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EFFECT OF CONTAMINATION ON SPACECRAFT SURFACES EXPOSED TO ROCKET EXHAUSTS

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ARO, Inc.

April 1968

AEROSPACE ENVIRONMENTAL FACILITY
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AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

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AEDC-TR-68-23, April 1968

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Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

Page 10, last paragraph of Section 4.2.3 should be replaced with:

The thermal control coatings exposed to pulse firings had decreases in reflectance of from 10 to 20 percent over most wavelengths. The solar absorptance change was as much as 146 percent. The largest solar absorptance changes of 83 percent for Z93 and 146 percent for LP40A would be detrimental to their design function of controlling heat loads. The decrease in reflectance and corresponding increase in solar absorptance for pulse exposed samples varied inversely with distance. These changes were caused primarily by decreases in reflectance below 0.7-μ wavelength. The decrease in reflectance for Z93 and AL2082 is accompanied by a shift in the reflectance cutoff wavelength.

Page 12, the third paragraph of Section V should be replaced with:

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FOREWORD

The work reported herein was done at the request of the Department of the Air Force for the Aerospace Corporation under Program Element 6340940F/632A.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The tests were conducted from April 13 through August 4, 1967, under ARO Project No. SM0708, and the manuscript was submitted for publication on December 27, 1967.

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This technical report has been reviewed and is approved.

Paul L. Landry
Major, USAF
AF Representative, AEF
Directorate of Test

Roy R. Croy, Jr.
Colonel, USAF
Director of Test

ABSTRACT

This report describes the contamination effects caused by rocket exhaust impingement on spacecraft surfaces. A rocket engine with a hypergolic propellant combination was fired at a simulated altitude of 300,000 ft. Thermal control coatings, highly reflective surfaces and transmission samples were exposed to the exhaust plume at various distances. For longer duration firings, reflectance and transmittance changes of less than 10 percent were measured for the exposed samples. A comparison of the effects from pulse operation and longer duration firings indicate that contamination occurs during ignition and shutdown. Samples exposed to the exhaust plume during pulse operation had a 10 to 20 percent decrease in reflectance and transmittance. Solar absorptance changes calculated from the reflectance varied from 10 to 147 percent. The contamination during pulse operation varied inversely with distance. Contaminants will be deposited on spacecraft surfaces exposed to the exhaust from a liquid propellant engine. The effects accumulated from many starts will jeopardize the purpose of functional spacecraft surfaces.

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SECTION I
INTRODUCTION

The deposition of contaminants from rocket engine exhaust gases impinging on spacecraft surfaces and associated spaceborne equipment has been recognized as a potential problem area (Refs. 1 and 2). This problem can be significant if the contaminants cause deterioration of the surface function, for all exterior surfaces of a spacecraft that are functional (e.g., passive thermal balance, waste heat radiator, and view port). The contamination could be cumulative for long duration rocket firings or multiple pulse firings, increasing the probability of deterioration on long term spacecraft missions such as the Manned Orbiting Laboratory or the Lunar Excursion Module. Investigations have been conducted and significant deposits and/or damage to surface coatings have been reported in Refs. 3 and 4.

The uncertainties concerning the deposition rate of contaminants and the magnitude of the effect on spacecraft surfaces pointed out an immediate need to investigate contamination and determine whether it was a major design problem. The purpose of this test was to measure the changes of two major physical characteristics, transmittance and reflectance, of test samples exposed to a rocket exhaust at simulated altitudes.

The tests were conducted at a simulated altitude of 300,000 ft using a liquid-propellant rocket motor. Various surface samples were exposed to either pulse or long duration firings at various locations in the chamber. Rocket engine firings of from 3 to 8 sec were considered long duration compared to pulse firings of 0.0225 sec. The transmission samples were silica and Pyrex®. The reflectance samples were platinum mirrors and three thermal control coatings. Visible contamination did occur and the effects were measured.

SECTION II
APPARATUS

2.1 MARK I AEROSPACE ENVIRONMENTAL CHAMBER

The Mark I system (Ref. 5) consists of a large cylindrical vacuum tank, pumping systems, thermal environmental systems, vibration system, controls, and instrumentation suitable for conducting tests on large space vehicles. A schematic of the facility is shown in Fig. 1, Appendix I. The chamber and associated equipment areas are shown in Fig. 2.

The Mark I chamber (Fig. 2) is a cylindrical vessel 42 ft in diameter and 82 ft high with 0.875-in.-thick walls and 1.5-in.-thick elliptical heads. The inside working dimensions of the chamber are 35 ft in diameter and 65 ft in height. The chamber shell is constructed of type 304L stainless steel for low outgassing and good corrosion resistance. Vehicle entrance to the chamber is through a 20-ft-diam hatch located in the top of the chamber. Personnel access to the chamber is through a hatch 8 ft in diameter near the bottom of the chamber.

Three pumping systems are available for evacuating the Mark I chamber: (1) a three-stage increment of the Propulsion Wind Tunnel Facility (PWT) plenum evacuation system; (2) a conventional vacuum pumping system consisting of roughing pumps, forepumps, booster pumps, and diffusion pumps; and (3) a cryopumping system cooled by a 90-kw liquid nitrogen and 10-kw gaseous helium system.

2.2 ROCKET ENGINE

Testing was conducted using a 23-lb_f pitch/yaw engine manufactured by Bell Aerosystem Company. The installation schematic and nozzle dimensions are shown in Fig. 3.

The engine was mounted in a supporting frame located on the chamber floor (Fig. 4). The rocket engine was fired vertically upward with the rocket nozzle centerline located near the test chamber vertical centerline. The thrust chamber and nozzle were constructed in a stainless steel heat-sink configuration, duplicating the internal geometry of the prototype engine.

A hypergolic propellant combination was used in the engine. The fuel was monomethylhydrazine (MMH) and conformed to the analysis of Military Specification MIL-P-27404-MMH. The oxidizer was nitrogen tetroxide (N_2O_4) and conformed to the analysis of Military Specification MIL-P-26539-N_2O_4. The fuel cleanliness conformed to class four or better of "Bell Specification BPS4276A" (see Appendix III). The propellant mixture ratio was 1.60 ±0.05, and the flow rates are given in Ref. 6. The engine was operated at a combustion chamber pressure of 125 psia. The engine and propellant temperatures were maintained at 21 ± 10°C (70 ± 18°F).

2.3 SURFACE SAMPLES

The test samples (Fig. 5) used in this test were three types of thermal control coatings, platinum mirrors, Pyrex slides, and silica disks. The

surface areas of the test samples were between 0.7 and 1.7 in.^{2}. The transmittance of silica and Pyrex was measured before and after exposure to the rocket exhaust. Reflectance measurements of the thermal control coating and platinum mirror surfaces were made before and after exposure to the rocket exhaust. The composition of the thermal control coatings are given in Table I, Appendix II. The three coatings are designated as AL2082, Ceramic Enamel, LP40A, and Z93.

Platinum was selected for use as mirror surfaces after withstanding test exposures to rocket exhaust. Prior tests ruled out aluminum.

2.3.1 Sample Mounting

Surface samples were mounted at various distances from the engine nozzle exit. The sample locations and their relation to the exhaust plume are shown in Fig. 6. The superimposed plume boundary was calculated for stable engine operation at the test altitude. The samples were enclosed in an "optically tight" temperature controlled container shown in Fig. 7. This container prevented direct impingement from any oil backstreaming or dripping from cryopanels. The sample container was remomotely opened for the duration of the engine firing. The thermal control sample surfaces were mounted parallel to streamlines emanating from the engine exit, and the mirror and glass sample surfaces were mounted perpendicular to the streamlines. Samples and a deposit thickness monitor located 10 ft from the engine exhaust were mounted from a traversing beam. Before most engine firings, the traversing beam and the attached samples or instrmentation were relocated. Mirrors and glass samples were located in the nozzle exit plane during the pulse operation. The samples were mounted parallel and perpendicular to the nozzle exit plane at three locations shown in Fig. 6. The samples were protected by a shield from drippings of the cryopanels.

2.4 INSTRUMENTATION

2.4.1 Laboratory Instrumentation

A Beckman Model DK-2A spectrophotometer and associated transmittance and reflectance attachments were used to obtain transmittance and reflectance measurements, respectively, for the wavelength range of 0.25 to 2.5 μ.

The repeatability and accuracy of the electrical system is within ±1 percent of full-scale value. When used to measure transmittance, it has

been observed to yield data within these limits. When used as a spectro-reflectometer, the limits of error are increased because of the use of magnesium oxide (MgO) standards.

The resultant spectral reflectance measurement is relative to MgO and is corrected with reported absolute spectral reflectance values for MgO (Ref. 7). The reflectance of MgO varies with time, therefore the MgO plates are resmoked for each series of measurements associated with a chamber pumpdown or exposure test. The MgO plates smoked at the same time, under similar conditions, have absolute reflectance which can vary ±3 percent.

The infrared reflectance measurements were accomplished with a Beckman IR-4 spectrophotometer and two specular reflectance attachments. The wavelength range of this instrument is from 1 to 15 μ with an accuracy to 0.015 μ and a reproducibility of 0.005 μ. The accuracy of the reflectance data is ±1 percent. The standard for the infrared reflectance measurements was vacuum-evaporated gold. The specular reflectance of gold is given in Ref. 8.

