The results of thermal analyses performed on the Apollo 14 LRRR to determine operating temperature levels and heat exchange between the Array and Structure Assembly are contained herein. Thermal design adequacy of the revised LRRR configuration is analytically confirmed by a favorable comparison with the Apollo 11 LRRR thermal/optical performance and by conformance to Exhibit B-1, "Design and Performance Specification for Laser Ranging Retro-Reflector Experiment", revised 30 March 1970. The thermal analysis of the Alsep Flight 4 LRRR was authorized under BxA CCP 259 to contract NAS 9-5829.

Prepared by: E. A. Granholm

Approved by: J. L. McNaughton

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

A thermal analysis has been conducted to determine Apollo 14 LRRR operating temperature levels and heat exchange between the Array and Structure Assembly for the Fra Mauro (W 17.5°, S 3.7°) deployment site as defined by Reference 1. Long term LRRR temperature control is passively achieved with Z-93 white inorganic coating, the identical thermal design concept described in Reference 2 for the Apollo 11 LRRR.

Thermal re-evaluation of the LRRR was necessitated by major mechanical design changes in the Structure Assembly to reduce weight and utilization of the 6° corner retaining ring to lessen optical obscuration. Radiation view factors and hence, net heat interchange between the Structure Assembly, the Array, the lunar surface and space are affected by the former. Revised values of solar absorptance and infrared emittance at the Array top surface are attibuted to the latter. Figure 1 shows the Apollo 14 LRRR deployed on a simulated lunar landscape.

The aforementioned design changes coupled with deployment at the Fra Mauro landing site make application of Reference 2 results to the Apollo 14 LRRR difficult and at best, somewhat dubious. On this basis, Reference 8 directed BxA to conduct additional detailed thermal analysis to verify the thermal/optical adequacy of the revised LRRR configuration.

