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BIPROPELLANT ATTITUDE CONTROL ROCKET (ACR) PLUME EFFECTS ON SOLAR CELLS, OPTICS AND THERMAL PAINT

P.J.. MARTINKOVIC

TECHNICAL REPORT AFRPL-TR-70-87

AUGUST 1970

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AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTORATE OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

AFRPL-TR-70-87

BIPROPELLANT ATTITUDE CONTROL ROCKET (ACR) PLUME EFFECTS ON SOLAR CELLS, OPTICS AND THERMAL PAINT

P. J. Martinkovic

FOREWORD

This report summarizes work performed during a USAF in-house program under project 632A00DRI, during the period November 1969 through January 1970.

The program was conducted by the Liquid Rocket Division of the Air Force Rocket Propulsion Laboratory at Test Stand 1-15, Space Chamber Number 4. Mr. Paul J. Martinkovic was the project engineer.

The author gratefully acknowledges the assistance of the following individuals in support of the Bipropellant Attitude Control Rocket (ACR) Plume Effects on Solar Cells, Optics and Thermal Paint: Mr. Dave Massie, Mr. G. M. Kevern and Mr. R. E. Wallis of the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, who conducted the pretest and posttest measurements of the solar cells; Mr. Robert Winn of the Air Force Material Laboratory, Wright-Patterson AFB, Ohio, who conducted the pretest and posttest measurements of the Optics and Thermal Paint.

This report has been reviewed and approved:

DONALD H. CLEGG, Captain, USAF
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ABSTRACT

This report presents the results of the Bipropellant Attitude Control Rocket (ACR) Plume Effects on Solar Cells, Optics and Thermal Paint. The objectives of this effort were to: (1) Determine exhaust plume effects on the functional surfaces of a spacecraft, i.e., a change, if any, in the operational characteristics of this equipment and (2) identify the contaminant. Tests were conducted under vacuum conditions using a Marquardt R1E attitude control rocket engine. The propellants were nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH). The analysis of the test data revealed that the bipropellant attitude control rocket engine exhaust plume does have an effect on the operational characteristics of the spaceborne equipment, in varying degrees, dependent upon the location of the equipment with relation to the rocket engine nozzle exit. The exhaust plume contaminant has been identified as monomethylhydrazine nitrate.

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SECTION I

INTRODUCTION

Attitude Control Rocket (ACR) plume impingement on spacecraft functional surfaces can result in subjecting spaceborne equipment to high exhaust gas temperatures, mechanical effects such as sandblasting, and coating by exhaust contaminants. The degree of damage to spacecraft functional surfaces due to plume impingement is largely dependent upon factors such as: (1) size of the ACR engine, (2) propellants used for engine operation, (3) propellant and engine hardware temperatures, (4) engine pulse width, (5) total engine on-time for a given space mission, (6) location of the spaceborne equipment relative to both the rocket engine nozzle exit and the exhaust plume centerline and (7) temperature of the equipment during plume impingement.

ACR plume impingement on solar cells could physically damage the cell leads and/or the fused silica coverslide due to high exhaust gas temperatures. Moreover, the operational characteristics of the cell can be affected by exhaust contaminant build-up. These adverse conditions can cause deterioration of the power output of the solar cell panels. Exhaust contamination of optics, used for various functions, i.e., telescopes, viewports, and sensor windows used in combination with navigational equipment, can create major problems, such as image distortion, loss of optical transmittance and deterioration of optical anti-reflective coatings. Thermal paint can be degraded, by ACR exhaust impingement, relative to the ratio of solar absorptivity and emissivity. This condition can, in turn, cause thermal problems within a vehicle housing temperature-sensitive components.

An ACR plume contamination program, just recently completed at AFRPL, reference technical document AFRPL-TR-69-251, "Bipropellant Attitude-Control (ACR) Plume Contamination Investigation" has revealed that a brownish viscous material is emitted from the rocket engine nozzle

exit during engine pulsing. This material has been identified as monomethylhydrazine nitrate.

SECTION II

OBJECTIVES

The objectives of this program were to: (1) investigate bipropellant attitude control rocket engine exhaust plume effects, on selected space-borne equipment, i.e., coating, abrasion and/or physical damage, (2) determine degradation, if any, in the operational characteristics of this equipment, and (3) identify the exhaust contaminant.

SECTION III

EXPERIMENTAL PROCEDURE

The solar cells, optics and thermal paint were subjected to a series of bipropellant attitude control rocket engine firings under the low pressure environment. During a test series, in situ measurements were taken at various intervals to analyze contamination trends for correlation with post-test measurements. The test specimens were maintained under the low pressure environment during the entire test phase, and upon completion of each test phase, the test coupons were removed from the altitude chamber under a gaseous nitrogen atmosphere and placed into their respective shipping containers. The test specimens were maintained in this inert environment to minimize atmospheric contamination during shipment to the various laboratories for the post-test measurements.

SECTION IV

TEST FACILITY AND TEST SYSTEM

A. ALTITUDE CHAMBER

The test facility used for these tests was Space Chamber No. 4, located in Test Area 1-15. The altitude chamber (reference Figure 1) is 8 feet in diameter and 13 feet in length and incorporated a 5- by 5-foot cryogenic (LN_2) panel which served a twofold purpose: (1) cryopumping to obtain the high start altitude and (2) the entrapment of exhaust particles to minimize recirculation of the exhaust particles during an ACR firing. The pumping system consisted of two 300-cfm mechanical pumps, a Roots blower rated at 615 cfm and two 10-inch diffusion pumps, each rated at a pumping capacity of 4200 liters per second. The pumping system incorporated three isolation valves to isolate the altitude chamber from the pumping system. Such isolation (1) maintained a vacuum in the altitude chamber during the evening hours and weekends without the pumping system on the line to prevent atmospheric contamination of the test specimens during extended test periods and (2) prevented ingestion of large quantities of propellants by the pumping system in the event of a major failure of the rocket engine and/or the ACR subsystem during tests. The test start altitude and altitude degradation following each rocket engine firing was measured by the use of an Pirani and ion vacuum gage and recorder on a Leeds and Northrup Type "G" Recorder.

B. PLUME SOURCE ACR ENGINE

The ACR engine used for the bipropellant plume contamination tests was a Marquardt R1E engine. Engine technical data are as follows:

Thrust	22 lbs
Nozzle Area Ratio	40:1
Propellants	Nitrogen Tetroxide and Monomethylhydrazine
Chamber Pressure	98 psia

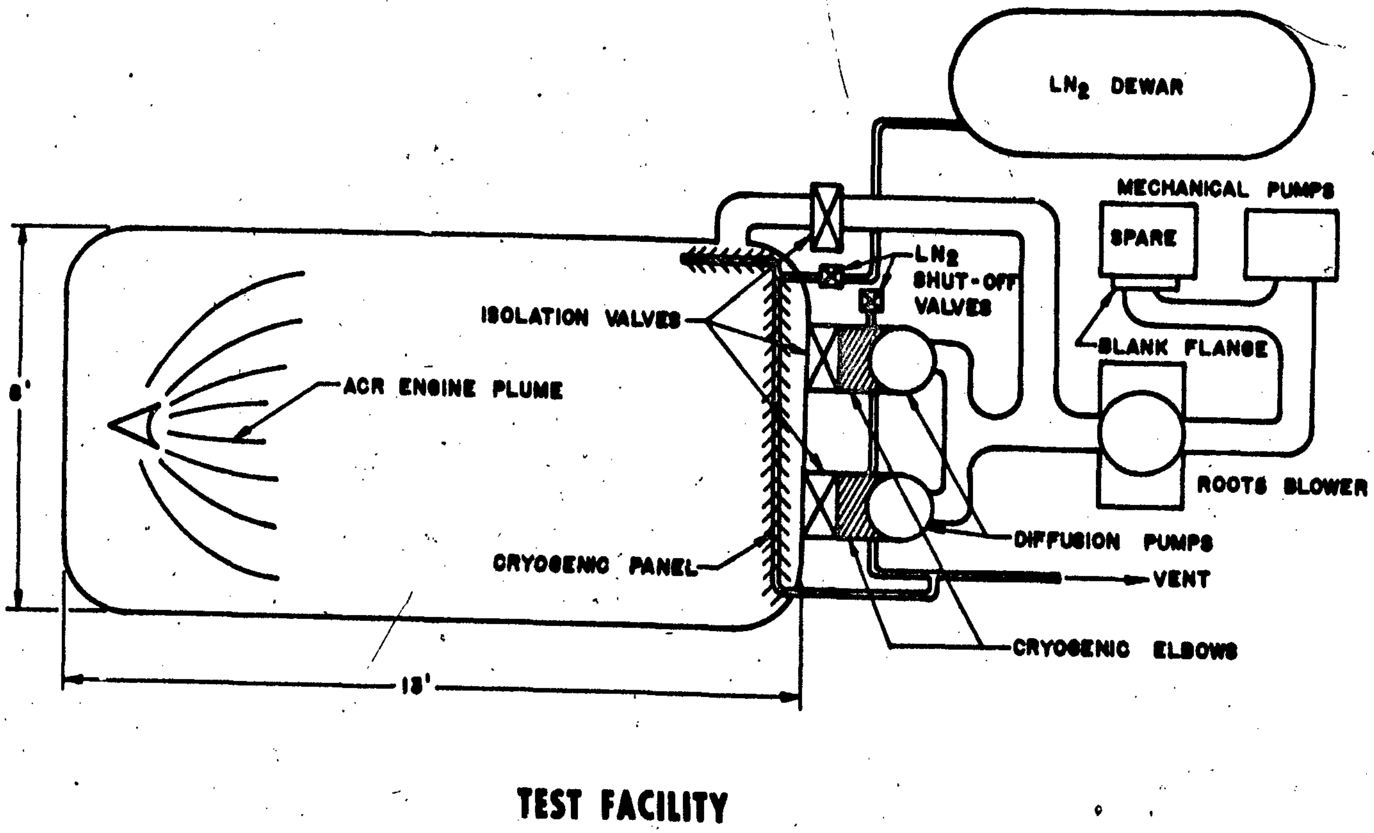

Figure 1. Test Facility

SECTION V

PROBLEM AREAS

During tests two problems were experienced. The first problem that occurred was the loss of a photocell for the number 2 optical coupon shortly after initiation of tests. The second problem occurred during the 305th ACR firing which resulted in a slightly longer pulse width than the schedule 100 millisecond firing. At first, it was thought that the engine timer had momentarily malfunctioned, however, a thorough check of the timer revealed no abnormalities. At the present time there is no explanation as to what was the contributing factor concerning the second problem.

SECTION VI

SOLAR CELLS AND OPTICS TESTS

A. TEST CONFIGURATION

The test hardware used for the solar cells and optics tests, reference Figure 2, consisted of two major components: (1) a reference test specimen module of two solar cells and two optical coupons, protected from the engine plume by the use of a solenoid-actuated protective shield; and (2) the main test specimen module which incorporated six solar cells, six optical coupons and a contamination coupon. The main test specimen module was positioned perpendicular to the centerline of the ACR engine for the direct plume impingement tests. For the in situ measurements, the main specimen module was rotated to the horizontal position for exposure of the test specimens to standard illumination (Sylvania Sun Guns). Rotation of the main test specimen module was accomplished by the use of an AC motor in combination with mechanical linkage. The specimens used for these tests were as follows:

Solar Cells:	N/P Silicon solar cells 2 x 2 cm, minimum 9 % space efficiency 7-14 ohm cm, 20 mil fused silica covers attached with Sylgard 182 adhesive.
Optics:	KZFSN4 glass with an OCLI red reflecting cyan transmitting filter. SF2 glass with an OCLI high efficiency anti-reflective coating
Contamination Coupon:	Quartz glass

The solar cells were procured from the Heliotek Division of Textron Electronics Inc., Sylmar, California, and the optical coupons were purchased from the Optical Coating Laboratory, Inc. (OCLI), Santa Rosa, California.

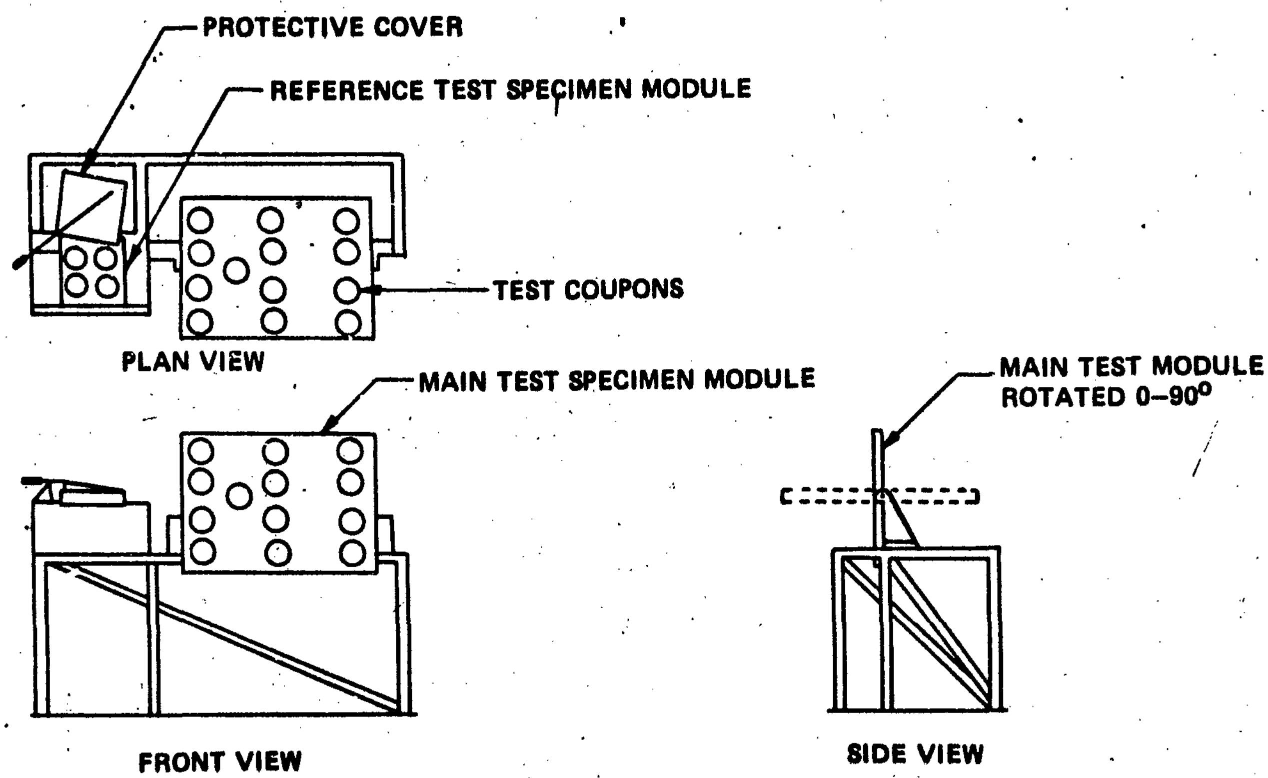

Figure 2. Solar Cell and Optical Test Hardware

The solar cells were bonded to a teflon disk, reference Figure 3, 1.5 inches in diameter and 0.250 inch thick. The solar cell coupons, reference Figure 4, were secured to the specimen module by the use of a retainer ring. Solar cell coupons Nos 1, 2, 3, 4, 5, and 6, reference Figure 5, were subjected to the ACR plume. Solar cell coupons Nos 7 and 8 were control coupons and were protected from the ACR plume.

The optical coupons (reference Figure 6) were 1.5 inches in diameter and 0.250 inch thick. These coupons were secured to the specimen module by the use of a cross-slit collimator as shown in Figure 7. The light collimator was used to narrow down the acceptance angle of the photocell which is normally rated at 5 percent, but which can, based on past experiences, in some cases be as much as 15 percent. The inner dimensions of the cross-slit collimator were 1.75 inches in length and 1.00 inch in diameter. The slot widths were 0.70 inch, and the interior of the unit was painted flat black to minimize reflection. Optical coupons 1, 2, 3, and 4 were SF2 glass (fuzed quartz) with an OCLI high efficiency anti-reflective coating and coupons Nos 6, 7, 8, and 9 were KZFSN4 glass (fused quartz) with an OCLI red reflecting cyan transmitting filter. Optical test specimens 1, 2, 3, 6, 7, and 8 (reference Figure 5) were subjected to the ACR plume. Optical coupons 4 and 9 were control specimens and were protected from the ACR plume. The purpose of the contamination coupon was to obtain and identify a sample of the exhaust contaminant. The size and shape of the contamination coupon were identical to the optical coupons. This coupon was also secured to the main specimen module by the use of a retainer ring.

During tests in situ measurements were taken, i.e., solar cell output and optical transmittance using standard illumination. These measurements, which are not considered refined, were taken to plot contamination trend, if any, for correlation with laboratory post-test measurements. The equipment used to measure the power output of the solar cells was a Moseley strip chart recorder. The optical transmittance measurements were