2.4.2 Contamination Mass Deposit Measurements

A Sloan DTM-2A quartz crystal thickness monitor was installed in the Mark I chamber for the purpose of measuring the relative quantities of rocket plume materials which condensed on the crystal during a firing. The instrument used a crystal oscillator circuit within the chamber which changed in output frequency when mass was deposited on the crystal. The output frequency change was monitored by a 5 MHz counter to ±1 Hz. The crystal holder was temperature controlled by resistance heating to approximately 21°C (70°F).

2.4.3 Chemical Analysis

An infrared spectrochemical analysis to determine contaminants was made of crystalline salt (NaCl) disks which had been exposed to the rocket plume. The salt disks were mounted in the sample containers perpendicular to the streamlines emanating from the nozzle exit. The accumulative residue deposited on the chamber walls was analyzed for comparison to the exposed salt crystals. The liquid contamination deposited at the nozzle exit was captured during pulse firing in a container (Fig. 8). The chemical sample container was sealed with a solenoid operated vacuum valve immediately after completing the pulse firings. The container remained closed until the samples were removed at the laboratory for chemical analysis.

2.4.4 Chamber Pressure

The chamber pressure was monitor with two Alphatron® gages, two ionization gages, and one Baratron® gage. Absolute pressure transducers measured rocket engine chamber pressure.

SECTION III
PROCEDURE

3.1 SURFACE SAMPLES

Transmittance measurements were made of Pyrex slides and fused silica samples. Prior to any data being taken, the slides were washed in isopropyl alcohol, given a final rinse in clean alcohol, and wiped dry with a fresh optical tissue. After cleaning, each slide was held by a spring clip and hung in a storage box until used. The mirrors used in reflectance measurements were individually mounted in a protective box from the time they were made until used. The salt disks were stored in a desiccator except when used in the chamber.

All test samples were mounted in their sample containers immediately prior to sealing the Mark I chamber. The sample container temperature was monitored and controlled during the chamber pumpdown, testing, and repressurization. The sample containers were opened only during rocket firings. Immediately after opening the chamber, the samples were removed and placed in their protective containers.

3.2 TEST PROCEDURE

The test samples were mounted in the sample containers prior to sealing the Mark I chamber. The Mark I chamber was initially evacuated to 5×10^{-6} torr to achieve a nominal 300,000 ft (10^{-3} torr) simulated altitude during engine firings. The containers were opened exposing the samples during the rocket engine firing. Then the sample containers were closed while the desired chamber pressure was re-established. This sequence was repeated until the desired exposure time was accumulated. The samples were removed from the Mark I chamber immediately after repressurization.

The engine was remotely fired by energizing the bipropellant valve for the firing duration required. Rocket engine firings of 0.0225 sec are denoted as pulse firings, and firings of from 3.0 to 8.0 sec are denoted as long duration firings. During the pulse mode of operation there was one firing every 3.0 sec until the total exposure time was accumulated.

The sample containers were not closed between the individual firings of pulse operation. A typical engine combustion chamber pressure during pulse firing is given in Fig. 9.

3.3 INSTRUMENTATION

Reflectance of each sample was measured over a wavelength range of 0.25 to 2.5 μ, relative to fresh MgO reference. The samples were then stored in protective enclosures until placed in the test cell. After removal from the test cell the samples were returned to the laboratory where the relative reflectance was again measured versus the MgO reference.

For transmittance measurements, a clean sample was placed in the sample beam of the spectrophotometer and data taken over a wavelength band of from 0.190 to 2.8 μ. The reference path contains only air, the same gas as is present in the sample path. The recorded data are then the absolute transmission of the sample. After the sample was subjected to contamination, its absolute transmission was obtained for the same wavelength band. The change in transmittance is assumed to be entirely caused by absorption by the contaminant.

Reflectance of the sample platinum mirrors was measured over a wavelength range from 1.0 to 15.0 μ, relative to a gold reference. The samples were then stored in protective enclosures until placed in the test cell. After removal from the test cell, the reflectance was again measured relative to the same gold standard mirror. The measurements represent both changes in the substrate (platinum) surface caused by changes in the mirror and to deposited layers of exhaust products.

SECTION IV
RESULTS AND DISCUSSION

The appearance of the contaminants on the sample surfaces is described. The chemical analysis data and the effects of surface contamination on optical properties are presented.

4.1 VISIBLE EFFECT

4.1.1 Thermal Control Coatings

Normally there were no visible changes on the thermal control coating surfaces as a result of contamination. A typical exposed surface

and a damaged LP40A surface are shown in Fig. 10. The LP40A sample was located 51 in. from the engine exit when damaged. The damage appears to be a bond failure of the brittle material. Since the LP40A surface was not damaged at the closer distances of 10 and 23.3 in., the bond failure could be viewed as an exception not caused by exposure to the rocket exhaust.

4.1.2 Mirror and Glass Slides

Colorless contaminants were visible on the exposed surfaces of the mirrors and glass slides. The contamination was uniformly distributed and did not obstruct vision through the glass samples. Photomicrographs of a mirror surface before and after exposure are shown in Fig. 11. The contamination film consisted of a series of droplets or beads.

The contaminants deposited on the samples appeared to be stable. An exception was the deposit on one silica disk which changed while the transmittance was being measured. The data from two successive analyses varied as much as 30 percent and are presented in Fig. 12 without explanation.

The contaminants on glass slides and mirrors exposed to long duration firings were deposited in a thin hazy film. The contaminants deposited during the pulse firings formed a thick film or puddle on the glass slides and mirrors. During pulse firings, contamination was deposited on the glass and mirror samples 13 and 20 ft from the engine in the nozzle exit plane (Fig. 6). These locations would be outside of an exhaust plume formed at equilibrium conditions of longer duration firings.

During pulse firings, the surfaces of the mirrors (Fig. 13), at 23 and 51 in. in front of the engine exit, were damaged. The mirror surface at 23 in. had over 65 percent of its area stripped, and the remaining portion was not a good reflector. About 10 percent of the mirror surface at 51 in. was stripped, and 60 percent of the surface was cracked.

4.1.3 Rocket Engine Exit

During pulse operation, contaminants were deposited at the nozzle exit in sufficient quantity to spill over the side of the nozzle as evident in Fig. 14. This deposition, a brown viscous liquid, could explain the contamination observed outside the exhaust plume. The contaminants at the nozzle exit appeared to shake or jump when the engine fired. Therefore the deposit could have been blown outside the plume. The deposit at the nozzle exit appeared to scintillate. This may be explained by

reflection of photographic lights or by explosions. Explosions could blast the contaminants outside the exhaust plume.

4.2 EFFECT ON OPTICAL PROPERTIES

The effects of contamination on the optical properties of transmittance and reflectance were in general related to the amount of deposition. The reflectance and transmittance of samples exposed to the longer duration firings experience changes of less than ±10 percent over the wavelength span measured. Samples with the larger amount of deposits from cumulative exposure to the pulse firings experienced a decrease in transmittance and reflectance of from 10 to 20 percent.

4.2.1 Transmittance Measurements

Pyrex slides were exposed for the combinations of longer duration firings and the various locations listed in Table II. The transmittance changes during these exposures were very small, varying from the measured clean values by no more than 7 percent. A typical transmittance change for these exposures is shown in Fig. 15.

Pyrex slides were exposed during the pulse operation at the locations listed in Table II. The effect on the contaminant was a decrease in transmittance over the measured wavelength range. Figure 16 shows the transmittance decrease for slides mounted in front of the engine exit of 6 percent at 51 in. and 12 percent at 23 in. The samples in the nozzle exit plane experienced contamination (Fig. 17), including the locations outside the plume. For the samples in the nozzle exit plane, the surfaces parallel to the plane had larger transmittance changes than surfaces at similar locations perpendicular to the plane. The transmittance decrease was greater when the slides were closer to the nozzle exit as indicated by Figs. 16 and 17.

Data for the transmittance change of a contaminated silica disk after pulse exposure are shown in Fig. 18. The transmittance change of silica disks exposed to longer duration firing was less than the change from pulse exposure. Both types of exposures had the major changes between the wavelengths of 0.2 and 0.3 μ.

4.2.2 Reflectance Measurements of Mirrors

Platinum mirrors were used in all combinations of exposure time and location (Table II) during the test sequence. The clean reflectance data from 0.2 through 14 μ varied considerably between the various mirrors used in the test (e.g., from 65 to 85 percent at 1.5 μ)

Mirrors exposed to long duration firings had a decrease in reflectance of less than 10 percent over the wavelength range from 0.3 to 2.5 μ. A typical change is presented in Fig. 19. The infrared reflectance data, from 2 to 14 μ, for the same mirrors resulted in negligible change at all exposures except the 24-sec duration. The samples exposed 24 sec had a reflectance increase of 12 percent at 23.3 in. from the nozzle exit and 25 percent at 51.3 in.

The mirrors exposed to pulse firings and located in front of the nozzle exit suffered surface damage. The reflectance surfaces (Fig. 13) were ruined at these locations. The damage was more severe for the sample closer to the engine exit. Based on experience from this test, damage to reflective surfaces similarly exposed would be highly probable in actual flight.

The platinum mirrors exposed to pulse firings and located in the nozzle exit plane were covered with a thin film of contaminant. These mirrors experienced a reflectance decrease over the wavelength from 0.27 to 2.5 μ.

The typical reflectance change is plotted in Fig. 20. The maximum reflectance decrease of 40 percent occurred at 0.26 μ. The reflectance reduction for surfaces parallel to the nozzle exit plane were larger than for surfaces at corresponding locations perpendicular to the plane. The reflectance decrease varied inversely with distance of the sample from the nozzle exit.