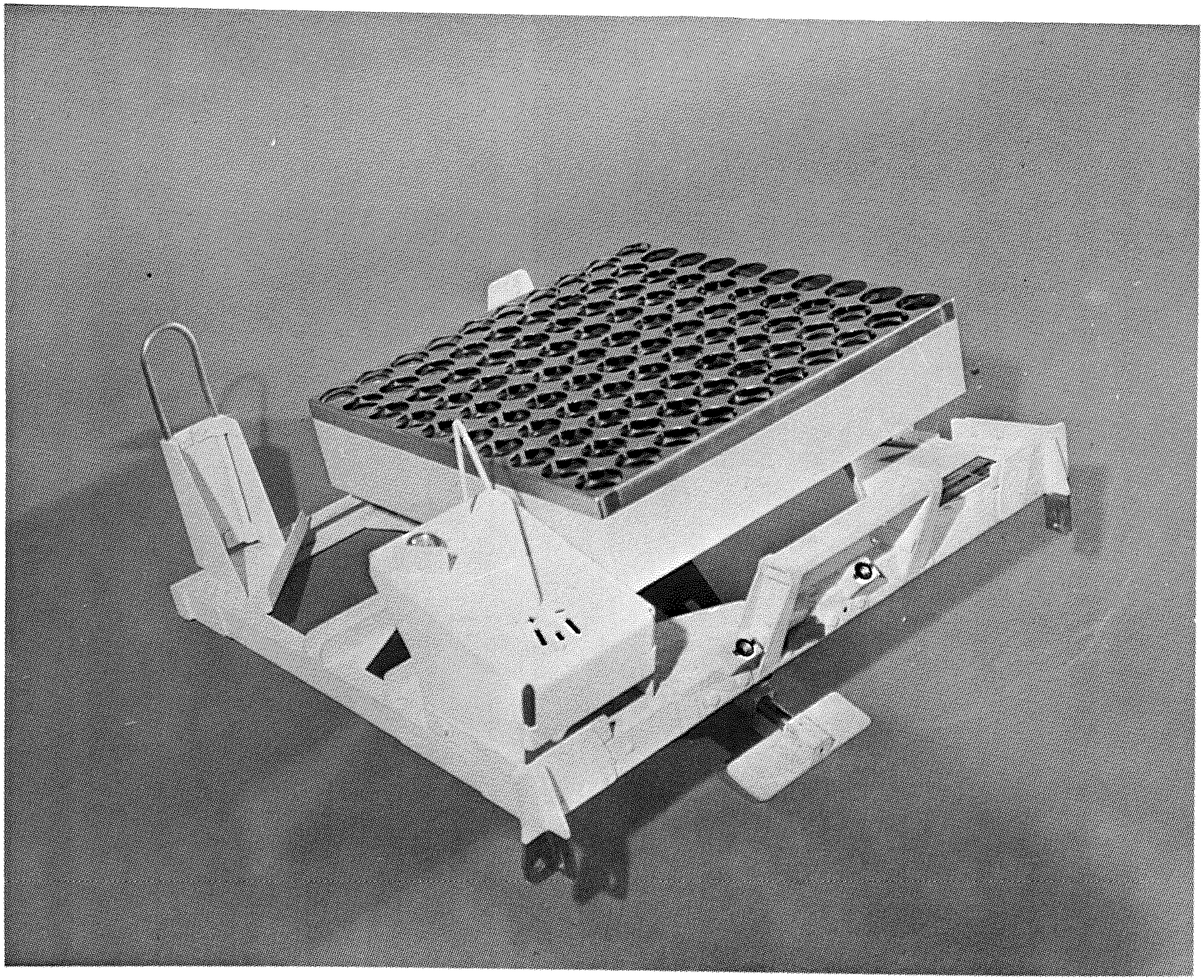


Figure 1 - Deployed Apollo 14 LRRR

2.0 SUMMARY

The results of Apollo 14 LRRR thermal analysis indicate that maximum temperature levels and the maximum heat leak absorbed by the Array from the Structure Assembly are comparable to corresponding Reference 2 values previous reported for Apollo 11. Highlights of the comparison are presented in Table I.

TABLE I

COMPARISON OF THERMAL RESULTS FOR APOLLO 11 AND APOLLO 14

	Apollo 11 LRRR (Array Tilt Angle, $\psi = 34.0°$)	Apollo 14 LRRR (Array Tilt Angle, $\psi = 17.5°$)
Max Array Temp	164°F	183°F
Max Insul Temp	184°F	143°F
Max Struct Temp	90°F	151°F
Max Struct Heat Absorbed by Array	13.5 watts	23.9 watts

Previous Apollo 11 LRRR Thermal/Vacuum qualification testing, described in Reference 3, at temperature levels of 250 ± 10°F and at a surrounding pressure of 5×10^{-6} torr have demonstrated thermal integrity for the Array and Structure Assembly.

Thermal analysis data (Reference 4) were forwarded to ADL so that optical return intensity levels could be determined. The resulting ADL generated relative central irradiance profile meets and exceeds thermal/optical design requirements defined in Paragraph 3.1.5 "Thermal Control" of Reference 5, which is outlined below:

> "The temperature gradient maintained across any reflector during 75% of the lunar cycle... shall be such that the return light intensity... be at least 80%....
> The minimum return at any time during the lunar cycle shall be no less than 30%....

Examination of the Apollo 14 relative central irradiance profile reveals that for approximately 90% of the lunar cycle the optical return is at least 80% and the minimum return at any time is 63%.

3.0 THERMAL ANALYSIS

The analyzed LRRR configuration and modes of heat transfer within the package and from the package to the surroundings are presented in Figure 2. Thermal/optical performance for the LRRR is dependent upon deployment site, solar incidence angle, surface optical properties, and a rather complex heat exchange network between the Array, Structure Assembly, the shadowed and sunlit lunar surface, and space. Long term temperature control is achieved by application of Z-93 white inorganic coating to the Structure Assembly. Multilayer insulation, attached to the lateral and bottom surfaces of the Array, is covered with Beta cloth to provide protection against LM ascent plume heating.

The values of "ϕ" and "θ", also contained in Figure 2, represent solar incidence angles to normals constructed at the lunar and Array surfaces, respectively. The Array deployment angle with respect to the lunar surface is designated as "ψ" and the relationship between the three angles is $\theta = \phi - \psi$. For the Apollo 14 analysis, $\psi = 17.5°$ which corresponds to the Fra Mauro landing site described in Reference 1.

Thermal/optical properties (Reference 2) used in the analysis are presented below in Table II.