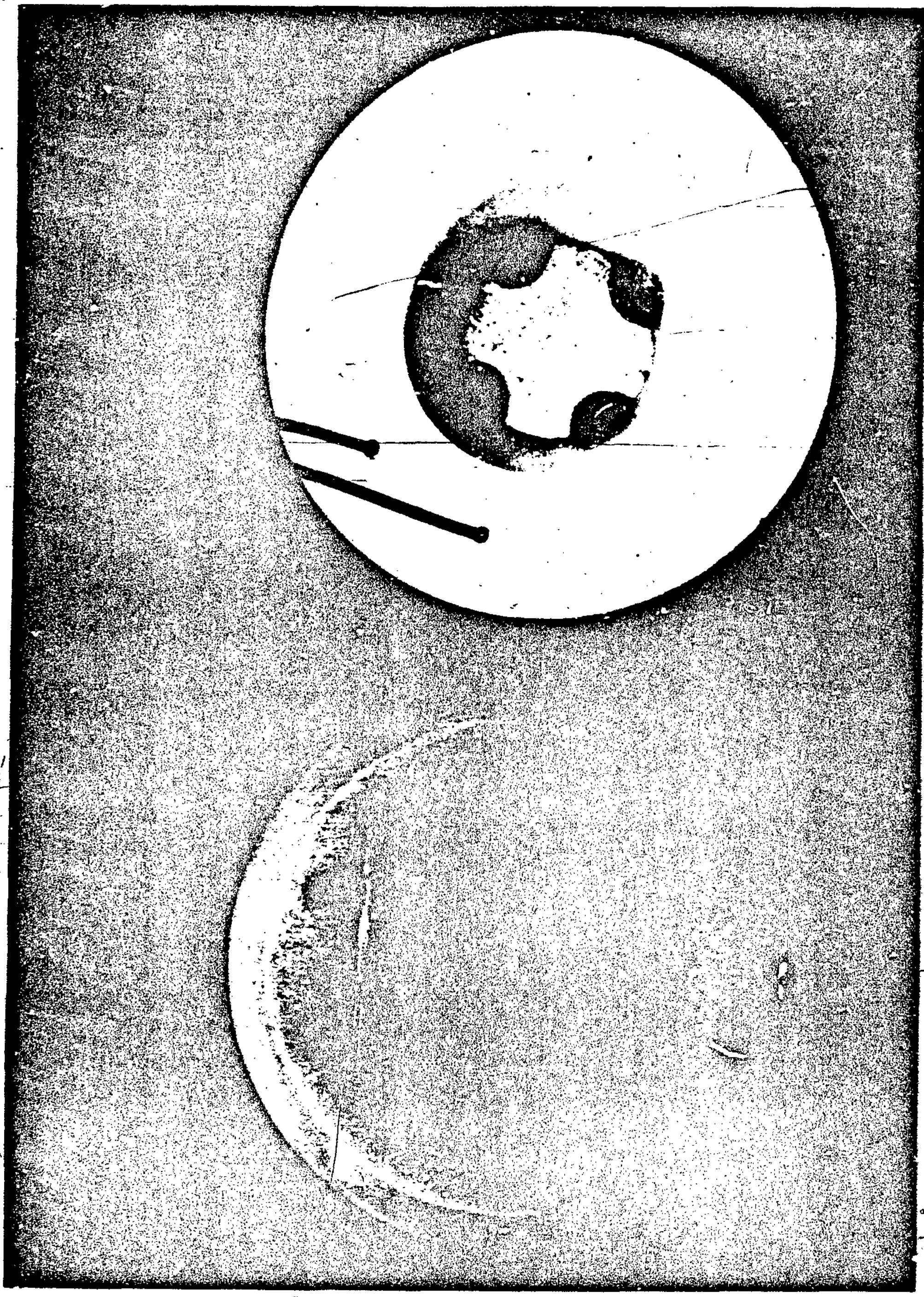

Figure 3. Solar Cell

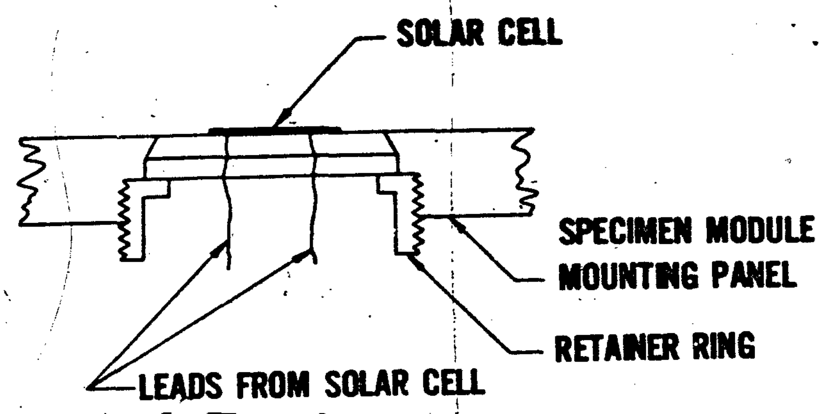

Figure 4. Solar Cell Installation

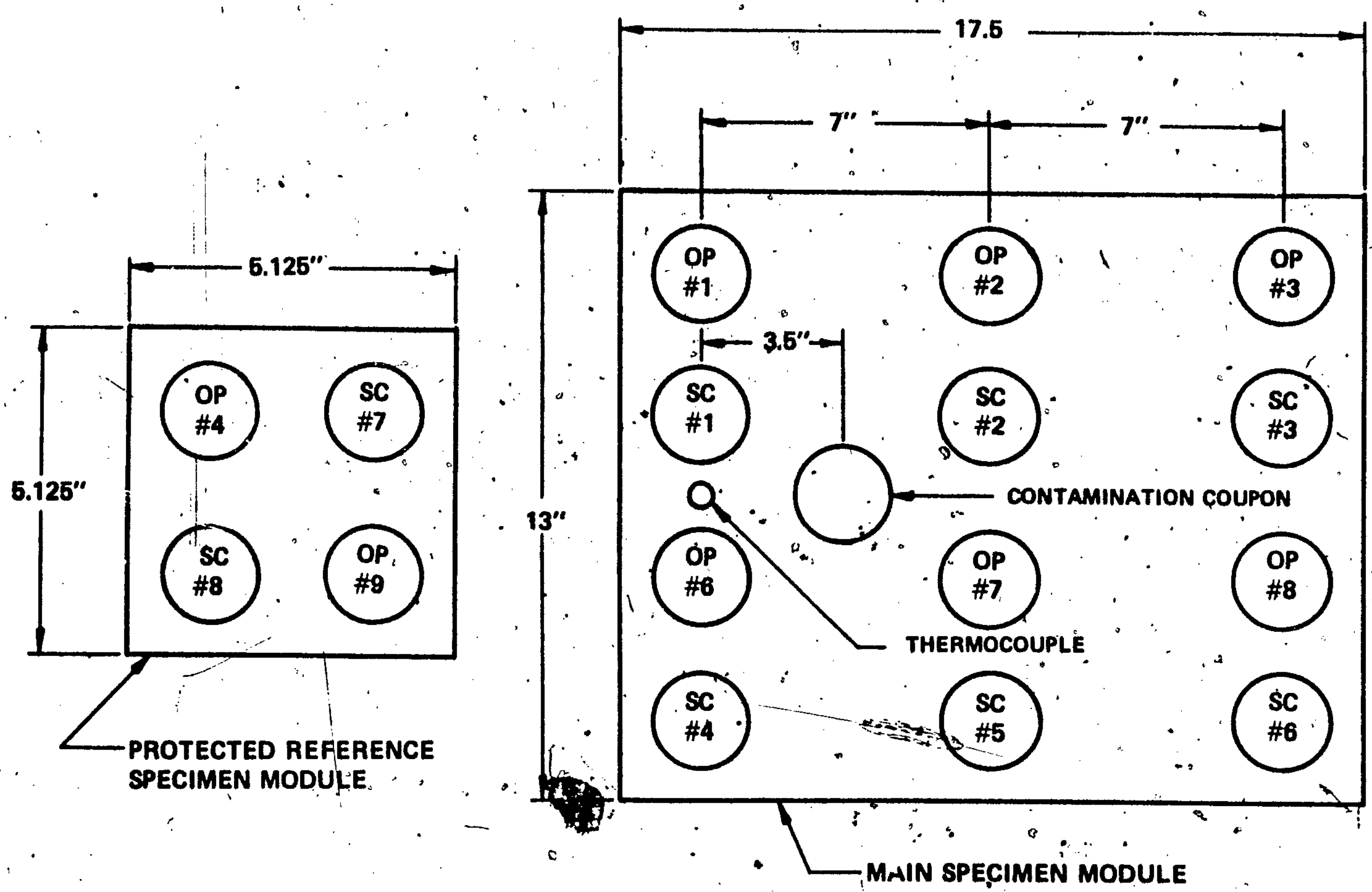

Figure 5. Test Locations of Optical and Solar Cell Coupons

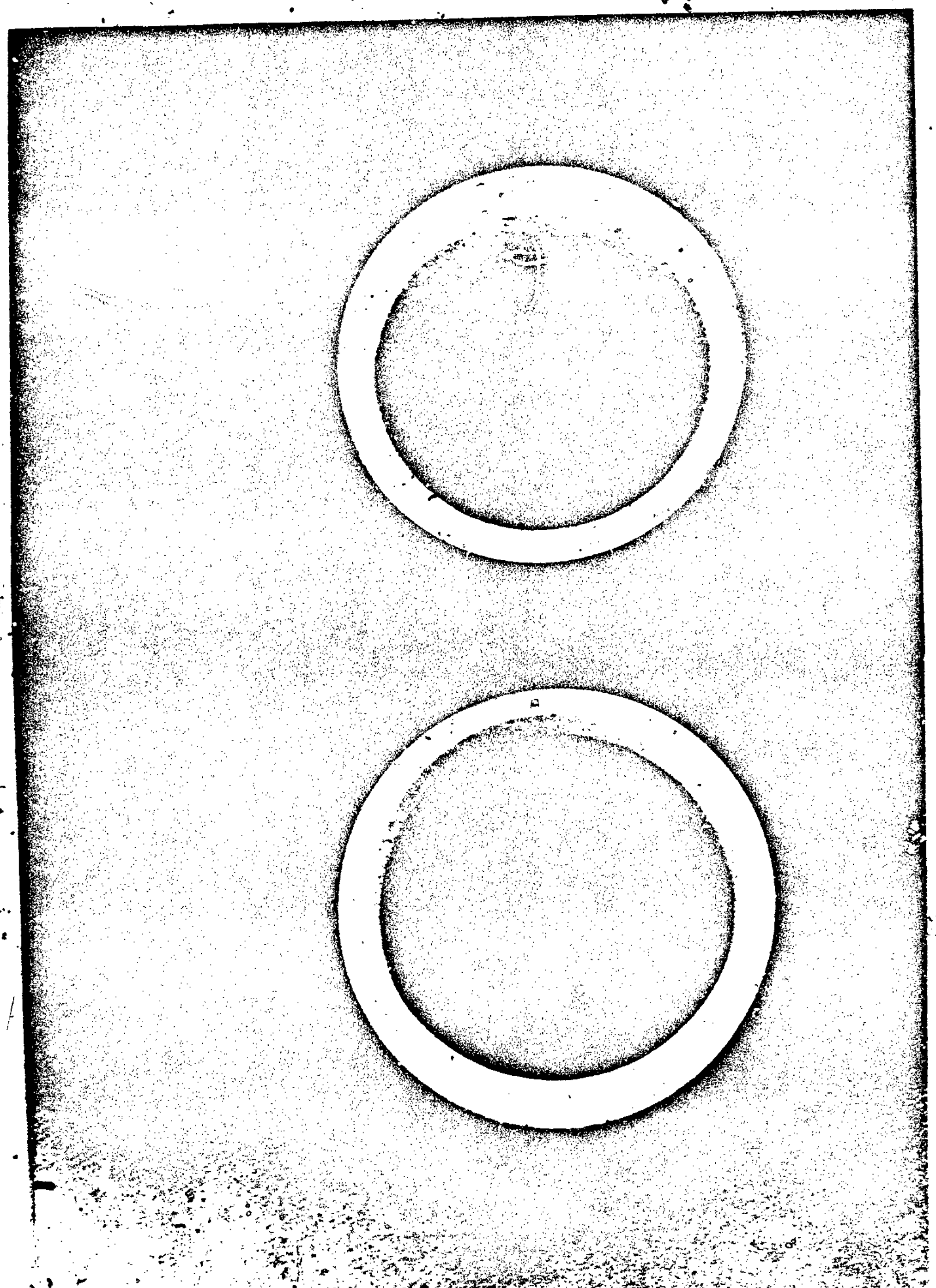

Figure 6. Optical Coupon

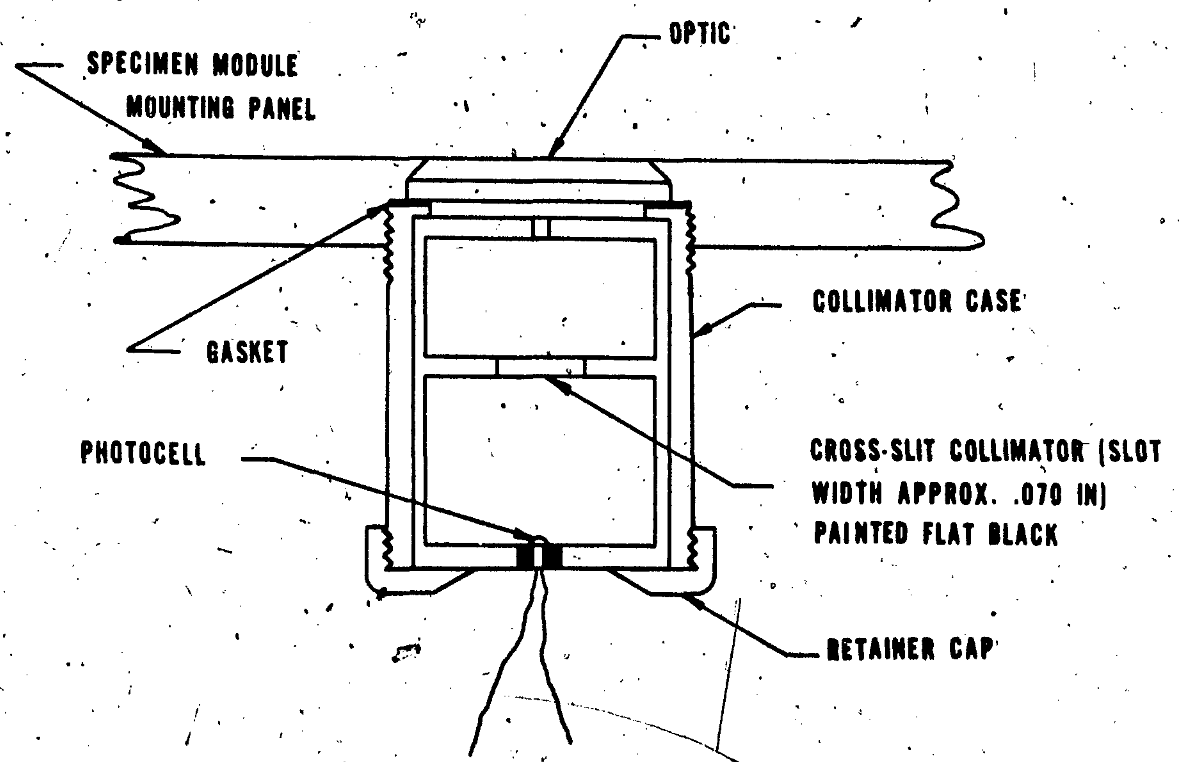

Figure 7. Cross-slit Collimator

accomplished by the use of a photocell in combination with a cross-slit collimator, reference Figure 7. The photocell output was also recorded on a Moseley strip chart recorder.

The laboratory equipment, used for the pre-test and post-test electrical performance measurements of the solar cells, was a Spectrolab X-259613L Xenon-Arc solar simulator, a Spectrolab D-550 Electronic load and Moseley 135 X-Y recorder. The spectral response measurements were obtained using a filter wheel containing 8 narrow band interference filters in combination with the equipment mentioned with the exception of the electronic load unit, which was disconnected. Other equipment utilized as a substitute solar simulator was a standard 1000 w, 28 volt, sealed beam aircraft landing lamp (General Electric NR 4615). Temporary failure of the X-259613C Xenon-Arc solar simulator necessitated the use of this equipment.

The laboratory equipment, used for all the pre-test and post-test spectral transmittance measurements of the optical coupons, was a Beckman Model DK-2 ratio recording spectrophotometer. This instrument has a range of 0.25 to 2.5 microns (2500 to 25000 Angstroms) and employs a magnesium oxide (MGO) coated integrating sphere for collecting the energy transmitted through the samples.

B. TEST POSITION

The test hardware was positioned five feet downstream of the rocket engine nozzle exit, reference Figure 8. The contamination coupon, on the main test specimen module, was positioned on the centerline of the rocket engine nozzle for reference purposes. Sylvania Sun Guns were positioned directly above, the reference and main test specimen module, to provide illumination for the in situ measurements taken at various test intervals. The lamp reflectors were protected from the ACR exhaust particles during engine firings by the use of a solenoid-actuated protective shield.

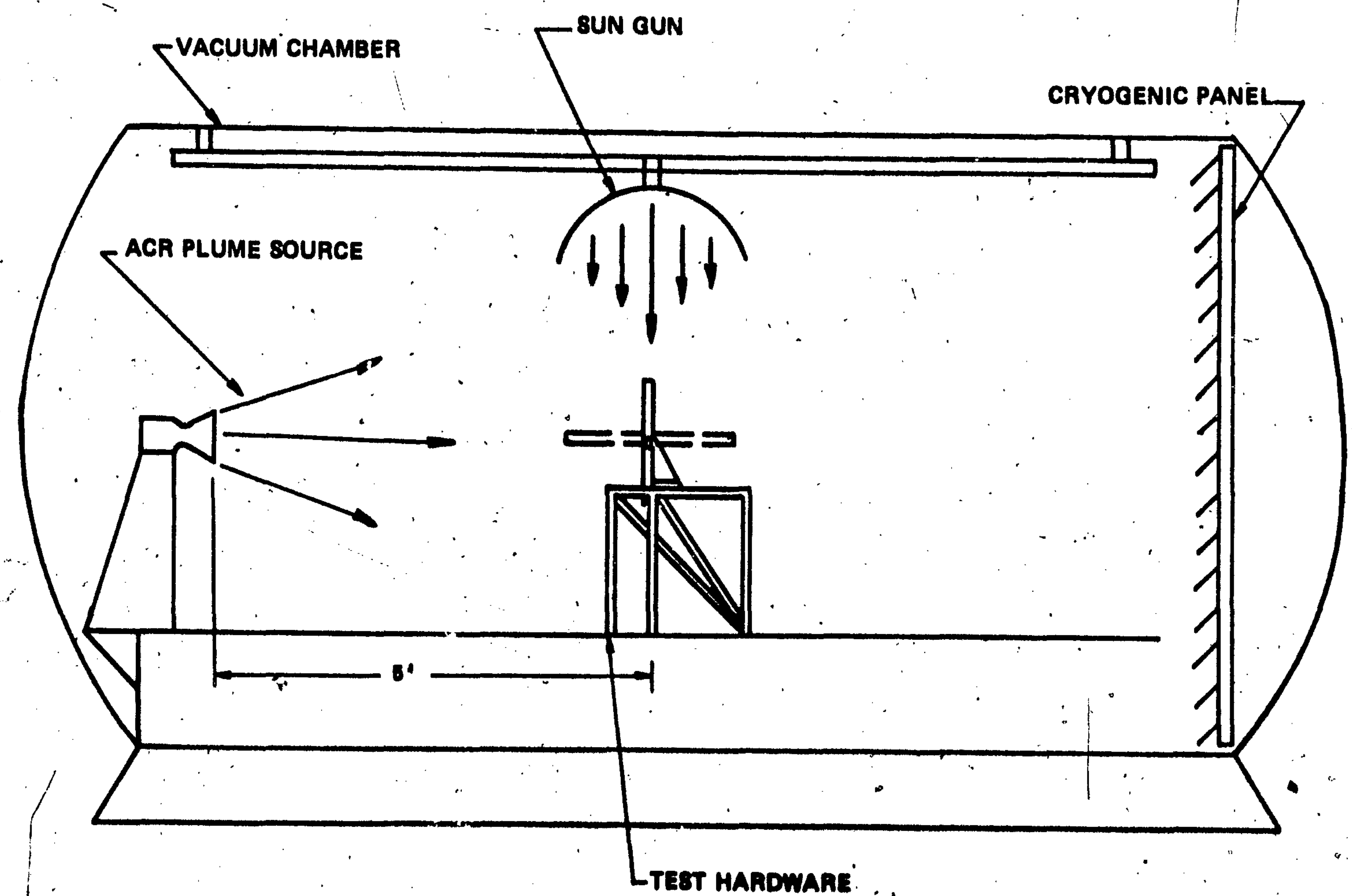

Figure 8. Solar Cell and Optical Test Position

C. TEST CONDITIONS

During tests the solar cells and optical coupons were maintained under a continuous vacuum condition for a period of 336 hours and during this time period were subjected to 400 ACR firings at an engine pulse width of 100 milliseconds. The start altitude for an engine firing was 400,000 feet and upon completion of the engine firing, the altitude had decreased to 205,000 feet. The altitude recovery time between engine pulses was approximately five minutes. In situ measurements were taken following 50, 100, 150, 200, 250, 300, 350, and 400 ACR firings. During the test series the engine injector temperature varied between 39°F and 75°F. The temperature of the main test specimen module varied between 38°F and 47°F.

D. TEST RESULTS

Visual observation of the test specimens, through one of the altitude chamber viewports during various test intervals revealed the presence of a frost-like material deposited on solar cells and optics, as well as on the face of the main test specimen module. The heaviest concentration being within a 9.50 inch radius of the contamination coupon which was positioned on the centerline of the engine. The build-up of this material was uniform up until the completion of 300 ACR firings. For some unknown reason, as previously mentioned, the 305th engine firing resulted in a slightly longer engine pulse width which caused a disturbance (scattering effect) of the frost-like material (reference Figure 9). Visual observation of the rocket engine nozzle lip revealed a build-up of a brownish material which also had a crystal-like structure. At the completion of 400 ACR firings this material had completely coated the nozzle lip 360 degrees. Moreover, there were whitish particles on the inner surface of the rocket nozzle which varied in size form 0.062 to 0.125 inches in diameter. The review of the colored test movies substantiated the visual observations previously mentioned. These test movies are available on a loan basis for a period of two (2) weeks.