The effect on infrared reflectance data of contamination on mirrors in the nozzle exit plane exposed to pulse firings was a variation from an increase to a decrease of infrared reflectance. The reflectance change of the individual mirror was fairly consistent over the wavelength range from 2 to 14 μ as shown in Fig. 21. The variation of percent reflectance change at 8 μ is shown below for the mirrors in the nozzle exit plane. The infrared reflectance increases as the surface is exposed closer to the engine.

PERCENT REFLECTANCE CHANGE AT 8 MICRONS

Distance from nozzle exit[a], ft	20	13	2
Perpendicular[b]	-16	-2	16
Parallel[c]	15	27	31

[a]See Fig. 6
[b]Mirror surface perpendicular to nozzle exit plane
[c]Mirror surface parallel to nozzle exit plane

4.2.3 Reflectance Measurements of Thermal Control Coatings

Reflectance data for the three thermal control coatings are presented in Figs. 22 through 27. There are two graphs for each coating: (1) a typical change after exposure to long duration firings, and (2) the changes after exposure to pulse firings. The reflectance data changes caused by contamination were used to calculate the corresponding effect on the solar absorptance. The solar absorptance change listed in Table III is indicative of change in the ability of the thermal control coating to function in controlling thermal heat loads.

The thermal control coatings exposed to long duration firings had reflectance changes of less than 10 percent over most of the 0.25- to 2.5-μ range. The largest reflectance change was experienced by the LP40A sample in the wavelength range from 0.28 to 0.45 μ as shown in Fig. 22. The maximum solar absorptance change for AL2082 and Z93 were 11 and 17 percent. The large reflectance change from 0.28 to 0.45 μ for LP40A caused the solar absorptance to change as much as 46 percent.

The thermal control coatings exposed to pulse firings had decreases in reflectance of from 10 to 20 percent over most wavelengths. The solar absorptance change was as much as 146 percent. The largest solar absorptance changes of 83 percent for Z93 and 146 percent for LP40A would be detrimental to their design function of controlling heat loads. The decrease in reflectance and solar absorptance for pulse exposed samples varied inversely with distance. These decreases were primarily caused by changes in reflectance below 0.7-μ wavelength. The decrease in reflectance for Z93 and AL2082 is accompanied by a shift in the reflectance cutoff wavelength.

4.3 CONTAMINATION MASS DEPOSIT MEASUREMENTS

A deposit thickness monitor was used to measure the accumulation of contaminants for rocket firings at various plume locations. The detector was initially located at the outer part of the plume. After most engine firings the detector would be relocated, thus scanning past the engine centerline, through the plume. Data taken for the engine firings during three separate chamber evacuations are recorded in Table IV. Contaminant deposition was recorded in the outer portion of the plume, whereas mass removal or cleaning was experienced in the central core. During two pumpdowns, the deposit thickness monitor failed because the platinum surface of the detector was removed or cleaned. The central core of the plume, where surfaces were cleaned, had a 1.5-ft radius 10 ft from the nozzle exit. The central core

would form an 8.5-deg half-angle cone with the apex at the nozzle exit. The mass of contaminants deposited cannot be determined because the deposition was not an even film (liquid drops) and its specific gravity is unknown.

4.4 CHEMICAL ANALYSIS

The NaCl crystals were exposed to several rocket firings during a pumpdown. The deposition on the NaCl crystals was analyzed by infrared spectroscopy and the resulting spectra had strong nitrate peaks. The nitrate concentration of the deposit on a mirror exposed beside a NaCl crystal was determined as 0.08 mg for the 12 cm^2 surface area. Ammonium nitrate was identified as the deposit on a protective wrapping of aluminum foil which had been exposed to many rocket firings during several chamber pumpdowns.

The contaminants generated during pulse firing were entrapped in a sample container. The contaminants in the container, when opened for chemical analysis, were liquid with an 8-mm-diam ball of liquid-impregnated crystals. When the crystals were spread on a microscope slide, they turned to liquid; the infrared spectrum of the material is presented in Fig. 28. The sample contained amine and nitrate groups and was slightly acidic to litmus. The wide melting point range of from -54 to -37°C (-65 to -35°F) indicates that the material is not a pure compound. Preignition reaction products have been observed (Ref. 9). The adducts formed were described in this reference as a clear, yellow, viscous liquid, and the infrared spectrum (Fig. 29) was similar to the liquid formed in pulse operation.

SECTION V
CONCLUSIONS

It has been shown that contaminants are deposited on surfaces exposed to the rocket exhaust of a liquid-propellant engine. The deposition was a thin hazy film of clear viscous liquid droplets evenly distributed on the sample surface. The hazy film, visible on the glass and mirror samples, changed reflectance and transmittance. The visible contamination film appeared stable, and its thickness varied inversely with the distance from the engine.

Sample exposures accumulated from long duration firings (3 sec or greater) caused up to 10 percent changes in reflectance and transmittance.

The mirrors experienced reflectance decreases up to 10 percent. The measured changes were 7 percent for glass and 10 percent for thermal control coatings. The maximum changes in solar absorptance for the thermal control coating were: 11 percent for AL2082, 17 percent for Z93, and 46 percent for LP40A.

Sample exposures accumulated from pulse firings (0.0225 sec) caused decreases of feflectance and transmittance of from 6 to 20 percent. In the wavelength range from 0.25 to 2.5μ the transmittance, reflectance, and solar absorptance decreased inversely with the distance from the engine. The infrared reflectance of the mirror samples experienced both decreases and increases. The change of infrared reflectance varied directly with the distance from the engine. Surface damage was experienced by the mirror surfaces directly in front of the engine exit during pulse operation. The maximum decreases in solar absorptance for the thermal control coatings were: 25 percent for AL2082, 83 percent for Z93, and 146 percent for LP40A.

Mass removal or cleaning was experienced in the central core of the exhaust plume. Brown viscous liquid contaminants were deposited at the nozzle exit during the pulse mode of operation. The deposition was much greater during the pulse operation. This indicates that contamination occurs primarily during engine ignition and shutdown. The engine was a prototype of an engine rated for pulse mode operation, and the test results are directly applicable. An increase of solar absorptance and a decrease of infrared emittance of thermal control coatings would result in more heat being retained in the spacecraft. This case is possible if the results of the exposed mirrors, showing increasing infrared reflectance, are applicable to thermal control coatings. The increased heat load on the spacecraft would damage temperature sensitive, critically designed components.