TABLE II

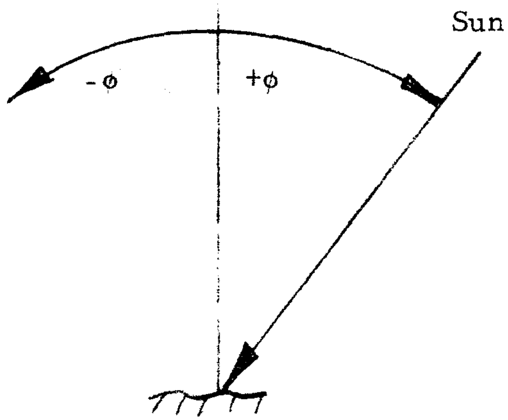
APOLLO 14 LRRR OPTICAL PROPERTIES

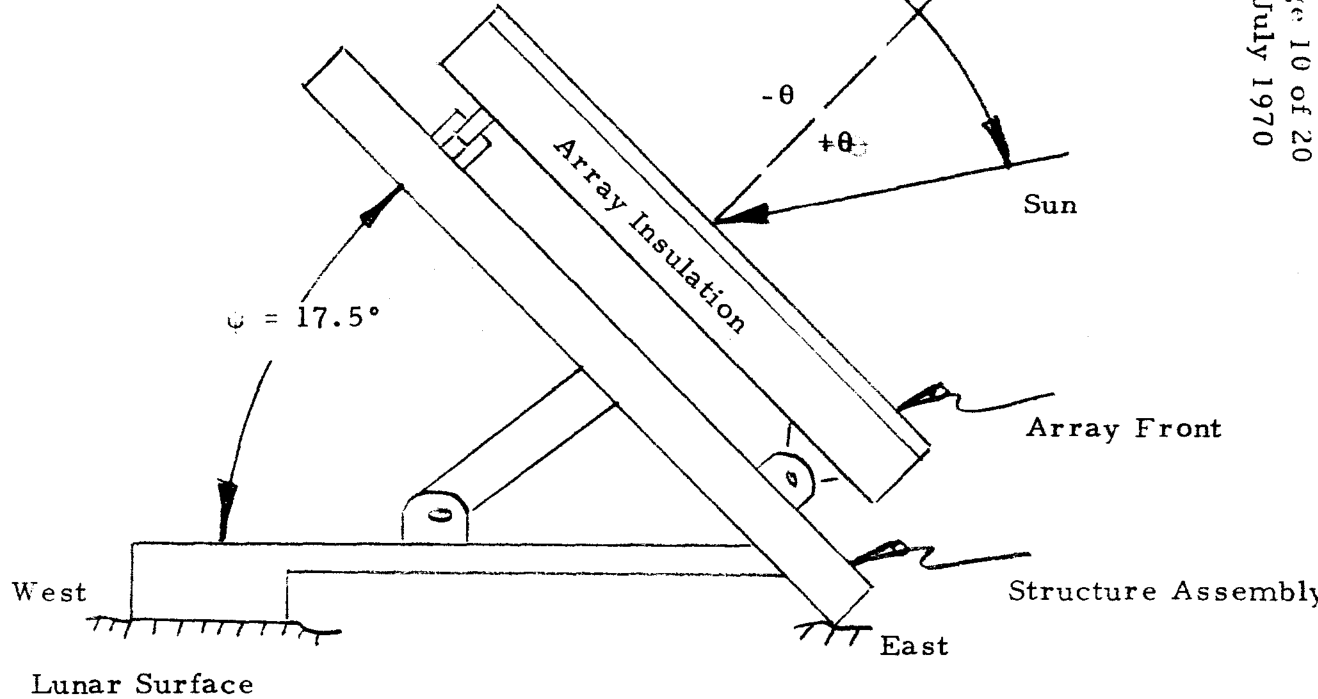
Surface	Material	Solar Absorptance α_s	Infrared Emittance ϵ_{ir}
Structure Assy Surfaces	white Z-93 coating	0.2	0.9
Lateral and bottom Array Surface	heat resistant Beta cloth	0.4	0.86
Lunar Surface	dust	0.9	1.0

Figu

APOLLO 14 LRRR

ANALYZED CONFIGURATION AND COORDINATE SYSTEM





———	Structure Assembly	Array	Lunar Surface	Space
Structure Assembly	———	Conduction Radiation	Conduction Radiation	Radiation
Array	Conduction Radiation	———	Radiation	Radiation
Lunar Surface	Conduction Radiation	Radiation	———	Radiation
Space	Radiation	Radiation	Radiation	———

MODES OF HEAT TRANSFER

Optical properties of the Array top surface are dependent upon solar incidence angles and are depicted in Figure 3. The Apollo 14 LRRR has been improved by a revised cavity design to reduce optical obscuration. The modification consists of a 6° tapered corner retaining ring as opposed to the 1-1/2° ring previously employed for Apollo 11. The difference in optical properties, as displayed in Figure 3, can be attributed to the improved optical design.

The lunar cycle was assumed to be sufficiently long (29.5 days) so that boundary conditions were considered constant which enabled steady-state thermal analysis techniques to be employed. Eight solar angles of particular interest such as the corner break-through points, array noon, etc, were individually investigated by using the "quasi" steady-state approach.