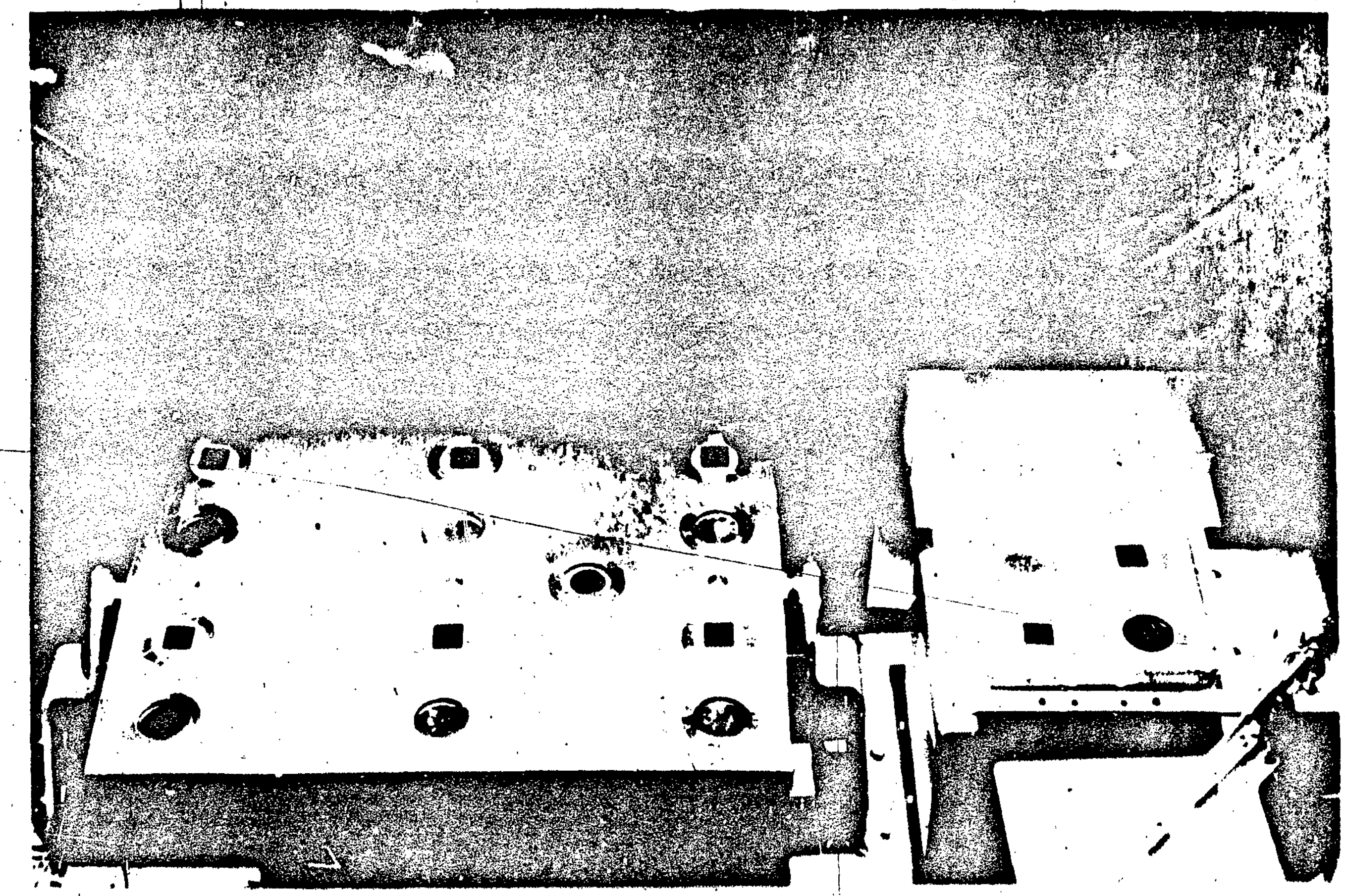

Figure 9. Contaminated Test Specimens

SOLAR CELL PRE-TEST AND POST-TEST MEASUREMENTS

The following is a summary of the test data, concerning pre-test and post-test of the solar cells which was extracted from the Air Force Aero Propulsion Laboratory Technical Memorandum APIP-TM-70-6 "Degradation of Solar Cells Caused by Bipropellant Attitude Control Rocket Plume Contamination" dated February 1970.

The comparison of the solar cell pre-test and post-test measurements relative to short circuit current and maximum power is shown in Table I. In all but one case, there was a deterioration in short circuit current which varied from 1.5 percent to 5.3 percent. One cell showed an increase of 0.8 percent. There was a degradation of all cells in maximum power which varied from 2.2 percent to 7.8 percent. These changes do not greatly exceed the tolerance of the laboratory equipment used which is ±2 percent. The spectral response measurements of the solar cells, Table II, showed a slight deterioration at all wavelengths, in approximate proportion to short circuit current degradation.

Visual inspection of the solar cells revealed that all test specimens experienced contamination in varying degrees, reference Figure 10. Cells 1, 2, 4, and 5 which were located 4.032, 4.032, 5.906, and 5.906 inches from the plume centerline respectively experienced the most contamination. Cells 3 and 6, which were located 10.687 and 11.531 inches respectively, from the plume centerline, were slightly contaminated and the contaminant had a translucent appearance. Review of photograph Figure 9 shows that the heaviest concentration of the contaminant on the main test specimen module was in a radius of 9.500 inches from the contamination coupon which was positioned on the centerline of the rocket engine. Cells 1, 2, 4, and 5 were located within this radius.

Following the post-test measurements and visual inspection, the cells were cleaned. This was accomplished by removing much of the contaminant with ordinary Kleenex tissue using light pressure. This was followed by

TABLE I. SOLAR CELL PRE-EXPOSURE ELECTRICAL PERFORMANCE

Cell	Open Circuit Voltage (Volts)	Short Circuit Current (ma)	Voltage at Maximum Power (Volts)	Current at Maximum Power (ma)	Maximum Power (mw)
1	.53	131	.37	115	42.5
2	.54	130	.43	115	49.5
3	.55	137	.40	120	48
4	.55	140	.42	121	50.8
5	.53	133	.42	121	50.8
6	.55	134	.42	121	50.8
*7	.55	132	.43	115	49.5
*8	.55	140	.42	121	50.8

SOLAR CELL POST-EXPOSURE ELECTRICAL PERFORMANCE

Cell	Open Circuit Voltage (Volts)	Short Circuit Current (ma)	Voltage at Maximum Power (Volts)	Current at Maximum Power (ma)	Maximum Power (mw)
1	.52	124	.37	106	39.2
2	.53	131	.42	113	47.5
3	.54	131	.40	112	44.8
4	[illegible]	134	.42	113	47.5
5	.53	131	.42	118	49.5
6	.54	131	.425	117	49.7
*7	.54	135	.43	115	49.5
*8	.54	137	.42	116	48.8

* Control Cells

TABLE II. SOLAR CELL PRE-EXPOSURE SPECTRAL RESPONSE

Cell	ma/mw at .4 Micron	ma/mw at .5 Micron	ma/mw at .6 Micron	ma/mw at .7 Micron	ma/mw at .8 Micron	ma/mw at .9 Micron	ma/mw at 1.0 Micron	ma/mw at 1.1 Micron
1	.05	.27	.35	.39	.39	.32	.12	.01
2	.04	.25	.35	.41	.44	.46	.31	.06
3	.06	.28	.37	.43	.46	.47	.33	.07
4	.06	.29	.37	.42	.45	.45	.32	.06
5	.04	.26	.36	.41	.46	.46	.32	.06
6	.04	.26	.36	.42	.46	.46	.33	.08
*7	.03	.24	.34	.40	.44	.45	.32	.06
*8	.05	.29	.37	.43	.46	.47	.32	.07

SOLAR CELL POST-EXPOSURE SPECTRAL RESPONSE

Cell	ma/mw at .4 Micron	ma/mw at .5 Micron	ma/mw at .6 Micron	ma/mw at .7 Micron	ma/mw at .8 Micron	ma/mw at .9 Micron	ma/mw at 1.0 Micron	ma/mw at 1.1 Micron
1	.06	.25	.33	.38	.39	.33	.14	.01
2	.05	.23	.33	.40	.44	.44	.30	.06
3	.07	.26	.34	.40	.44	.44	.31	.07
4	.07	.27	.35	.41	.44	.44	.31	.06
5	.06	.25	.34	.41	.44	.45	.31	.06
6	.06	.24	.33	.40	.44	.45	.31	.08
*7	.06	.24	.33	.41	.45	.45	.32	.06
*8	.07	.27	.36	.42	.45	.46	.32	.07

* Control Cells

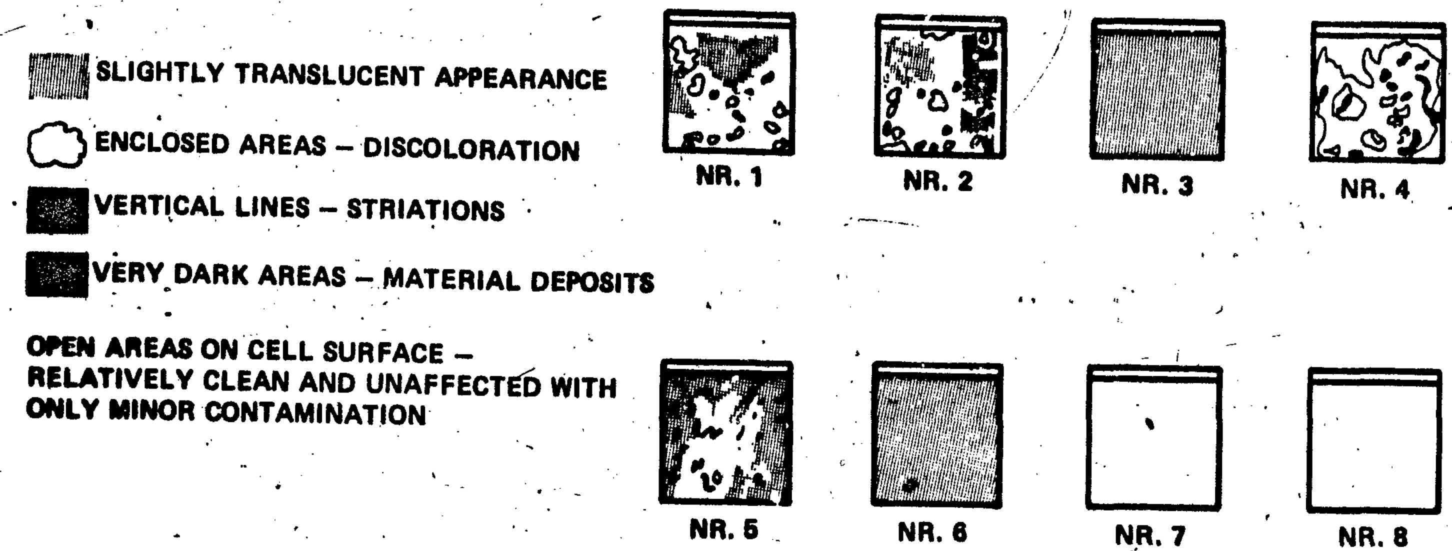

Figure 10. Solar Cell Contamination

the use of a liquid glass cleaner consisting of Isopropanol, a wetting agent, and water. This cleaning procedure was very effective in removing this type of contaminant from the solar cells. The cleaned test specimens matched the laboratory control samples in appearance. There was no noticeable physical change, i.e., abrasion. The test specimens were again checked for electrical performance and spectral response. The average deterioration in short circuit current was 0.7 percent compared to 2.8 percent prior to cleaning. The average maximum power degradation was 2.3 percent compared to 5.1 percent prior to cleaning. There was no significant change in spectral response.

OPTICAL PRE-TEST AND POST-TEST MEASUREMENTS

The following is a summary of the test data, regarding pre-test and post-test of the optics, which was extracted from the Air Force Materials Laboratory, Technical Memorandum MAY-TM-70-1 "Spectral Transmittance Measurements on Optical Coupons Before and After Exposure to the Plume of a Bipropellant Attitude Control Rocket," dated February 1970.

The comparison of the pre-test and post-test measurements, reference Figures 11, 12, 13, 14, 15, and 16 reveals that optical coupons 1, 2, and 3 experienced a slight decrease in transmittance in the lower micron range, however, a slight increase in the 1.1 to 2.5 micron range. The most noticeable decrease in transmittance, relative to optical coupon 6, 7, and 8, was at 0.86 microns. Following completion of the post-test measurements the test specimens were cleaned which was accomplished by a mild detergent wash followed by four rinses in distilled water and a final rinse in methyl alcohol. After the test coupons were cleaned, the same measurements were taken to ascertain whether or not there was a permanent change in optical transmittance as a result of the exhaust contaminant coming in contact with the optical coatings. The results of these measurements are shown in Table III. Coupons 1, 2, and 3 showed no residual change in spectral transmittance; however, coupons 6, 7, and 8 showed a permanent change in spectral transmittance. It is surmised that the red reflecting, cyan transmitting coating on these optics is being affected by the exhaust contaminant.

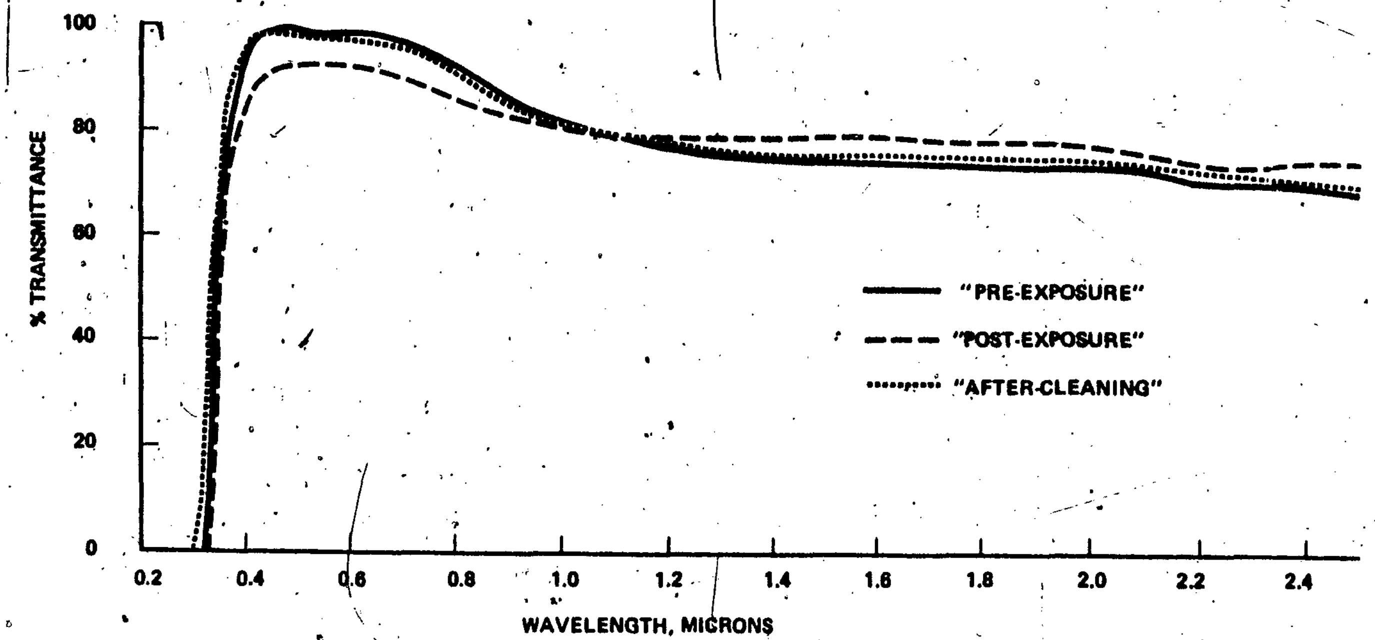

Figure 11. Spectral Transmittance of AFRPL Coupon No. 1.

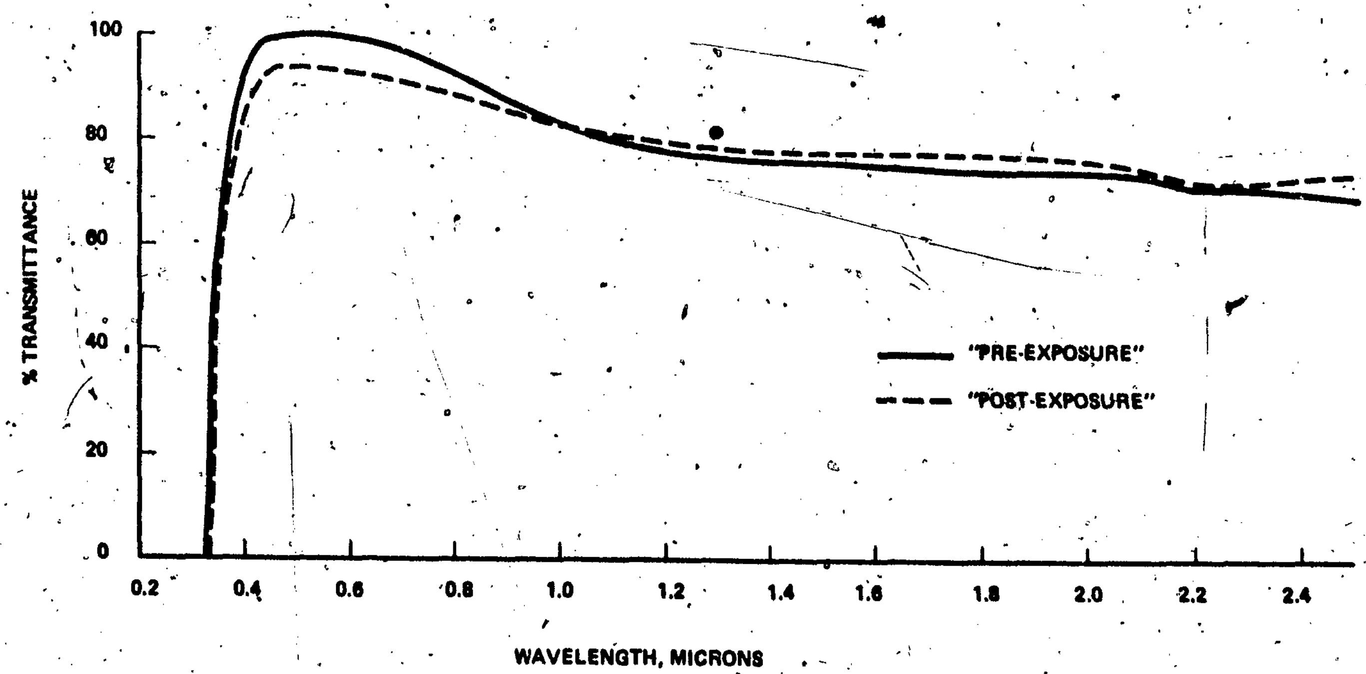

Figure 12. Spectral Transmittance of AFRPL Coupon No. 2.

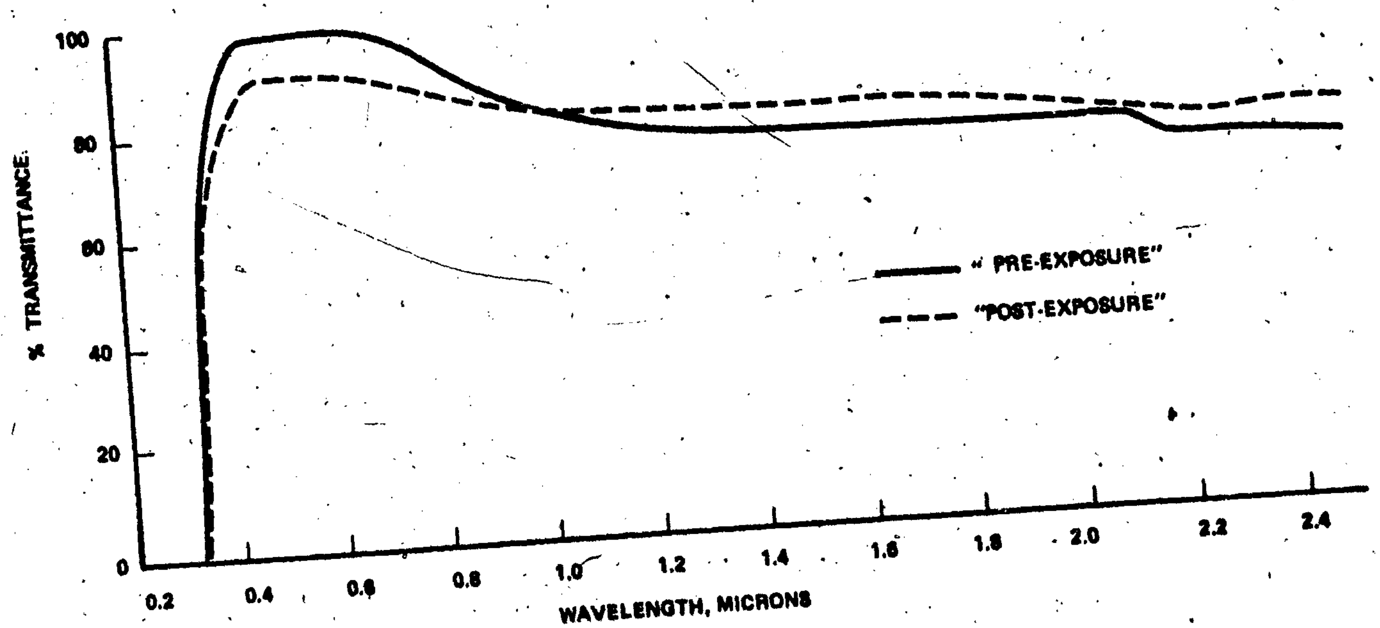

Figure 13. Spectral Transmittance of AFRPL Coupon No. 3.

