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LOCKHEED MISSILES & SPACE COMPANY
HUNTSVILLE RESEARCH & ENGINEERING CENTER
HUNTSVILLE RESEARCH PARK
4800 BRADFORD DRIVE, HUNTSVILLE, ALABAMA

STUDY OF THERMAL CONDUCTIVITY REQUIREMENTS

VOL. III

ANALYTICAL AND EXPERIMENTAL HEAT TRANSFER STUDY OF A VENTING CRYOGEN TANK FINAL REPORT

June 1971

Contract NAS8-26189

Prepared for National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

by
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FOREWORD

This report represents the results of work performed by the Thermal Environment Section of the Aeromechanics Department of Lockheed Missiles & Space Company, Huntsville Research & Engineering Center, for the National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama, under Contract NAS8-26189. The NASA contract monitor was Mr. John Austin of the MSFC Astronautics Laboratory.

The report for "Study of Thermal Conductivity Requirements" consist of three volumes:

Volume I: Study of Thermal Conductivity Requirements — Multilayer Insulation Thermal Conductivity Test Program — Final Report - NAS8-26189

Volume II: Study of Thermal Conductivity Requirements — Multilayer Insulation Data Manual — Final Report - NAS8-26189

Volume III: Study of Thermal Conductivity Requirements — Analytical and Experimental Heat Transfer Study of a Venting Cryogen Tank — Final Report - NAS8-26189.

SUMMARY

A subscale cryogen tank insulated with a multi-layer insulation (MLI) composite was analyzed and tested to determine the applied thermal conductivity of the MLI. This approach is necessary because the MLI is degraded when it is applied to a tank by the structural supports, fasteners, compressive loading and other non-ideal conditions. The analytical predictions were made prior to the tests and were used in the development of the test plan and selection of the instrumentation. The experimental program was conducted by NASA-MSFC personnel. The comparisons of analytical and experimental data are presented, and show good agreement.

The following conclusions were drawn from the study:

1. The analytical technique used in the pretest predictions was correct.
2. The new approach of conducting a series of tests at different heater stimulated flow rates can be used to accurately determine the applied thermal conductivity of MLI.
3. Cooling the ventline top did not completely eliminate the heat leak through the vent line for the tank considered.

Based on the results of this study, the following recommendations were made regarding future tank tests:

1. Prior to the test an analysis should be conducted to determine the heat leak through the vent line. The results of the analysis can be used to develop the test plan and select instrumentation and can be combined with test data to determine the applied thermal conductivity of the MLI.

2. If the vent line heat leak is high, with respect to the heat leak through the MLI, it should be reduced by increasing the boiloff rate.

3. When possible, conduct a series of tests with variable boiloff rates. The resulting data can be used to verify the heat leak through the MLI.

CONTENTS

NOMENCLATURE

Symbol	
A	area (ft^2)
DAM	double aluminized mylar
K	thermal conductivity (Btu/hr-ft-^{o}F)
LN_2	liquid nitrogen
MLI	multilayer insulation
T_{inner}	inside temperature of insulation (^{o}F)
T_{outer}	outside temperature of insulation (^{o}F)
Q_{heater}	heater power (Btu/hr)
Q_{MLI}	heat leak thru MLI (Btu/hr)
Q_{total}	sum of Q_{heater}, Q_{MLI}, $Q_{vent\ line}$ (Btu/hr)
$Q_{vent\ line}$	heat leak thru vent line (Btu/hr)
Δx	insulation thickness (in.)

Section 1
INTRODUCTION

The most efficient method of blocking heat transmission to stored cryogens in the space environment is to insulate the storage tanks with multilayer insulation (MLI) composites. The most important parameter in the design of MLI systems for flight tankage is the thermal conductivity of the MLI. Calorimetric techniques of high accuracy and economy are currently available for measuring thermal conductivity under highly controlled laboratory conditions. The electrical cylindrical calorimeter which was analyzed, designed, fabricated, and used to acquire data during this contract is one important tool for the measurement of MLI thermal conductivity as a function of both temperature and layer density. Flat plate calorimeters are also used for thermal conductivity measurement for MLI composites.

However, when cryogen tanks are insulated with MLI composites, the calorimetric conditions cannot be duplicated. The size and geometry of such tanks necessitate gaps in the insulation blanket, degrading structural supports and fasteners, variations in layer density and compressive loading, and other non-ideal conditions not experienced in calorimetric tests. As a result of the disparities between calorimetric and tank test conditions, the "applied" thermal conductivity of an MLI composite tested on a cryogen tank is always greater than the "calorimetric" thermal conductivity. Therefore, the design of flight MLI systems cannot be based solely upon calorimetric data. Since flight tank insulation systems will be plagued with the same degradations as test tanks, NASA-MSFC is currently active in MLI testing on subscale cryogen tanks.

The heat leak to the cryogen through the vent line of these test tanks is important for two reasons: (1) this vent line heat leak must be distinguished from the MLI heat leak in order to determine the "applied" thermal conductivity of the MLI being studied, and (2) structural lines similar to the vent-line will be associated with flight tanks, and methods of predicting their heat leaks must be developed. The purpose of this study was to predict in advance the heat leak to the cryogen through the vent line of a cryogen test tank and then verify the predictions experimentally. Concurrent objectives were to determine the applied thermal conductivity of an MLI system designed and fabricated by Lockheed-Huntsville during a previous NASA study, and to provide recommendations for future NASA tank tests.

Section 2
TEST TANK AND INSULATION SYSTEM

The test tank considered in this analytical and experimental study is shown in Fig. 1. The tank is a 20-inch diameter cylindrical tank with ellipsoidal ends. Under NASA-MSFC Contract No. NAS8-21347, Lockheed-Huntsville designed and fabricated an MLI insulation system for this tank. The MLI composite chosen was double-aluminized mylar (DAM)/nylon net because of the favorable thermal and structural characteristics of this material combination. The "calorimetric" thermal conductivity of this composite is shown as a function of layer density in Fig. 2 for the boundary temperatures to be experienced in the tank test. Since the optimum value of layer density is shown to be approximately 80 layers per inch, this value was chosen for use in the tank insulation system.

To minimize undersirable gaps in the insulation blanket, the cylindrical and ellipsoidal surfaces of the tank were wrapped simultaneously with one piece of insulation. To allow a smooth, uniform layering on the ellipsoidal surfaces, this single piece of insulation was pre-cut to accurately fit the ellipsoidal ends. This was accomplished by pre-cutting 16 ellipsoidal lunes to fit each end. The lunes converge at the apexes of the ellipsoids and are small enough to approximate an ellipsoidal surface. The nylon lunes butt together, while the mylar lunes are allowed a small overlap for greater gap prevention. Another piece of insulation was used for the neck, and it was applied at the same time as the tank insulation layer, using overlap for the mylar junction and butting for the nylon junction.

