

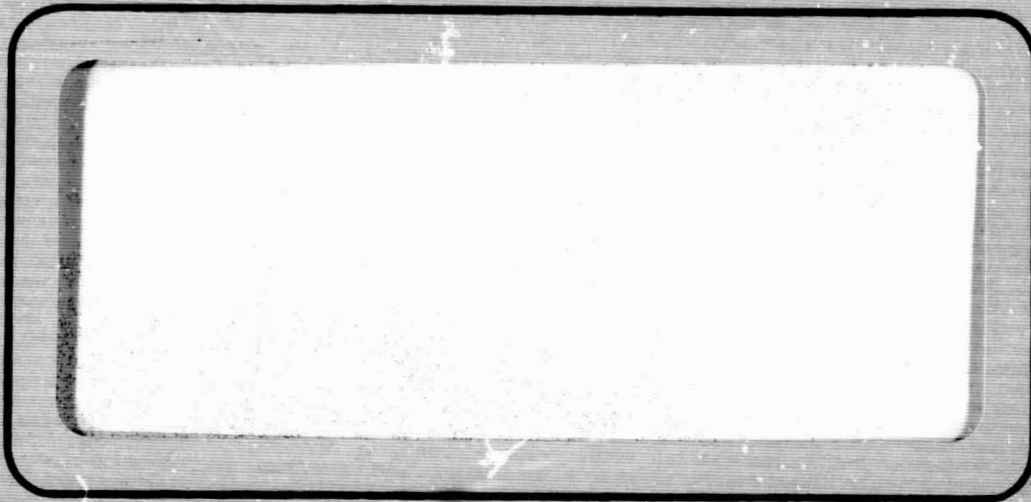
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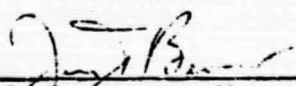
DESIGN STUDY TO IMPROVE
PIONEER LOUVER SYSTEM THERMAL PERFORMANCE

by
O. W. Clausen

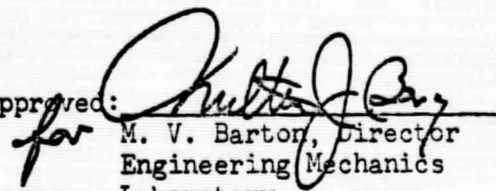
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One Space Park
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NASA CR-73179

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PIONEER LOUVER SYSTEM THERMAL PERFORMANCE

By O. W. Clausen

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Prepared under Contract No. NAS2-4266
TRW SYSTEMS GROUP
One Space Park
Redondo Beach, California

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report was prepared by TRW Systems Group for the Ames Research Center of the National Aeronautics and Space Administration. The work, performed under Contract NAS2-4266, was administered by the Systems Engineering Division of Ames Research Center. Mr. J. P. Kirkpatrick was the Contract Technical Monitor.

The work described in this report was performed in the period from 1 June 1967 to 1 February 1968; this is the final report for the contract.

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The author gratefully acknowledges the design work performed by Mr. A. R. Dare of the Product Design Group in the evolution of the improved louver system configuration. Significant contributions in the execution of this contract were also made by Messrs. I. Shuldiner and G. M. Orellana of the Heat Transfer and Thermodynamics Department, and by Messrs. T. J. Ockey and D. A. Corbett of the Design Analysis Department. The analytical prediction of the effective emittance of an open louver system (Appendix II) was extracted from original work by B. R. Loya and E. B. Robinson reported in internal TRW documentation.

ABSTRACT

This report describes the results of a design study directed towards improving the thermal performance of the present PIONEER VI thermally actuated louver system. An experimental program was conducted to quantitatively assess the heat losses of the present unit in a closed condition. Based on the results of these tests and on analytical studies of the characteristics of an open system, an improved configuration was designed, fabricated and thermally tested. The improved design had an effective emittance of 0.82 in the open position (compared to 0.73 for PIONEER) and 0.07 in the closed condition (0.20 for PIONEER). These results show a 220% increase in the dynamic range (open to closed emittance ratio). Preliminary structural and dynamic analyses performed on the improved system indicated the unit could withstand the vibration environment associated with a typical PIONEER launch.

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1.0 INTRODUCTION

A considerable amount of interest and effort has been devoted to the application of thermostatically actuated louver systems for problems of spacecraft thermal control (e.g., see Refs. 1, 2, 3). Functionally, in one form or another, these systems act to control the heat rejection of a radiating platform by varying the angular position of a set of highly reflecting blades or shutters. A bimetallic spring, thermally coupled to the platform, provides the motive force for altering the angle of each blade. In a closed condition the heat rejection of the platform is minimized by virtue of the "blockage" of the blades while open louvers provide the platform with a nearly unobstructed view of space (and, consequently, a high heat rejection rate). Figure 2-1 shows the platform-louver assembly for the PIONEER VI Spacecraft.

It is traditional to define the action of the louver system in terms of the "effective emittance" ($\bar{\epsilon}_p$) of the platform. In equation form

$$Q_r = \bar{\epsilon}_p (T_p) A_p \sigma T_p^4 \quad (1)$$

where Q_r = heat rejection rate, Btu/hr

T_p = average platform temperature, $^{\circ}\text{R}$

A_p = platform area, ft^2

σ = Stefan-Boltzmann constant (0.1713×10^{-8} Btu/hr-ft ^{2} - $^{\circ}\text{R}^4$)

The term $\bar{\epsilon}_p$ is shown as a function of T_p since it is dictated by the louver blade angle (spring position) which, in turn, is dictated by the radiating platform temperature. The activation range (closed to open) is determined by the characteristics of the bimetallic spring and its thermal connection with the platform; typically, the range is from 40°F (fully closed) to 85°F (fully open).

The existing PIONEER louver system has an effective emittance of approximately 0.73 in the open position and 0.2 in the closed condition. Within the 40°F to 85°F activation range this variance can accommodate as much as a five-fold change in thermal load. However, advanced design studies of deep space problems have shown a clearcut need for louver systems with much greater capability. A spacecraft at 0.3 AU, for example, will encounter a ten-fold variation in solar energy in transit from earth.

The experimental portion of the program documented in this report was directed to identification of heat losses in the closed condition and towards a reduction of the effective emittance in this condition. Thermal effects of end and edge gaps, blade conduction, actuator housing losses, etc., were quantitatively assessed, the values serving as a basis for an improved design having an effective emittance of 0.05 as the design goal. Areas for increasing the open emittance, including smaller actuator housing, thinner blades and higher emittance paint on the platform were examined analytically, the results being integrated into the improved design when not detrimental to a low (closed condition) emittance. A design goal of 0.8 for the open emittance was established at the outset of the program.

Based on the results of the experimental and analytical studies, an improved louver configuration was designed, fabricated and tested. This configuration, described in detail in Section 3.2, contains single piece beryllium blades, a unit (five blade) actuator housing assembly and more effective insulation to reduce heat leaks. Subsequent thermal tests showed the improved design to have a closed emittance of 0.07, and an open emittance of 0.82. Within the 40°F to 85°F activation range this unit can accommodate more than a sixteen-fold change in thermal load.

The preliminary and final test results are presented in this report together with configurations considered in the evolution of the improved design.

2.0 THERMAL TESTS OF PIONEER LOUVER SYSTEM

Thermal-vacuum tests were conducted to determine the relative effects of the heat "leaks" from the present PIONEER louver system in a closed position. Categorized as heat "leaks" are those thermal losses from the platform to space in excess of the losses expected if the louvers acted as pure radiation shields. The contributors initially expected to have the largest influence were;

- radiation through gaps at the ends of each blade,
- radiation through gaps at the mating edges of the blades, and
- conduction short circuiting of the radiative path between the platform and the louver blades.

An additional leak identified by the test results was radiation loss from the supposedly well-insulated actuator housings. This section documents thermal testing of the present PIONEER louver system including the test model, procedure, experimental results and the probable uncertainty in these results. Test results of the improved configuration are discussed in Section 4.0.

2.1 Present PIONEER Louver System

The PIONEER louver system, shown pictorially in Fig. 2-1, consists of 30 individually actuated blades or vanes positioned radially on a circular equipment platform. The configuration is shown in Fig. 2-1 in the open or 90° position. The spacecraft platform is $3/4$ " aluminum honeycomb, approximately 35" in diameter with an $8-3/4$ " hole in the center to accommodate an engine. Each trapezoidal blade is supported on the larger end by a bimetallic spring/actuator housing assembly and on the smaller end by a teflon bushing contained in the center support ring. A cut-away view of a single louver element is shown in Fig. 2-2; a sketch of an individual louver blade cross-section is shown as Design A in Fig. 3-1. Each blade is constructed from two .003" aluminum foil sheets (1100-H18) for cross-sectional stiffness and contains a hollow internal shaft for longitudinal rigidity. The overall blade thickness is approximately $1/4$ ".

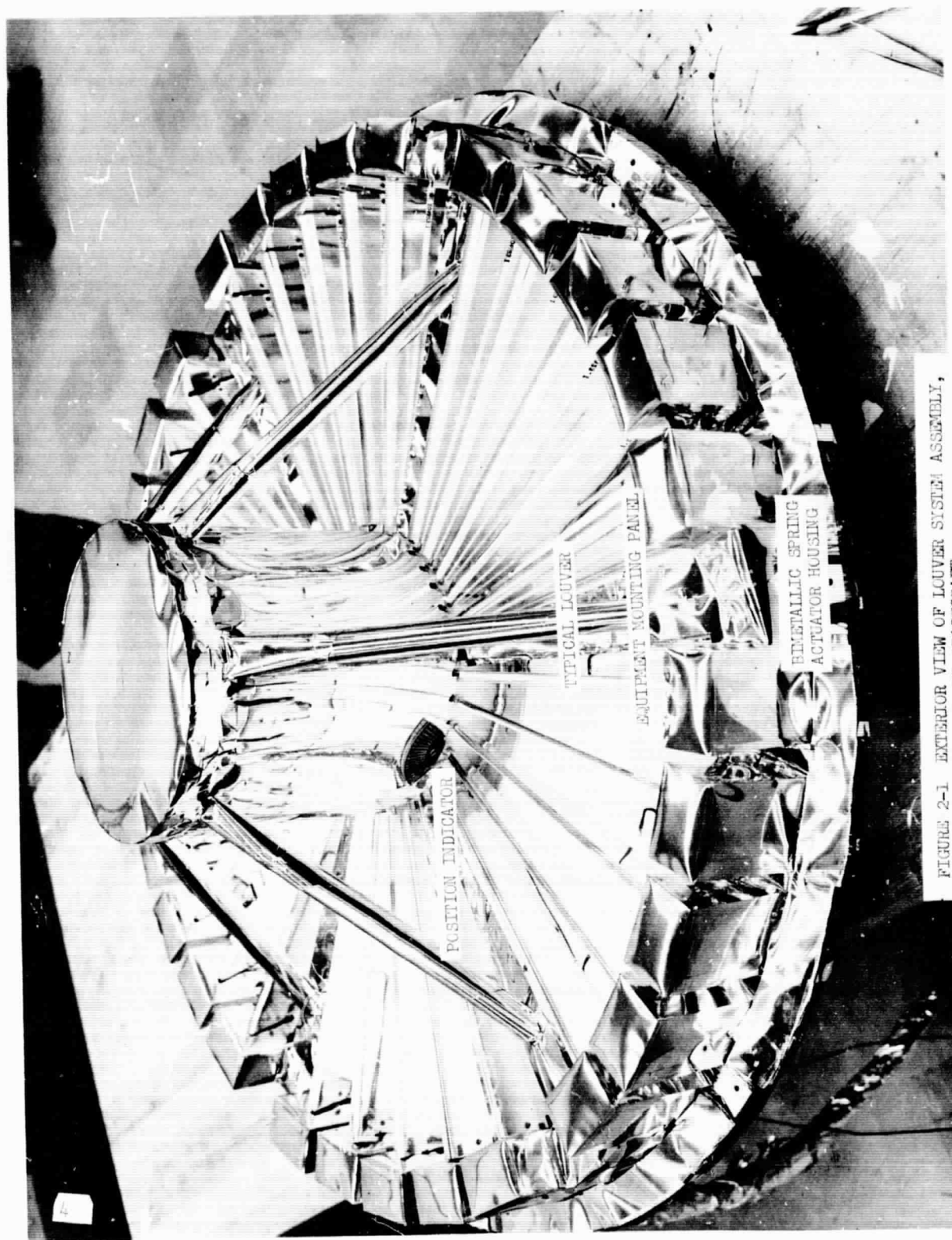


FIGURE 2-1 EXTERIOR VIEW OF LOUVER SYSTEM ASSEMBLY,
PIONEER VI SPACECRAFT



FIGURE 2-2 CUT-AWAY VIEW OF AN INDIVIDUAL LOUVER ELEMENT AS USED IN THE PIONEER VI SPACECRAFT

The bimetallic spring is thermally connected (radiatively) to the platform and varies the angular setting of the blades according to the platform temperature in its particular sector. A louver angle-spring temperature plot is shown in Fig. 2-3; also presented in Fig. 2-3 are test data of the effective emittance as a function of platform temperature. Each actuator housing is individually insulated with an aluminized Mylar "hat" (see Fig. 2-2). The platform was coated with a high emittance paint ("Cat-a-lac" white; $\epsilon = 0.85$) to obtain a high effective platform emittance in the open position, while the louver blade facing the platform was bare aluminum ($\epsilon = .04$) to minimize radiative exchange between the platform and the blade. The strips of white paint on the outside of the blades (Fig. 2-1) were used to minimize solar radiation during short periods of S/C misorientation. As shown in Fig. 2-4, the heat rejection from the platform ($\epsilon\sigma T^4$) within the control range of 40 to 85°F is approximately 5 : 1.

2.2 Test Model

To study experimentally the PIONEER louver system heat "leaks", a five blade ($\sim 60^\circ$) segment of the platform was selected. Flight-type bimetallic springs, bearings, actuator housings and insulation, blade support tubes and a 60° sector of the center support ring were mounted on a $1/4$ " aluminum plate simulating the equipment platform. This thickness was chosen to minimize temperature gradients on the plate. As on PIONEER, the platform was coated with "Cat-a-lac" flat white paint on the side facing the louvers and had a 100 Manganin wire heater bonded to the opposite side. Thermal energy to maintain the platform at the desired temperature was supplied by the electrical heater. An electrically heated guard plate was provided below the platform and controlled to the same temperature as the platform to minimize heat losses from the platform other than through the louver system.

