat conduction and

$$q = k_y A \left(\frac{\Delta T}{x}\right)$$

for conduction normal to the face of the test specimen.

The results of the computer study are presented in Figure 38. For a test area of approximately 100 square inches (11-inch diameter), a guard diameter of 16 inches allows less than 1 percent error for specimens of 0.5 to 1.5 inches thick.

The second step in the thermal analysis was to determine the magnitude of the heat flux from the guard vessel to the measuring vessel. This heat flux is due to the temperature gradient between the cryogen in the guard vessel and that in the measuring vessel. This temperature gradient is a function of the pressure difference between the two vessels, stratification of the cryogen in the vessels, and the overall heat transfer coefficients across the wall.

The results presented in Reference 5 (page 254) indicate that for a pressure of one atmosphere and a temperature difference less than 10 degrees between

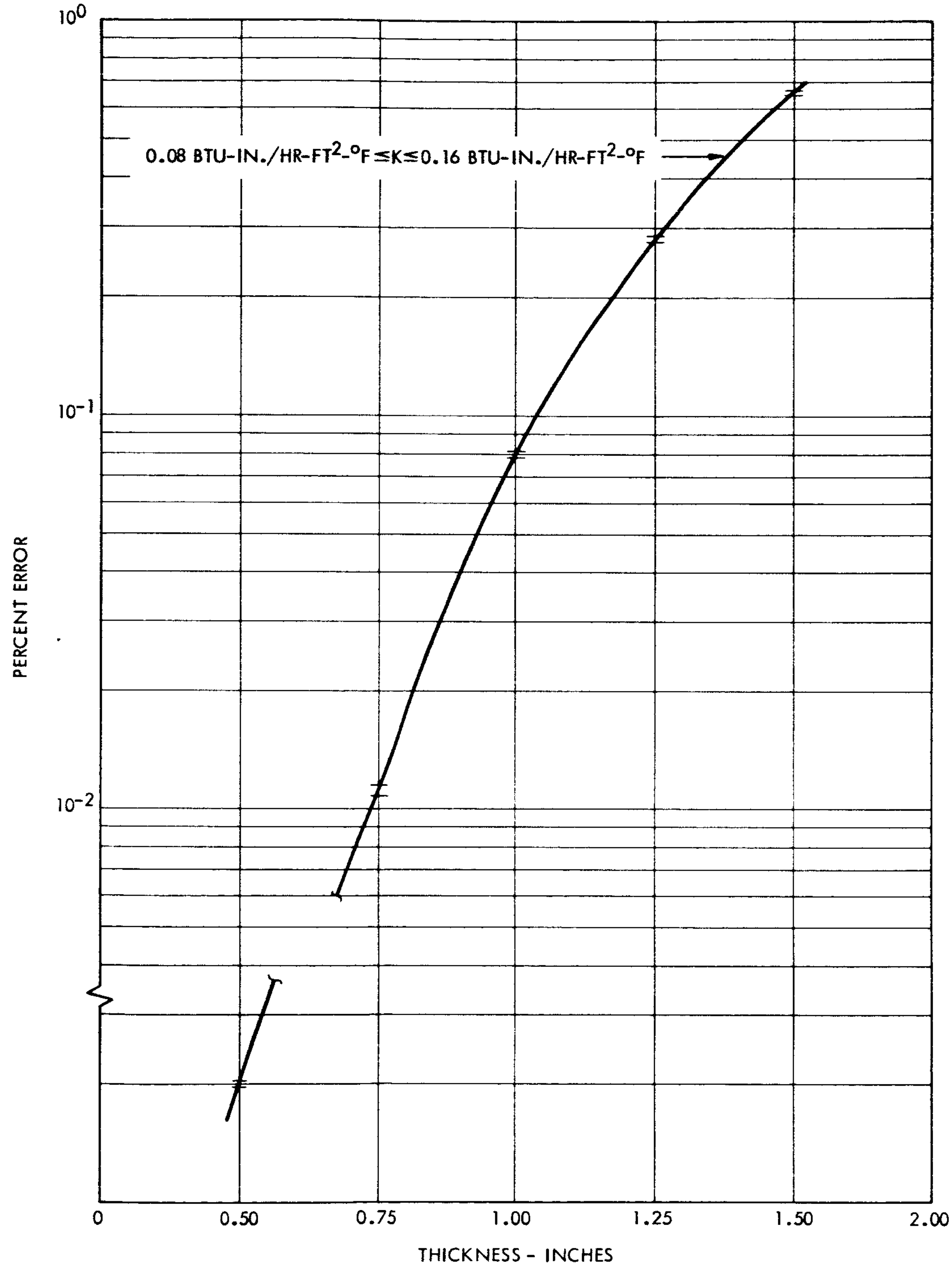


Figure 38. Conductivity versus Thickness
Flat Plate Calorimeter

the liquid hydrogen and heater plate, nucleate boiling takes place in the fluid. In determining the heat transfer coefficient on the guard side of the test vessel, it was assumed that the boiling liquid would exhibit some influence. The coefficient, assuming free convective heat transfer, was determined using the following relationship:

$$Nu = 0.56\ (Gr\ Pr)^{0.25},$$

and the resultant expression for the film coefficient as a function of temperature is

$$h = 18.7\ (\Delta T)^{0.25},$$

where

$$h = BTU/hr\text{-}ft^2\text{-}{}^{o}F.$$

The coefficient, assuming forced convection, was determined using the following relationship:

$$Nu = 0.664\ (Pr)^{0.33}\ (Re)^{0.5},$$

and the resultant expression for the film coefficient as a function of velocity is

$$h = 31.2\ (V)^{0.5},$$

where

$$h = BTU/hr\text{-}ft^2\text{-}{}^{o}F$$

$$V = ft/sec.$$

The heat flux through the measuring vessel wall could be on the order of 10 $BTU/hr\text{-}ft^2$ for a temperature difference of 0.1^{o}F. Since this heat flux is so sensitive to small temperature differentials and because of the uncertainty of the boiling effects on the film coefficient, any calculated heat flux value is quite nebulous. To eliminate this problem, provisions for evacuating the space between the measuring and guard vessel were incorporated in the calorimeter design. This evacuated space will reduce this heat flux to a fraction of one percent.

The conductive heat flux down the fill and vent tube was determined using the fin equations in Reference 4 (page 42). The temperature distribution down the tube was determined using the following relationship:

$$\frac{t_e - t_f}{t_1 - t_f} = \frac{1}{\cosh mL = (h/mk) \sinh mL},$$

where

t_1 = the external temperature of the tube (ambient),
t_f = the temperature of the gas in the tube (-423°F),
t_e = the temperature of the tube at a distance L.

The temperature at the base of the six-inch foam insulation was determined to be -399°F. The temperature of the tube at the entrance to the measuring vessel with one inch of liquid in the guard vessel was found to be -422.98°F. The heat flux from this temperature differential to the test tank is negligible.

The final step in the thermal analysis of the calorimeter was the determination of the radiation heat flux into the measuring vessel from the fill and vent tube. The radiation effects were determined using the following relationship:

$$q = \epsilon \sigma F \left(T_1^4 - T_2^4\right),$$

where

ϵ = the emittance of the inside of the tube,
σ = Stefan-Boltzman constant = 0.1714 x 10^{-8} BTU/hr-ft^2-°R^4,
F = view factor,
T_1 = external temperature of tube,
T_2 = temperature inside tube.

The view factor was determined using the relationship in Reference 4 (page 398). The emittance value was obtained from Reference 6. The amount of heat flux due to radiation was found to be negligible.

The heights of the measuring and guard vessels were determined by considering the amount of cryogen that would boil off during the test. It is necessary to have enough liquid in the measuring vessel so that the test can be completed before refilling is required. To determine the amount of liquid hydrogen that will boil off during a test, the following relationship was used:

$$\frac{M_v}{t} = \frac{q}{L_v} \frac{\rho_{liq} - \rho_{vap}}{\rho_{liq}}$$ (Reference 7, page 221),

where

M_v = mass of vapor vented,

t = time,

q = heat leak,

L_v = latent heat of vaporization (194.2 BTU/lb),

ρ_{liq} = density of liquid (4.4 lb/ft^3),

ρ_{vap} = density of vapor.

The correction factor $\rho_{liq}/(\rho_{liq} - \rho_{vap}) = 1.019$ for hydrogen (Reference 7).

For a 100-square-inch specimen 0.75-inch thick, thermal conductivity of 0.1 BTU-in./hr-ft^2-$^\circ$F, and a temperature differential of 300°, the heat leak is 61 BTU/hr. The amount of hydrogen that boils off in 4 hours is

$$W = \frac{61(4)}{194.2} = 1.26 \text{ lb.}$$

The volume of liquid hydrogen required is

$$V = \frac{1.26}{4.4} = 0.286 \text{ ft}^3 = 495 \text{ in}^3.$$

Thus the height of the measuring vessel should be greater than

$$h = \frac{\text{volume}}{\text{area}} = \frac{495}{\frac{\pi}{4}(11)^2} = 5.2 \text{ in.}$$

The height of the measuring vessel is 14 inches. The average case above of medium boil-off rate and medium response time indicates that this height is adequate. The guard vessel height is 24 inches, which permits the entire assembly to be placed into a vacuum system and reduces the number of filling operations for the guard vessel.

2. Construction Details

The design drawing of the cold guard calorimeter is shown in Figure 39. The calorimeter consists essentially of an 11-inch-diameter x 14-inch-high, vacuum-jacketed measuring vessel mounted concentrically inside an insulated 16-inch-diameter x 24-inch-high guard vessel. The measuring vessel is supported by a 1-inch-diameter thin wall stainless steel tube that is soft soldered to the bushing in the top of the guard vessel. The bottom surfaces of the measuring and guard vessels were machined flat to within ±0.001 inch to provide a relatively smooth surface in contact with the test specimen.

The cold guard calorimeter, as fabricated, is shown in Figure 40. An insulation jacket (see Figure 41) was installed, bonded, and secured with a glass cinch wrap to the outer surface of the guard vessel as shown in Figure 42. This insulation jacket consisted of a 0.4-inch-thick, sealed-cell, Mylar honeycomb sandwich with an inner skin of 2-mil Mylar film and an outer skin of 1-1/2 mil MAM. Additional insulation of the calorimeter was accomplished by foaming in place a six-inch-thick layer of two-pound-density polyurethane foam over the entire cylindrical and upper regions of the calorimeter. The heat lamp assembly shown in Figure 39 uses quartz lamps to supply radiant heating to the test surface.

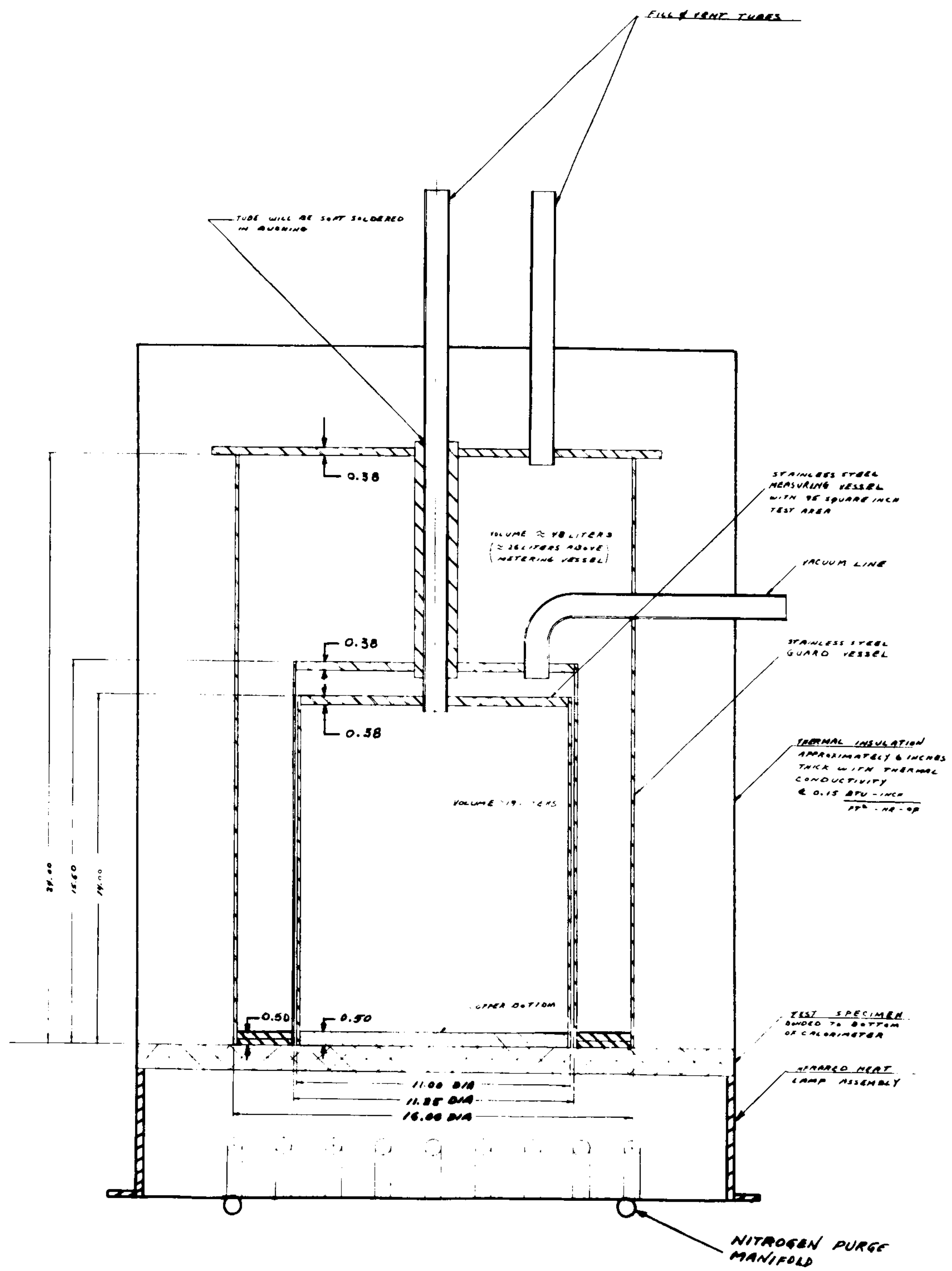


Figure 39. Cold Guard Calorimeter Design

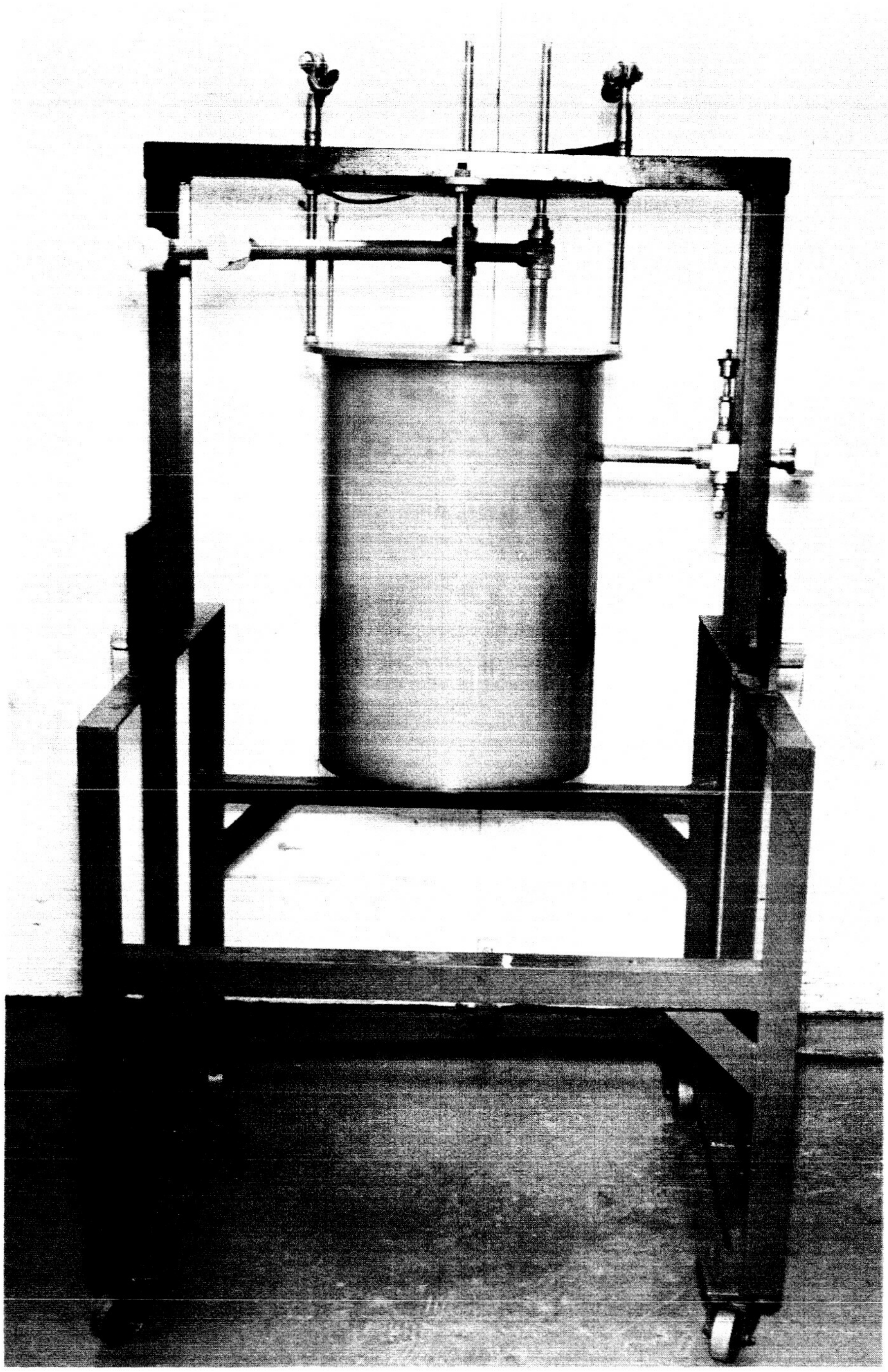


Figure 40. Fabricated Cold Guard Calorimeter

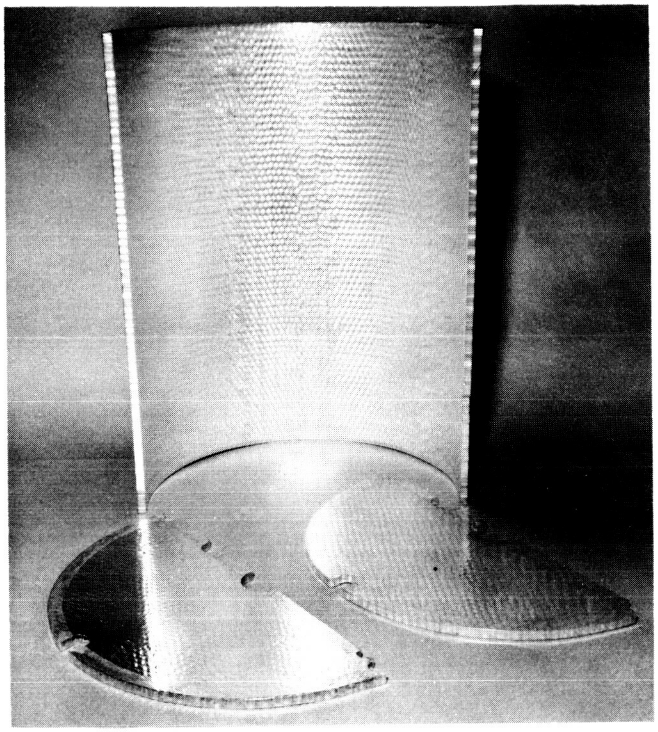


Figure 41. Calorimeter Outer Insulation Jacket Components

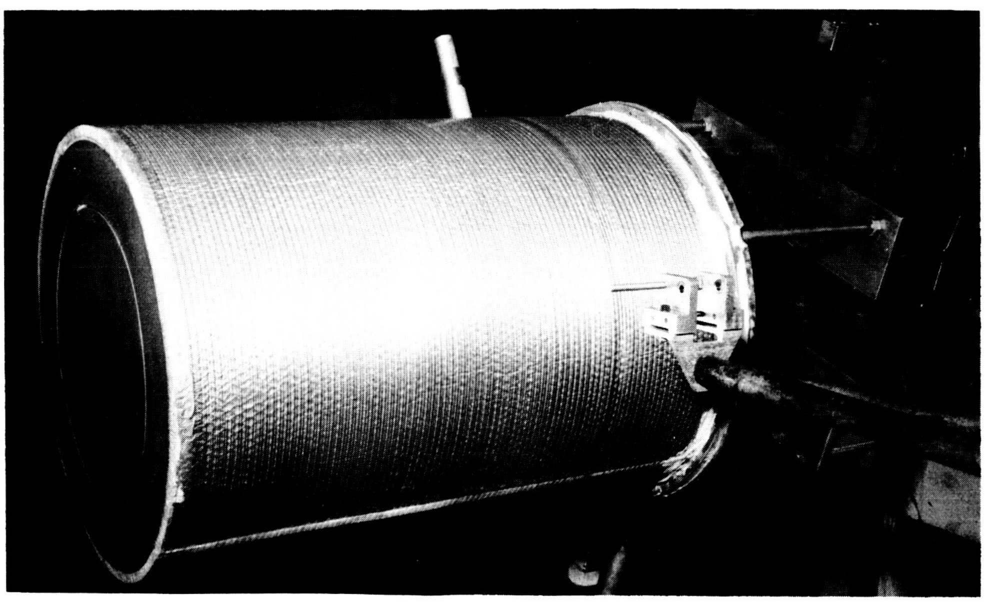


Figure 42. Glass Cinch Wrapping of Insulation Jacket to Calorimeter Guard Vessel

B. CALORIMETER TEST SETUP

1. Instrumentation System Design

The instrumentation and associated hardware necessary for operating the flat plate calorimeter was selected to be compatible with the calorimeter design and suitable for thermal conductivity measurements in the range from 0.08 to 0.20 BTU-in./ft^2-hr-^{o}F on materials ranging in thickness from 0.50 to 1.5 inches. Since the calorimeter was specifically designed for operation with liquid hydrogen, all possible precautions were taken to select components that would minimize the hazards involved in working with hydrogen at the test site. Where technically and economically practical, commercially available components were used in the instrumentation system.

Consideration was given first to the capacity of the meter that would be required to measure the boil-off rate of liquid hydrogen from the measuring vessel. Assuming the conductivity of the worst sample to be 0.2 BTU-in./ft^2-hr-^{o}F with a thickness of 0.5 inch, the boil-off rate from the measuring vessel was determined as follows:

$$q = \frac{kA}{\Delta x} (T_1 - T_2),$$

where

q = heat flux through test sample (BTU/hr),

k = thermal conductivity of test sample (BTU-in./hr-ft^2-^{o}F),

A = area of test sample (ft^2),

Δx = thickness of test sample (inches),

T_1 = temperature of hot side (300^{o}F),

T_2 = temperature of cold side (-423^{o}F),

and

$$Q = \frac{q}{L_v \rho}$$

where

Q = volume flow rate (ft^3/hr),

q = heat flux (BTU/hr),

L_v = latent heat of vaporization (BTU/lb),

ρ = density of hydrogen gas at 70°F (lb/ft^3).

For the conditions stated above,

$$q = \frac{0.2}{0.5} (0.7) [300 - (-423)] = 196 \text{ BTU/hr}$$

and

$$Q = \frac{196}{194.2 (0.0052)} = 194 \text{ ft}^3/\text{hr}.$$

To monitor this amount of hydrogen gas at 70°F, two wet-test gas meters connected in parallel were selected. Each meter has the following specifications:

Rated Capacity/Hour	100 ft^3
Minimum Capacity/Hour	10 ft^3
Maximum Capacity/Hour	120 ft^3
Accuracy	±1/2 percent
Volume/Revolution	1 ft^3
Registers (four dials)	10,000 ft^3
Pressure Range (inches of water)	-0.5 to 1.0 psi

The next step in the design of the instrumentation system was to determine the size of a water-type counter-flow heat exchanger required to warm the boil-off gas from -423 to 70°F at the inlets to the gas meters. To accomplish this, a program for the analysis of heat transfer to hydrogen gas flowing in a pipe was written for the IBM 1410 computer. The program determines the temperature, Reynolds number, pressure drop, and internal heat transfer coefficient, at specified intervals of pipe length, for hydrogen gas entering the pipe with a specified initial temperature and mass flow rate. The external temperature and heat transfer coefficient must also be specified. The results of the computer study for a given set of parameters (to simulate conditions in the heat exchanger) are as follows:

Mass flow rate = 0.0175 lb/min (hydrogen)
Initial temperature = $-423^{o}F$ (hydrogen)
Pipe diameter = 1 inch
Ambient temperature = $150^{o}F$ (water)
External heat transfer coefficient = 100 BTU/hr-ft^2-^{o}F (water)

Length of pipe (ft) =	4.0	6.0	10.0
Exit temperature (^{o}F) of hydrogen gas =	-119	-45	70

The results of the computer study indicate that at least 10 feet of 1-inch-diameter pipe is necessary to warm the hydrogen gas from -423 to $70^{o}F$.

To reduce the size of the heat exchanger and allow for the large temperature variation in the pipe, a single shell-type exchanger was decided upon. The overall length of the exchanger is six feet and the diameter is eight inches.

To determine the flow rate of the water in the exchanger use the following relation for the heating of fluids in turbulent flow through pipes (Reference 8):

$$\frac{hD}{k} = 0.023\,(Re)^{0.8}\,(Pr)^{0.3},$$

where

h = the film coefficient (BTU/hr-ft^2-^{o}F),
D = 4 times the hydraulic radius,
k = the thermal conductivity of water at $160^{o}F$ (BTU/hr-ft-^{o}F).

The value of the film coefficient used was that used in the computer study (h = 100 BTU/hr-ft-^{o}F). Rearranging the terms of the above expression,

$$Re = \left[\frac{hD}{0.023k\,(Pr)^{0.3}}\right]^{1.125}.$$

The Reynolds number was found to be Re = 9000, which is in the turbulent flow range. The velocity through the eight-inch shell for this Reynolds number is 425 ft/hr. By taking the ratio of areas, the flow through the 3/4-inch water pipes was determined as 4460 ft/hr. This requires a mass flow rate from the water heater of 840 lb/hr.

To deliver this amount of water, a small (5 gal/min) pump was used between the water heater and heat exchanger. The heating unit for the water is a 55-gallon standard water heater. The water heater is capable of supplying 9000 watts of power.

To ensure accurate boil-off measurements, a Cartesian manostat was selected for maintaining the pressure in the guard vessel slightly positive with respect to that in the measuring vessel. By use of this method, the temperature of liquid hydrogen in the guard vessel can be accurately maintained above the temperature of gaseous hydrogen in the measuring vessel vent tube so that no recondensation of gaseous hydrogen will occur.

A helium purge system was incorporated into the instrumentation system so that all lines can be purged prior to the transfer of liquid hydrogen. All lines coming from the calorimeter (Figure 43) are one-inch-diameter tubing to reduce line pressure drops. Bellows sealed low-pressure gate valves having 3/4-inch-diameter ports were used in all hydrogen gas transfer lines to ensure minimum pressure drops across the valves. Burst discs were installed in the vent lines of the measuring and guard vessels, which are rated for 25 psi at 70^{o}F.

A 15-cfm-capacity mechanical vacuum pump was selected for evacuating the space between the measuring and guard vessels. This pump, combined with the cryopumping that resulted when the vessels were filled with liquid hydrogen,

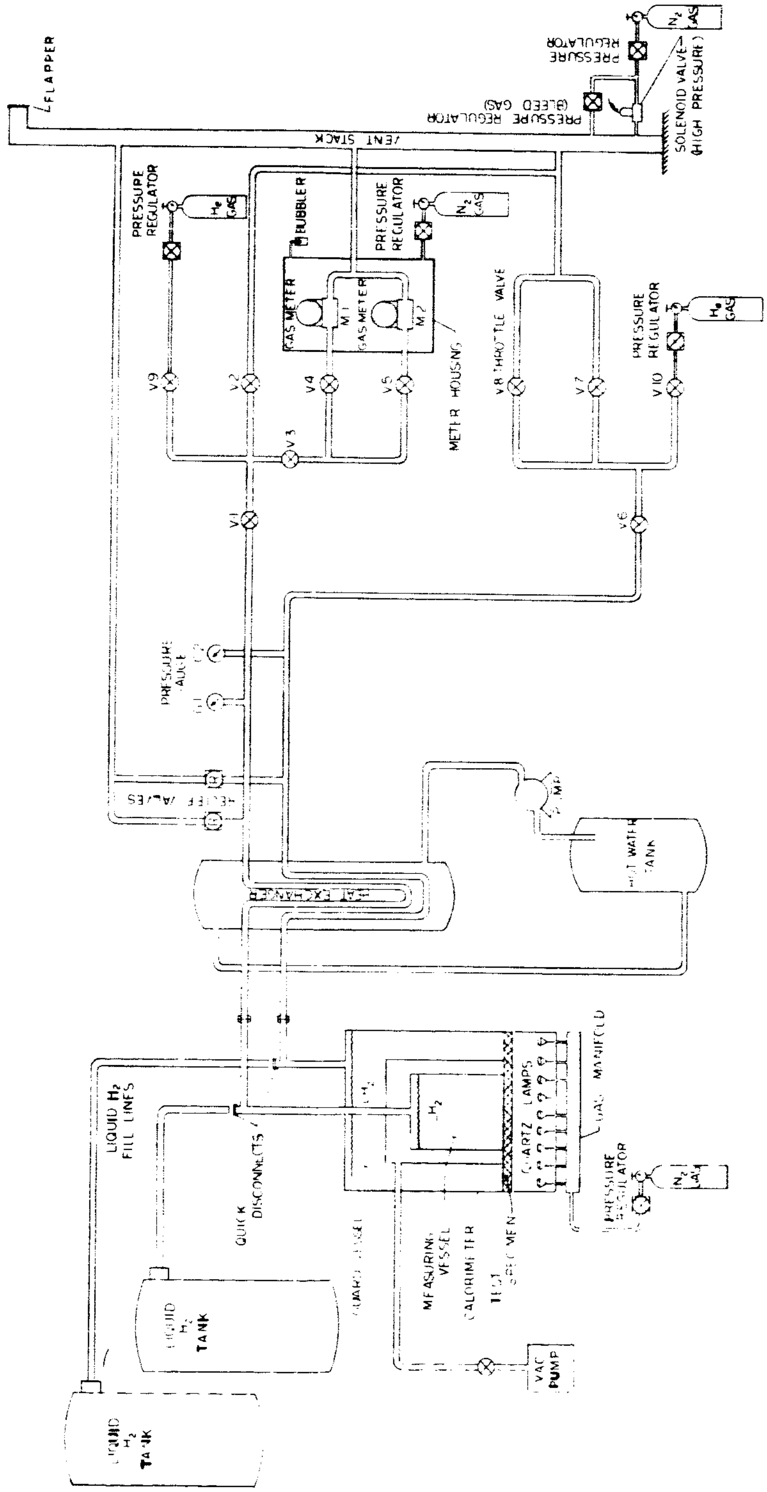


Figure 43. Calorimeter Gas Flow Diagram

provided the hard vacuum necessary to reduce heat transfer to the measuring vessel. Pressure measurements were made using conventional thermocouple and ionization gages.

2. Description

The plumbing system, shown in Figure 43, consists of the following basic components:

(1) Liquid Hydrogen Guard and Measuring Vessels. Transfer of LH_2 from storage vessels is accomplished by use of vacuum-jacketed transfer lines inserted through O-ring type quick-disconnect fittings (see Figure 44).

(2) Heat Exchanger. The cold gaseous hydrogen from the vessels is heated prior to entering the gas meters or the vent stack (see Figure 45).

(3) Hydrogen Gas Lines with Relief Valves, Pressure Gages, and Bellows-Sealed Valves. The system is designed to permit controlled pressure differential between the guard and measuring vessels.

(4) Gas Meters. Two wet-test gas meters installed in parallel are used to measure boil-off from the guarded section of the calorimeter (see Figure 45). Whether one or both of the meters are used during a test is dependent upon the magnitude of the boil-off rate.

(5) Nitrogen Gas Purge System. This system provides a means of purging the gas lines, calorimeter, and meters before using hydrogen. Nitrogen gas is bled continually into the vent stack during a test to guard against entrance of air into the vent stack. Nitrogen gas at a higher pressure is also available to permit a high flow of inert gas, through a solenoid-operated valve, into the vent stack in the event of ignition of hydrogen at the outlet of the vent stack.

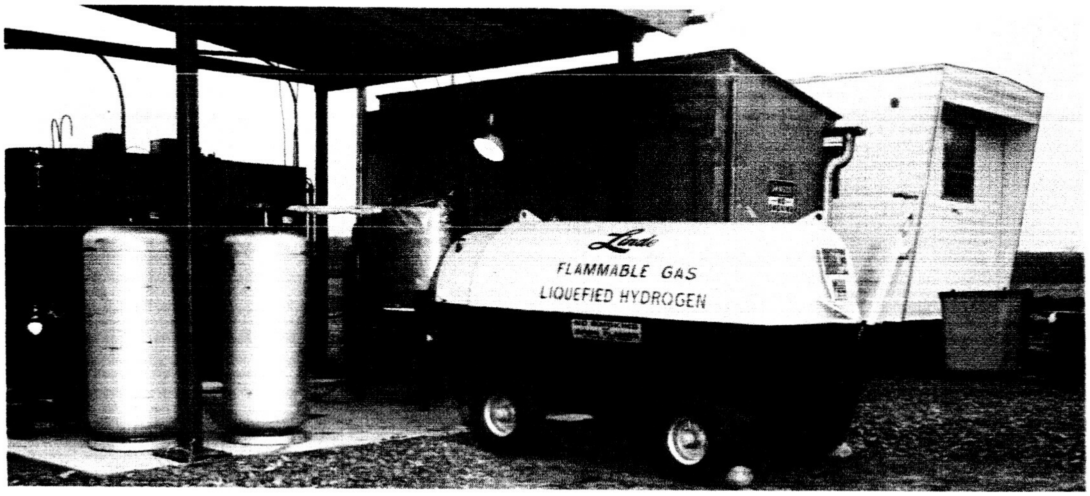


Figure 44. Calorimeter Test Setup - LH_2 Supply Tank

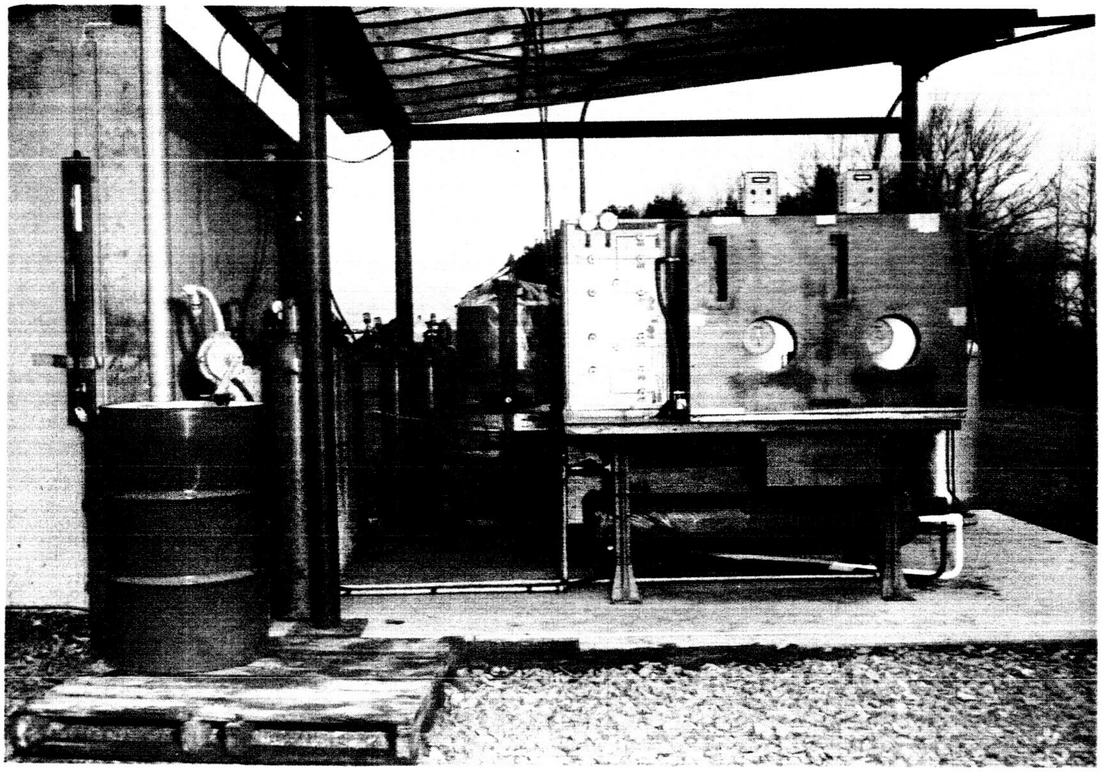


Figure 45. Calorimeter Test Setup - Flow Meters for Measuring Boil-Off

(6) Helium Purge System. This system is used to purge the calorimeter, vent lines, and liquid transfer hoses after initial cool-down with liquid nitrogen and immediately before initiating flow of liquid hydrogen into the calorimeter.

(7) Vacuum Pumping System. The space between the guard and measuring vessels is evacuated by a mechanical pump to minimize the possibility of heat transfer between the two vessels.

(8) Specimen Heating System. The outer surface temperature of the test panel is controlled by use of a bank of translucent quartz infrared lamps (see Figure 46). A manually operated variac regulates power to the lamps. A metal shroud between the test specimen and the reflector of the lamp bank eliminates air currents or a "chimney" effect. The distance between lamps and specimen surface is sufficient to eliminate hot spots on the specimen. A slight amount of gaseous nitrogen is bled into the heat chamber through the lamp terminals to provide an inert atmosphere and to minimize moisture condensation on the test panel during controlled temperature tests.

C. TEST PROCEDURES

1. General

The detailed procedures established for safe operation of the calorimeter facility are summarized as follows:

(1) Gaseous nitrogen purge
(2) Continuous purge of vent stack with nitrogen
(3) Liquid nitrogen cool-down
(4) Gaseous helium purge
(5) Liquid hydrogen cool-down and filling
(6) Completion of LH_2 boil-off

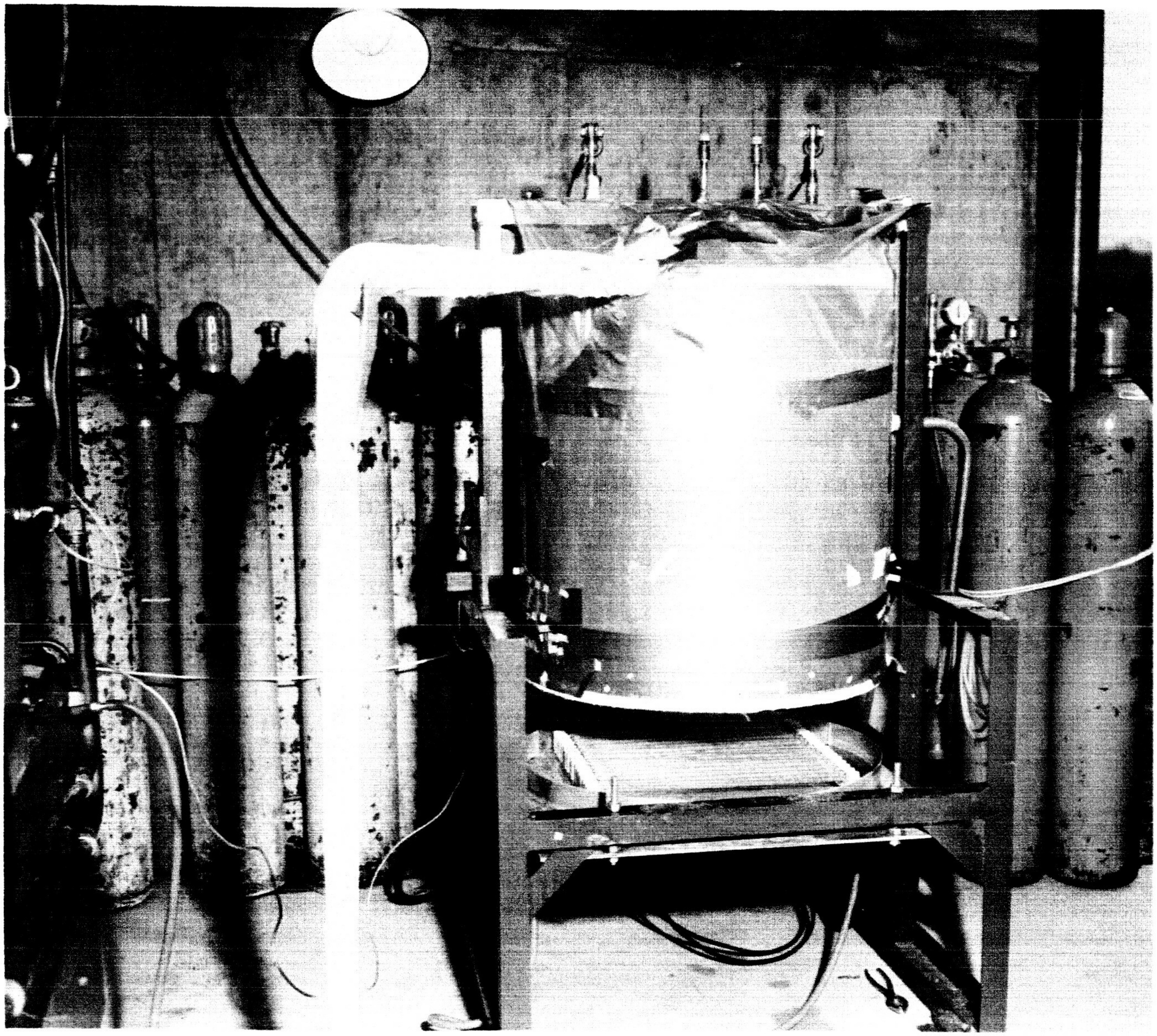


Figure 46. Calorimeter Test Setup - Close-Up Showing Quartz Heating Lamps

(7) Gaseous helium purge

(8) Gaseous nitrogen purge

2. Pressure Differential between Guard and Measuring Vessel

To prevent recondensation of boil-off gas from the measuring vessel, the guard vessel must be maintained at a slight positive pressure with respect to the measuring vessel. This was successfully accomplished by adjustment of a throttling valve in the vent gas line from the guard section. A pressure differential of between 1/4 to 1/2 psig was maintained during all testing. Pressure of the gas from the measuring vessel was virtually zero because of the combination of low flow rates and the large diameter (1.0 inch) copper tubing used in the plumbing system.