Figures 3 through 7 show the tank during different stages of the wrapping operation. Twenty layers each of 1/4-mil double-aluminized mylar and 9-mil nylon net were applied with a thickness of 1/4-in. to establish a layer density of 80 layers per inch, an optimum density for thermal conductivity. A cooling coil was attached at the top of the vent line, as shown in Fig. 8. The cooling coil was made of 5/8-in. o.d. copper tubing and was wrapped six times around the tank neck and soldered in place. Aluminum foil beneath the coil allows a good heat conduction path and lowers contact resistance between the coil and neck.

An electric resistance heater was installed inside the tank by NASA-MSFC before testing and was used to artificially increase the boiloff nitrogen flow rate. The insulated tank was well-instrumented with thermocouples and delivered to NASA-MSFC for testing.

Section 3
ANALYTICAL HEAT TRANSFER PREDICTIONS

A computer thermal analysis was conducted for the test tank to determine the vent line heat leak to the cryogen as a function of mass flow rate. The complex heat exchanges occurring in the vent line include conduction, convection, radiation, and enthalpy flow in the boiloff fluid. Because of the large length-to-diameter ratio of the vent line, radiation was found to be negligible in the analysis and was neglected to increase computer speed. The results of the analysis are presented in Fig. 9. These results were first presented in Ref. 1* in February 1970 before any tests had been conducted. These results will be compared to the experimental results in Section 4.

The decrease in vent line heat leak with increasing flow rate is due to the convective cooling of the line by the boiloff gas. This effect will be referred to again in the discussion of the empirical data.

*Hale, D.V., and M.J. O'Neill, "Study of Thermal Conductivity Requirements — High Performance Insulation — Final Report," LMSC-HREC D162128, Lockheed Missiles & Space Company, Huntsville, Ala., February 1970.

Section 4
EXPERIMENTAL HEAT TRANSFER DATA

In order to verify the analytical data, it was desired to obtain experimental vent line heat leak data at different flow rates of boiloff cryogen. This was accomplished by varying the heat input to the resistance heater submerged in the cryogen. Four tests were run at four different flow rates, and one final test using the neck cooling coil for comparison. These tests are tabulated in Table 1. The column labeled $Q_{total}-Q_{heater}$ represents the heat leak to the cryogen through the MLI (Q_{MLI}) plus the heat leak through the vent line ($Q_{vent\ line}$) and is plotted in Fig. 10.

Figure 10 shows that the curve asymptotically approaches 9.1 Btu/hr as the flow rate increases. This is due to elimination of $Q_{vent\ line}$ as the flow rate increases, leaving only Q_{MLI} as the residual heat leak. Since Q_{MLI} is independent of mass flow rate, the value of 9.1 Btu/hr can be subtracted from each of the data points to obtain $Q_{vent\ line}$ for each of them. The resultant curve is shown in Fig. 11, and will shortly be compared to the analytical prediction of $Q_{vent\ line}$ versus mass flow rate.

It is also apparent from Fig. 11 that cooling the top of the vent line by means of the LN_2 cooling coil did not reduce the vent line heat leak as effectively as the mass flow convection.

Section 5
COMPARISON OF ANALYTICAL PREDICTIONS AND EXPERIMENTAL DATA

The analytical vent line heat leak curve shown in Fig. 9, which was published well in advance of the experimental testing, can now be compared to the experimental data points shown in Fig. 11. This comparison is given in Fig. 12. The good correlation between prediction and data is evident. The error bands on each experimental data point were calculated from the test data and are due principally to fluctuations in flow rate and tank ullage pressure during the test.

Section 6

APPLIED THERMAL CONDUCTIVITY DETERMINATION

The "applied" thermal conductivity of the MLI can now be determined. The heat rate through the MLI was 9.1 Btu/hr, as shown before. Other pertinent quantities are:

Tank Area (A) = 17.2 ft^2
Inside Temperature (T_{inner}) = $-320.4^{o}F$
Outside Temperature (T_{outer}) = $70^{o}F$
Insulation Thickness (Δx) = 0.25 in.

Therefore:

$$K = \frac{Q_{MLI}\,\Delta x}{A\,(T_{outer} - T_{inner})} = 2.82 \times 10^{-5} \frac{Btu}{hr\text{-}ft\text{-}^{o}F}$$

As expected, the "applied" thermal conductivity is higher than the calorimetric value of 1.75×10^{-5} Btu/hr-ft ^{o}F. The ratio of applied to calorimetric conductivities is sometimes useful in measuring the degradation caused by gaps, seams, supports, etc. In this case, the degradation factor is 1.61, which is low when compared with most factors found in the literature.

Section 7
CONCLUSIONS AND RECOMMENDATIONS

The conclusions drawn from this study are summarized below:

1. The analytical predictions made by Lockheed-Huntsville for vent line heat leak were accurate.
2. Conducting tests at variable rates by using a heater to control the flow rate allows the asymptotic Q_{MLI} to be determined and used to calculate applied thermal conductivity. This is a new approach in separating $Q_{vent\ line}$ from Q_{MLI} and can be used successfully.
3. Cooling the ventline top with LN_2 did not eliminate the vent line heat leak for the tank considered.

It is recommended that the following be considered in future tank tests:

1. Conduct thermal analyses to find $Q_{vent\ line}$ as a function of mass flow rate for each new tank test, for use in determining the applied thermal conductivity of the MLI.
2. If the analyses predict undesirable vent line heat leaks, these can be reduced by heater-stimulated boiloff rate increase.
3. If possible, conduct tests with variable mass flow rates to determine the asymptotic value of Q_{MLI} to verify the analytical predictions.