The LRRR mathematical model contains 15 nodal points to define the Structure Assembly and Array. Dimensions and materials used in determining the modified structure thermal resistances were obtained from the Reference 6 drawing. Boundary conditions, reflecting the lunar thermal environment, were represented by three nodal points — the shadowed lunar surface, the sunlit lunar surface and space. LRRR radiation interchange factors to the shadowed and sunlit portions of the lunar surface were calculated at each solar angle investigated. Lunar surface temperature levels were obtained by utilizing the "Average" ($\gamma = 750$) temperature profile presented in Reference 7.

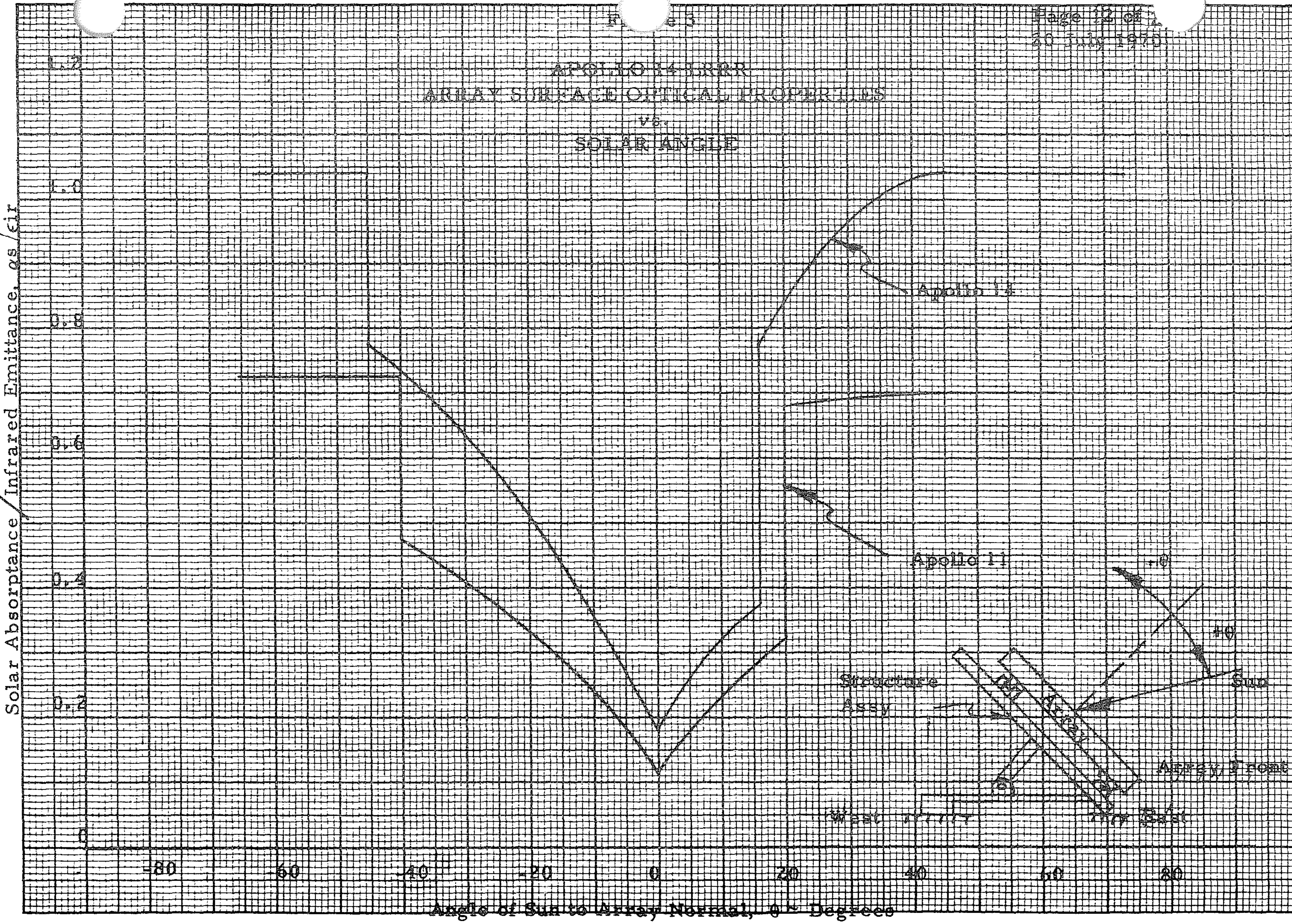


Figure 3
APOLLO 14 LRRR
ARRAY SURFACE OPTICAL PROPERTIES
vs.
SOLAR ANGLE
Solar Absorptance/Infrared Emittance, αs/εir
1.2
1.0
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80
Angle of Sun to Array Normal, θ ~ Degrees
Apollo 14
Apollo 11
+θ
-θ
Sun
Structure
Assy
Array
Array Front
West
East

4.0 RESULTS

Highlights of the Apollo 14 LRRR Thermal analysis are summarized in Table III. The table presents the solar angles at which thermal analyses were performed, effective optical properties at the Array surface, heat flow absorbed (or rejected) by the Array and pertinent Apollo 14 temperature levels.