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APPENDIXES

I. ILLUSTRATIONS
II. TABLES
III. PROPELLANT CONTAMINATION CONTROL SPECIFICATIONS

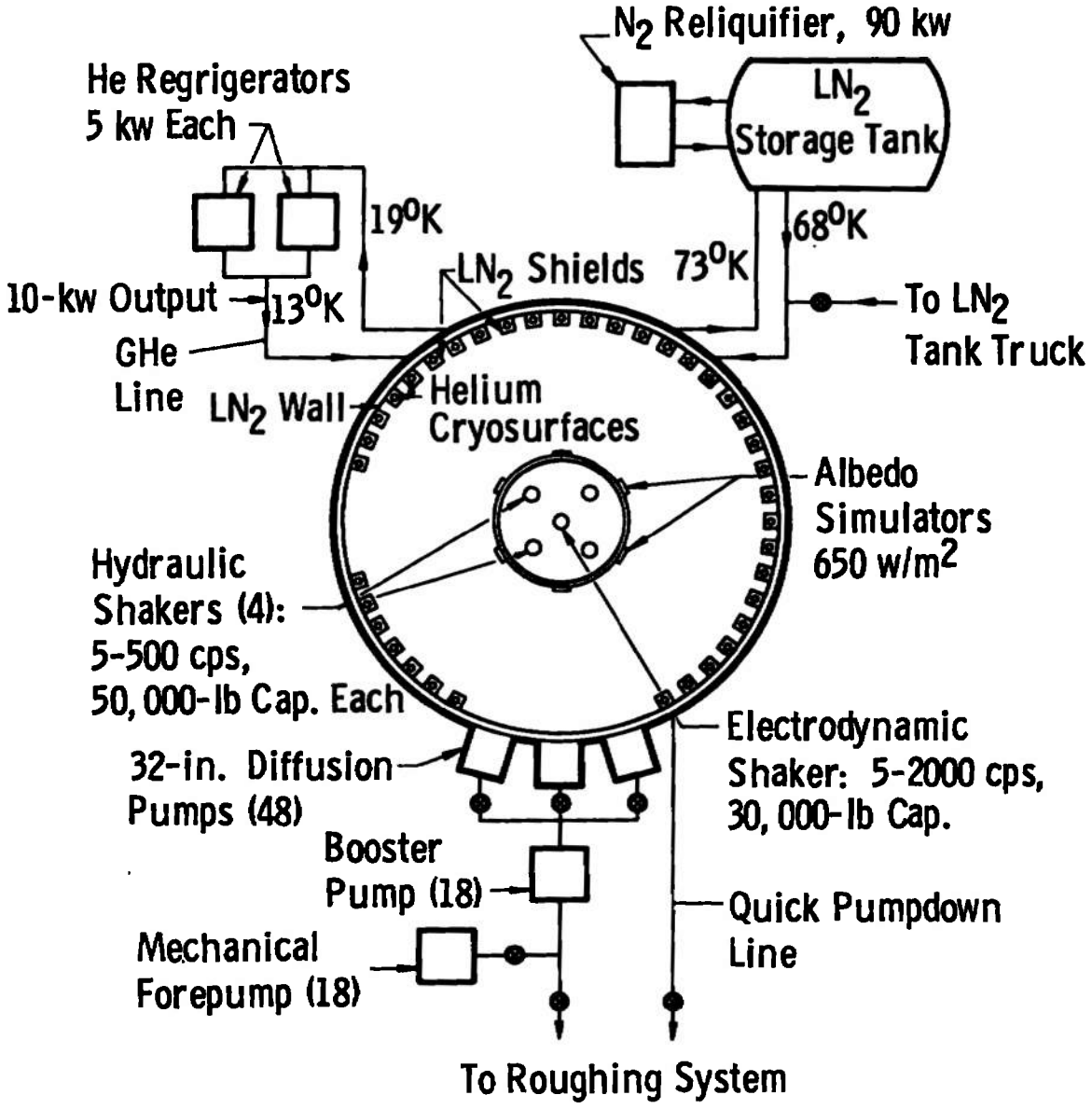


Fig. 1 Mark I Schematic