TABLE AND FIGURES

Table 1

TEST SERIES						
Test No.	Neck Cooling	Heater Power (watts)	LN_2 Boiloff Rate (lbm/hr)	Q_{Total} (Btu/hr)	Q_{Heater} (Btu/hr)	$Q_{Total}-Q_{Heater}$ (Btu/hr)
1	No	0	0.160	13.632	0	13.632
2	No	3.98	0.295	25.134	13.583	11.550
3	No	16.01	0.753	64.156	54.642	9.514
4	No	25.04	1.110	94.572	85.462	9.110
5	Yes	0	0.135	11.502	0	11.502

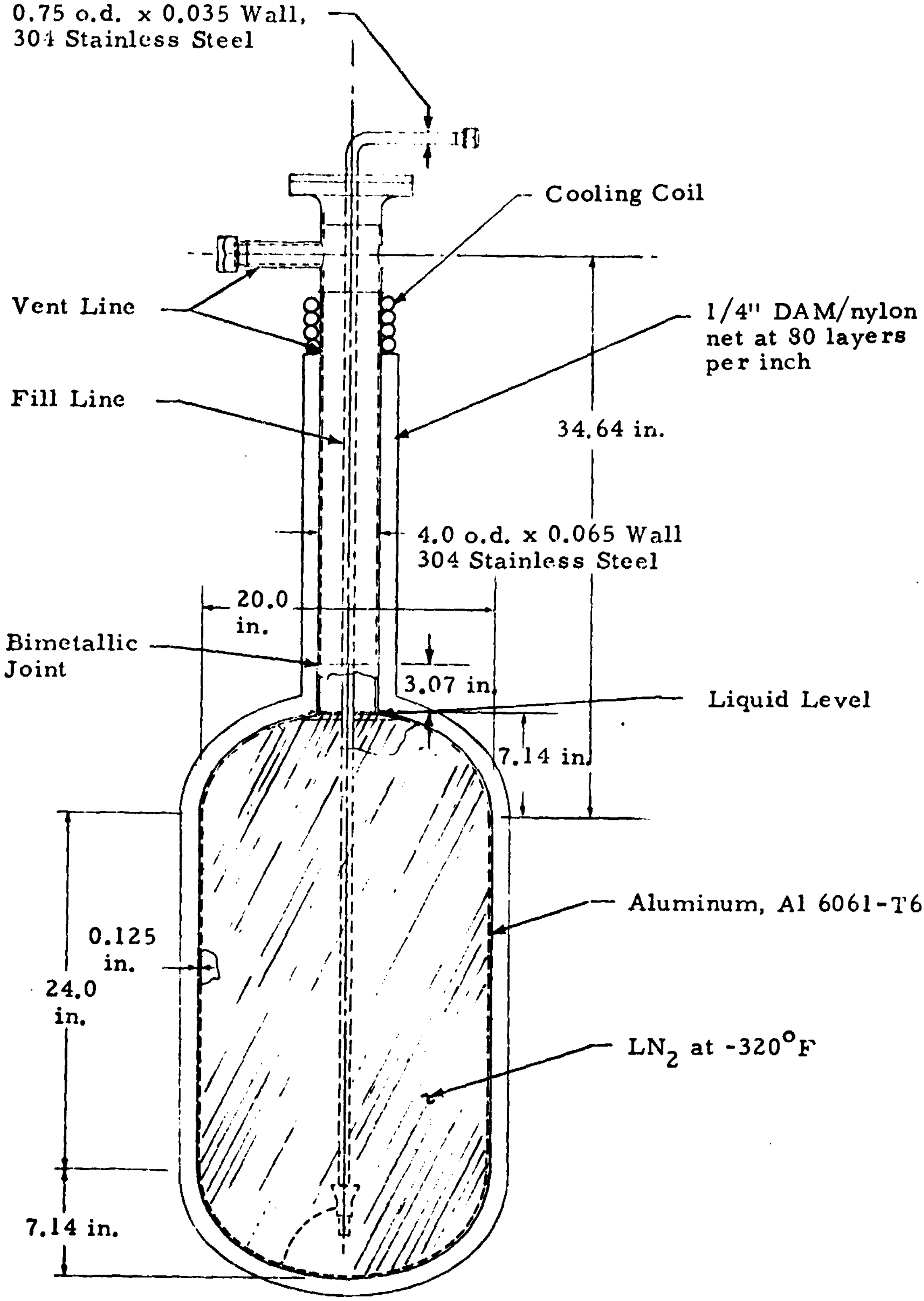

Fig. 1 - Schematic of MSFC 20-Inch Cryogenic Tank

Fig. 3 - Tank During Wrapping Process Showing Mylar Lunes To Be Applied to End of Tank