FIGURE 2-3: ANGULAR RESPONSE OF PIONEER LOUVERS TO TEMPERATURE

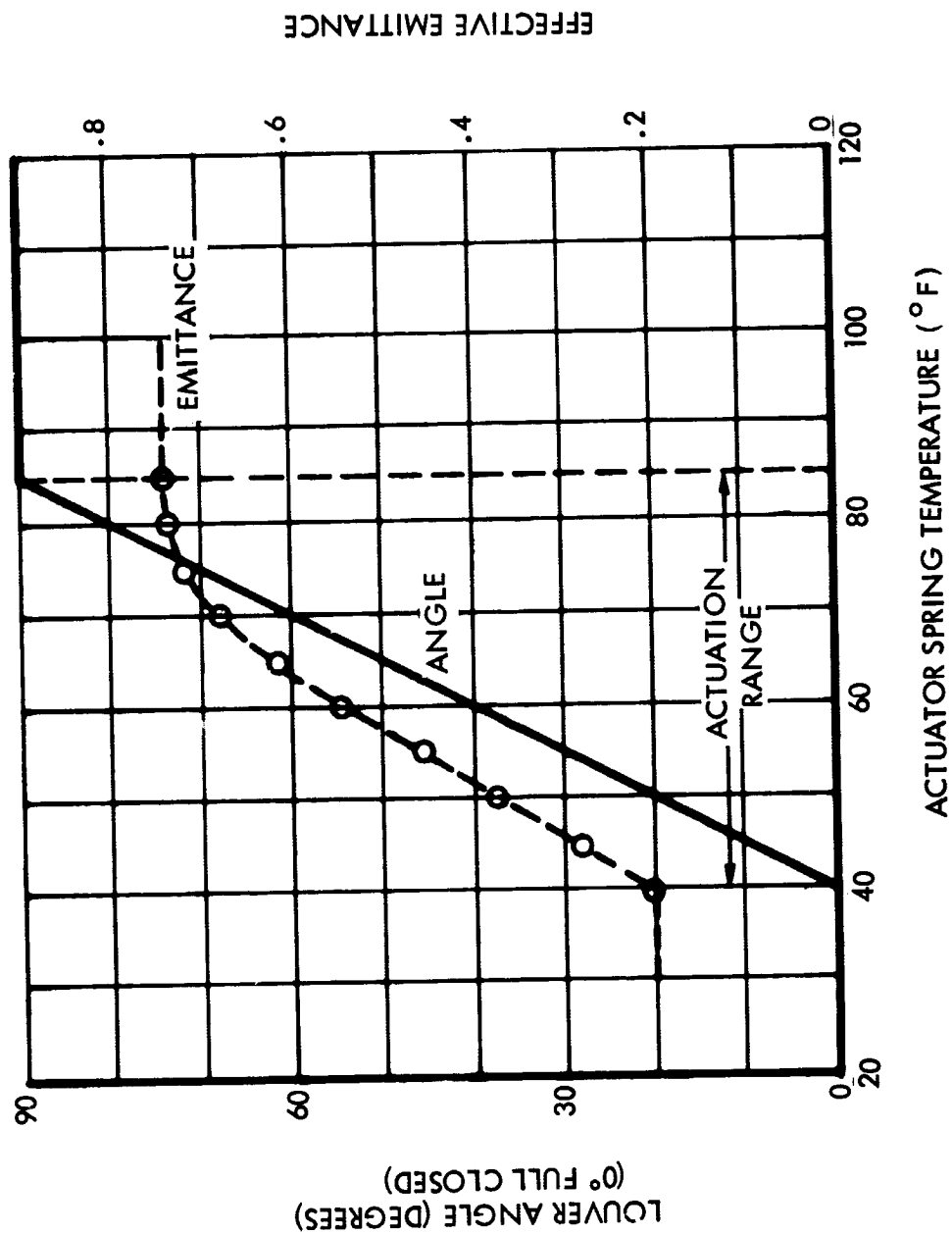
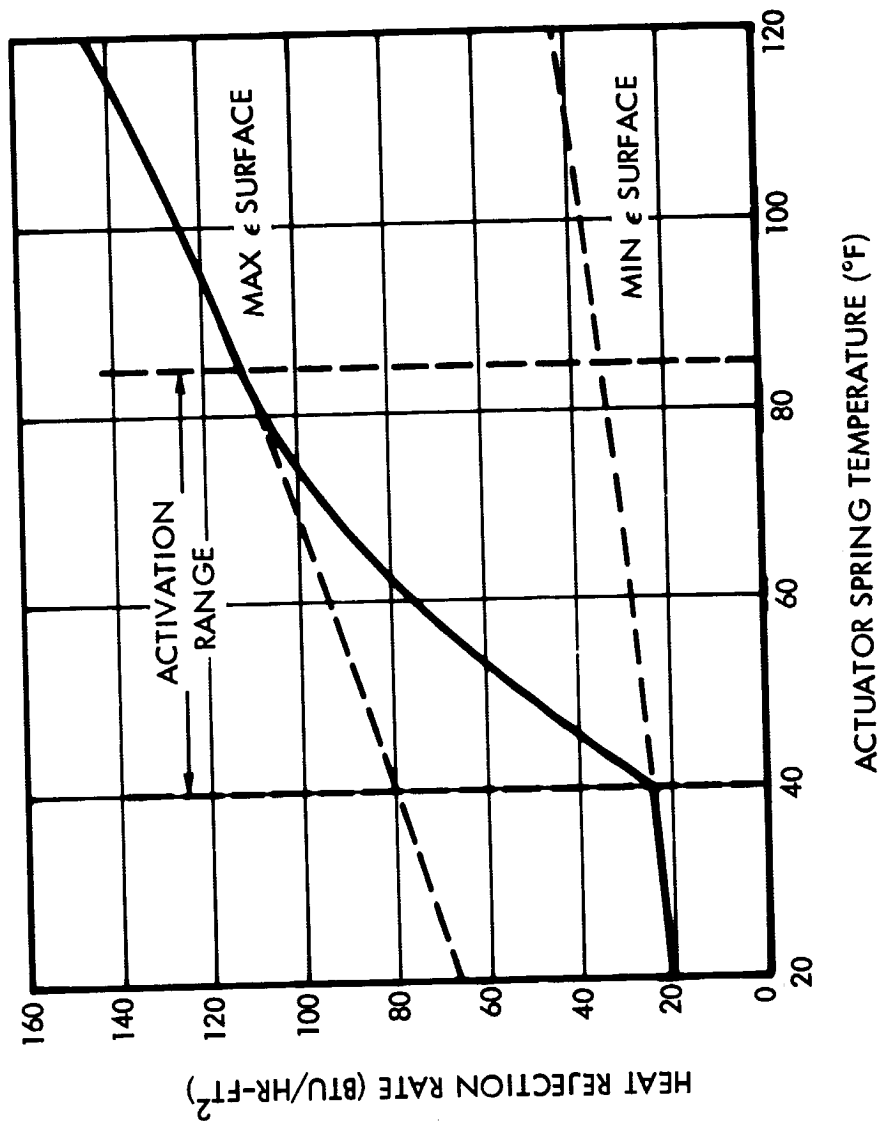


FIGURE 2-4: HEAT REJECTION RATE FROM PIONEER LOUVERED SURFACE



Highly reflective fences were used on each side of the 60° segment to prevent platform radiation losses out the sides of the assembly (beneath the edges of the outer blades). For Tests 1 - 5 these fences extended approximately 1-1/2" above the plane of the louver surface; for Tests 6 - 8 these two fences were cut to the height of the louver plane. Also for Tests 6 - 8, electrically heated guard plates were installed adjacent to and outside of the side fences, center support ring and actuator housings to minimize possible heat losses from the sides of the test rig.

The test unit was heavily insulated on the exterior sides with 15 layers of 1/4 mil aluminized Mylar (crinkled) to guard against heat leaks not present in the PIONEER system. Insulation was also provided between the platform and the bottom guard heaters to minimize effects of small temperature differences and, on the modified rig, between the side fences and the side guard plates. The center support ring was insulated on the exterior facing side only. Figure 2-5 shows the location of most of the insulation; on the sides, the blankets extended to the height of the side fences. Standard spacecraft techniques were used in the application and, where possible, a single, 15 layer blanket was used to avoid losses associated with joints.

Tests 5 - 8 included a single bat of insulation (15 layers aluminized Mylar) over the actuator housings (in addition to the flight-type insulation) as well as a blanket over the inside face of the center support ring. The unit altered to include the additional insulation and the side wall guard heaters is referred to as the modified test rig. Figure 2-6 shows the modified rig used in Tests 5 - 8.

Four different louver surface configurations were used in this preliminary test series. They were:

- 1) Simulated louver surface (0.006" 1100 aluminum alloy) cut to cover the entire area between the side fences, center support ring and actuator housing. All edges and gaps were covered with aluminum foil tape.

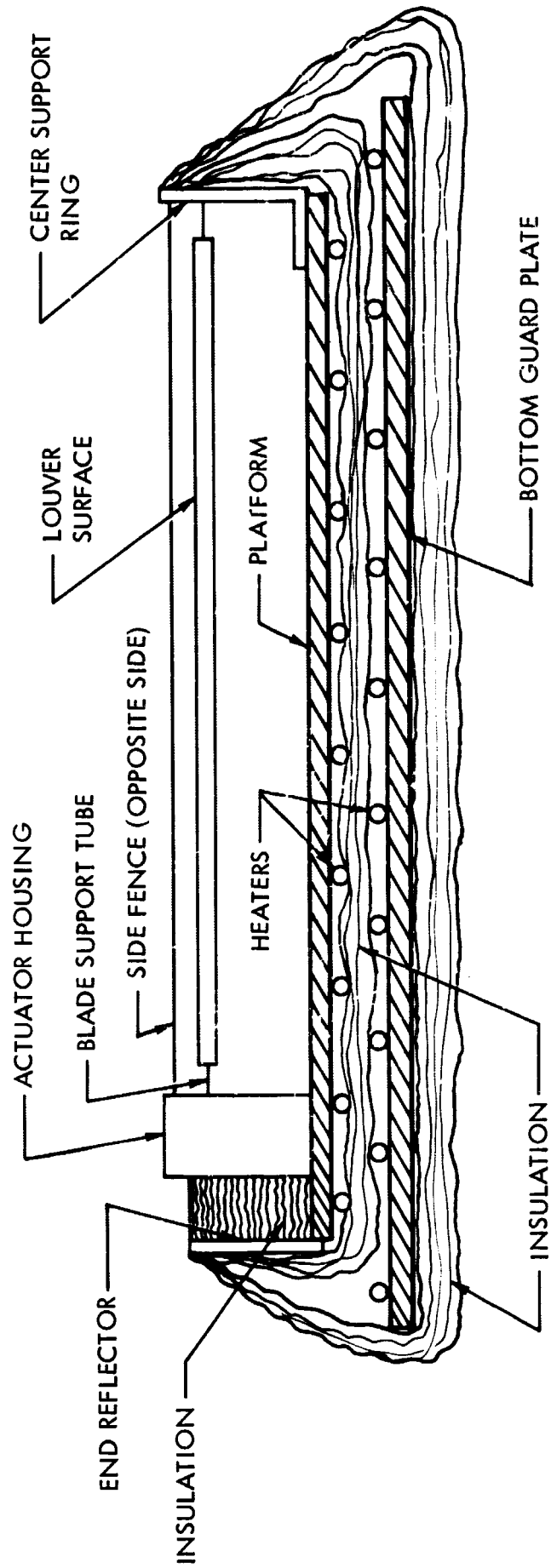


FIGURE 2-5: CUT-AWAY SKETCH OF THERMAL TEST MODEL



FIGURE 2-6: EXTERIOR VIEW (1) OF FULLY INSULATED
MODIFIED TEST MODEL

- 2) Simulated louver surface (0.006" 1100 aluminum alloy) cut to outer dimensions of five closed blades. Edges at side fences were taped. Actuator housing and center support ring gaps remained open.
- 3) Five actual PIONEER louver blades (closed position).
- 4) Simulated louver surface (.030" thick aluminized fiberglass) cut and taped as in 1) above.

Configuration 4) was used in the totally insulated test model shown in Fig. 2-6. The model was suspended in the vacuum chamber by four dacron cords to minimize conduction losses from the unit to the chamber walls.

2.3 Test Equipment

2.3.1 Test Chamber

The thermal-vacuum chamber utilized in this experimental program was cylindrical (4' diameter x 4' high) and contained a liquid nitrogen-fed cold wall. Dimensions internal to the cold wall were 40" diameter x 35" high. A 600 liter LN₂ truck was used to fill the cold wall, the level being sensed by monitoring the temperatures at the top of the cold wall. Vacuum was provided with an 8" NRC oil diffusion pump backed with a Welch Model 1397 mechanical pump. An LN₂ cold trap was provided between the diffusion pump and the vacuum chamber. Pressure measurements were made with NRC 0521 Thermocouple Gauge from ambient pressure to 10 microns, and with an NRC 563P Ionization Gauge from 10 microns down. A minute leak in the LN₂ cold wall prevented operation at pressures below about 1×10^{-4} mm Hg.

2.3.2 Instrumentation

Copper-constantan thermocouples (30 gage) were used to monitor the model and cold wall temperatures; a summary of the TC locations for each test is given in Table 2-1. A guard heater was installed on the

TABLE 2-1: THERMOCOUPLE LOCATIONS

T/C No.	Location Tests 1 - 5	Location Tests 6 - 8	Location Tests II-1 - II-4
1	Platform	Platform	Platform
2	Platform	Platform	Platform
3	Platform	Platform	Platform
4	Platform	Platform	Platform
5	Guard Heater - Bottom	Guard Heater - Bottom	Guard Heater - Bottom
6	Guard Heater - Bottom	Guard Heater - Bottom	Guard Heater - Bottom
7	Guard Heater - Bottom	Guard Heater - Bottom	Guard Heater - Bottom
8	Fence - Right Side	Fence - Right Side	Fence - Right Side
9	Fence - Left Side	Fence - Left Side	Fence - Left Side
10	Fence - Back	Side Guard - Housing End	Side Guard - Housing End
11	Simulated Louver	Simulated Louver	Louver
12	Center Support Ring	Center Support Ring	Center Support Ring
13	Center Support Ring	Side Guard - Left Side	Side Guard - Left Side
14	Center Support Ring	Side Guard - Support Ring	Side Guard - Support Ring
15	Center Support Ring	Side Guard - Right Side	Side Guard - Right Side
16	Simulated Louver	Simulated Louver	Louver
17	Simulated Louver	Simulated Louver	Louver
18	Simulated Louver	Simulated Louver	Louver
19	Cold Wall - Bottom Center	Cold Wall - Bottom Center	Cold Wall - Bottom Center
20	Cold Wall - Top	Cold Wall - Top	Cold Wall - Top
21	Cold Wall - Bottom	Cable Guard Heater	Cable Guard Heater
22	Cold Wall - Upper Side	Cable Guard Heater - Upper Side	Cable Guard Heater - Upper Side
23	Cold Wall - Upper Side	Cable Guard Heater - Upper Side	Cable Guard Heater - Upper Side
24	Cable Guard Heater	Cable Guard Heater - Bottom	Cable Guard Heater - Bottom
25	Cold Wall - Top	Cold Wall - Top	

thermocouple/power lead wire bundle and controlled to the platform temperature to minimize conduction heat leaks. The TC millivolt readings were taken using an 8686 L / N Potentiometer capable of detecting a 0.001 millivolt change. An ice bath provided the reference junction.

Platform, guard heater and wire bundle power readings were taken with a Sensitive Research Instrument Corp. Model UTS Universal Measuring Test Set. This instrument is capable of detecting 0.1 volt and 0.01 amp changes in heater power inputs. Corrections were made for lead-in resistances. Regulated DC power was provided with a Model 809A Harrison Laboratories, Inc. supply.

2.4 Test Procedure

After installation of the test model and checkout of the instrumentation, the mechanical pump was turned on and chamber evacuation initiated. Roughing was continued at least 12 hours to remove gas trapped within the insulation layers. At a pressure of about 50 microns the oil diffusion pump was turned on and the cold trap filled. As the pressure dropped to the 10^{-5} range, LN_2 was introduced into the cold wall until all sensors read $-260^{\circ}F$ or below. Electrical power inputs to the platform, guard and thermocouple bundle heaters were adjusted to achieve the desired temperatures (see Table 2-3 for a summary of test conditions). Continual adjustment of the power inputs was required during the early stages of the test as the temperatures throughout the model reacted to the environment.

All thermocouple and power readings were taken every 30 minutes and the critical values plotted. Figure 2-8 shows some representative time-temperature plots for Test 2; these results are typical for the other seven tests. The test continued until none of the thermocouples on the platform experienced a change greater than $1/2^{\circ}F$ in an hour period. The system was assumed to be in steady-state when this criteria had been satisfied and the data accepted as valid. Table 2-2 gives the steady-state temperatures for each test.