3. Evacuation of Space between Guard and Measuring Vessel

A mechanical vacuum pump provided a pressure of 2 microns (2×10^{-3} mm Hg) before cool-down as measured by a thermocouple vacuum gage. When the vessels contained liquid hydrogen, the cryopumping resulted in pressures below the limits of this type of gage, thus assuring that a good vacuum existed between the two vessels.

4. Boil-Off Measurement

Two Precision Instrument Company wet test meters were employed to measure the boil-off from the measuring vessel of the calorimeter. The manufacturer of these meters certifies that they are accurate to within ±1/2 percent. Temperature of the gas passing through the meters is measured by precision thermometers which are an integral part of the meters.

5. Temperature Measurements on Test Specimen

Temperatures at the prescribed locations on the specimen were sensed by thermocouples and recorded on a 24-point Minneapolis-Honeywell strip chart recorder. Thermocouple junctions were welded together and securely bonded to the selected surfaces. Accuracy of the thermocouples was verified by the fact that a variation of no more than ±1°F was indicated on the specimen when allowed to come to equilibrium overnight prior to testing.

D. PANEL TESTS

1. General

The test panels listed in Table 10 were fabricated as described in Section IV. Each panel was subjected to ambient temperature, 40°F, 75°F, and a high temperature. The first two panels were tested at 355°F elevated temperature. However, it was mutually agreed that 250°F was a more meaningful test, and the other panels were tested at this temperature. Temperature and boil-off data were recorded. Figure 47 shows relative boil-off curves for all panels.

Table 10. Summary of Calorimeter Test Results

Calorimeter Test Panel		Test Run				
No.	Description	No.	Date	T_1(°F)	Q	K_a
1	0.4" thick Mylar core, HT-424 adhesive bond to aluminum film	1	11/25/64	48	115	0.214
		2	11/25/64	72	122	0.218
		3	12/1/64	-46	74	0.181
		4	12/1/64	353	312	0.368
2	0.6" thick Mylar core, HT-424F roller-coat adhesive	1	1/6/65	71	121	0.298
		2	1/7/65	-54	74	0.244
		3	1/11/65	38	104	0.275
		4	1/11/65	353	316	0.503
3	Same as No. 1 except CO_2-filled Mylar core cells	1	1/26/65	43	(Data no good; see run No. 4.)	
		2	1/26/65	75	87.8	0.161
		3	1/28/65	-40	51	0.122
		4	1/28/65	43	74.5	0.146
		5	1/29/65	250	176.5	0.240
		6	1/29/65	65	82.2	0.154
		7	2/1/65	73	83	0.153

Table 10. Summary of Calorimeter Test Results (Continued)

Calorimeter Test Panel		Test Run				
No.	Description	No.	Date	T_1(°F)	Q	K_a
4	0.6" thick Mylar core, AF-111 adhesive on aluminum film. Roller-coat polyurethane adhesive on core only.	1	2/24/65	46	91.5	0.238
		2	2/25/65	75	104.6	0.257
		3	2/26/65	-72	51	0.178
		4	3/2/65	76	104	0.256
		5	3/2/65	249	195	0.354
		6	3/3/65	78	181.5	0.442
5	Same as No. 4 except both Mylar skin and core roller coated. Tried aluminum spray radiation shield in guard area.	1	3/24/65	45	103	0.320
		2	3/25/65	77	119	0.347
		3	3/25/65	-64	60	0.244
		4	3/26/65	75	141.5	0.413
		5	3/26/65	255	228	0.490
6	MMA center skin and G-208 bond	(Panel no good; no tests run.)				
7	0.6" thick Mylar core, MAAM center skin. Both Mylar skin and core roller coated with polyurethane adhesive.	1	6/3/65	-21	91	
		2	6/3/65	44	111	
		3	6/4/65	-29	105	
		4	6/4/65	82	136.5	
		5	6/7/65	-46	138.2	
		6	6/7/65	246	274	
		7	6/8/65	-64	129.2	
		8	6/8/65	82	160	
		9	6/9/65	-110	109	
		10	6/10/65	70	239	

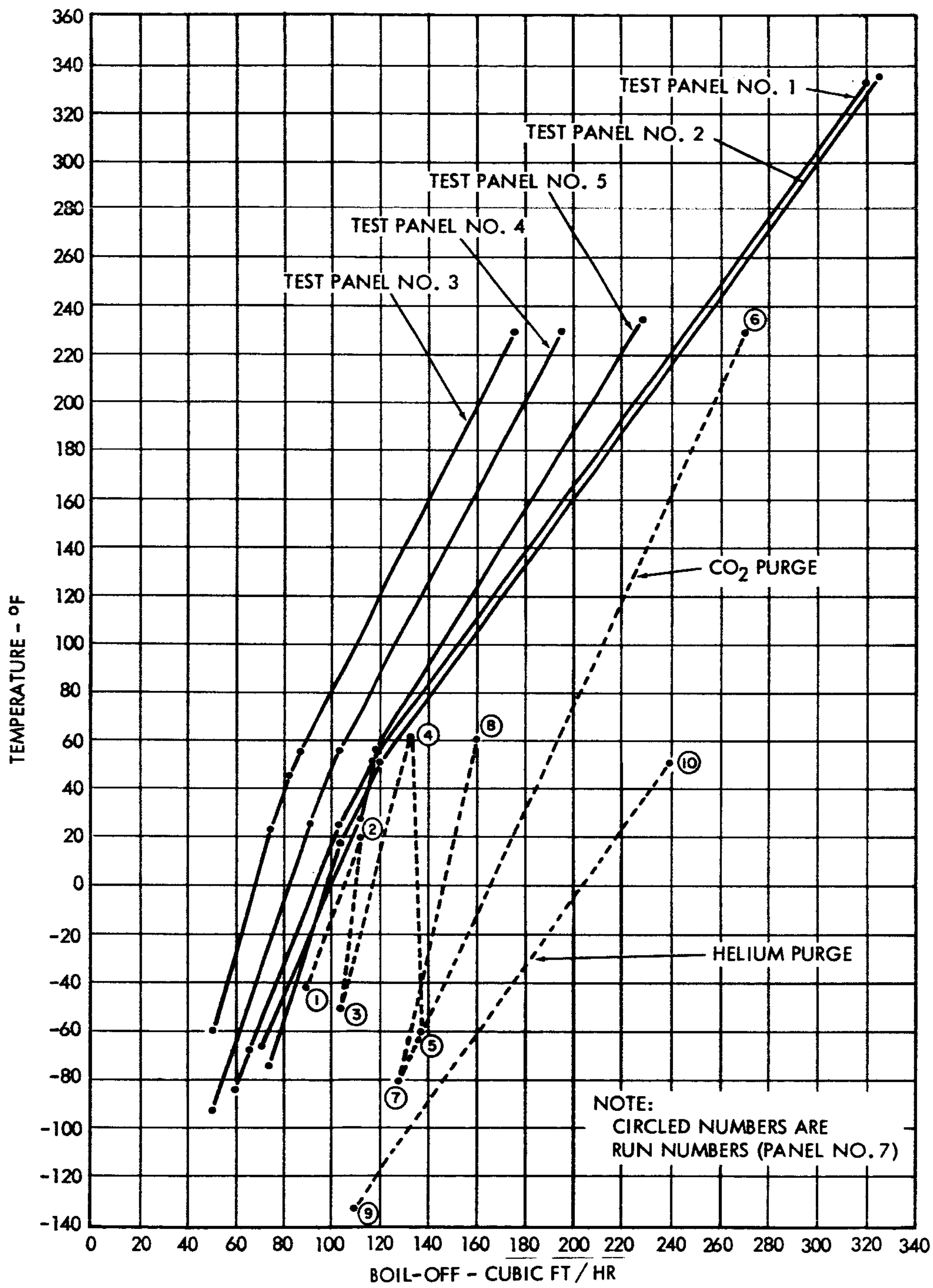


Figure 47. Relative Boil-Off for Calorimeter Test Panels No. 1 through 5 and 7

2. Thermal Calculations

To calculate the apparent thermal conductivity of the test sample, the following basic expression for heat transfer though a composite material was used:

$$K_{total} = \frac{\Delta x_{total}}{\frac{\Delta x_1}{K_1} + \frac{\Delta x_2}{K_2} + \ldots + \frac{\Delta x_n}{K_n}}$$

where

K_{total} = conductivity of composite slab (BTU-in./hr-ft^2-^{o}F),
K_1 = conductivity of 1st slab (BTU-in./hr-ft^2-^{o}F),
K_2 = conductivity of 2nd slab (BTU-in./hr-ft^2-^{o}F),
K_n = conductivity of nth slab (BTU-in./hr-ft^2-^{o}F),
Δx_1 = thickness of 1st slab (inches),
Δx_2 = thickness of 2nd slab (inches),
Δx_n = thickness of nth slab (inches),

and

$$\dot{q} = K_{total} A \frac{\Delta T}{\Delta x_{total}}$$

$$\dot{q} = QL_v,$$

where

$\dot{q}$ = heat flux (BTU/hr),
Q = gas flow (ft^3/hr),
L_v = latent heat of vaporization (BTU/ft^3),
A = test area of sample (ft^2),
ΔT = temperature difference across sample,
Δx_{total} = thickness of sample,
K_{total} = thermal conductivity of sample.

Calculations of the apparent thermal conductivity for a typical test follow. The calculations incorporate a temperature correction for the boil-off gas. Barometric pressure corrections were negligible and therefore not required. Panel temperatures (T_1 and T_2) are averages of total thermocouple readings across the panel, recorded at a stable point during the test.

Calculation of Apparent Thermal Conductivity

$$K_a = \frac{QL_v \Delta_x}{A \Delta T},$$

where

L_v = volumetric latent heat of vaporization (1.005 BTU/ft^3),

Δ_x = total thickness of insulation (inches),

A = area of insulation normal to heat flow (ft^2) $= \frac{\pi}{4}\left(\frac{11}{12}\right)^2 = 0.66$ ft^2,

ΔT = temperature difference across insulation ($^{\circ}$F),

Q = boil-off rate (ft^3/hr),

Temperature correction for Q $= \left[\frac{460 + 70}{460 + t}\right]$; t = temperature of boil-off gas.

Run No. 1 - across Total Thickness ($T_1 = 48^{\circ}$F, $T_3 = -423^{\circ}$F)

$$(K_a)_{total} = 115.36 \left[\frac{460 + 70}{460 + 92}\right]\left[\frac{(1.005)(0.6)}{\frac{\pi}{4}\left(\frac{11}{12}\right)^2 (48 + 423)}\right]$$

$$= \underline{\underline{0.214 \text{ BTU-in./hr-ft}^2\text{-}^{\circ}\text{F}}}.$$

Run No. 1 - across Mylar Honeycomb ($T_2 = 17^{\circ}$F, $T_3 = -423^{\circ}$F)

$$(K_a)_1 = 115.36 \left[\frac{460 + 70}{460 + 92}\right]\left[\frac{(1.005)(0.4)}{(0.66)(17 + 423)}\right]$$

$$= \underline{\underline{0.153 \text{ BTU-in./hr-ft}^2\text{-}^{\circ}\text{F}}}.$$

3. Calorimeter Panel No. 1

This panel had 0.4-inch-thick Mylar core. The aluminum skins were bonded to the HRP core using HT-424 adhesive film. The chronological history is as follows:

11/13/64: Panel bonded to calorimeter.
11/19/64: Panel at Wingfoot Lake test site.
11/21/64: Preliminary LN_2 cool-down.
11/24/64: Second LN_2 cool-down.
11/25/64: First test run $T_1 = 48^oF$.
11/25/64: Second test run $T_1 = 72^oF$.
12/1/64: Third test run $T_1 = -46^oF$.
12/1/64: Fourth test run $T_1 = 353^oF$.
12/4/64: Panel dissected.

Thermocouple temperature readings, boil-off, and thermal conductivity data are given in Tables 11 and 12 and Figure 48.

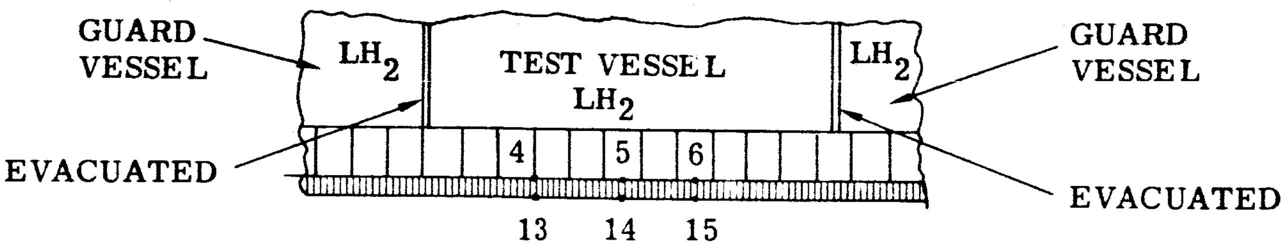
After testing, the panel was dissected in layers and visually inspected. As shown in the photographs taken during this operation (Figures 49 through 52), there was no visual evidence of degradation.

4. Calorimeter Panel No. 2

This panel had a 0.6-inch Mylar core. The HRP core was roller coated with HT-424F adhesive for bonding the 0.003- and 0.0015-inch aluminum skins, which were primed with HT-424 A/B primer. The chronological history of the test sample is as follows:

12/31/64: Panel bonded to calorimeter.
1/5/65: Panel at Wingfoot Lake test site.
1/6/65: First test run $T_1 = 71^oF$.
1/7/65: Second test run $T_1 = -54^oF$.

Table 11. Temperatures Used in Calculation of Apparent Thermal Conductivity - Calorimeter Panel No. 1



Run No. 1 — Thermocouples (^oF)

Time	4	5	6	13	14	15
To	18	18	18	48	49	49
To +30 min	19	19	19	48	48	48
To +60 min	19	19	19	50	49	49

Run No. 2 — Thermocouples (^oF)

Time	4	5	6	13	14	15
To	40	40	40	70	71	71
To +30 min	41	41	41	73	72	72
To +60 min	42	42	42	72	73	73

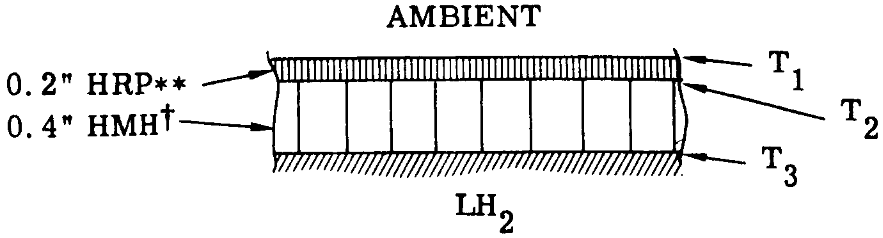
Run No. 3 — Thermocouples (^oF)

Time	4	5	6	13	14	15
To	-61	-56	-53	-44	-39	-37
To +30 min	-60	-55	-52	-35	-31	-30
To +60 min	-69	-63	-60	-47	-40	-37

Run No. 4 — Thermocouples (^oF)

Time	4	5	6	13	14	15
To	263	273	275	351	352	342
To +30 min	289	294	291	342	345	338
To +60 min	302	307	304	354	360	355

Table 12. Summary of Apparent Thermal Conductivity Calorimeter Panel No. 1*



Test Run No. 1 — Ambient Temperature (50°F) Q = 115.4

Section	T_1	T_2	T_3	ΔT	K_a (BTU-in. /hr-ft²-°F)
Over-all panel	48		-423	471	0.214
0.2" HRP	48	17		31	1.085
0.4" HMH		17	-423	440	0.153

Test Run No. 2 — Ambient Temperature (51°F Q = 122.6

Section	T_1	T_2	T_3	ΔT	K_a (BTU-in. /hr-ft²-°F)
Over-all panel	72		-423	495	0.218
0.2" HRP	72	39		33	1.090
0.4" HMH		39	-423	462	0.155

Test Run No. 3 — Ambient Temperature (23°F) Q = 74.5

Section	T_1	T_2	T_3	ΔT	K_a (BTU-in. /hr-ft²-°F)
Over-all panel	-46		-423	377	0.181
0.2" HRP	-46	-68		22	1.032
0.4" HMH		-68	-423	355	0.128

Test Run No. 4 — Ambient Temperature (23°F) Q = 312

Section	T_1	T_2	T_3	ΔT	K_a (BTU-in. /hr-ft²-°F)
Over-all panel	353		-423	776	0.368
0.2" HRP	353	291		62	1.535
0.4" HMH		291	-423	714	0.266

*MSFC dual-seal concept (HT-424 film adhesive).
**HRP is heat-resistant phenolic honeycomb.
†HMH is Hexcel Mylar Honeycomb.

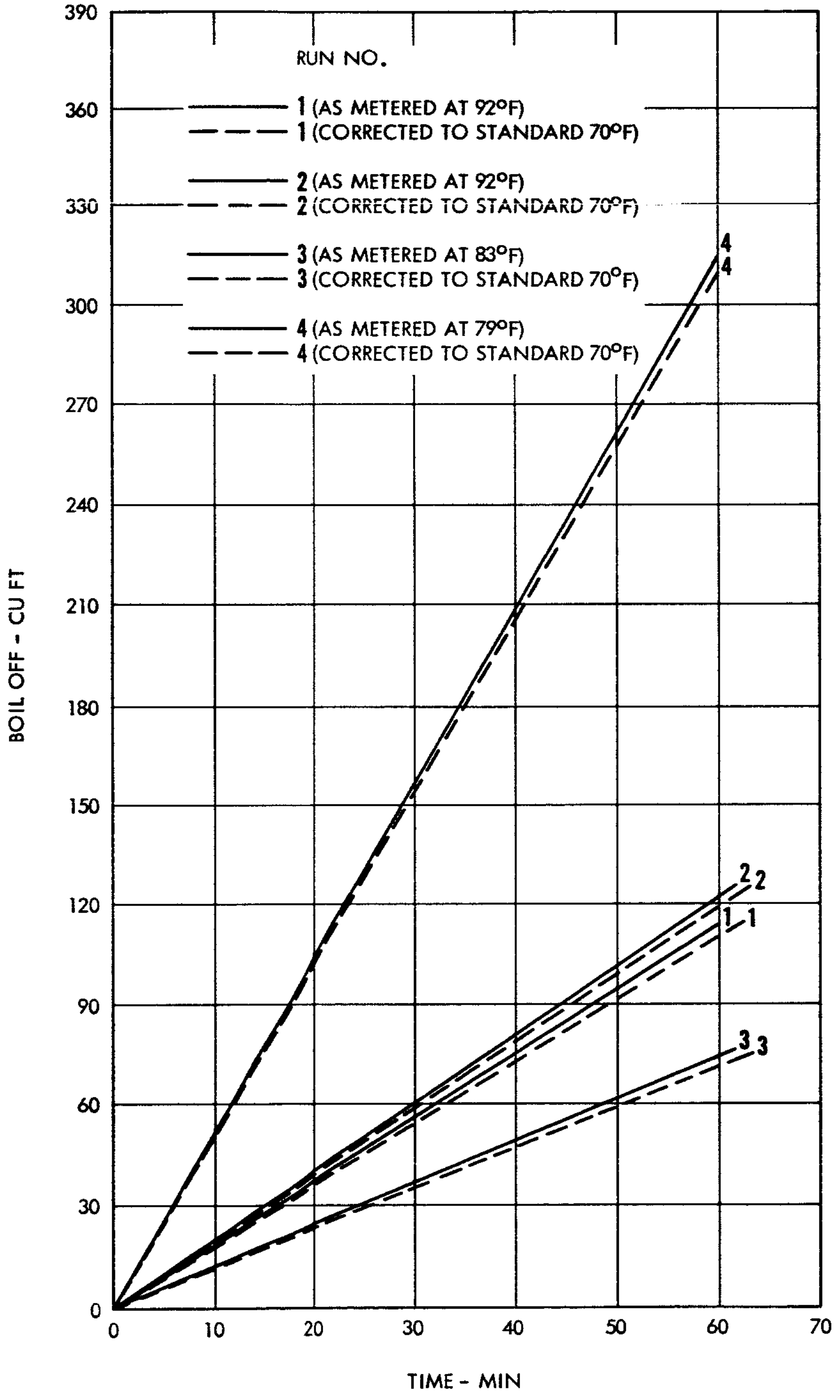


Figure 48. LH_2 Boil-Off versus Time - Calorimeter Panel No. 1

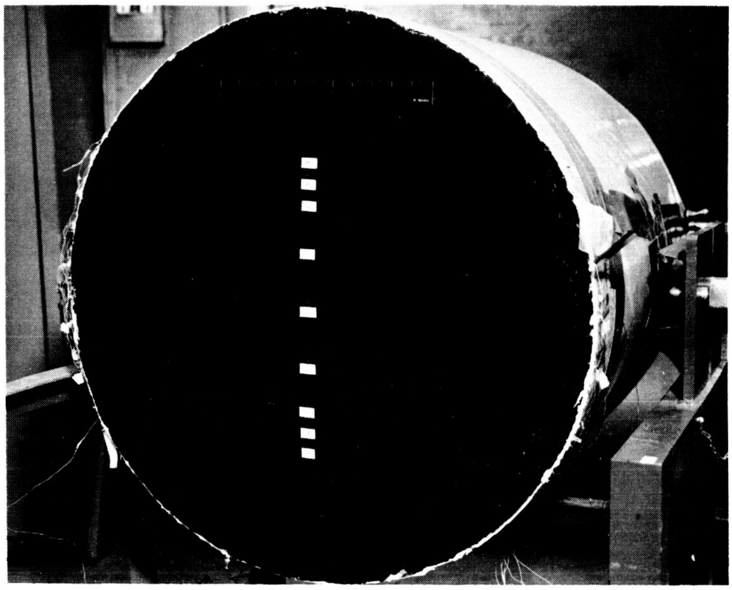


Figure 49. Instrumented Dual-Seal Calorimeter Panel No. 1

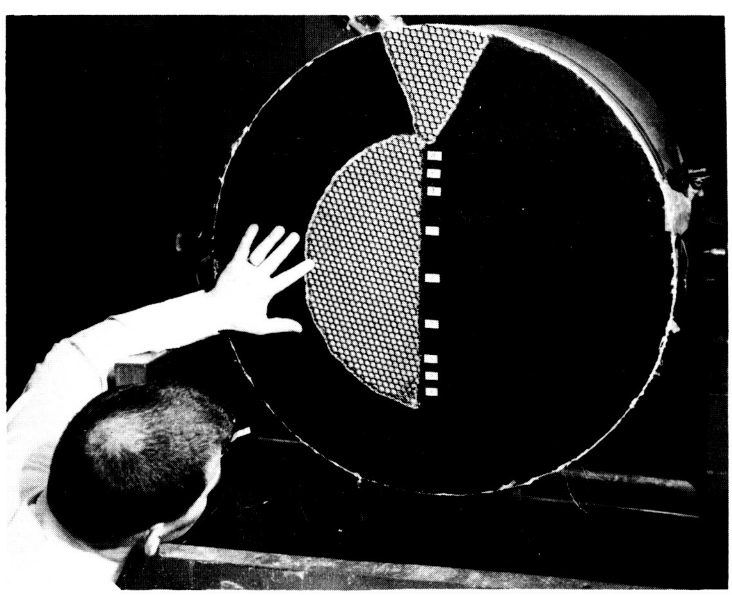


Figure 50. Visual Inspection of HRP Core during Dissection of Dual-Seal Calorimeter Panel No. 1

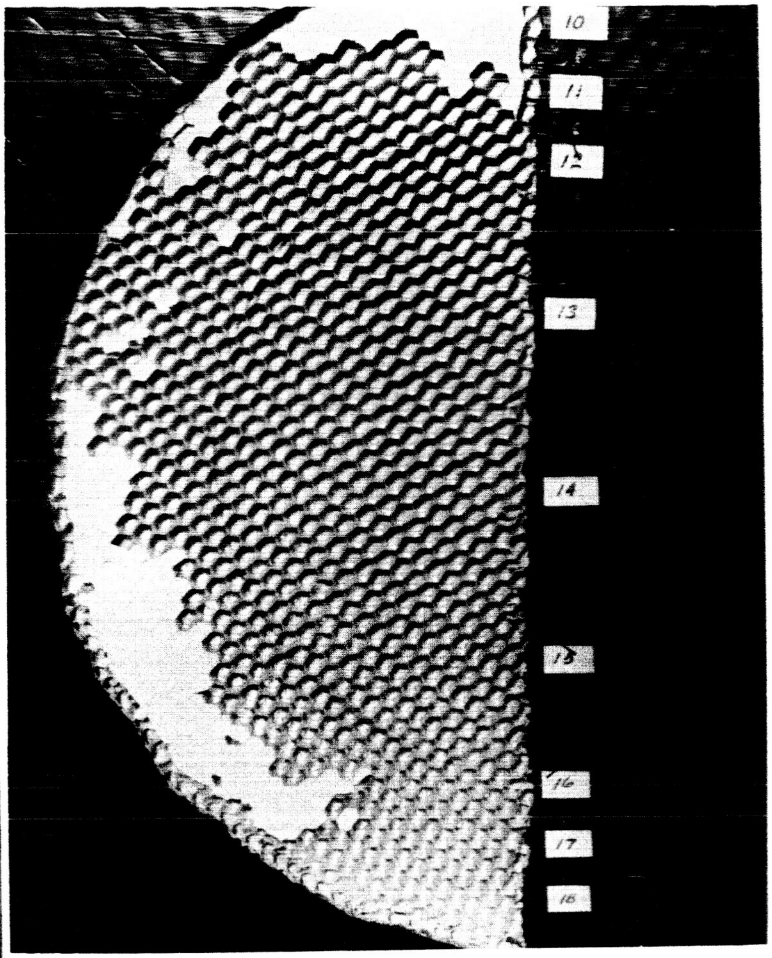


Figure 51. Visual Inspection of Mylar Core during Dissection of Dual-Seal Calorimeter Panel No. 1

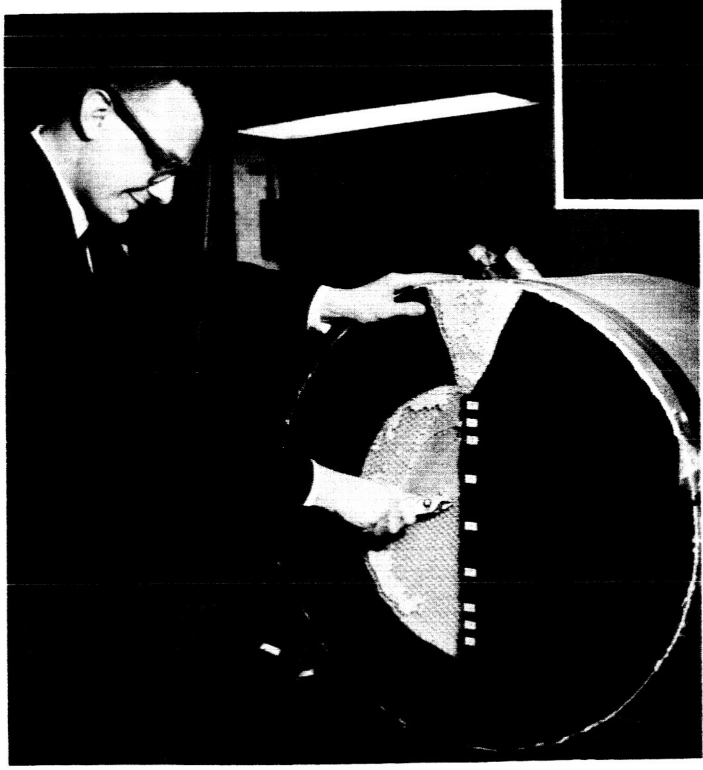


Figure 52. Removing Mylar Core in Dissecting Dual-Seal Calorimeter Panel No. 1

1/11/65: Third test run $T_1 = 38^oF$.
1/11/65: Fourth test run $T_1 = 353^oF$.
1/12/65: Return to lab.
1/13/65: Panel dissected.

The temperatures and apparent thermal conductivities are given in Tables 13 and 14. The boil-off curves in Figure 53 have been corrected to standard condition.

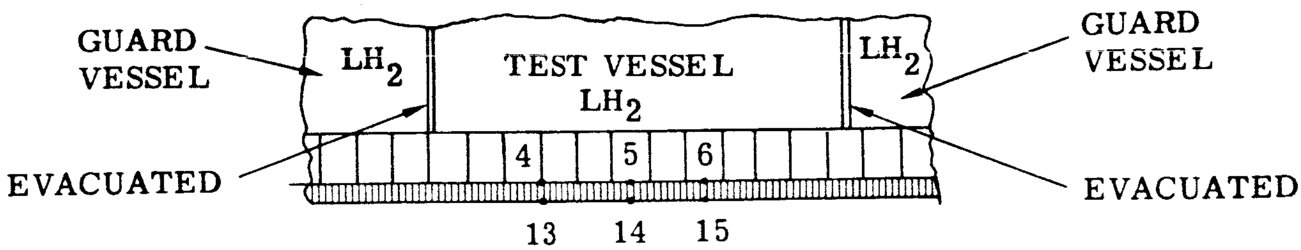
After the test, a visual inspection revealed no indications of degradation. Further inspection during dissection of the panel during removal revealed no bond failures.

5. Calorimeter Panel No. 3

The fabrication of this panel was identical with panel No. 1 except that the 0.4-inch Mylar core sealed cells were filled with CO_2 instead of air. The chronological history of the test sample is as follows:

1/13/65: CO_2 purge and start final cure of panel.
1/19/65: Bond panel to calorimeter.
1/22/65: Complete installation of thermocouples.
1/25/65: Set up at Wingfoot Lake test site.
1/26/65: Run No. 1 (40^oF) - results not valid.
1/26/65: Run No. 2 (75^oF).
1/28/65: Run No. 3 (ambient).
1/28/65: Run No. 4 (40^oF) - rerun of No. 1.
1/29/65: Run No. 5 (250^oF).
1/29/65: Run No. 6 (75^oF).
2/1/65: Run No. 7 (75^oF).
2/4/65: Dissect panel.

Table 13. Temperatures Used in Calculation of Apparent Thermal Conductivity - Calorimeter Panel No. 2



Run No. 1 (1/6/65) — Thermocouples (°F)

Time to stabilize 2-1/2 hr	4	5	6	13	14	15
	49	46	42	75	67	67

Run No. 2 (1/7/65) — Thermocouples (°F)

Time to stabilize 2 hr, 15 min	4	5	6	13	14	15
	-72	-75	-77	-52	-56	-58

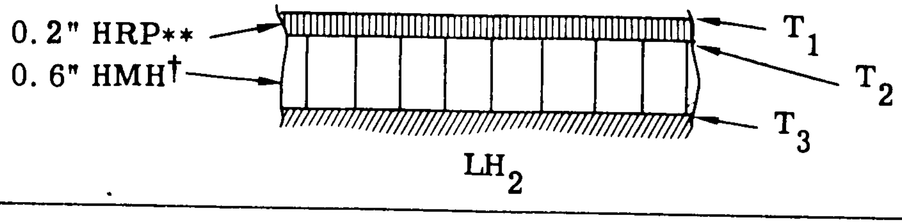
Run No. 3 (1/11/65) — Thermocouples (°F)

Time to stabilize 1-1/2 hr	4	5	6	13	14	15
	10	7	25	35	35	46

Run No. 4 (1/11/65) — Thermocouples (°F)

Time to stabilize 30 min	4	5	6	13	14	15
	305		302	352	363	356

Table 14. Summary of Apparent Thermal Conductivity Calorimeter Panel No. 2*



Test Run No. 1 — Q = 121

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all panel	71		-423	494	0.298
0.2" HRP	71	46		25	1.470
0.6" HMH		46	-423	469	0.235

Test Run No. 2 — Q = 74

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all panel	-54		-423	369	0.244
0.2" HRP	-54	-79		25	0.902
0.6" HMH		-79	-423	344	0.197

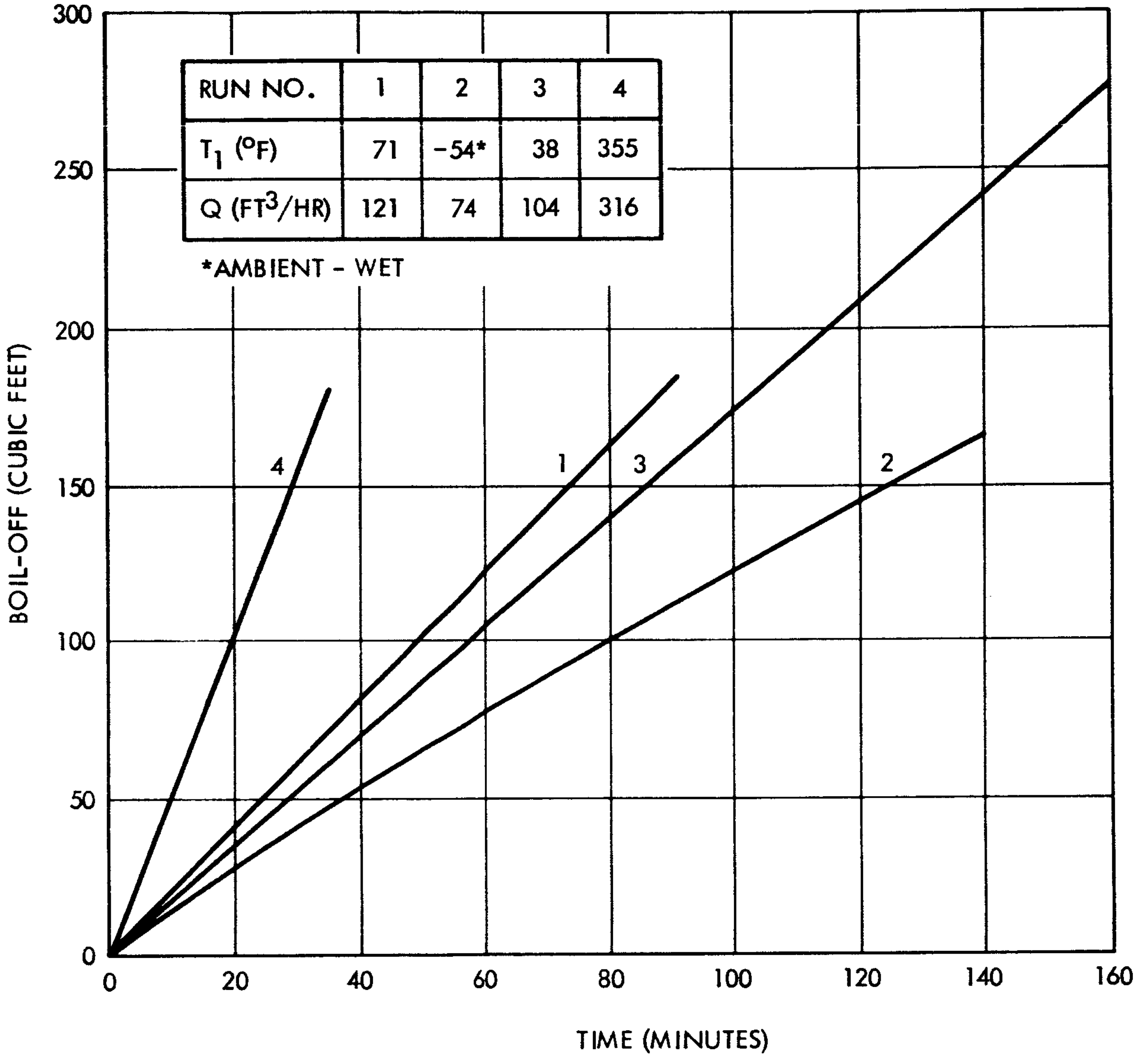
Test Run No. 3 — Q = 104

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all panel	38		-423	461	0.275
0.2" HRP	38	15		23	1.377
0.6" HMH		15	-423	438	0.217

Test Run No. 4 — Q = 316

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all panel	353		-423	776	0.503
0.2" HRP	353	298		55	1.750
0.6" HMH		298	-423	721	0.401

*MSFC dual-seal concept (HT-424F).
**HRP is heat-resistant phenolic honeycomb.
†HMH is Hexcel Mylar honeycomb.

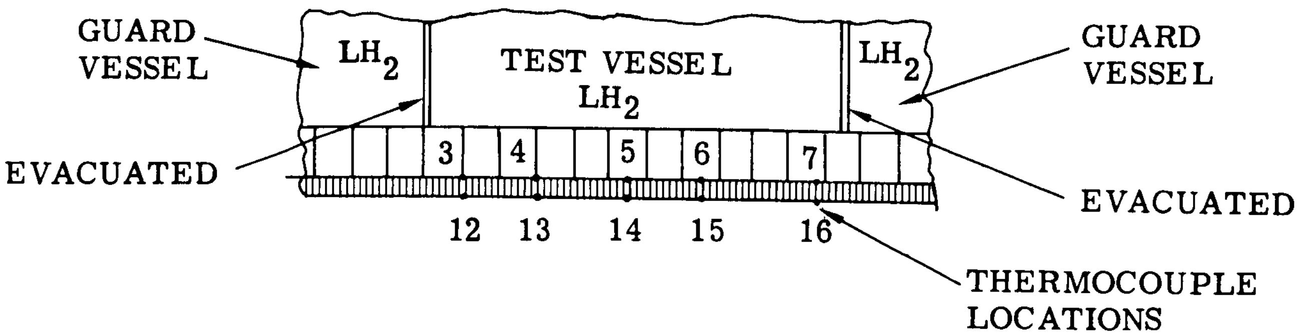


RUN NO.	1	2	3	4
T_1 (°F)	71	-54*	38	355
Q (FT^3/HR)	121	74	104	316

*AMBIENT - WET

Figure 53. LH_2 Boil-Off versus Time - Calorimeter Panel No. 2

Table 15. Temperatures Used in Calculation of Apparent Thermal Conductivity - Calorimeter Panel No. 3



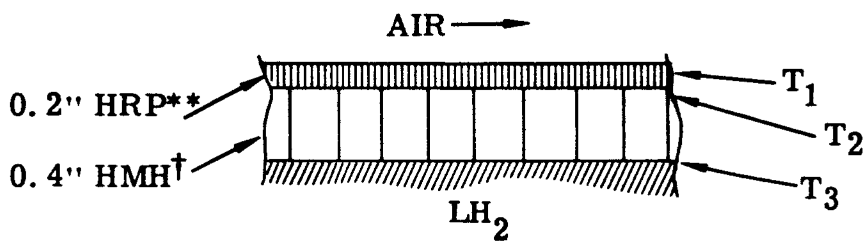
Run No.	Thermocouples (^oF)									
	3	4	5	6	7	12	13	14	15	16
1 (1/26/65)* Amb - 50^oF	4	9	12	12	7	36	40	43	47	44
2 (1/26/65) Amb - 34^oF	-17	-5	2	0	-10	64	74	79	81	78
3 (1/28/65) Amb - 18^oF	-93	-91	-90	-93	-100	-36	-39	-41	-42	-43
4 (1/28/65) Amb - 14^oF	-47	-36	-26	-23	-31	30	38	48	51	50
5 (1/29/65) Amb - 8^oF	130	145	151	149	140	233	248	259	258	253
6 (1/29/65) Amb - 6^oF	-27	-17	-10	-10	-17	55	64	70	71	61
7 (2/1/65) Amb - 20^oF	-22	-10	-1	0	-10	60	70	78	81	78

*Run No. 1 did not stabilize. This test was repeated as run No. 4.

The temperatures and apparent thermal conductivities appear in Tables 15 and 16. The boil-off curves in Figure 54 have been corrected to standard condition.

The HRP core was helium-purged prior to run No. 1 and then pinched off. No additional purging was done during the remaining tests. The relatively low apparent K factor for the HRP sandwich indicates that there was probably air instead of helium in the cells.