The Array and Structure Assembly temperature profiles are given in Figure 4. Maximum temperatures of the Array and Structure are 183°F and 151°F, respectively, Corresponding levels previously reported for the Apollo 11 configuration (Reference 2) are 164°F and 90°F. It is felt that higher solar absorptance and lower infrared emittance associated with the Apollo 14 6 degree retaining ring are the principal contributors to the higher Array temperature.

The higher Structure temperature for the Apollo 14 LRRR results from the revised mechanical configuration to reduce weight. The new structure consists of an open aluminum framework having modified radiation view factors to the Array, lunar surface, and space as compared with the Apollo 11 pallet, which was essentially a continuous plane surface. The higher Apollo 14 structure temperature demonstrates increased radiation heat transfer with the hot lunar surface and reduced radiant transport to space.

Shown in Figure 5 is the heat absorbed by the Array from the structure for various solar angles. The maximum Apollo 14 structure heat leak to the Array is 23.9 watts and the corresponding value for Apollo 11 is 13.5 watts. The increased heat leak is due to two factors—(1) the higher structure temperature as discussed above, and (2) the use of four (4) Array/structure mounting points instead of two (2) connecting points previously employed for Apollo 11. The maximum Structure/Array temperature difference (54°F) and hence, the maximum heat leak occurs at noon time with respect to the Array.

Thermal analysis results were transmitted (Reference 4) to ADL for relative central irradiance determination. Figure 6 presents a direct comparison of ADL generated irradiance data reflecting the structure heating influence on the Array for the Apollo 11 and 14 configurations. Generally, the revised Apollo 14 LRRR represents an improved thermal/optical design, since at most solar angles the optical return is very close to or greater than the Apollo 11 return. The minimum relative central irradiance levels are 0.58 and 0.63 corresponding to Apollo 11 and 14.

TABLE III

APOLLO 14 LRRR
RESULTS OF THERMAL ANALYSIS

Run#	Description	ϕ Deg	θ Deg	Array α_s	Array ϵ_{ir}	Array Q_{Solar} Watts	Array Q_{Cond} Watts	Array Q_{Insul} Watts	Array Q_{Total} Watts	T_{Moon} °F	T_{Insul} °F	T_{Array} °F	T_{Struct} °F
(1)	Prior to Dawn	91	73	0.51	0.49	0	0.409	0.078	0.487	-300	-308	-302	-302
(2)	Lunar Sunrise	90	72	0.51	0.49	48.6	-31.9	-.503	-32.4	-200	-83	-45	-118
(3)	Prior to AM Break Thru	35	17	0.41	0.53	114.6	-14.3	-1.29	-15.5	213	87	183	151
(4)	AM Break Thru	34	16	0.20	0.53	56.3	7.18	-.504	6.68	213	80	117	134
(5)	Array Noon Time	18	0	0.11	0.60	32.1	23.9	.008	23.9	242	87	88	142
(6)	PM Break Thru	-27	-45	0.38	0.49	78.5	-5.01	-.150	-5.16	225	140	151	140
(7)	Post PM Break Thru	-28	-46	0.51	0.49	103.4	-13.8	-.497	-14.3	225	143	180	149
(8)	Lunar Sunset	-90	-108	0.51	0.49	0	9.91	1.33	11.2	-170	18	-81	-59

NOTES:

(1) LRRR Angle of Deployment, $\psi = 17.5°$

(2) See Figure 2 for description of "ϕ", "θ", and "ψ".