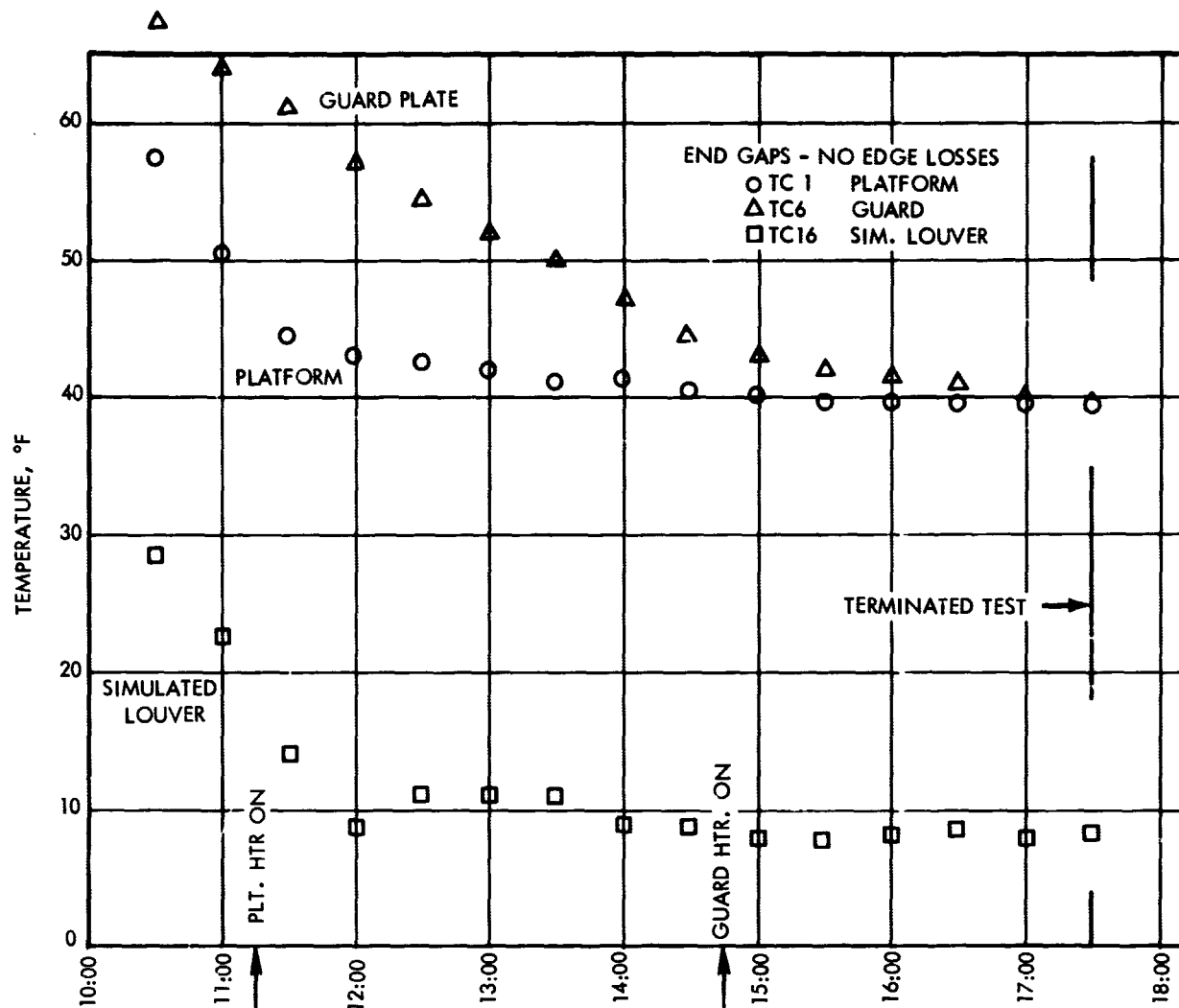


FIGURE 2-8: TEST 2 - SIMULATED LOUVERS

TABLE 2-2A: SUMMARY OF RECORDED TEST DATA

T/C No.	Location	Temperatures °F				
		Test 1	Test 2	Test 3	Test 4	Test 5
1	Platform	38.0	39.4	40.8	42.7	36.0
2	Platform	38.1	39.5	42.0	42.9	36.1
3	Platform	37.6	39.0	40.4	42.5	36.1
4	Platform	1.6	12.9	—	—	—
5	Guard Heater (Bottom)	39.6	39.8	37.6	37.0	39.6
6	Guard Heater (Bottom)	39.6	39.8	37.4	37.0	39.6
7	Guard Heater (Bottom)	39.6	39.8	37.1	—	39.6
8	Fence - Right Side	5.7	5.0	-11.0	1.0	-7.5
9	Fence - Left Side	2.8	3.0	-10.6	-8	-7.2
10	Fence - Back	-7.0	-6.0	-10.6	3.3	3.6
11	Simulated Louver	-1.2	8.0	10.5	-26.3	-11.6
12	Center Support Ring	-6.8	-3.9	-10.9	5.7	6.2
13	Center Support Ring	-7.0	-4.0	-13.3	-1.0	-10.7
14	Center Support Ring	-10.0	-4.0	-48.2	-29.9	-29.0
15	Center Support Ring	-8.0	-4.0	-13.5	3.4	-11.1
16	Simulated Louver	+0.3	8.0	-6.9	-21.5	-15.4
17	Simulated Louver	—	—	—	—	—
18	Simulated Louver	0.0	8.6	-5.9	-23.5	-16.5
—	TC Wire Bundle	46.5	—	41.5	39.2	—
—	Platform Heater Power*, Watts	3.90	4.41	5.00	4.07	2.57
—	Chamber Pressure, mm Hg.	1.1×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.2×10^{-4}	1.0×10^{-4}

* Recorded value (uncorrected for lead-in losses)

TABLE 2-2B: SUMMARY OF RECORDED TEST DATA - Continued

T/C No.	Location	Temperatures, °F		
		Test 6	Test 7	Test 8
1	Platform	116.7	8.0	8.0
2	Platform	117.3	5.7	4.9
3	Platform	117.1	6.4	5.7
4	Platform	116.9	6.4	5.8
5	Guard Heater (Bottom)	106.7	11.1	13.5
6	Guard Heater (Bottom)	—	—	—
7	Guard Heater (Bottom)	105.9	11.7	13.9
8	Fence - Right Side	85.9	-17.5	-17.4
9	Fence - Left Side	92.0	-15.4	-15.1
10	Side Guard - Housing End	—	-35.8	+35.3
11	Simulated Louver	85.5	-22.0	-22.8
12	Center Support Ring	95.7	-9.8	-9.2
13	Side Guard - Left Side	—	-37.5	+33.5
14	Side Guard - Support Ring	84.7	-32.6	+33.7
15	Side Guard - Right Side	84.6	-33.4	+36.5
16	Simulated Louver	—	—	—
17	Simulated Louver	84.7	-22.5	-24.0
18	Simulated Louver	—	—	—
—	TC Wire Bundle	104.7	9.9	3.8
—	Guard Heater Power*, Watts	2.87	1.224	1.224
—	Chamber Pressure, mm Hg.	1.0×10^{-4}	$.9 \times 10^{-4}$	1.3×10^{-4}

* Recorded value (uncorrected for lead-in losses)

TABLE 2-3: SUMMARY OF TEST CONDITIONS & RESULTS

Test No.	Test Condition	Average Temperatures, °F			Heat Loss		Effective Emittance	
		Platform	Simulated Louver	Bottom Guard	Watts	Btu/hr	①	②
1	Simulated Alum Louvers End & Edge Gaps Taped	38.0	-0.3	39.6	3.56	10.68	.143	.116
2	Simulated Alum Louvers End Gaps Open	39.3	+8.2	39.8	4.10	12.26	.162	.131
3	PIONEER Louver Blades Closed	41.1	-0.8	37.4	4.77	14.19	.185	.149
4	Sim. Fiberglass Louvers End & Edge Gaps Taped	42.7	-23.7	37.0	3.77	11.28	.145	.117
5	Ditto 4) - Actuator Housing Insulation Increased	36.1	-14.5	39.6	2.35	6.75	.092	.074
6	Modified Test Article Fiberglass Sim. Louver Guard Htrs. at Min. Loss	117.0	83.9	106.3	2.70	7.90	.059	.048
7	Ditto 6) - Side Guard Htrs. 20°F Too Cold	6.6	-22.3	11.4	1.27	3.72	.064	.052
8	Ditto 7) - Side Guard Htrs. 50°F Too Hot				No Measurable Change in Four Hours			

Notes: ① Based on louver surface area (0.71 ft²)

② Based on louver surface area + actuator housing area (0.88 ft²)

The unit was then shut down and the LN_2 supply closed. After the walls were warm, the vacuum chamber was opened and model changes required for the next test were made. Variations of any of the above procedures for a specific test (if any) are mentioned in Section 2.5 in the discussion of the results.

2.5 Experimental Results

The measured heat loss from the platform (E_M = electrical power to the platform heater minus line losses) is shown in Table 2-3 for each of the eight test conditions. Effective emittances, $\bar{\epsilon}$, were computed using the equation (1) in the form

$$\bar{\epsilon} = \frac{E_M}{A\sigma T_p^4} \quad (2)$$

where, as before, σ is the Stefan-Boltzmann constant and T_p the average platform temperature. Two different areas, A , were used in the computation, the first being the area of the louver surface plane only and the second including the platform area blocked by the actuator housing. Since the housing detracts from the platform area available for heat rejection, it is reasonable that its area should be included in the emittance determination. Since previous PIONEER data has not included the area blockage by the housing, both effective emittances will be carried along in this report.

The effective emittance of the closed PIONEER system was found, in previous testing, to be between 0.18 and 0.22. This value is in good agreement with the emittance of 0.182 measured in Test 3.

Referring to Tests 1 and 2, the influence of blade and end gaps is seen to be approximately 0.02 while the mating gap edge losses contribute about the same (Tests 2 and 3). Heat conduction within the blade can be seen to have no appreciable effect by comparing the results of Test 1

(aluminum simulated louver) with Test 4 (fiberglass simulated louver). Combined, the results of Tests 1 - 4 did not provide the desired level of improvement and thermal losses of other areas were examined. A prime candidate for additional losses was the actuator housings. Substantially increasing the insulation on the housings by inclusion of a single batt (of 15 layers aluminized Mylar) caused a decrease of $\bar{\epsilon}$ of approximately 0.04.

It should be noted that the heat loss data in Table 2-3 represents the measured electrical power minus and estimated loss from the side fences. These fences do not extend above the louver plane level in the actual PIONEER system and should not, therefore, be counted in evaluating an equivalent effective emittance. See Appendix I for a computation of the side fence losses.

Tests 6, 7 and 8 were conducted with a modified model which had been totally re-insulated, which had the side fences cut to the level of the louver plane (no correction was necessary in these tests), and which had side guard heaters installed to minimize thermal leaks out the side. Figure 2-6 shows this version of the test model. The results of Tests 6 and 7 show substantial improvement in the effective emittance. It must be concluded that this reduction in $\bar{\epsilon}$ was due primarily to better insulation on the housing assembly, on the side fences as well as the internal portion of the center support ring. This result clearly points out the criticality of the insulation system in maintaining a low value for $\bar{\epsilon}$. Test 6 was conducted at 117°F platform temperature while Test 7 was conducted at 7°F. Test 8 was conducted in order to assess the side leak effects by operating the side guard heaters at a temperature 50°F hotter than the model fences. No influence in platform or louver surface temperature was detected after four hours of operation. Relative results of Tests 7 and 8 confirm the thermal integrity of the side and bottom insulation and that no measureable heat "leaks" from the model other than through the louver system were present.

In order to achieve a thermal balance on each test, estimates were made of the various heat paths from the platform and compared with measured power inputs. The paths considered included;

- 1) radiation exchange with the louver surface (and ultimately radiated from the plates to space),
- 2) conduction exchange with the louver surface (also radiated to space),
- 3) edge losses (due to mismatching of louver edges),
- 4) end losses (due to gaps at end of blades),
- 5) actuator housing losses,
- 6) side fences (due to ineffective insulation and radiation from interior facing sides),
- 7) end column losses (due to ineffective insulation and radiation from interior facing sides),
- 8) guard plate losses (from heated platform through insulation to heated guard plate), and
- 9) thermocouple and heater wire bundle losses (due to gradient from platform to bundle).

The experimental setup was designed to minimize items 8) and 9); the results of Tests 7 and 8, in part, substantiate this claim. The other factors are summarized in Table 2-4 for each test; procedures used in estimating the losses are presented in Appendix I.

A number of pertinent conclusions can be formulated from Table 2-4. First, the radiative loss from the louver blades (or simulated blades) represents a relatively small portion of the total electrical power input. The flight insulated actuator housings, for example, contributed a substantially greater heat loss than closed PIONEER louver blades (Test 3). Unfortunately, losses from the side fences and end column were not negligibly small leading to the modified design used for Tests 6, 7 and 8. As mentioned previously, edge and end losses were comparable in value and, interestingly, were approximately equal to the total radiative loss from the louver surface.

TABLE 2-4: SUMMARY OF HEAT LOSS CALCULATIONS

Test No.	Condition	Louver Radiation			Edge Loss Btu/h
		$\bar{T}, ^\circ\text{F}$	σT^4	Q_L Btu/hr	
1	Simulated Alum Louvers End and Edge Gaps Taped	-0.3	76.5	1.90	0
2	Simulated Alum Louvers End Gaps Open	+8.2	82.4	2.04	0
3	Pioneer Louver Blades Closed	-0.8	76.2	1.89	2.00
4	Simulated Fiberglass Louvers End and Edge Gaps Taped	-23.7	62.1	1.54	0
5	Simulated Fiberglass Louvers End and Edge Gaps Taped Actuator Housing Insulation Increased	-14.5	67.5	1.67	0
6	Modified Test Article Fiber- glass Simulated Louver Guard Htrs. at Min. loss	83.9	150.0	3.73	0
7	Modified Test Article Fiber- glass Simulated Louver Guard Htrs. at Min. Loss - Side Guard Htrs 20 $^\circ$ F too cold	-22.3	62.91	1.65	0
8	Modified Test Article Fiberglass Simulated Louver Guard Heaters Minimum Loss - Side Guard Heaters 50 $^\circ$ F Too hot	-22.3	62.91	1.65	0

* Actual Meas. = 8.72 [0.82 Btu/l hr assumed
in 1 $^\circ$ F/h increase in platform temperature]

Symbols

$\bar{T}$ = average temperature

Q_L = louver radiant heat loss

Q_s = false fence radiant heat

Edge Loss tu/hr	End Gaps Btu/hr	Act. Housing Loss Btu/hr	Side Fence $\bar{T}, ^\circ\text{F}$ σT^4 Q_s Btu/hr			End Column $\bar{T}, ^\circ\text{F}$ σT^4 Q_c Btu/hr			ΣQ Btu/hr	$Q_{\text{meas.}}$ Btu/hr	Unacct. For Btu/hr
0	0	5.03	+4.3	79.7	1.16	-9.0	70.9	.07	8.06	11.84	3.78
0	1.69	5.03	+4.0	79.4	1.16	-4.0	74.1	.08	10.00	13.42	3.42
2.06	1.69	5.03	-10.8	69.8	1.02	-13.4	68.2	.07	11.76	15.21	3.45
0	0	5.03	+0.1	76.8	1.12	+3.7	79.2	.08	7.71	12.40	4.69
0	0	0	-7.4	71.9	1.05	-10.8	69.8	.07	2.79	7.80	5.01
0	0	0	0	0	0	0	0	0	3.73	7.90	4.17
0	0	0	0	0	0	0	0	0	1.65	3.72	2.07
0	0	0	0	0	0	0	0	0	1.65	3.72	2.07

Q_c = end column radiant heat loss

loss ΣQ = total calculated heat loss

heat loss Q_{meas} = measured heat loss

FOLDOUT FRAME

The most obvious conclusion to be drawn from Table 2-4 involves the unaccounted-for thermal loss column. While the absolute value in this column is small (5 Btu/hr corresponds to an average test model temperature change rate of about 1.25° F/hr), the relative magnitude is sizeable. Realistic estimates of the above nine heat paths could total only about 45% of the measured electrical power in Test 7 and 75% in Test 2. Further, a substantial error in any one of the thermal loss estimates in Table 2-4 would be necessary to have much effect on the unaccounted-for loss column. Even the experiments with the modified test model with improved insulation did not reduce the disagreement in the heat balance.

The only calculated contributor to the heat balance in Tests 7 and 8 was radiation loss from the louver surface. To ascertain if the surface emittance had been increased due to chamber contamination, an in-place emittance measurement was made after Test 8. The device described in Ref. 2 was used and indicated that the hemispherical emittance after testing was not greater than 0.04 versus a pre-test value of 0.034 at room temperature. This difference is well within the experimental accuracy of the thermophysical test equipment and cannot account for the discrepancies noted; an emittance of approximately 0.083 would be necessary to achieve a heat balance in Test 7.