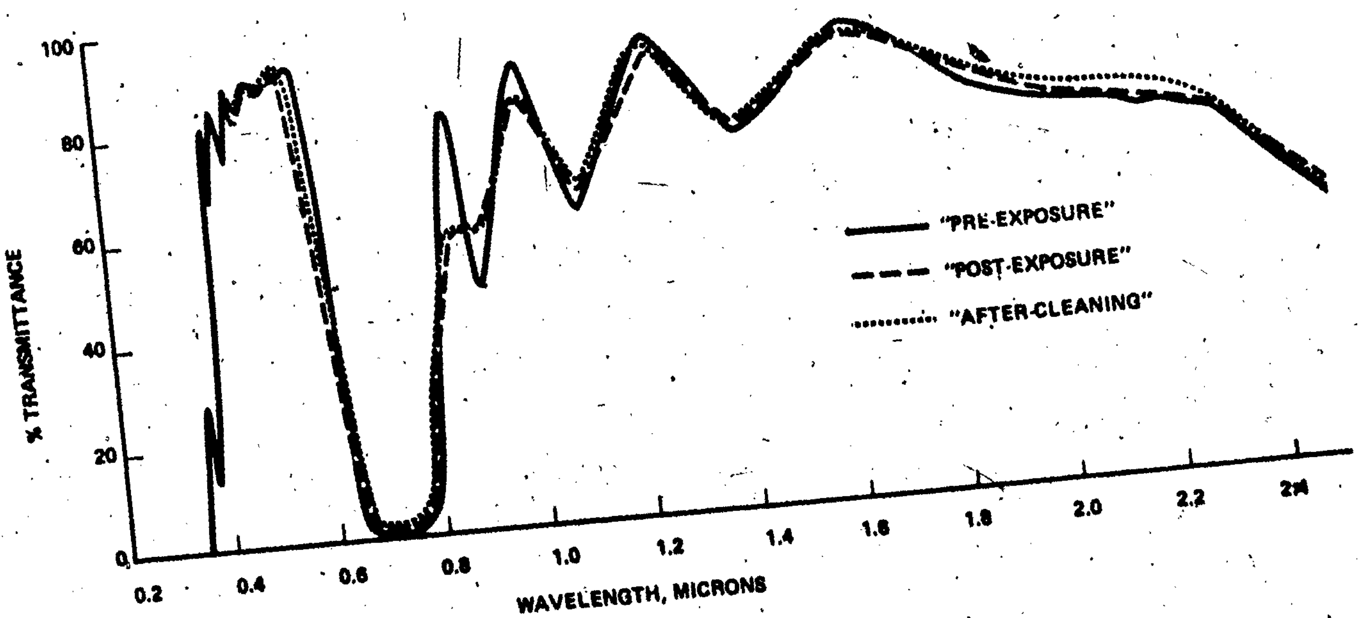

Figure 14. Spectral Transmittance of AFRPL Coupon No. 6.

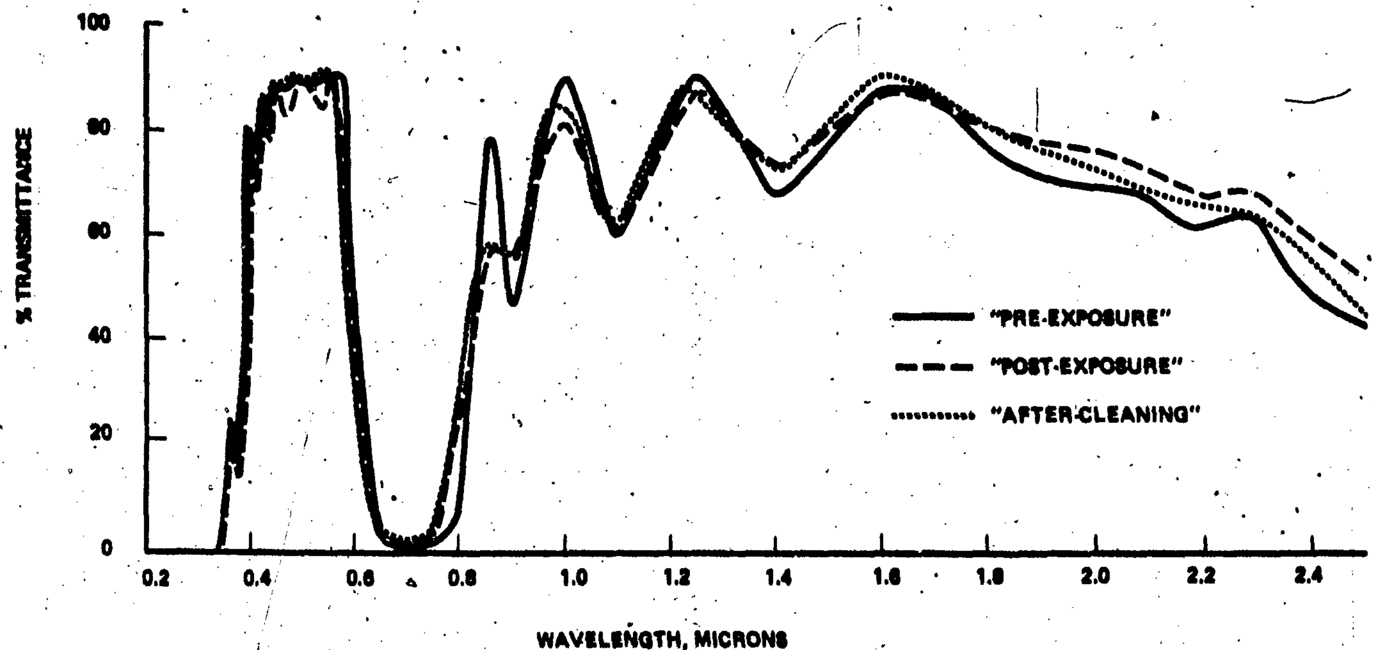

Figure 15. Spectral Transmittance of AFRPL Coupon No. 7.

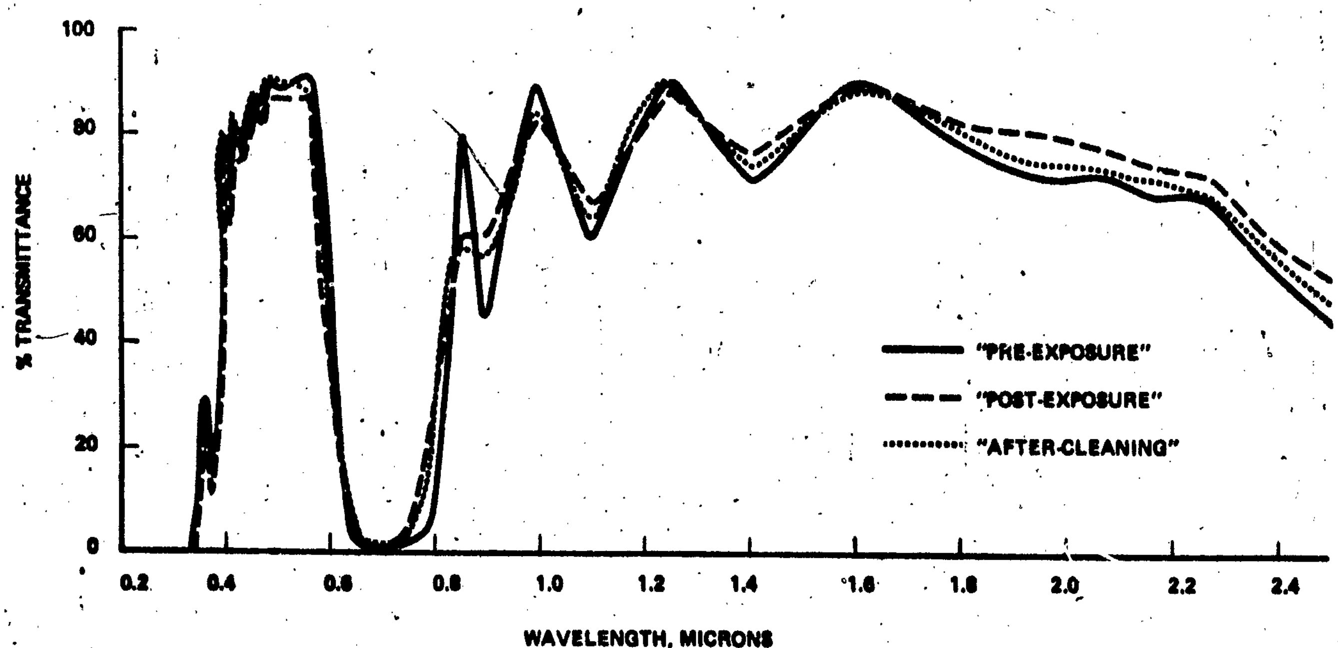

Figure 16. Spectral Transmittance of AFRPL' Coupon No. 8.

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS

% Transmittance

Wavelength λ, microns	Coupon Number 1a*	1b*	1c*	2a	2b	2c
0.250	0.0	0.0	0.0	0.0	0.0	0.0
0.260	0.0	0.0	0.0	0.0	0.0	0.0
0.270	0.0	0.0	0.0	0.0	0.0	0.0
0.280	0.0	0.0	0.0	0.0	0.0	0.0
0.290	0.0	0.0	0.0	0.0	0.0	0.0
0.300	0.0	0.2	0.0	0.0	0.2	0.0
0.310	0.0	0.2	0.2	0.0	0.2	0.2
0.320	0.4	0.4	0.8	0.0	0.8	0.8
0.330	12.3	11.3	14.0	10.2	12.1	14.0
0.340	40.6	36.6	43.3	37.8	34.8	43.3
0.345	50.6	---	---	---	---	---
0.350	59.8	56.3	74.9	58.6	54.2	74.9
0.350	65.2	60.2	71.5	57.4	59.0	71.5
0.365	79.2	---	---	---	---	---
0.380	88.1	81.6	---	83.8	81.2	---
0.400	94.4	86.7	96.7	92.7	86.9	96.7
0.405	95.4	---	---	---	---	---
0.410	96.8	---	---	---	---	---
0.425	98.5	---	---	98.4	---	---
0.440	98.9	91.8	---	---	92.4	---
0.455	99.4	---	---	99.0	---	---
0.470	99.8	92.8	---	---	94.0	---
0.495	99.4	93.2	---	---	94.4	0.0
0.515	98.7	---	---	100.0	---	---
0.550	98.5	92.6	99.6	99.5	94.6	99.6
0.560	98.3	---	---	---	---	0.0
0.600	98.6	92.8	98.3	99.5	94.4	98.3
0.650	98.8	91.2	---	99.0	93.8	---
0.700	97.1	91.2	97.5	97.4	92.8	97.5
0.750	96.0	89.0	96.3	94.9	92.4	96.3

* a - "pre-exposure" measurements
b - "post-expcsure" measurements
c - "after-cleaning" measurements

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	Coupon Number 1a*	1b*	1c*	2a	2b	2c
0.550	98.7	93.3	99.6	98.4	93.9	---
0.570	98.9	92.3	---	---	---	---
0.600	99.4	92.2	99.4	99.5	93.5	98.3
0.650	99.2	91.2	98.6	99.5	---	---
0.700	97.9	90.0	97.5	97.9	91.8	96.3
0.750	95.6	90.6	96.3	---	---	---
0.800	93.7	86.4	90.0	93.7	88.4	90.0
0.860	89.9	84.5	---	---	---	---
0.900	86.7	83.7	85.6	87.9	85.1	85.6
1.000	82.7	82.0	82.0	83.2	82.9	82.0
1.100	79.7	80.8	79.5	80.0	81.0	79.5
1.200	77.8	80.0	78.1	77.9	79.6	78.1
1.250	76.9	79.8	---	---	---	---
1.300	76.6	79.8	77.1	76.8	79.0	77.1
1.400	75.5	79.3	76.0	76.2	78.5	76.0
1.500	75.1	79.2	76.0	75.3	78.1	76.0
1.600	75.1	79.4	76.2	75.3	77.8	76.2
1.630	75.1	79.4	---	---	---	---
1.700	74.8	79.4	76.0	75.3	77.8	76.0
1.800	74.5	79.0	75.7	74.7	77.4	75.7
1.900	74.2	78.6	75.3	74.6	77.5	75.3
2.000	74.1	78.1	75.3	74.5	76.7	75.3
2.060	74.5	77.4	---	---	---	---
2.100	74.5	77.0	74.6	73.7	74.7	74.6
2.130	73.8	76.4	---	73.2	---	---
2.200	70.5	74.7	72.7	70.5	72.3	72.7
2.230	70.8	74.1	---	---	---	---
2.300	71.0	73.6	72.0	70.9	71.4	72.0
2.400	70.8	74.9	71.3	70.4	73.8	71.3
2.500	69.0	73.7	70.7	69.0	72.7	70.7

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	Coupon Number 3a*	3b*	3c*	4a	4b	4c
0.250	0.0	0.0	0.0	0.0	0.0	0.0
0.260	0.0	0.0	0.0	0.0	0.0	0.0
0.270	0.0	0.0	0.0	0.0	0.0	0.0
0.280	0.0	0.0	0.0	0.0	0.0	0.0
0.290	0.0	0.0	0.0	0.0	0.0	0.0
0.300	0.0	0.0	0.0	0.0	0.2	0.0
0.310	0.0	0.0	0.2	0.0	0.2	0.2
0.320	0.0	0.6	0.8	0.2	1.0	0.8
0.330	10.2	8.2	14.0	10.7	13.8	14.0
0.340	37.8	29.9	43.3	38.0	40.5	43.3
0.345	---	---	---	---	---	---
0.350	57.5	47.9	74.9	58.3	59.6	74.9
0.350	59.3	51.6	71.5	58.2	61.2	71.5
0.365	---	---	---	---	---	---
0.380	85.3	74.8	---	85.0	86.6	---
0.400	92.7	81.9	96.7	93.2	93.3	96.7
0.405	---	---	---	---	---	---
0.410	---	---	---	---	---	---
0.425	97.9	---	---	97.4	97.2	---
0.440	---	88.3	---	98.4	97.6	---
0.455	99.0	---	---	99.0	98.2	98.8
0.470	---	90.4	---	---	---	---
0.495	---	91.2	---	99.5	98.8	99.2
0.515	99.0	---	---	---	---	---
0.550	99.0	91.2	99.6	99.0	99.2	99.6
0.560	---	---	---	99.0	---	---
0.600	99.0	90.4	99.4	99.5	99.4	99.4
0.650	99.5	89.6	98.6	99.0	99.2	98.6
0.700	98.4	89.0	97.5	97.9	98.6	97.5
0.750	95.8	89.0	96.3	96.4	97.0	96.3

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	Coupon Number 3a*	3b*	3c*	4a	4b	4c
0.550	98.9	90.1	---	98.9	99.2	---
0.570	---	---	---	---	---	---
0.600	99.5	89.9	98.3	98.4	99.4	98.3
0.650	99.5	---	---	99.0	---	---
0.700	97.4	88.0	96.3	97.4	97.0	96.3
0.750	---	---	---	---	---	---
0.800	93.2	85.5	90.9	93.2	92.0	90.9
0.860	---	---	---	---	---	---
0.900	86.9	83.3	85.6	87.4	86.5	85.6
1.000	82.2	82.2	82.0	82.3	84.1	82.0
1.100	80.0	81.2	79.5	79.6	80.5	79.5
1.200	77.5	80.0	78.1	77.4	78.9	78.1
1.250	---	---	---	---	---	---
1.300	76.4	80.6	77.1	76.4	77.7	77.1
1.400	75.3	80.3	76.0	75.3	76.7	76.0
1.500	75.3	80.1	76.0	74.9	76.5	76.0
1.600	74.9	80.5	76.2	74.9	76.3	76.2
1.630	---	---	---	---	---	---
1.700	75.3	80.2	76.0	74.9	76.1	76.0
1.800	74.7	79.9	75.7	73.8	75.9	75.7
1.900	74.2	78.6	75.3	73.7	75.4	75.3
2.000	74.1	78.1	75.3	73.7	74.7	75.3
2.060	74.5	77.4	---	---	---	---
2.100	74.5	77.0	74.6	73.2	74.0	74.6
2.130	73.8	76.4	---	---	---	---
2.200	70.5	74.7	72.7	70.2	72.3	72.7
2.230	70.8	74.1	---	70.0	---	---
2.300	71.0	73.6	72.0	70.0	72.2	72.0
2.400	70.8	74.9	71.3	70.2	72.7	71.3
2.500	69.0	73.7	70.7	68.1	69.6	70.7

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	6a*	6b*	6c*	7a	7b	7c
			Coupon Number			
0.250	0.0	0.0	0.0	0.0	0.0	0.0
0.260	0.0	0.0	0.0	0.0	0.0	0.0
0.270	0.0	0.0	0.0	0.0	0.0	0.0
0.280	0.0	0.0	0.0	0.0	0.0	0.0
0.290	0.0	0.0	0.0	0.0	0.0	0.0
0.300	0.0	0.0	0.0	0.0	0.0	0.0
0.310	0.0	0.0	0.2	0.0	0.0	0.0
0.320	0.0	0.0	0.8	0.0	0.0	0.0
0.330	0.0	0.0	0.0	0.0	0.0	0.0
0.340	0.0	0.6	0.4	0.5	0.6	0.4
0.345	0.5	---	---	1.1	1.6	---
0.350	3.7	4.5	4.6	3.7	4.9	4.6
0.350	5.3	5.5	10.0	8.9	6.3	10.0
0.365	29.8	23.0	27.1	25.4	22.4	27.1
0.380	29.8	23.0	12.7	14.2	11.9	12.7
0.400	45.5	53.3	78.8	64.2	68.9	78.8
0.405	79.6	74.2	---	75.9	76.6	---
0.410	64.9	62.6	65.8	67.5	65.1	65.8
0.425	85.3	82.5	---	83.2	84.6	84.9
0.440	75.4	73.7	---	76.7	76.6	77.5
0.455	88.5	87.6	---	87.4	89.4	88.8
0.470	84.7	81.7	---	86.6	83.4	84.8
0.495	90.0	89.3	89.2	90.4	90.2	---
0.515	88.4	87.1	---	88.4	88.6	---
0.550	91.1	90.3	89.7	91.1	91.6	92.1
0.560	91.6	91.3	---	91.1	92.0	---
0.600	61.5	52.7	33.1	45.8	40.8	33.1
0.650	2.1	1.2	1.6	1.5	2.2	1.6
0.700	1.0	1.2	1.0	1.0	1.4	1.0
0.750	1.6	1.6	1.4	1.6	2.0	1.4

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	Coupon Number 6a*	6b*	6c*	7a	7b	7c
0.550	89.9	85.8	---	90.6	84.8	---
0.570	92.6	77.4	---	91.7	---	---
0.600	81.1	46.2	49.1	71.9	37.1	49.1
0.650	2.[illegible]	4.6	1.2	1.6	2.4	1.2
0.700	1.0	1.2	1.0	0.5	1.2	1.0
0.750	1.6	2.6	---	1.0	3.4	---
0.800	6.8	20.1	26.6	6.7	23.1	26.6
0.860	80.6	57.7	58.8	79.7	56.9	58.8
0.900	46.6	57.9	56.1	45.8	56.9	56.1
1.000	89.5	81.9	83.2	90.6	81.1	83.2
1.100	59.9	62.9	64.0	59.6	62.2	64.0
1.200	82.7	79.7	86.7	81.8	81.9	86.7
1.250	92.1	88.2	---	91.2	87.6	90.0
1.300	86.8	85.3	84.2	84.4	83.4	84.2
1.400	72.1	74.7	74.4	68.2	73.6	74.4
1.500	79.1	78.9	80.7	77.6	80.1	80.7
1.600	90.5	88.0	90.7	88.6	88.7	90.7
1.630	91.6	89.0	90.9	89.1	89.0	90.9
1.700	89.0	88.0	88.4	87.5	87.3	88.4
1.800	80.6	82.3	81.7	77.6	81.5	81.7
1.900	75.3	78.0	78.1	71.9	78.8	75.8
2.000	72.8	74.9	76.4	69.4	76.6	73.3
2.060	72.8	---	---	69.3	---	---
2.100	72.8	72.7	75.4	67.7	72.1	69.3
2.170	70.5	---	---	61.5	---	---
2.200	71.1	70.6	74.0	62.7	67.5	65.4
2.230	70.7	---	---	64.6	68.3	---
2.300	69.3	69.9	71.0	63.5	68.0	64.3
2.400	58.2	61.3	61.0	48.7	59.8	55.5
2.500	50.5	53.3	55.0	43.4	52.8	45.6