Table 16. Summary of Apparent Thermal Conductivity Calorimeter Panel No. 3*



Test Run No. 1

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in./hr-ft^2-°F)
Over-all panel	43		-423	466	Test did not stabilize;
0.2" HRP	43	7		36	test results void.
0.4" HMH		7	-423	430	

Test Run No. 2 Q = 87.8

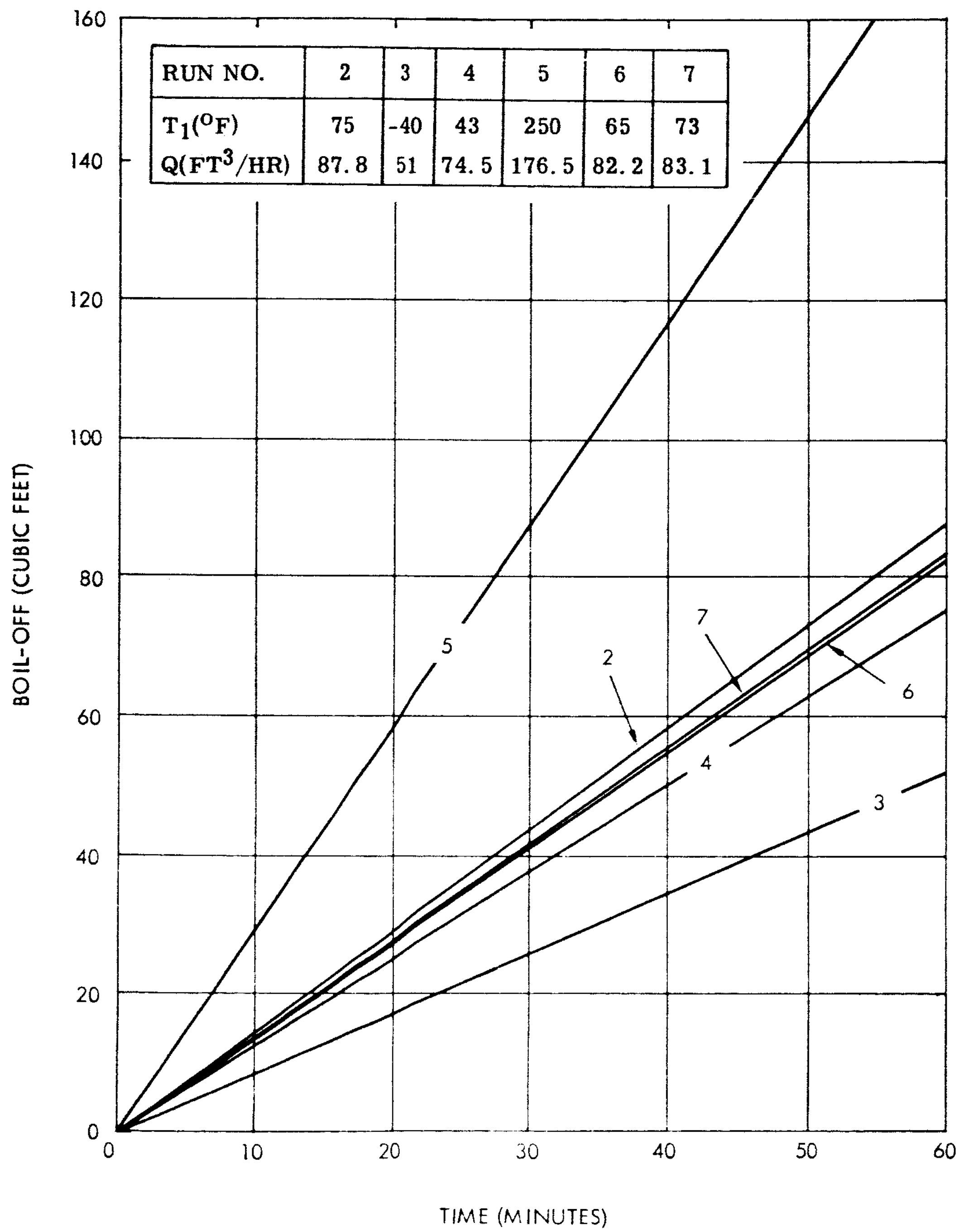
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in./hr-ft^2-°F)
Over-all panel	75		-423	498	0.161
0.2" HRP	75	-6		81	0.329
0.4" HMH		-6	-423	417	0.128

*MSFC dual-seal concept (HT-424 film adhesive)
**HRP is heat-resistant phenolic honeycomb.
†HMH is Hexcel Mylar honeycomb (CO_2 purged).

Table 16. Summary of Apparent Thermal Conductivity
Calorimeter Panel No. 3* (Continued)

Section	T_1	T_2	T_3	ΔT	K_a(BTU-in./hr-ft^2-^oF)
Test Run No. 3				Q = 51	
Over-all panel	-40		-423	383	0.122
0.2" HRP	-40	-92		52	0.299
0.4" HMH		-92	-423	331	0.094
Test Run No. 4				Q = 74.5	
Over-all panel	43		-423	466	0.146
0.2" HRP	43	-33		76	0.298
0.4" HMH		-33	-423	390	0.116
Test Run No. 5				Q = 176.5	
Over-all panel	250		-423	673	0.240
0.2" HRP	250	143		107	0.502
0.4" HMH		143	-423	566	0.190
Test Run No. 6				Q = 82.2	
Over-all panel	65		-423	488	0.154
0.2" HRP	65	-16		81	0.309
0.4" HMH		-16	-423	407	0.123
Test Run No. 7				Q = 83	
Over-all panel	73		-423	496	0.153
0.2" HRP	73	-8		81	0.309
0.4" HMH		-8	-423	415	0.122

*MSFC dual-seal concept



RUN NO.	2	3	4	5	6	7
T_1(°F)	75	-40	43	250	65	73
Q(FT^3/HR)	87.8	51	74.5	176.5	82.2	83.1

Figure 54. LH_2 Boil-Off versus Time
Calorimeter Panel No. 3

After the test, a visual inspection revealed no indications of degradation. A hot wire was used to slice through the Mylar core to separate the sandwich (see Figure 55). Examination indicated good bond fillets on both faces. Close examination of Mylar film to calorimeter bond showed air bubbles in the center of cells. Even with these bubbles, the bond to the tank was excellent, and it was very difficult to remove the film and clean the calorimeter surface.

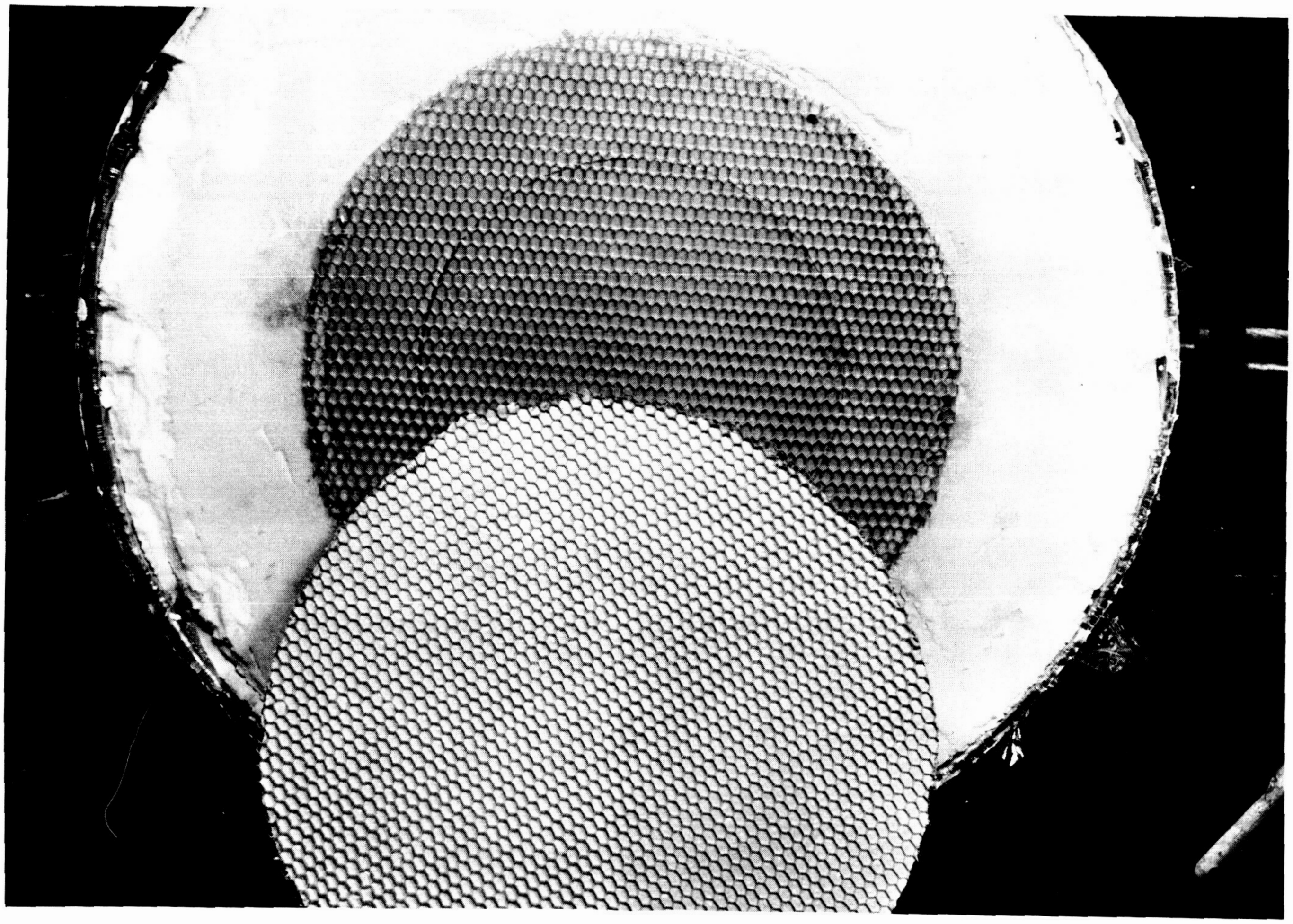


Figure 55. Calorimeter Panel No. 3 after Slicing Mylar Core with Hot Wire

6. Calorimeter Panel No. 4

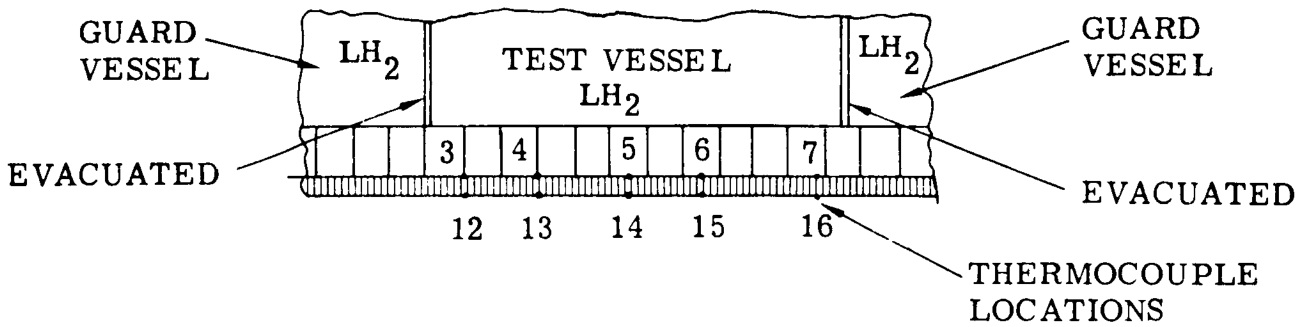
This panel was fabricated using 0.6-inch Mylar core and only the core, not the Mylar film, was roller coated with polyurethane adhesive. The chronological history of panel fabrication and testing is as follows:

1/26/65:	Cure panel.
2/16/65:	Bond panel calorimeter.
2/22/65:	Complete installation of thermocouples.
2/23/65:	Panel at Wingfoot Lake test site.
2/24/65:	Run No. 1 (46.6°F).
2/25/65:	Run No. 2 (75.4°F).
2/26/65:	Run No. 3 (-71.8°F).
3/2/65:	Run No. 4 (76.4°F).
3/2/65:	Run No. 5 (249.4°F).
3/3/65:	Run No. 6 (78.6°F).
3/9/65:	Dissect panel.

The test panel was helium purged prior to each test run. Thermocouple readings used for calculation of apparent thermal conductivity are tabulated in Table 17. The temperatures and apparent thermal conductivity are given in Table 18. The boil-off curves are shown in Figure 56.

Apparently something happened to the panel during or after run No. 5 as indicated by data taken on run No. 6. The temperature profile, as obtained from the thermocouples, indicates that a large amount of degradation occurred between thermocouples 3 and 5 on the center skin. All thermocouple wires were checked after the test and found to be satisfactory. A detailed inspection of the test panel and setup revealed no visible discrepancies. The most likely possibility of degradation would be helium leakage through the walls. The temperatures

Table 17. Temperatures Used in Calculation of Apparent Thermal Conductivity - Calorimeter Panel No. 4

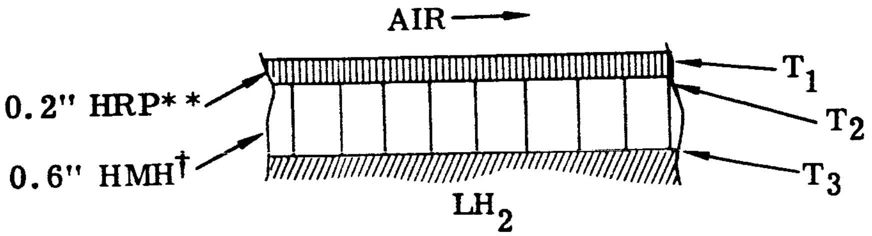


Run No.	Amb (°F)	Thermocouples (°F)									
		3	4	5	6	7	12	13	14	15	16
1 (2/24/65)	32	7	10	10	9	2	47	48	48	47	44
2 (2/25/65)	25	33	36	37	34	27	74	78	80	75	70
3 (2/26/65)	14	-109	-110	-102	-107	-102	-77	-74	-71	-70	-67
4 (3/2/65)	51	36	36	34	27	19	82	82	80	72	66
5 (3/2/65)	51	188	192	197	192	185	245	250	256	250	246
6 (3/3/65)	48	-3	-44	-10	+12	+15	75	60	78	87	91

encountered in the previous high temperature run could have caused delamination of the surface layers, causing a pinhole in the aluminum to become uncovered.

A hole 0.00025 x 0.00025 inch in the 1-1/2-mil aluminum skin of the panel would leak enough helium in about 20 minutes to thermally degrade the panel to the extent that was noted in test No. 6. This degradation, however, would require penetration through the core walls. This could have occurred over a period of time by permeation through the cell walls or the adhesive joints.

Table 18. Summary of Apparent Thermal Conductivity - Calorimeter Panel No. 4*



Test Run No. 1	Q = 91.5				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-°F)
Over-all panel	46.6	7.6	-423	469.6	0.238
0.2" HRP				39	0.715
0.6" HMH			-423	430.6	0.195
Test Run No. 2	Q = 104.6				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-°F)
Over-all panel	75.4	33.4	-423	498.4	0.257
0.2" HRP				42	0.763
0.6" HMH			-423	456.4	0.211
Test Run No. 3	Q = 51				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-°F)
Over-all panel	-71.8	-106	-423	351.2	0.178
0.2" HRP				34.2	0.644
0.6" HMH			-423	317	0.145
Test Run No. 4	Q = 104				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-°F)
Over-all panel	76.4	30.4	-423	499.4	0.256
0.2" HRP				46	0.695
0.6" HMH			-423	453.4	0.212

* MSFC dual-seal concept (AF-111 film adhesive).
** HRP is heat-resistant phenolic honeycomb.
† HMH is Hexcel Mylar honeycomb (air filled).

Table 18. Summary of Apparent Thermal Conductivity Calorimeter Panel No. 4* (Continued)

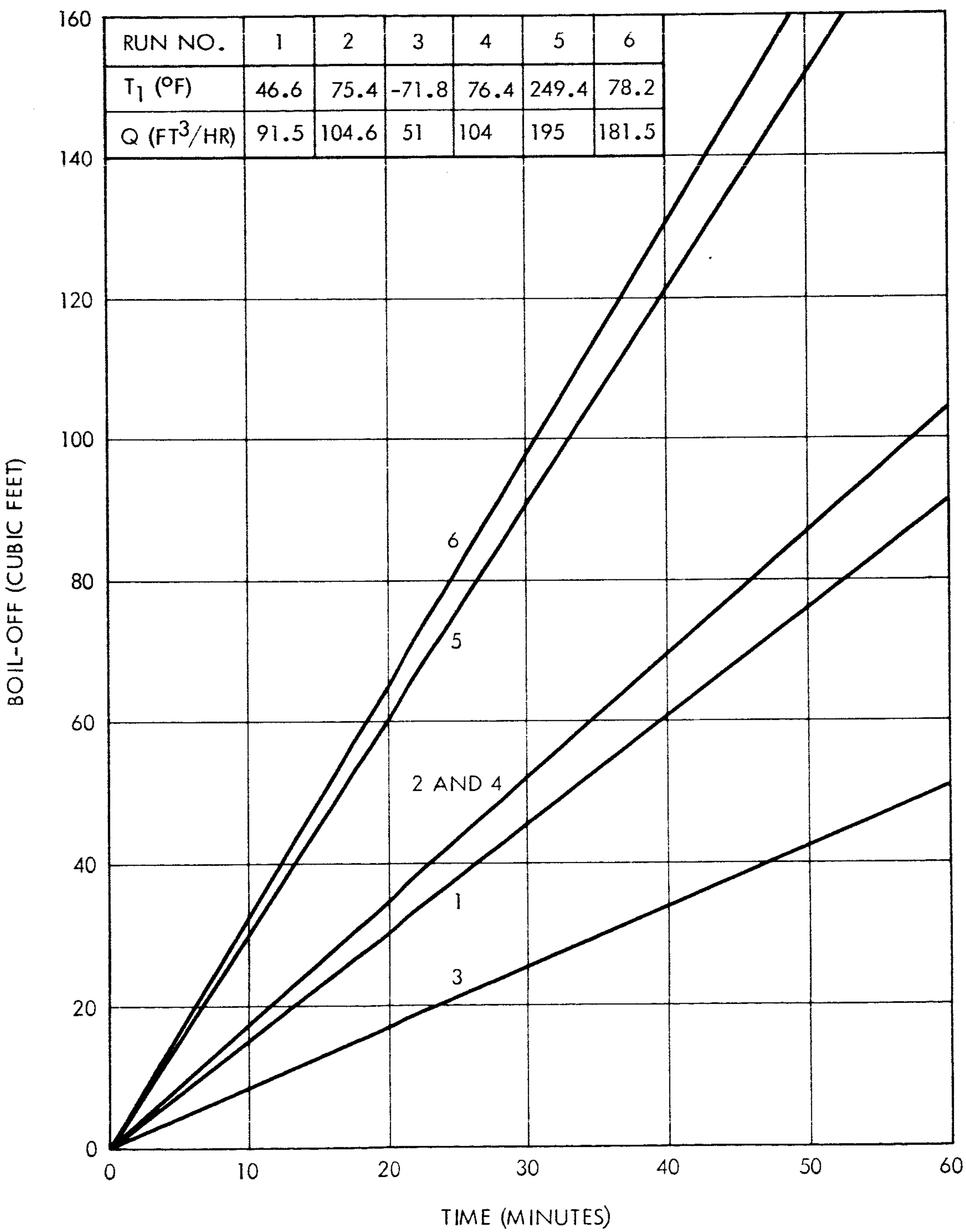
Test Run No. 5	Q = 195				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all Panel	249.4	190.8	-423	672.4	0.354
0.2" HRP				58.6	1.025
0.6" HMH			-423	613.8	0.292
Test Run No. 6	Q = 181.5				
Section	T_1	T_2	T_3	ΔT	K_a(BTU-in. /hr-ft^2-^oF)
Over-all panel	78.2	-6	-423	501.2	0.442
0.2" HRP				72.2	0.770
0.6" HMH			-423	417	0.398

* MSFC dual-seal concept.

Shorting out by helium may occur in only a small region; however, the temperature profile from thermocouple readings will be changed over a larger region due to heat being conducted along the aluminum foil in the lower surface layer.

If the helium leaks into the lower panel, the hot side of the lower panel at that point would reach a temperature of about -150^{o}F. The temperature profiles obtained would seem to verify such a result.

During dissection of the panel, the ring area extending beyond the calorimeter was removed without damaging the sandwich. A helium detector check indicated the presence of helium in the Mylar core sealed cells. It is assumed that the helium permeated the Mylar skin from the purge chamber. Helium could leak in from the outside area of the specimen, but this seems highly unlikely when one looks at the temperature profiles that were obtained (see Table 17). Therefore,



RUN NO.	1	2	3	4	5	6
T_1 (°F)	46.6	75.4	-71.8	76.4	249.4	78.2
Q (FT^3/HR)	91.5	104.6	51	104	195	181.5

Figure 56. LH_2 Boil-Off versus Time - Calorimeter Panel No. 4

the most probable explanation would be that a small pinhole was uncovered in the aluminum foil at the conclusion of the high-temperature run (No. 5). The helium that surrounded the specimen then had adequate time to leak in and degrade the specimen before the next test (No. 6) was run.

7. Calorimeter Panel No. 5

This panel was essentially the same as panel No. 4 with two exceptions:

(1) The Mylar film and the core were roller coated with polyurethane adhesive.

(2) A radiation barrier was installed in the guard area to reduce edge defects. The radiation barrier consisted of spraying two concentric rings of aluminum paint in the Mylar core. This paint was applied prior to bonding on the Mylar face sheet. While it was not apparent during fabrication and installation of the panel, the aluminum paint acted as a contaminant. Therefore, the bond was so poor in this area that it failed during testing.

The chronological history of the test sample is as follows:

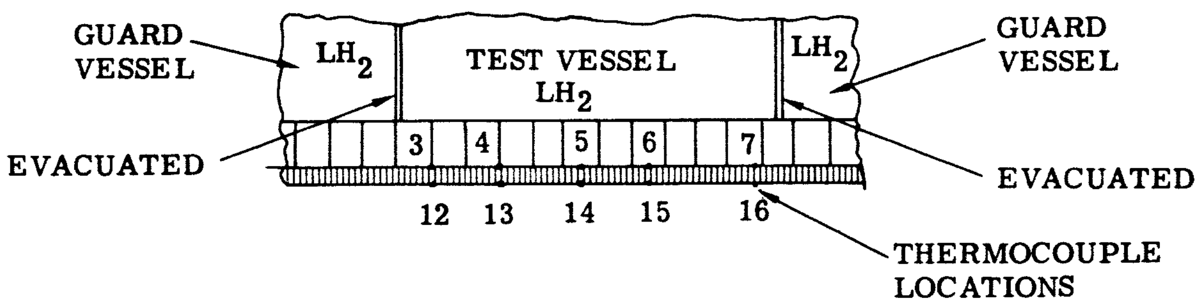
2/24/65:	Cure panel.
3/16/65:	Bond panel to calorimeter.
3/23/65:	Set up at Wingfoot Lake test site.
3/24/65:	Run No. 1 (45^{o}F).
3/25/65:	Run No. 2 (77^{o}F).
3/25/65:	Run No. 3 (-64^{o}F).
3/26/65:	Run No. 4 (75^{o}F).
3/26/65:	Run No. 5 (255^{o}F).
3/29/65:	Lost vacuum in calorimeter; terminate test.
4/6/65:	Dissect panel.

During the testing, it was noted that the vacuum between the test chamber and the guard deteriorated as the test progressed. After test No. 5, it was impossible to pull the vacuum; therefore, test No. 6 was not run.

Temperatures used in the calculation of apparent thermal conductivity are tabulated in Table 19. The temperatures and apparent thermal conductivities are given in Table 20, and the boil-off curves are shown in Figure 57.

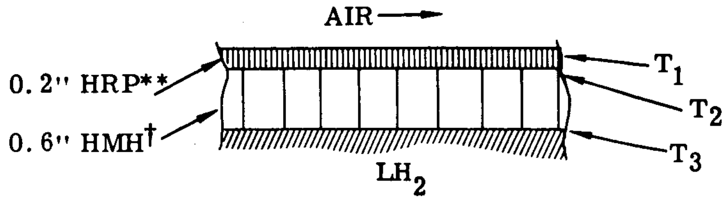
The test panel was helium purged before each run. During dissection of the panel, all bonds were carefully examined. The core to skin bonds had good

Table 19. Temperatures Used in Calculation of Apparent Thermal Conductivity - Calorimeter Panel No. 5



Run No.	Amb (^oF)	Thermocouples (^oF)									
		3	4	5	6	7	12	13	14	15	16
1 (3/24/65)	30	-5	12	16	17	3	34	44	49	51	45
2 (3/25/65)	29	25	45	54	56	40	59	74	86	88	80
3 (3/25/65)	34	-100	-88	-86	-88	-100	-68	-63	-60	-62	-69
4 (3/26/65)	29	10	47	54	50	24	55	76	87	84	70
5 (3/26/65)	27	147	200	207	197	158	234	261	273	265	245

Table 20. Summary of Apparent Thermal Conductivity Calorimeter Panel No. 5*



Section	T_1	T_2	T_3	ΔT	K_a(BTU-in./hr-ft^2-^oF)
Test Run No. 1			Q = 102.87		
Over-all panel	44.8		-423	467.8	0.320
0.2" HRP	44.8	8.6		36.2	1.04
0.6" HMH		8.6	-423	431.6	0.260
Test Run No. 2			Q = 119.22		
Over-all panel	77.2		-423	500.2	0.347
0.2" HRP	77.2	43.8		33.4	1.30
0.6" HMH		43.8	-423	466.8	0.278
Test Run No. 3			Q = 60.42		
Over-all panel	-64.4		-423	358.6	0.244
0.2" HRP	-64.4	-92.4		28.0	0.784
0.6" HMH		-92.4	-423	330.6	0.199
Test Run No. 4			Q = 141.50		
Over-all panel	75		-423	498	0.413
0.2" HRP	75	37		38	1.350
0.6" HMH		37	-423	460	0.336
Test Run No. 5			Q = 228.28		
Over-all panel	255.2		-423	678.2	0.490
0.2" HRP	255.2	182		73.2	1.14
0.6" HMH		182	-423	605	0.413

*MSFC dual-seal concept
**HRP is heat-resistant phenolic honeycomb.
†HMH is Hexcel Mylar honeycomb.

RUN NO.	1	2	3	4	5
T_1 (°F) Q (FT^3/HR)	45 102.9	77 119	-64 60.4	75 141.5	255 228

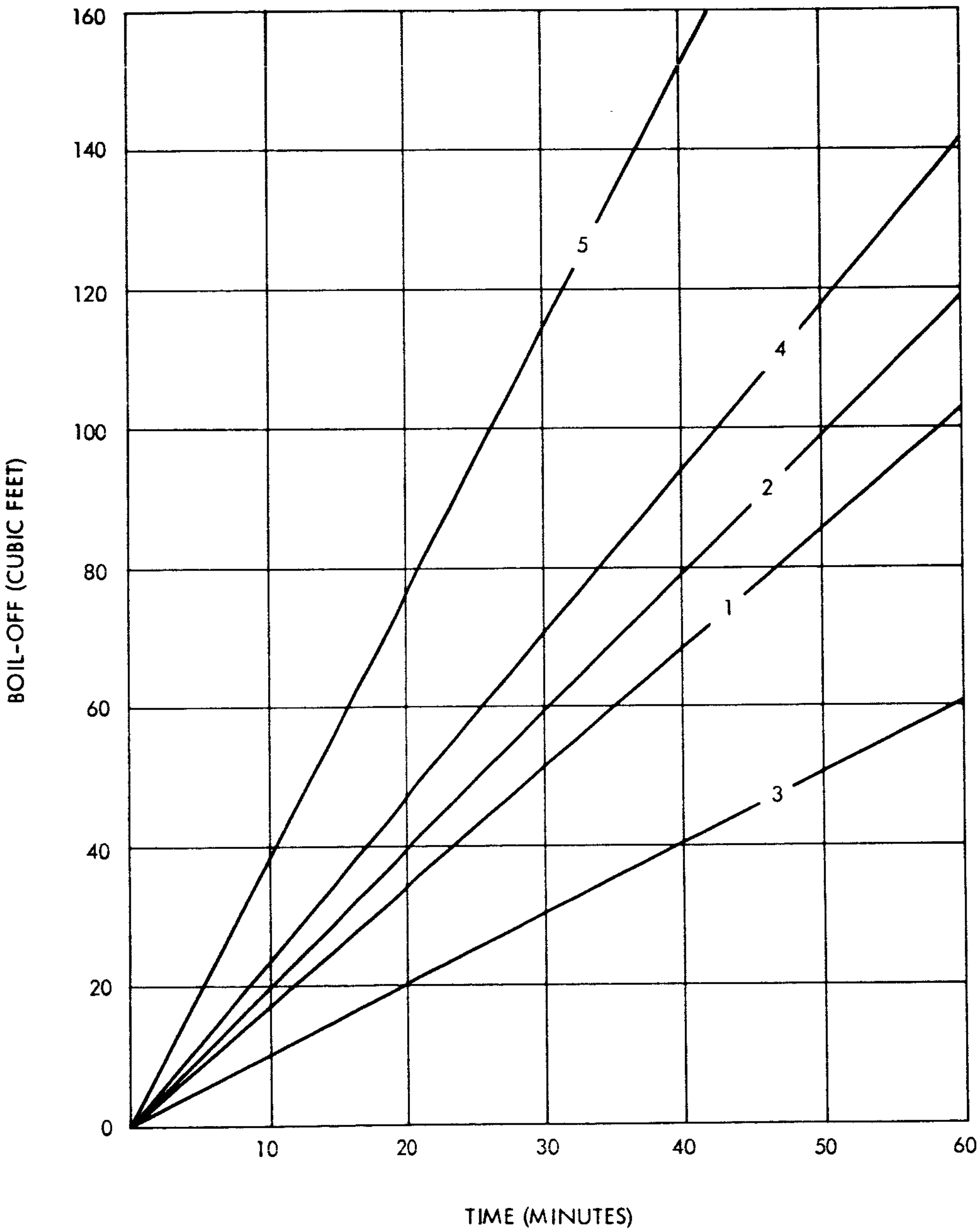


Figure 57. LH_2 Boil-Off versus Time Calorimeter Panel No. 5

fillets except in the area of the aluminum paint radiation shield. On one side of the panel, there appeared to be air pockets between the tank surface and Mylar skin. While these were small, it is possible that the helium could have found a passage through these pockets into the vacuum ring, which would account for the loss of vacuum. It is believed that the guard area became saturated with helium due to the bond failure caused by the radiation barrier. Also, the test panel gradually deteriorated from edge permeation of helium as indicated by the difference between the test data of panel No. 5 and panel No. 4.

8. Calorimeter Panel No. 6

This panel was fabricated similar to test panel No. 5. However, MMA (Mylar, Mylar, aluminum) film was substituted for the 0.0015-inch aluminum center skin, which was bonded to the Mylar core with G-208 adhesive (roller coat). During fabrication, the adhesive roller coat seemed thinner than other previously used materials, but it appeared to bond satisfactorily during cure. However, after bonding the panel to the calorimeter, it appeared dished, and a tapping test indicated voids. It was assumed that the bond failures were between the tank and the Mylar skin; however, further investigation revealed the failure to be at the G-208 adhesive bond. No tests were run. It was concluded that more development would be required on the G-208 system. Because of the time schedule, it was not feasible to attempt to resolve this problem during this program.

9. Calorimeter Panel No. 7

This panel was a 0.6-inch Mylar core sandwich with an MAAM center skin. Both Mylar core and film were roller coated with polyurethane adhesive. The chronological history of the test panel is as follows:

5/19/65: Cure panel.

5/26/65: Bond panel to calorimeter.

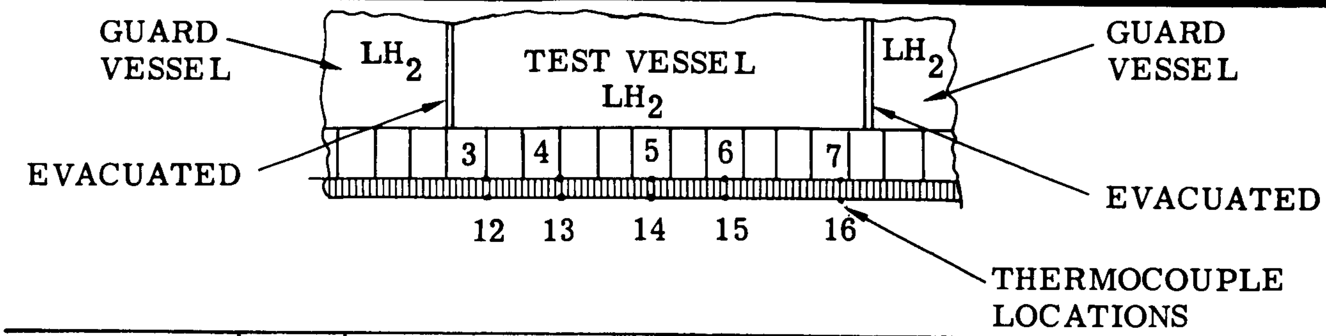
6/3/65:	Run No. 1 (-21°F).
6/3/65:	Run No. 2 (44°F).
6/4/65:	Run No. 3 (-29°F).
6/4/65:	Run No. 4 (82°F).
6/7/65:	Run No. 5 (-46°F).
6/7/65:	Run No. 6 (246°F).
6/8/65:	Run No. 7 (-64°F).
6/8/65:	Run No. 8 (82°F).
6/9/65:	Run No. 9 (-110°F).
6/10/65:	Run No. 10 (70°F).
6/11/65:	Dissect panel.

On runs No. 1 through 8, CO_2 was used to purge the HRP core instead of helium as in previous tests. Although the panel had obviously degraded, runs No. 9 and 10 were conducted using a helium purge to compare the two gases. Temperature readings are given in Table 21. Boil-off data is given in Table 10 and Figure 47, which indicate the progressive degradation of the panel.

During the test, it was noted that it was difficult to hold a vacuum on the calorimeter. During dissection and inspection of the panel, it was discovered that there was a partial void between the tank and Mylar skin from the edge into the vacuum ring. Also, there were breaks in the Mylar skin along the vacuum ring. The panel itself looked good, and bond fillets were sound.

Because of the bond problem and subsequent helium contamination in the area of the vacuum ring, the data is not representative of the panel. Therefore, no calculations of conductivity (K_a) were made. The available data, however, does show relative effects of CO_2 versus helium as a purge gas.

Table 21. Temperature Readings - Calorimeter Panel No. 7



Run No.	Amb (°F)	Thermocouples (°F)									
		3	4	5	6	7	12	13	14	15	16
1 (6/3/65)	63	-101	-101	-102	-102	-111	-18	-18	-22	-25	-24
2 (6/3/65)	70	-62	-55	-55	-58	-91	40	46	46	43	44
3 (6/4/65)	68	-108	-104	-105	-106	-114	-27	-24	-28	-31	-36
4 (6/4/65)	72	-60	-26	-31	-32	-76	76	88	82	81	81
5 (6/7/65)	80	-127	-115	-113	-120	-126	-48	-36	-43	-46	-59
6 (6/7/65)	75	7	111	100	98	12	236	262	255	249	229
7 (6/8/65)	77	-136	-120	-114	-130	-136	-67	-43	-59	-70	-80
8 (6/8/65)	71	-106	-35	-44	-48	-108	77	97	86	85	74
9 (6/9/65)	71	-150	-131	-141	-140	-150	-104	-103	-115	-118	-109
10 (6/10/65)	80	-16	38	28	29	-12	59	89	71	71	59

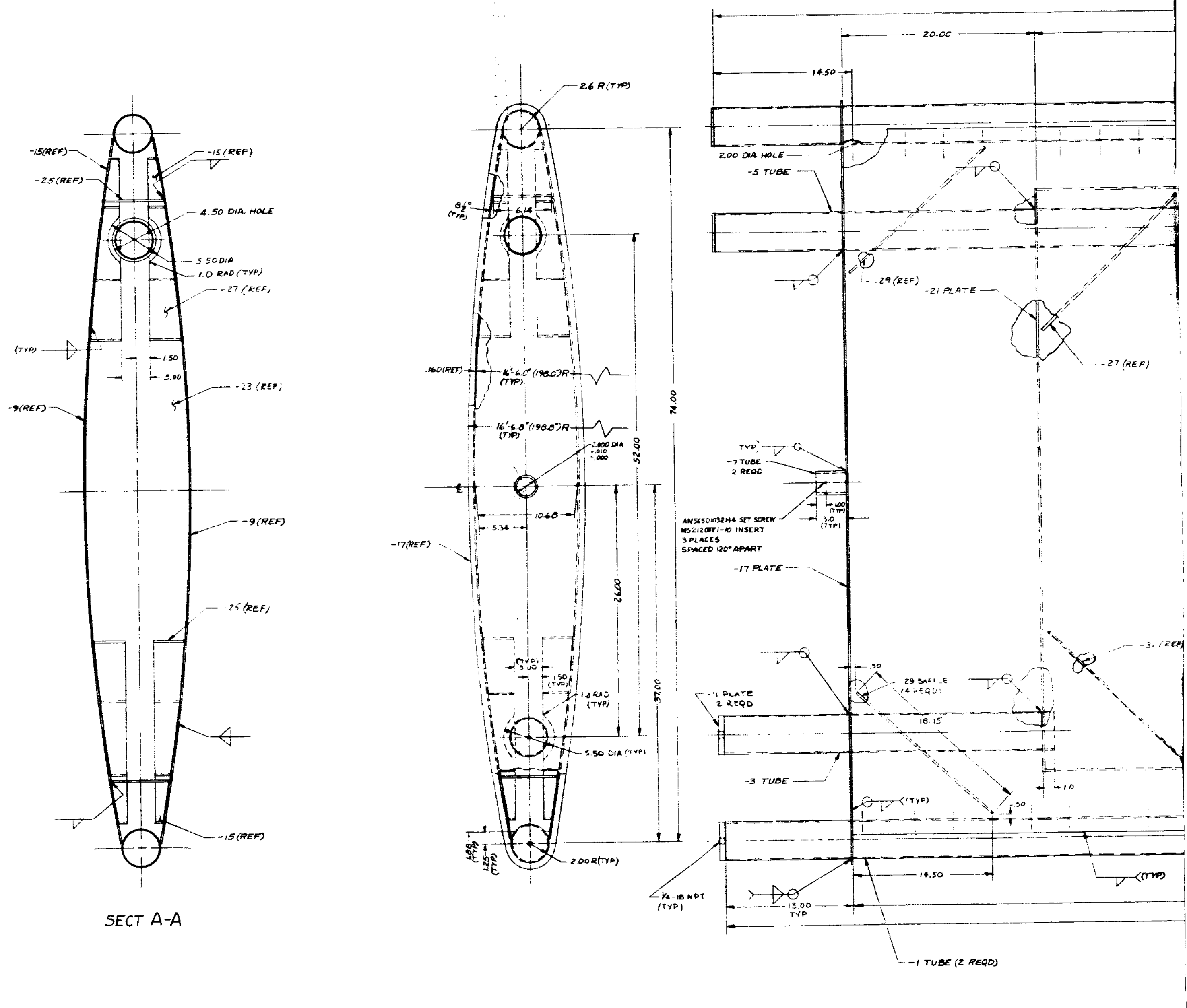


Figure 58. Test Tank Design for LH_2 Insulation Systems Tests

SECTION VIII. LH_2 TANK TESTS

A. TEST TANK

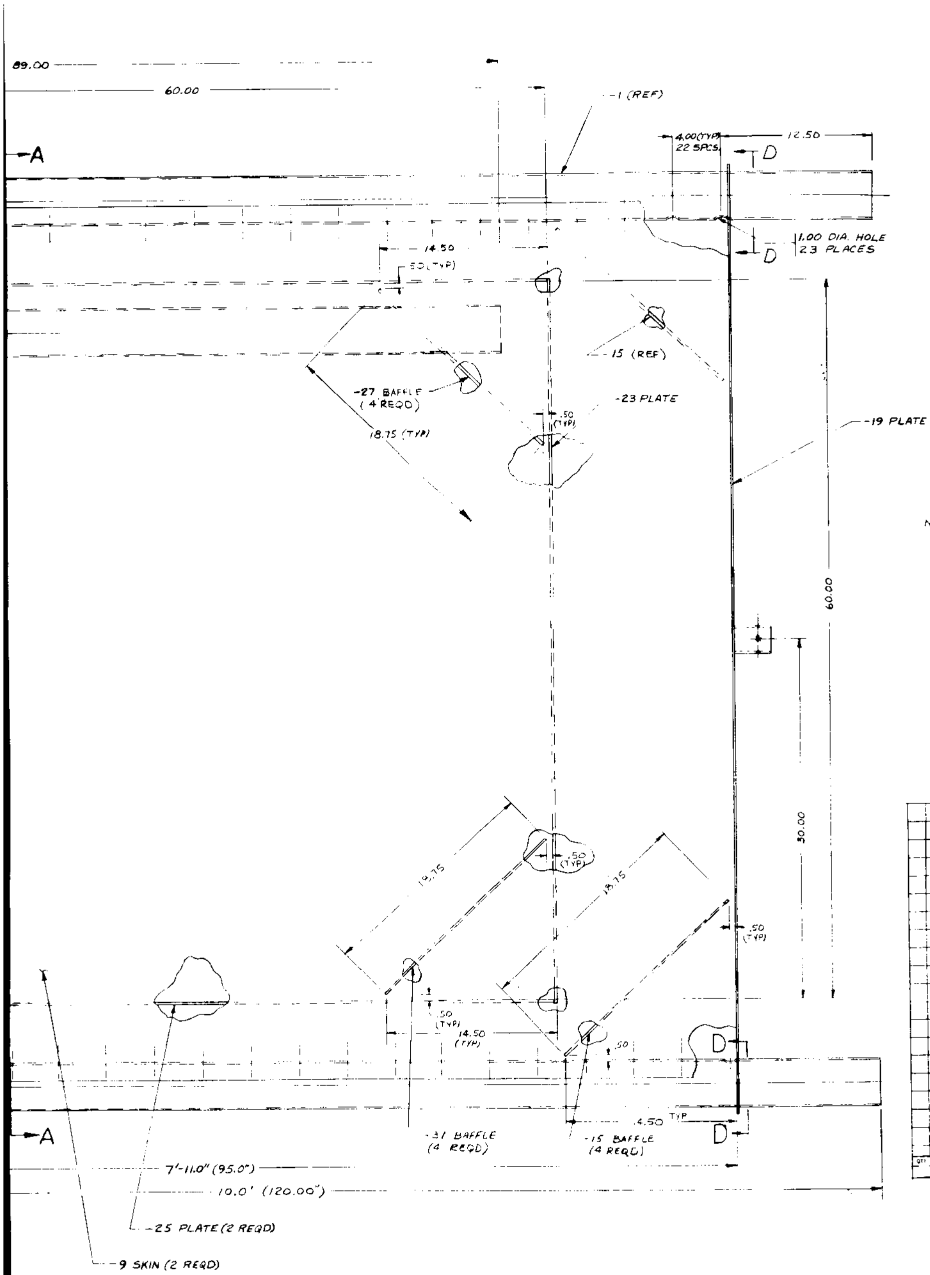
The design of the metal test tank for testing insulation panels under actual liquid-hydrogen fill and drain cycles is shown in Figure 58. The tank comprises a 5 x 5 foot measuring vessel surrounded by a cold guard. It was fabricated of 0.160-inch-thick 2219 aluminum alloy skins. Considerable difficulty was experienced with warping during welding. Major distortions were straightened, but some waviness remained in the weld areas. This caused difficulties in obtaining 100 percent area bond during installation of the insulation panels. The completed tank mounted in the support stand is shown in Figure 59.