A strong contender to account for the breakdown in the law of conservation of energy is residual gaseous conduction within the vacuum chamber. The average pressure (see Table 2-2) was about 10^{-4} mm Hg at the chamber diffusion pump inlet port. Presumably, this pressure was even higher at the test article. To evaluate this effect the total heat loss (conduction and radiation) from the louver surface was equated with the electrical input and the following equation form assumed:

$$E_m = \bar{\epsilon} A [\sigma T_L^4 - \sigma T_N^4] + \bar{c} A [T_L - T_N] \quad (3)$$

where $\bar{\epsilon}$ = effective louver surface emittance
 $\bar{c}$ = average gaseous conduction
 T_L = louver surface temperature
 T_N = cold wall temperature
 A = surface area

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Using the data from Test 6 and 7 and assuming constant (with temperature) values of $\bar{\epsilon}$ and $\bar{c}$ produced the following results

$$\bar{\epsilon} = 0.059$$

$$\bar{c} = 0.00716 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Operation in the model in a true vacuum environment could result in an effective emittance as low as 0.029 for Test 7 and 0.157 for the present PIONEER louver blades.

The Knudsen equation for free molecule gaseous conduction at 1×10^{-4} mm Hg gave a value for $\bar{c}$ of about 0.0035. However, the pressure near the test article could have easily been twice the measured value resulting in a $\bar{c}$ in very good agreement with test. It seems a little unlikely that $\bar{\epsilon}$ was as high as 0.06 although the physical differences between surfaces having emittances of 0.04 and 0.06 are admittedly quite small. Using an $\bar{\epsilon}$ of 0.06 in Test 1 and a value of $\bar{c}$ from the louver surface, -exposed side fences and end column of 0.00716 gave an estimated heat loss within 10% of the measured value. A similar improvement was seen in the heat balances of Tests 2, 3 and 4. Test 5 remains in particularly bad agreement; it was felt that the additional insulation on the actuator housing losses had not totally eliminated this loss.

Although gaseous conduction must be considered the most likely source of the unaccounted-for thermal energy, the experimental data collected in this program is not sufficient to rule out other possibilities; additional testing in a vacuum chamber capable of operation at pressures near 10^{-6} mm Hg near the model would be required. Also, test data for the actual louver blades without pressure correction were in agreement with results presented in Ref. 1. Those tests were conducted at 5×10^{-6} mm Hg chamber pressure. Therefore, effective emittance data presented in this report will not be corrected for effects of chamber pressure.

Another conclusion resulting from the experimental data concerns the radiative and conductive exchange paths between the platform and the simulated louver blades. Expressing the radiative exchange, E_r , in the form

$$E_r = \frac{A [\sigma T_p^4 - \sigma T_L^4]}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_L} - 1} \quad (4)$$

where T_p = platform temperature
 T_L = louver temperature
 ϵ_p = platform emittance (0.86)
 ϵ_L = louver emittance (0.04)

it can be shown that the radiative exchange in Test 7 is only 0.52 Btu/hr compared with a calculated louver rejection of 1.65 Btu/hr and a measured electrical power input of 3.72 Btu/hr. Clearly, even in the test where conduction is minimized through the use of a fiberglass simulated louver surface, conduction from the platform to the louver remains a major heat flow path. Careful attention to minimizing the many direct conduction paths is, therefore, essential to the design of a louver configuration with a very low effective emittance in the closed position.

2.6 Experimental Uncertainties

The uncertainties in the experimental results presented can be estimated by differentiating Eqn. (1) and rewriting in the form

$$\frac{d\bar{\epsilon}}{\bar{\epsilon}} = \pm \frac{dq_r}{q_r} \pm \frac{dA_p}{A_p} \pm 4 \frac{dT_p}{T_p} \quad (5)$$

where the terms have been defined previously. Note, however, that dq_r is not simply the error in the electrical input to the platform, but is the difference between the electrical input and all thermal losses in the test unit which are not radiated via the louver system (blades, springs, housings, center support ring, etc.) to the cold wall. As such dq_r must include losses through the superinsulated sides of the test fixture as well as gaseous conduction from the platform. In equation form

$$\frac{dq_r}{q_r} = \pm \frac{\delta_E}{E} \pm \frac{\delta_I}{I} \pm \frac{q_s}{q_r} + \frac{q_f}{q_r} + \frac{q_g}{q_r} \quad (6)$$

where δ_E , δ_I = uncertainties in voltage (E) and current (I) measurements, respectively

q_f = text fixture thermal loss

q_g = gaseous conduction

q_r = heat storage due to non equilibrium conditions (thermal mass temperature change rate)

The last two terms in the expression are always positive; the others may be positive or negative.

A similar argument will show that $d\bar{T}_p$ must account also for the variance in the cold wall temperature, T_N . However, T_N is small relative to $\bar{T}_p$ and can be ignored in the approximations of this error analysis.

The following conservative estimates were made for the individual terms in Eqns. (5) and (6);

$$dA_p \approx \pm .01 \text{ ft}^2$$

$$d\bar{T}_p \approx \pm 2^\circ\text{F}$$

$$\frac{\delta E}{E} \approx \frac{\delta I}{I} \approx \pm .01$$

$$\left. \begin{array}{l} \frac{q_f}{q_r} \approx .01 \\ \frac{q_s}{q_r} \approx \pm .01 \end{array} \right\} \text{For the range of power inputs in Tests 1 - 8}$$

The resultant uncertainty in $\bar{\epsilon}$ under the worst combination of factors is 7%; for $\bar{\epsilon}$ of 0.10, the probable, maximum, error is ± 0.007 .

The gaseous conduction has been excluded from this error analysis primarily because of the questions raised in Section 2.5. The effect of this uncertainty is always positive (will add to $\bar{\epsilon}$) and has been included in the emittance values reported. Additional testing would be necessary to effectively identify the error introduced by this factor. Gaseous conduction will be essentially constant with emittance and will exercise a small influence at larger values of $\bar{\epsilon}$.

Application of Eqns. (5) and (6) to the results of the open emittance tests (II-1, Section 4.0) gives a probable maximum error of about $\pm 3\%$ ($\Delta\epsilon \pm .025$).

2.7 Thermophysical Property Measurements

The integrated normal reflectance and total hemispherical emittances were determined experimentally for each of the possible louver surface and platform coatings; the results of these measurements are presented in Table 2-5. The normal reflectance data were obtained using a Gier-Dunkle Heated Cavity Absolute Reflectometer (Ref. 5) combined with a Perkin-Elmer Model 99 monochromator. The spectral data were numerically integrated by multiplying the average reflectance of each wavelength band by the fraction of energy emitted by a 300°K black body in the same spectral band and summing the resulting products.

Normal spectral reflectance measurements in the wavelength region 0.3 to 2.5 μ were made with a modified Beckman DK-2A Spectrophotometer which includes an integrating sphere of the type described by Edwards, et al. (Ref. 6). The solar absorptances were then determined by integrating the reflectance data with respect to the Johnson solar energy spectrum (Ref. 7).

Total hemispherical emittance data were obtained calorimetrically. The experiment unit consists of a vacuum system, a bell jar and a liquid nitrogen cooled enclosure. By measuring the electrical power input to the sample (a wire wound heater sandwiched between two 4" x 4" thin metal plates containing the coating), and by measuring very accurately the sample temperature, the hemispherical emittance can be calculated. Sample temperatures from -100 to +100°C are possible.

The probable uncertainty in hemispherical emittance is not greater than ± 0.005 for the low emittance samples and ± 0.025 for the white paints. The other data are provided for reference only and the errors were not assessed.

TABLE 2-5: RESULTS OF THERMOPHYSICAL PROPERTY MEASUREMENTS

No.	Material Description	Solar Absorbance	Normal Reflectance	Hemispherical Emittance at T, °F			
				-22	+32	+86	+140
<u>Louwer Blade Materials</u>							
1	Vacuum Deposited Aluminum on Resin	—	.978	.028	.032	.034	.035
2	Vacuum Deposited Gold on Resin	—	.981	.021	.024	.025	—
3	1170 Clad on 2014 Alum	.11	.97	.037	.040	.042	.043
4	1100 H-18 Aluminum Alloy	—	.97	.035	.039	.041	.042
5	Vacuum Deposited Alum on Fiberglass	—	.98	.028	.032	.034	.035
<u>Platform Coatings</u>							
6	IITRI Z-93	.20	.08	.88	.89	.90	.90
7	IITRI S-13G*	.19	.10	.86	.87	.88	.89
8	Dr. Schutt's No. 9	.22	.05	—	—	—	—

* Selected for Platform in Improved Design

3.0 IMPROVED CONFIGURATION DESIGN STUDY

The test results presented in Section 2.0 suggested several design areas for increasing the dynamic performance range ($\epsilon_{\text{open}}/\epsilon_{\text{closed}}$) of the present PIONEER louver system. The more important of these include;

- redesign of the actuator housings to allow for more effective insulation and to reduce end gaps,
- thinner blade construction to increase emittance in the open position,
- platform coating with increased thermal emittance to improve open performance,
- minimize heat conduction path between platform and blade, and
- careful application techniques to increase general effectivity of insulation.

The basic geometrical constraints of the PIONEER spacecraft (radial blades, platform area, center support ring, etc.) were assumed to be invariant in the above study. Where possible, existing PIONEER parts were to be utilized.

3.1 Design Considerations

3.1.1 Actuator Housing

It became apparent in the preliminary testing that the use of five individual actuator housings represented a significant source of heat leak in the initial test model, in spite of the insulation "hats" shown in Figs. 2-1 and 2-2. Approximately 1/3 of the total platform energy loss measured for the actual PIONEER louver blades (Test 3) could be attributed directly to the actuator housing. The concept of separate insulation/housing assemblies for each actuator spring is inherently inefficient from a thermal standpoint due to the increased surface area, large number of corners and bends to compress the insulation, short conductance paths in the heavy face sheets, difficulty of manufacture, etc. Additionally, there are spaces between the individual housing assemblies contributing to the end gap losses.

Consequently, it was decided to concentrate effort on the improved configuration towards a unit actuator housing design incorporating all five louver blades in the 60° segment. The difficulties of achieving effective insulation for this design are substantially less; conventional techniques using a single fifteen layer blanket folded loosely over the housing appears sufficient to minimize this part of the total heat loss.

Other considerations in the design work on the unit housing concept included providing conductive isolation of the blades from the platform and reducing the platform area covered or blocked by the housing assembly. While this latter effect does not appear a significant factor on PIONEER, the platform area under the housing cannot contribute to the total available for heat rejection in an open position. For situations where the total area (platform + housing) is fixed, the maximum heat rejection capabilities of the system is reduced by the blockage. Based on this total area concept, a thinner housing assembly serves to increase the effective emittance in both the open and closed condition.

A structural and dynamic evaluation of the final housing configuration selected was also conducted to insure that the design would at least be "representative" of flight-type hardware.

3.1.2 Louver Blades

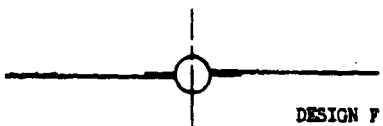
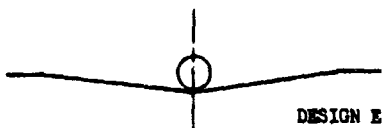
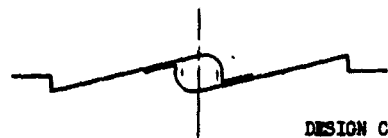
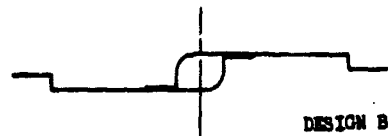
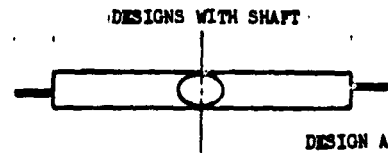
The results of the preliminary thermal test program suggested no changes to the present PIONEER louver blade which would offer much reduction to the closed position platform emittance. Conduction within the blades was determined to be a small factor (Tests 1 and 4) and the surface emittance of 0.041 for 1100 H-18 aluminum alloy (present material) could not be reduced significantly even with a vacuum deposited aluminum or gold coating. Edge losses were also determined to be small and provided little potential for reduction of $\bar{\epsilon}_{\text{closed}}$.

On the other hand, analytical studies of an open louver system (see Appendix II) showed that a sizeable gain in $\bar{\epsilon}_{\text{open}}$ over the present value of 0.73 was possible and, further, that thickness and surface coatings

were the primary blade factors to be examined. The existing blade is approximately 0.26" thick with 0.13" diameter shaft ends. Approximately 10% of the platform area is effectively blocked in that the flat edge segments reflect emitted energy back to the platform where most of it is absorbed. The present surface emittance of 0.041 could be improved slightly through the use of a vacuum deposited aluminum coating. From a thermal standpoint, the optimum blade design has zero thickness and a reflectance of unity.

Figure 3.1 presents some of the louver blade cross-sections considered in the evolution of an improved design. Initial configuration review was directed to a 0.16" thick blade using the present PIONEER 0.003" thick aluminum foil surfaces and an elliptical cross-section shaft (Design A, Fig. 3.1). This design provides a 40% reduction in platform blockage, is structurally acceptable and would be of comparable weight to the present blades. Design G, while still 0.16" thick, offers some thermal improvement over A through the elimination of the flat edges. No surfaces on G will reflect radiation directly back to the platform in the open position. However, Design G is structurally inferior to A (due to slightly reduced cross-section) and would probably require heavier gauge material.

Designs B through F represent attempts to combine a single piece blade construction and a tubular shaft. Note that the results of the preliminary test program do not indicate a thermal requirement for a double material blade construction. Consequently single piece blade configurations were given prime attention. The shaft in the above design gives the necessary longitudinal stiffness while the blade material would provide the cross-sectional stiffness. Since the platform blockage is still effectively 0.16", these designs represent no real advantage over A and are inferior (slightly) to G. It is unlikely that Designs B through F could be made lighter than the present louver assembly due to the need for increased blade material thickness.



DESIGNS WITHOUT SHAFTS

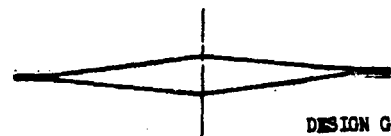


FIGURE 3.1
LOUVER BLADE CROSS-SECTION CONFIGURATIONS

Designs H and J are single piece blades and contain no longitudinal shaft; end fittings must be provided for mounting to the actuator spring assembly. Design H is slightly superior structurally by virtue of the cross-section; Design J uses material thickness alone for longitudinal and cross-sectional stiffness. Platform blockage by the blade will be smaller in Design J. Both single blade, no shaft designs (H and J) will be heavier than the present PIONEER louver blade configuration.

Design J was ultimately selected as a reasonable thermal/structural/fabrication compromise. It offers the thermal advantages of being relatively thin (minimizing platform blockage) and having a very predictable geometry (making correlation of analysis and experiment in the open position more reliable). Fabrication is extremely simple at the expense of blade weight. Also, heavier blade material makes possible more positive blade to blade mating (than the thin wall double blade construction) and minimizes the danger of blade damage during fabrication and handling of the spacecraft.