Figure 4

APOLLO 14 LRRR
ARRAY AND STRUCTURE ASSEMBLY TEMPERATURE PROFILE

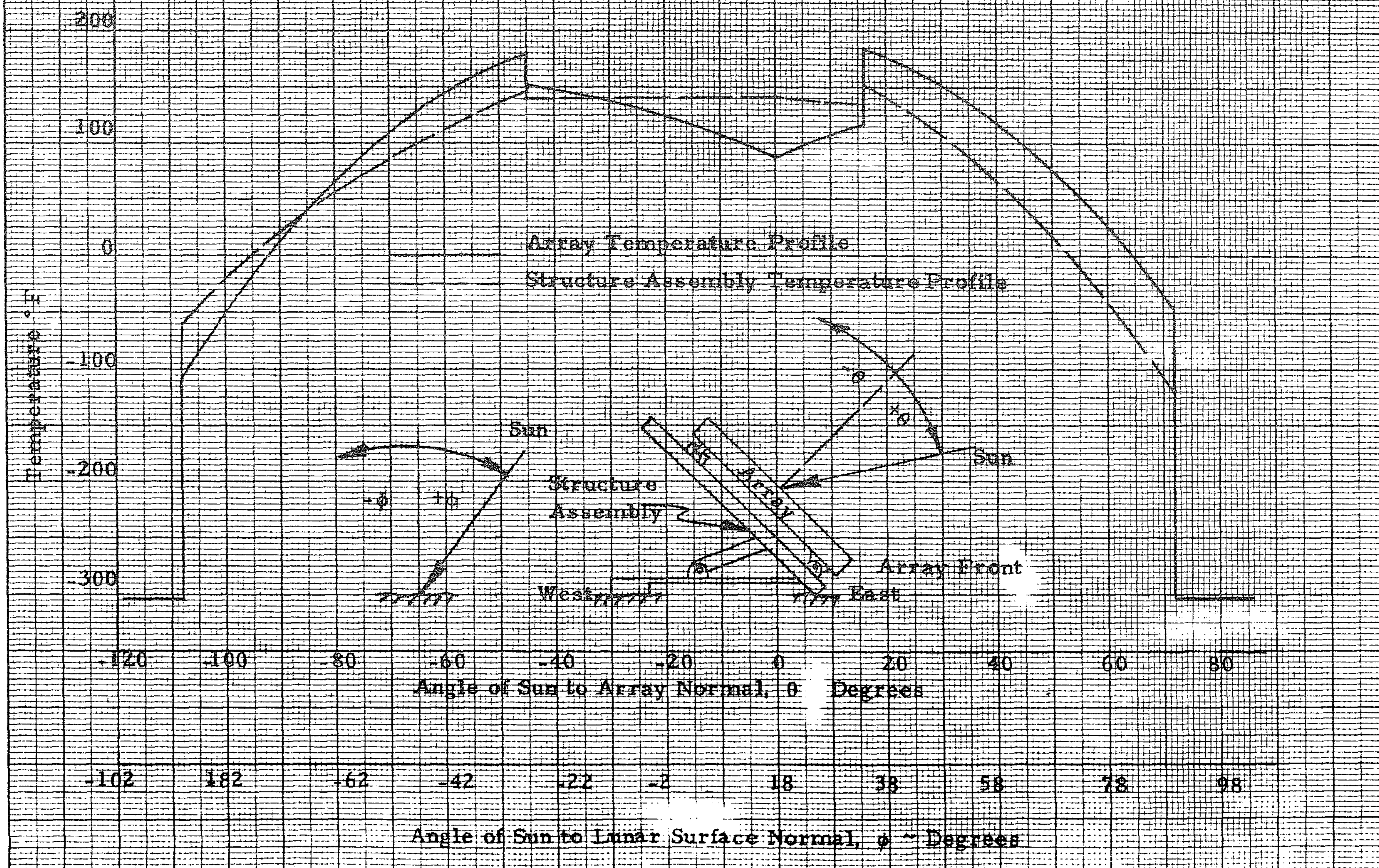


Figure 5