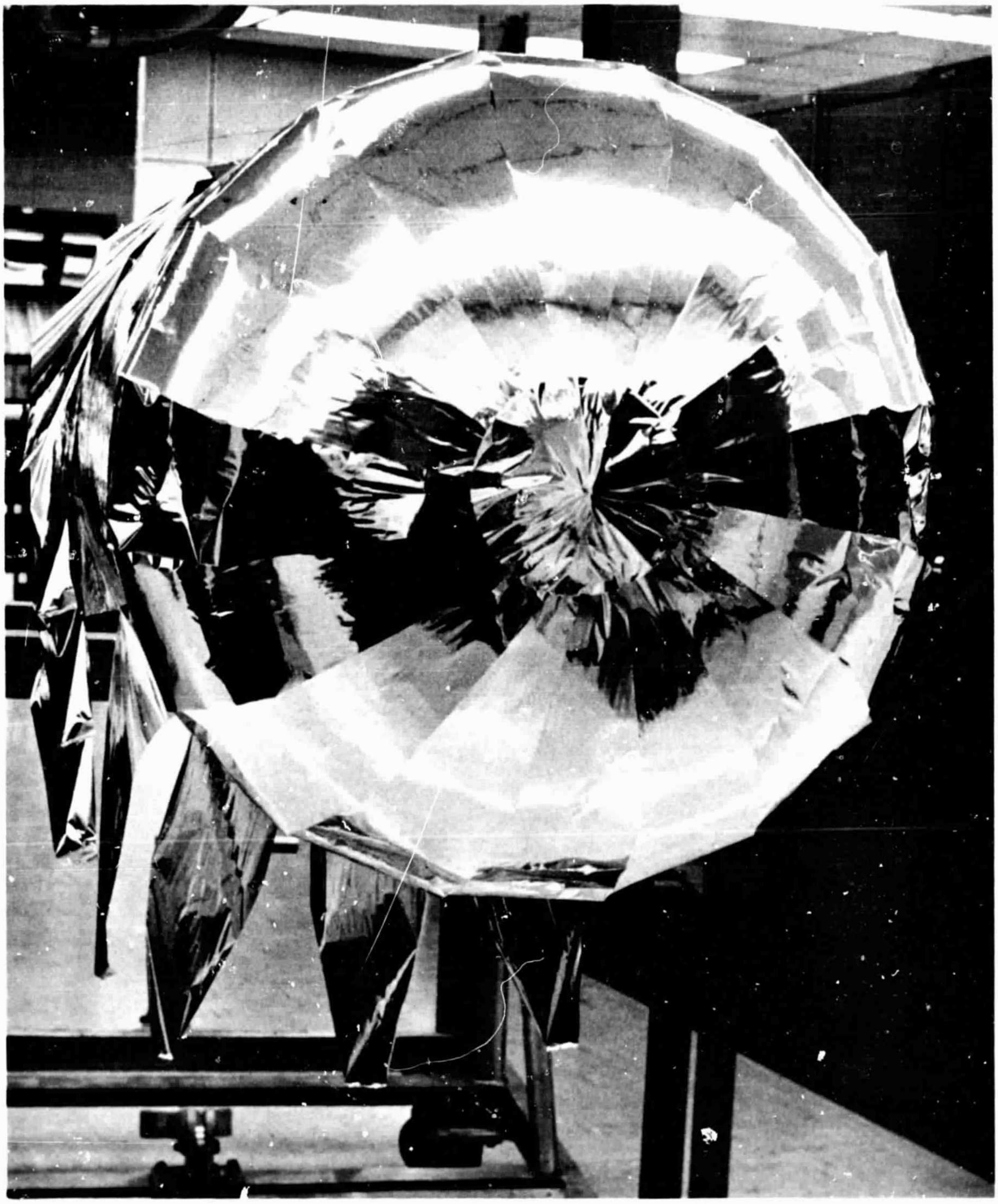

Fig. 4 - Tank During Wrapping Process Showing Completed Mylar End Layer

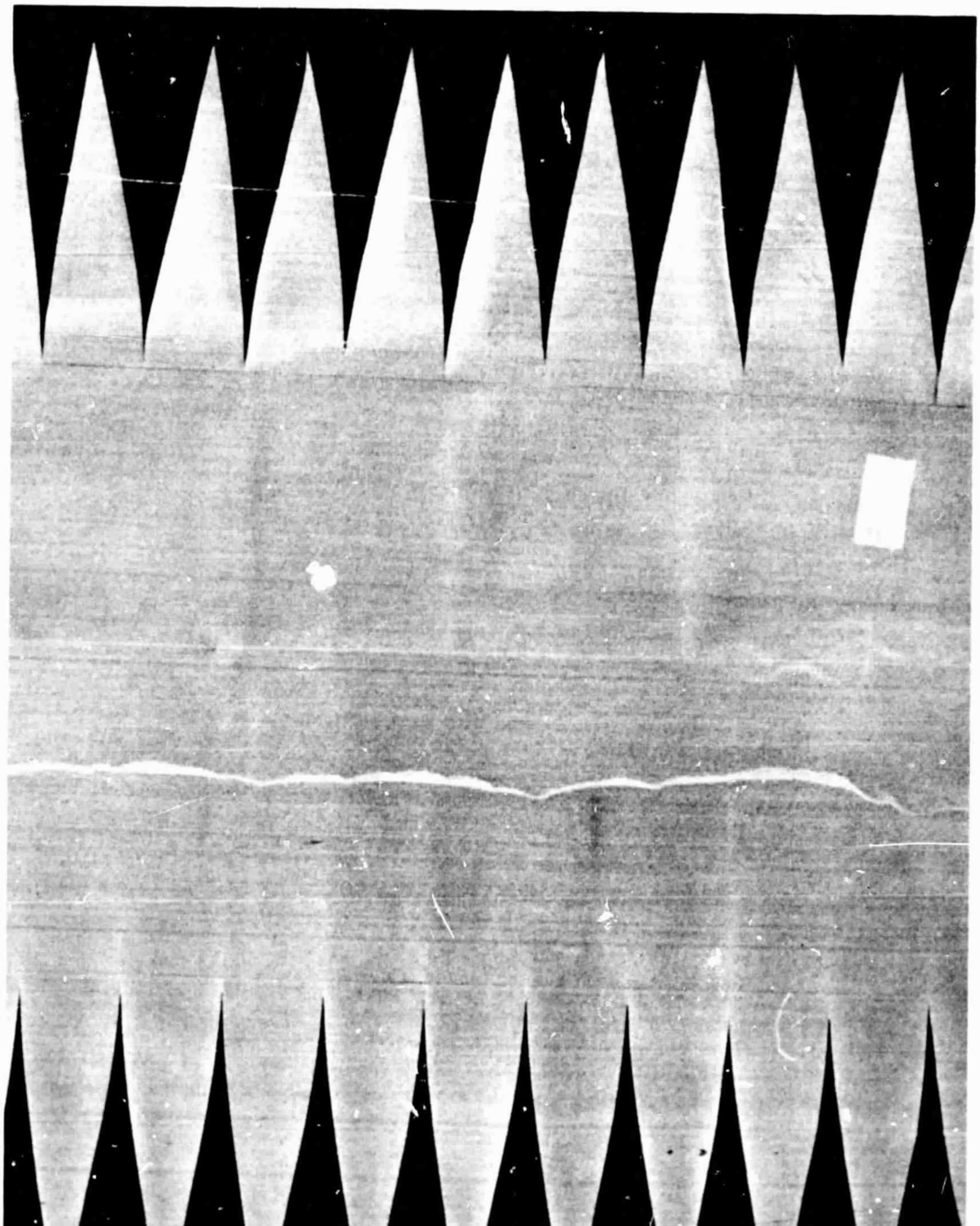

Fig. 5 - Nylon Net Insulation Layer Prior to Application on Tank Showing Geometry of Ellipsoidal Lunes