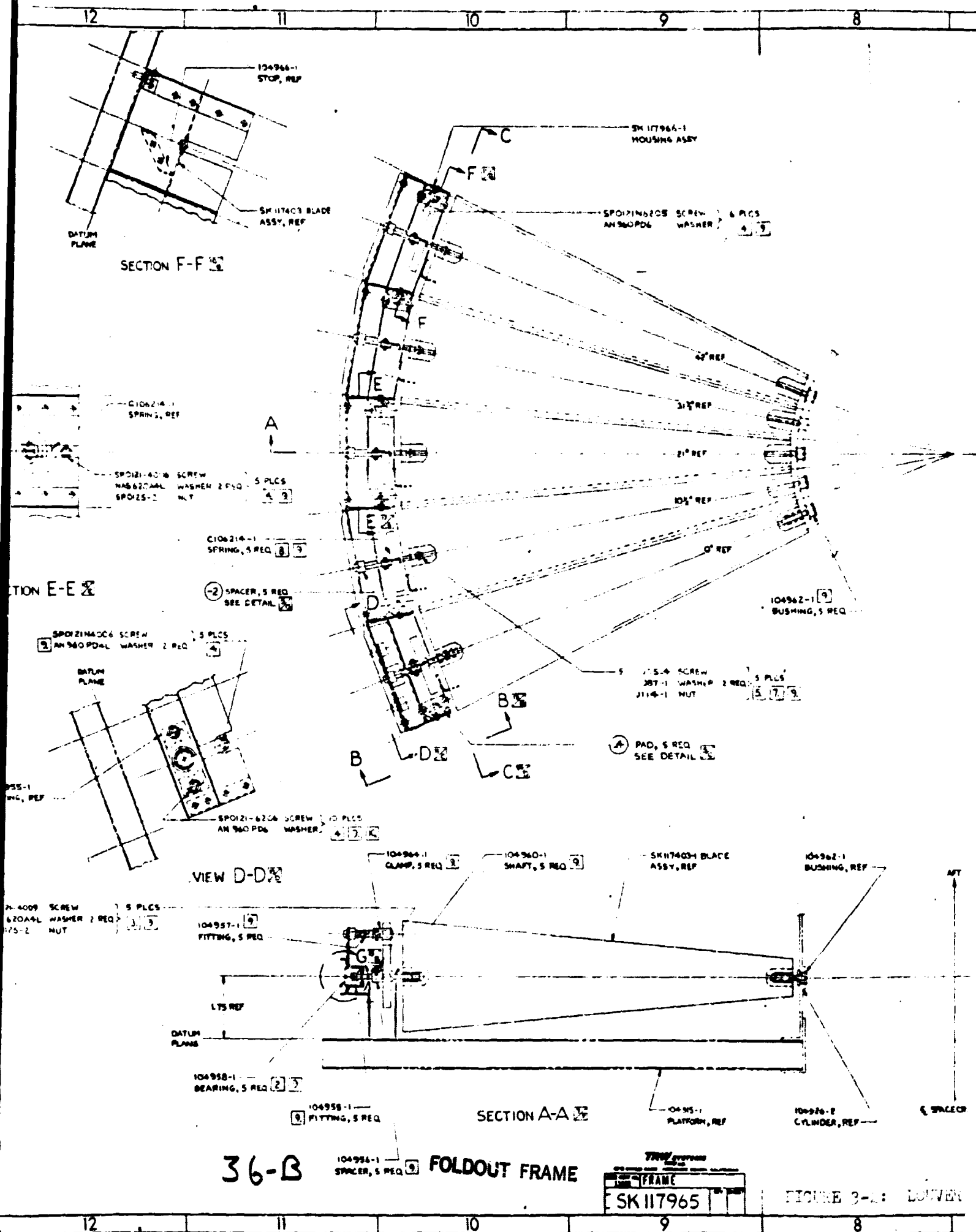
A preliminary structural analysis identified the vibration environment as being the governing design criteria for a single thickness blade. Experiments on PIONEER and other programs have indicated that blades with a first natural frequency in the range between 50 and 100 cps are desirable (excluding 65 cps which is the resonant frequency of the PIONEER VII platform). On this basis beryllium was selected as the blade material because of its very high stiffness/density ratio compared to aluminum and magnesium. A blade thickness of 0.040" was calculated to have a natural frequency of about 55 cps, within the desirable range.

An additional consideration in the selection of beryllium as the blade material was to gain experience in the handling, bonding and coating of this very promising structural material.

3.2 Improved Design Configuration

Detailed design drawings for the improved louver system selected are presented in Figs. 3-2 through 3-4. As discussed in Section 3.1, the

36- A FOLDOUT FRAME



SCREW 6 PCS
WASHER 4

DETAIL (2), SCALE 4/1
6061-T6 AL ROD, QQ-A-200/A

DETAIL ③, SCALE 4/1
 NYLON, MIL-M-20493, TYPE I
 (MAY BE MADE FROM SP-2097
 -18, -21, -23 OR -27 WASHER)

DETAIL (4), SCALE 4/1
D60 THK, 2024-T3 AL SM, QC-A-25C/4

REG 132
TAIL 132

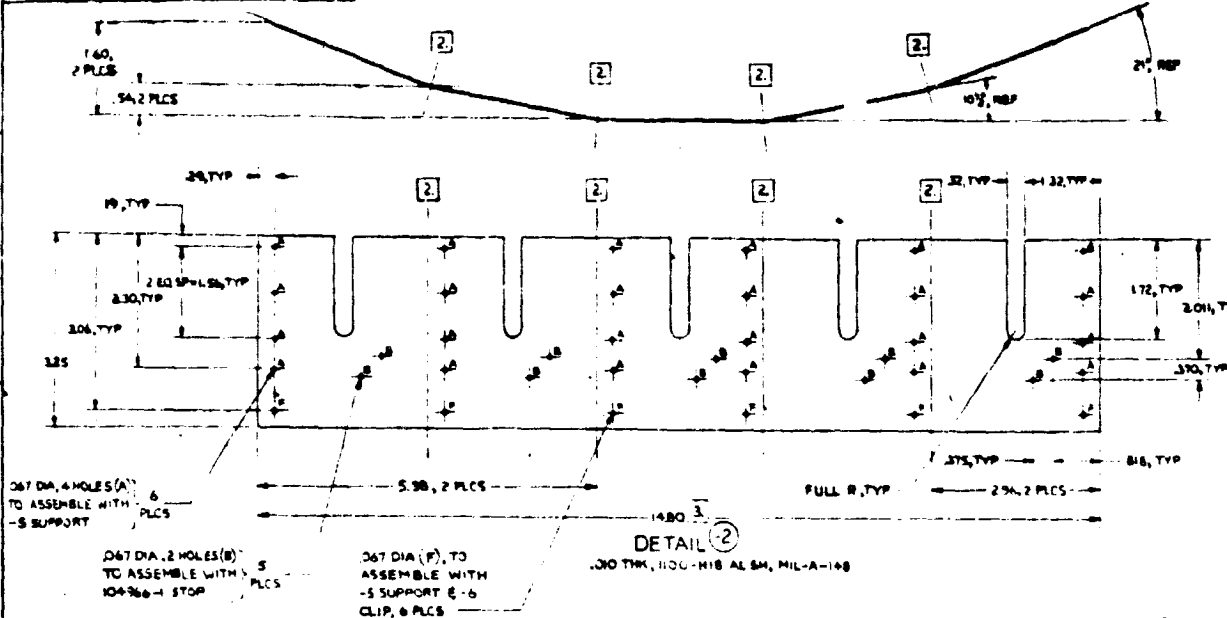
 **Twitter**

4. CLEARANCE BETWEEN MOUNTING HOLES IN SK117866-1 HOUSING ASBY AND SPO21-6206 SCREWS ALLOWS FOR BLADE ADJUSTMENT. POSITION 104955-1 FITTING TO OBTAIN MINIMUM GAP BETWEEN BLADES IN CLOSED POSITION AND TIGHTEN SPO21-6206 SCREWS
5. MAY BE SALVAGED FROM PREVIOUS IMPLS TEST RIG
6. C106214-1 SPRING IS CONSIDERED TO BE CENTERED ABOUT 104960-1 SHAFT WHEN SK117863 BLADE ASBY IS IN THE CLOSED POSITION (PER SECTION C-11 REPLACE THE CENTER END OF SAME IS FREE TO ASSUME A UNRESTRAINED POSITION, ANGULARLY & RADIALY. WITH 104957-1 FITTING & 104964-1 CLAMP TIGHTENED IN PLACE, THE C106214-1 SPRING MUST BE CENTERED ABOUT 104960-1 SHAFT WITHIN 2 OS
7. SEAL THREADS IN IMPL PER MIL-S-21473, USING GRADE 'C' SEALANT
8. SK117863 BLADE ASBY TO BE FREE OF GREASE, OIL, SCRATCHES DEEPER THAN 1/8", & DENTS DEEPER THAN .006
9. TORQUE 240830 IN/OZ
10. TORQUE 40835 IN/LB
11. TORQUE 560850 IN/OZ
12. TORQUE 40810 IN/LB

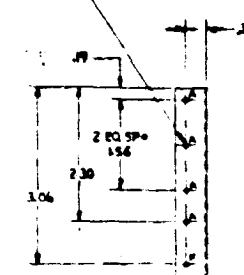
5. OPERATING INSTRUCTIONS IN CONFORMANCE WITH THE SYSTEM SPEC. TO LSI-1

FIGURE 3-2: LOWER INSTALLATION DRAWING ~~NOTE: UNLESS OTHERWISE SPECIFIED~~

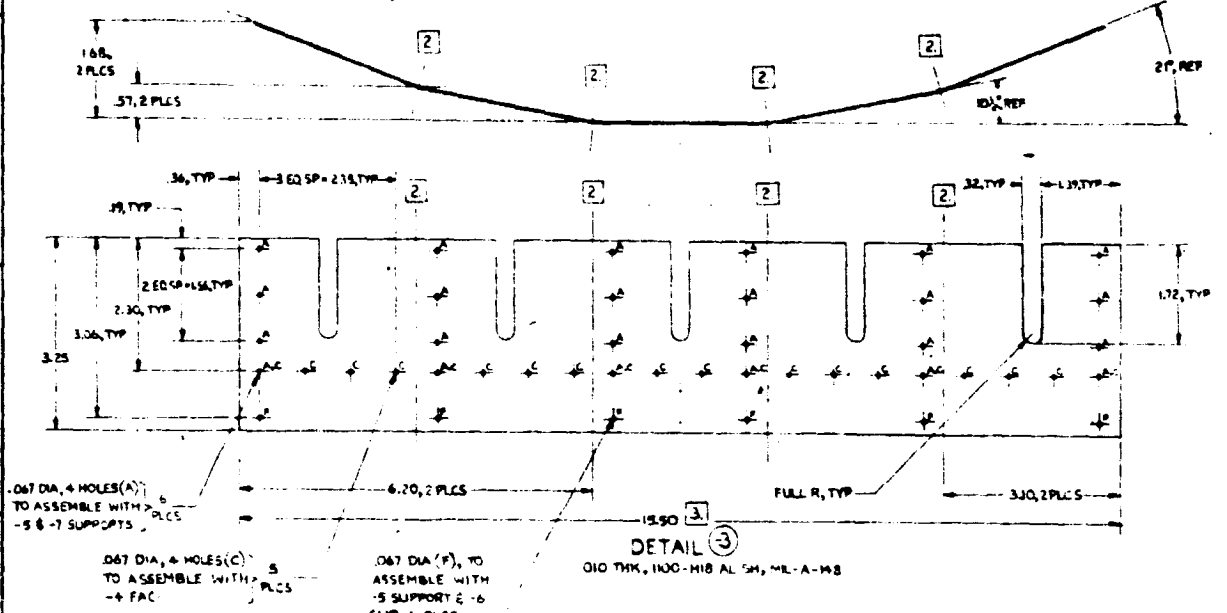
THE INFORMATION AND TECHNICAL DATA CONTAINED ON THIS DRAWING ARE THE PROPERTY OF THE UNITED STATES GOVERNMENT AND ARE NOT TO BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC OR MECHANICAL, INCLUDING PHOTOCOPYING, RECORDING, OR BY ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT PERMISSION IN WRITING FROM THE UNITED STATES GOVERNMENT. THIS DRAWING IS NOT TO BE USED FOR ANY PURPOSE OTHER THAN THAT AUTHORIZED BY THE UNITED STATES GOVERNMENT. THE UNITED STATES GOVERNMENT MAKES NO WARRANTY, REPRESENTATION, OR GUARANTEE, EXPRESS OR IMPLIED, REGARDING THE ACCURACY, COMPLETENESS, OR RELIABILITY OF THE INFORMATION AND TECHNICAL DATA CONTAINED ON THIS DRAWING. THE UNITED STATES GOVERNMENT SHALL NOT BE LIABLE FOR ANY DAMAGES, INCLUDING REASONABLE ATTORNEY'S FEES, ARISING OUT OF OR FROM THE USE OF THIS DRAWING.



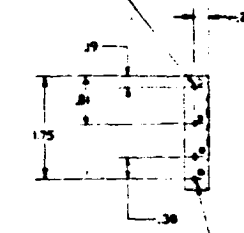
.067 DIA, 4 HOLES (A) REB FLANGE TO ASSEMBLE WITH -5 -6 FACES



DETAIL (3) 100 THK, 2074-T3 AL SM



.067 DIA, 2 HOLES (D) TO ASSEMBLE WITH -4 FACE



.067 DIA, 2 HOLES (S) TO ASSEMBLE WITH -4 FACE E-6 CHANNEL

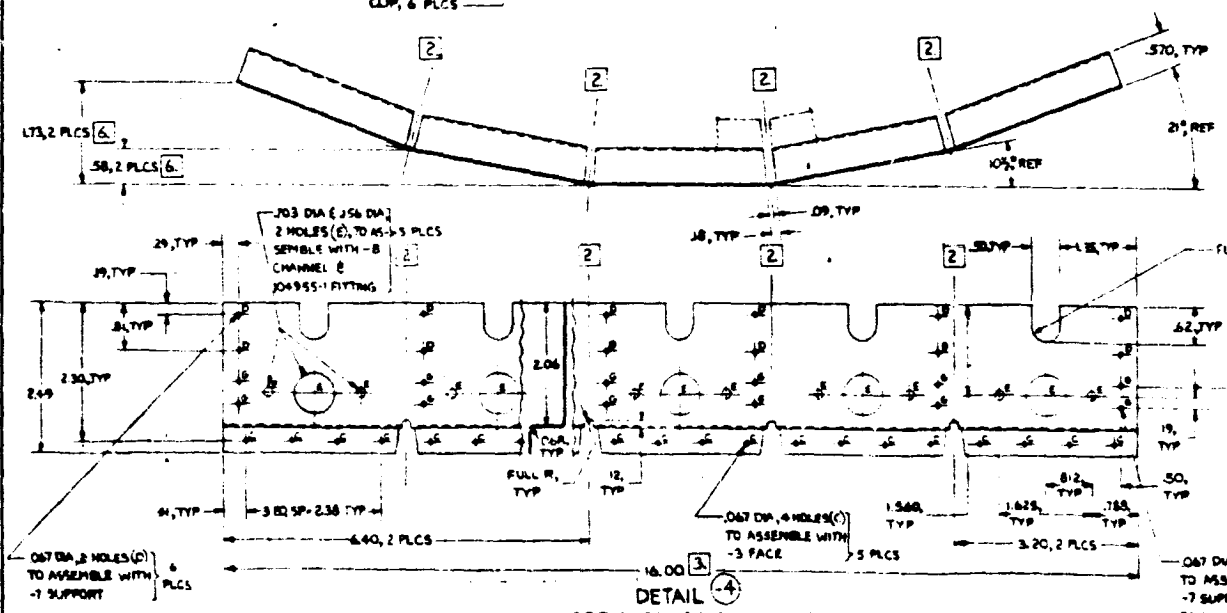
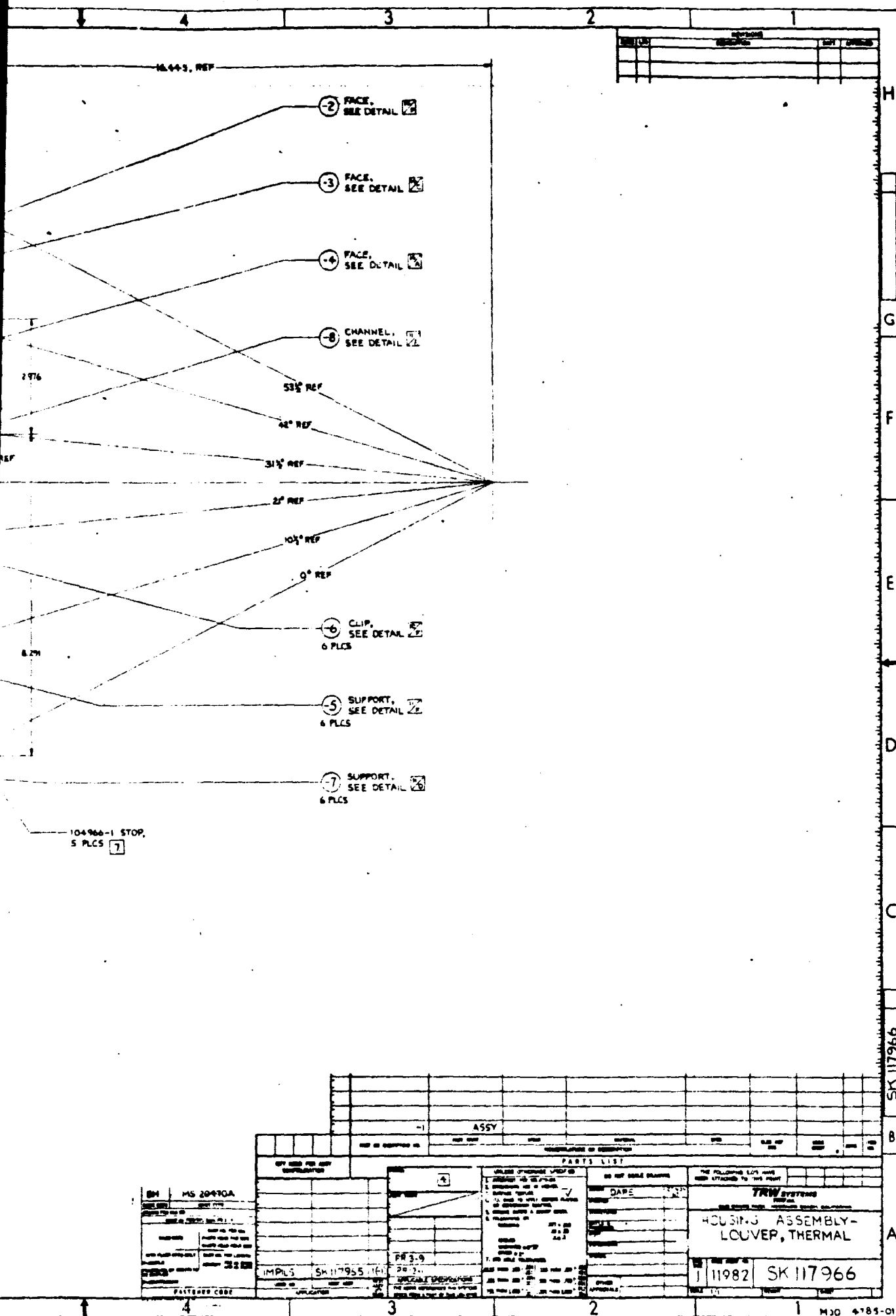