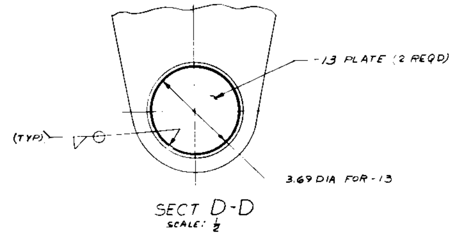
B. INSULATION PANELS

The insulation panels were fabricated and bonded to the tank as indicated in Section IV. Dual-seal insulation was used to cover the edges and top and bottom of tank (see Figure 60). Foam was used to insulate the tube ends and fittings (see Figure 61). During fabrication of the panels, internal thermocouples were installed. External thermocouples were bonded to the outer surface. Thermocouple locations are shown in Figure 62. The test area of the panel was painted with black epoxy to provide better heat control.

C. TEST FACILITY

All testing with liquid hydrogen was done at GAC's Wingfoot Lake test site, located approximately five miles from the main plant. The test facility comprises a control room, a patio for small calorimeter testing, a test pad enclosed in an earth bunker, a control and instrumentation wireway, and an LH_2





NOTES: UNLESS OTHERWISE SPECIFIED

1. ALL SEAM WELDS & FILLET WELDS ENCLOSING TANK MUST BE AIR TIGHT
2. WHERE SKINS MEET -1 TUBES WELD SO THAT WELD AREA FOLLOWS CONTOUR OF SKIN BECOMING TANGENT TO TUBE O.D.

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SIZE	SPECIFICATION	ZONE	ITEM NO.
4		-31	GUSSET	2219-T87 AL ALLOY .160 x 3.50 x 9.00	MIL-A-8920 TEMP-T87		
4		-29	GUSSET	2219-T87 AL ALLOY .160 x 3.00 x 19.00	MIL-A-8920 TEMP-T87		
4		-27	GUSSET	2219-T87 AL ALLOY .160 x 3.50 x 19.00	MIL-A-8920 TEMP-T87		
2		-25	PLATE	2219-T87 AL ALLOY .160 x 6.50 x 61.00	MIL-A-8920 TEMP-T87		
2		-23	PLATE	2219-T87 AL ALLOY .160 x 6.50 x 61.00	MIL-A-8920 TEMP-T87		
1		-21	PLATE	2219-T87 AL ALLOY .160 x 11.50 x 72.00	MIL-A-8920 TEMP-T87		
1		-19	PLATE	2219-T87 AL ALLOY .160 x 11.50 x 72.00	MIL-A-8920 TEMP-T87		
1		-17	PLATE	2219-T87 AL ALLOY .160 x 3.50 x 80.[illegible]	MIL-A-8920 TEMP-T87		
4		-15	BAFFLE	2219-T87 AL ALLOY .160 x 3.00 x 19.[illegible]	MIL-A-8920 TEMP-T87		
2		-13	PLATE	2219-T87 AL ALLOY .160 x 4.25 x 4.25	MIL-A-8920 TEMP-T87		
2		-11	PLATE	6061-T6 AL ALLOY .50 x 4.25 x 4.25	QQ-A-327 TEMP T6		
2		-9	SKIN	2219-T87 AL ALLOY .160 x 75.00 x 95.50	MIL-A-8920 TEMP T87		
2		-7	TUBE	6061-T6 AL TUBE .250 WALL x 2.50 O.D. x 3.25	WW-T-789 TEMP-T6 TYPE I		
1		-5	TUBE	6061-T6 AL TUBE .125 WALL x 4.00 O.D. x 89.25	WW-T-789 TEMP-T6 TYPE I		
1		-3	TUBE	6061-T6 AL TUBE .125 WALL x 4.00 O.D. x 34.75	WW-T-789 TEMP T6 TYPE I		
2		-1	TUBE	6061-T6 AL TUBE .25 WALL x 4.00 x 120.00	WW-T-789 TEMP T6 TYPE I		
X		-101	TEST TANK				

LIST OF MATERIALS

130-2

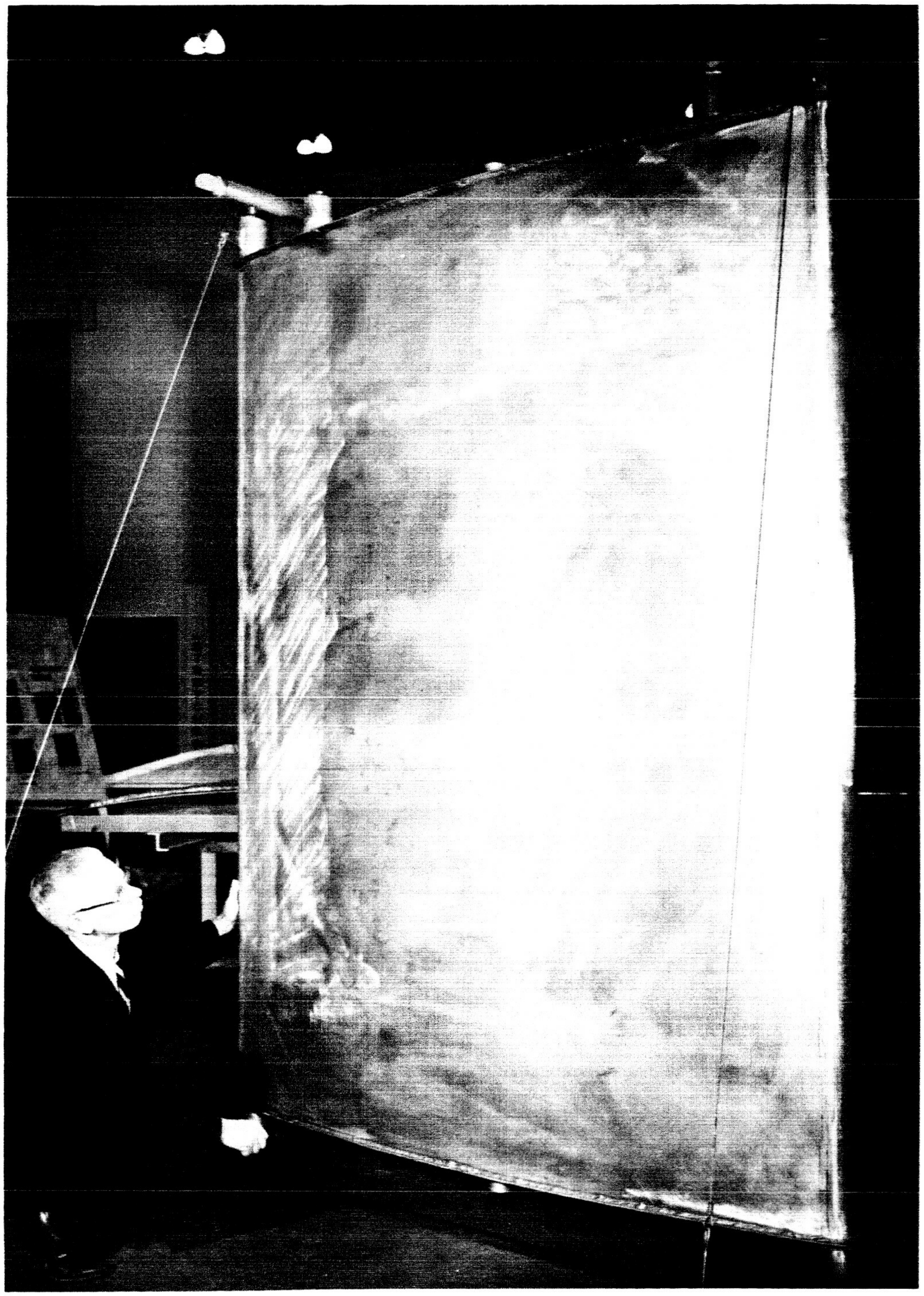


Figure 59. LH_2 Test Tank

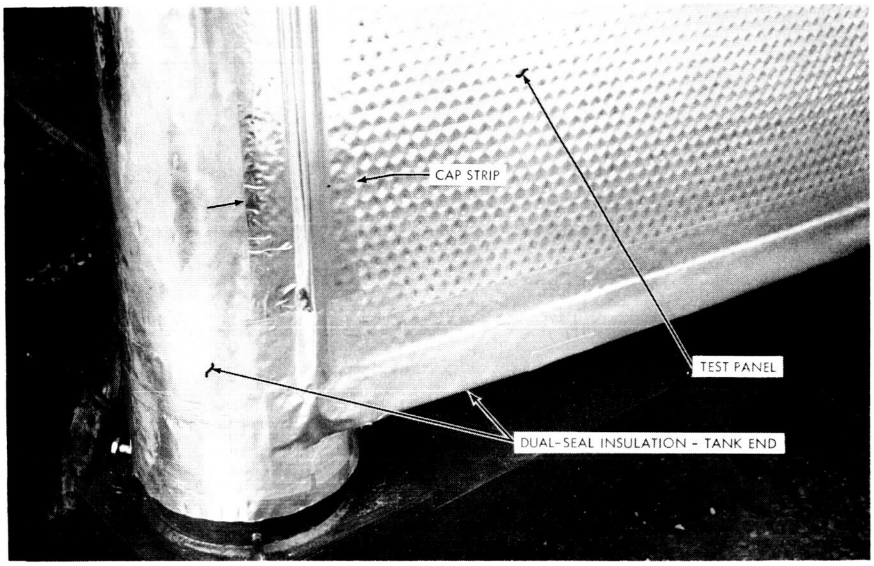


Figure 60. Dual-Seal-Insulated Test Tank

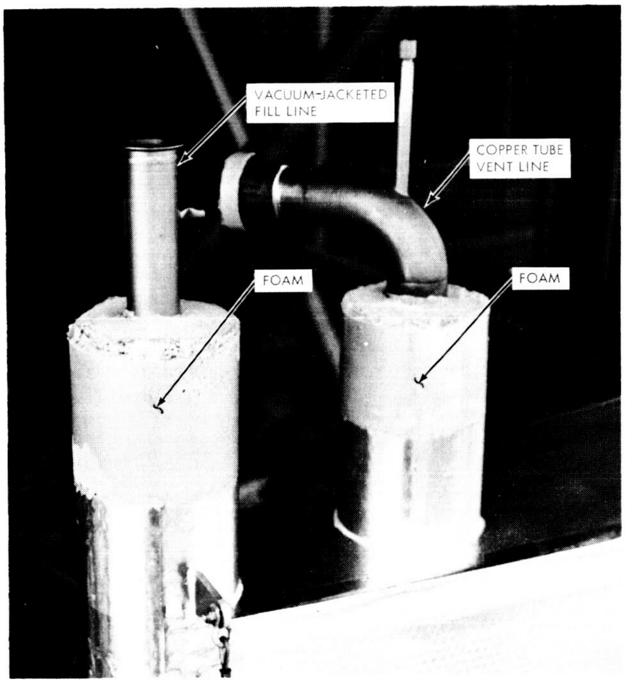
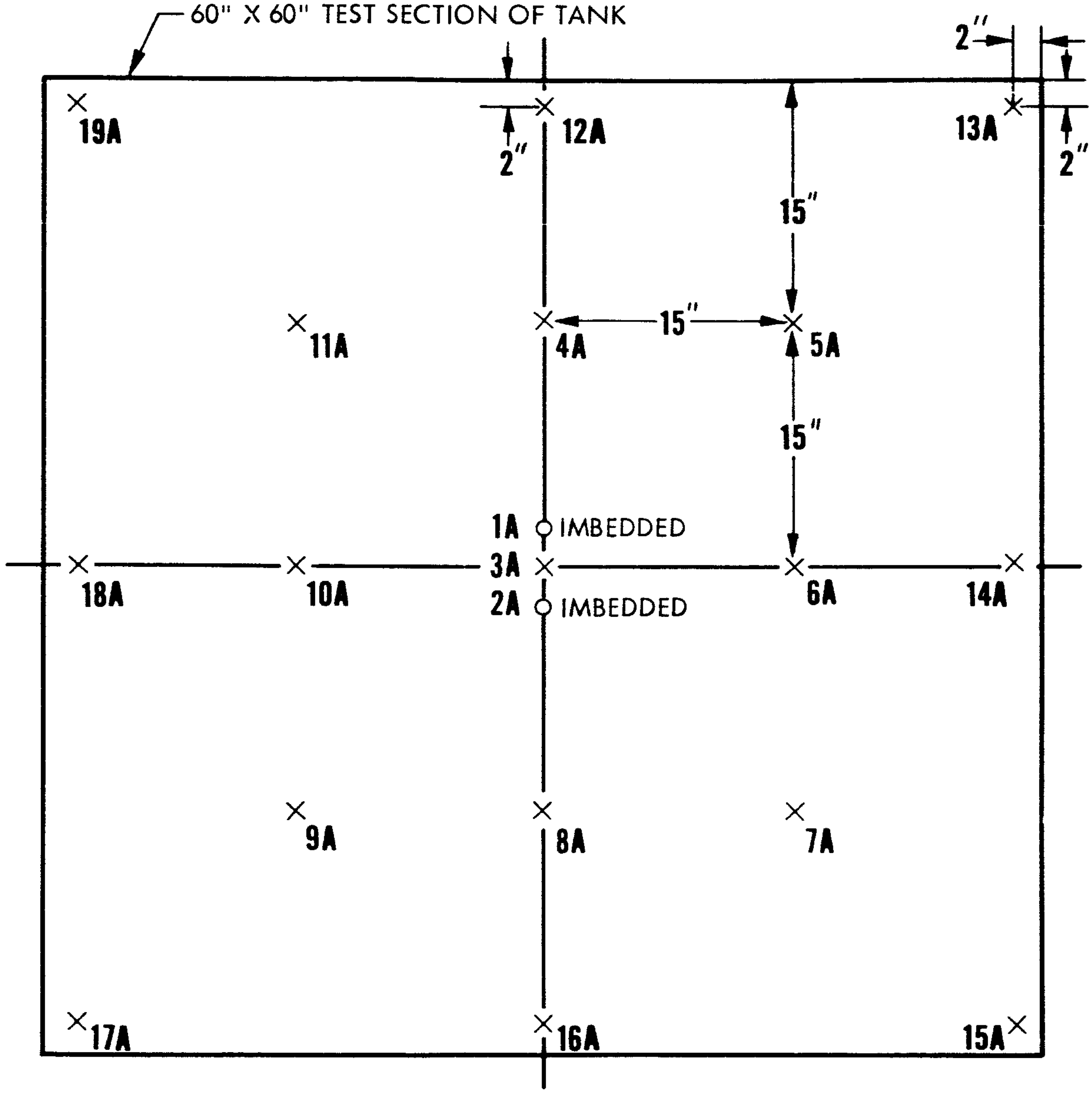


Figure 61. Foam-Insulated Test Tank



SIDE A THERMOCOUPLE LOCATIONS ON TEST TANK.

SIDE B LOCATIONS ARE REVERSED FROM LEFT TO RIGHT IN ORDER THAT POSITION OF EACH NUMBER IS LOCATED IN SAME RELATIVE POSITION ON OPPOSITE SIDE OF TEST TANK (I.E., 15B IS DIRECTLY BEHIND 15A).

Figure 62. Location of Thermocouples on Test Panels - Systems No. 1 and 2

storage tank. The trailer control room is located 300 feet from the bunker-enclosed test pad. Figure 63 shows the control trailer and test patio with calorimeter test setup. Figure 64 shows the inside of the control trailer. Figures 65, 66, and 67 show the relative layout of the control trailer, wireway, and test bunker. Figure 68 shows the test pad inside the bunker with the tanks, transfer lines, and test equipment. Figure 69 shows the 13,000-gallon LH_2 storage tank with connecting supply line at the rear of the bunker.

D. APPARATUS AND TEST SETUP

The LH_2 test tank is positioned on the test pad inside the protective bunker as shown in Figure 70. During the heating cycle, the quartz lamp heating fixtures are located as shown in Figure 71. The test setup is shown schematically with a flow diagram of the LH_2 transfer system in Figure 72. A diagram of the tank and locations of the liquid level measuring sensors is shown in Figure 73.

The apparatus for conducting the large tank tests has been successful in providing a flow control system that is safe, relatively simple to operate, and capable of generating reliable test data. Basic components of the system are discussed in the following paragraphs.

1. Liquid Hydrogen Transfer Lines

All LH_2 lines are 3/4-inch vacuum-jacketed stainless-steel tubing. Bayonet-type fittings with O-ring seals are used to join the various sections of vacuum-jacketed lines. All plumbing is located above the test tank so that gas leaks, if any, will not pass around the electric heating equipment adjacent to the test panels.

2. Cryogenic Valves

All valves used in the control of liquid hydrogen are vacuum jacketed. The 1-inch liquid withdrawal valve at the storage tank is manually operated. Valve

Figure 63. Test Facility at Wingfoot Lake Test Site

Figure 64. Inside of Control Trailer

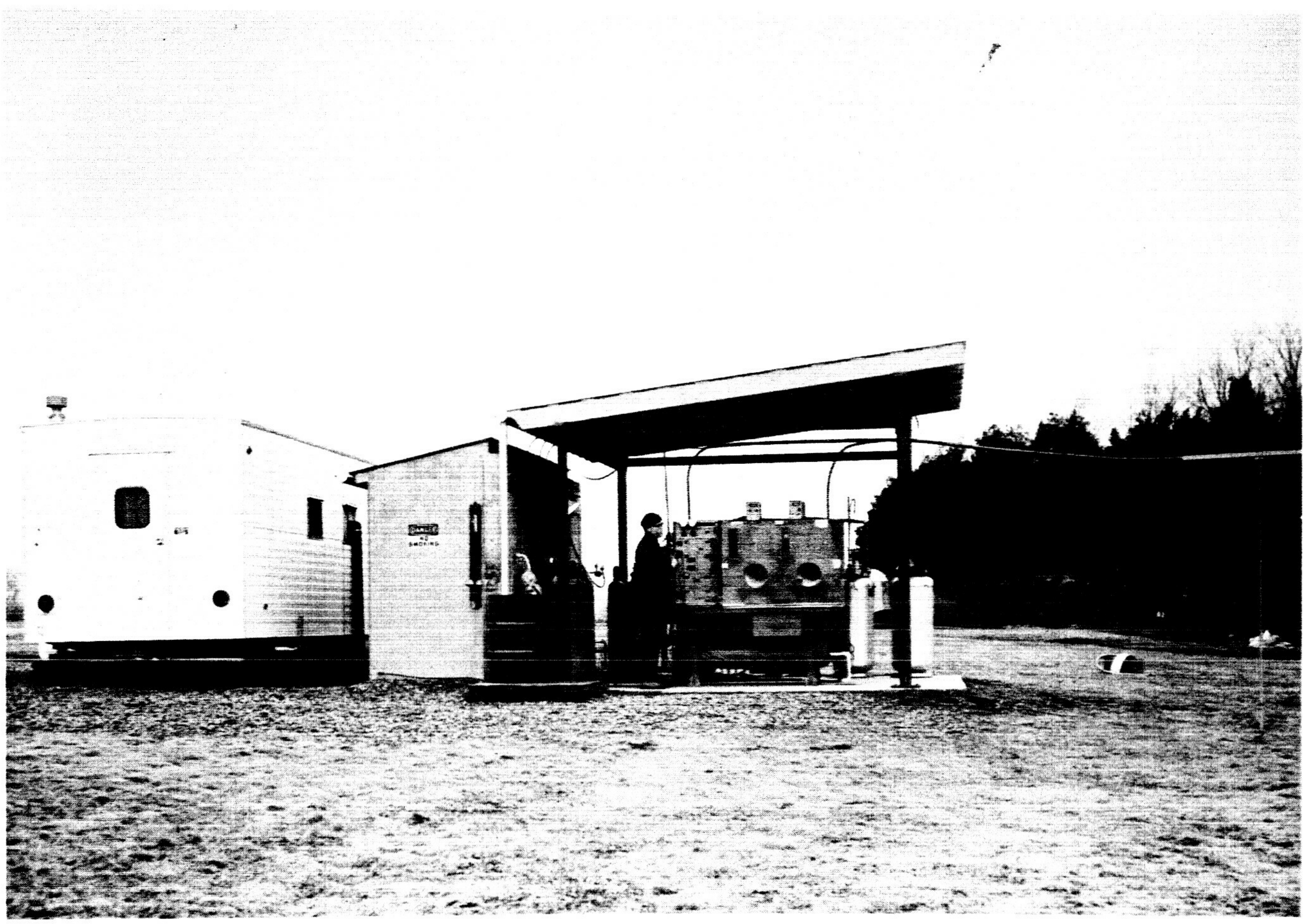


Figure 65. Test Site with Bunker in Background

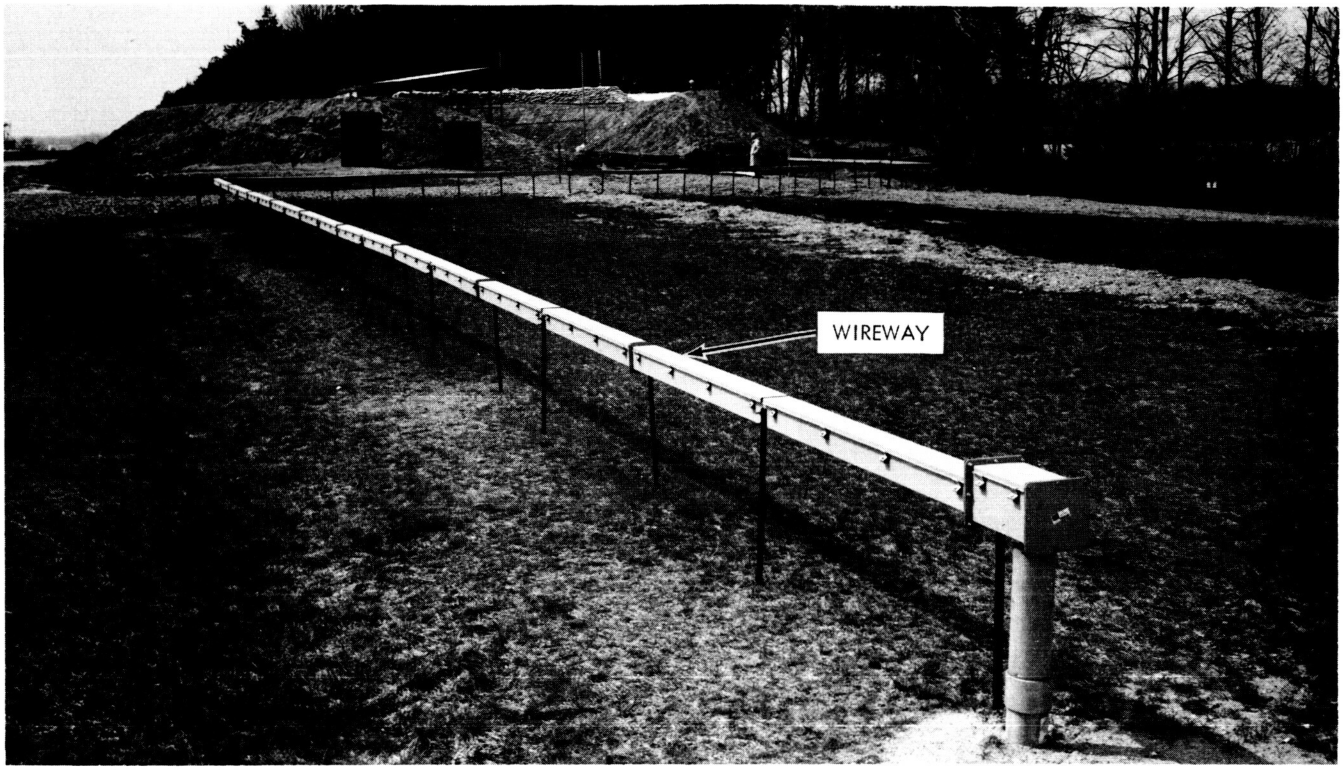


Figure 66. View Looking from Control Trailer toward Test Bunker

Figure 67. View of Test Setup in Bunker

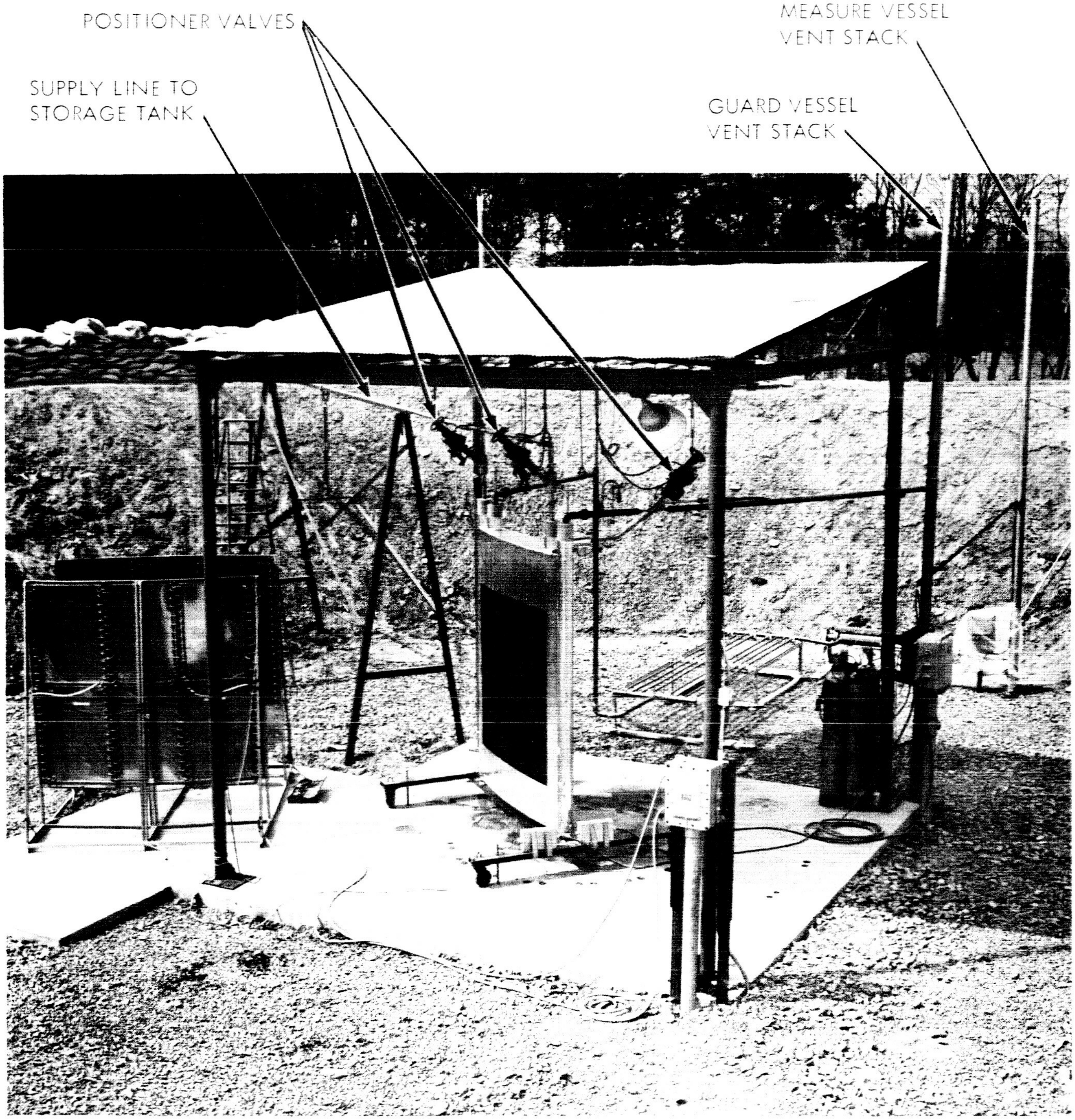


Figure 68. LH_2 Tank on Test Pad

Figure 69. LH_2 Storage Tank at Rear of Test Bunker

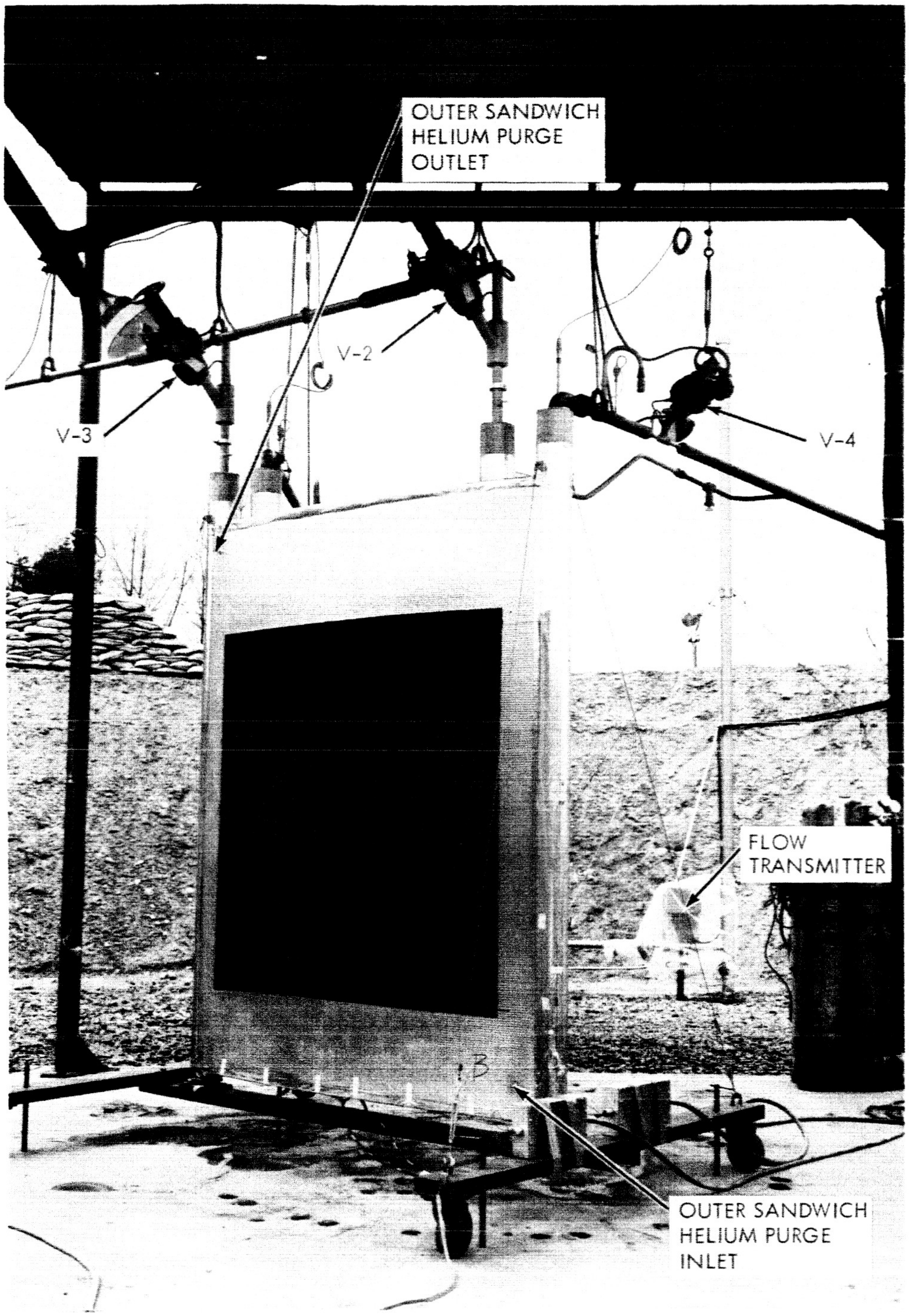


Figure 70. Close-Up of LH_2 Tank and Control Valves

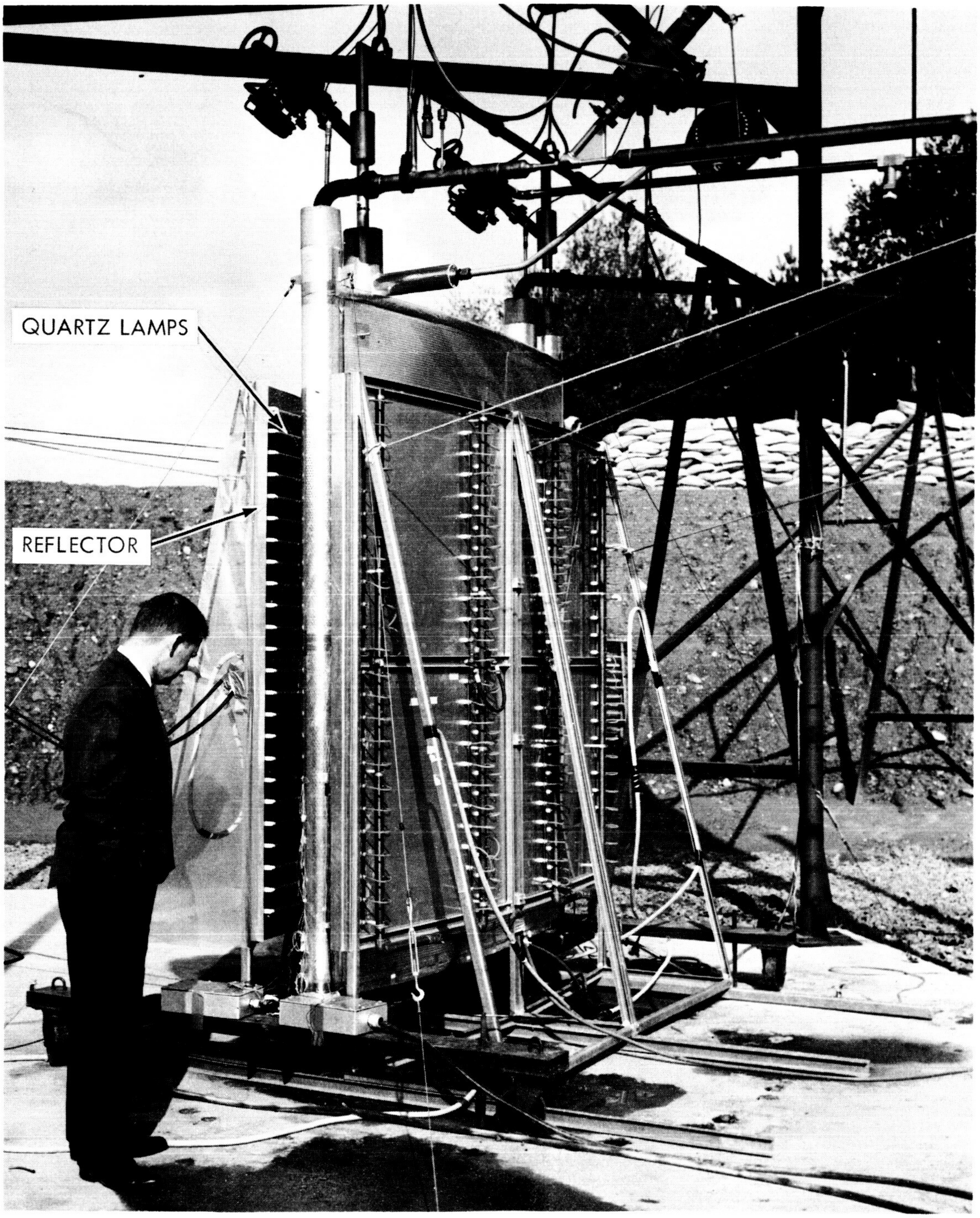


Figure 71. LH_2 Test Tank Setup with Heating Lamps in Position

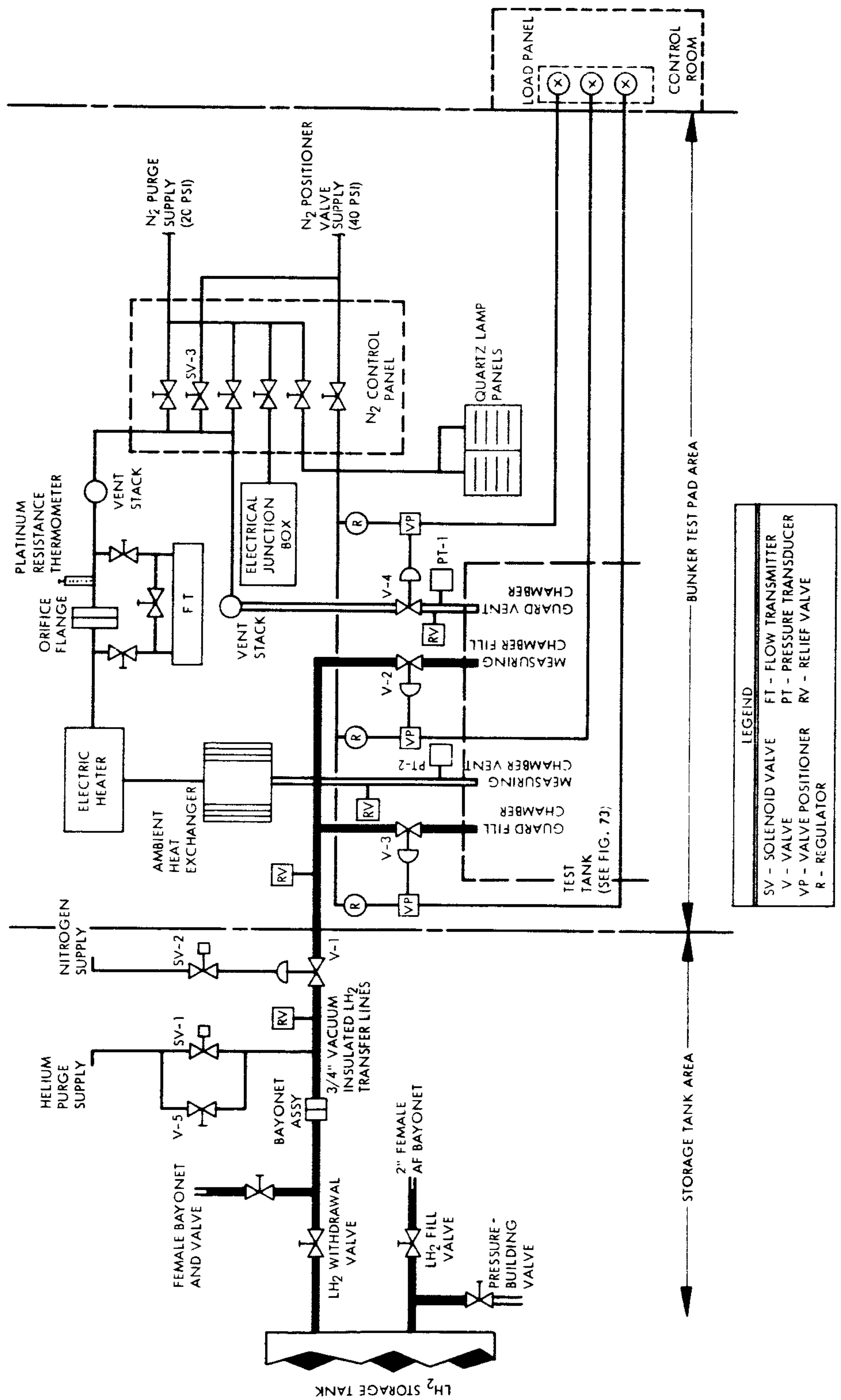


Figure 72. Flow Diagram of LH_2 Transfer System

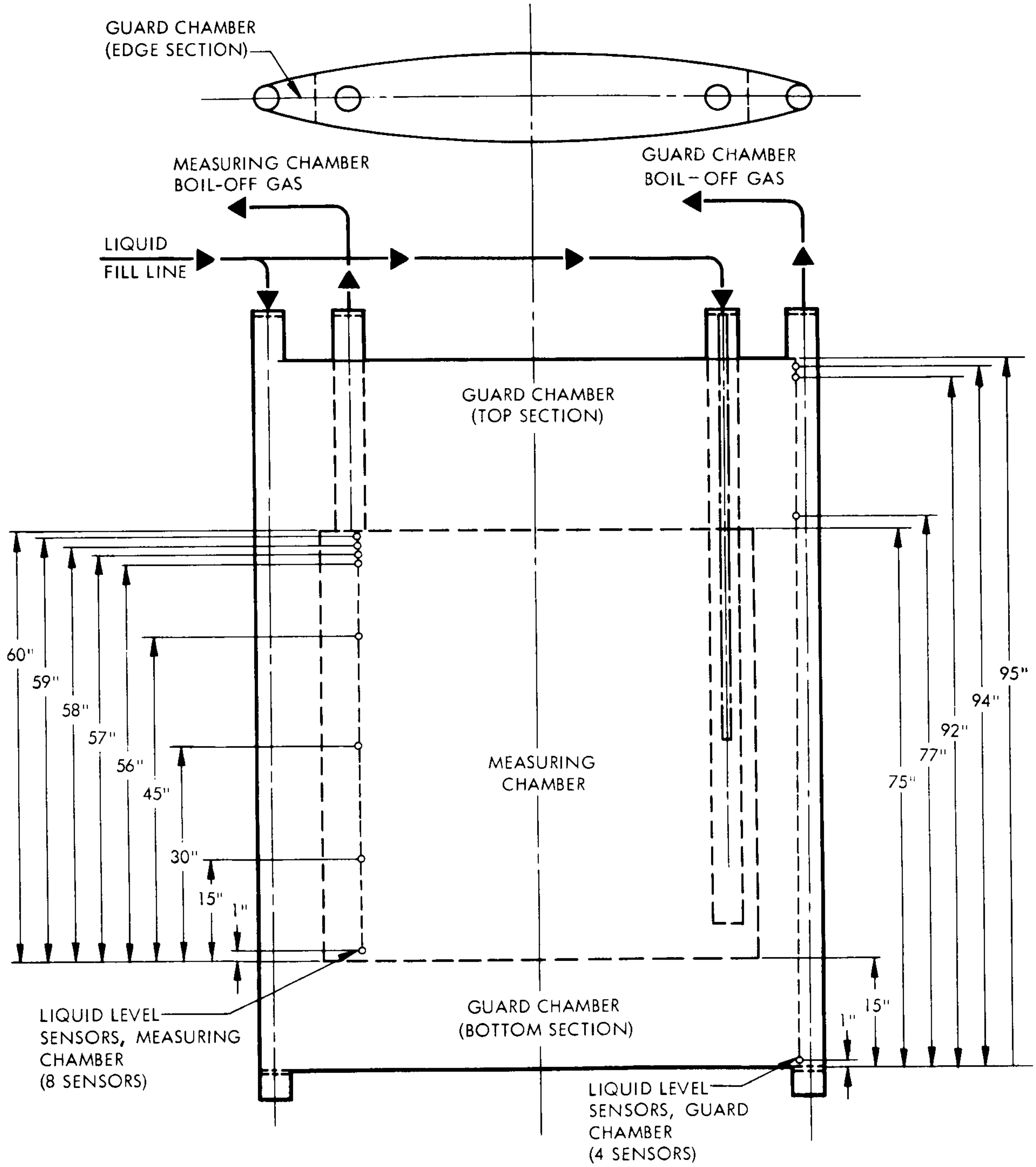


Figure 73. LH_2 Sector Test Tank

V-1 is a 3/4-inch pneumatically operated two-way valve remotely controlled by solenoid valve SV-2. Valves V-2, V-3, and V-4 are 3/4-inch pneumatic-positioner-type valves remotely controlled through valve positioners.