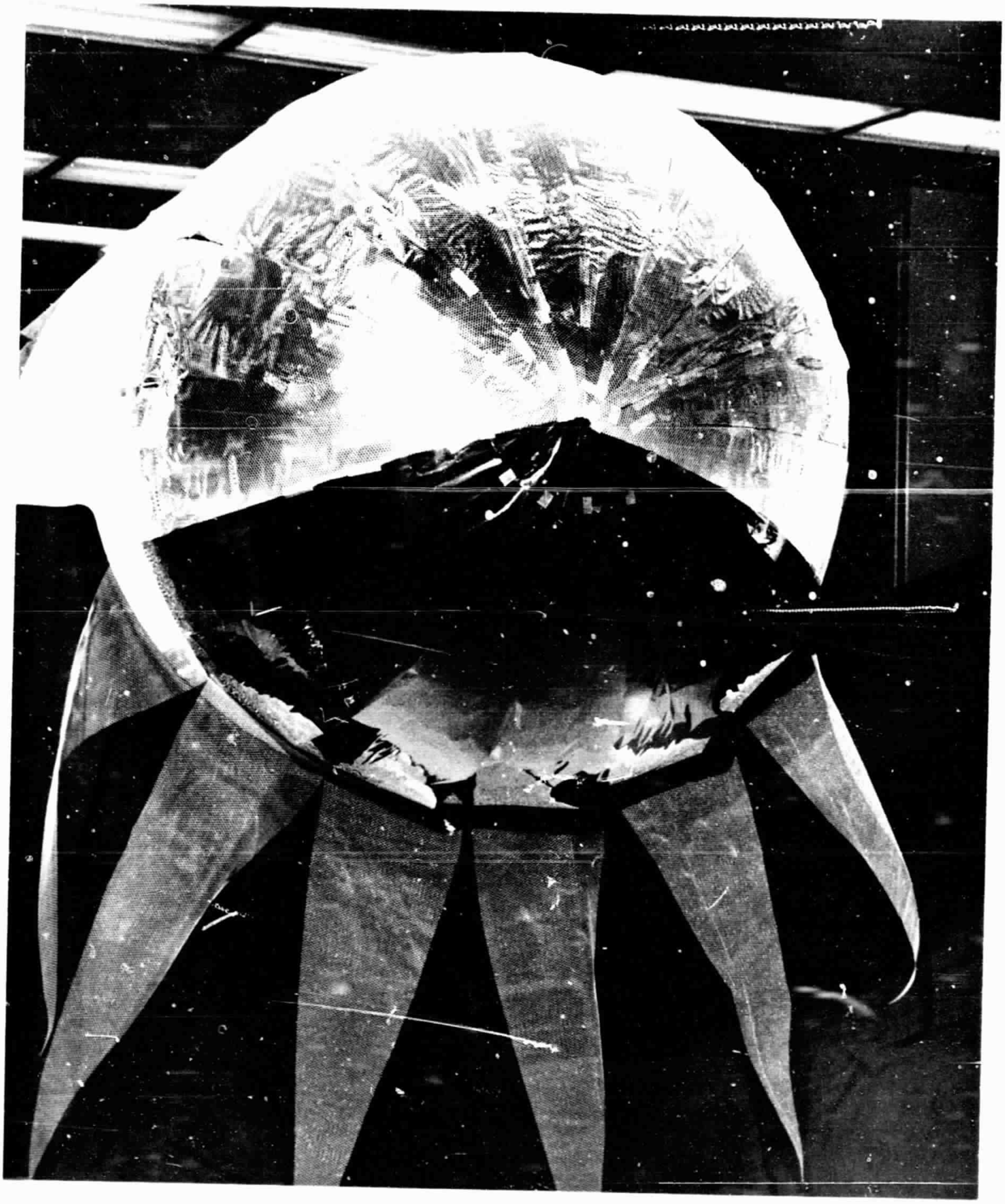

Fig. 6 - Tank During Wrapping Process Showing Application of Nylon Lunes on End of Tank

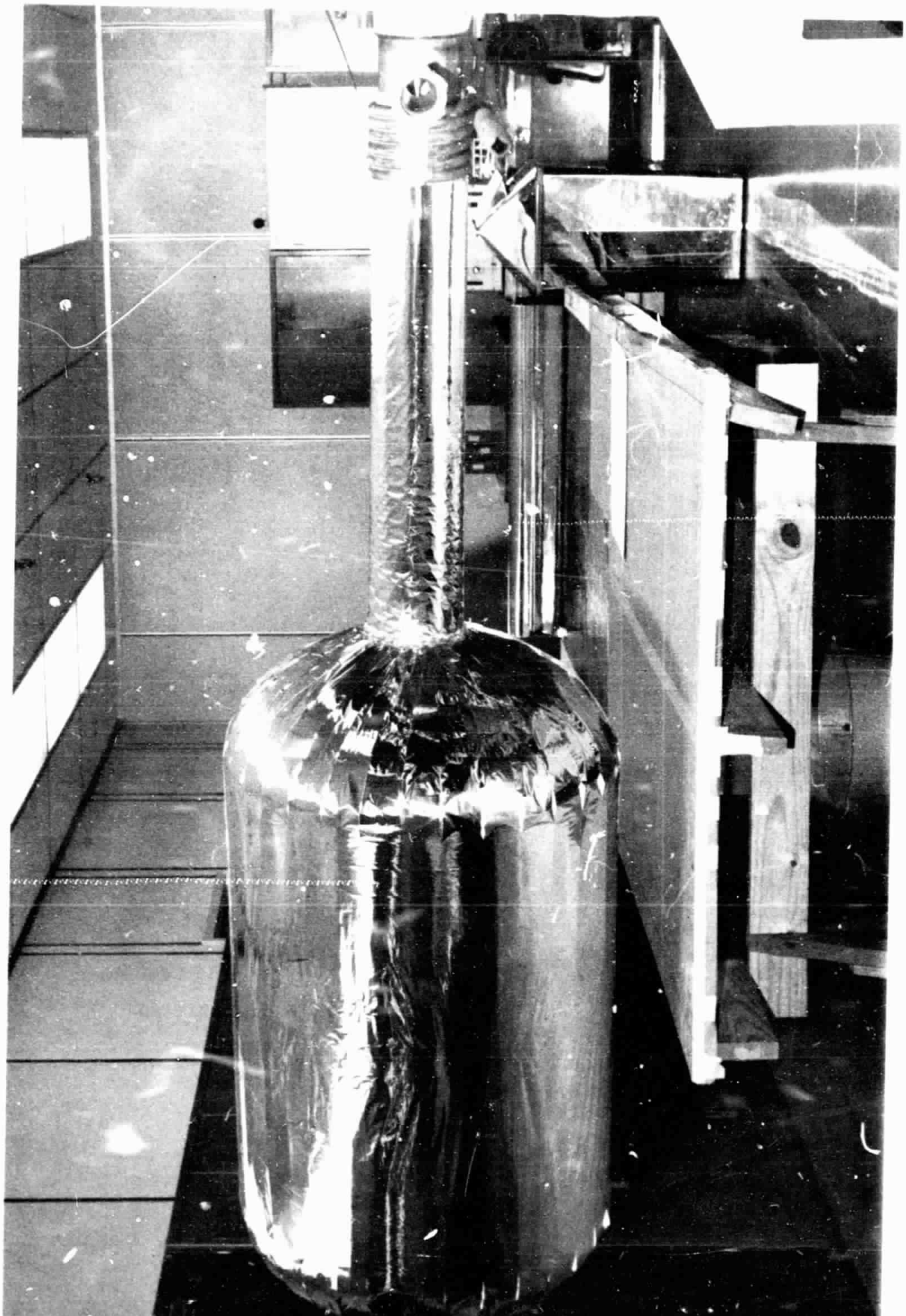

Fig. 7 - Tank Insulated with 21 Layers of Mylar and 20 Layers of Nylon Net Applied with Thickness of 1/4 Inch