FIGURE 3-3: MOUNTING ASSEMBLY DRAWING



primary difference between this design and the present PIONEER louver system centers about the unit housing construction (with improved insulation) and the single piece 0.040" beryllium blades. A photograph of the improved configuration integrated in the test rig is shown in Fig. 3-5.

The housing design was complicated by the decision to use the present PIONEER bearing/shaft assembly which was made to mount to the inside rather than outside of the housing wall. The improved configuration calls for two parallel sheets bent to follow the louver contour and separated by internal radiation shields. However, it was necessary to provide a third parallel sheet (see Fig. 3-4) as a mounting surface for the bearing/spring/shaft assembly. This external plate is artificial in that it could be eliminated with a redesign of the bearing assembly for mounting external to the second (or middle) sheet. The housing (without the bearing assembly) was made primarily from 0.010" thick sheets of 1100 H-18 aluminum alloy held together with 1/16" aluminum rivots. The unit (including the artificial plate) weighs 3.30 ounces compared to 1.37 ounces for five individual housings on the present PIONEER configuration. The area blockage for a flight configuration would be approximately $11\frac{1}{2}$ in² compared to $20\frac{1}{2}$ in² for the present configuration. The platform area "seen" by each spring has also been reduced (2.75 in² to 2.25 in²) which will increase the response time required by the system. However, it is felt that the improved insulation concept will compensate for this effect and negate any change in the spring-platform temperature difference (5°F for the present PIONEER louver system). The unobstructed platform area available for heat rejection has been increased from 0.71 ft² to 0.775 ft².

In order to insure that the improved housing design might be considered "representative" of flight-type hardware, a very brief structural evaluation was made by personnel experienced in the problems of the PIONEER spacecraft. While time and money did not permit the rigorous analytical and experimental studies required to certify the structural integrity of a flight item, it was concluded that the housing/bearing/spring assembly would conservatively withstand the vibration environment of a typical PIONEER launch.

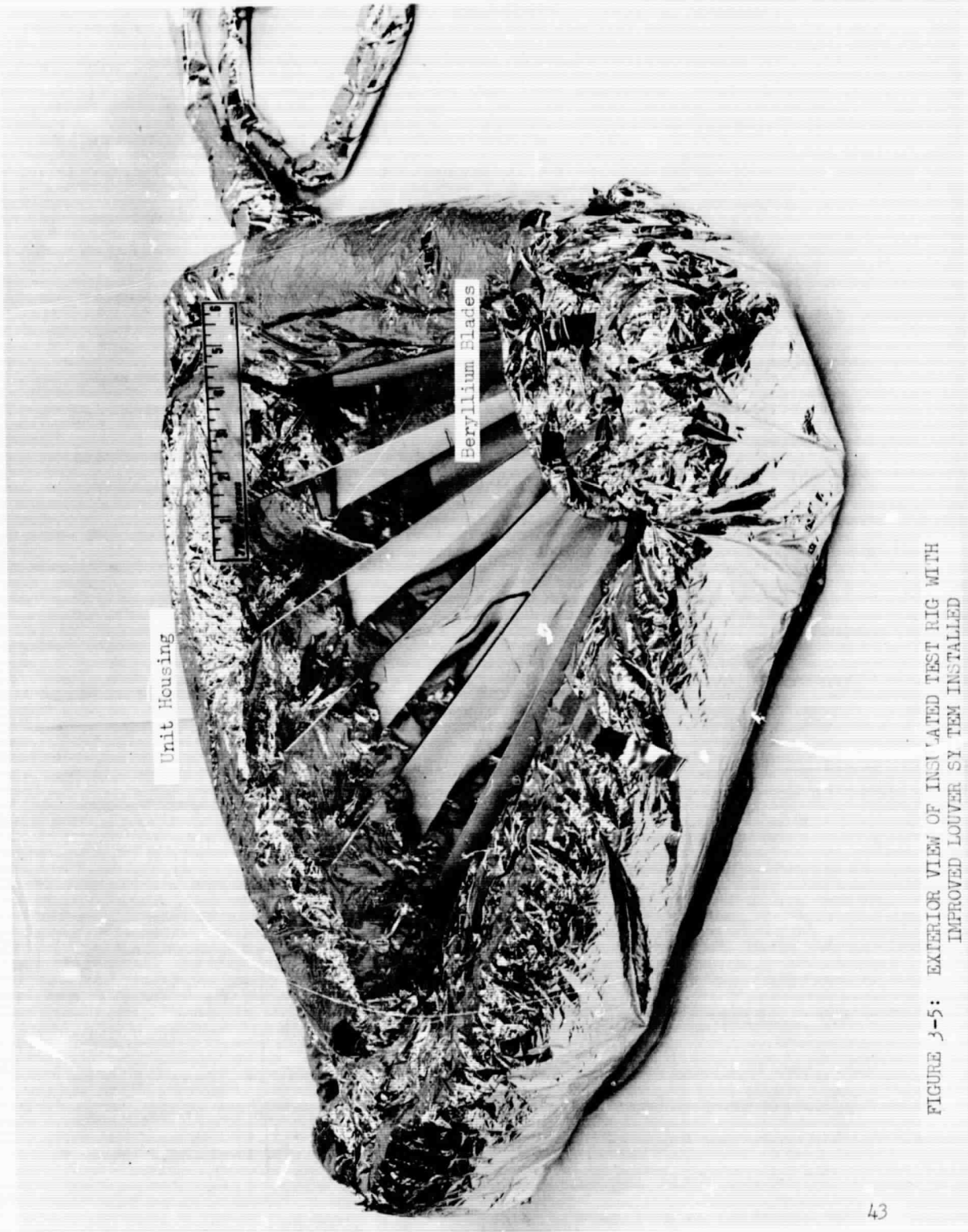


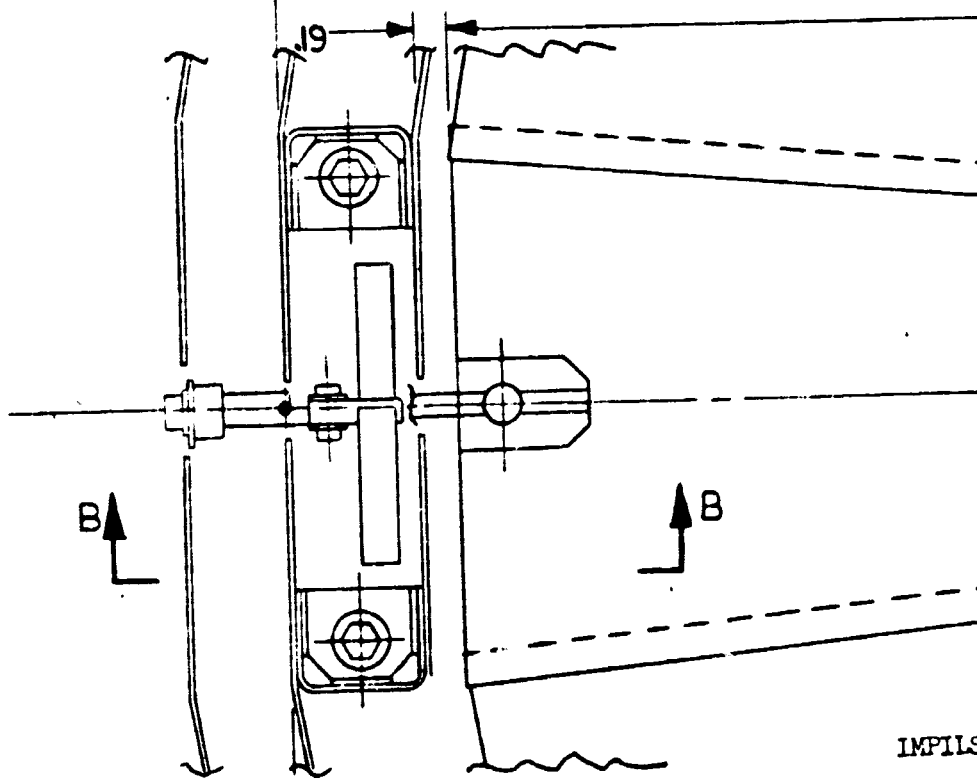
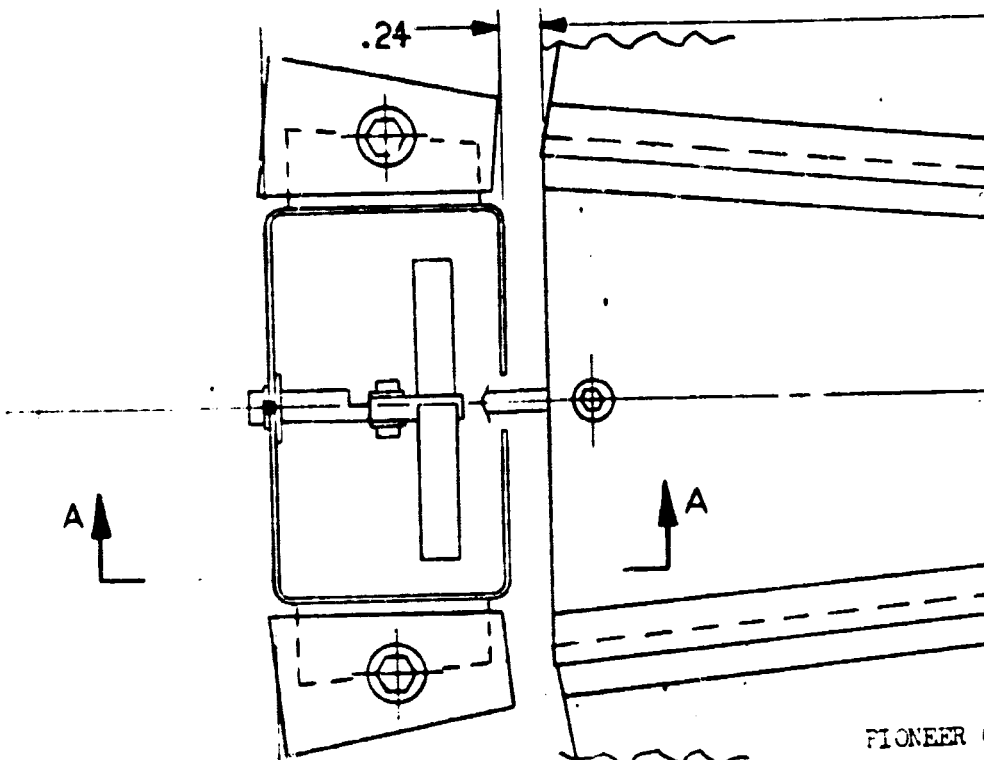
FIGURE 3-5: EXTERIOR VIEW OF INSULATED TEST RIG WITH
IMPROVED LOUVER SYSTEM INSTALLED

The louver blade selected for the improved configuration is a 0.040" thick beryllium blade coated on both sides with vacuum deposited aluminum (resin undercoat). Fittings to accommodate the shafts at each end were made from aluminum and bonded to the beryllium with EC 1469 adhesive (3M Company). The blades are slightly longer than the present system ($11\frac{1}{4}$ vs $10\frac{1}{2}$) due to the change in the actuator housing. Each beryllium blade weighs approximately 0.75 ounces versus 0.32 ounces for the present blade. The total S/C weight increase with the use of thirty beryllium blades is about 1.1 lb.

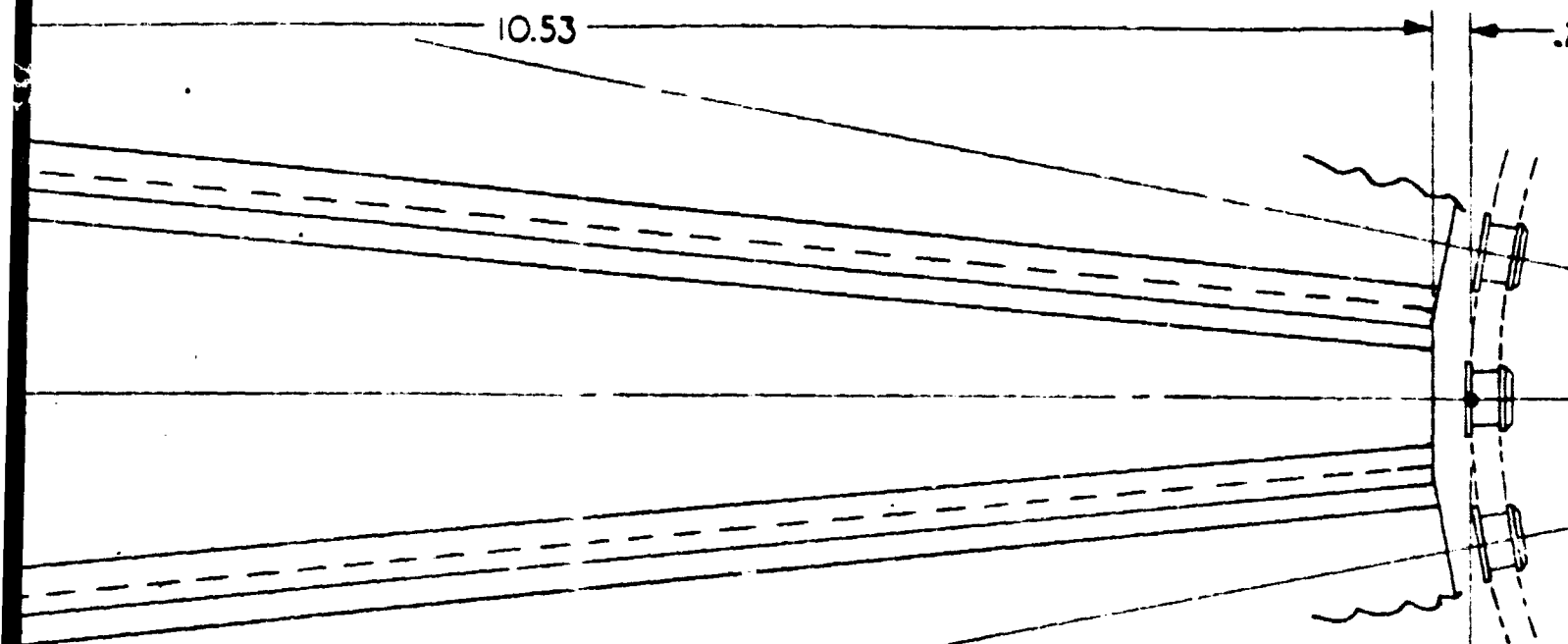
Figure 3-4 shows the improved blade design and the aluminum end fittings. Figure 3-6 presents a graphic comparison of the PIONEER and improved louver systems. Beryllium was selected as the blade material rather than aluminum because of its very high strength to density ratio; an aluminum blade with comparable stiffness would be 0.062" thick and weigh 1.75 ounces. Machining of beryllium is complicated due to the extreme toxicity of the dust produced. In the manner shown they are harmless.