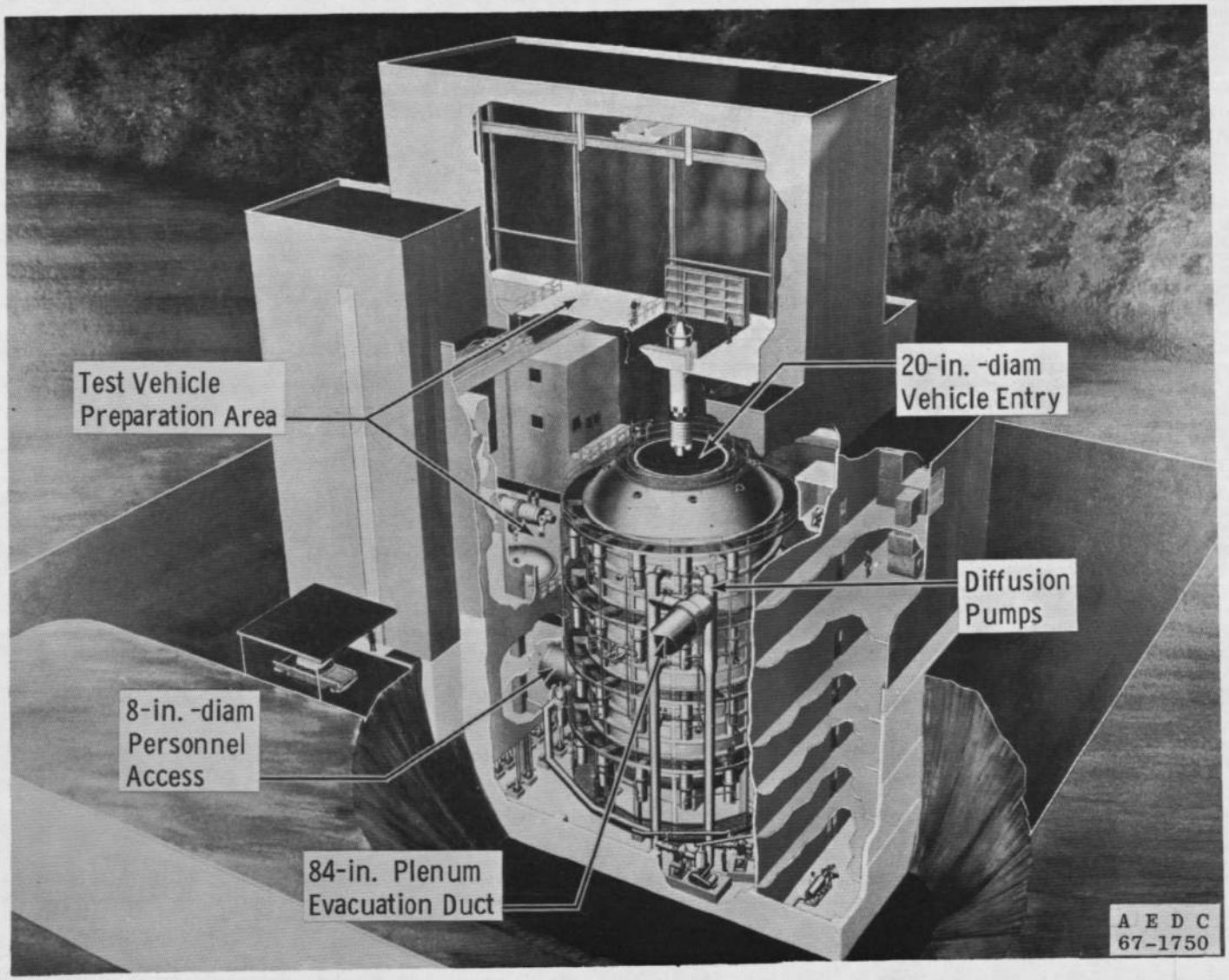


Fig. 2 Mark I Chamber

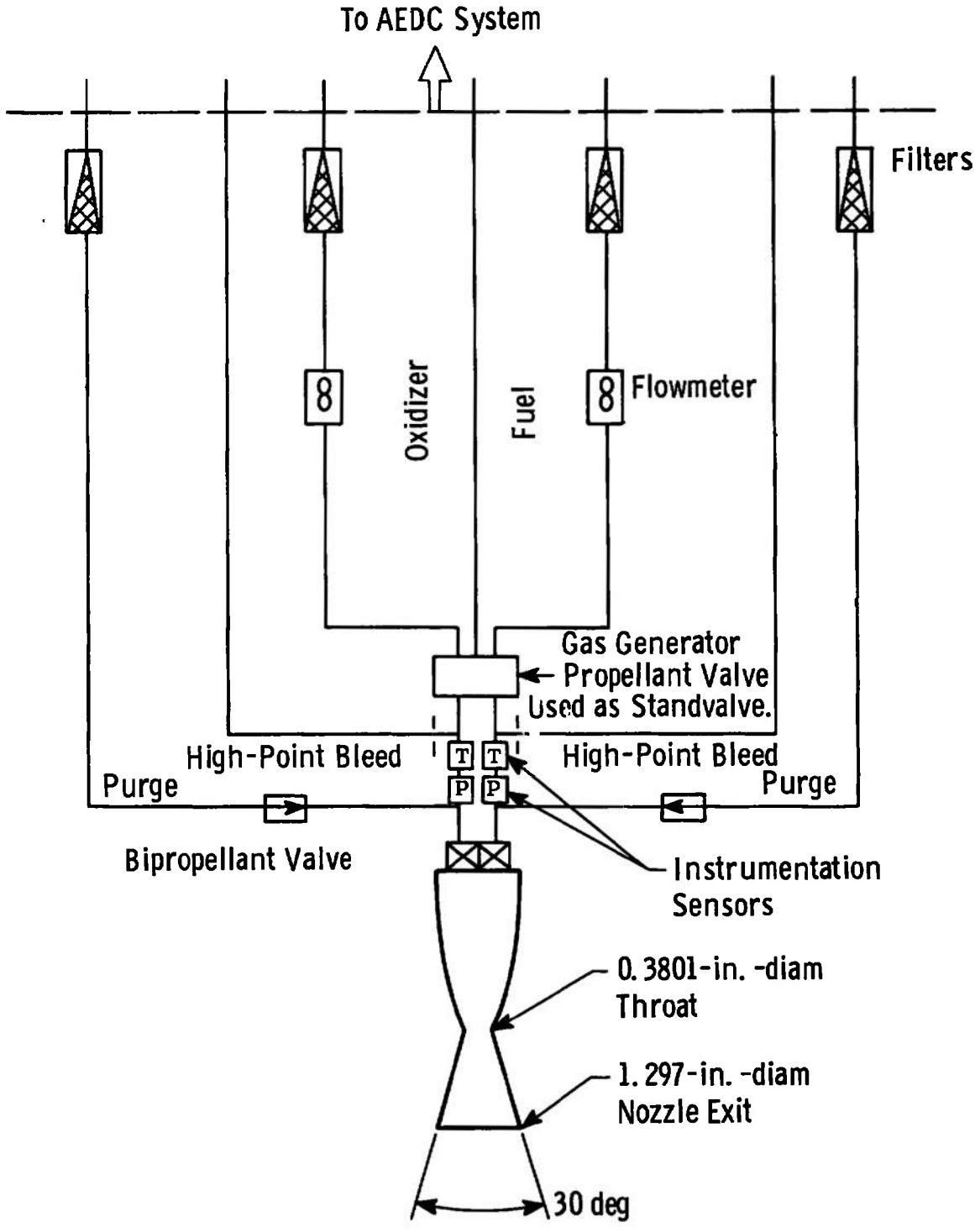


Fig. 3 Rocket Engine Test Module Schematic

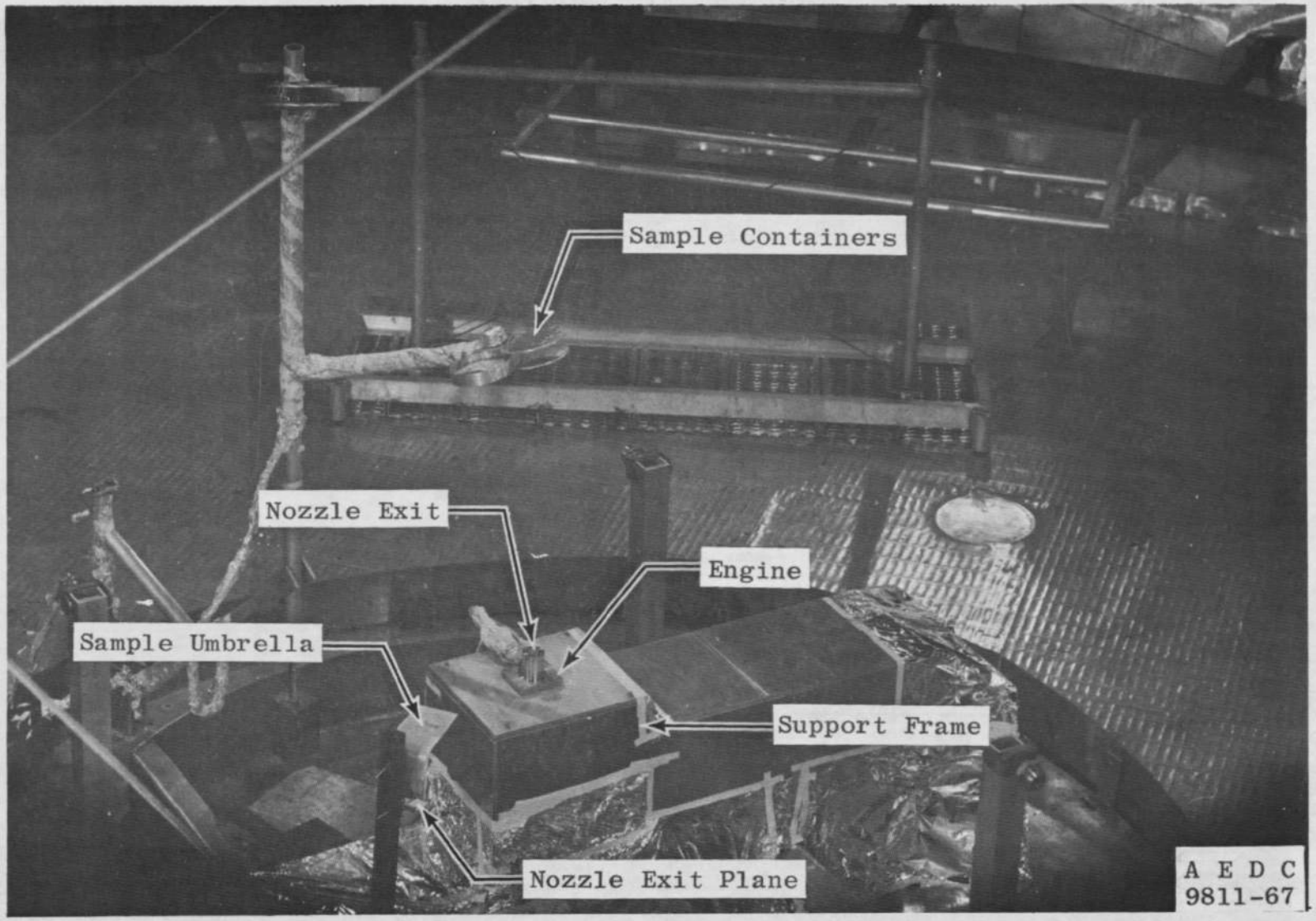


Fig. 4 Test Installation

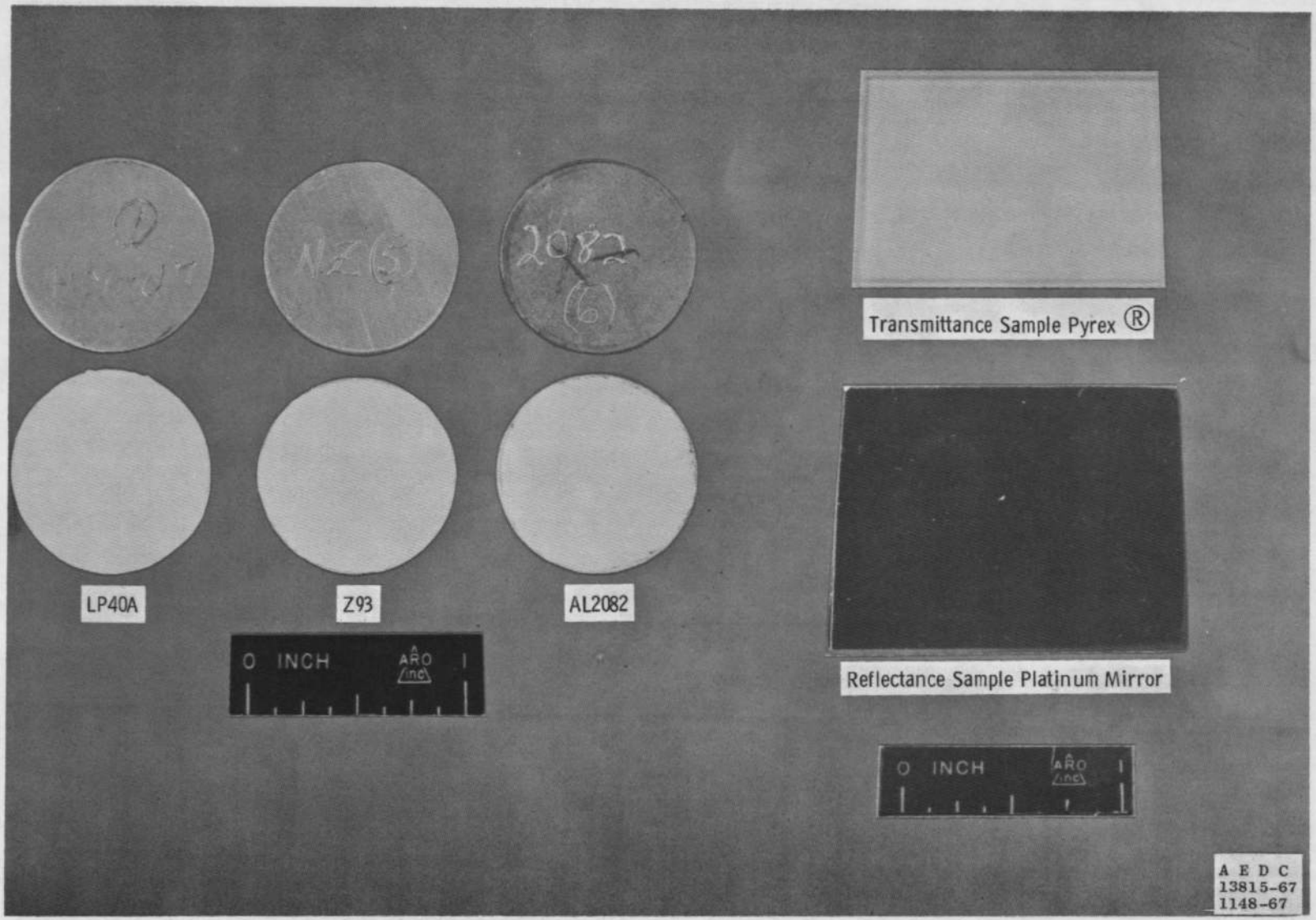