3. Vent Lines

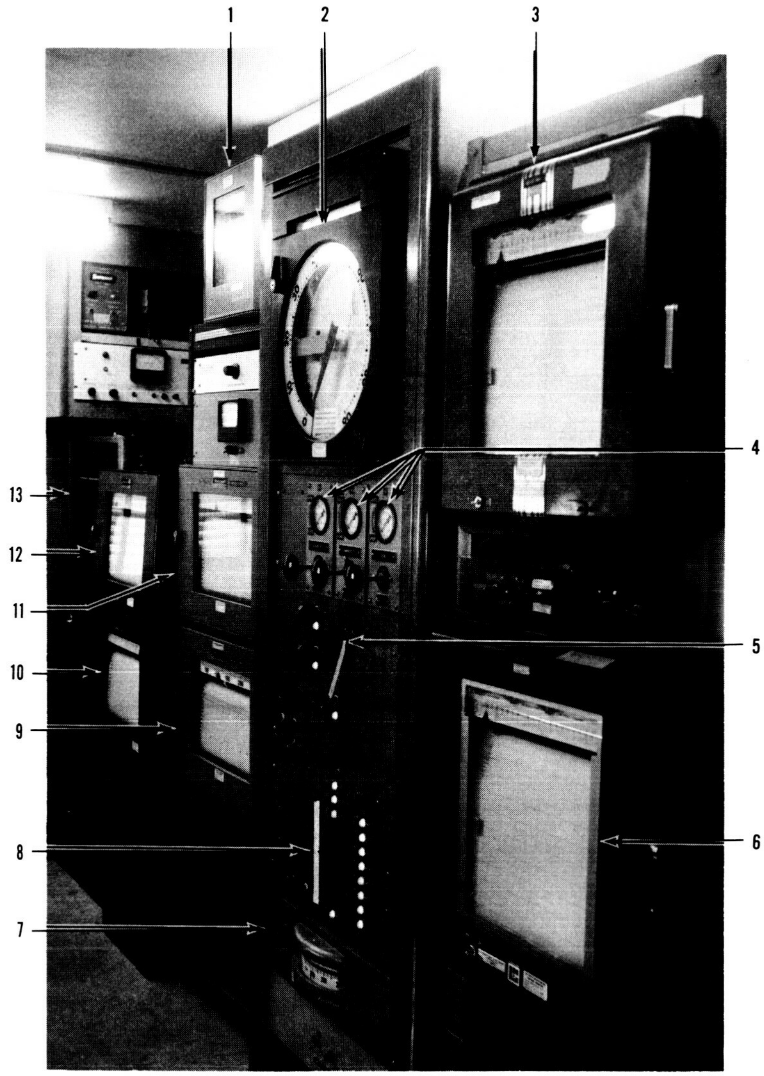
Two separate vent systems are provided, one for the guard and one for the measuring chamber of the test tank. Both vent lines are fabricated with two-inch copper tubing. The guard vent line runs directly to one of two four-inch diameter copper vent stacks. The gas in this line is remotely throttled by valve V-4 to provide a controlled pressure differential between the guard and measuring chambers. Boil-off gas from the measuring chamber is run through an ambient heat exchanger, electrical heater, flow meter, and then into a separate four-inch-diameter vent stack.

4. Gas Conditioning System

The gas conditioning system is required to heat the boil-off gas and maintain it at a constant temperature through the flow meter. The gas is first passed through an ambient heat exchanger that comprises eight parallel copper tubes, 1-1/8-inch OD and 10 feet long. The gas is then run through a 3-kw electric heater, which supplies additional heating if necessary. Temperature of the gas is sensed by a platinum resistance thermometer and is recorded on a continuous strip-chart recorder (1, Figure 74).

5. Flow Measuring System

The boil-off gas from the measuring chamber is measured by an orifice-type flow transmitter. The orifice plate and flow tube are specifically designed to operate in the range of flow rates expected in this application. A flow meter (2, Figure 74) provides a continuous recording of gas flow through the orifice meter.



1. Boil-off Gas Temperature Recorder
2. Boil-off Gas Flow Meter
3. Guard Vessel Pressure Recorder
4. Panel Loaders for Positioner Valves
5. LH_2 Flow Control Panel
6. Measuring Vessel Pressure Recorder
7. Heat Exchanger Controller
8. Liquid Level Indicator Lights
9. 24-Point Recorder (Panel B)
10. Continuous Recorder (T_2)
11. 24-Point Recorder (Panel A)
12. Continuous Recorder (T_1)
13. Quartz Lamp Power Controller

Figure 74. Control Trailer Instrumentation

6. Liquid Level Sensors

Sensors are located in the test tank as shown in Figure 73 to permit continuous monitoring of liquid levels in the guard and measuring chambers. Sensors are connected to lights (8, Figure 74) on the liquid level indicator panel in the control room.

7. Test Tank Heating System

Two large panels consisting of quartz tube infrared lamps mounted on curved aluminum reflectors as shown in Figure 71 are used to heat the outer surface of the insulated test tank. Power to the lamps is regulated manually by use of an ignitron tube power controller (13, Figure 74).

8. Pressure Sensors

A strain-gauge-type pressure transducer is located on each of the two vent lines from the test tank. The electrical signals from the transducers are fed into two AZAR (adjustable zero and range) strip-chart recorders (3 and 6, Figure 74) for continuous recording of pressures. Pressures in the guard and measuring sections of the tank are maintained at 0.4 and 0.2 psi respectively during the test runs.

E. TEST PROCEDURE

The setup is completed and the flow system is checked for operation before starting the test. If the test is for a temperature-controlled condition, the heating fixtures are positioned. The helium purge line to the outer sandwich (see Figure 70) is connected, and a small amount of helium gas (approximately 5 cfh) is allowed to bleed through the panel during the test. After the test is initiated, no one is permitted within the test bunker until completion of the final purging operation.

The procedure used to conduct the tests is described in the following paragraphs.

1. Purging before LH_2 Fill

The system is initially purged with nitrogen by connecting a liquid nitrogen Dewar at the bayonet fitting shown in Figure 72. By regulating the flow into the system, cold nitrogen gas replaces the air and then also serves to cool down the tank and plumbing. After cool-down, the LN_2 Dewar is removed from the system and the connection to the LH_2 storage tank is made. The entire system is then helium purged by manually opening valve V-5. Both vent stacks are continually purged with nitrogen throughout the entire test.

2. LH_2 Cool-Down and Fill

After completion of the helium purge, the LH_2 withdrawal valve at the storage tank is manually opened. Since the test tank cannot withstand pressures greater than 1.5 psi, the flow rate of LH_2 during cool-down is extremely critical. Cool-down is achieved without exceeding 1.0 psi by remote control of positioner valves V-2 and V-3 and by manual throttling with the withdrawal valve at the storage tank. Completion of cool-down is indicated when a steady, nonsurging flow of gas is observed. The measuring and guard sections are filled simultaneously. Filling rates in both sections of the tank are indicated by lights on the liquid level indicator panel in the control room and are controlled by throttling valves V-2 and V-3 with the panel loaders.

3. Boil-Off and Temperature Measurement

When the test tank and its insulation have reached thermal equilibrium, valves V-2 and V-3 are adjusted in a position to maintain a constant level of liquid in the guard and measuring sections. The guard level is held at the 92-inch level and the measuring chamber at the 59-inch level (see Figure 73). Boil-off gas from the measuring chamber is continuously recorded on a circular chart recorder. The indicated boil-off, of course, must be corrected to account for (1) the amount of vaporization caused by heat leaks through the transfer lines, valves, and fittings and (2) the liquid that flashes into gas when going from an elevated pressure to a lower pressure. The correction can be computed from data published by manufacturers of the hardware and from the T-S diagram for hydrogen. A more accurate method for determining the correction is to temporarily eliminate all of these sources of error. This was done intermittently during all the test runs by quickly closing the inlet to the measuring chamber (valve V-2) and noting the immediate drop in indicated boil-off rate. The magnitude of the indicated drop in boil-off rate is then used as the correction factor.

Temperatures of the outer surface, T_1, and inner surface, T_2, were sensed by iron-constantan thermocouples and recorded during the tests on two 24-point strip-chart recorders. When conducting the time-temperature profile tests, two of the thermocouples (one each for T_1 and T_2) were wired into continuous strip-chart recorders. The thermocouple that sensed the outer surface temperature, T_1, was used as the control.

4. Purging after Completion of Test

At the completion of each test run, the LH_2 withdrawal valve at the storage tank was closed and the liquid hydrogen in the transfer lines and the test tank was allowed to vaporize. The drop in liquid level was monitored by observing the lights on the indicator panel. When the liquid levels dropped to approximately one inch from the bottom of the chambers, the solenoid valve (SV-1) at the helium supply was opened. The helium purge was continued until all liquid had vaporized and the temperature of the system was above the nitrogen liquification temperature. The entire system was then thoroughly purged with nitrogen gas.

F. LH_2 TANK TEST - SYSTEM NO. 1

1. Chronological History

The chronological history of the test tank is as follows:

2/23/65:	Panel A fabrication complete.
3/3/65:	Panel B fabrication complete.
3/9/65:	Panels bonded to tank.
3/30/65:	Complete splice cap strips and outlet insulation.
4/5/65:	Preliminary LN_2 check-out - partial fill.
4/13/65:	Ship tank to Wingfoot Lake test site.
4/20/65:	Run system check-out with LN_2.
4/22/65:	First LH_2 fill - system check-out - ambient temperature.
4/26/65:	Second LH_2 fill - ambient temperature.
4/28/65:	Third LH_2 fill - ambient temperature.
4/30/65:	Fourth LH_2 fill - heat lamps on to control temperature.
5/4/65:	Fifth LH_2 fill - heat lamps on to control temperature.
5/7/65:	Sixth LH_2 fill - transient temperature profile.
5/10/65:	Seventh LH_2 fill - transient temperature profile (CO_2 purge).

2. Preliminary LN_2 Test and Check-Out

Before shipping the tank to the test site, the tank was partially filled with LN_2 to check for possible problems. This cool-down fill lasted one hour, and at termination approximately 95 percent of the tank was frosted. The tank contracted 0.280 inch over the 6.5-foot width. Some wrinkles were observed in the splice cap strips; however, after the tank warmed up, no visual degradation had occurred. After installation at the test site, the tank was partially filled with LN_2 to check out the transfer system and instrumentation. As in the previous check, the cap strips showed wrinkles when cold but returned to normal after the tank warmed up.

3. First LH_2 Fill and Drain

a. Test Sequence

10:25 - Start LN_2 cool-down.

10:45 - Finish LN_2 cool-down.

12:50 - Helium purge tank.

13:03 - Start LH_2 fill (storage tank pressure at 10 psi).

16:03 - Shut off LH_2 supply and allow to boil off.

b. Comments: The weather was clear and sunny. The temperature was 55°F. The reflectors were in position but not turned on. Nine hundred gallons of LH_2 were used during the test.

4. Second LH_2 Fill and Drain

a. Test Sequence

12:15 - Start LN_2 cool-down.

12:25 - End LN_2 cool-down.

12:30 - Helium purge.

13:00 - Start LH_2 fill.

14:30 - Measure and guard vessels full.

18:30 - Shut off LH_2 supply.

21:35 - Start helium purge.

b. Comments: The weather was cloudy and windy. The temperature was 41°F. The test was run with ambient temperature (no heat). Visual inspection revealed no apparent effects.

5. Third LH_2 Fill and Drain

a. Test Sequence

8:30 - Start LN_2 cool-down.

8:58 - Stop LN_2 cool-down.

9:30 - Start LH_2 fill.
11:30 - Measure and guard vessels full.
15:00 - Shut off LH_2 supply.
17:00 - Tank drained.

b. Comments: This ambient temperature test was the same as No. 2. The weather was partly sunny. The temperature was 52°F. During testing, considerable frost build-up was noted.

6. Fourth LH_2 Fill and Drain

a. Test Sequence

9:53 - Start LH_2 fill.
10:35 - Start applying heat (35 amps).
11:12 - Measure and guard tanks full.
11:30 - Heat control at 80 amps, surface temperature 32°F.
12:15 - Heat control at 82.5 amps, surface temperature 77°F.
14:42 - Shut off LH_2 supply.

b. Comments: This was a controlled temperature test using heat lamps. The weather was sunny and windy. The temperature was 77°F. Twelve hundred gallons of LH_2 were used during the test.

7. Fifth LH_2 Fill and Drain

a. Test Sequence

10:15 - Start LH_2 fill.
10:27 - Start applying heat (40 amps).
10:32 - 30 inches in measure - raise power to 50 amps.
10:40 - 45 inches in measure, 77 inches in guard - raise power to 60 amps.
11:02 - Measure full - raise power to 70 amps.
11:12 - Raise power to 83 amps to get average 75°F surface temperature.

14:00 - Power reduced to 70 amps to get average of 40°F surface temperature.

15:00 - Shut off supply of LH_2.

b. Comments: This was a controlled temperature test using heat lamps. The weather was partly cloudy with a gusty SW wind. The average temperature was 85°F. Fifteen hundred gallons of LH_2 were used from the storage tank at 8 psi. Visual inspection revealed no apparent degradation to the insulation panels.

8. Sixth LH_2 Fill and Drain

a. Test Sequence

10:00 - LH_2 purge and helium purge. Check out lamps.

11:00 - Start LH_2 fill.

11:45 - Measure full - turn on power (55 amps).

13:00 - Start time-temperature profile. Shut off LH_2 supply.

b. Comments: This was a transient temperature profile test. The weather was partly sunny with a west wind. The temperature was 77°F. Fifteen hundred gallons of LH_2 were used during the test. Visual inspection revealed no apparent degradation to the insulation panels. Thermocouple No. 3A was used as the control on the continuous recorder during the temperature profile. Thermocouple No. 1A was also recorded on a continuous recorder. Figure 75 shows the temperature profile. During the heating cycle, the power controller was turned fully on until 355°F was reached. Note that this took longer than the theoretical temperature profile. At the peak temperature, the power was shut off until the temperature returned to 75°F.

9. Seventh LH_2 Fill and Drain

a. Test Sequence

8:45 - Start CO_2 purge in HRP core.

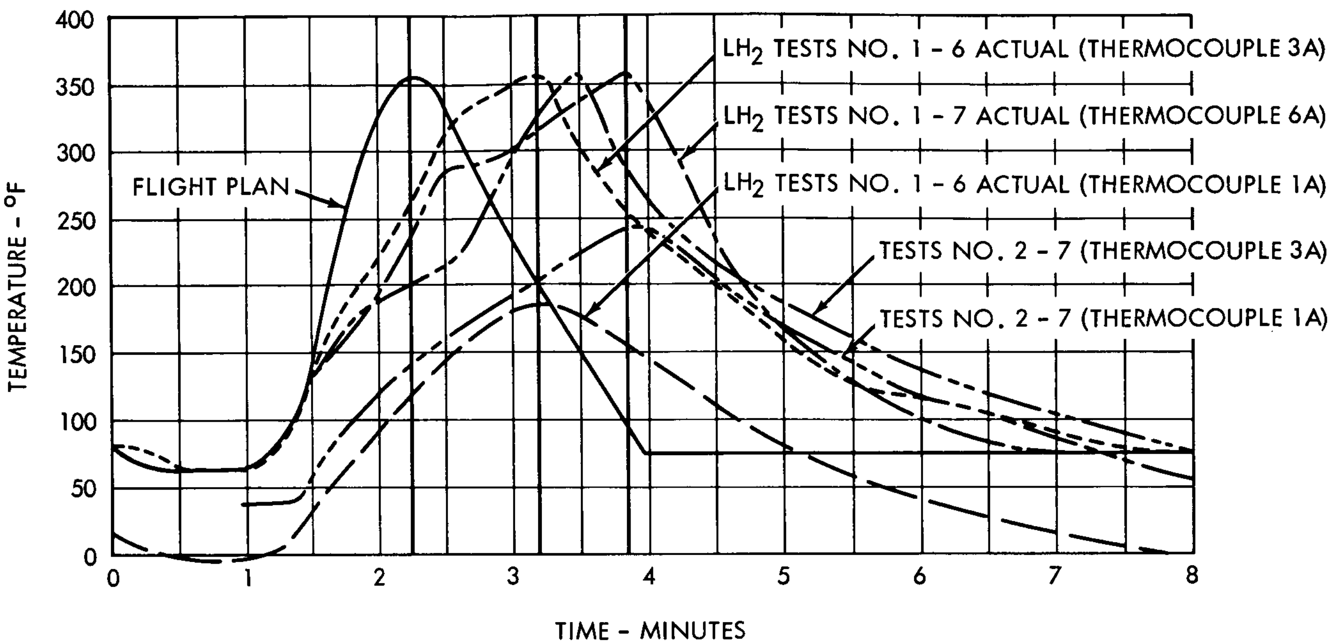


Figure 75. Time-Temperature Profile for Systems No. 1 and 2

10:45 - LN_2 purge tank.

10:37 - Start LH_2 fill.

11:25 - Tank full.

12:02 - Turn on heat lamps (55 amps).

12:12 - Raise power to 60 amps.

13:07 - Shut down. Pressure surge on guard indicator; appeared to be an erratic reading.

13:18 - Restart.

14:16 - Shut off flow of LH_2 and start temperature profile.

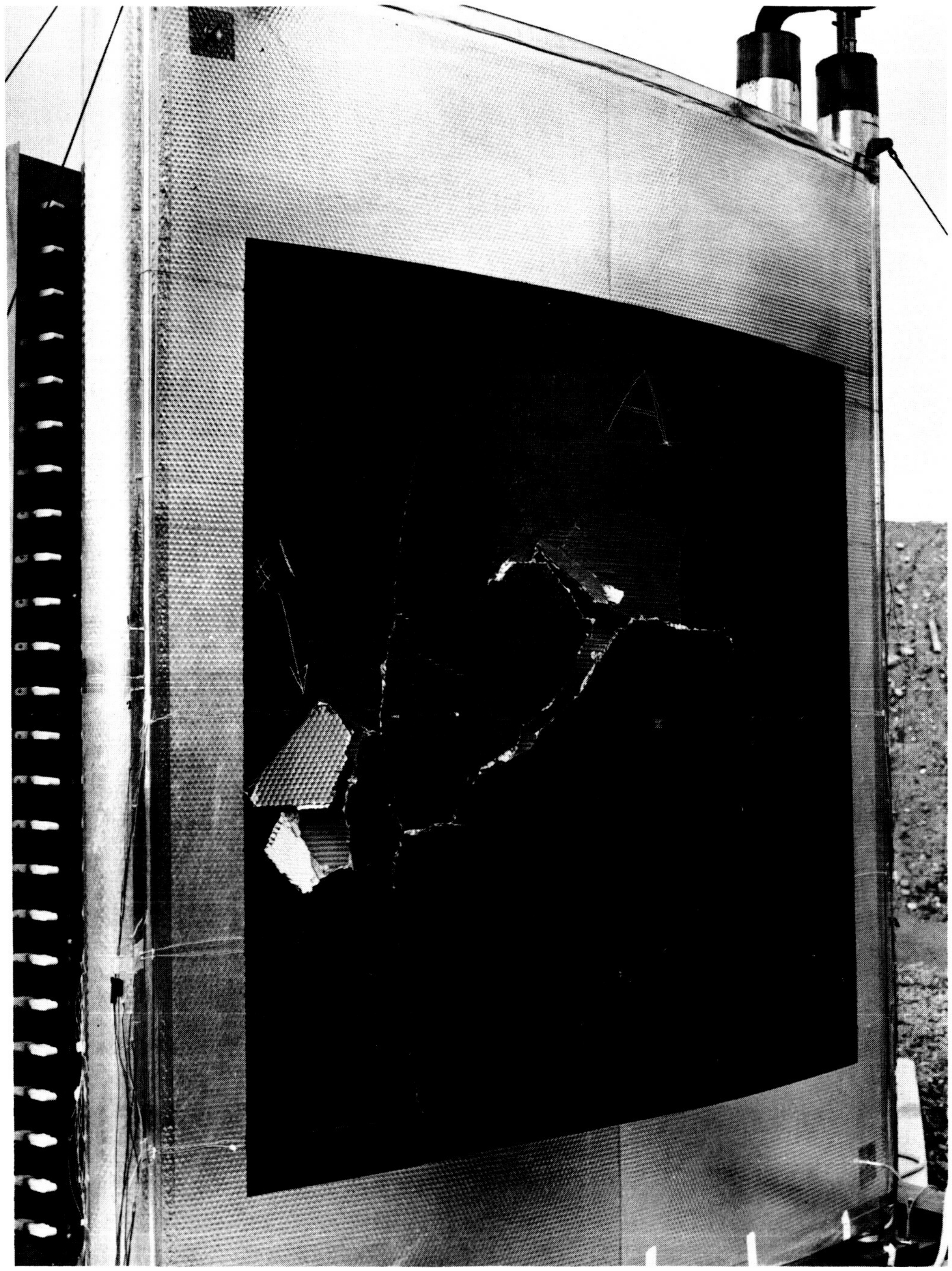
b. Comments: This was a transient temperature profile test. The weather was partly cloudy with a SW wind. CO_2 gas was used to purge the insulation instead of helium, which was used on previous tests. The procedure used during the temperature profile was the same as for test No. 6. At the beginning of the test, thermocouple No. 3A was much lower than expected; therefore, No. 6A was used as a control during the temperature profile run. Thermocouple No. 1A was pegged out at less than -150°F during the test; therefore, no usable data was recorded. The temperature curve is shown in Figure 75. After the LH_2 had been drained, an explosion occurred during the helium purge cycle. Within a period of 10 minutes, a second explosion was seen and heard. The outer sandwich of panel A had failed as shown in Figures 76 and 77.

c. Inspection of Panels. After test No. 7, the sealed cells of panel B were probed with a helium leak detector. The presence of helium is indicated in Figure 78. Because of the damage to panel A, a helium check was impractical.

No damage occurred to any of the cap strip splices. During dissection of the panels, the joints appeared as good as when first installed.

Panel B showed no external degradation. A detailed inspection of the panels indicated no internal bond failures or unbonded areas in the sandwich other than the explosion damage to panel A.

The outer sandwich was removed by cutting through the Mylar core with a hot wire. Although the bond of the Mylar skin to the Mylar core was good, there were areas of poor bond between the Mylar skin and the tank. This was apparently caused by variations in surface contour of the tank (distortions caused by welding). The worst area on panel A was in the region of thermocouple No. 17. Panel B had several void areas around the periphery of the measuring vessels. These areas coincided essentially with the low thermocouple readings. It appears possible that helium could have flowed through these unbonded paths from the edge into larger void areas. The helium could have permeated through the Mylar skin, decreasing the cryopumping efficiency of the sealed cells.



NOTE: No damage around edge joints.

Figure 76. Panel A after LH_2 Tank Test Run No. 7

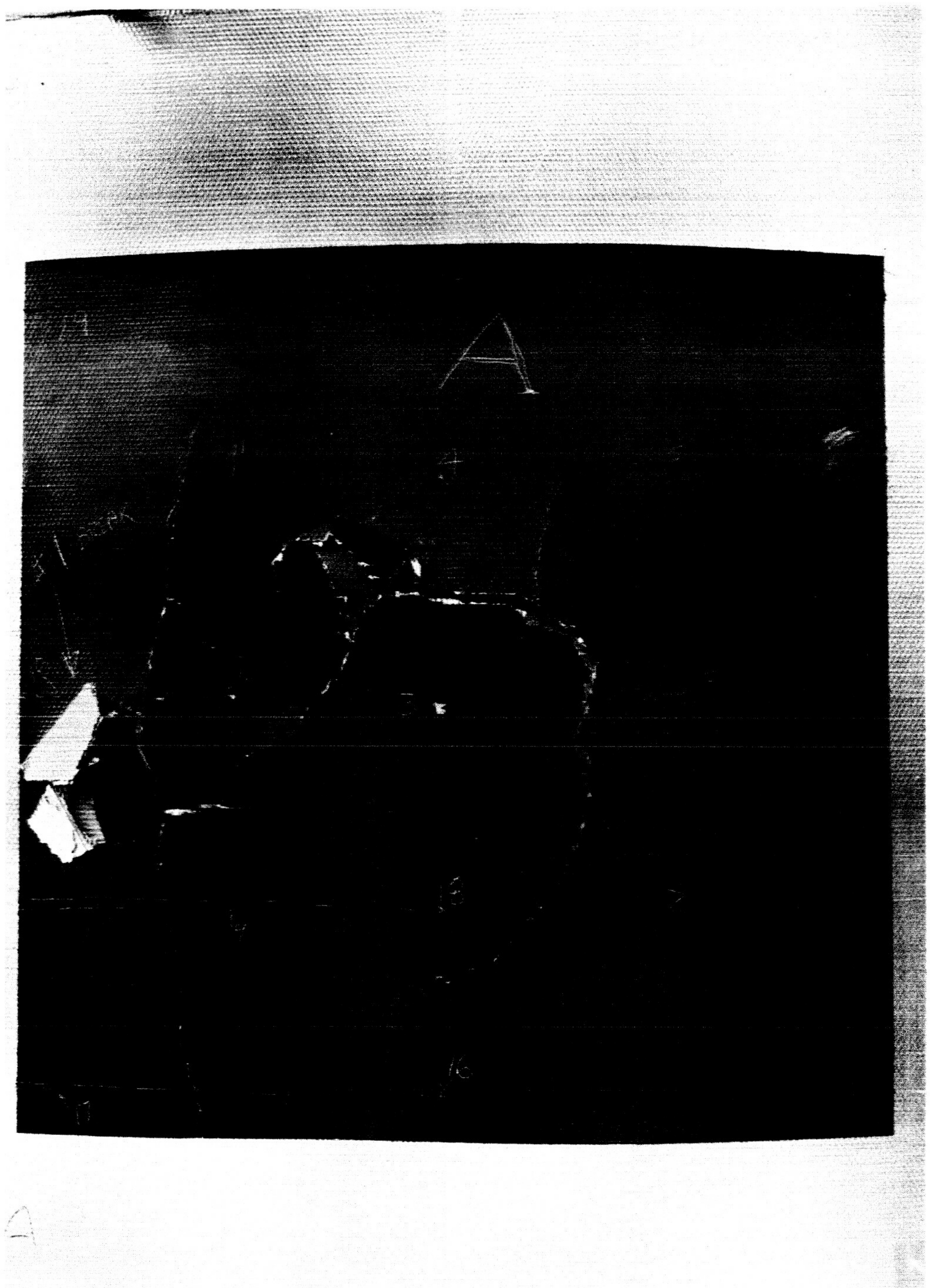


Figure 77. Damaged Panel A

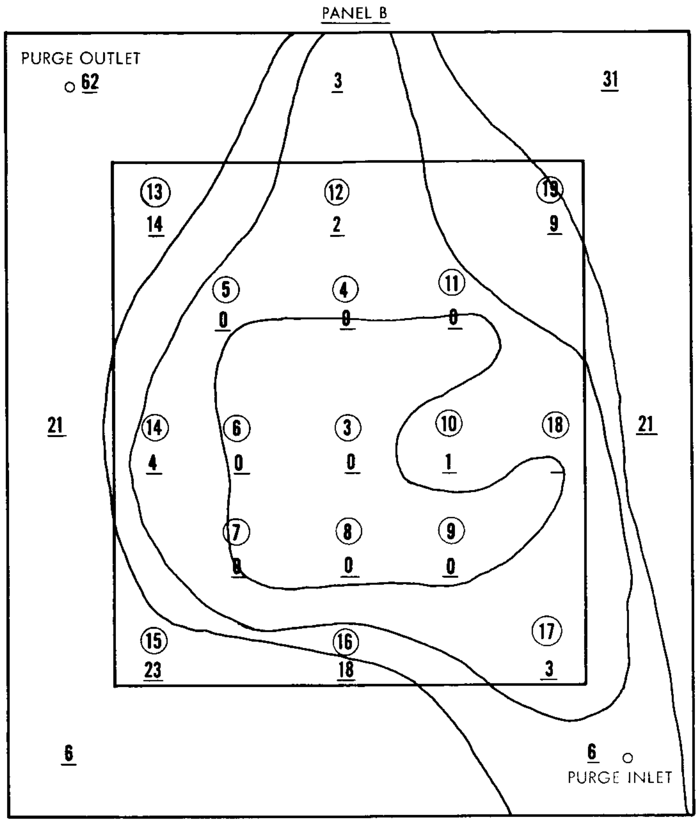


Figure 78. Helium Contamination Level - LH_2 Test System No. 1

G. LH_2 TANK TEST - SYSTEM NO. 2

1. Chronological History

6/3/65: Panel A fabrication complete.

6/8/65: Panel B fabrication complete.

6/9/65: Panels bonded to tank.

6/10/65: Install splice cap strips.

6/14/65: Complete instrumentation and ship to Wingfoot Lake.

6/16/65: First LH_2 fill - ambient temperature, reflectors not in position.

6/17/65: Second LH_2 fill - ambient temperature, lamps in position.

6/18/65: Third LH_2 fill - ambient and temperature controlled.

6/21/65: Fourth LH_2 fill - ambient and temperature controlled.

6/23/65: Fifth LH_2 fill - ambient temperature, reflectors not in position.

6/25/65: Sixth LH_2 fill - temperature controlled and transient temperature profile.

6/30/65: Seventh LH_2 fill - temperature controlled and transient temperature profile.

2. Instrumentation

The location and installation of the thermocouples were similar to system No. 1 except for those on the subpanel (T_2). On panels A and B, thermocouple No. 1 is located under thermocouple No. 3 and thermocouple No. 2 is located under thermocouple No. 4. Because of the splice on panel B, a third thermocouple, No. 20, was added under thermocouple No. 8.

3. First LH_2 Fill and Drain

a. Test Sequence

12:00 - Start LN_2 cool-down.
12:37 - Helium-purge tank.
13:11 - Start LH_2 fill (9-psi storage tank pressure).
14:00 - Measure and guard full.
16:00 - Start draining LH_2.

b. Comments: The weather was sunny with cool wind. The average temperature was 68°F. The test was run at ambient condition, and the heat reflectors were not in position. It was noted that thermocouple B6 readings were not consistent and therefore must be considered unreliable. It was not used throughout the series of tests. During the fill operation, some frost appeared on the surface, and the thermocouple readings dropped as low as 9°F. However, the thermocouples warmed up and the frost disappeared, indicating that cryopumping had taken place. Eight hundred gallons of LH_2 were used during the test.

4. Second LH_2 Fill and Drain

a. Test Sequence

11:46 - Start LN_2 cool-down.
12:15 - Helium-purge tank.
12:35 - Start LH_2 fill (8-psi storage tank pressure).
13:15 - Tank full.
14:22 - Electrical power lost during thunderstorm - valve shut.
15:15 - Power restored - reopen valve.
15:50 - Tank full (raining).
17:50 - Shut-off LH_2 supply.

b. Comments: The lamps were in position, but no temperature run was made because of the thunderstorm. The weather was partly cloudy with intermittent showers. The temperature ranged from 68 to 55°F. It was noted that the tank had considerable frost and the temperatures were low compared to the previous test. Twelve hundred gallons of LH_2 were used during the test.

5. Third LH_2 Fill and Drain

a. Test Sequence

9:27 - Start LN_2 cool-down.
9:57 - Helium-purge tank.
10:19 - Start LH_2 fill (8-psi storage tank pressure).
11:03 - Tank full.
13:37 - Turn on heat lamps to 40 amps.

13:50 - Raise lamp power to 50 amps.

16:00 - Shut off LH_2 supply.

b. Comments: The weather was partly cloudy with a strong NW wind. The temperature was 68°F. One thousand gallons of LH_2 were used during the test. Data was taken for ambient and temperature controlled conditions. Prior to the test additional plastic shrouds were added to the ends of the tank to limit edge effects. The wind was blowing toward side A. It was noted that the weather conditions (such as wind direction and velocity and whether or not the sun was shining) had considerable effect on the thermocouple readings.

6. Fourth LH_2 Fill and Drain

a. Test Sequence

11:02 - Start LN_2 cool-down.

11:28 - Helium-purge tank.

11:41 - Start LH_2 fill.

12:45 - Tank full - ambient condition.

13:30 - Turn on heat lamps to 30 amps.

13:50 - Raise heat lamps to 40 amps.

16:00 - Shut off LH_2 supply.

b. Comments: The weather was cloudy with a strong,gusty south wind (blowing toward panel B). The temperature ranged from 75 to 80°F. The run appeared satisfactory. Data for both ambient and temperature controlled conditions was compiled.

7. Fifth LH_2 Fill and Drain

a. Test Sequence

9:52 - Start LN_2 cool-down.

10:24 - Helium-purge tank.

10:45 - Start LH_2 fill (10-psi storage tank pressure).
12:40 - Tank full.
12:45 - Started raining hard - lasted 15 minutes.
12:56 - LH_2 supply shut off - power failure.
14:05 - Power on - reopen supply valve.
15:00 - Tank full.
15:41 - Violent thunderstorm.
16:30 - Shut off LH_2 supply.

b. Comments: This test was essentially a repeat of test No. 1, as the heat lamp reflectors were removed to check the effect they had on the insulation. The weather conditions varied from partly cloudy with a moderate south wind and a temperature of 84^{o}F to a violent downpour and a temperature of 61^{o}F. The two thunderstorms interrupted the testing cycle and had a marked effect on the temperature readings. During this run, it was noticed that the lower right-hand corner of panel A had much lower temperatures and a frosted area. Sixteen hundred gallons of LH_2 were used during the test.

8. Sixth LH_2 Fill and Drain - Temperature Profile

a. Test Sequence

11:20 - Start LN_2 cool-down.
11:49 - Helium-purge tank.
12:01 - Start LH_2 fill.
12:53 - Tank full - ambient condition.
13:41 - Heat lamps turned on to 45 amps.
14:23 - Increase power to 50 amps.
15:15 - Change power to 48 amps.
17:00 - Shut off LH_2 supply and start temperature profile.
17:17 - Reopen supply valve and adjust power to 48 amps.

17:45 - Tank full.

17:53 - Shut off LH_2 supply.

b. Comments: The weather was sunny with a NW wind. The temperature was 70°F. During the temperature profile run, the power was turned fully on (130 amp indicated). Thermocouple No. 3 on panel A was used as the control. The temperature climbed smoothly until 250°F was indicated after 1-1/2 minutes; then the readings were very erratic. The test was continued for 2 more minutes, and then the power shut off. The highest recorded temperature was 320°F; however, it is believed that this is not correct since thermocouple No. 1 reached a temperature of 270°F as compared to 180°F for thermocouple No. 1 during the system No. 1 test. After the test, a check of the thermocouple revealed no apparent reason for the erratic behavior. It was decided to repeat the temperature profile test, moving the heating lamps closer, to attempt to get usable data.

9. Seventh LH_2 Fill and Drain

a. Test Sequence

9:05 - Heating lamps on (40 amps).

9:57 - LN_2 cool-down.

10:24 - Helium-purge tank.

10:53 - Start LH_2 fill (cut back lamps to 20 amps).

11:46 - Tank full - increase power to 40 amps.

12:03 - Increase power to 45 amps.

12:50 - Increase power to 52 amps.

13:37 - Shut off LH_2 supply and run time-temperature profile.

b. Comments: The weather was partly cloudy with a light NW wind. The temperature was 70°F. Five hundred gallons of LH_2 were used during the test. The temperature profile data is shown in Figure 75.

c. Inspection of Panels. After test No. 7, a helium leak check was made on the panels as shown in Figure 79. This data cannot be compared directly to that of system No. 1, but does show that the areas having a high indication of helium also showed cold temperature readings.

The panels were dissected using a hot wire to cut through the Mylar core. Panel B looked very good. However, panel A showed an unbonded area between the tank and the panel in the lower right-hand corner where the low temperatures and the high concentration of helium occurred. Panel A also had areas of bond failure between the Mylar core and Mylar skin in areas at the edge of the measuring

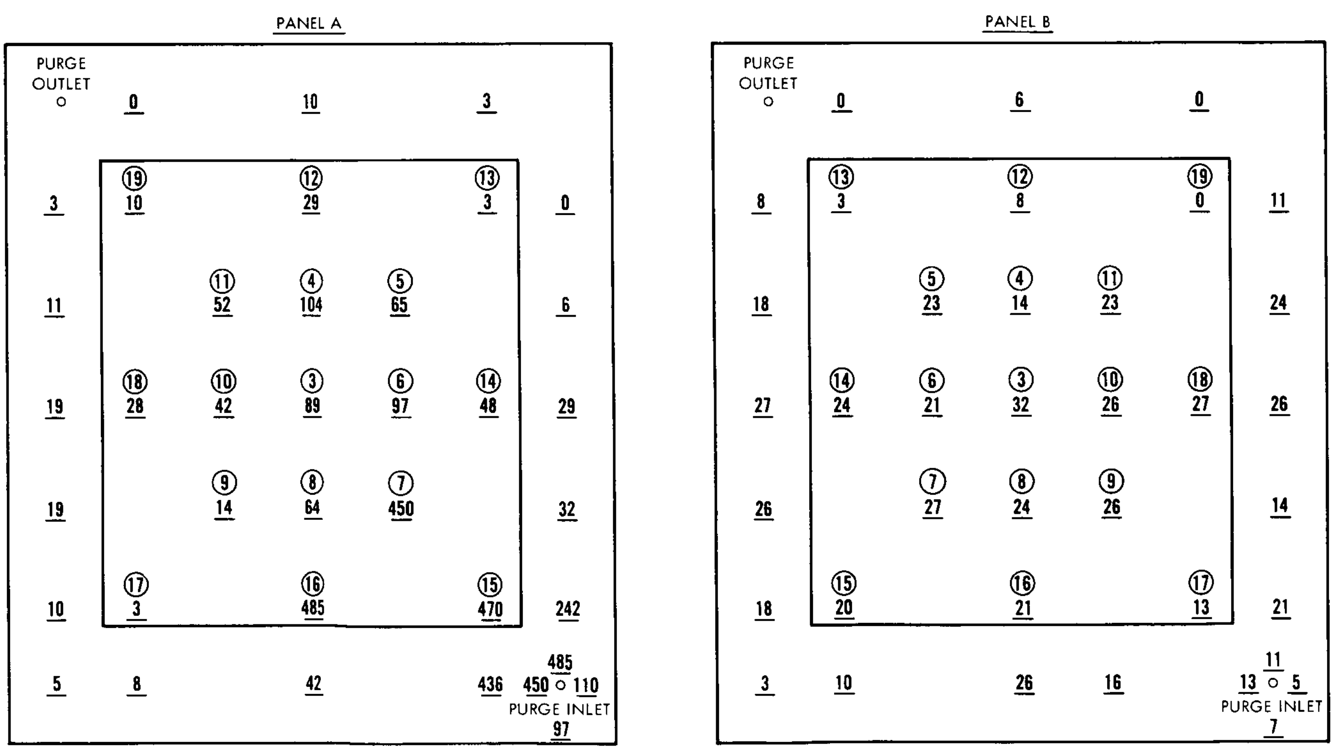


Figure 79. Helium Contamination Level - LH_2 Test System No. 2

vessel. This could have been caused by severe shear stresses set up during cool-down or warm-up. It is felt that it could also have occurred during the time-temperature profile. It is interesting to note that while there was a bond failure, it did not seem to affect the insulating properties. All the evidence points toward the fact that if helium is excluded the insulation works fine, but once helium permeates the insulation, the cryopumping stops and the efficiency drops. Since both panels A and B were processed the same except for the size, it would indicate that size may be a limiting factor.

H. LH_2 TANK TEST - SYSTEM NO. 3

1. Chronological History

The chronological history of the test tank is as follows:

11/1/65:	Panel A fabrication complete.
10/29/65:	Panel B fabrication complete.
11/2/65:	Panels bonded to tank.
11/6/65:	Complete splice cap strips and outlet insulation.
11/11/65:	Ship tank to Wingfoot Lake test site.
11/17/65:	Run system check-out with LN_2.
11/18/65:	First LH_2 fill and drain - ambient temperature.
11/19/65:	Second LH_2 fill and drain - ambient temperature.
11/20/65:	Third LH_2 fill and drain - ambient temperature.
11/22/65:	Fourth LH_2 fill and drain - ambient temperature.
11/23/65:	Fifth LH_2 fill and drain - ambient temperature.
11/24/65:	Sixth LH_2 fill and drain - ambient temperature.
11/27/65:	Seventh LH_2 fill and drain - ambient temperature.
11/29/65:	Eighth LH_2 fill and drain - ambient temperature.
11/30/65:	Ninth LH_2 fill and drain - ambient temperature.
12/2/65:	Tenth LH_2 fill and drain - ambient temperature, controlled heat, and temperature profile.