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength λ, microns	8a*	8b*	8c*	9a	9b	9c
			Coupon Number			
0.250	0.0	0.0	0.0	0.0	0.0	0.0
0.260	0.0	0.0	0.0	0.0	0.0	0.0
0.270	0.0	0.0	0.0	0.0	0.0	0.0
0.280	0.0	0.0	0.0	0.0	0.0	0.0
0.290	0.0	0.0	0.0	0.0	0.0	0.0
0.300	0.0	0.0	0.0	0.0	0.0	0.0
0.310	0.0	0.0	0.0	0.0	0.0	0.0
0.320	0.0	0.0	0.0	0.0	0.0	0.0
0.330	0.0	0.0	0.0	0.0	0.0	0.0
0.340	0.5	0.8	0.4	0.5	0.8	0.4
0.345	1.6	2.0	---	2.1	2.5	---
0.350	6.3	5.5	6.5	7.0	6.7	6.5
0.350	17.0	8.2	10.0	14.8	5.5	10.0
0.365	28.4	20.9	27.1	26.3	24.1	27.1
0.380	14.7	9.9	12.7	14.7	11.9	12.7
0.400	75.9	70.4	78.8	76.4	63.5	78.8
0.405	0.0	0.0	---	0.0	77.4	---
0.410	67.0	63.1	65.8	67.0	63.9	65.8
0.425	82.2	76.9	84.9	81.7	83.7	84.9
0.440	75.9	74.7	77.3	76.3	73.7	75.1
0.455	87.4	83.3	88.8	86.9	87.3	88.8
0.470	82.1	82.1	84.8	82.6	80.9	82.3
0.495	89.5	87.3	91.3	89.9	89.5	89.2
0.515	88.9	87.3	---	87.9	87.3	---
0.550	91.5	88.5	93.2	91.1	91.4	91.1
0.560	90.5	90.2	92.4	91.1	91.8	90.6
0.600	29.0	24.9	33.1	28.0	36.0	33.1
0.650	1.6	1.4	1.6	1.6	2.2	1.6
0.700	1.0	1.2	1.0	1.0	1.4	1.0
0.750	2.1	1.6	1.4	2.1	2.0	1.4

TABLE III. SPECTRAL TRANSMITTANCE MEASUREMENTS OF OPTICAL COUPONS (Cont'd)

% Transmittance

Wavelength, microns	8a*	8b*	8c*	9a	9b	9c
	Coupon Number					
0.550	90.5	82.0	---	90.0	83.2	---
0.570	91.5	---	---	91.6	---	---
0.600	63.2	34.7	49.1	49.5	32.7	49.1
0.650	5.2	2.2	1.2	1.6	2.2	1.2
0.700	0.5	1.0	1.0	0.5	1.2	1.0
0.750	0.5	3.8	---	1.0	4.4	---
0.800	5.2	25.4	26.6	4.7	25.9	26.6
0.860	79.6	60.5	58.8	79.6	58.6	58.8
0.900	46.6	61.0	56.1	46.6	58.9	56.1
1.000	89.5	82.3	83.2	89.5	81.9	83.2
1.100	60.2	66.7	64.0	59.7	63.9	64.0
1.200	82.2	83.3	86.7	83.2	83.7	86.7
1.250	91.1	88.0	90.0	91.1	88.6	90.0
1.300	85.3	84.7	84.2	83.8	83.8	84.2
1.400	71.6	77.3	74.4	71.1	74.5	74.4
1.500	80.0	82.5	80.7	80.0	80.7	80.7
1.600	90.6	89.5	90.7	89.5	89.0	90.7
1.630	90.5	89.9	90.9	89.5	89.2	90.9
1.700	86.8	88.5	88.4	86.4	87.3	88.4
1.800	78.5	83.7	81.7	78.5	80.9	81.7
1.900	74.2	81.5	76.9	73.8	76.6	76.9
2.000	72.1	79.8	74.9	72.1	73.9	74.9
2.060	73.2	---	---	72.6	---	---
2.100	72.1	77.0	73.7	72.6	72.9	73.7
2.180	68.6	---	---	68.6	---	---
2.200	69.5	73.9	71.5	68.6	71.0	71.5
2.230	69.5	---	---	69.6	70.0	---
2.300	66.7	72.0	67.0	66.5	68.4	67.0
2.400	53.7	60.3	56.7	54.0	56.5	56.7
2.500	45.7	54.0	49.1	46.5	49.0	49.1

Visual inspection of the optical coupons revealed various size droplets of a clear liquid on the front surfaces of the test specimens. Figures 17, 18, 19, 20, 21, 22, 23, and 24 are 4.4X enlargements of photographs of the front surfaces of coupon Nos 1, 2, 3, 6, 7, and 8. The test specimens experiencing the most contaminant were coupons Nos 1, 2, 6, and 7 which were located fairly close to the exhaust plume centerline. Some of these photographs, Figures 19, 20, and 22 give the misleading appearance of having small pits or bubbles extending into the surfaces of the samples, in reality these are small droplets of condensate on the surface of the optics. Visual inspection of control optical coupons 4 and 9, which were shielded from the ACR exhaust plume exhibited a minute amount of tiny droplets reference Figures 23 and 24. There is no explanation as to how these optical specimens were contaminated since the control solar cells Nos 7 and 8, which were very clean, following completion of test, were installed in the same reference specimen module.

IN SITU MEASUREMENTS - SOLAR CELLS AND OPTICS

The measurements taken during test showed a slight increase in solar cell output (cells 1 through 6) which varied from 0.8 to 3.9 millivolts. The measurement of solar cell No. 1, reference Figure 25, is typical of the measurement profile for cells 2 through 6. These data do not correlate with the laboratory post-test measurements which indicated in most cases a slight deterioration. When the in situ measurements were taken, the contaminant on the solar cells had the appearance of a frost-like material as previously mentioned, whereas during the laboratory measurements the contaminant had the appearance of a viscous material. It is unknown whether the change in contaminant structure had any bearing in the slight differences between the in situ and laboratory type measurement.

The optical measurements revealed a variation in the transmittance value of the optics located near the centerline of the exhaust plume. The measurement of optical coupon No. 6, reference Figure 26, is typical

Figure 17. Contamination of Optical Coupon No. 1.

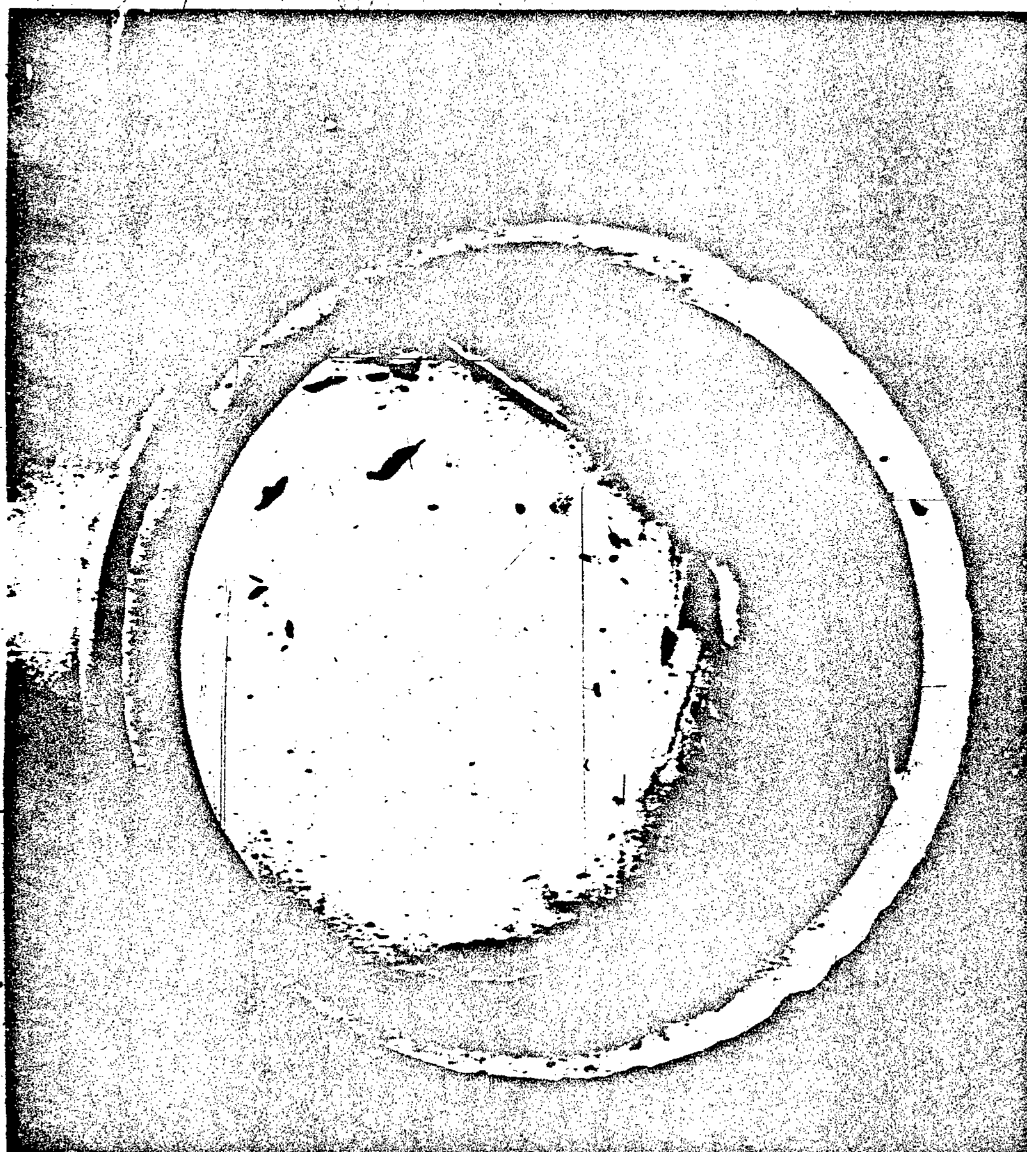

Figure 18. Contamination of Optical Coupon No. 2.

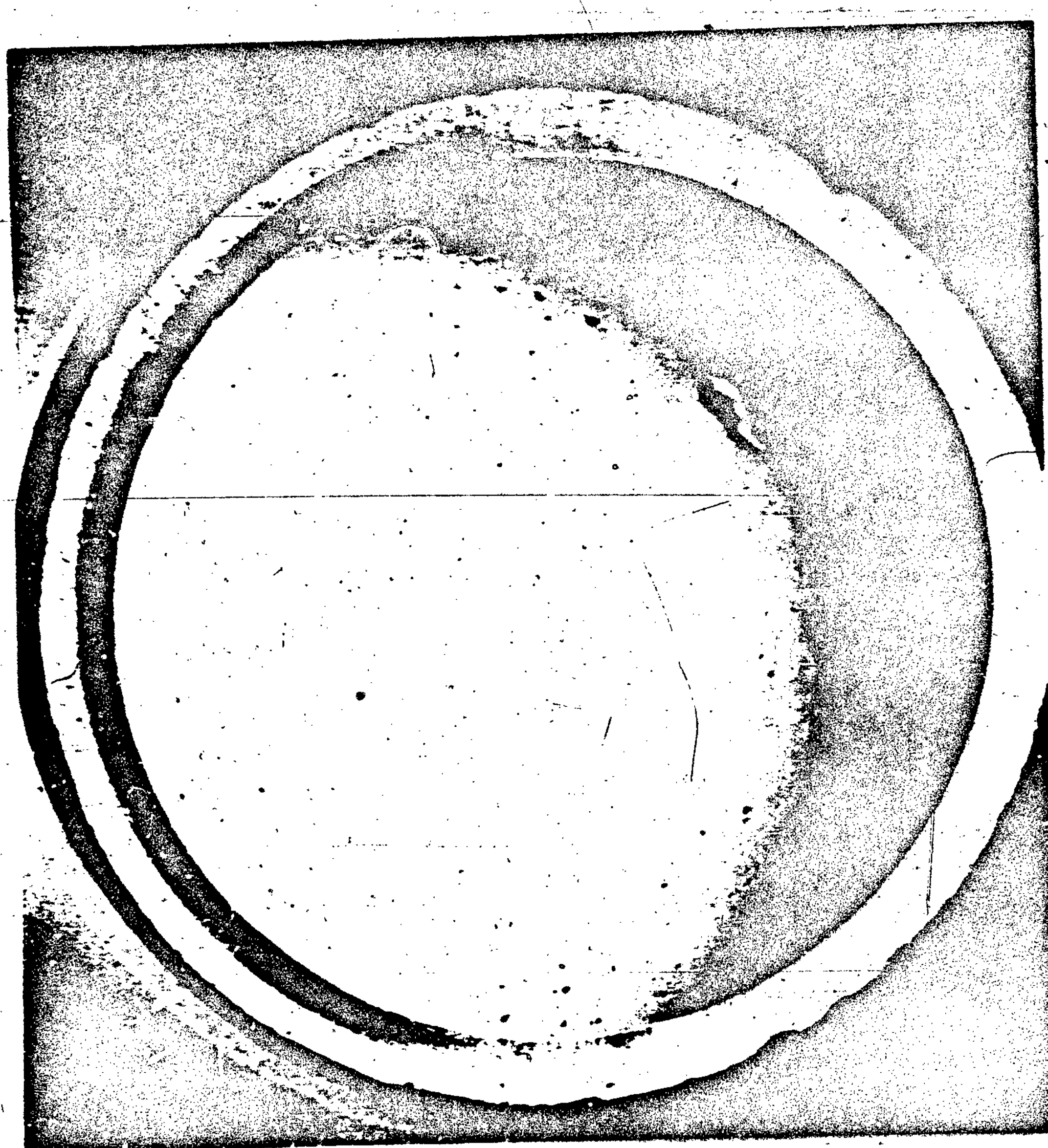

Figure 19. Contamination of Optical Coupon No. 3.

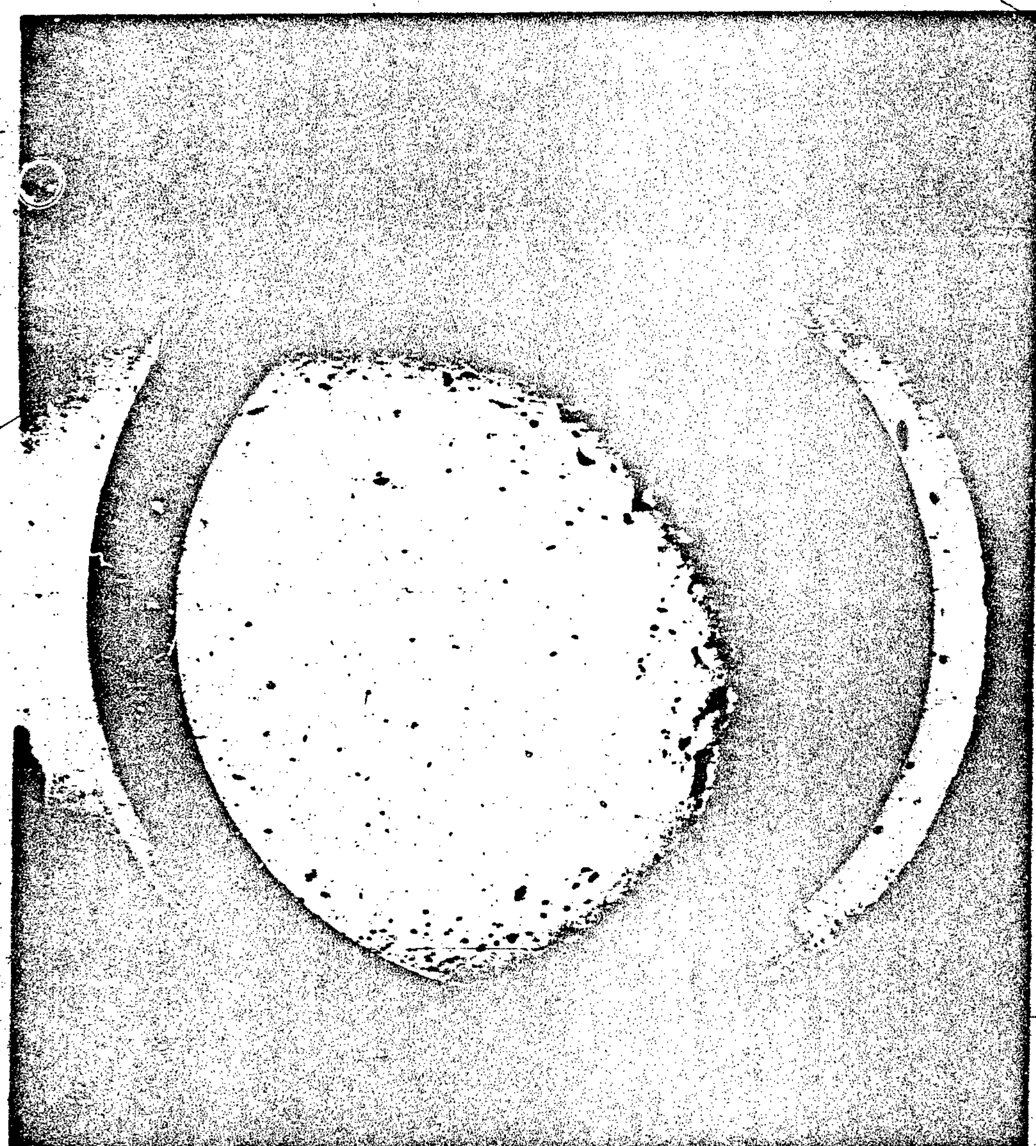

Figure 20. Contamination of Optical Coupon No. 6.

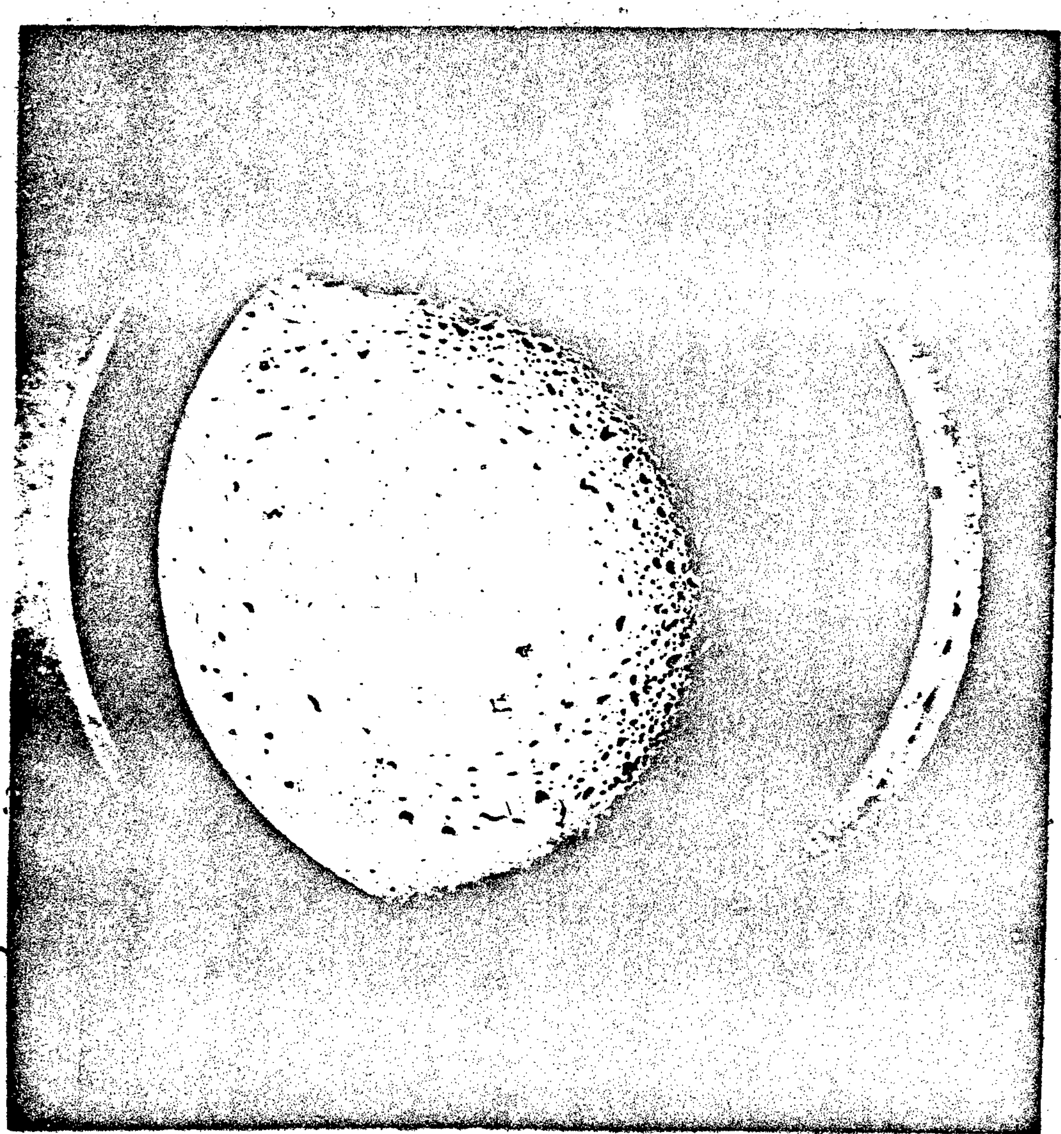

Figure 21. Contamination of Optical Coupon No. 7.