Fig. 5 Unexposed Surface Samples

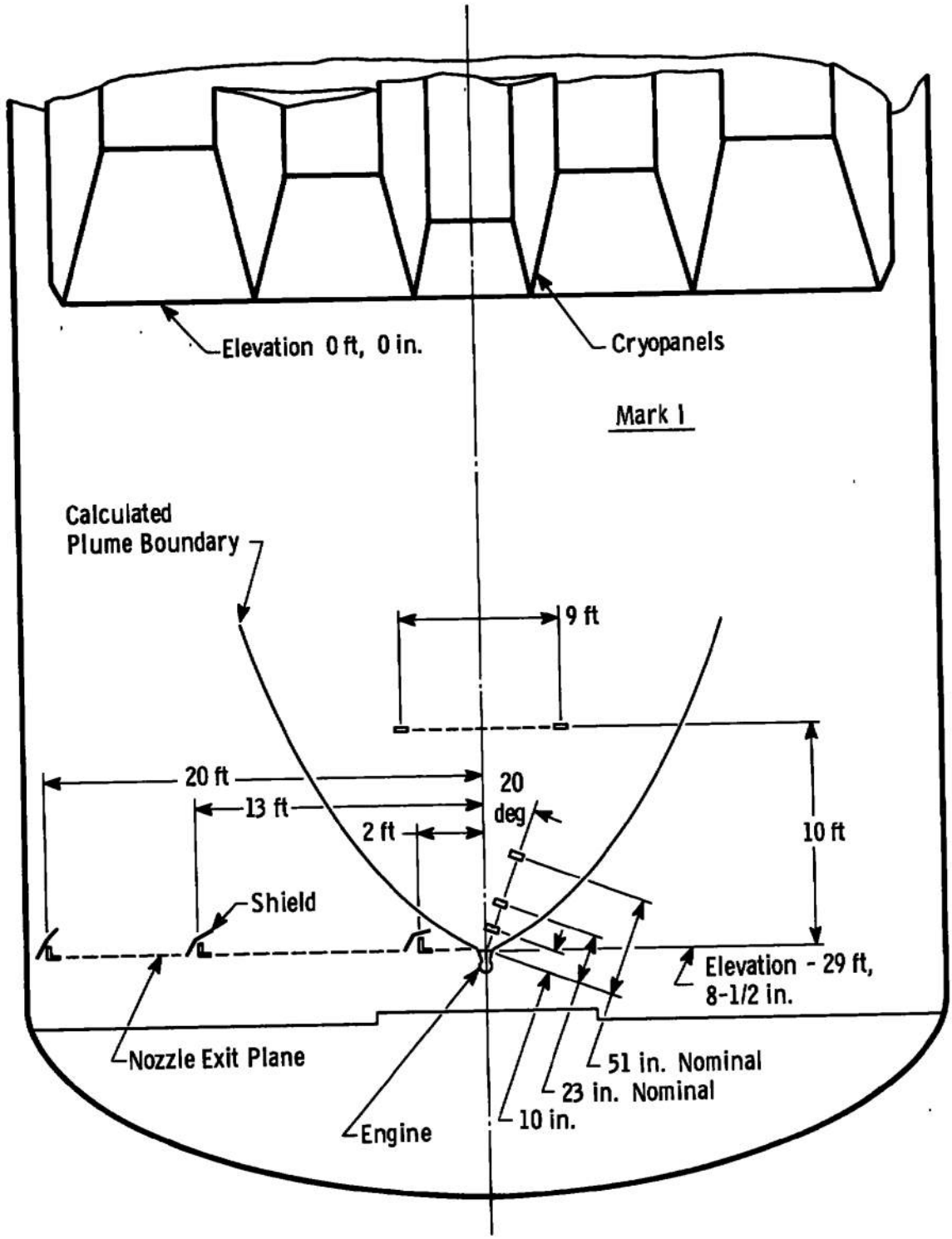


Fig. 6 Sample Location Schematic

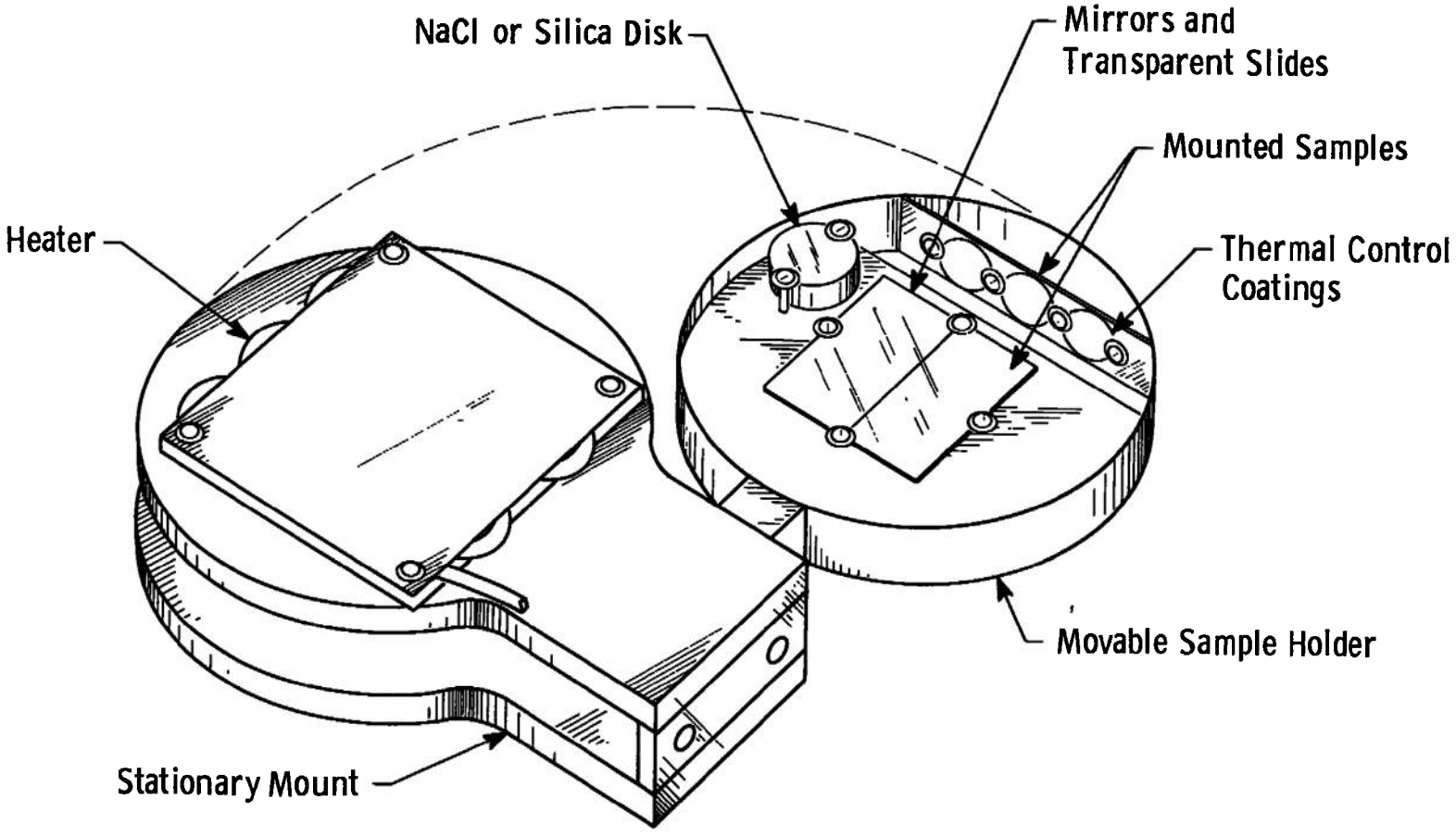


Fig. 7 Sample Container

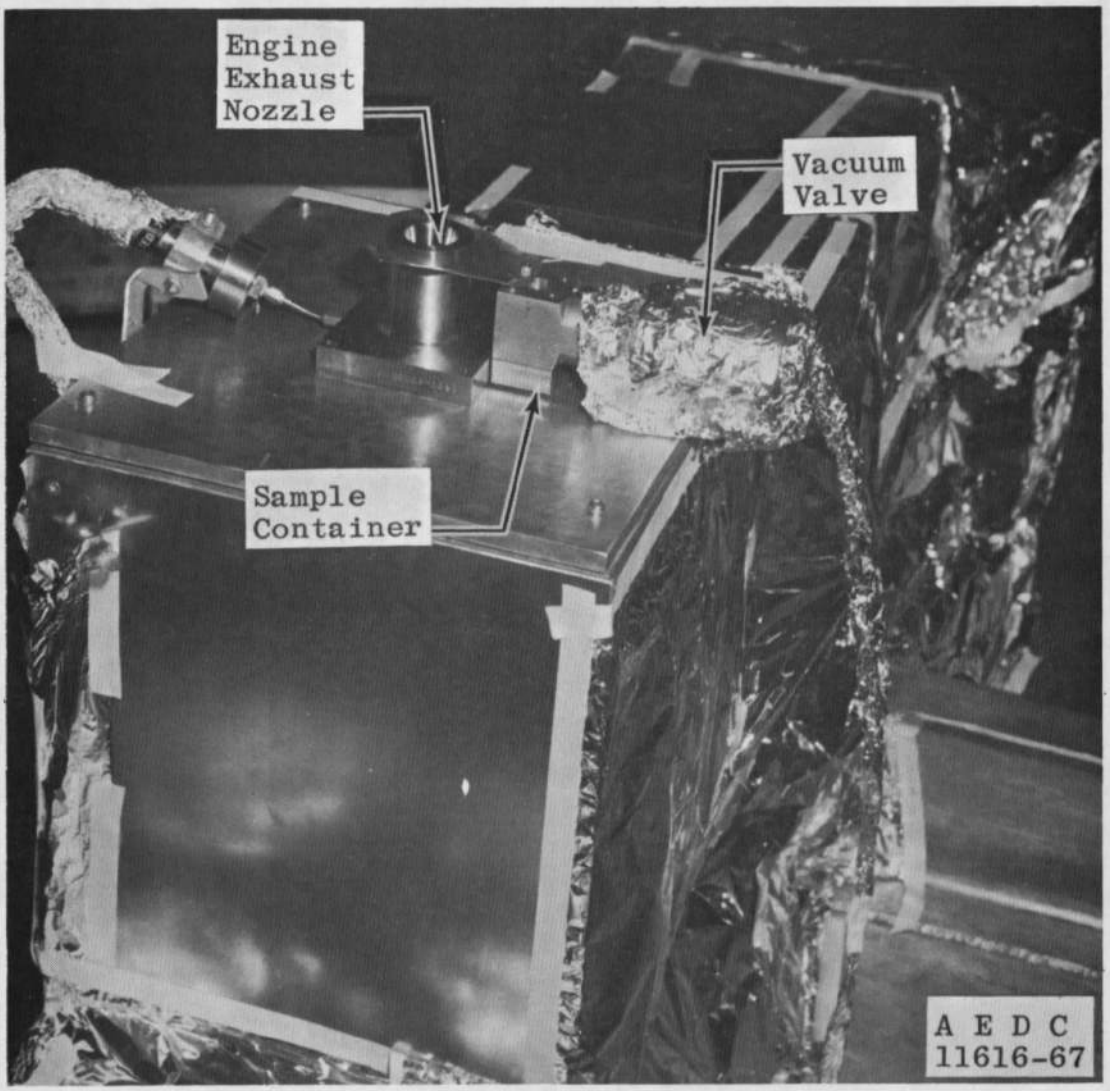