2. Fabrication of Insulation Panels

These panels duplicated the production panels of NAA/S&ID per their process and material specification MA 0605-004C, Revision E. The panel configuration is shown in Figure 80. The fabrication procedure was similar to that described in Section IV except as follows:

(1) Butt splices of Mylar core were bonded together by a strip of nylon fabric impregnated with 7343/7139 adhesive.

(2) HRP core joints were overlapped and mechanically interlocked.

(3) The panel was assembled in four steps as follows:

(a) Bond 3-mil aluminum to HRP core.

(b) Bond 1-1/2 mil aluminum to mylar core.

(c) Bond the two assemblies together.

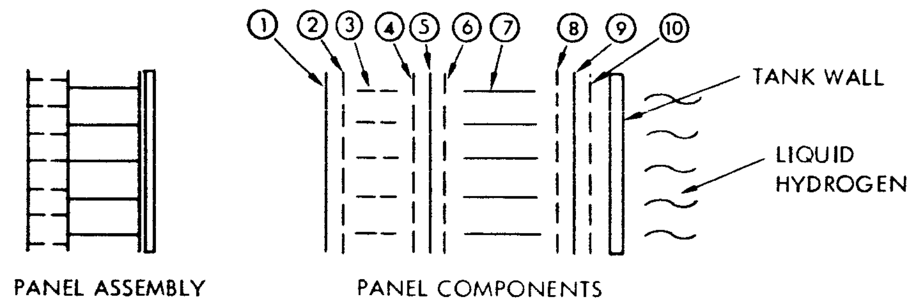
(d) Bond 2-mil Mylar to Mylar core.

Panel A was full size (6 x 8 feet), but panel B was split into two 6 x 4 foot pieces. Both panels were bonded to the tank at the same time under a vacuum bag, using 7343/7139 adhesive and a 12-hour cure at 160°F. The joint splice strips were 3-mil aluminum foil reinforced with nylon cloth. The nylon was impregnated, and the strips were bonded to the panels with polyurethane adhesive.

During fabrication, three thermocouples were imbedded in each panel. After bonding to the tank, 35 thermocouples were positioned on the surface of each panel as shown in Figure 81.

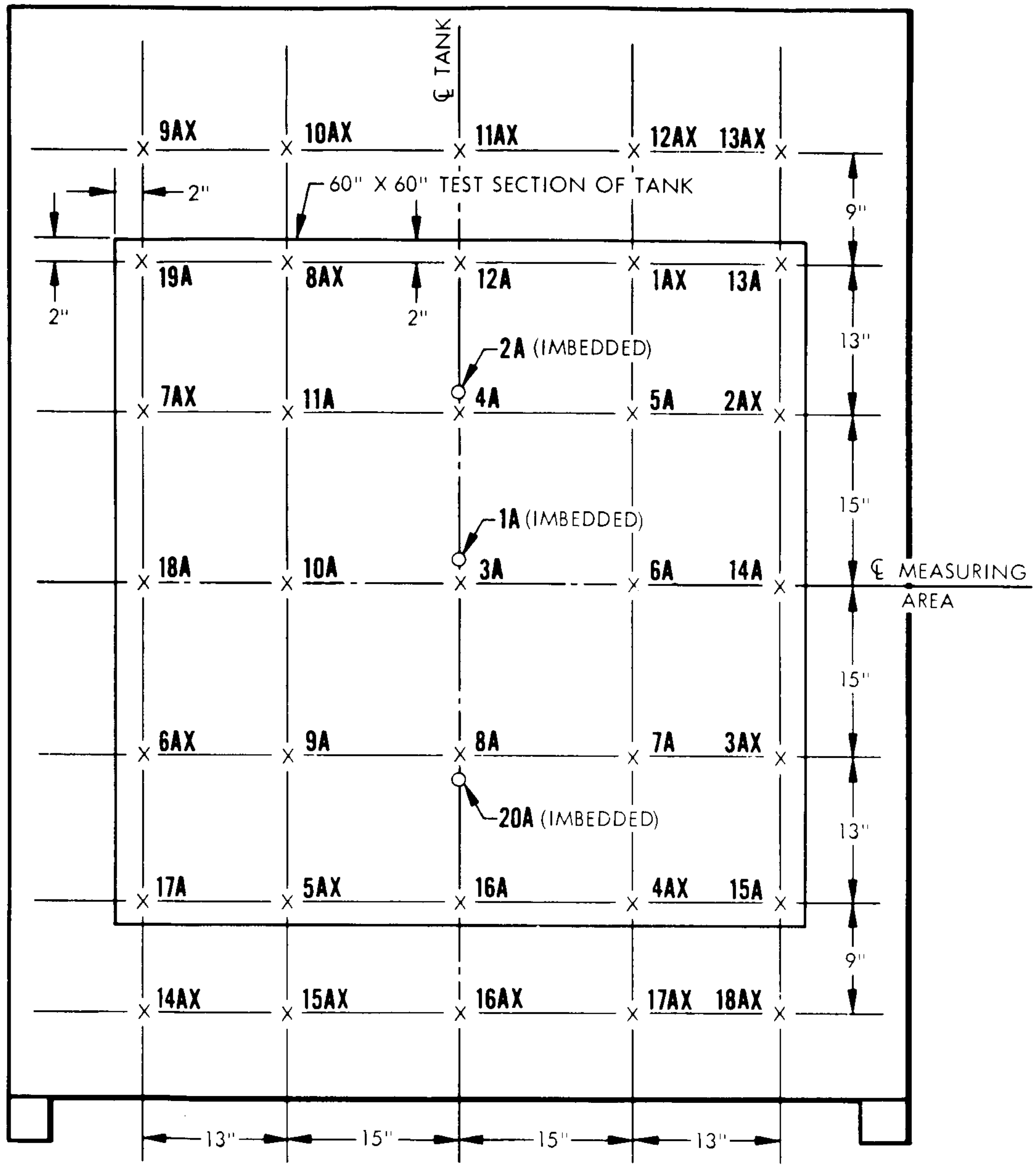
3. Test Procedure

The test panels were purged with dry nitrogen gas until cool-down; then helium gas was used during the run. Nine fill and drain cycles were run at ambient



Components	Description - Material
(1) Hot Face	0.003 inch aluminum foil. Prime with M-602.
(2) Bond Line	Hot Face to HRP core. 3M, AF-111 adhesive.
(3) HRP Core	Perforated honeycomb core. 3/8 inch cell size, 0.20 inch thick.
(4) Bond Line	HRP core to inner face. 3M, AF-111 adhesive.
(5) Inner Face	0.0015 inch aluminum foil. Prime with M-602.
(6) Bond Line	Inner face to Mylar honeycomb core. 3M, AF-111 adhesive.
(7) Mylar Honeycomb Core	3/8 inch cell size, 0.60 inch thick 0.003 inch Mylar. Prime with G-207.
(8) Bond Line	Mylar honeycomb core to cold face. Narmco 7343/7139 adhesive.
(9) Cold Face	0.002 Mylar. Prime with G-207.
(10) Tank Cold Face Bond Line	Cold face to tank wall. Narmco 7343/7139 adhesive. Tank wall primed with G-207.

Figure 80. Test Panel No. 3 Configuration



SIDE A THERMOCOUPLE LOCATIONS ON TEST TANK.

SIDE B LOCATIONS ARE REVERSED FROM LEFT TO RIGHT IN ORDER THAT POSITION OF EACH NUMBER IS LOCATED IN SAME RELATIVE POSITION ON OPPOSITE SIDE OF TEST TANK (I.E., 15B IS DIRECTLY BEHIND 15A).

Figure 81. Location of Thermocouples on Test Panels Systems No. 3 and 4

condition without the heat shields in place. Each run had a minimum hold time of 3.5 hours. The tenth fill and drain was run for 10 hours with the heating lamps in place but under ambient conditions. Then heat was applied to bring the surface up to an average temperature of 70°F during the remainder of the 12-hour hold. The temperature profile run was made directly after the 12-hour hold.

4. LH_2 Fill and Drain Cycles - Ambient Condition

A summary of the nine ambient fill and drain cycles is given in Table 22. During the testing, the insulation was covered with frost. The thickness of the frost varied with weather conditions; high humidity caused the thickness to increase.

Table 22. Summary of Ambient Fill and Drain Cycles
LH_2 Tank Insulation System No. 3

Run No.	Test Sequence - Time				Weather Conditions
	Start LN_2 Cool-Down	Start LH_2 Fill	Tank Full	End Test	
1	11:12	11:54	12:45	16:30	Sunny, 35°F, south wind
2	10:26	11:01	12:15	16:00	Cloudy, 36°F, moderate south wind
3	9:30	9:54	11:05	15:00	Partly sunny, 45°F
4	9:09	9:26	10:30	14:30	Intermittent light rain, 40°F
5	9:40	10:10	11:30	15:15	Partly cloudy, 38°F
6	8:37	9:16	10:12	14:12	Cloudy, 35°F, north wind (Toward end of test sun came out, 50°F)
7	8:16	8:45	10:24	14:11	Sunny, 36°F, 35-mph southwest wind
8	9:39	10:05	11:07	15:10	Temperature varied from 20 to 30°F
9	7:01	7:25	8:20	12:05	35°F

The thermocouple readings were affected by sun, wind, ambient temperature, and frost conditions. During run No. 2, the sun came out for a while, causing a 30° rise in surface temperature readings. An average of 1000 gallons of LH_2 was used for each fill and drain cycle.

5. Tenth LH_2 Fill and Drain - 12-Hour Hold and Temperature Profile

a. Test Sequence

6:01 - Start LN_2 cool-down.
6:29 - Start LH_2 fill.
7:30 - Tank full.
10:00 - Drop tank level to three-quarters full.
12:00 - Drop tank level to one-half full.
14:00 - Raise tank level to full.
18:00 - Turn on heat lamps.
18:20 - Heard a cracking sound.
18:30 - Face temperature stabilized.
20:00 - 12-hour hold complete - run temperature profile.

b. Comments

(1) After the ninth run an 8-inch crack was noticed on the left-hand side of panel A in the outer face. This was patched (see Figure 82).

(2) During previous runs, joint cap strips had become debonded in some areas. These were taped over for sealing purposes.

(3) The surface of the test panels was painted with a black epoxy.

(4) The heat lamps were set in position. Controlled heat was used during the latter part of the test.

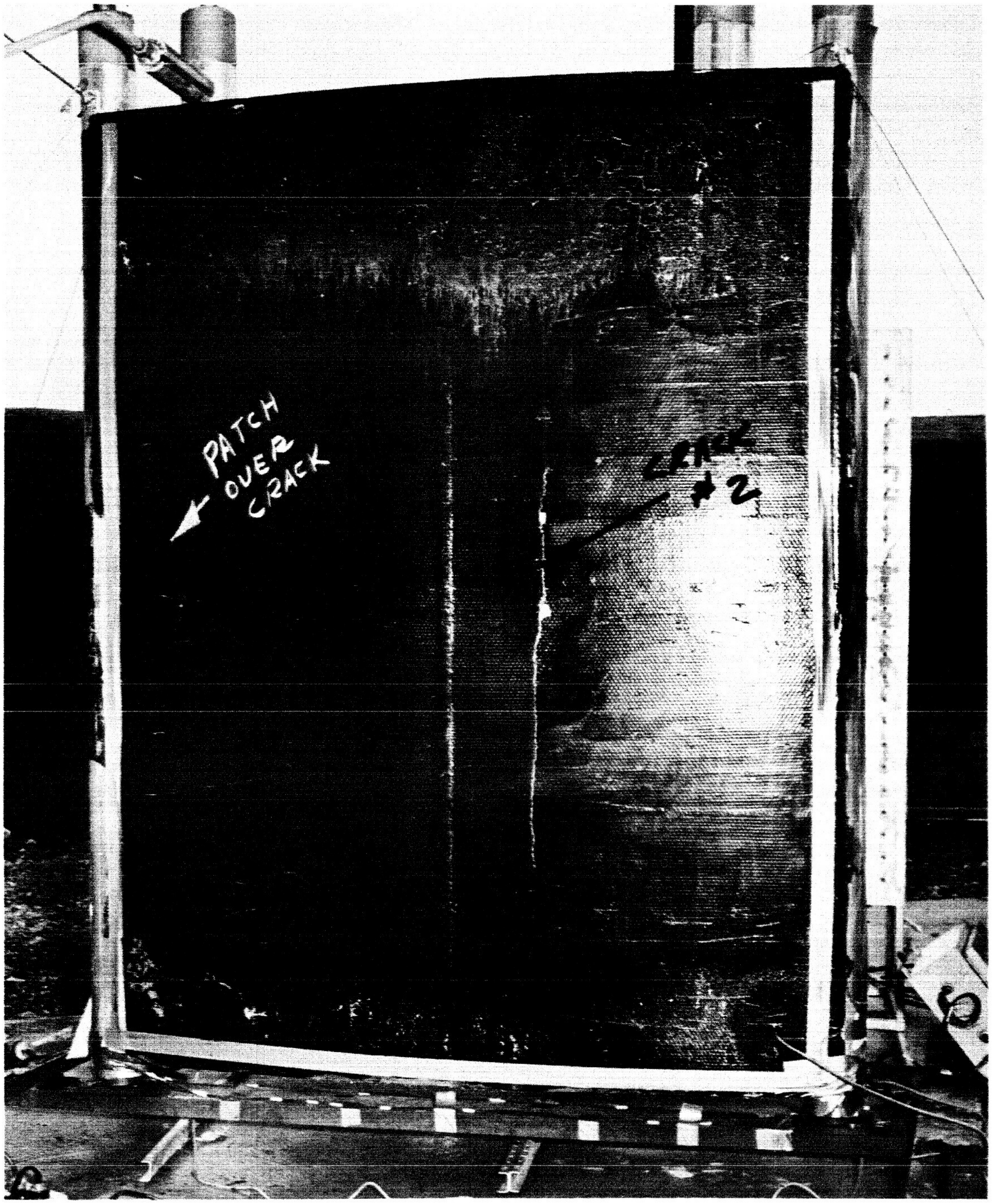


Figure 82. Panel A of LH_2 Tank No. 3 after Run 10

(5) During the hold cycle, the tank was stabilized at three-fourths full and one-half full, as well as completely full, to obtain comparative boil-off data, as requested by NASA.

(6) The temperature profile portion of the test was witnessed by Dr. James Stuckey, NASA/MSFC, and Mr. B. Strohman, NAA/S&ID.

(7) During the period of heating the surface up to 70°F, a sharp noise was heard. This noise probably was due to the failure (crack No. 2) that occurred on panel A (see Figure 82).

(8) During the long period at ambient temperature, considerable frost and ice built up on the insulation. While the measuring portion of the tank surface was warm at the beginning of the temperature profile run, the upper end of the tank was still covered with frost and ice. During the run, water from the melting frost ran down the tank surface, affecting thermocouple readings. The thermocouples connected to the continuous recorder were very erratic showing a maximum temperature of 250°F. Full power was maintained on the lamps for four minutes, at which time it was agreed to terminate the test. Data printed on the 24-pt recorders indicated that several thermocouples in the measuring area had exceeded 300°F, the maximum range of these recorders. An analysis of data shows that temperatures could have approached 350 to 400°F in areas not affected by water.

(9) 2800 gallons of LH_2 were used.

I. LH_2 TANK TEST - SYSTEM NO. 4

1. Chronological History

The chronological history of the test tank is as follows:

12/18/65:	Panel B fabrication complete.
12/22/65:	Panel B bonded to tank.
1/6/66:	Panel A fabrication complete.
1/7/66:	Panel A bonded to tank.
1/13/66:	Instrumentation complete.
1/18/66:	Ship tank to Wingfoot Lake test site.
1/20/66:	First LH_2 fill and drain - ambient temperature.
1/21/66:	Second LH_2 fill and drain - ambient temperature.
1/22/66:	Third LH_2 fill and drain - ambient temperature.
1/24/66:	Fourth LH_2 fill and drain - ambient temperature.
1/27/66:	Fifth LH_2 fill and drain - controlled heat and temperature profile.
1/27/66:	Sixth LH_2 fill and drain - controlled heat.

2. Fabrication of Insulation Panels

Based on the results of test No. 3 and directions from NASA, the following changes were incorporated in the System No. 4 test panels:

(1) The tank end insulation was isolated from test panels by seal strips to restrict purge gas to individual test panels and eliminate leakage around end insulation.

(2) Each panel had two purge inlets, one in each top corner and one outlet in the bottom center.

(3) Construction of panel A was changed as follows:

(a) HT-424 adhesive film instead of AF-111 was used to bond the HRP core to the outer and center aluminum skins.

(b) The HRP core had mechanical interlock joints.

(c) Other processing was the same as for system No. 3.

(4) Construction of panel B was as follows:

(a) One complete panel, not split as in system No. 3.

(b) The HRP core joints were interleaved but not mechanically interlocked.

(c) Other processing and materials were the same as for system No. 3.

(5) Each panel was bonded separately to the tank to improve vacuum pressure by reducing bag leakage.

3. Test Procedure

The test procedure was the same as for system No. 3 except as follows:

(1) Four fill and drain cycles were run at ambient condition without the heat shields in place for a minimum hold time of 3.5 hours.

(2) The purging system for the panels was set up so that each panel had an inlet pressure gage. One pressure transducer system was set up so that the outlet pressure of either panel A or panel B could be recorded. During the four ambient fill and drain cycles and the No. 5 controlled temperature and temperature profile cycle, a small positive outlet pressure was maintained.

(3) Another power controller was installed and the system revised so that each heating panel could be separately controlled. This change also

provided greater heating capacity so that the temperature profile could be more closely duplicated. The peak temperature of the profile was raised to 390°F.

(4) The temperature profile run, fill and drain cycle No. 5, was made starting with a tank free of frost. As the tank was filled, the surface temperature was brought up to approximately 70°F to prevent formation of frost. Once the tank was stabilized and full, the temperature profile was run.

4. LH_2 Fill and Drain Cycles - Ambient Condition

A summary of the four ambient fill and drain cycles is given in Table 23. A visual inspection after each fill and drain cycle showed no apparent degradation of insulation panels.

Table 23. Summary of Ambient Fill and Drain Cycles
LH_2 Tank Insulation System No. 4

Run No.	Test Sequence - Time				Weather Conditions
	Start LN_2 Cool-Down	Start LH_2 Fill	Tank Full	End Test	
1	9:48	10:23	11:19	15:12	Cloudy, 30°F, light northwest wind, snow flurries
2	9:42	10:12	11:08	14:45	Sunny, 32°F, light north wind
3	7:22	7:52	9:00	12:35	Cloudy, 30°F, 10-mph east wind, 85 percent humidity
4	11:33	12:18	13:30	17:10	Cloudy, 21°F, 8-mph southwest wind, 87 percent humidity

5. Fifth LH_2 Fill and Drain - Controlled Heat and Temperature Profile

a. Test Sequence

8:54 - Start LN_2 cool-down.

9:40 - Start LH_2 fill.

10:41 - Tank full.

11:50 - Run temperature profile.

b. Comments

(1) Between the fourth and fifth fill and drain cycles, the tank surface was dried off and the test panels painted with black epoxy. At this time there were no visible defects in the panels or cap strips. The heat lamps were positioned, and the controllers were checked out.

(2) The weather was snowy, $14^{\circ}F$, with 12-mph northwest winds.

(3) The heat lamps were on during entire cycle.

(4) The No. 5 thermocouples on panels A and B were connected to a continuous recorder for the temperature profile run. After the tank was full and the temperature and boil-off stabilized, the temperature profile was run. The data is given in Figure 83.

(5) After the tank was emptied and purged, an inspection was made by GAC and NASA representatives with the heat lamps still in position as shown in Figure 71. No visible defects were apparent on the outer surfaces of the insulation panels.

(6) It was decided to make another fill and drain temperature profile test. This time the purge gas pressure on the panels was to be raised to 3 psi.

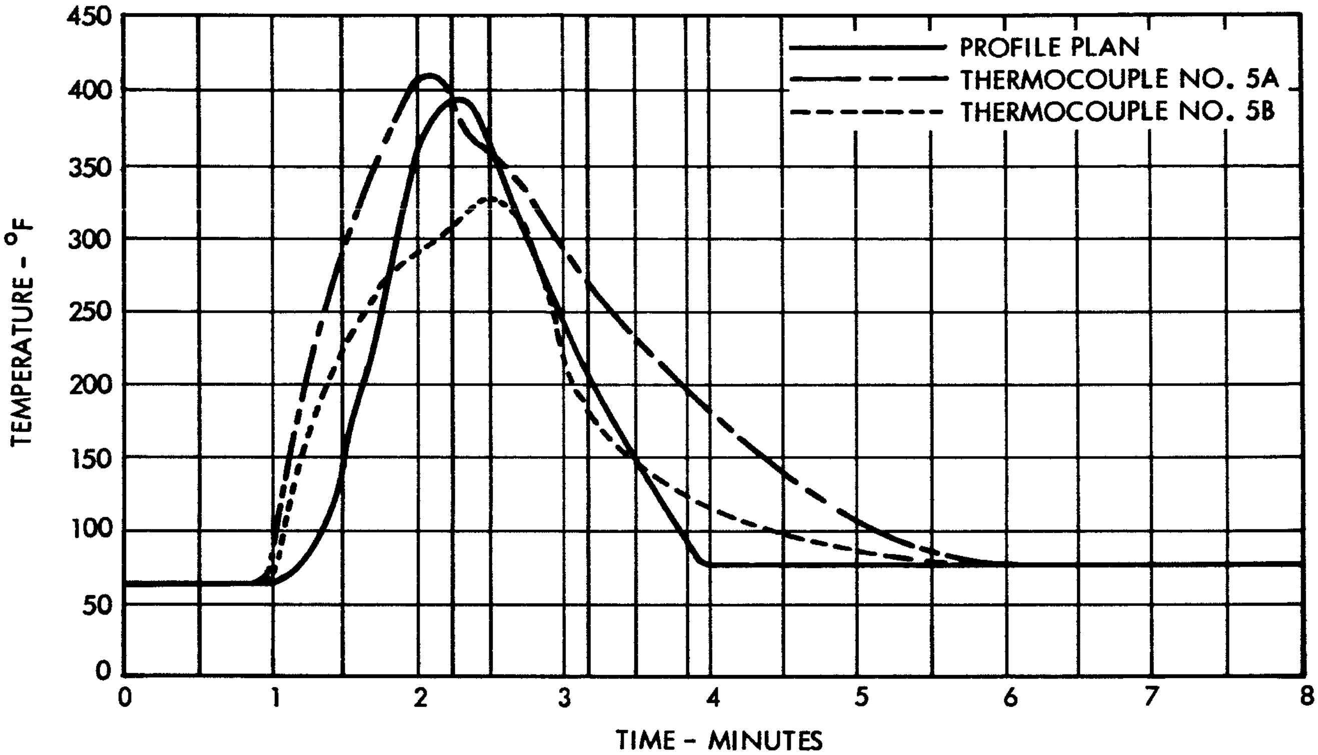


Figure 83. Time-Temperature Profile for System No. 4, Test No. 5

6. Sixth LH_2 Fill and Drain - Controlled Heat

a. Test Sequence

15:30 - Helium purge tank.

16:02 - Start LH_2 fill.

17:35 - Tank 3/4 full.

18:11 - Shut down test.

b. Comments

(1) Since the tank was still cool from run No. 5, an LN_2 cool-down was not required.

(2) The initial part of the fill cycle was similar to that of run No. 5; however, when the tank was approximately 1/4 full, the flow rate and gas pressure in the measuring vessel increased and the surface temperatures started to drop. The readings got progressively worse, and with the measuring vessel only 3/4 full, it was apparent that the insulation had seriously degraded so the test was terminated.

7. Post-Test Inspection

The outer surfaces of the insulation were inspected. Then the panels were dissected by cutting through the Mylar core with a hot wire.

The outer surface of panel A showed no apparent damage (see Figure 84). Dissection indicated no apparent degradation to the cores or the center skin. There were some areas where the Mylar skin was not bonded to the tank, but the bond between the skin and core was very good.

The outer surface of panel B (see Figure 85) contained several cracks in the 3-mil aluminum skin. Removal of the outer skin (see Figure 86) showed the same cracks and additional cracks in the AF-111 adhesive. Further dissection indicated that these failures also occurred in the HRP core and the 1-1/2 mil aluminum skin. There were some areas where the Mylar skin was not bonded to the tank, but the bond between the skin and core appeared very good.

J. ANALYSIS OF LH_2 TANK TEST RESULTS

1. General

The data accumulated during the fill and drain test cycles for the four systems is summarized in Tables 24 through 27. Based on this data, boil-off and thermal conductivity (K) curves were prepared, comparing tank test panels with calorimeter specimens 2 and 4, which were physically similar. Figure 87 shows boil-off

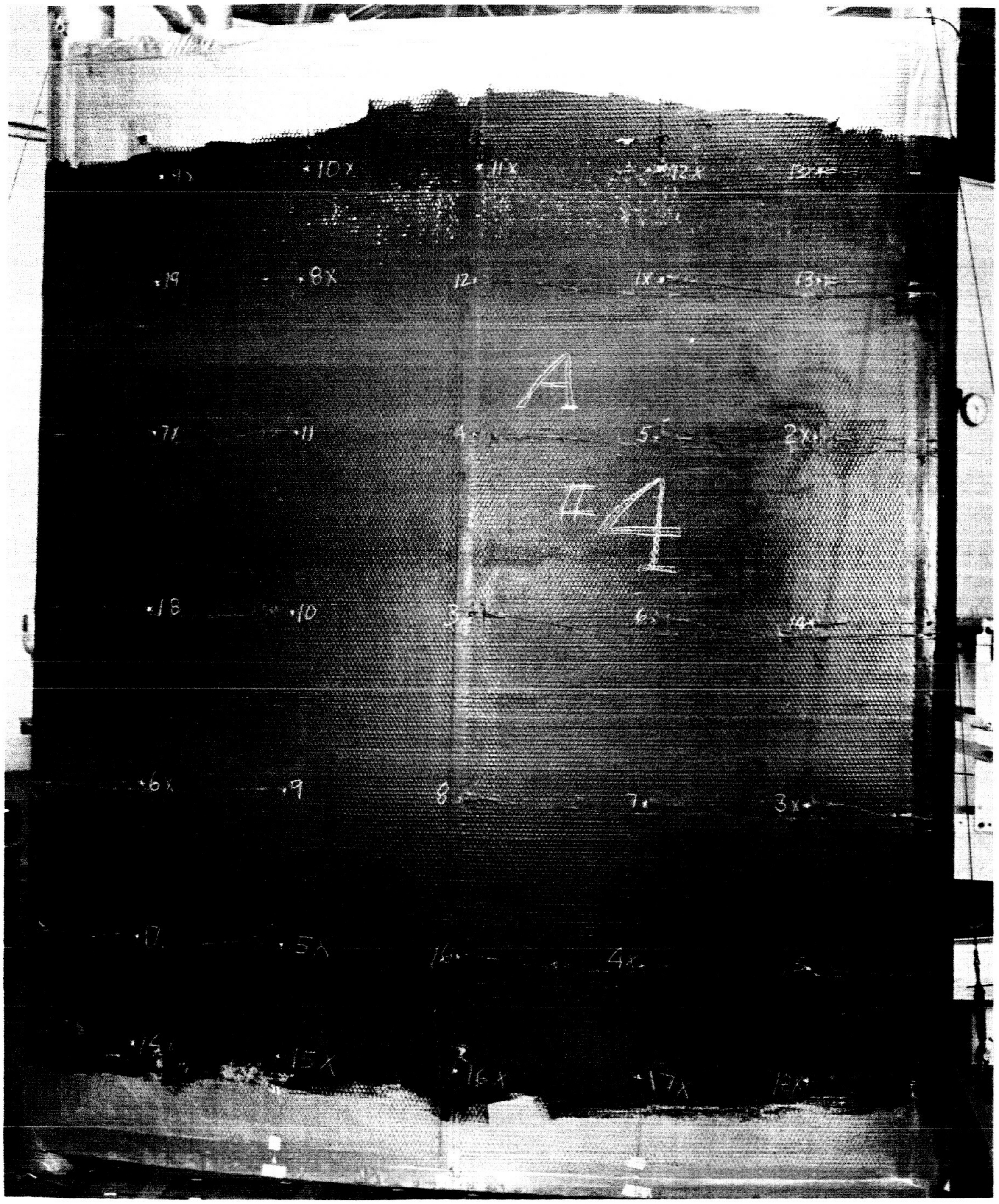


Figure 84. Panel A of LH_2 Tank No. 4 after Test

Figure 85. Panel B of LH_2 Tank No. 4 after Test, Showing Cracks in Outer Skin

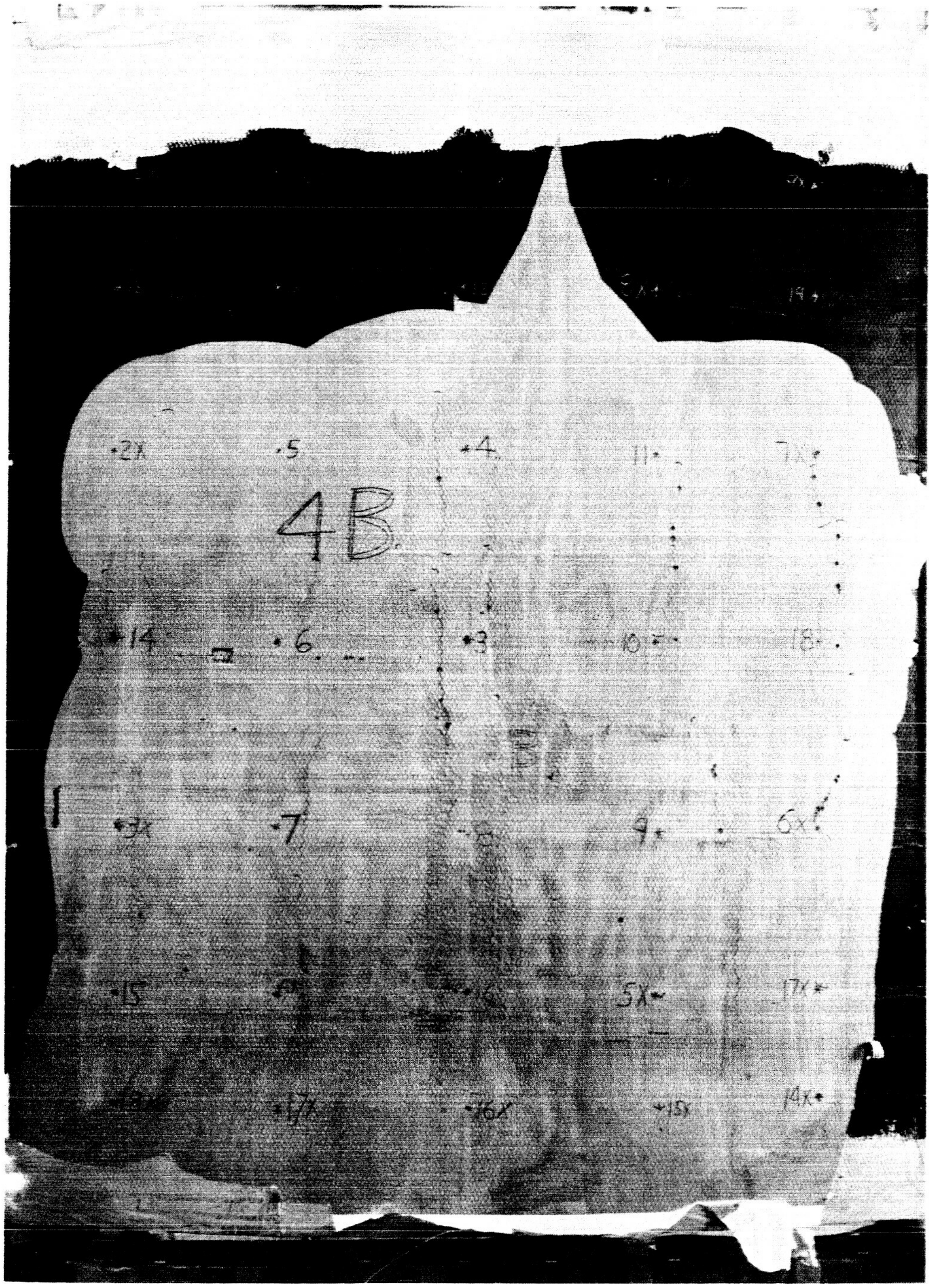


Figure 86. Panel B of Tank No. 4 after Test
with Outer Skin Removed

Table 24. Summary of Test Data for LH_2 Test System No. 1

Run No.	Boil-Off $\left(\frac{BTU}{hr\text{-}ft^2}\right)$	Temperature (°F)			$K\left(\frac{BTU\text{-}in.}{hr\text{-}ft^2\text{-}{}^oF}\right)$	
		Cold (T_3)	Sublayer (T_2)	Hot (T_1)	Subpanel	Overall
1	No data reported.					
2	116	-423	-146	-123	0.26	0.32
3	120	-423	-142	-118	0.26	0.30
4	272	-423	3	63	0.38	0.44
5	283	-423	1	65	0.40	0.46

Table 25. Summary of Test Data for LH_2 Test System No. 2

Run No.	Boil-Off $\left(\frac{BTU}{hr\text{-}ft^2}\right)$	Temperature (°F)			$K\left(\frac{BTU\text{-}in.}{hr\text{-}ft^2\text{-}{}^oF}\right)$	
		Cold (T_3)	Sublayer (T_2)	Hot (T_1)	Subpanel	Overall
1*	170	-423	8	41	0.24	0.29
2	108	-423	-86	-52	0.19	0.23
3	108	-423	-82	-48	0.19	0.23
3	154	-423	41	70	0.20	0.25
4	154	-423	-42	5	0.24	0.29
4	158	-423	12	51	0.22	0.26
5*	190	-423	15	45	0.26	0.33
6	174	-423	52	77	0.22	0.28
6	174	-423	50	75	0.22	0.28
7	200	-423	7	40	0.28	0.35

*Lamp reflectors were removed from around tank.

Table 26. Summary of Test Data for LH_2 Test System No. 3

Run No.	Boil-Off $\left(\frac{BTU}{hr\text{-}ft^2}\right)$	Temperature (°F)			$K\left(\frac{BTU\text{-}in.}{hr\text{-}ft^2\text{-}^oF}\right)$	
		Cold (T_3)	Sublayer (T_2)	Hot (T_1)	Sublayer	Overall
1	126	-423	-55	-30	0.206	0.257
2	100	-423	-124	-99	0.201	0.248
3	133	-423	-118	-77	0.260	0.306
4	108	-423	-146	-120	0.233	0.284
5	107	-423	-147	-125	0.233	0.288
6	109	-423	-139	-104	0.230	0.273
7	170	-423	-102	-44	0.318	0.360
8	125	-423	-150	-97	0.264	0.307
9	95	-423	-185	-140	0.239	0.272
10a	132	-423	-136	-99	0.275	0.325
10b	141	-423	-120	-83	0.280	0.332
10c	128	-423	-145	-110	0.276	0.328
10d	114	-423	-170	-128	0.271	0.310
10e	228	-423	-37	+57	0.354	0.379

Table 27. Summary of Test Data for LH_2 Test System No. 4

Run No.	Boil-Off $\left(\frac{BTU}{hr\text{-}ft^2}\right)$	Temperature (°F)			$K\left(\frac{BTU\text{-}in.}{hr\text{-}ft^2\text{-}^oF}\right)$	
		Cold (T_3)	Sublayer (T_2)	Hot (T_1)	Sublayer	Overall
1	88	-423	-95	-71	0.161	0.200
2	86	-423	-108	-85	0.164	0.204
3	79	-423	-114	-94	0.154	0.192
4	99	-423	-87	-69	0.177	0.223
5	173	-423	+23	+42	0.233	0.297
6	251	-423	-128	-77	0.510	0.580

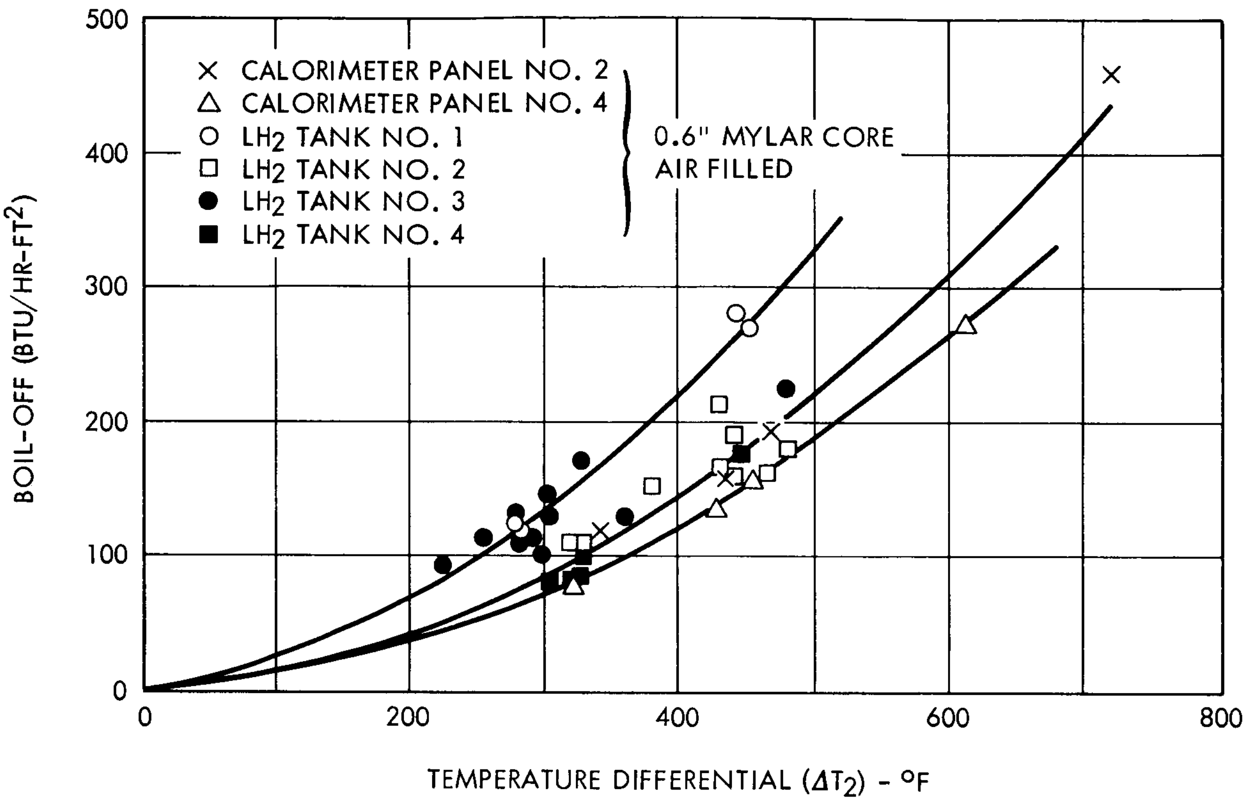


Figure 87. Boil-Off Curves - Fill and Drain Cycle Tests

versus ΔT_2. Figure 88 shows K_a versus T_1 for the overall panel. Figure 89 shows K_a versus T_2 for the sealed-cell subpanel. Temperatures T_1 and T_2 are average temperatures of both panel A and panel B.