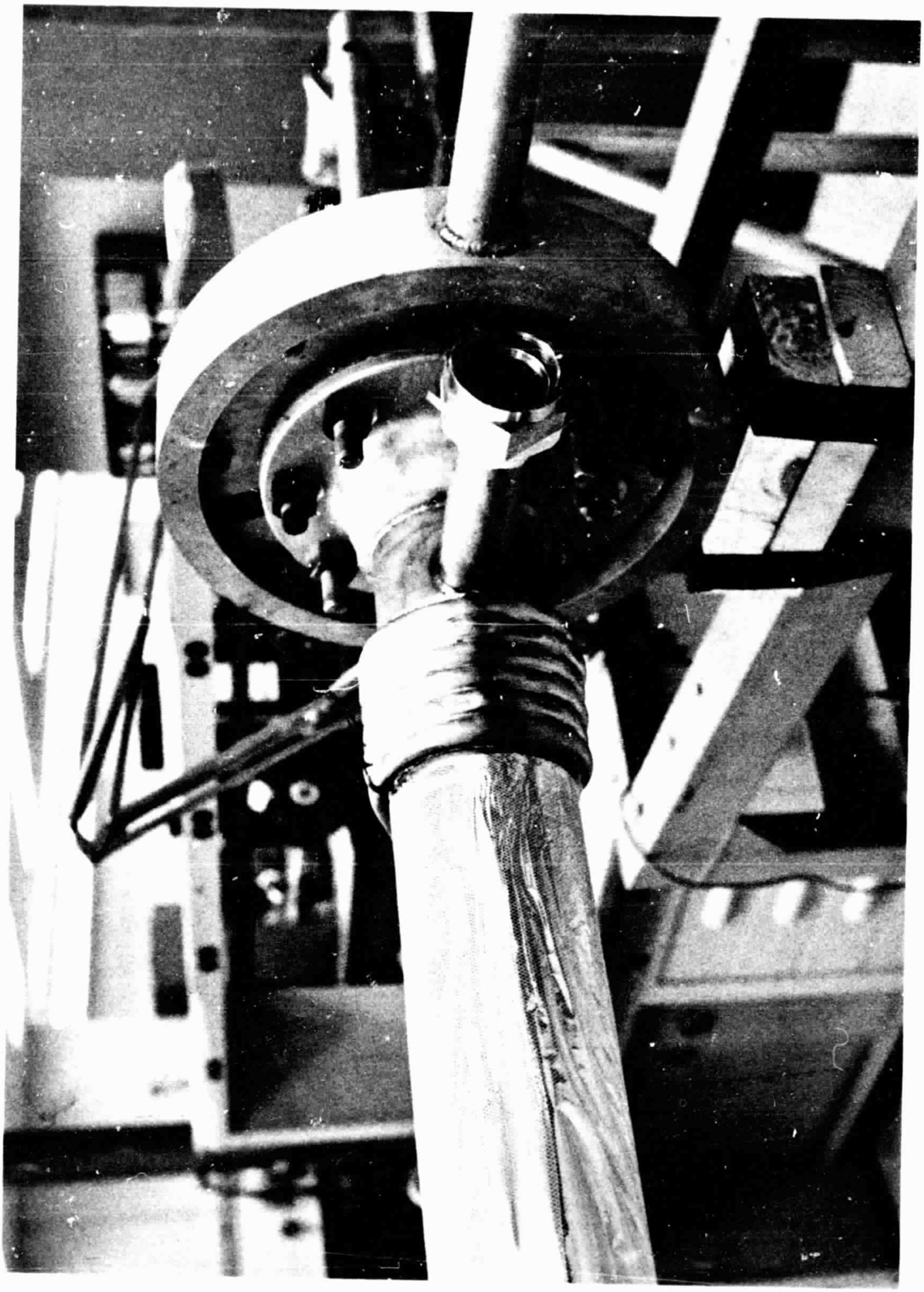

Fig. 8 - Cooling Coil on Tank Neck

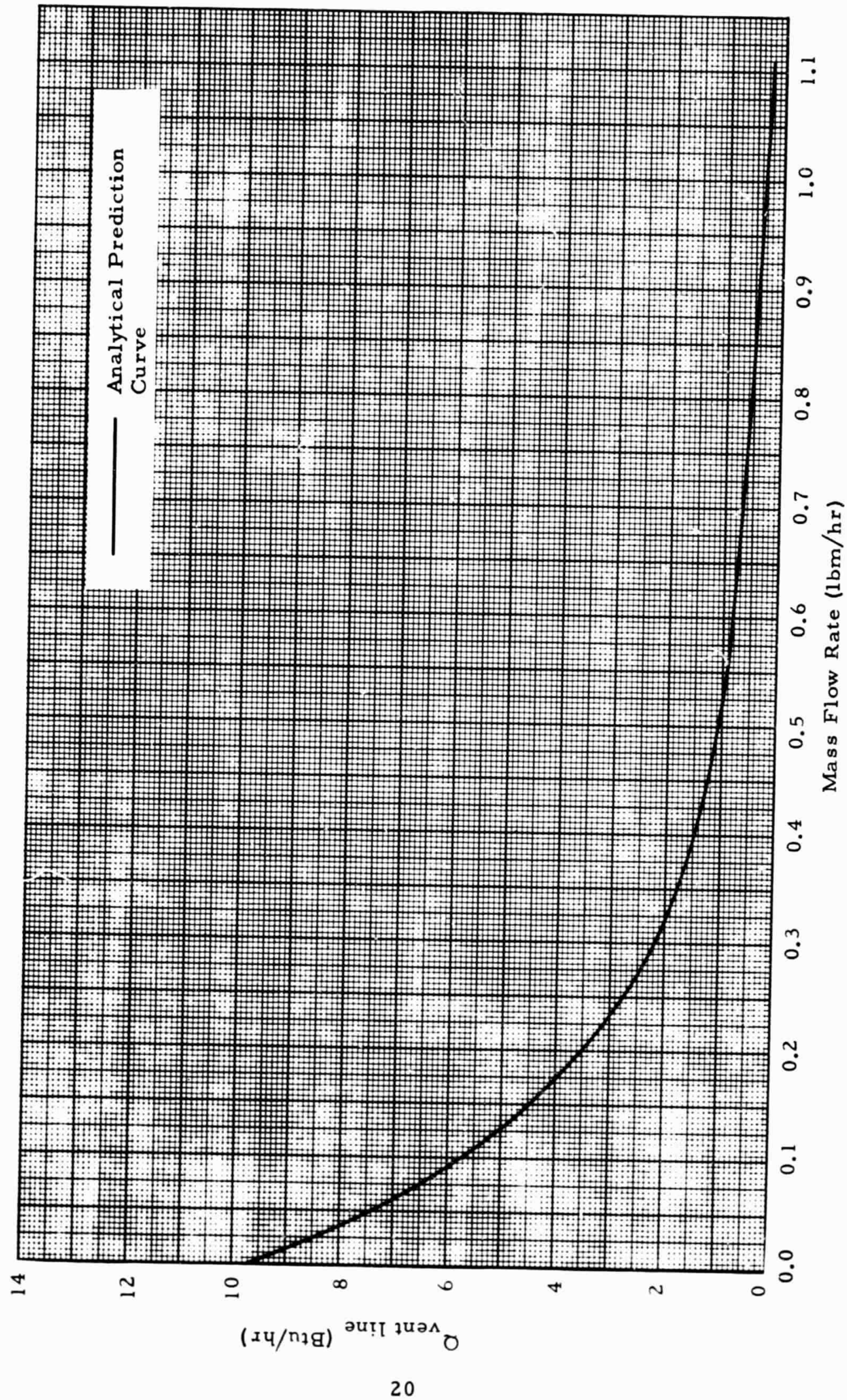

Fig. 9 - Analytical Curve for $Q_{vent\ line}$