APOLLO 14 LRRR
HEAT ABSORBED BY ARRAY
vs.
SOLAR ANGLE

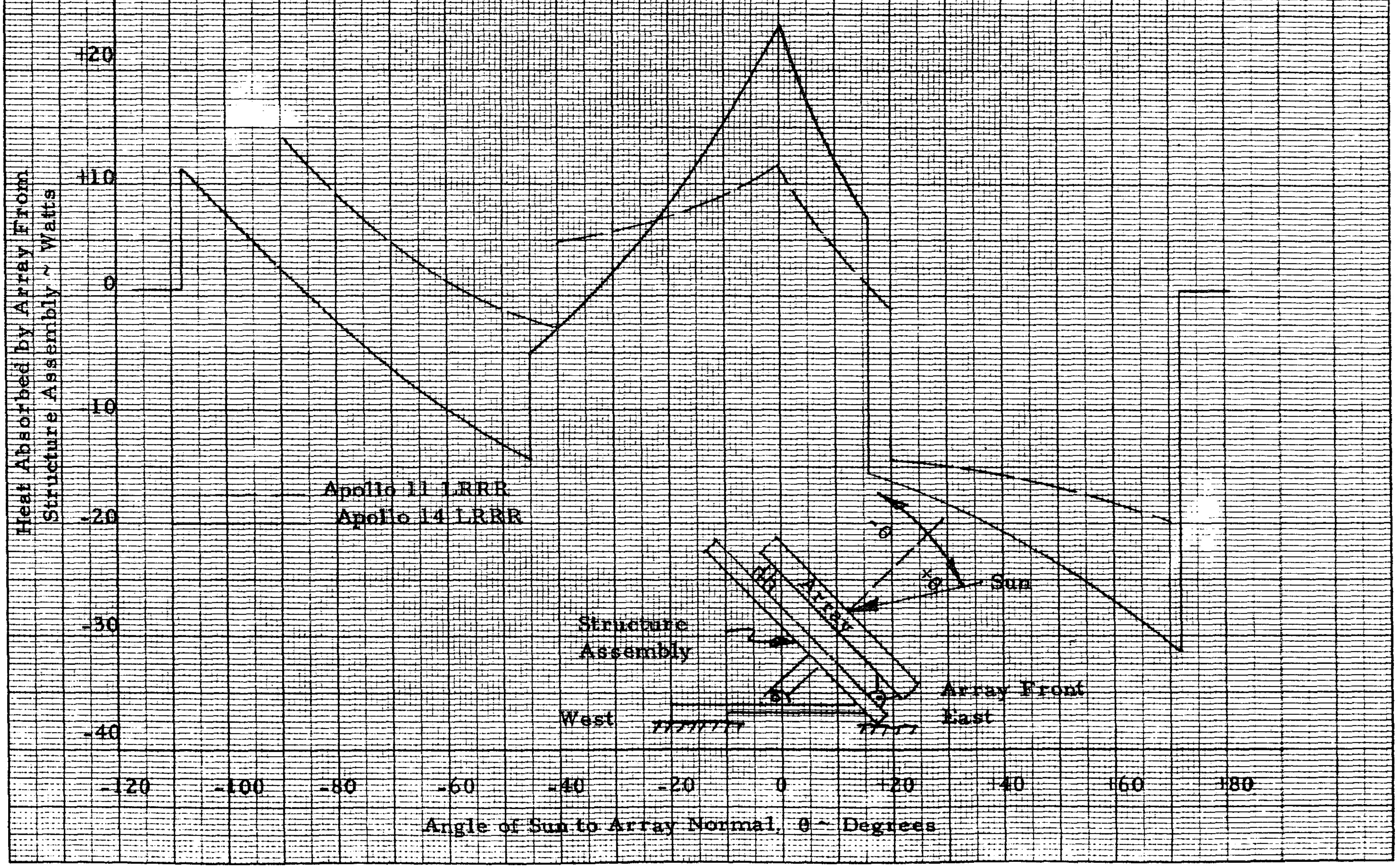
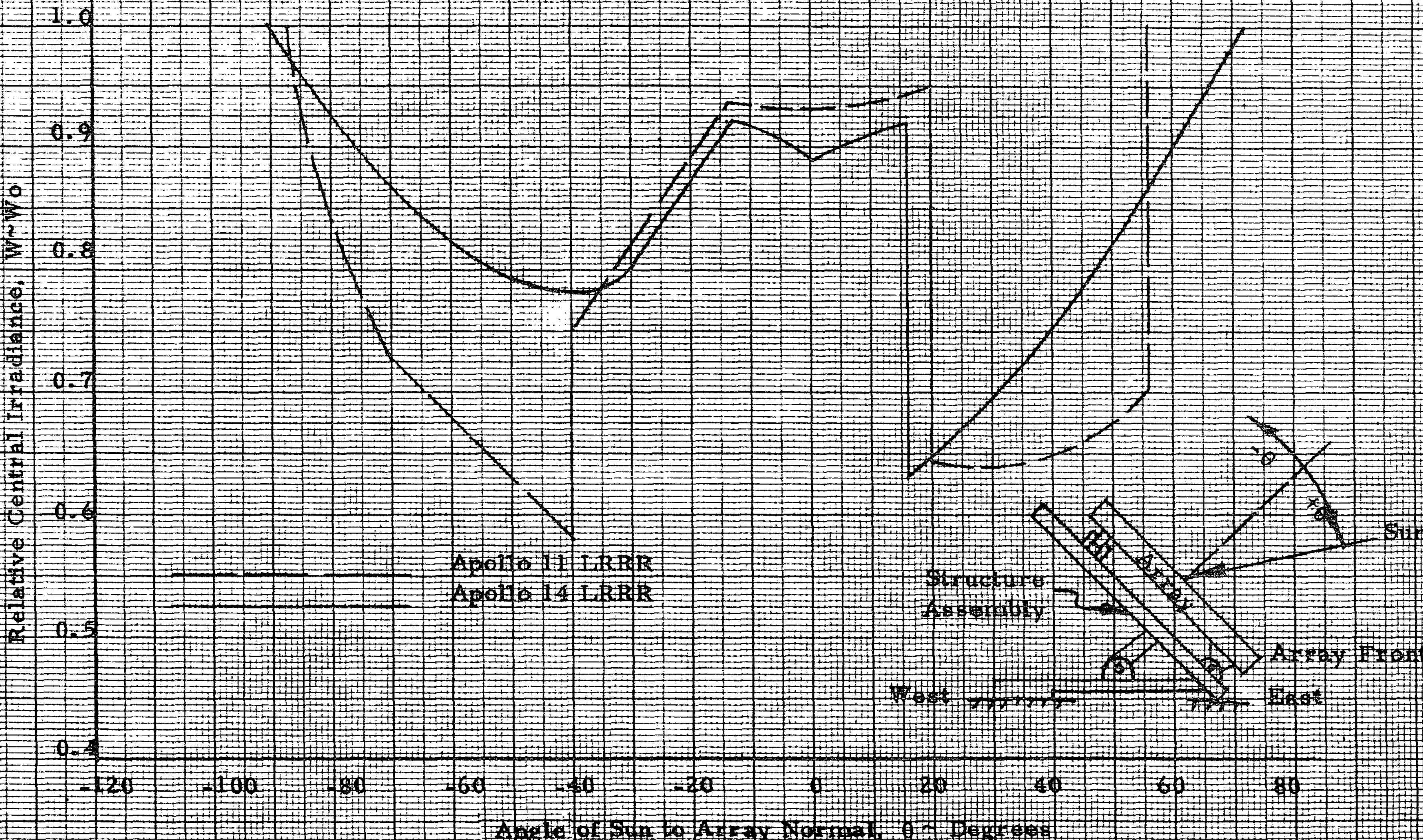