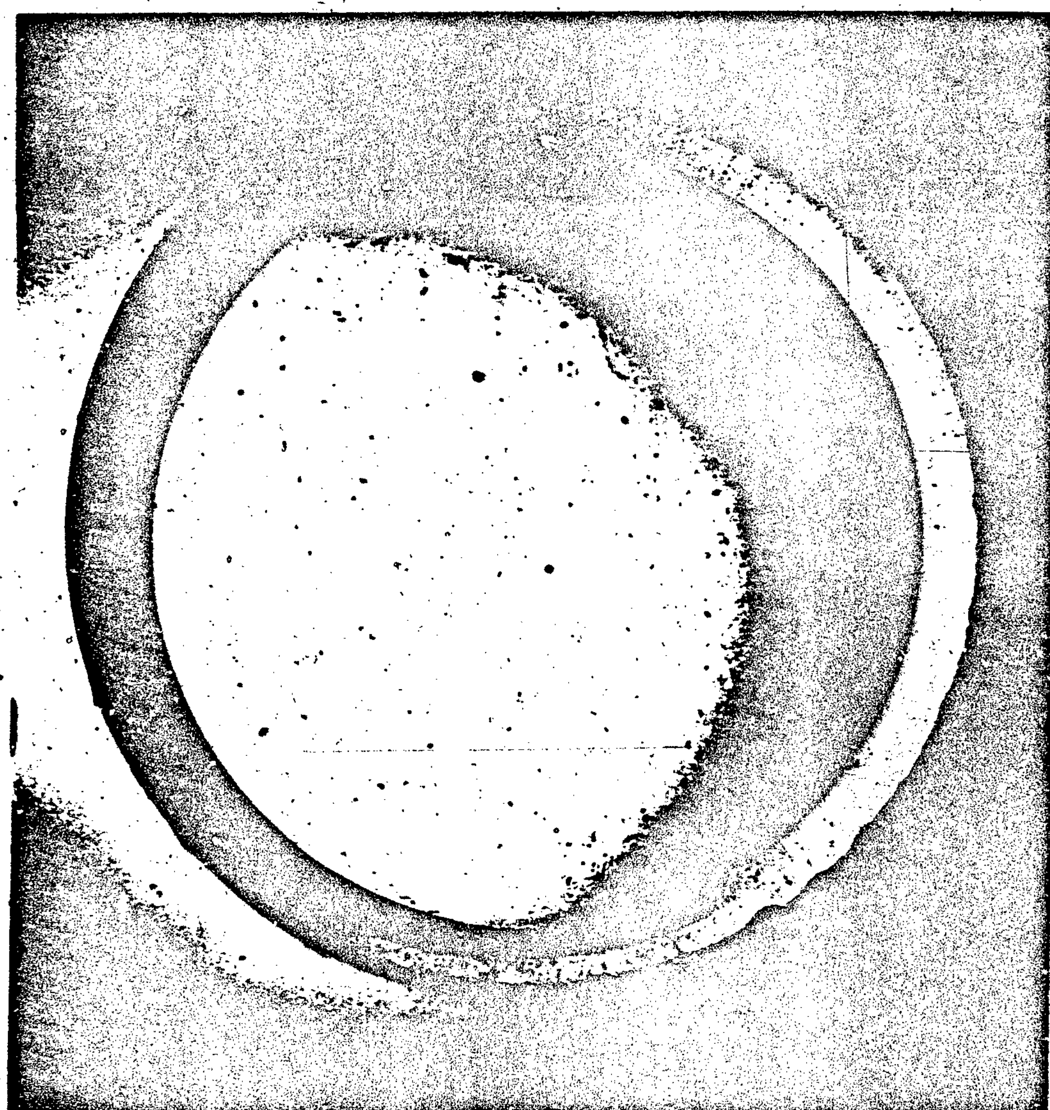

Figure 22. Contamination of Optical Coupon No. 8.

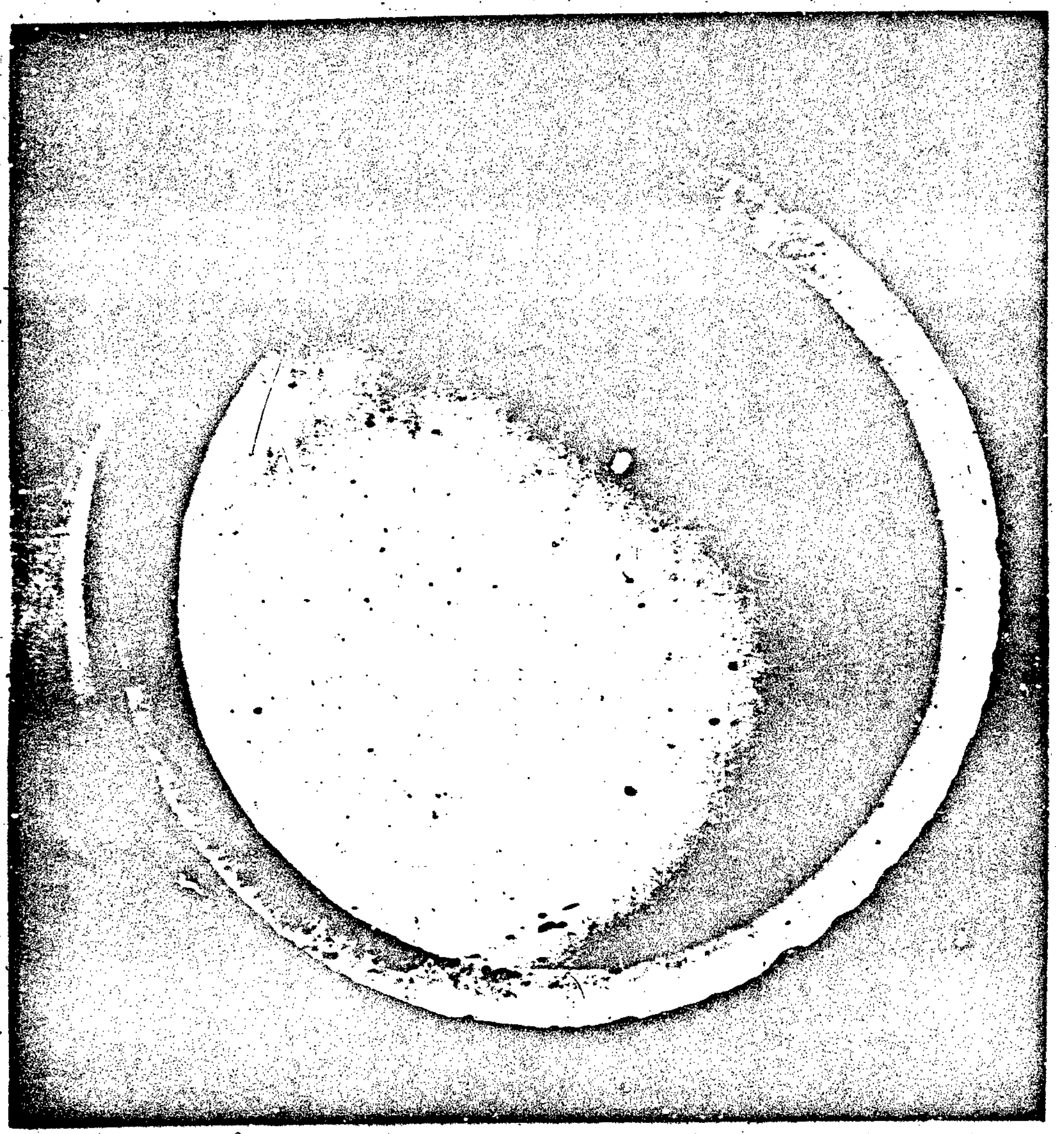

Figure 23. Contamination of Optical Coupon No. 4.

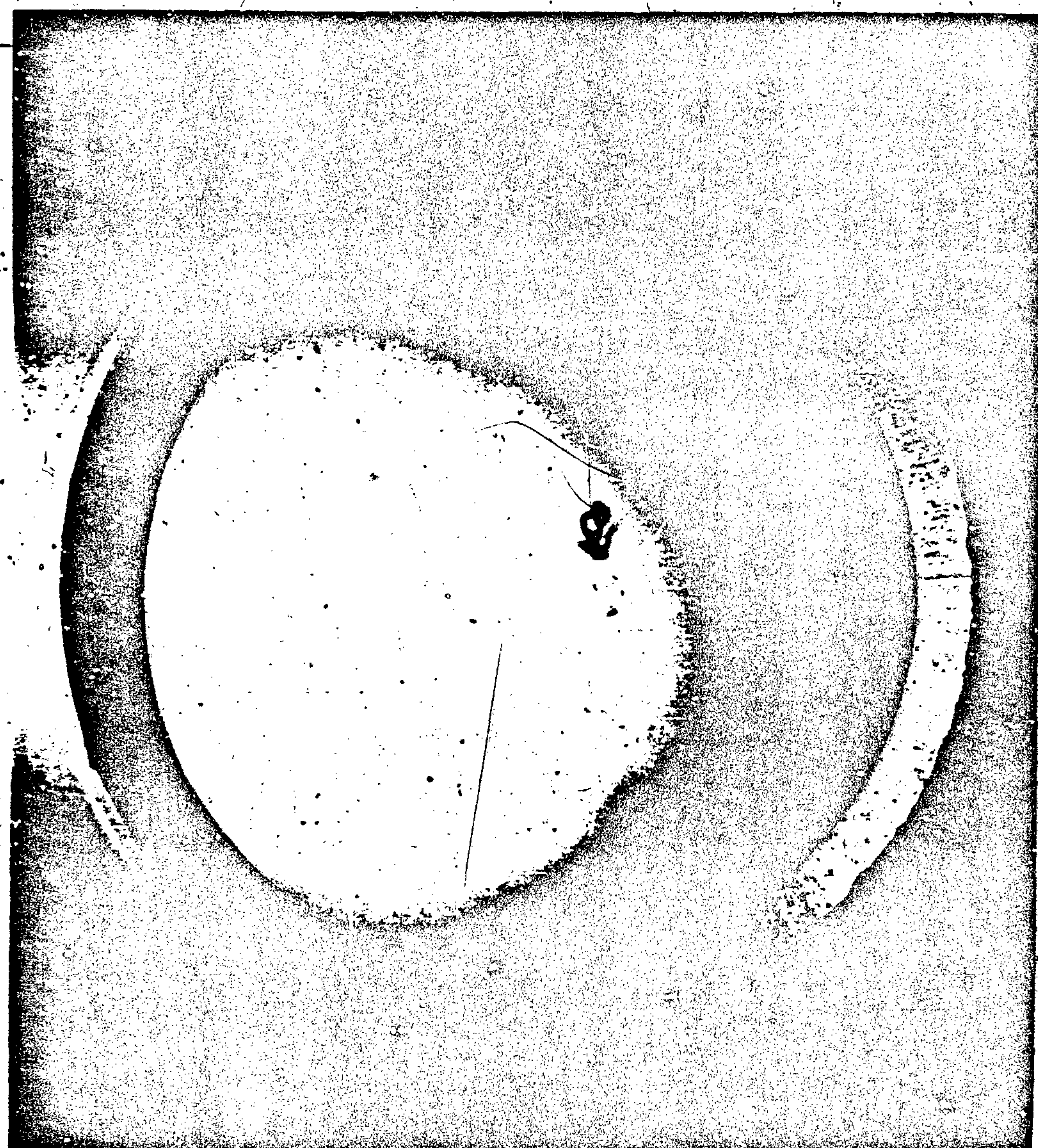

Figure 24. Contamination of Optical Coupon No. 9.

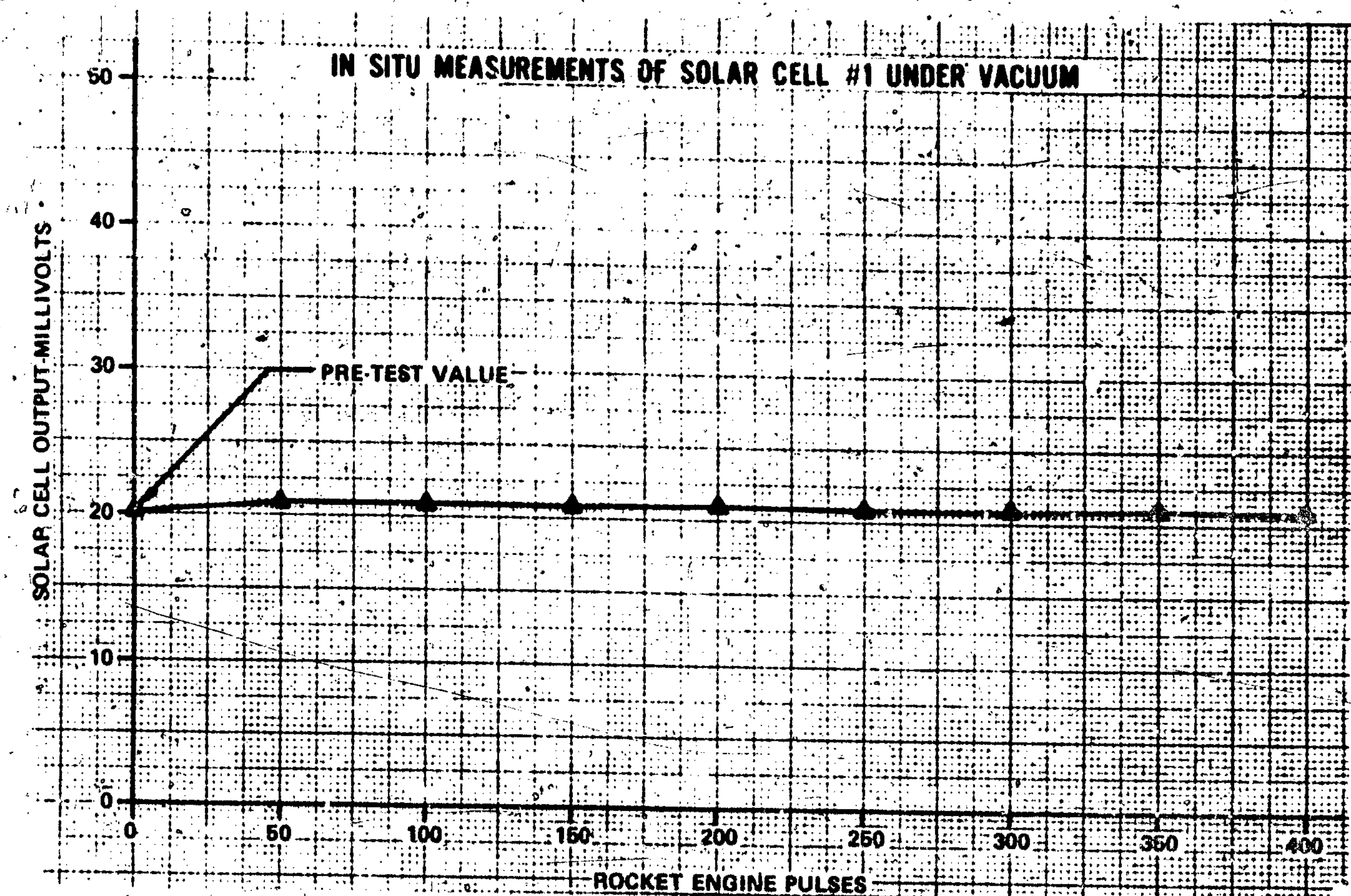

Figure 25. In SITU Measurements of Solar Cell No. 1. Under Vacuum

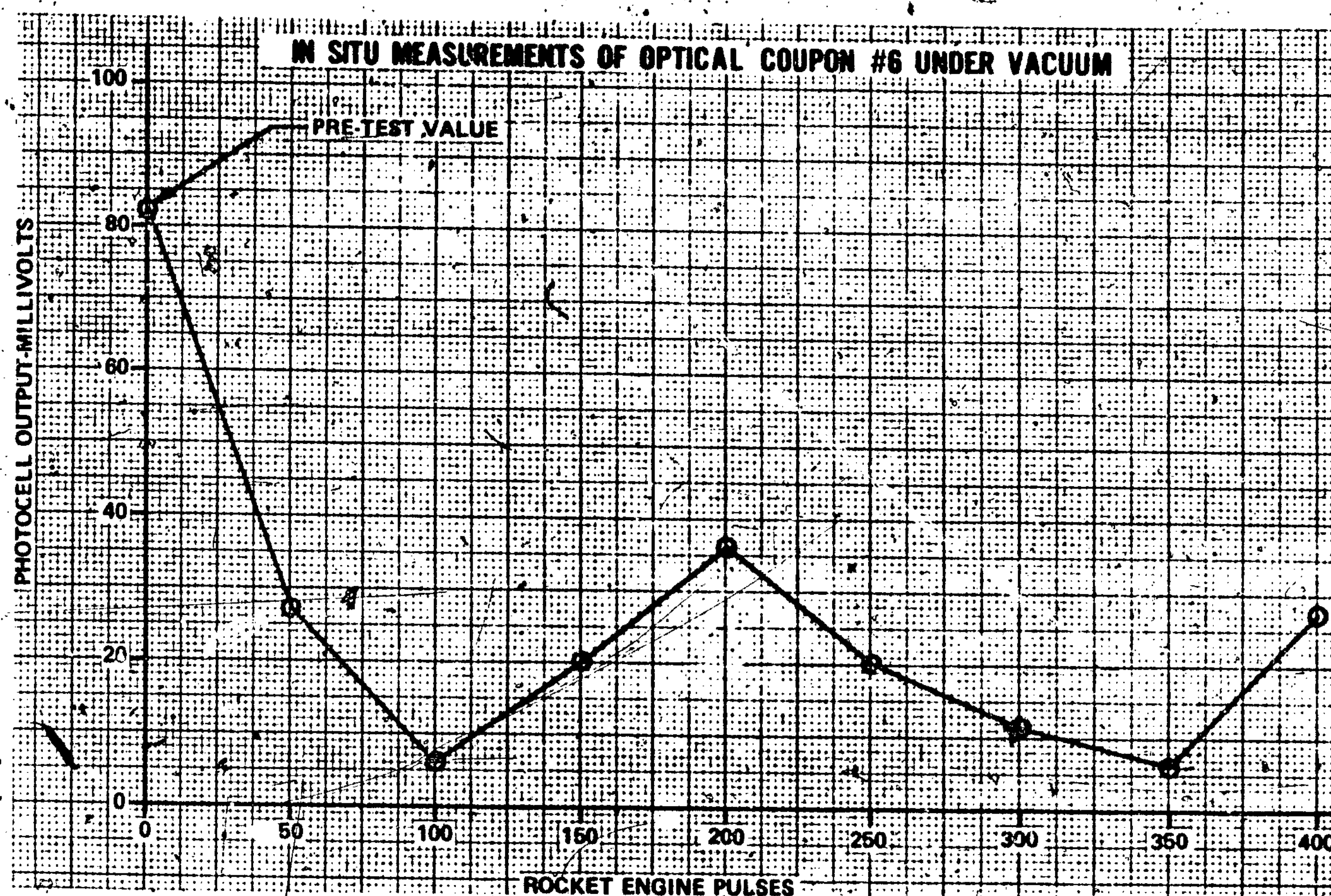

Figure 26. In SITU Measurements of Optical Coupon No. 6, Under Vacuum

of the transmittance variation also noted for coupons Nos 1 and 7. It is surmised that this variation in optical transmittance was caused by the deposit of the frost-like material on the face of the test specimens causing a light scattering effect. The measurement for coupon No. 2 was lost during test due to the malfunction of the photocell. The transmittance measurements of coupons Nos 3 and 8 showed no significant change in transmittance value. These coupons experienced the least contamination, reference Figure 9, since they were located on the outer edge of the contaminated area.