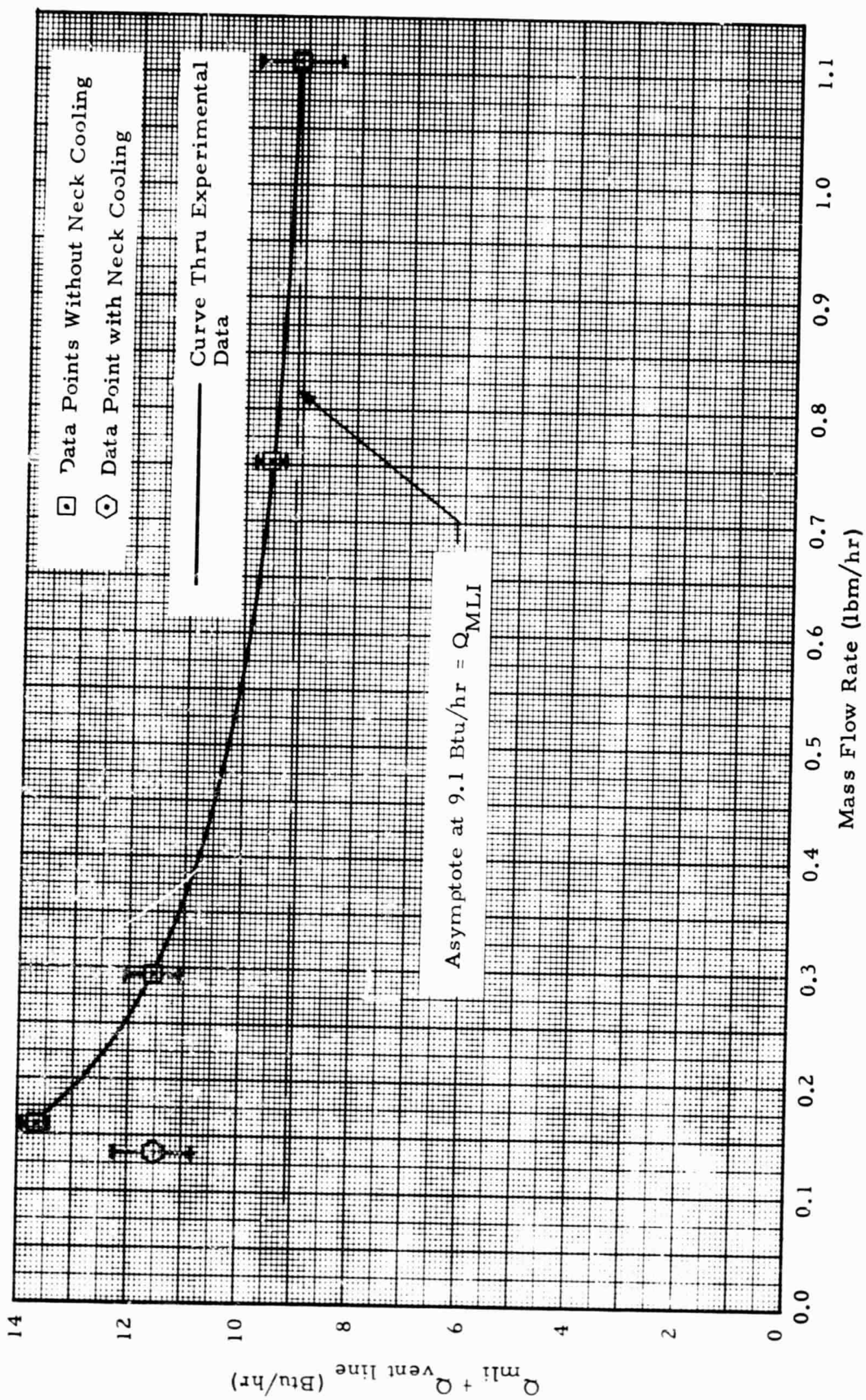

Fig. 10 - Experimental Data for $Q_{MLI} + Q_{vent\ line}$

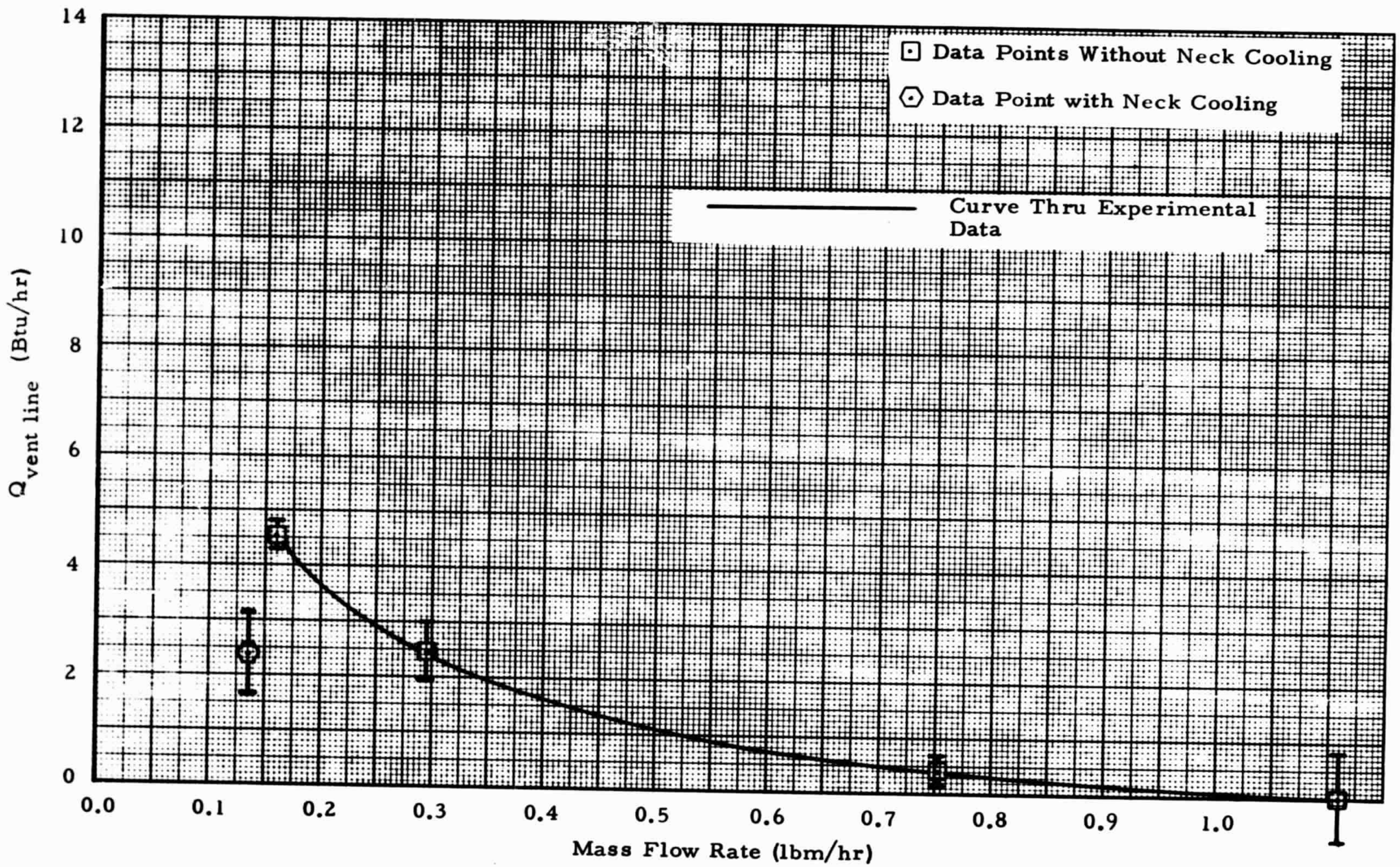