2. LH_2 Test System No. 1

Seven fill and drain cycles were run. However, the first fill and drain was considered a system check-out, and no significant data was recorded. Tests 2 through 5 were steady-state runs. The test data is given in Table 24. The boil-off rate test points (Figure 87) fit a curve running about 40 to 60 percent higher than calorimeter measurements. The heat transfer from test runs 2 through 5

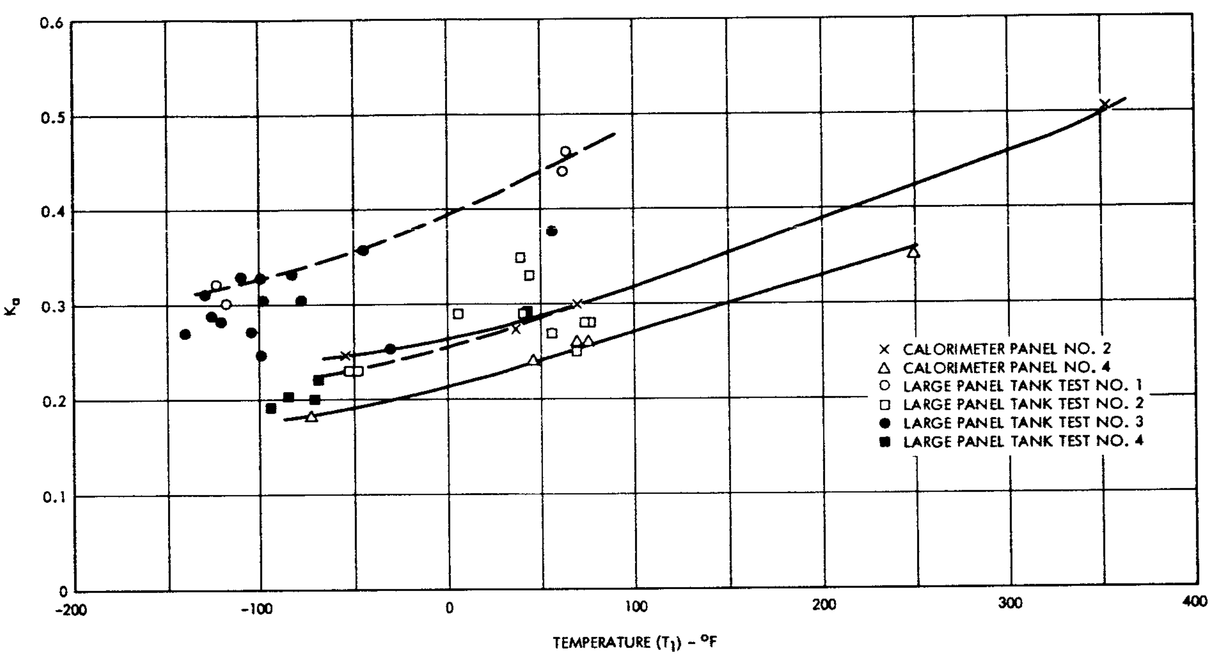


Figure 88. Apparent Thermal Conductivity for Overall Panel

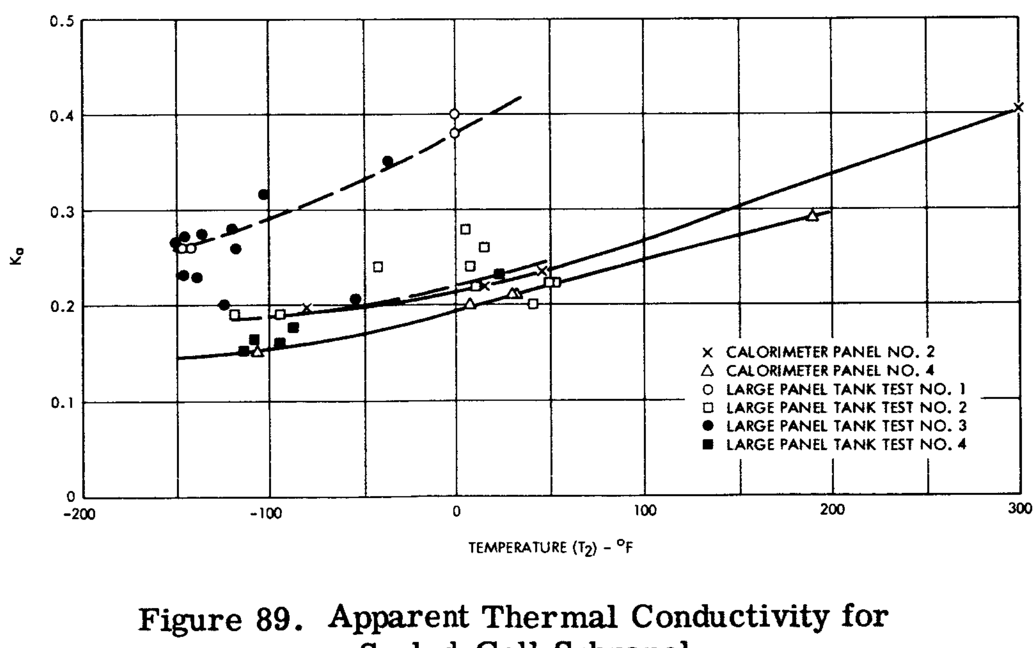


Figure 89. Apparent Thermal Conductivity for Sealed-Cell Subpanel

is for both sides of the tank (see Figure 87). The isotherm plots of panel A in Figure 90 and panel B in Figure 91 indicate that there is a distinct difference in the thermal behavior of the panels; i.e., panel B is a poorer insulator than panel A. A vertical pattern due to natural convection (cooled air spilling down the surfaces) and a perimeter pattern due to edge effects (difference in heat transfer due to light shields, wind, and guard) can be expected; however, when it is noted that the isotherms are equal increments, panel A definitely indicates a bad spot in the lower left-hand corner and panel B shows a definite perimeter degradation. These conclusions were substantiated after the final run, No. 7, when the lower left-hand corner of panel A came apart during warm-up and later when panel B was sniffed for helium and a perimeter pattern was found.

The last two tests, 6 and 7, were transient heating tests. Temperature readings are shown in Figures 92 and 93. The temperatures indicated a large degradation at the center and lower left corner of panel A after test run 6. To obtain approximate values for what happened to the insulation, a dynamic liquid level plot was made as follows. At the end of runs 6 and 7, the surface temperature was held at about 75°F, and the liquid level lights at 45, 30, and 15 inches were timed as to when they went out. This gave three points to which a curve was fitted to plot liquid level versus time. From these curves a number of slopes were read off to get the rate at which the level drop was changing with wetted area, or

$$q = C_1 \frac{dx}{dt}$$

$$= C_2 Kx\Delta T$$

or

$$K = C \frac{dx/dt}{x\Delta T} ,$$

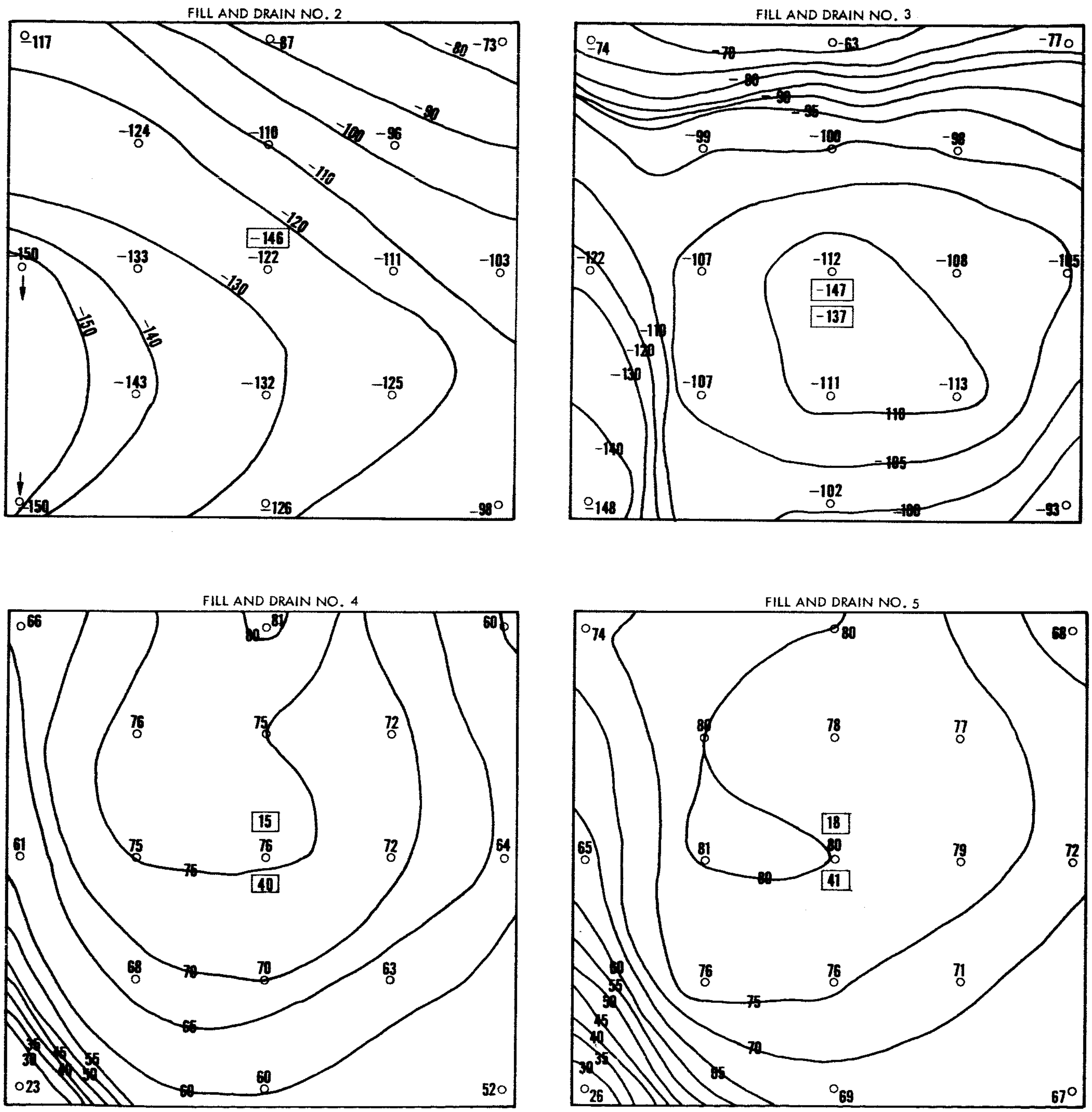


Figure 90. Isotherms for Panel A of LH_2 Test System No. 1

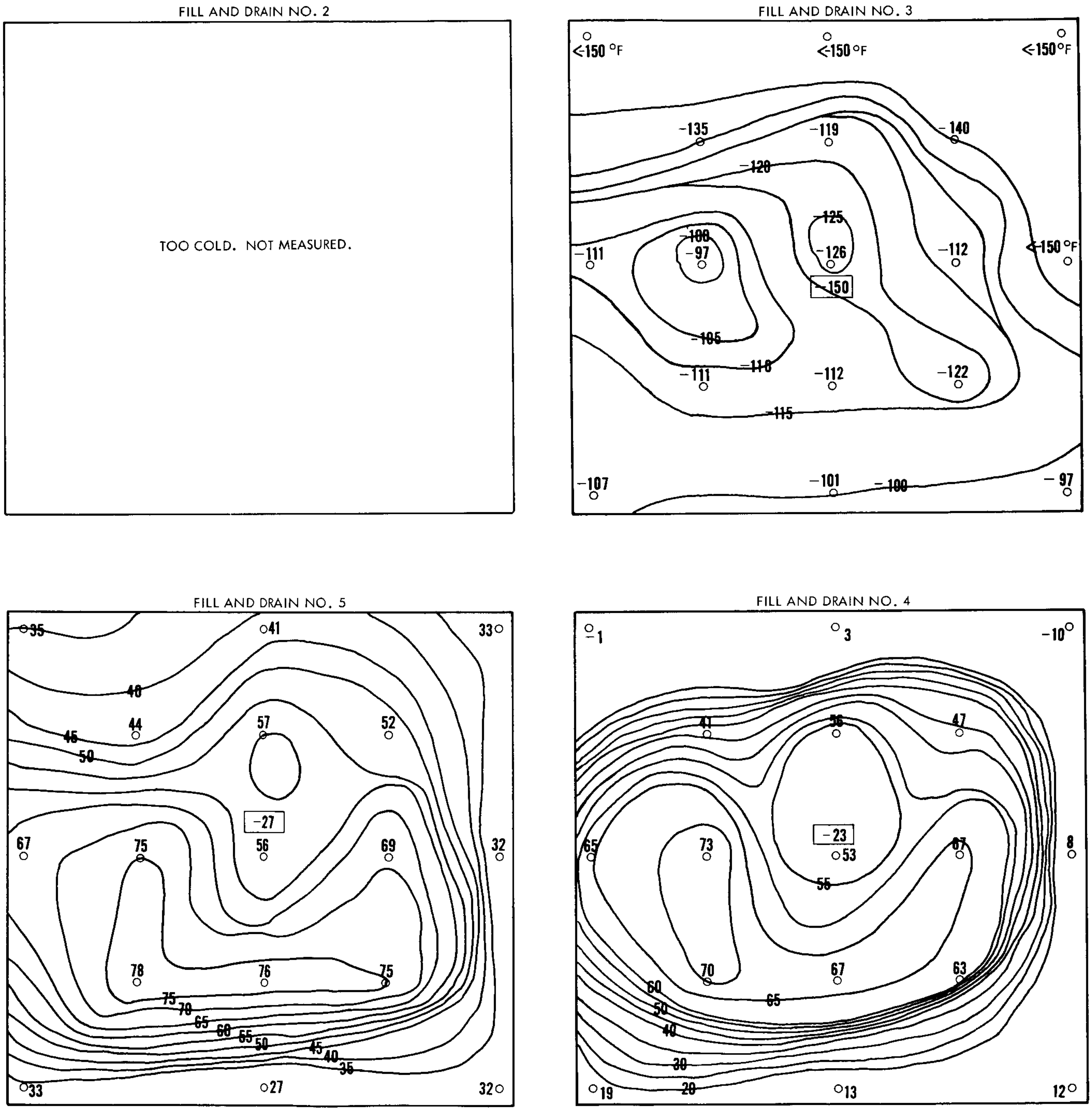


Figure 91. Isotherms for Panel B of LH_2 Test System No. 1

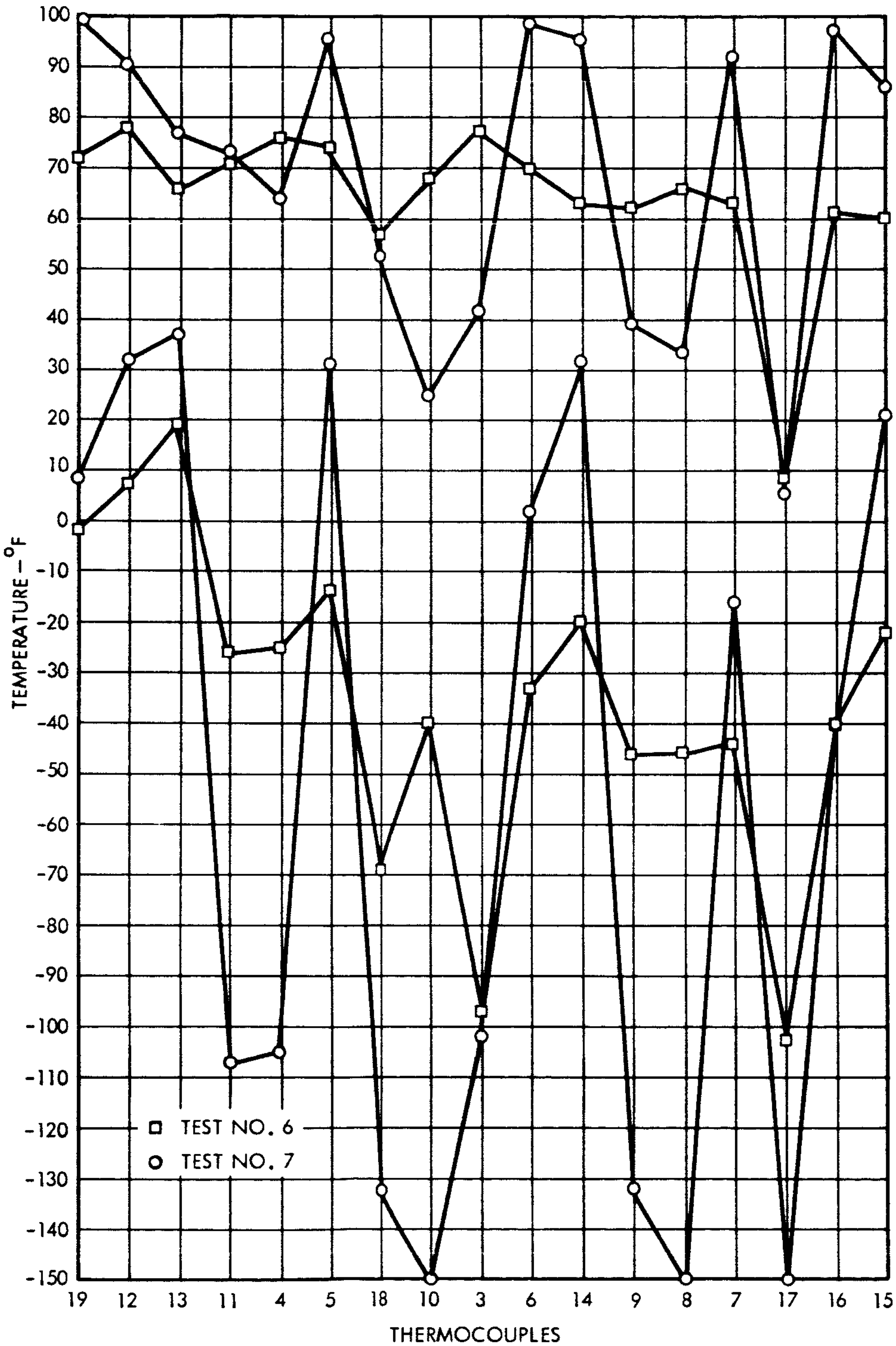


Figure 92. Panel A Temperature Readings with and without Heat

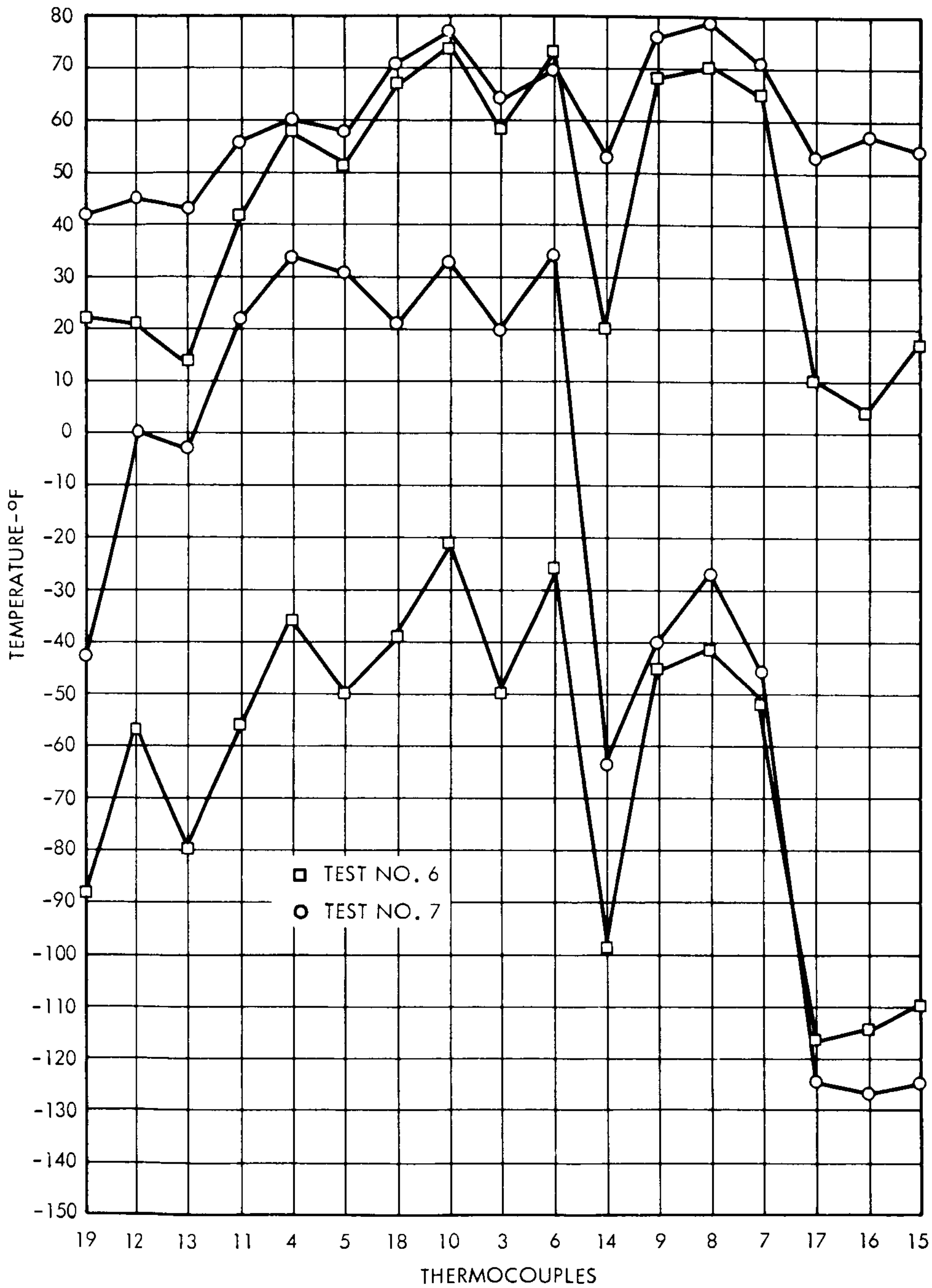


Figure 93. Panel B Temperature Readings with and without Heat

and if the temperature differentials are equal, the conductivity is proportional to the slope

$$K = C \frac{dx}{xdt} .$$

These plots are shown in Figure 94. The only steady-state run with any liquid level data was run 2. These curves show the degradation effects after the first transient heating run and after the second transient heating run. Run 6 has a slope about six times that of corrected run 2, and run 7 has a slope 12 times that of run 2.

From this data it is concluded that purge gas permeated slowly into the sealed cells from the edges, causing panel B to have a higher conductance than panel A. Apparently, during the two transient heating cycles, little or no additional purge gas got into the cells of panel B. However, panel A had a bad corner that failed during the first transient heating test, allowing the purge gas to get into the cells in large quantities, which resulted in the light boil-off at the end of this run. In the second transient cycle test, during the 3 to 4 hours of cold condition, CO_2 got in and solidified in the sealed cells, resulting in a still higher conductance. During warm-up at the conclusion of the test, the CO_2 vaporized rapidly, building up excess pressure which caused the failure in panel A.

3. LH_2 Test System No. 2

The analysis of system No. 2 is similar to that of system No. 1 except that more data is included (see Table 25). Boil-off data was measured before and after the temperature profile run; therefore, use of the dynamic liquid level technique was not necessary.

The isotherms for panels A and B are shown in Figures 95 through 100. The effects of the heating lamp reflectors as shields during ambient testing is shown in

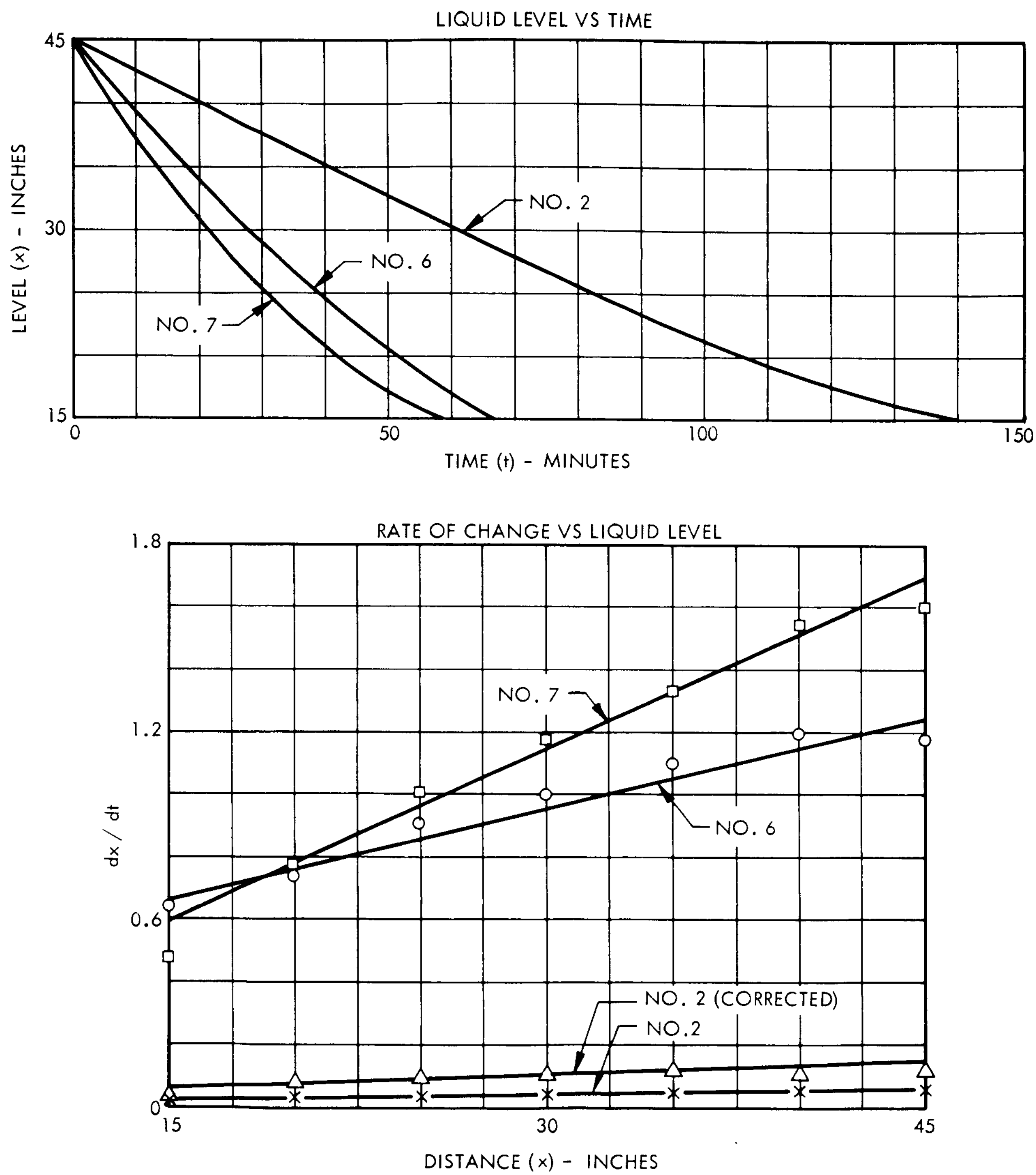


Figure 94. Dynamic Liquid Level Plots

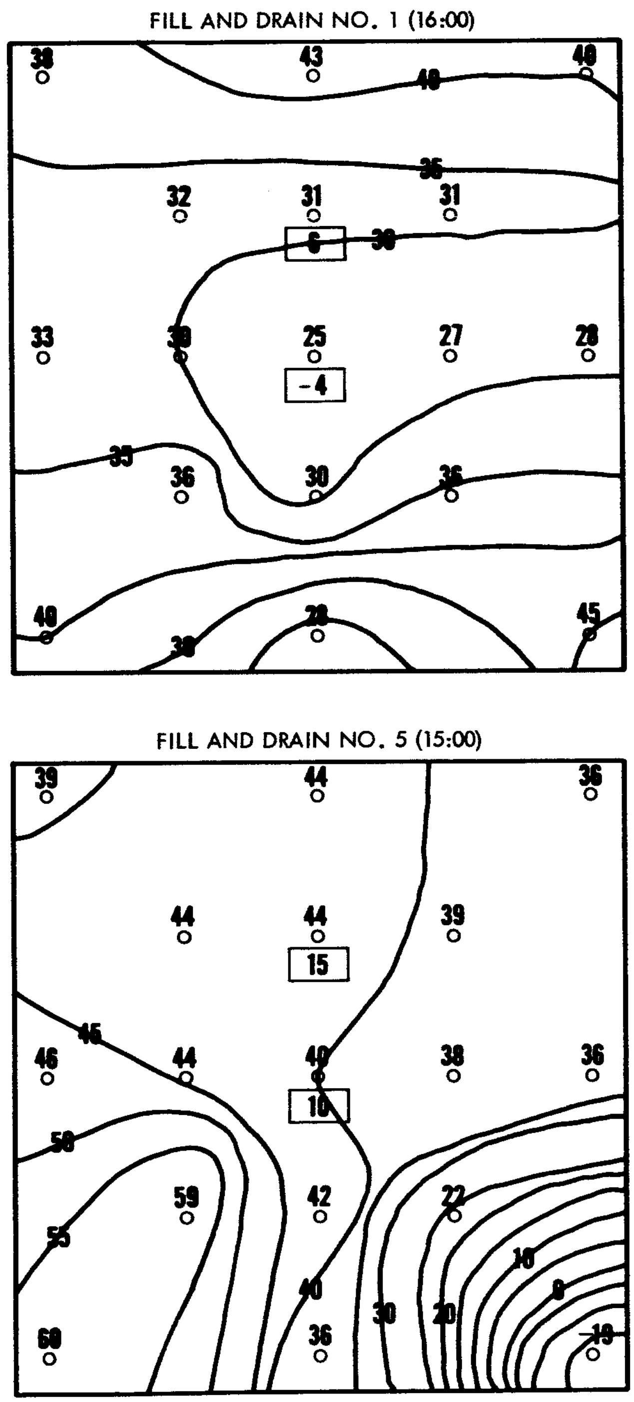


Figure 95. Isotherms for Panel A of LH_2 Test System No. 2 Heating Reflectors Removed

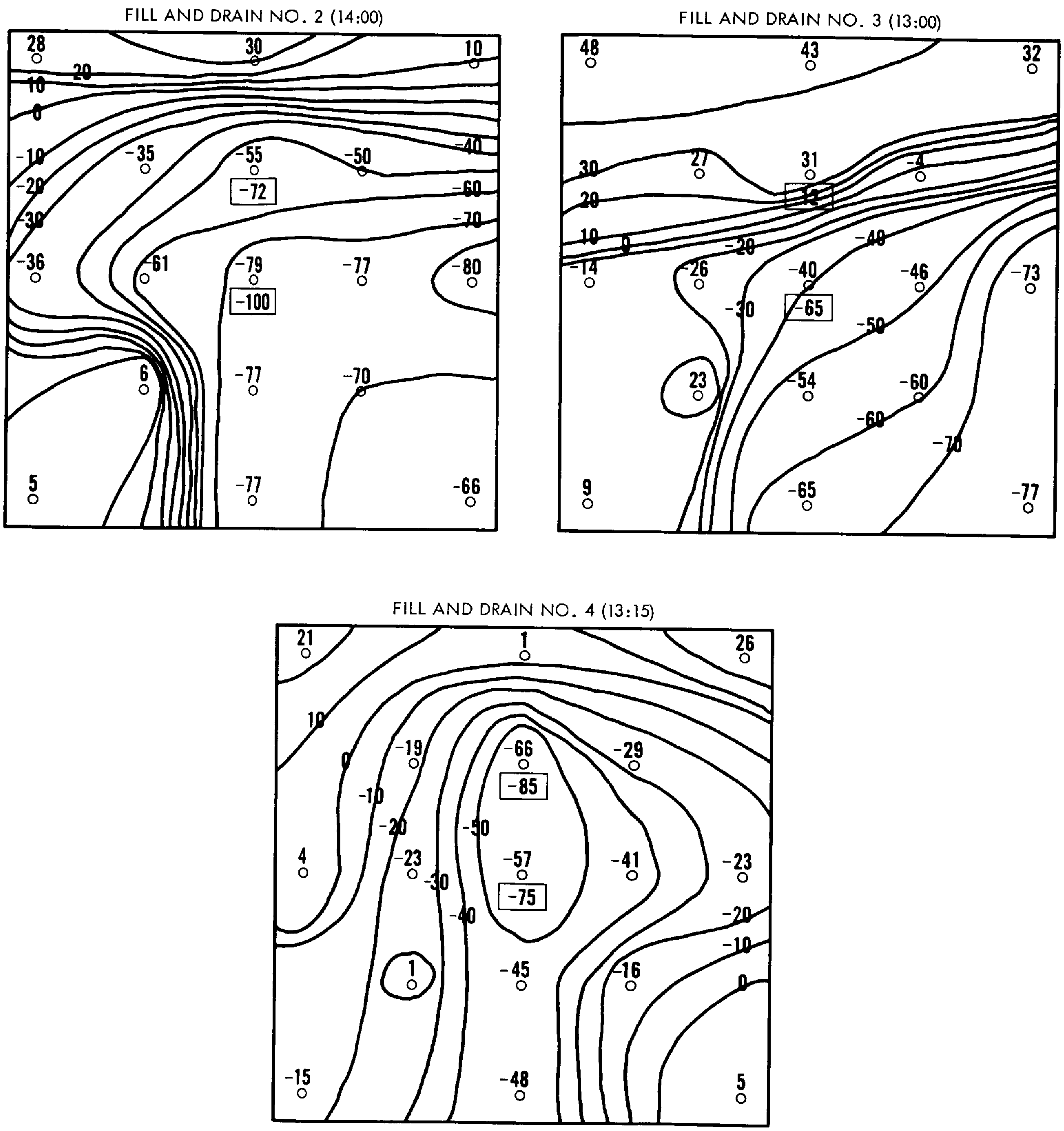


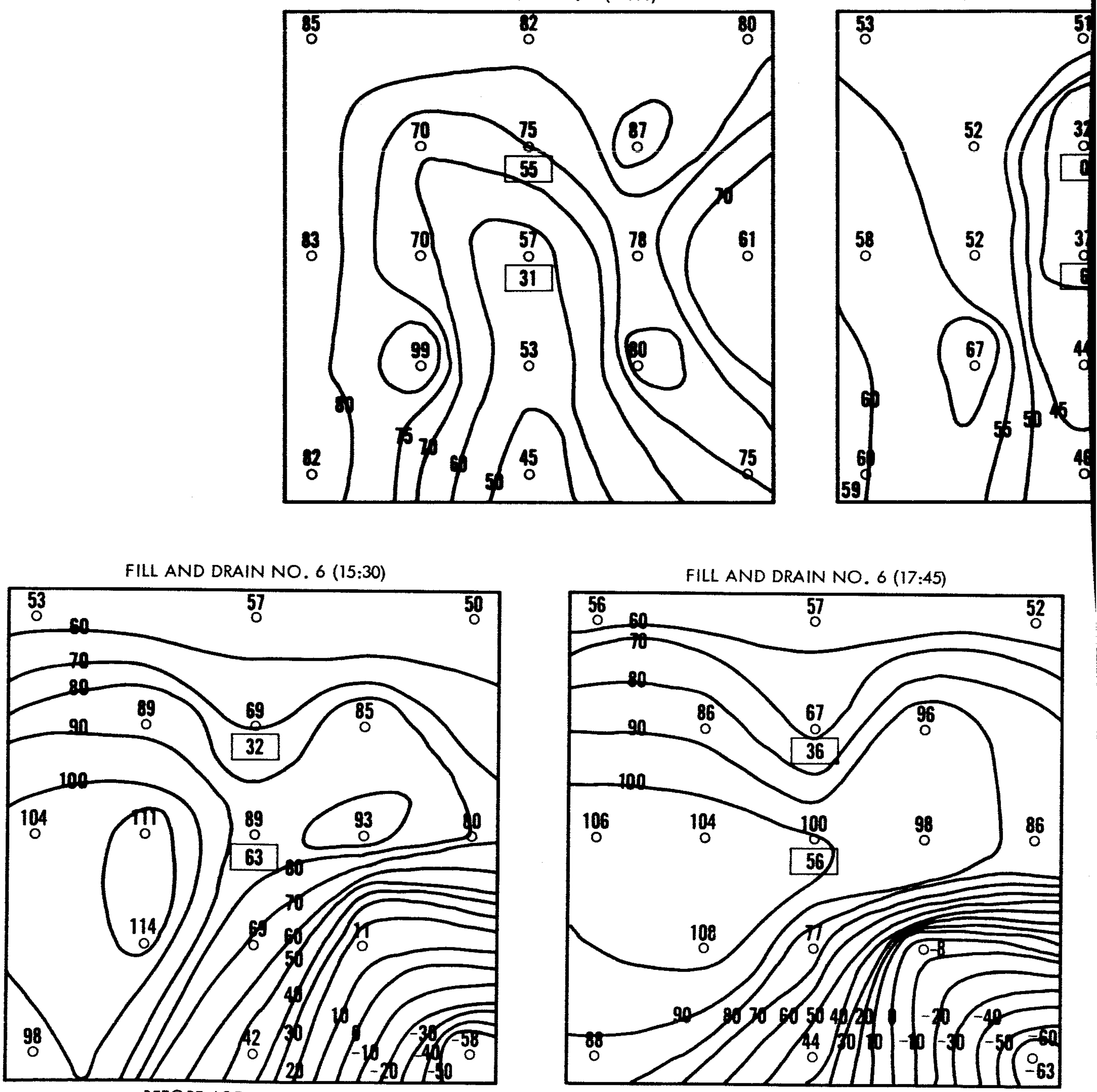
Figure 96. Isotherms for Panel A of LH_2 Test System No. 2 - Heating Reflectors in Position but No Heat Applied

FILL AND DRAIN NO. 3 (15:00)

FILL AND DRAIN

FILL AND DRAIN NO. 6 (15:30)

FILL AND DRAIN NO. 6 (17:45)



BEFORE ASCENT HEATING

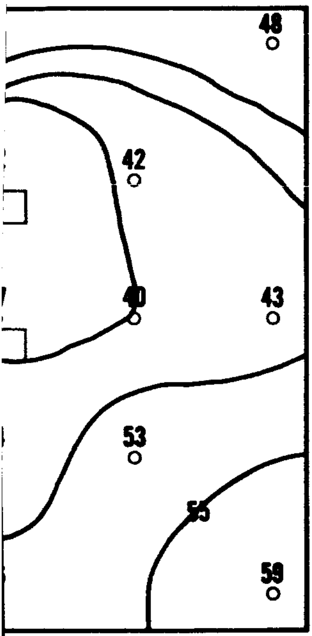
AFTER ASCENT HEATING

195

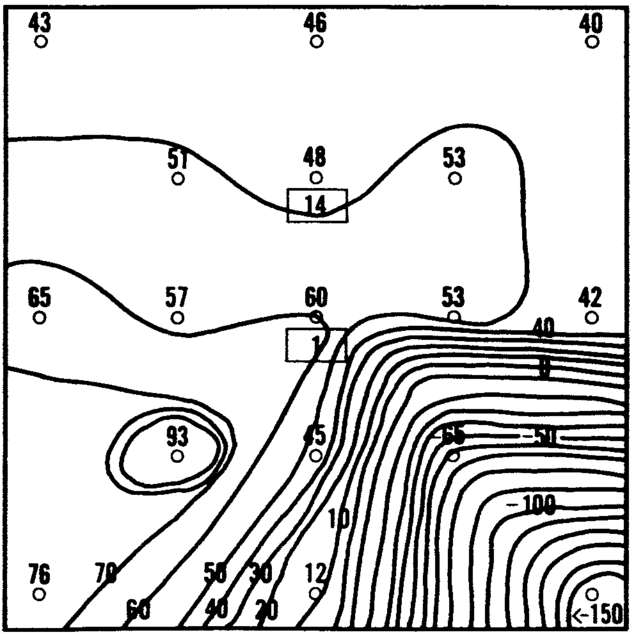
Figure 97. Isotherms for Panel A of LH_2 Test System No. 2 - Cont

195-1

NO. 4 (14:30)



FILL AND DRAIN NO. 7 (12:50)



BEFORE ASCENT HEATING

olled Heating Condition

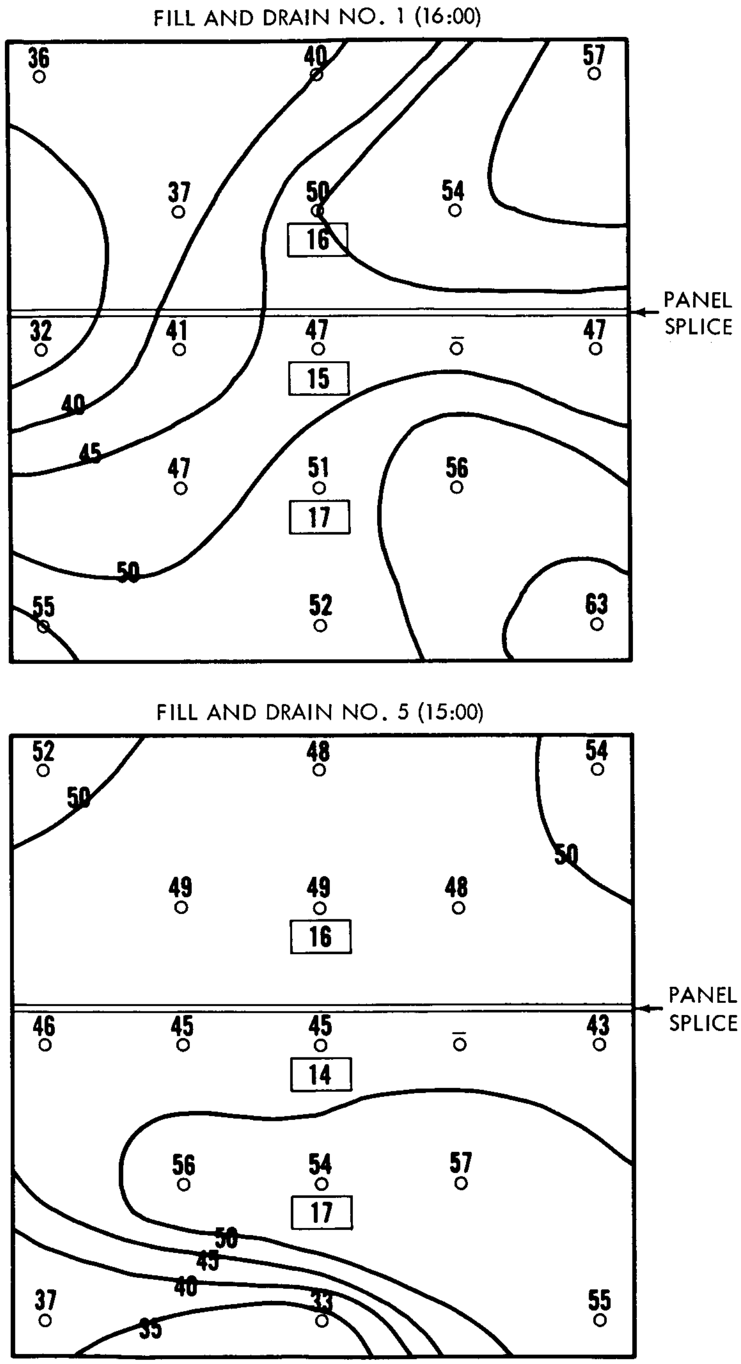


Figure 98. Isotherms for Panel B of LH_2 Test System No. 2 - Heating Reflectors Removed