Following completion of the test program, a cursory investigation was conducted to determine what caused the variation in optical transmittance of those specimens located in the area where the heaviest concentration of exhaust contamination occurred. The same test hardware, i.e., cross-slit collimator and optical coupon were enclosed in a column 4" x 4" x 11". A 1/2 inch opening was provided at the top of the column for the light source which was an incandescent light bulb. Moreover, to eliminate reflection, the internal surfaces of the column were sprayed with a flat black paint. The material used for the test was frost from a freezer unit which closely resembled the exhaust contaminant structure under vacuum conditions. Following the pre-test measurement, frost was applied to the face of the optics and immediately there was a substantial decrease in transmittance, however, when the test specimen was rotated and/or moved laterally there were fluctuations in the transmittance values in the order of 30 to 40 percent.

SECTION VII

ANALYSIS OF THE EXHAUST CONTAMINANT

Upon completion of the solar cell and optical test series, the contamination coupon was removed from the main test specimen module, under a GN_2 environment and placed in a special plastic container for shipment to the Laboratory for analysis. In addition, a sample of exhaust contaminant was obtained from the rocket engine nozzle lip for analysis. This contaminant was handled in the same manner as the contamination coupon. Prior to removal of the contaminant samples from the altitude chamber a visual inspection revealed: (1) The contaminant on the surface of the contamination coupon had the appearance of white crystals in the form of needles and (2) The contaminant on the rocket engine nozzle lip had the same structural appearance, but was brownish in color. The analysis of the contaminant, using an infrared spectrophotometer, showed it to be monomethylhydrazine nitrate.

SECTION VIII

THERMAL CONTROL COATING TESTS

A. TEST CONFIGURATION

The test hardware, reference Figure 27, consisted of a flat surface panel, 36 by 44 inches, which incorporated seven flush-mounted thermal-control paint coated coupons. The support stands for the test panel incorporated longitudinal and vertical adjustment features for proper positioning of the thermal paint coupons with relation to the rocket engine nozzle exit plane and rocket engine nozzle centerline.

The thermal-control coating was applied to a 3-inch-diameter aluminum disk which was epoxy-resin-bonded to a teflon flange (reference Figure 28). The purpose of the teflon flange was to minimize heat transfer between the coupon and the spacecraft panel during taking of in situ measurements with the Sylvania sun guns. The test coupons were attached to the spacecraft panel by the use of several wing nuts to facilitate their removal under a gaseous nitrogen atmosphere, upon completion of tests.

The instrumentation consisted of iron constantan (IC) thermocouples attached to the underside of the coupons, and the test data were recorded on a Leeds Northrup Type "G" recorder. Prior to testing, baseline measurements were taken of the coupons which consisted of measuring temperature rise and temperature at equilibrium over a 30-minute period using standard illumination. Recordings were taken every 5 minutes during this time period. During tests, temperature measurements were taken following 100, 200, 300, and 400 ACR firings at an engine pulse width of 100 milliseconds per firing.

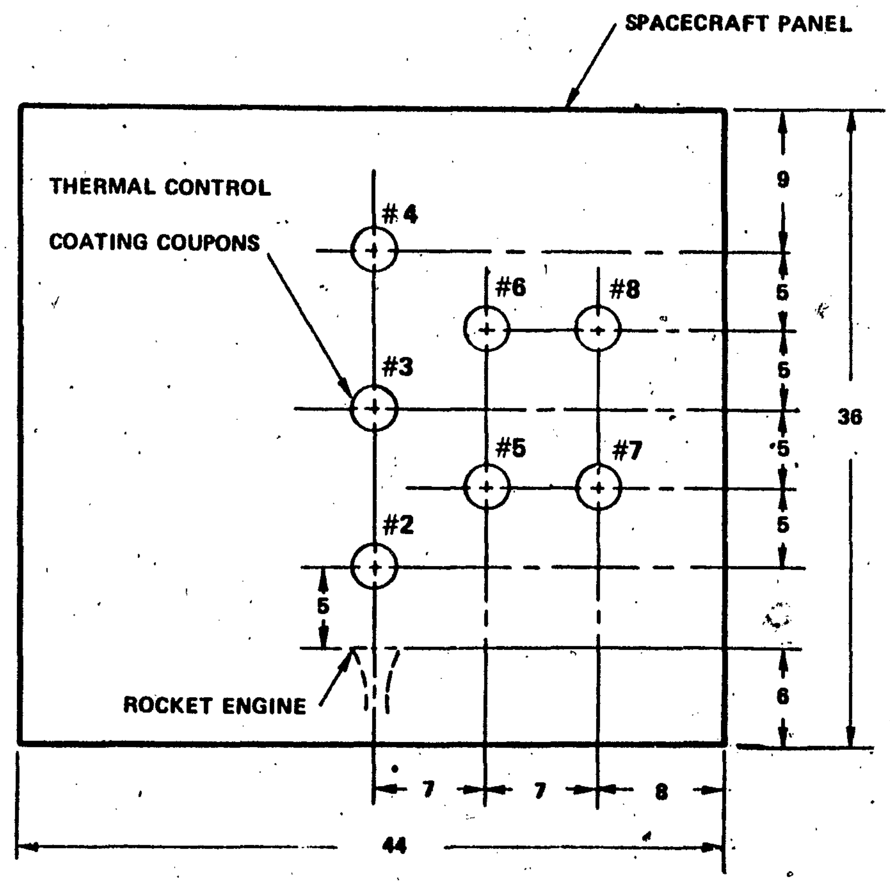

Figure 27. Thermal Paint Test Hardware

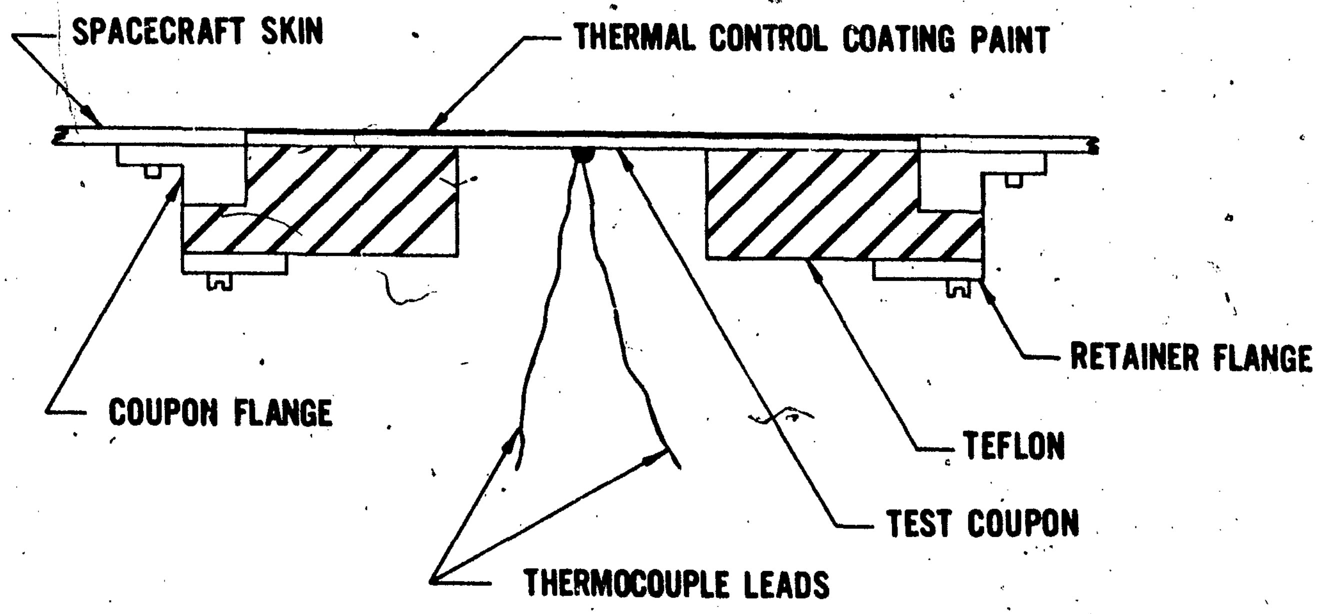

Figure 28. Thermal-control Coating Coupon

B. TEST POSITION

The test coupons, reference Figure 29, were positioned parallel to the ACR plume centerline and the distance from the centerline of the rocket engine to the surface of the panel was 3.5 inches. The Sylvania Sun Guns were positioned directly above the test specimens. The lamp reflectors were protected from ACR exhaust particles during engine firings by the use of a solenoid-actuated protective shield.

C. TEST CONDITIONS

Test specimens were subjected to 400 ACR firings at an engine pulse width of 100 milliseconds. The start altitude for the ACR firing was 400,000 feet and upon completion of a firing the altitude decreased to 205,000 feet. The altitude recovery time between engine pulses was approximately five minutes. In situ measurements were taken following 100, 200, 300, and 400 ACR firings. During the test series the engine injector temperature varied between 32°F and 74°F. The temperature of the spacecraft panel varied between 31°F and 50°F.

D. TEST RESULTS

The following is a summation of the test data, relative to the pre-test and post-test measurements of the thermal paint coupons, which was extracted from the Air Force Materials Laboratory Technical Memorandum MAY-TM-70-2, "Spectral Reflectance Measurements on Thermal Control Paint Coupons Before and After Exposure to the Plume of a Bipropellant Attitude Control Rocket," dated May 1970. The data, reference Figures 30, 31, 32, 33, 34, 35, and 36, reveal that all the test specimens experienced a decrease in reflectance which varied from 6 to 25 percent in the region of 0.42 microns. Coupon number 2, which was located 5 inches from the nozzle exit plane, showed a general decrease in reflectance throughout the entire micron range. The remaining coupons 3, 4, 5, 6, 7, and 8 showed a slight decrease in reflectance between 0.42 to 0.8 microns and 1.85 to 2.0 microns. Visual inspection of the coupons showed that the

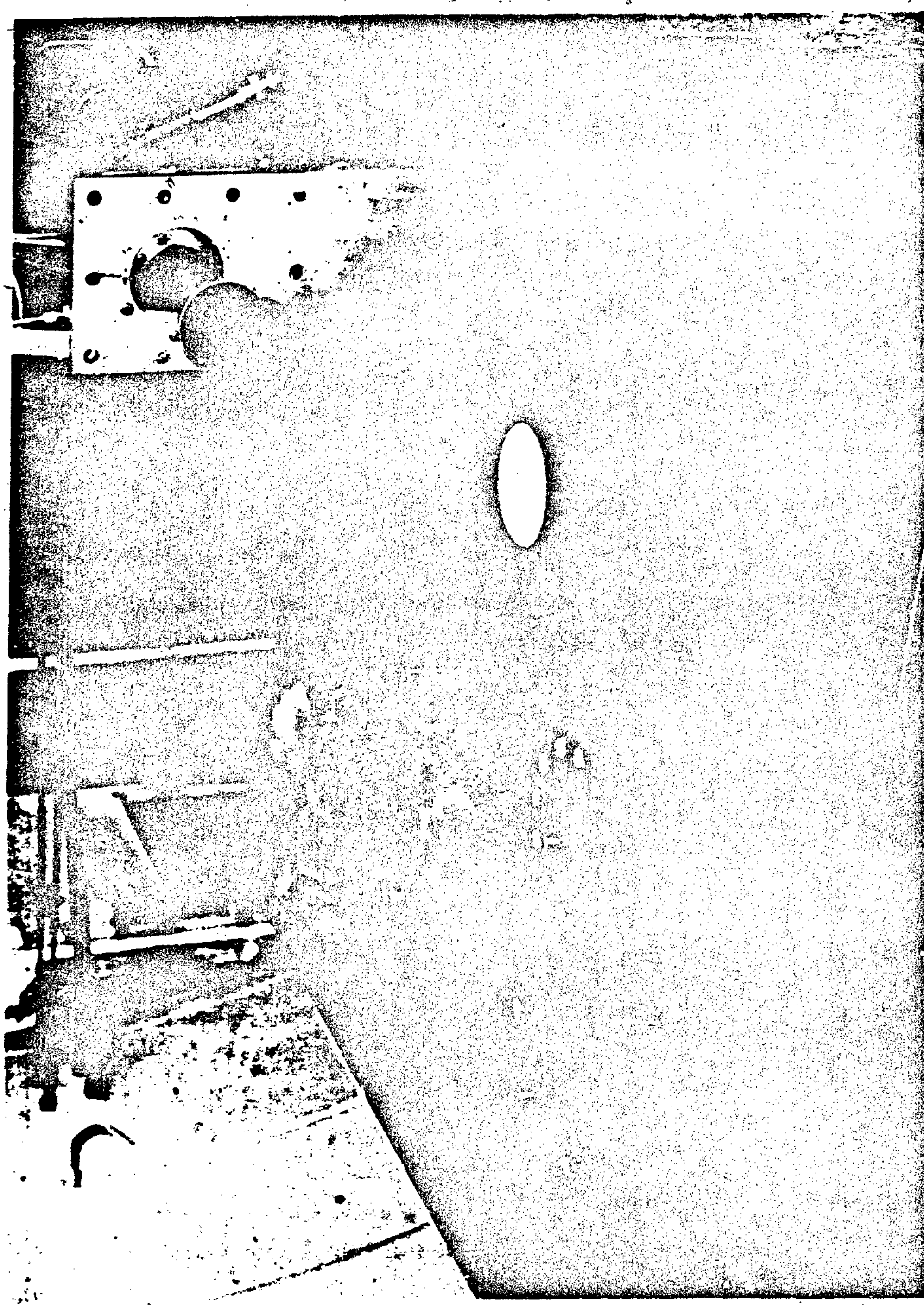

Figure 29. Thermal Paint Test Configuration

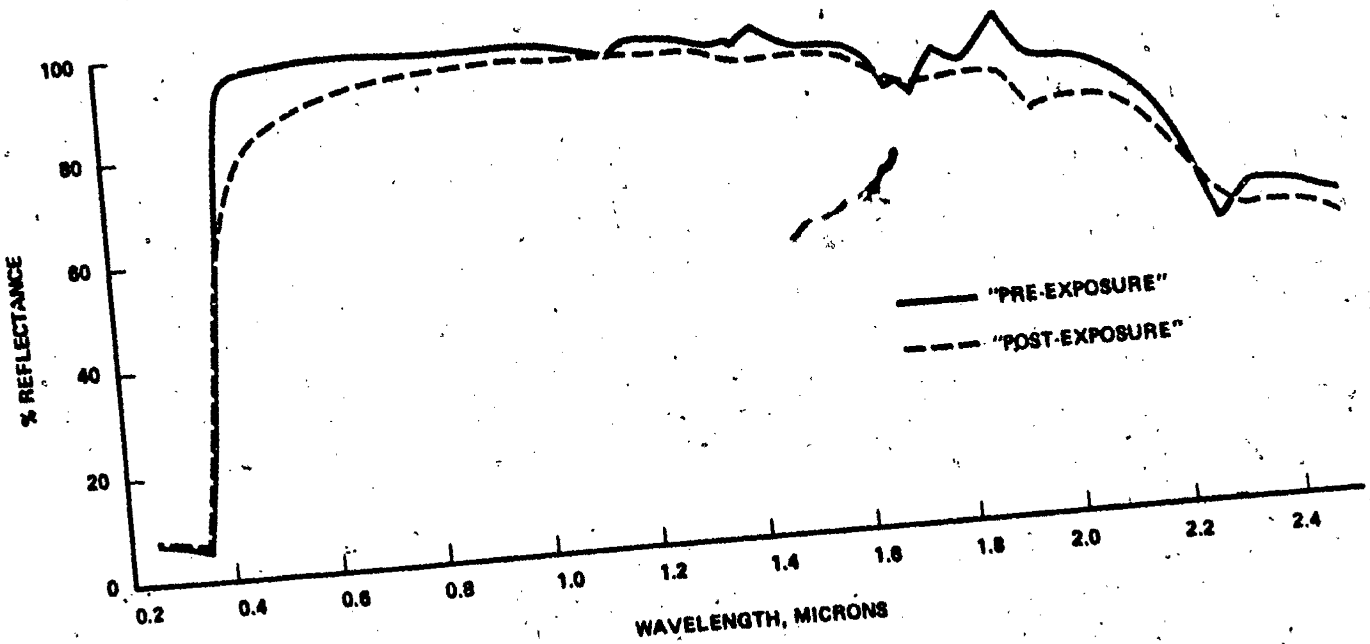

Figure 30. Spectral Reflectance of Thermal Control Paint Coupon No. 2 versus M_gO

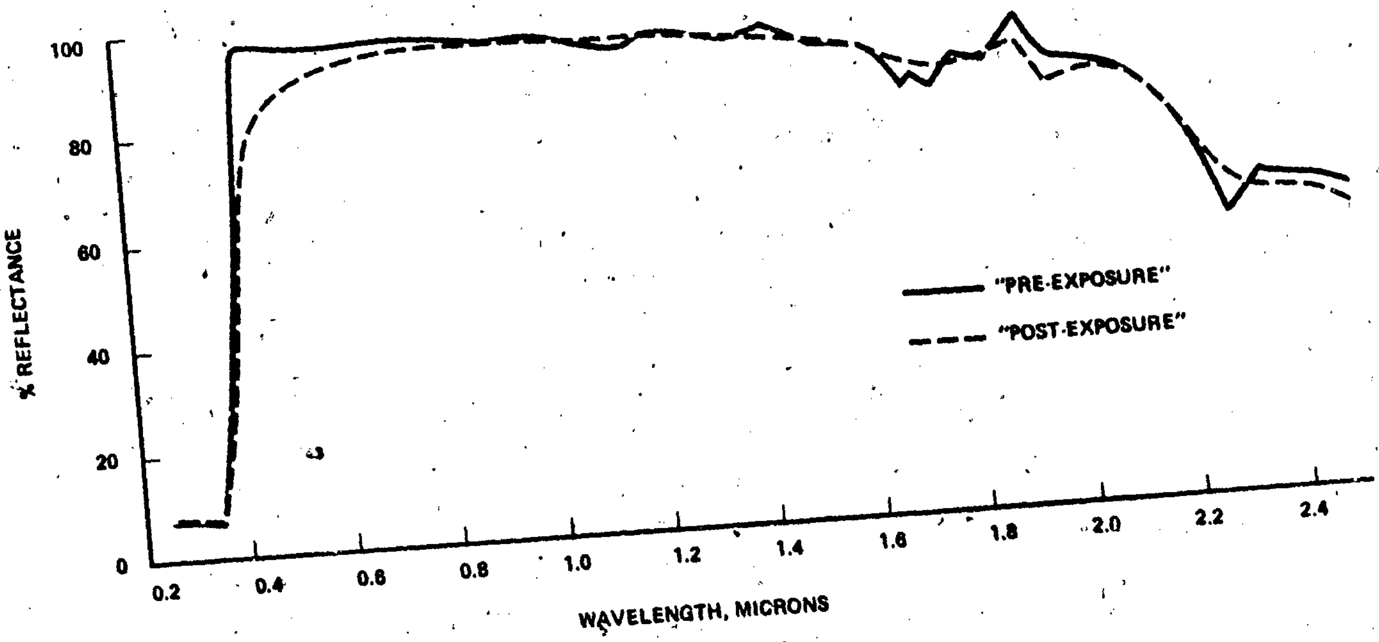

Figure 31. Spectral Reflectance of Thermal Control Paint Coupon No. 3 versus M_gO