Fig. 11 - Experimental Data for $Q_{vent\ line}$

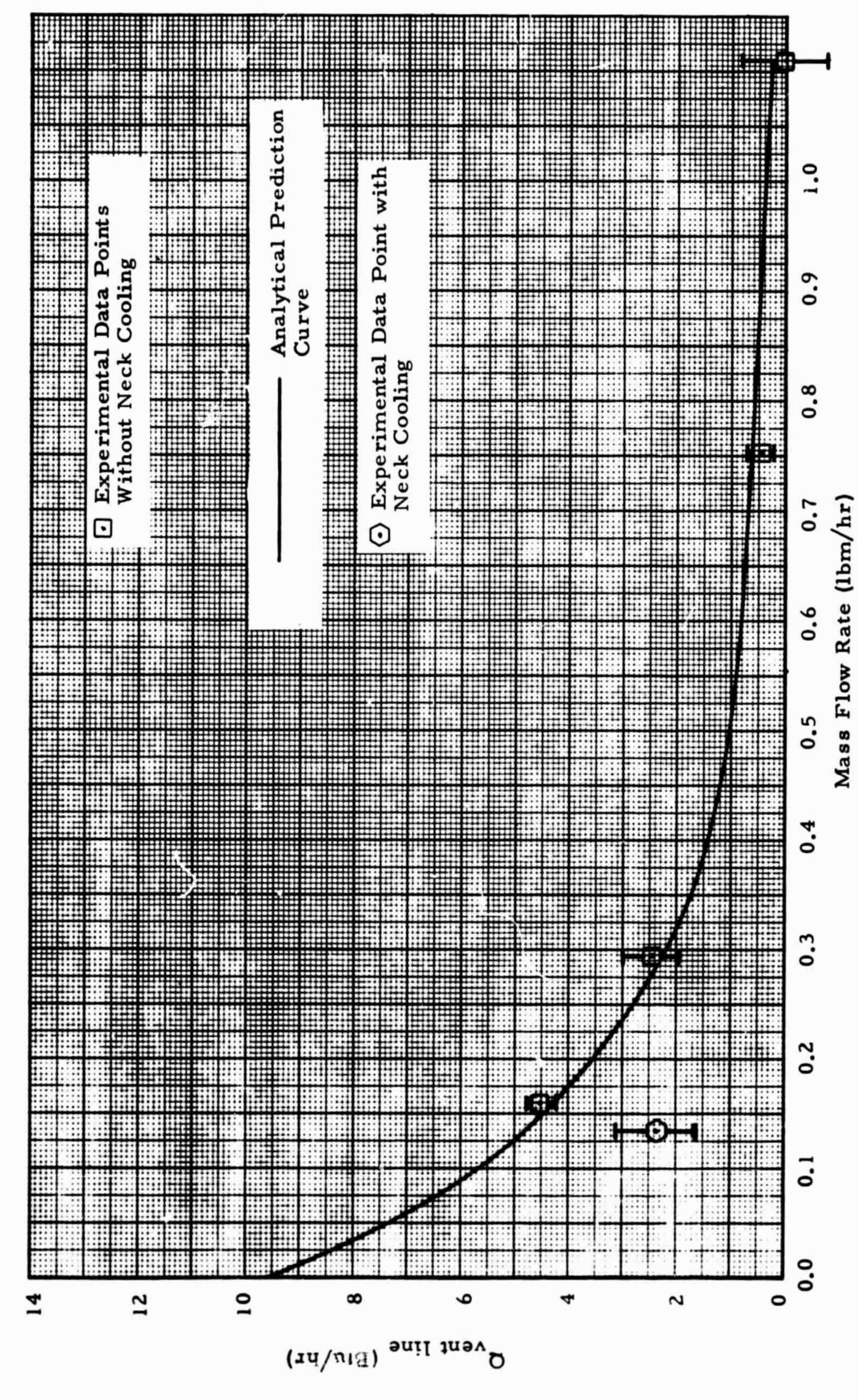

Fig. 12 - Comparison of Analytical Prediction Curve with Experimental Data Points