Fig. 8 Chemical Sample Container

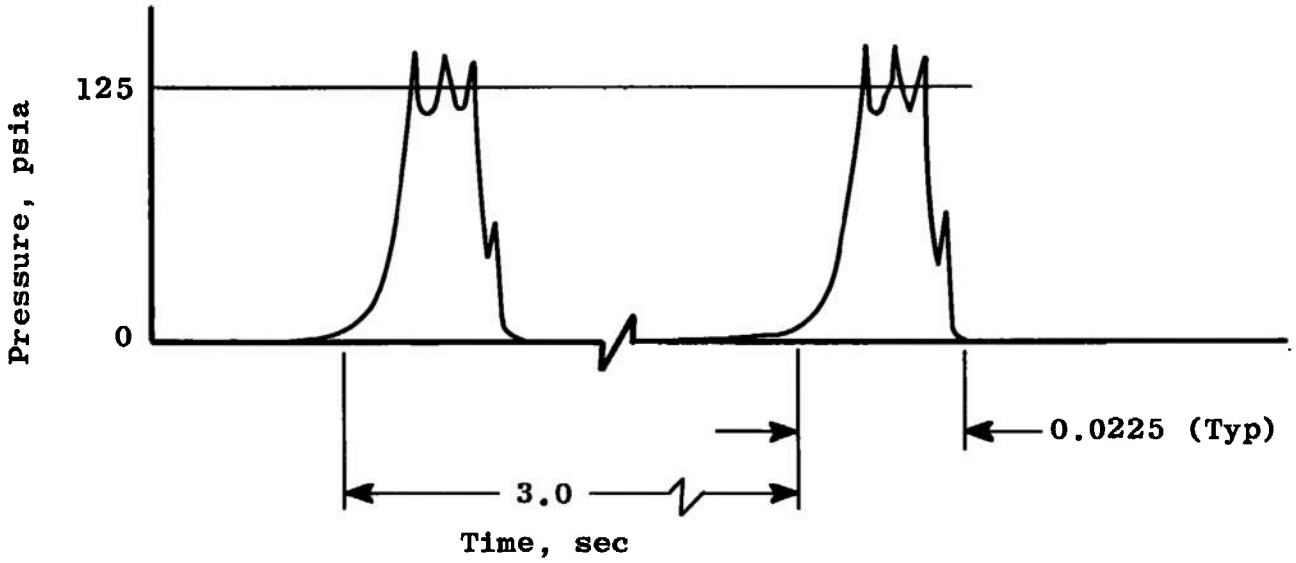


Fig. 9 Rocket Engine Combustion Chamber Pressure for a Typical Pulse Firing

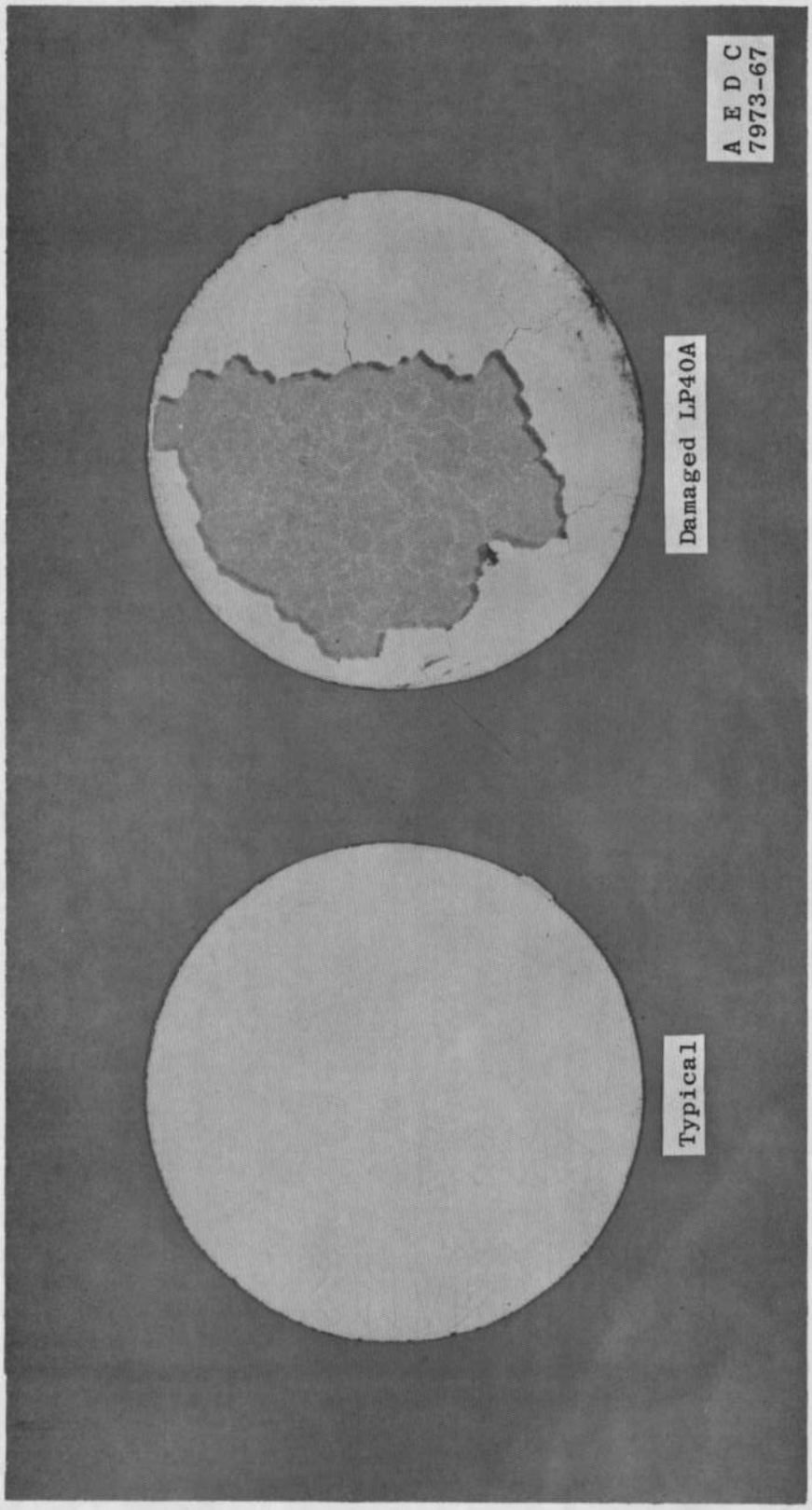
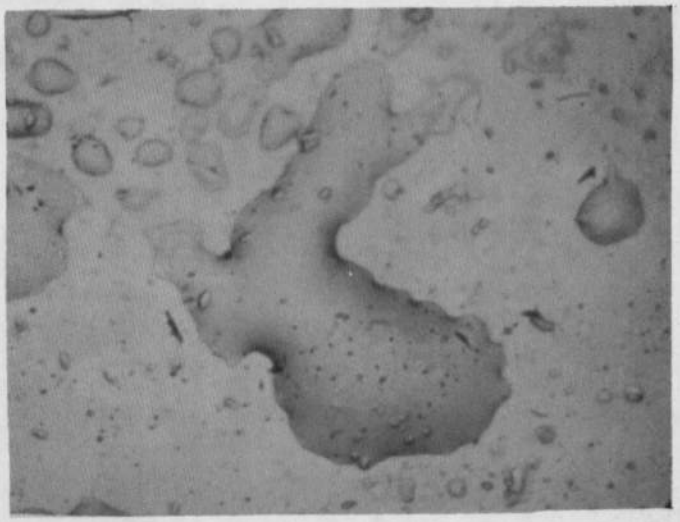