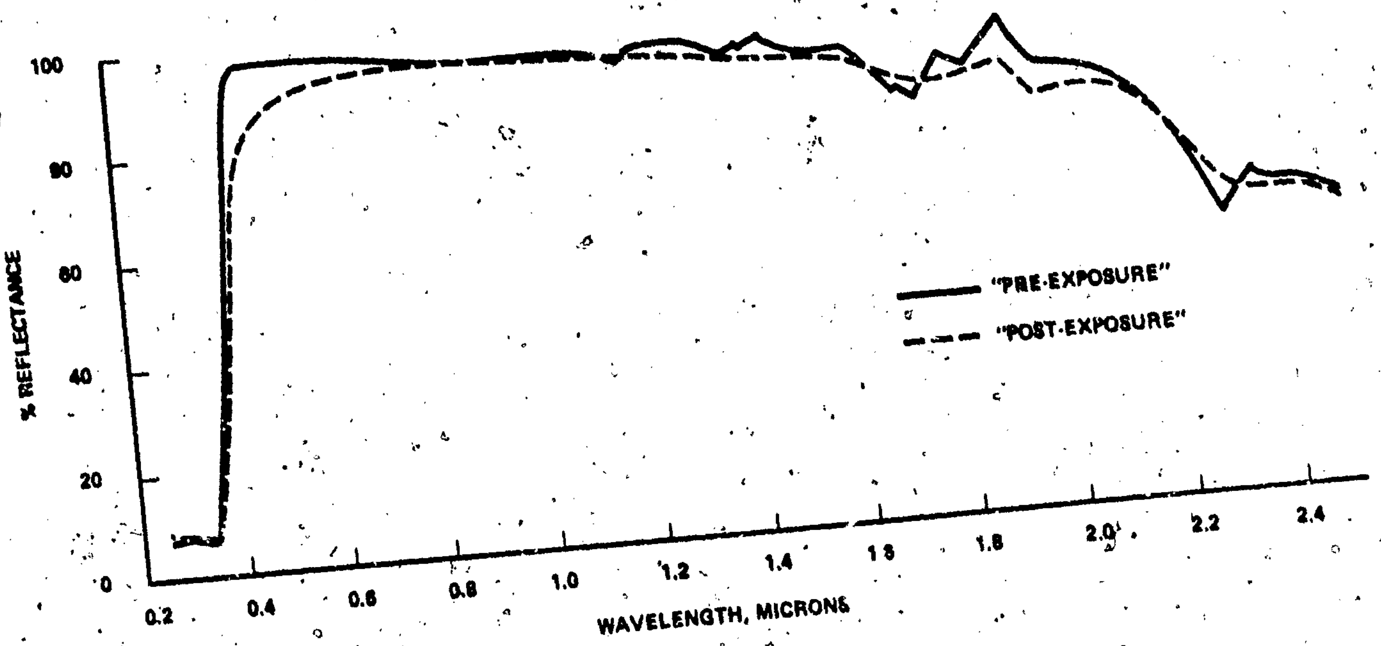

Figure 32. Spectral Reflectance of Thermal Control Paint Coupon No. 4 versus M_gO

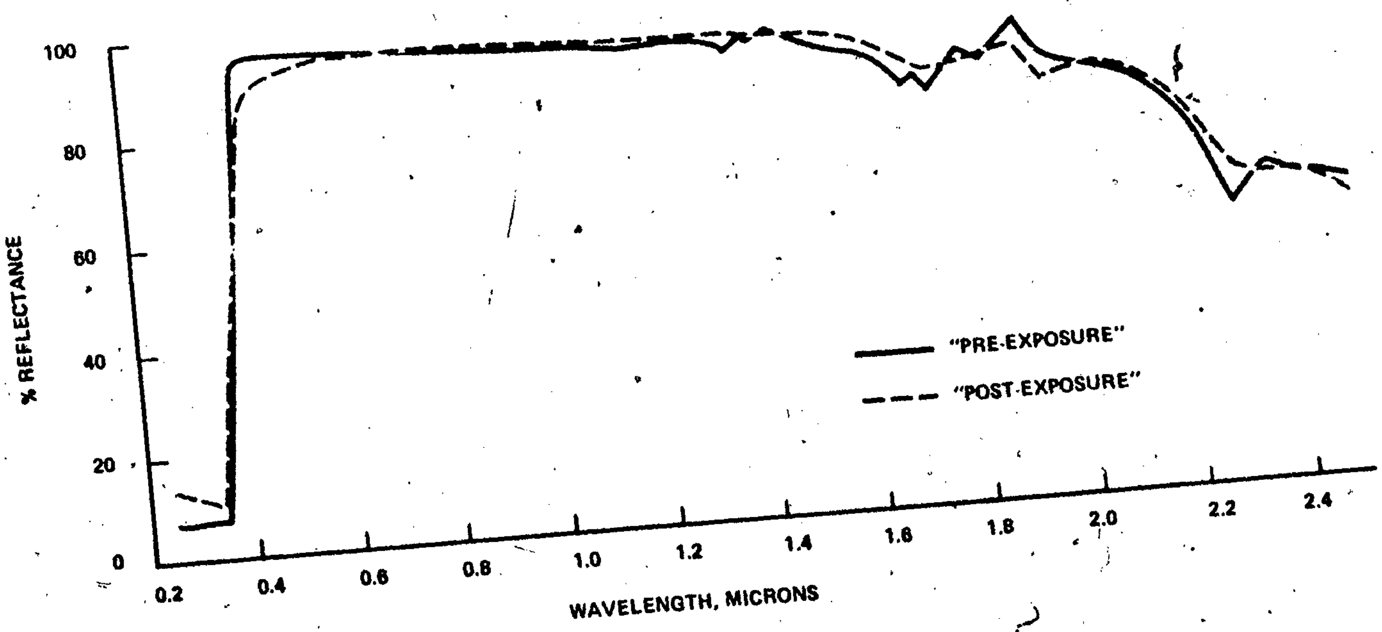

Figure 33. Spectral Reflectance of Thermal Control Paint Coupon No. 5 versus M_gO

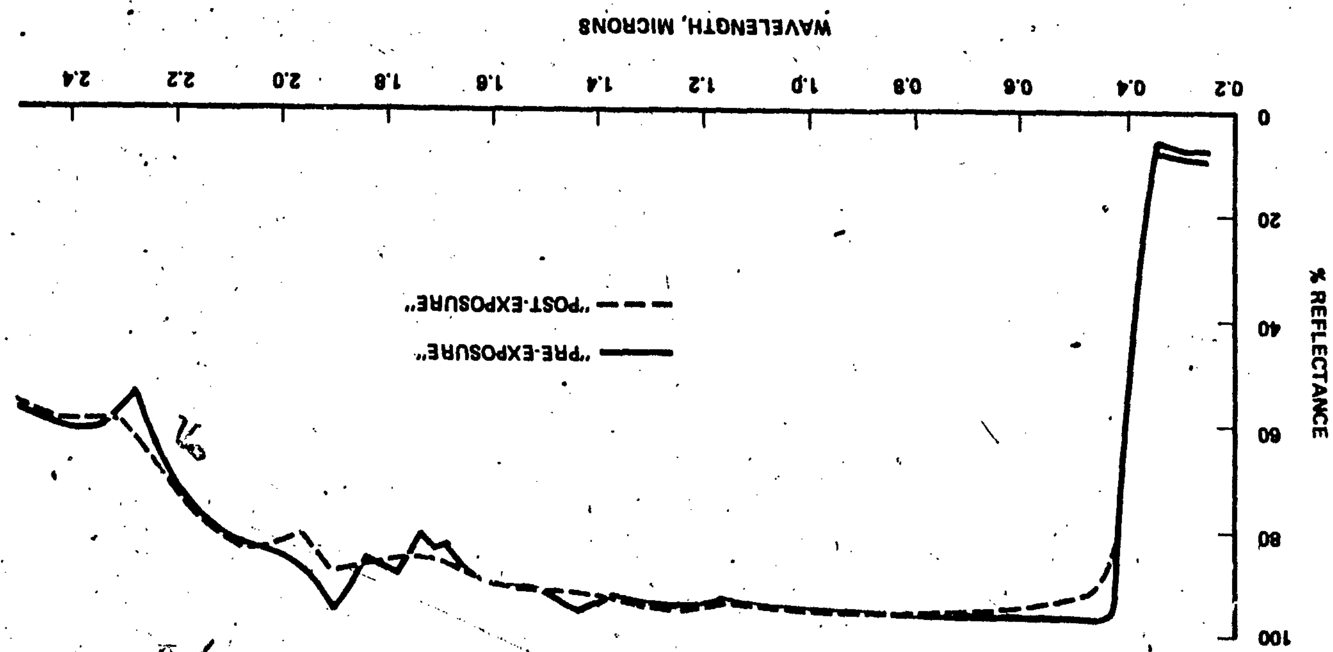

Figure 34. Spectral Reflectance of Thermal Control Paint Coupon No. 6 versus M_gO

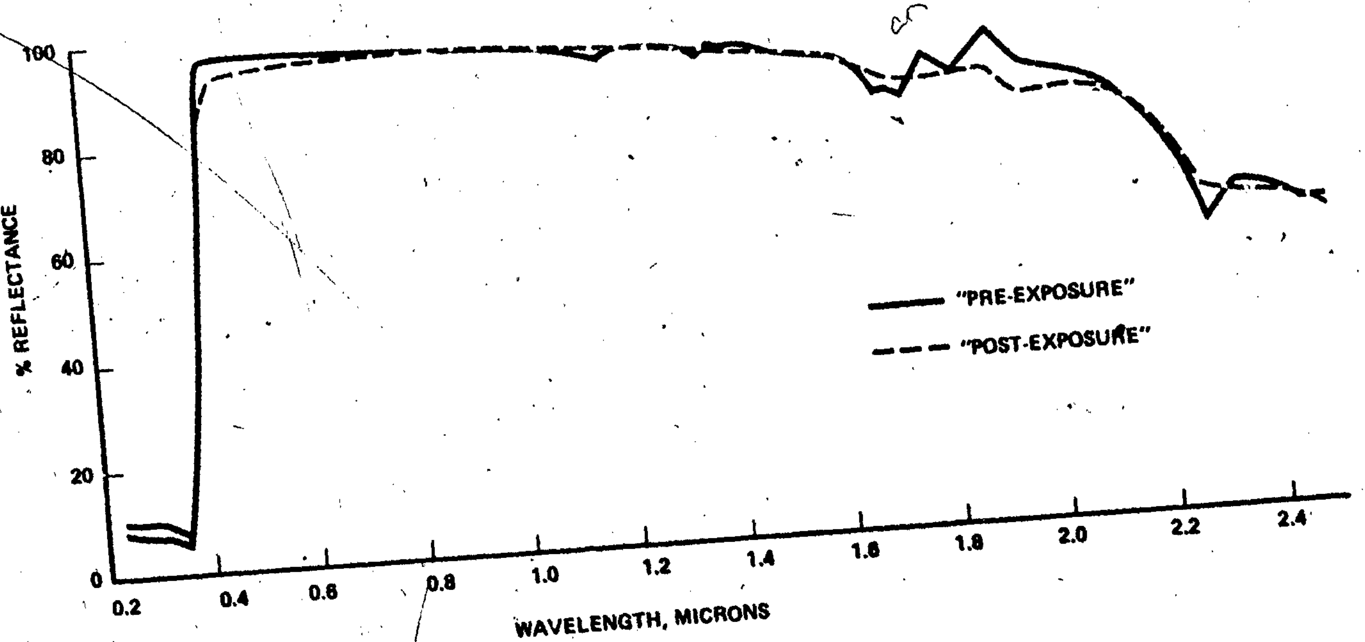

Figure 35. Spectral Reflectance of Thermal Control Paint Coupon No. 7 versus M_gO

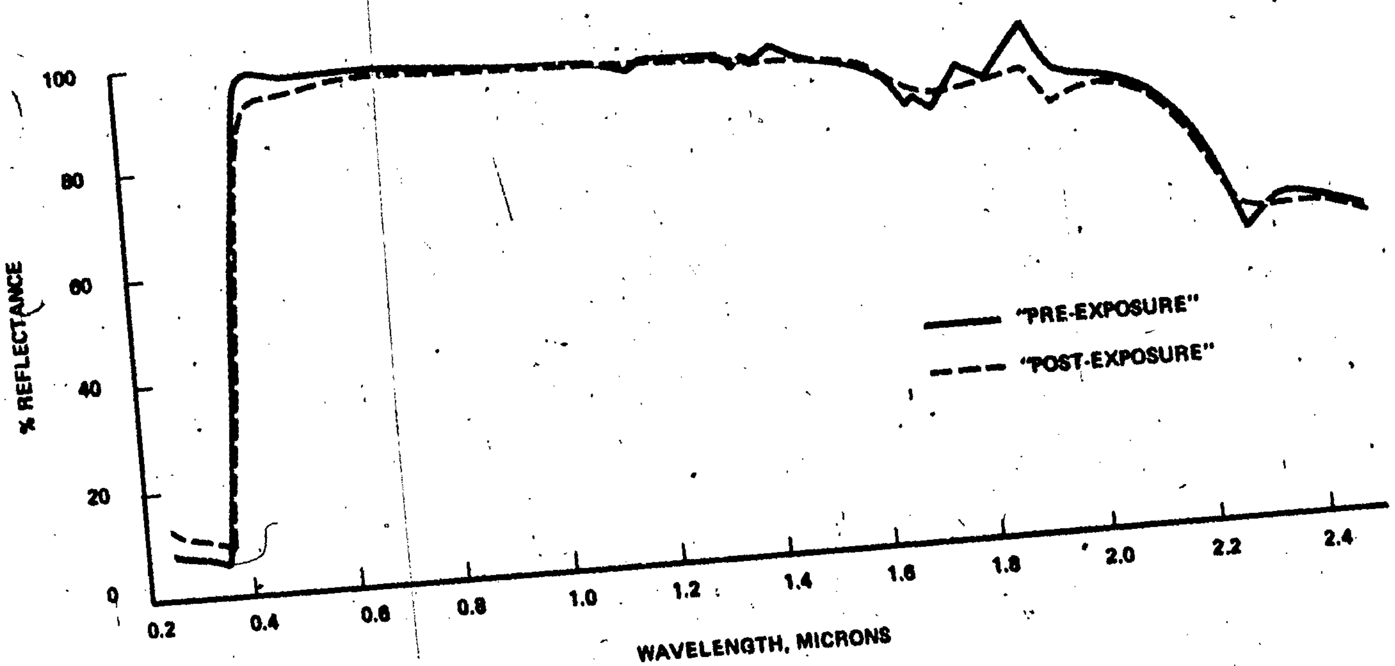

Figure 36. Spectral Reflectance of Thermal Control Paint Coupon No. 8 versus M_gO

surface texture of the paint coupons changed from a glossy to a dull finish as a result of repeated ACR firings. There also were brownish spots on some of the coupons located close to the rocket engine nozzle exit. This contaminant, in all probability, came from the engine nozzle lip, reference Figure 37.

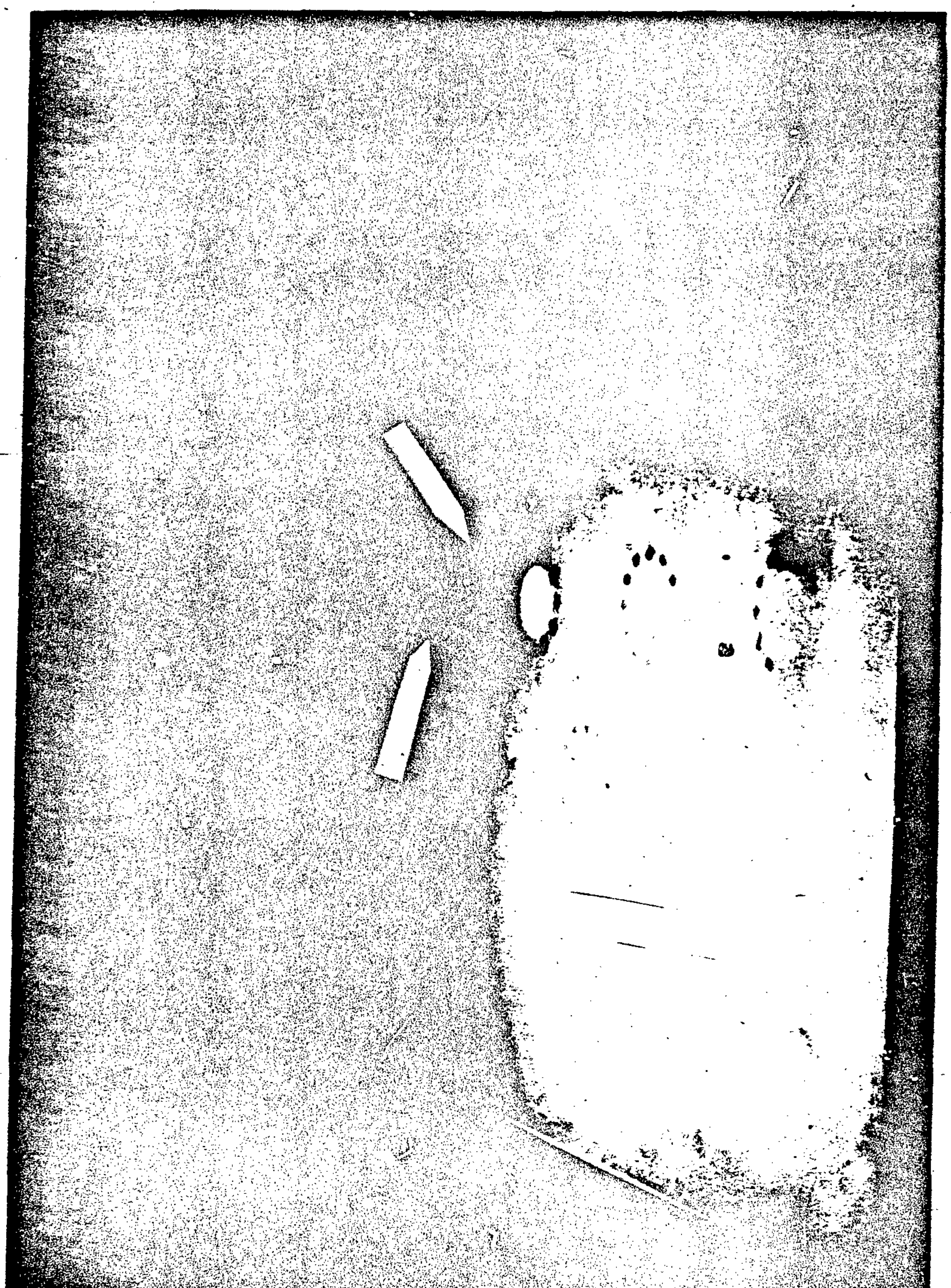

Figure 37. Nozzle Lip Contamination

SECTION IX

CONCLUSIONS

Direct plume impingement on optics and solar cells can result in a build-up of monomethylhydrazine nitrate in the form of a crystal-like structure. This condition can result in light scattering and/or image distortion of the optics. With regard to the solar cells, some deterioration in short circuit current and maximum power output will be experienced.

The thermal paint coupons which were subjected to parallel plume impingement experienced very little change in spectral reflectance with the exception of coupon number 2 which was located five (5) inches downstream of the rocket nozzle exit.

The texture of the exhaust contaminant changes from a crystalline structure when under vacuum conditions to an oily substance when exposed to the atmosphere.

SECTION X

RECOMMENDATIONS

It is recommended that laboratory-type equipment be used, if possible, in order to obtain realistic-type measurements under vacuum conditions, relative to changes in the operational characteristics of spaceborne equipment subjected to ACR plume contamination. The present method of removing the specimens from the vacuum environment for measurement in the laboratory under atmospheric conditions, presents several problems. These problems are (1) the change in contaminant structure prior to final laboratory measurements; (2) subjecting test specimens to air contamination and (3) time delay from completion of tests to obtainment of post-test measurements.

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13. ABSTRACT

This report presents the results of the Bipropellant Attitude Rocket (ACR) Plume Effects on Solar Cells, Optics and Thermal Paint. The objectives of this effort were to: (1) determine exhaust plume effects on the functional surfaces of a spacecraft, i.e., a change, if any, in the operational characteristics of this equipment and (2) identify the contaminant. Tests were conducted under vacuum conditions using a Marquardt R1E attitude control rocket engine. The propellants were nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH). The analysis of the test data revealed that the bipropellant attitude control rocket engine exhaust plume does have an effect on the operational characteristics of the spaceborne equipment, in varying degrees, dependent upon the location of the equipment with relation to the rocket engine nozzle exit. The exhaust plume contaminant has been identified as monomethylhydrazine nitrate.

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