Figure 6

APOLLO 14 LRRR
RELATIVE CENTRAL IRRADIANCE
vs.
SOLAR ANGLE



The optical return at array noon ($\theta = 0°$) for Apollo 14, where heating from the structure of the Array is maximum (23.9 watts), is 0.89. At this point the optical corners are totally reflective and Array solar heating is significantly reduced so that relative central irradiance remains high even with an appreciable heat load from the Structure Assembly. The optical return at array noontime for the Apollo 11 LRRR is 0.93 and the pallet/array heat load is 5.8 watts. There is, therefore, a slight decrease in the Apollo 14 LRRR optical performance at the Array noontime due to increased heating effect of the revised Structure Assembly.

5.0 CONCLUSIONS

The maximum Apollo 14 Array temperature level is 183°F as opposed to 164°F previously reported for Apollo 11. However, the increase is slight and temperatures are well below the acceptable qualification test limit of 250° ± 10°F (Reference 3).

As stated in Section 2.0 (SUMMARY) of this ATM, the revised LRRR meets and exceeds the optical design criteria outlined in Reference 5. For 90% of the lunar cycle the optical return is greater than 80% and the minimum return is 63%.

Therefore, the Apollo 14 LRRR thermal design is adequate and should provide improved long term optical performance at Fra Mauro as compared to the previous EASEP LRRR for Apollo 11.

6.0 REFERENCES

1. Contact Report 9883-951-019, "New Apollo 14 Fra Mauro Site Coordinates", 5-29-70.

2. EATM-61, "Thermal Analysis of the LRRR Array and Support Structure", 2-28-69.

3. EATM-81, "LRRR Qualification Thermal/Vacuum Final Test Report", 4-25-69.

4. Letter No. 70-210-190, "Apollo 14 LRRR, Preliminary Release of Thermal Analysis Data and Results", dated 6-10-70.

5. Exhibit B-1, "Design and Performance Specification for the Laser Ranging Retro-Reflector Experiment", 3-4-70, revised 3-30-70.

6. Drawing number 2345727, "Structure Assembly", 4-30-70.

7. Document No. LED-502-1F "LM Design Criteria and Environments", 5-15-66.

8. JC931/L405-70/T94, "Contract NAS 9-5829, Thermal Analysis of New Mechanical Structure — LRRR, CCP No. 259", 6-19-70.