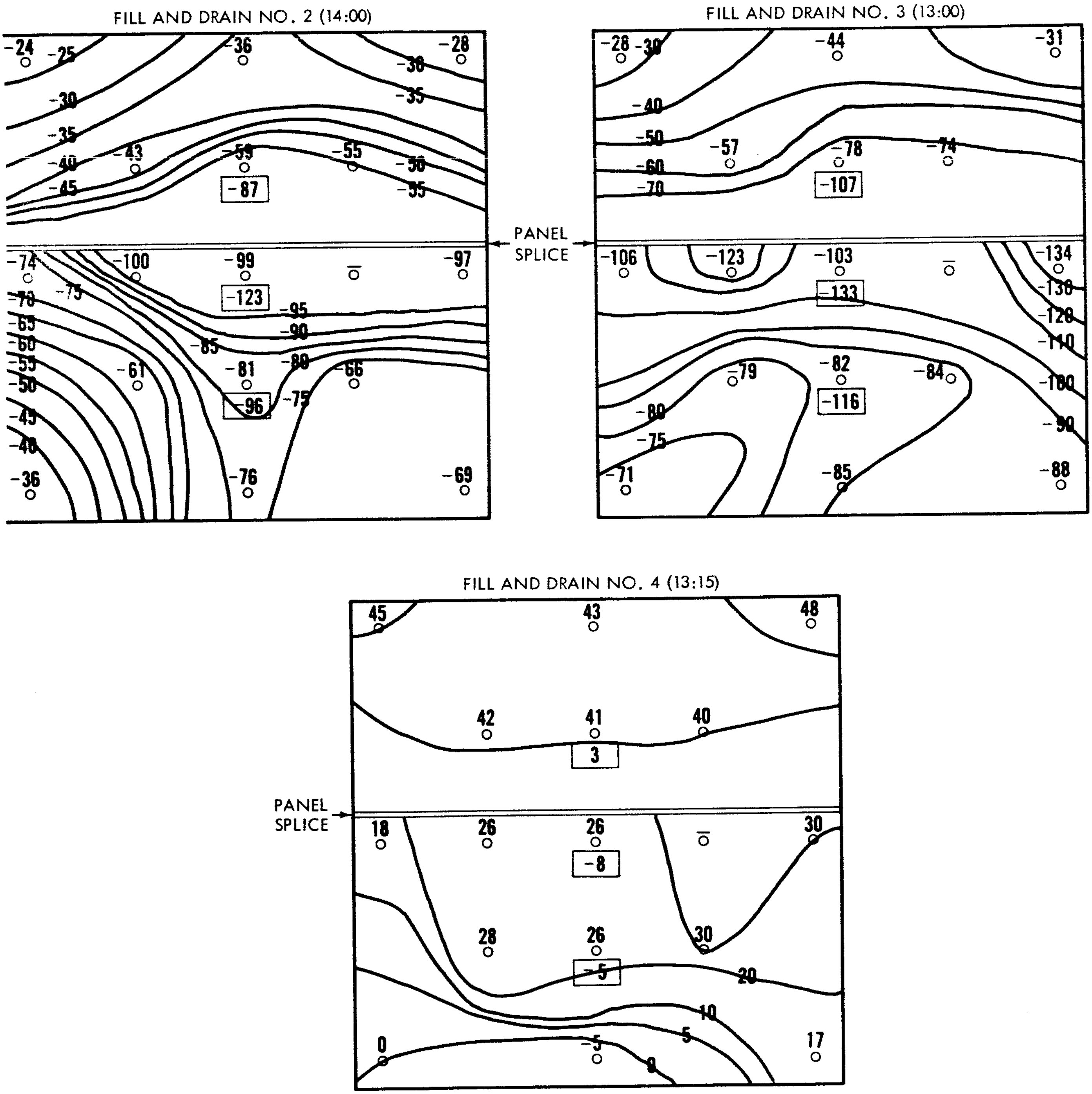
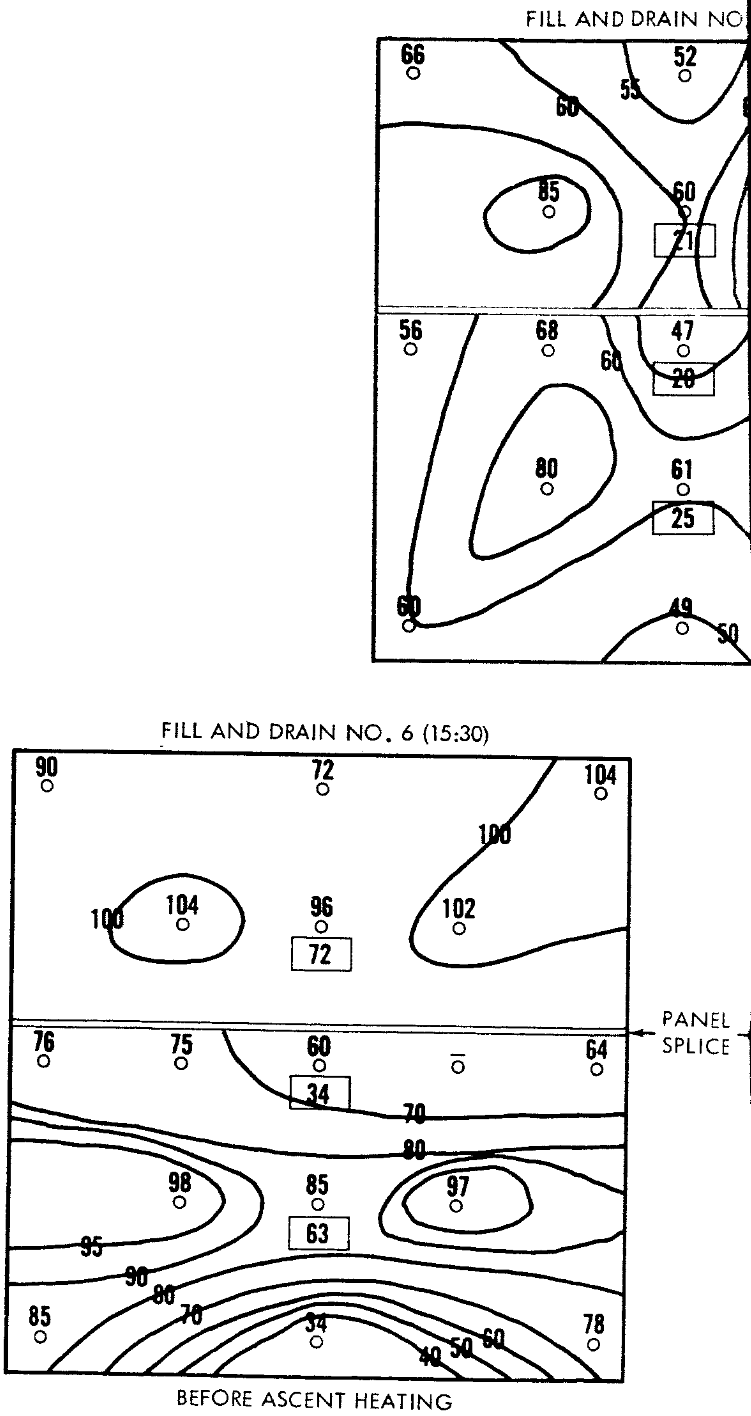
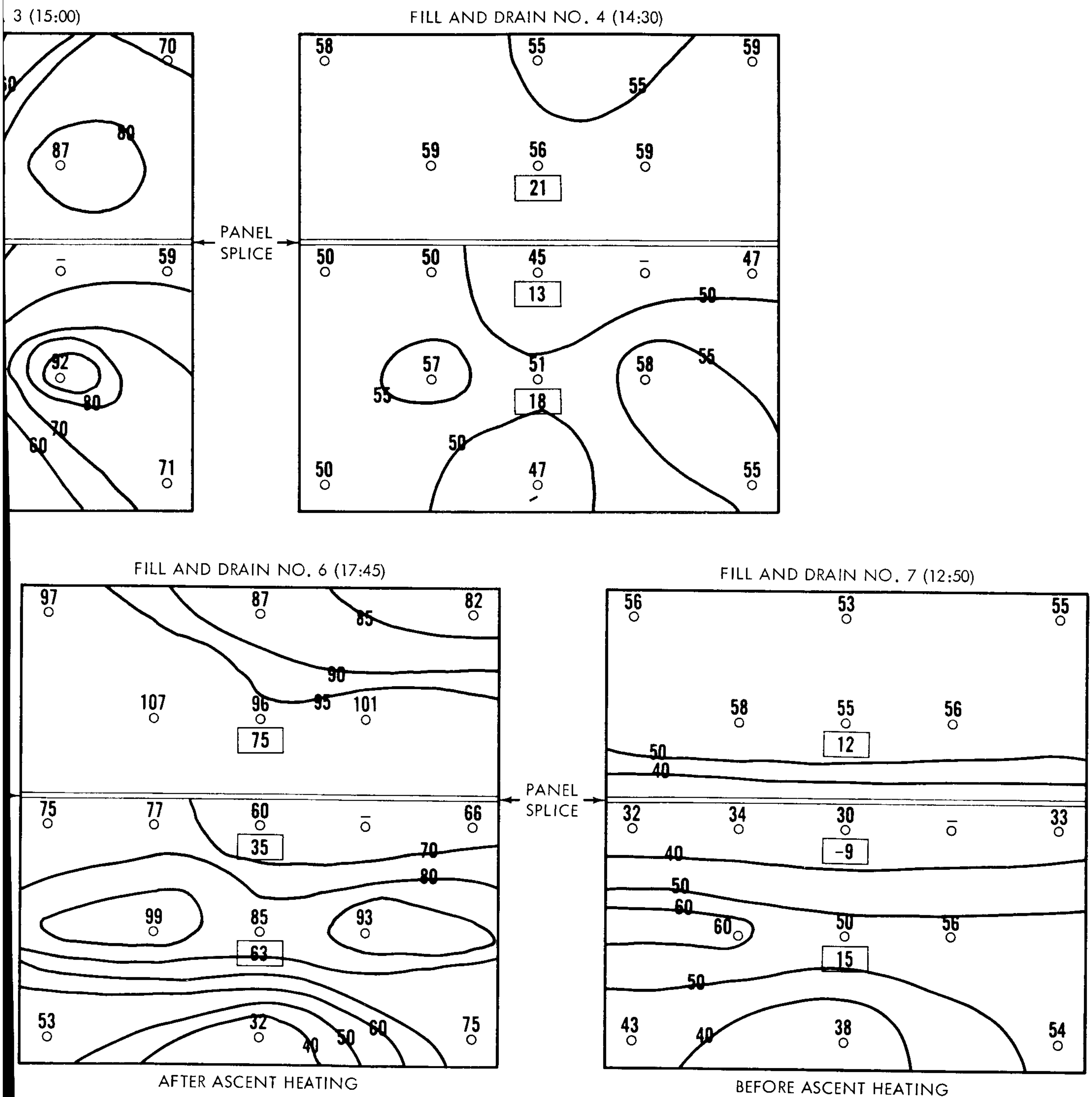


Figure 99. Isotherms for Panel B of LH_2 Test System No. 2 Heating Reflectors in Position but No Heat Applied



198

Figure 100. Isotherms for



Panel B of LH_2 Test System No. 2 - Controlled Heating Condition

Figures 96 and 99 as compared to the same test condition with the reflectors removed as shown in Figures 95 and 98. The reflectors act as additional insulation to the panels, resulting in lower temperature along with steeper temperature gradients around the edges from heat leaks and effects of directional winds or subcooled air spillage.

The isotherm curves shown in Figures 95 and 96 indicate that the lower right-hand area of panel A degraded after fill and drain No. 4. A helium leak check and panel dissection indicated that helium had permeated from the edge in this area. Figure 99 isotherms show the effect of the foam-filled splice in panel B. The temperature readings are lower, indicating that the insulating properties of the foam are not as good as the dual seal.

4. LH_2 Test System No. 3

The data for the 10 fill and drain test cycles is summarized in Table 26. During run 10, data was reported for the following conditions:

(1) Run 10a - tank full stabilized under ambient condition

(2) Run 10b - tank three-fourths full under ambient condition

(3) Run 10c - tank one-half full under ambient condition

(4) Run 10d - tank full under ambient condition

(5) Run 10e - tank full with heat lamps on

Figures 101 through 105 show isotherm plots for runs 1, 4, 8, 10a, and 10e. Figures 106 and 107 show plots of K versus T_2 and T_1 temperatures for various runs. The isotherm plots show a gradual lowering of temperatures as the testing progresses, particularly at the splice on side B and at some local and corner spots.

In Figures 106 and 107 it can be seen that K varies directly with the temperature and the length of time the panel has been subjected to testing. The K versus

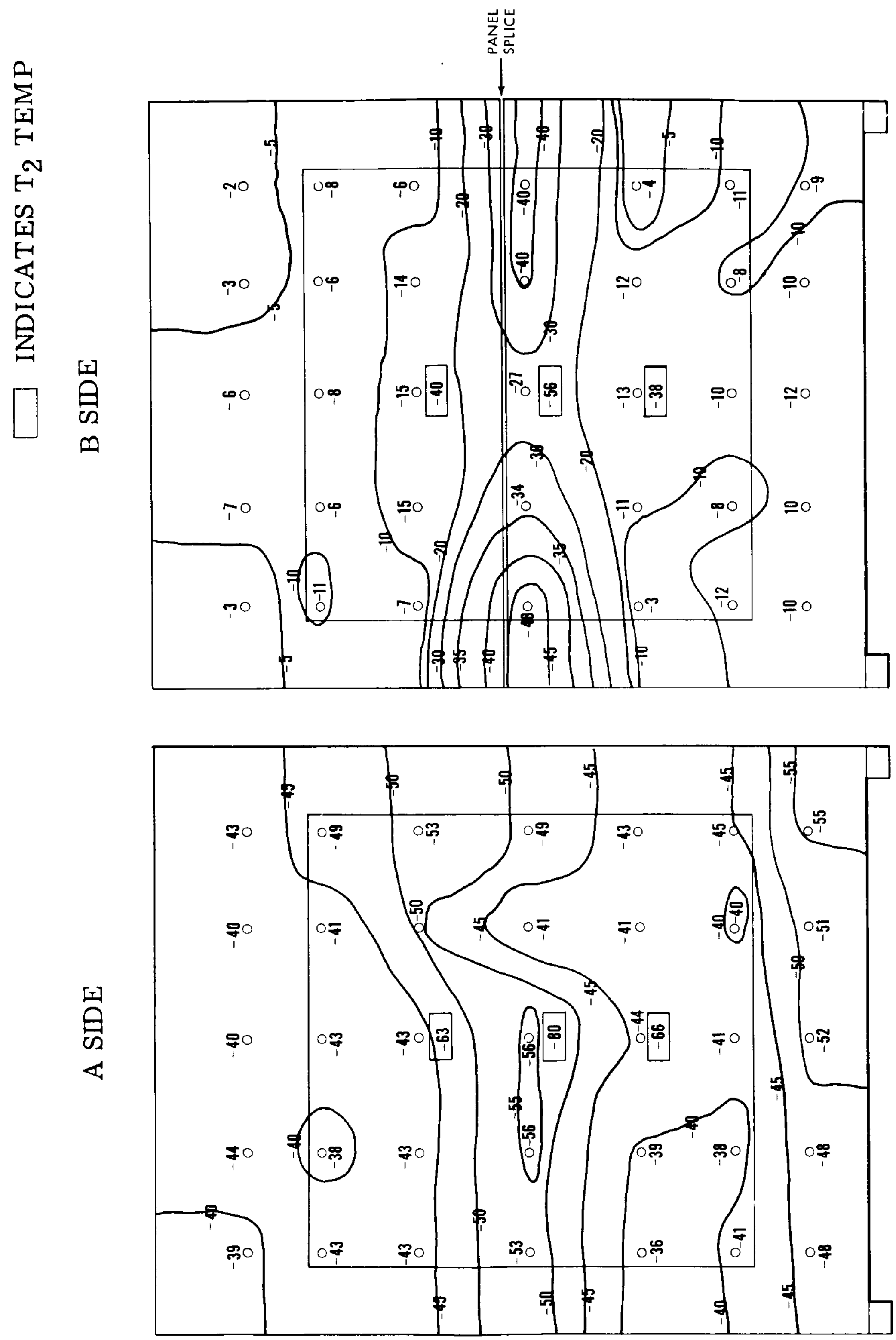


Figure 101. Isotherms for Run 1 of LH_2 Test System No. 3

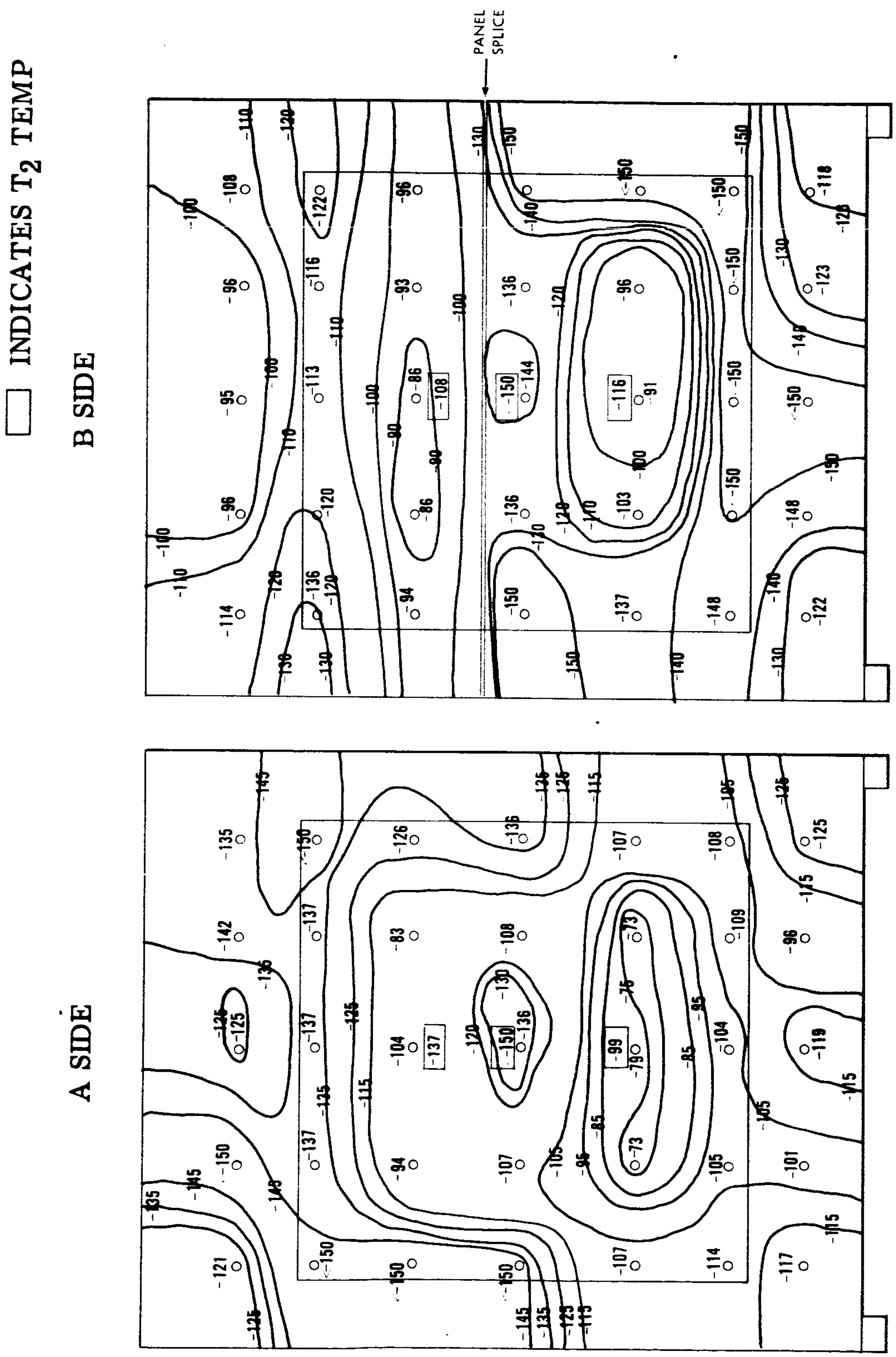


Figure 102. Isotherms for Run 4 of LH_2 Test System No. 3

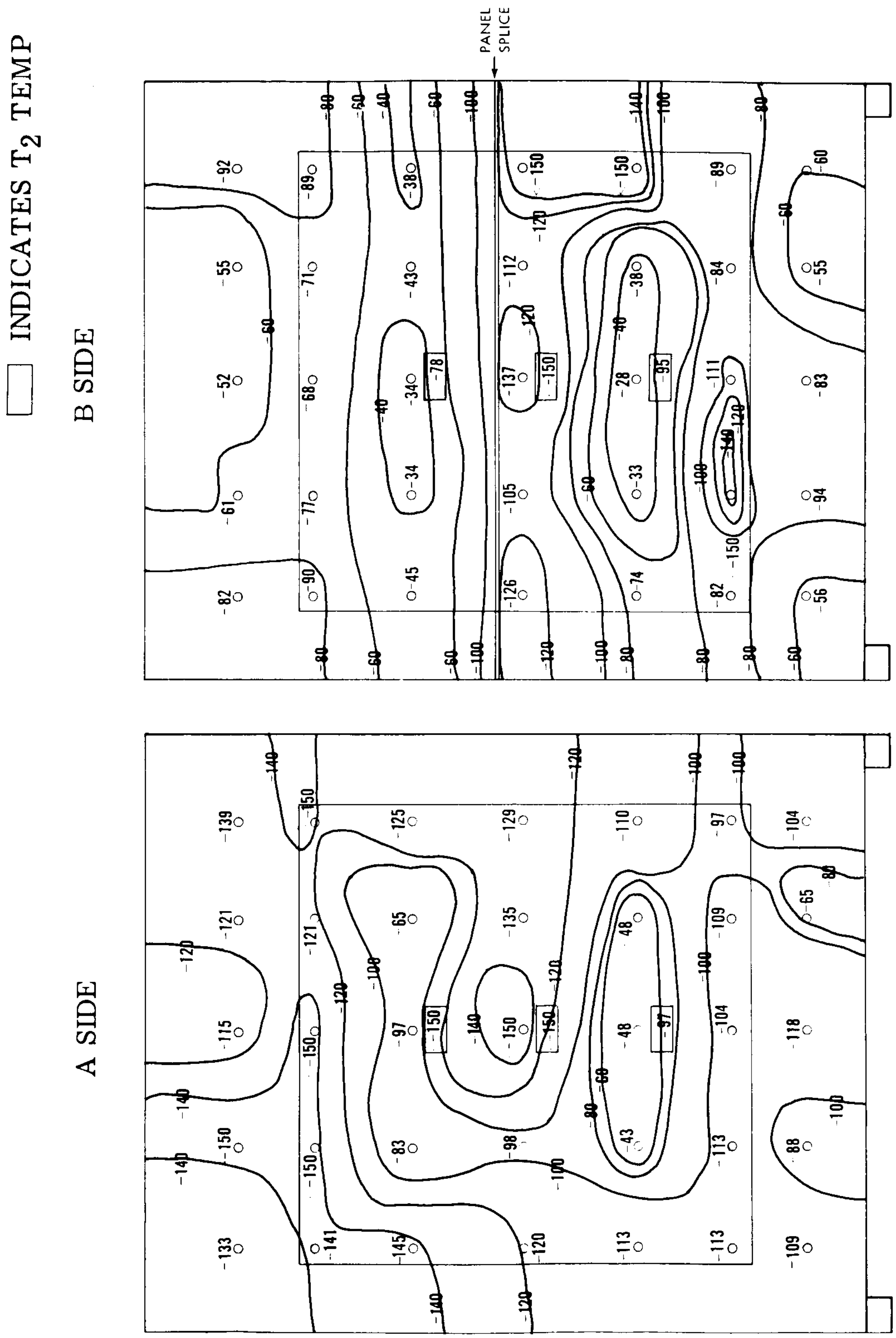


Figure 103. Isotherms for Run 8 of LH_2 Test System No. 3

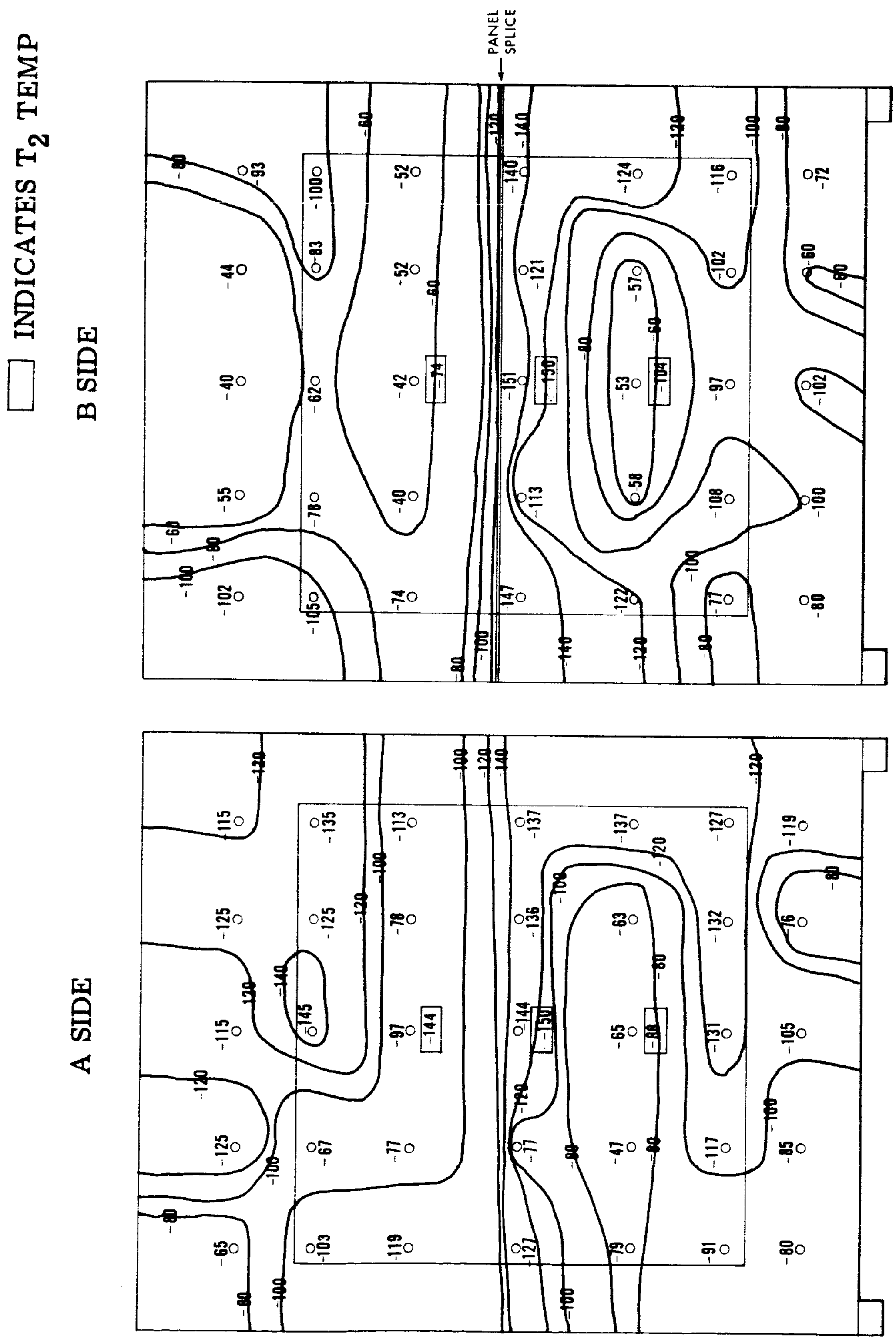


Figure 104. Isotherms for Run 10a of LH_2 Test System No. 3

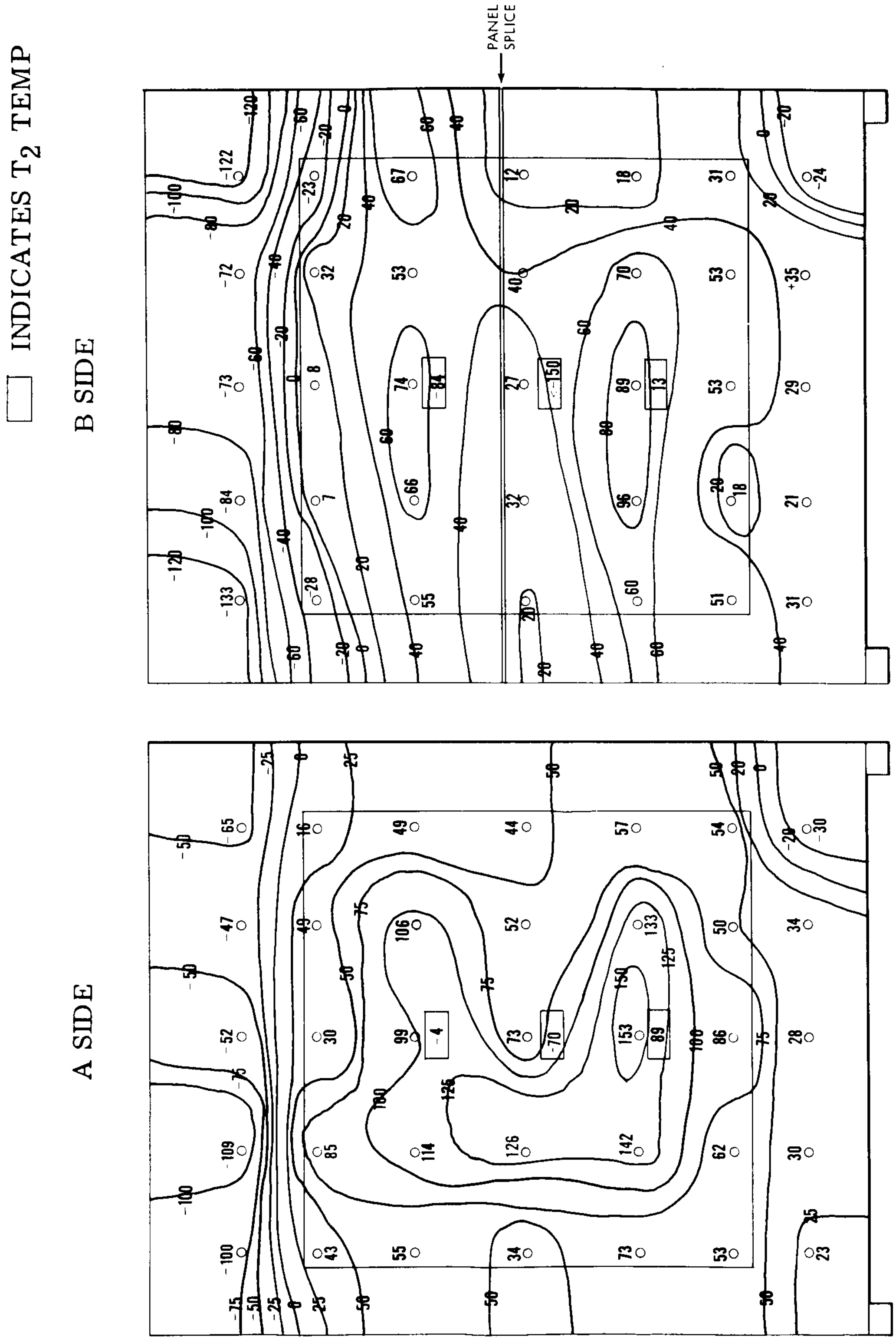


Figure 105. Isotherms for Run 10e of LH_2 Test System No. 3

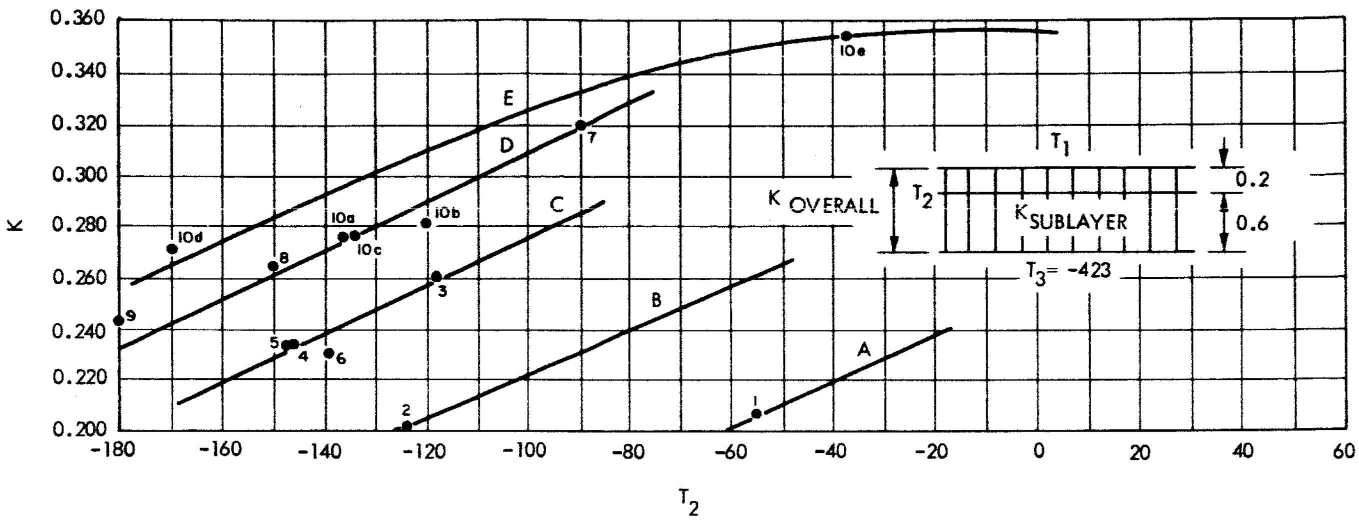


Figure 106. K (Sublayer) versus T_2

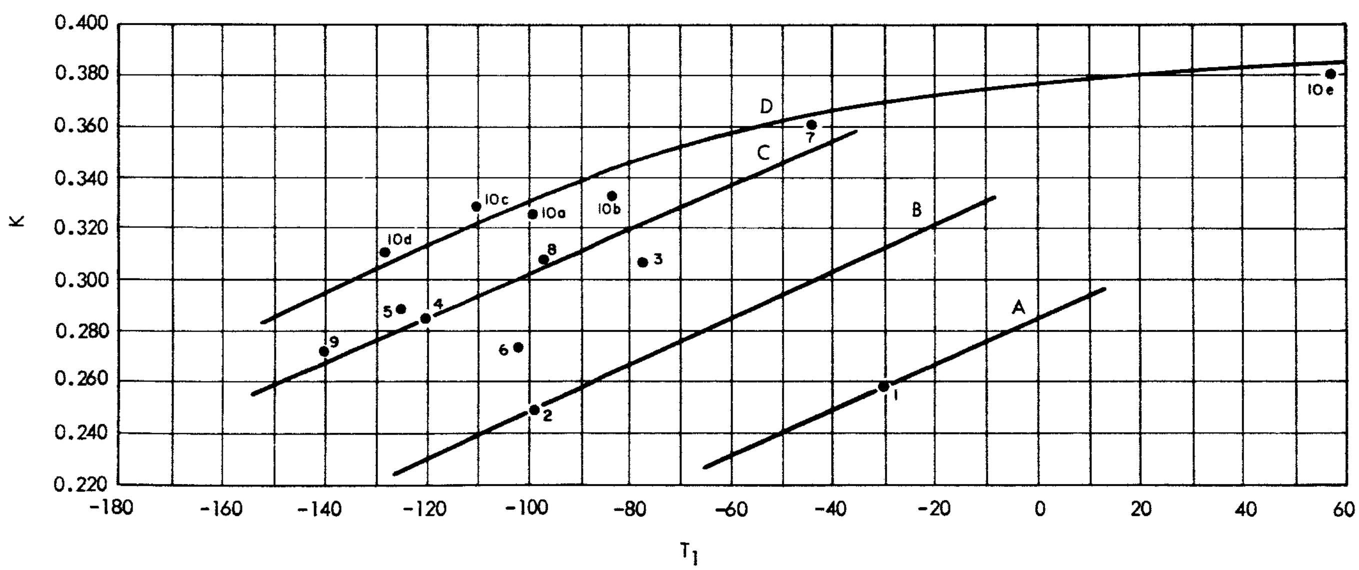


Figure 107. K (Overall) versus T_1

temperature curve itself shifts upward as the test progresses. This upward movement of K is a sign of some deterioration of the panel.

In Figure 107, for example, there seems to be a marked deterioration up until about the third cycle test (see curves A, B, and C in Figure 107). By run 3 the curve (curve C) seems to have settled down. After the severe conditions of run 10, there seems to be a slightly increased deterioration, as shown in curve D. This same general trend is observed in Figure 106. Here there seems to be a more marked deterioration between runs 6 and 7, as shown in curves C and D.

Run 10a was similar to the previous runs. However, in run 10b the measuring tank was only three-fourths full of LH_2 and in run 10c the tank was half full. The K's were calculated using only the area of the measuring tank that contained the LH_2. For example, when the tank was half full, the boil-off and temperature difference for the calculation of K was obtained by using half of the total measured boil-off and the temperatures on the lower half of the tank.

5. LH_2 Test System No. 4

A summary of test data for the six liquid hydrogen fill and drain cycles conducted on insulation system No. 4 is given in Table 27. Figure 108 shows comparative surface temperatures for run 5 stabilized at controlled heat and run 6 prior to termination of testing. The boil-off and thermal conductivity (K_a) data given in Table 27 is compared with that of the other three systems in Figures 87, 88, and 89.

The thermal performance of this system during ambient cycling, as well as during the first controlled heat and temperature profile cycle, was as good or better than all other systems tested.

The attempt to conduct a second controlled heat and temperature profile cycle (No. 6) on this system was terminated when excessive degradation was indicated

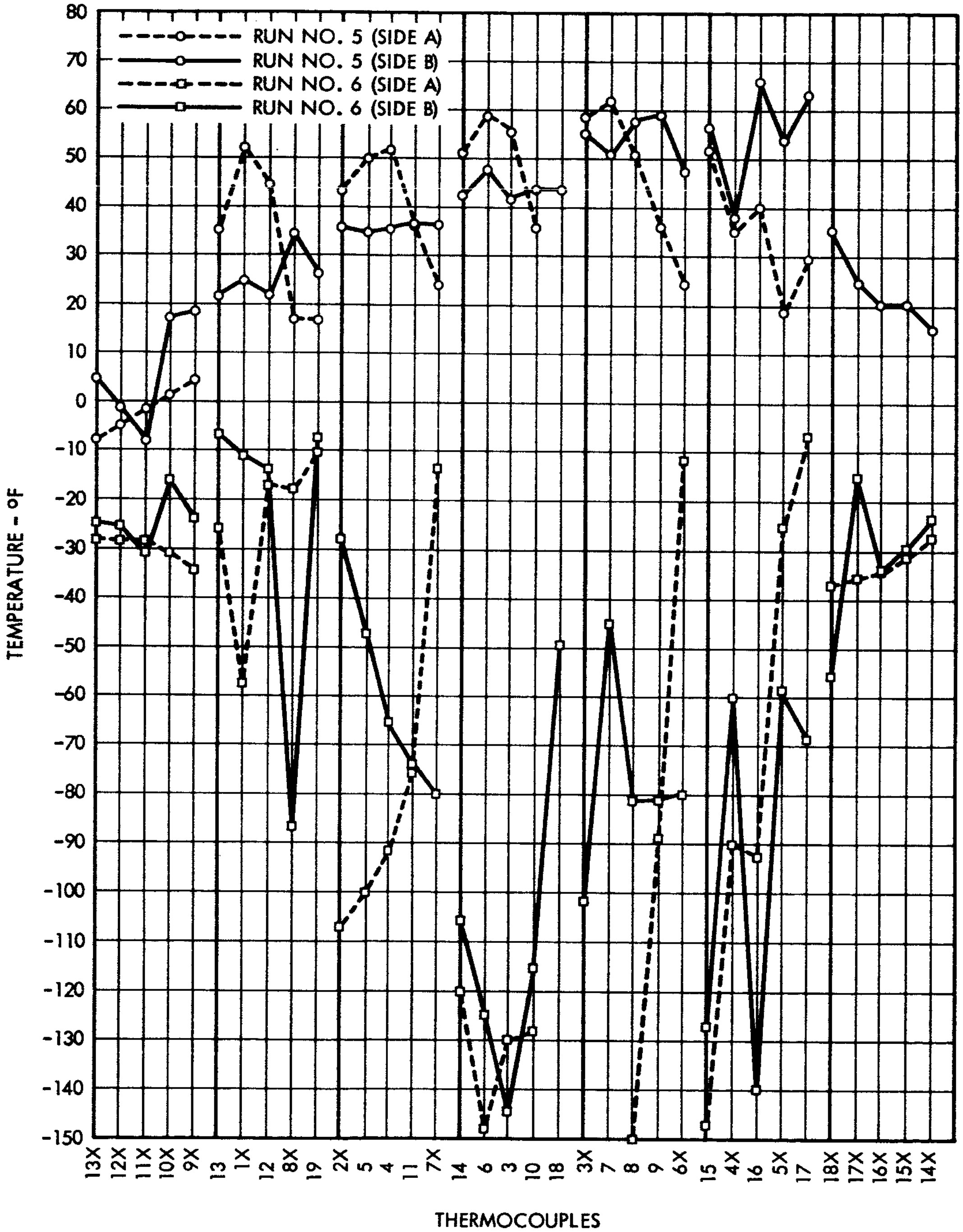


Figure 108. Surface Temperatures for Runs 5 and 6 of LH_2 Test System No. 4

by instrumentation measurements. Following complete boil-off and warm-up of the test tank, the two dual-seal panel constructions making up insulation system No. 4 were visually inspected for surface damage. The outer surface of panel A showed no sign of damage except for the squaring of HRP cells, which was evident at the end of the fifth test cycle. Panel B had numerous cracks in the outer aluminum foil covering and the adhesive layer bonding it to the HRP perforated core. Dissection of the panels showed no evidence of degradation in panel A, but splitting of the HRP core in panel B was observed as well as cracks through the interseal and adhesive layers. These interseal cracks would account for serious degradation of the thermal performance of panel B, inasmuch as they provided direct paths for the helium purge gas to enter the sealed Mylar honeycomb cells and to destroy the essential cryopumping feature of the dual-seal concept.

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