Consideration was given in the selection of the louver blade coating to a vacuum deposited silver overcoated with a TRW proprietary treatment called Siloxane. This latter coating serves to protect the silver from tarnishing without degrading its radiative properties; measured values of α_s and $\bar{\epsilon}$ are 0.05 and 0.025, respectively. The process was eventually rejected since a very small value of α_s is not the primary concern to this program. Also, it was felt the process required some additional testing in order to verify its performance in space. For application to louver systems where incident sunlight is a serious problem, this process merits examination.

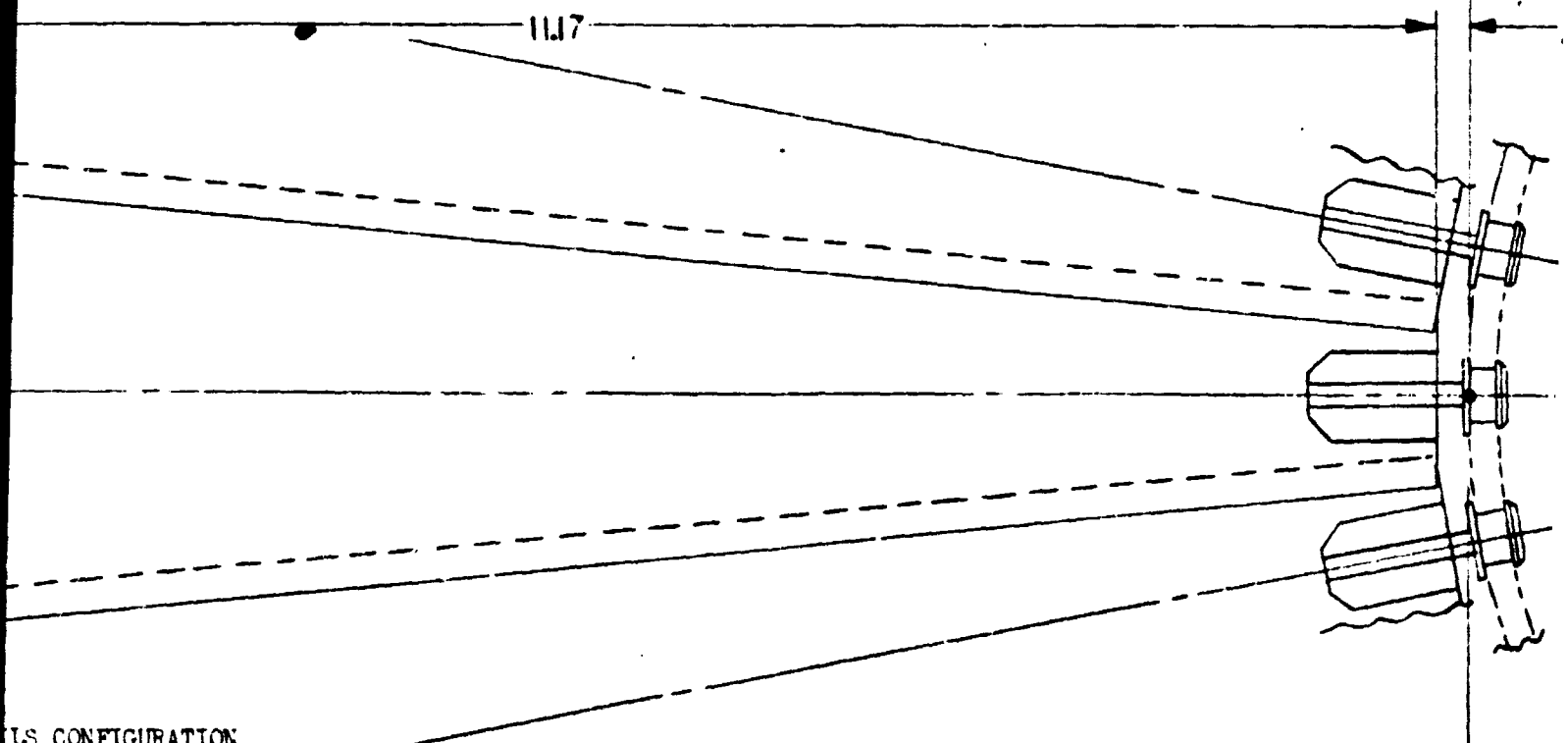
The heat conductive paths from the platform into the louver blades were minimized in the improved design with the inclusion of an insulator (nylon) between the housing and the platform and in the bearing assembly between the metal shaft lip and the metal support ring. The center support ring was made from fiberglass rather than aluminum in order to reduce heat conduction into that end of the blade.



45-A



ER CONFIGURATION

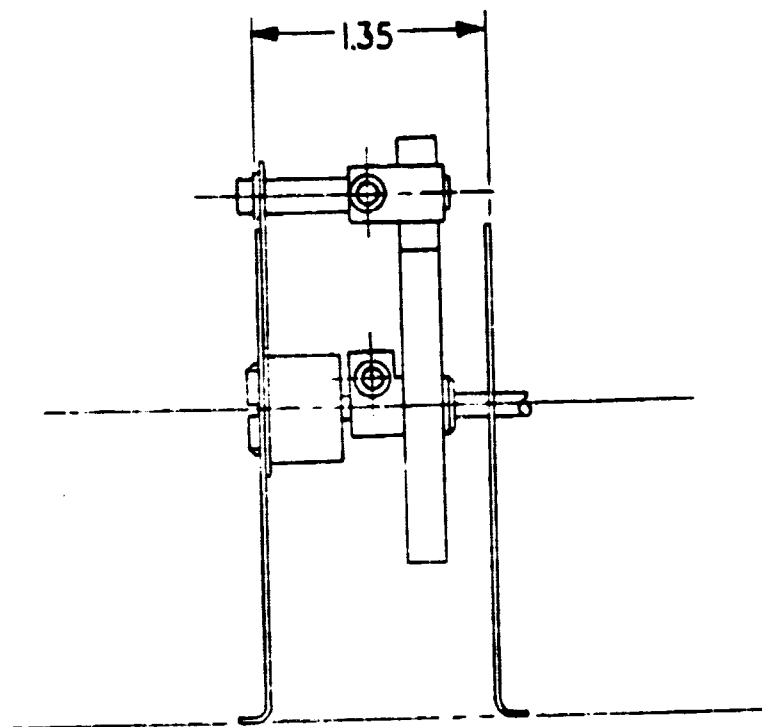


LS CONFIGURATION

FIGURE 3.6
LOUVER BLADE INSTALLATION

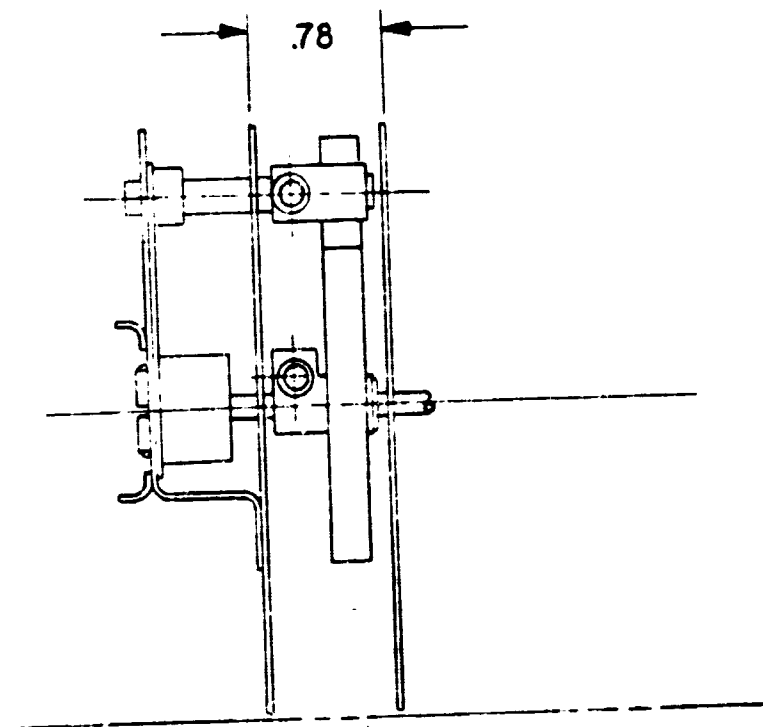
45-B

.22



SECTION A-A

.19



SECTION B-B

45-C

Single piece batts (15 layers of crinkled aluminized Mylar) were used to insulate the actuator housing and the center support ring. Care was taken to avoid compression areas and to provide areas for effective venting. A completely insulated unit ready for test is shown in Fig. 3-5.

3.3 Predicted Thermal Performance Characteristics

The prediction of effective emittance in a closed condition is clouded by two major factors. First, the heat leaks are small, difficult to estimate, but will have a significant influence on the effective emittance. It is virtually impossible, for example, to obtain a meaningful estimate of the effect of conductivity isolation of the louver blades from the platform. The second confusion factor is the unknown heat leak in the preliminary test work. While residual gaseous conduction is suspected, sufficient evidence is not available to rule out other considerations. Consequently, estimates of the closed emittance must assume the presence of this leak on the modified configuration.

Computed heat leaks for the improved (larger) louver system are shown below using three different preliminary test results as the bas's:

TABLE 3-1
PREDICTED CLOSED EMITTANCE -
IMPROVED CONFIGURATION

<u>Item</u>	<u>Test 3</u>	<u>Test 5</u>	<u>Test 7</u>
1) Measured Power Dissipation (Corrected to 40° F, New Area) Btu/hr	15.21	7.80	4.89
2) Energy Unaccounted For (Corrected to 40° F, New Area) Btu/hr	3.45	5.01	2.72
3) Louver Surface Δ , Btu/hr	0.18	0.15	0.42
4) Edge Losses Δ , Btu/hr	0.31	2.17	2.17
5) Side and Column Δ , Btu/hr	-1.09	-1.12	0
6) End Gaps Δ , Btu/hr	-0.97	+0.72	+0.72
7) Actuator Δ , Btu/hr	-5.03	0	0

TABLE 3-1 (Continued)
PREDICTED CLOSED EMITTANCE -
IMPROVED CONFIGURATION

<u>Item</u>	<u>Test 3</u>	<u>Test 5</u>	<u>Test 7</u>
Net Energy - Upper Btu/hr	8.43	9.72	8.20
Lower Btu/hr	4.98	4.71	5.48
Effective Emittance - Upper	.102	.118	.099
Lower	.060	.057	.066

The reader is referred to Table 2-4 and to Appendix I for specific identification of the above heat leaks. The large value of $\bar{\epsilon}_{\text{closed}}$ for Test 5 is felt to be caused by an additional loss through the actuator housing; results of Tests 3 and 7 are in good agreement.

Introduction of high conduction resistance between the platform and the blade is estimated to cause a $\Delta\bar{\epsilon}$ of approximately 0.01; the estimated emittance of the unit is, therefore, expected to be between 0.09 and 0.06, depending on the cause of the unaccounted-for energy in the preliminary test model and whether or not this effect has been eliminated in the improved test model.

As estimate of the effective emittance of the improved louver system in the open position is given in Appendix II. Based on 0.040" thickness blade, platform emittance of 0.88 and a blade reflectance of 0.96, the open position emittance is expected to be 0.83. Note that this point is not on the prediction curve of Fig. II-1 but displaced downward to account for the disagreement with experiment on the PIONEER system. The analysis is admittedly approximate, requiring a number of simplifying assumptions for solution. It should, however, provide an accurate measure of the relative effects of platform emittance, blade thickness, blade coating, etc.

4.0 THERMAL TESTS OF IMPROVED LOUVER SYSTEM

Thermal-vacuum tests were then conducted to determine the effective emittance of the improved louver system as a function of blade angle (0° closed, 90° open). Approximate platform temperature at each angle was selected based on the spring-angle calibration data reported in Ref. 1 (for purposes of this test a zero spring to platform temperature difference was assumed). The conduct and results of these tests are presented in this section.

4.1 Test Model

The test model utilized in the tests of the improved system was basically the same as the modified unit used for Tests 6, 7 and 8 (Section 2.2). The difference was, of course, the installation of the improved louver system consisting of a unit actuator housing, beryllium blades (coated with vacuum deposited aluminum), a fiberglass center support ring and the required insulation of these items. The platform was coated with S-13G white paint ($\alpha_s = .19$, $\bar{\epsilon} = .88$). A photograph of the improved configuration ready for test is shown in Fig. 3-5.

Instrumentation locations on the test model were identical to those used in Tests 6, 7 and 8 (Table 2-1).

4.2 Test Procedure

A total of four thermal tests were conducted on the improved louver system using the following combination of louver angles and approximate platform temperatures:

TABLE 4-1: LOUVER ANGLES - IMPROVED SYSTEM TESTS

<u>Test No.</u>	<u>Louver Angle</u>	<u>Platform Temperature</u>
II-1	90° (Open)	85°F
II-2	60°	70°F
II-3	30°	55°F
II-4	2°	40°F

TABLE 4-2: SUMMARY OF RESULTS IMPROVED SYSTEM TESTS

T/C No.	Location	Test II-1	Test II-2	Test II-3	Test II-4
1	Platform	81.0	67.9	53.8	50.1
2	Platform	—	—	—	—
3	Platform	83.6	69.4	53.9	49.6
4	Platform	83.3	68.8	53.1	49.9
5	Guard Heater (Bottom)	84.1	66.3	55.1	49.6
6	Guard Heater (Bottom)	—	—	—	—
7	Guard Heater (Bottom)	83.9	66.3	55.1	49.6
8	Fence - Right Side	58.6	62.6	48.7	34.9
9	Fence - Left Side	51.0	35.6	20.3	19.5
10	Side Guard - Housing End	58.8	49.2	40.5	29.5
11	Louver Blade	29.6	16.7	4.2	3.0
12	Center Support Ring	72.6	72.4	72.6	72.5
13	Side Guard - Left Side	57.0	47.9	39.3	27.7
14	Side Guard - Support Ring	58.0	48.2	39.7	28.7
15	Side Guard - Right Side	58.3	48.8	40.1	28.7
16	Louver	—	—	—	—
17	Louver	19.5	7.8	-6.5	-10.3
18	Louver	26.5	14.6	0.9	-5.2
	TC Wire Bundle	82.1	64.3	55.4	44.8
	Platform Heater Power*, Watts	31.1	23.1	10.95	2.47
	Chamber Pressure, mm Hg.	9×10^{-5}	9×10^{-5}	8×10^{-5}	7×10^{-5}

* Recorded value (uncorrected for lead-in losses)

The louver angle desired for a particular test was adjusted manually prior to the test and held in place during measurements with a wad of cotton in the bearing assembly attached to the actuator housing. The angle was checked before and after each run to insure no change occurred during the test. This procedure was selected in preference to permitting the free spring movement so that $\bar{\epsilon}$ versus θ data would be obtained directly and can be easily extrapolated to springs having different temperature-angle relations. The procedure also insured the same angular setting for each blade. Platform temperatures during the test followed only approximately the above table.

In the construction of the improved louver test model, allowance in the blade movement was not made for the finite blade thickness. Consequently, the large end of the blade did not close when the small end was mated; the angular setting of the blade in this position was approximately 4° . Slight reduction of this angle (to 2°) was achieved by holding the large end of each blade to the next with a small piece of Mylar tape. Measured angles for all five blades averaged about 2° . Note that this problem can be easily eliminated by offsetting the height (above the platform) of each blade assembly by an amount equal to the blade material thickness. It was necessary, however, in the tests reported in this section to extrapolate the results to a louver angle of 0° .

Procedures concerning the conduct of the tests and the recording of data were otherwise identical with those outlined in Section 2.4.

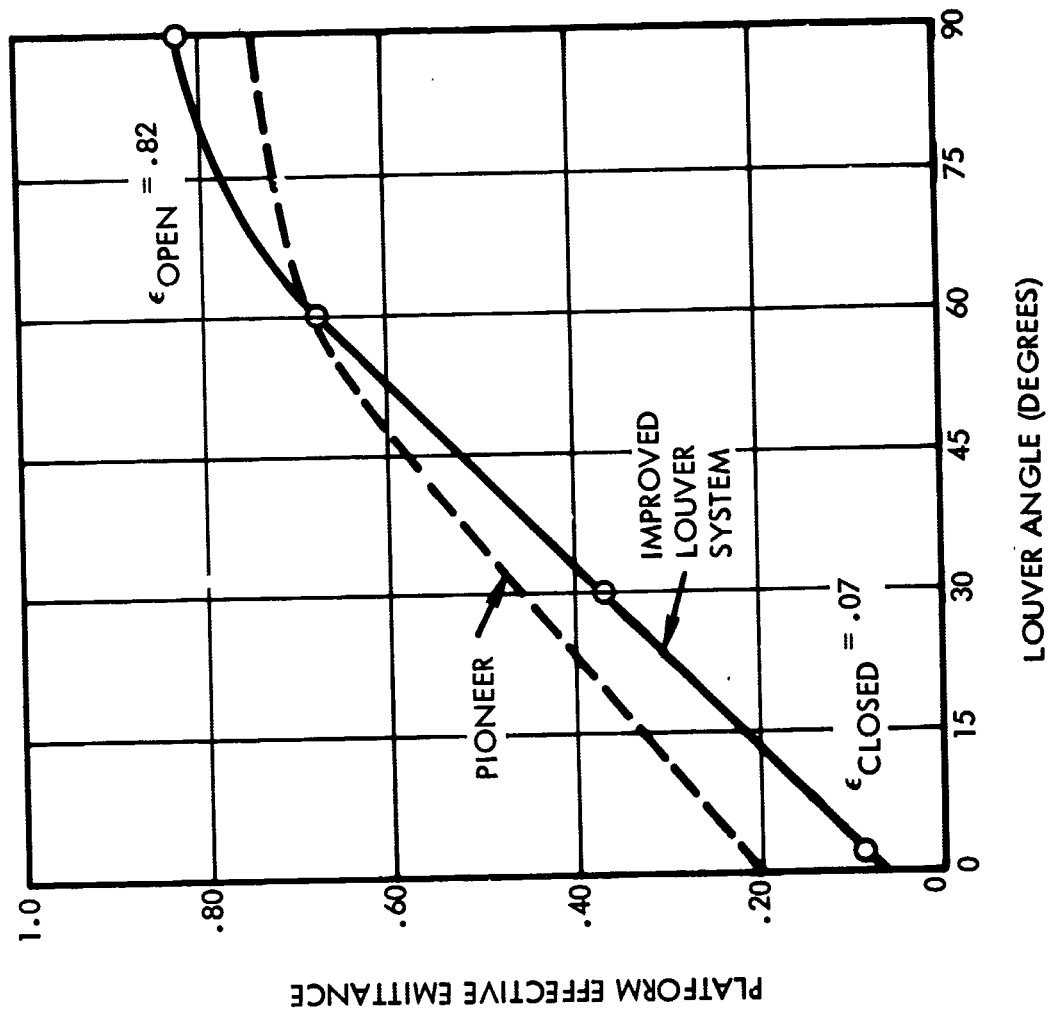
4.3 Results

The steady-state temperature and electrical power input data for each of the improved PIONEER louver system tests are presented in Table 4-2. The resultant effective emittance data are shown in Fig. 4-1 as a function of louver angle and are compared with similar data from tests on the present system. An open emittance of 0.82 was obtained with the beryllium blade/unit actuator housing configuration and the value in the closed position was 0.07 (extrapolated from the 2° test value). The dynamic range (open to closed ratio) was 11.7. Comparable data for PIONEER are 0.74 (open $\bar{\epsilon}$), 0.20 (closed $\bar{\epsilon}$) and 3.7 (ratio).

Agreement between experimental results and predicted values of emittance (Section 3.3, Appendix II) is remarkable in both positions in spite of the many assumptions required in the analysis. For the most part, this agreement is a testimony to the repeatability of the many factors making up the so-called heat loss rather than to the rigor of the analysis.

The heat loss criteria used on the preliminary test results (1 - 8) were also applied to the closed position test (II-4) of the improved system. Assuming a) the mating loss was identical to preliminary tests, b) a 50% reduction in the edge losses, and c) no loss through the actuator housing, it is possible to account for only about 2/3 of the total energy input for Test II-4. Using the gaseous conductance factor estimated in Section 2.5 ($\bar{c} = 0.00716$), the heat balance discrepancy for Test II-4 is reduced to less than 10% lending additional support to the theory that gaseous conduction accounts for a significant amount of the test heat leak. Deducting this factor from the present $\bar{\epsilon}$ of 0.07 would produce a closed position emittance of 0.045. This value is not claimed in the presentation of these results; additional testing would be required for verification or rejection of this factor.

FIGURE 4-1:
THERMAL PERFORMANCE
IMPROVED LOUVER SYSTEM



5.0 CONCLUSIONS AND RECOMMENDATIONS

The test results for the improved louver assembly demonstrated a significant improvement over the thermal characteristics of the present PIONEER system. Effective emittances of 0.82 in the open position (vs .73 for PIONEER) and 0.07 in the closed position (0.20 - PIONEER) were measured. A fully qualified flight unit for application to the basic PIONEER configuration using the unit housing/single piece beryllium blade concept is expected to have similar properties provided sufficient care is taken to obtain effective housing insulation, reduced end gap spaces and conduction decoupling of the blade from the radiating platform. The flight unit (30 blade set) will weigh approximately one pound more than the present system.

Potentially, an additional improvement (reduction) in the closed condition properties is possible. A balance of measured power input and calculated thermal output from the test article could not be obtained. The prime suspect for the unaccounted-for energy in this balance was residual gaseous conduction in the test chamber. Since this factor will not be present in actual space conditions and since its elimination could result in a closed emittance as low as 0.045, additional testing of the improved louver experimental unit in a vacuum chamber capable of 10^{-6} mm Hg is suggested as future work.

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APPENDIX I - Analytical Estimate of Heat Leaks -
Initial Test Model

The physical arrangement of the initial test model is expected to minimize all but the following heat paths from the platform to space;

- radiation exchange with the louver plate,
- conduction exchange with louver plate,
- edge losses (due to mismatching of louver edges),
- end losses (through gaps at each end of the blades),
- actuator housing losses,
- side fences (due to ineffective insulation and radiation from interior facing sides), and
- end column (ditto side fences for center support ring).

This section outlines the calculation procedure for estimating these losses.

Exchange with Louver Plate

Both radiation and conduction exchange between the platform and the louver plate must be ultimately radiated to space by the plate. These losses (q_L) can, therefore, be expressed as

$$q_L = \bar{\epsilon}_L A_L \sigma \left[\bar{T}_L^4 - T_{cw}^4 \right] \quad (I-1)$$

where $\bar{\epsilon}_L$ = louver surface hemispherical emittance (~ 0.035)
 A_L = louver surface area (0.71 ft^2)
 $\bar{T}_L$ = average louver surface temperature
 T_{cw} = cold wall temperature

For the range of test conditions encountered, T_{cw}^4 is negligible relative to $\bar{T}_L^4$ and Eqn. (I-1) reduces to

$$q_L = 0.0248 \sigma \bar{T}_L^4 \text{ (Btu/hr)} \quad (I-2)$$

Edge Losses

Based on the results of Tests 2 and 3, the radiant heat loss due to mismatch of the louver blade edges is

$$q_E = 15.21 \left[\frac{108.1}{107.1} \right] - 13.42 \left[\frac{106.5}{107.1} \right] = 2.06 \text{ Btu/hr} \quad (\text{I-3})$$

The ratios 106.5/107.1 and 108.1/107.1 are used to correct for variances in platform temperature and references everything to 40°F.

End Gaps

Based on the results of Tests 1 and 2, the end gap losses are

$$q_G = 13.42 \left[\frac{106.5}{107.1} \right] - 11.84 \left[\frac{105.3}{107.1} \right] = 1.69 \text{ Btu/hr} \quad (\text{I-4})$$

corrected to 40°F platform temperature.

Actuator Housing Loss

Using the results of Tests 4 and 5, and correcting to 40°F platform temperature

$$q_A = 12.40 \left[\frac{109.5}{107.1} \right] - 7.80 \left[\frac{103.8}{107.1} \right] = 5.03 \text{ Btu/hr} \quad (\text{I-5})$$

Side Fences

Assuming an average emittance of 0.05 for the aluminum shield, this heat leak estimate becomes

$$\left. \begin{aligned} q_s &= .0146 \sigma \bar{T}_s^4 && \text{for Tests 1 - 4} \\ q_s &= .0107 \sigma \bar{T}_s^4 && \text{for Test 5} \\ q_s &= 0 && \text{for Tests 6, 7 and 8} \end{aligned} \right\} \quad (\text{I-6})$$

The difference between Tests 4 and 5 results from a reinsulation of the external facing area. The configuration was altered between Tests 5 and 6 to minimize this factor (see Section 2.0).

End Column

Using an assumed emittance of 0.2 for the metal support ring, this loss becomes

$$\left. \begin{array}{ll} q_c = 0.00102 \sigma \bar{T}_c^4 & \text{for Tests 1 - 5} \\ q_c = 0 & \text{for Tests 6 - 8} \end{array} \right\} \quad (I-7)$$

Again the differences result from a complete reinsulation of this section between Tests 5 and 6.

The above losses have been computed for each of the eight tests and are presented in Table 2-4, Section 2.0.

APPENDIX II - Analytical Predictions of the Effective Emittance of an Open Louver System

Figure II-1 shows a cross-sectional view of two blades in the present PIONEER louver system. Because of the trapezoidal nature of the blades, the dimensions a, b, c, d and t vary with distance along the blade making detailed evaluation of the radiative paths extremely difficult. For purposes of simplification the configuration dimensions were assumed constant with length and were taken to be the half-way values of the PIONEER system. Additional assumptions include:

- o Louver blades and radiator surfaces are infinite in extent.
- o Louvers reflect specularly and emit diffusely.
- o Radiator surface reflects and emits diffusely.
- o All surfaces are grey in the wavelengths of interest.
- o Each surface is isothermal.

The subsequent equations were extracted from TRW reports by B. R. Loya and E. B. Robinson.

The effective emittance (ϵ^*) of a louver system can be written

$$\epsilon^* = \epsilon_R \left(1 - \frac{H_{L,R}}{\sigma T_R^4} \right) \quad (\text{II-1})$$

where ϵ_R = radiator surface emittance
 $H_{L,R}$ = infrared energy emitted by louvers and impinging on radiator ($H_{L,R}$)_E, plus the energy emitted by the radiator to the louvers and reflected back to the radiator ($H_{R,R}$)_B.
 T_R = radiator surface temperature

The energy emitted by the louvers and incident on the radiator is given by

$$(H_{L,R})_E = 2 \epsilon_L \sigma T_L^4 \sum_{n=0}^{\infty} \rho_L^{2n} F_{R'-L1} (L_2^n, L_1^n) + \sum_{n=1}^{\infty} \rho_L^{2n-1} F_{R'-L1} (L_1^n, L_2^{n-1}) + F_{R-B} A_R \quad (II-2)$$

where ϵ = emittance (infrared)
 ρ = reflectance (infrared)
 F = view factor
 A = area

The subscript L refers to the louver surface, R to the radiating area and R' to the displaced radiating area (see Fig. II-1). The factor F_{R-B} is the view factor from the radiator to the bottom edge of the louver. The term $F_{R'-L1} (L_1^n, L_2^n)$ is the angle factor of surface L1 after "n" reflections in surfaces L1 and L2; initial energy from R emitted directly to L1. The term $F_{R'-L1} (L_1^n, L_2^{n-1})$ considers the angle factor to L1 after "n" reflections with initial energy from R reaching L1 via reflection from L2. For a treatment of specular reflections see Refs. 8, 9 and 10.

Infrared energy leaving R and reflected back via the bottom of the louvers is given by

$$(H_{R,R})_B = 2\rho_L F_{RB} \epsilon_R \sigma T_R^4 + \rho_R H_{L,R} \quad (II-3)$$

where all terms have been defined previously. The factor $\rho_R H_{L,R}$ simply relates that energy initiated at the louver surface, arriving at the radiator and reflected back to the louver surface. Then $F_{RB} \rho_R H_{L,R}$ will reach the bottom of the louver surface and $\rho_L F_{RB} H_{L,R}$ will be returned to the radiator.

Letting

$$\delta_1 = 2 \sum_{n=0}^{\infty} \rho_L^{2n} F_{R'-L1} (L_2^n, L_1^n) \quad (II-4)$$

$$\delta_2 = 2 \sum_{n=0}^{\infty} \rho_L^{2n} F_{R'-L1} (L_1^n, L_2^{n-1})$$

and combining Eqns. II-1, II-2 and II-3 gives

$$\epsilon^* = \epsilon_R \left[1 - \frac{\epsilon_L (2F_{R-B} + \delta_1 + \delta_2) \left(\frac{T_L}{T_R}\right)^4 + 2\rho_L F_{R-B}}{1 - 2\rho_L \rho_R F_{R-B}} \right] \quad (II-5)$$

Since

$$F_{R-B} = 2 \frac{1}{2} \frac{t}{a}$$

and

$$A_{R'} = \frac{d}{a} A_R$$

Equation II-5 can be written in terms of the dimensions on Fig. II-1:

$$\epsilon^* = \epsilon_R \left[1 - \frac{\epsilon_L \left(\frac{t}{a} + \frac{d}{a} (\delta_1 + \delta_2) \right) \left(\frac{T_L}{T_R}\right)^4 + \rho_L \frac{t}{a}}{1 - \rho_L \rho_R \frac{t}{a}} \right] \quad (II-6)$$

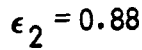
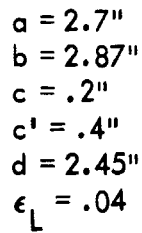
Forming a heat balance involving the radiator, louver blades and space, it is possible to show that T_L/T_R is approximately 0.81 for a wide range of geometric conditions. Also, the sum $(\delta_1 + \delta_2)$ turns out to be a function only of the ratio d/b ; in the case of d/b of 0.729 (2.45/2.87) this term is 1.09.

Using the geometric and reflectance data shown in Fig. II-1, an effective open emittance of 0.76 was calculated for PIONEER which is in good analytical agreement with the experimental value of 0.743. To a good approximation, Eqn. (II-6) gives values of ϵ^* directly proportional to the radiator emittance (ϵ_R). Also, for fixed values of ϵ_L , a and d/b (per Fig. II-1), the equation reduces to

$$\frac{\epsilon^*}{\epsilon_R} = 1 - \frac{.9772 t/a + .0137}{1 - .96 \rho_R t/a} \quad (\text{II-7})$$

Also shown in Fig. II-1 is a plot of this function for the measured platform emittance of 0.88.

Using the discrepancy between calculated and measured data for the present PIONEER louver system and correcting for the ratio of platform emittances (0.88/0.85), the predicted open emittance of the improved louver system is 0.83. It should be noted that the equations developed in Appendix II are highly idealized and are primarily useful in showing trends; i.e., the effect of varying blade thickness, platform coating, blade coating, etc., rather than in absolute predictions of louver system open emittance.



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