Fig. 10 Exposed Thermal Control Coatings

Clean Surface - 510X



Contaminated Surface - 510X

Fig. 11 Photomicrograph of Contamination Film

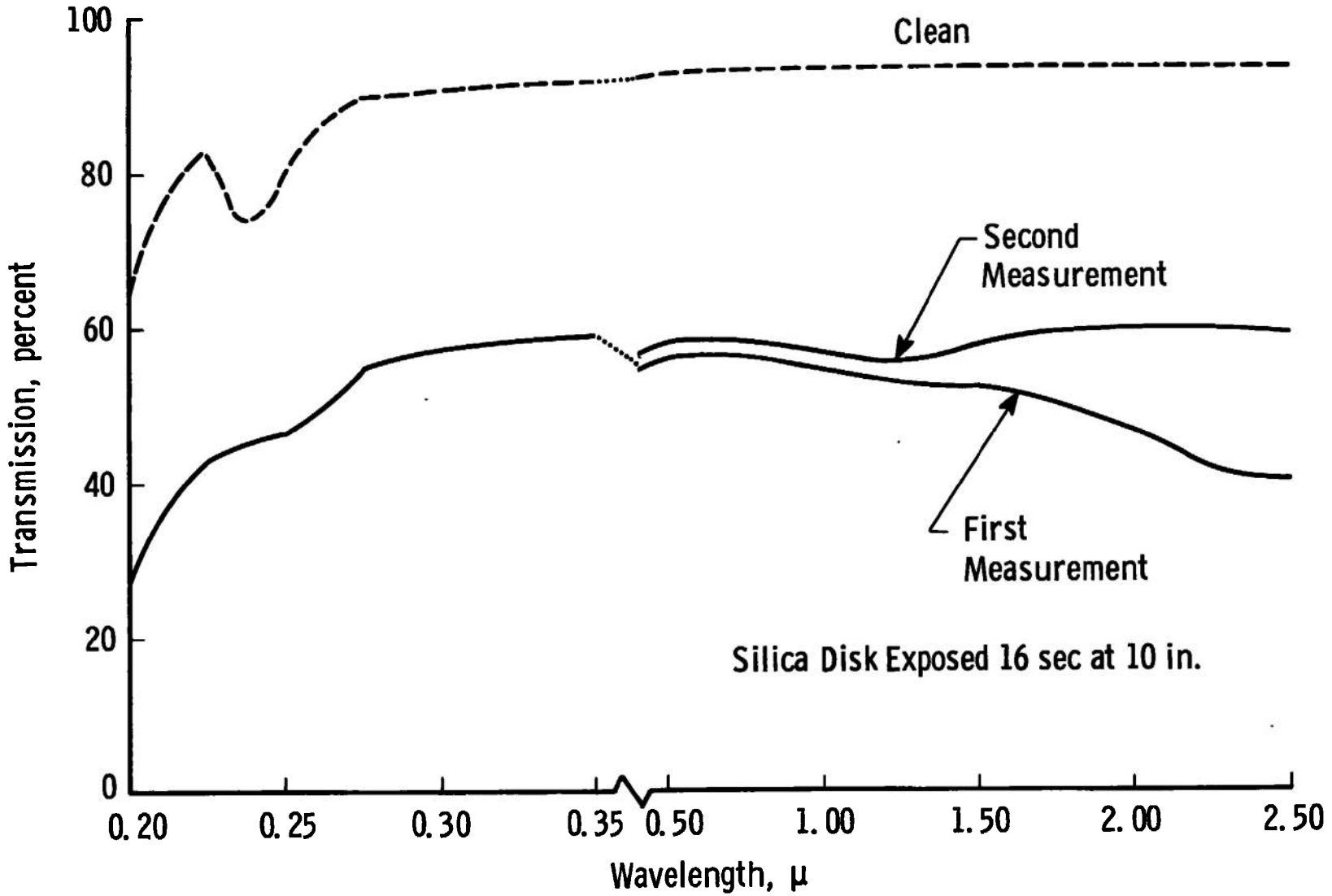


Fig. 12 Transmission Change of Volatile Deposition

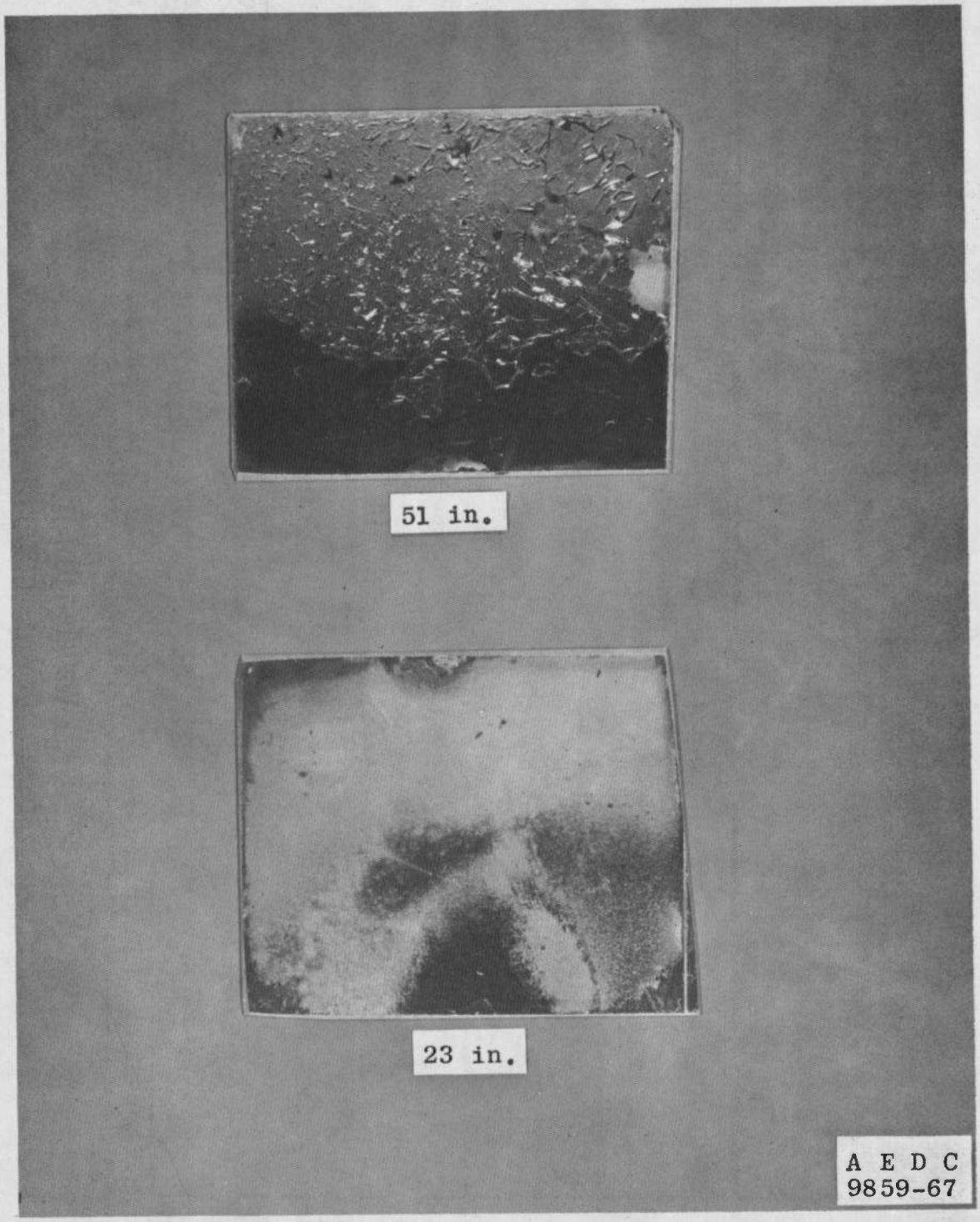


Fig. 13 Platinum Mirror Surface Damage - Pulse Exposure

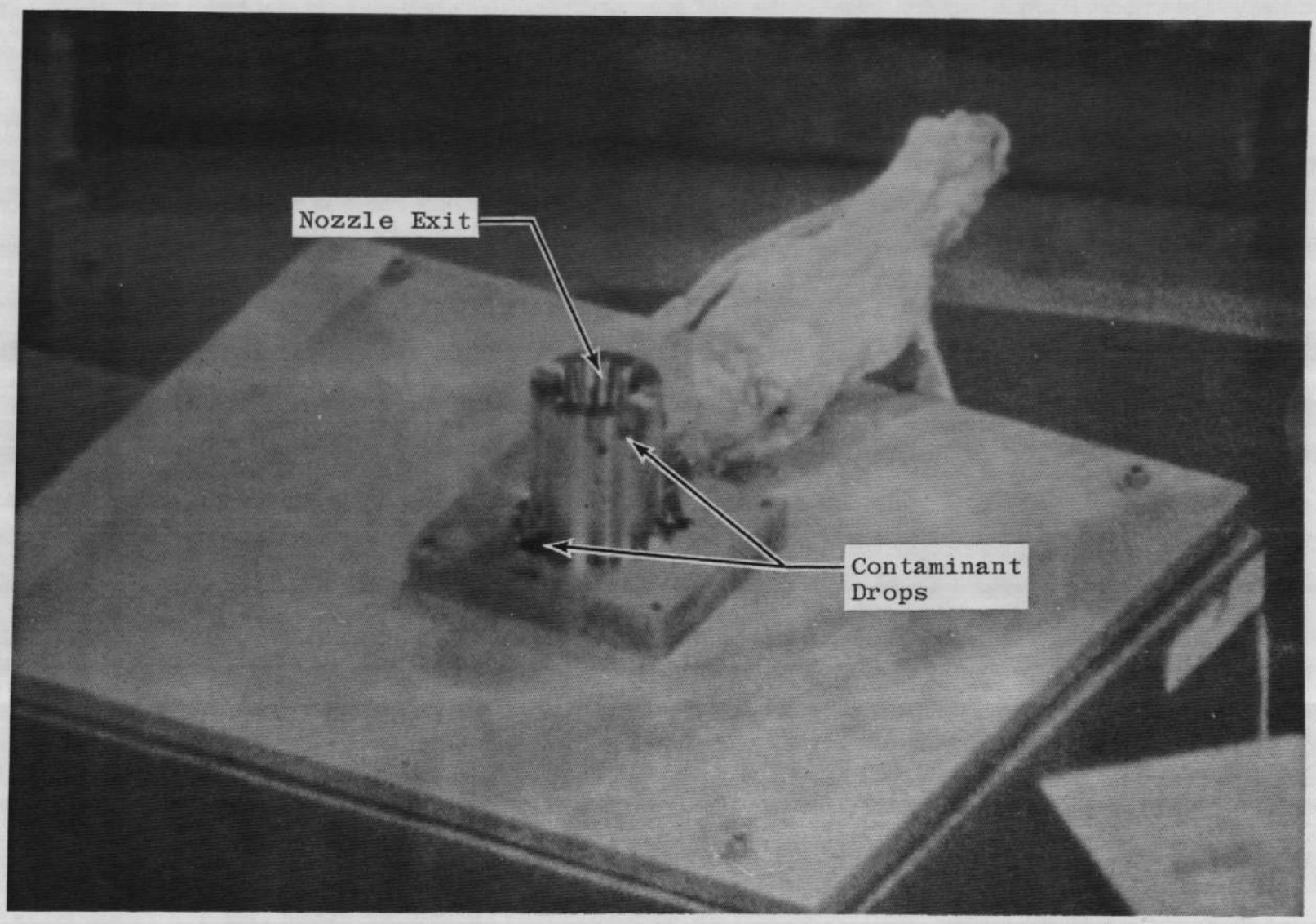


Fig. 14 Contamination during Pulse Engine Operation

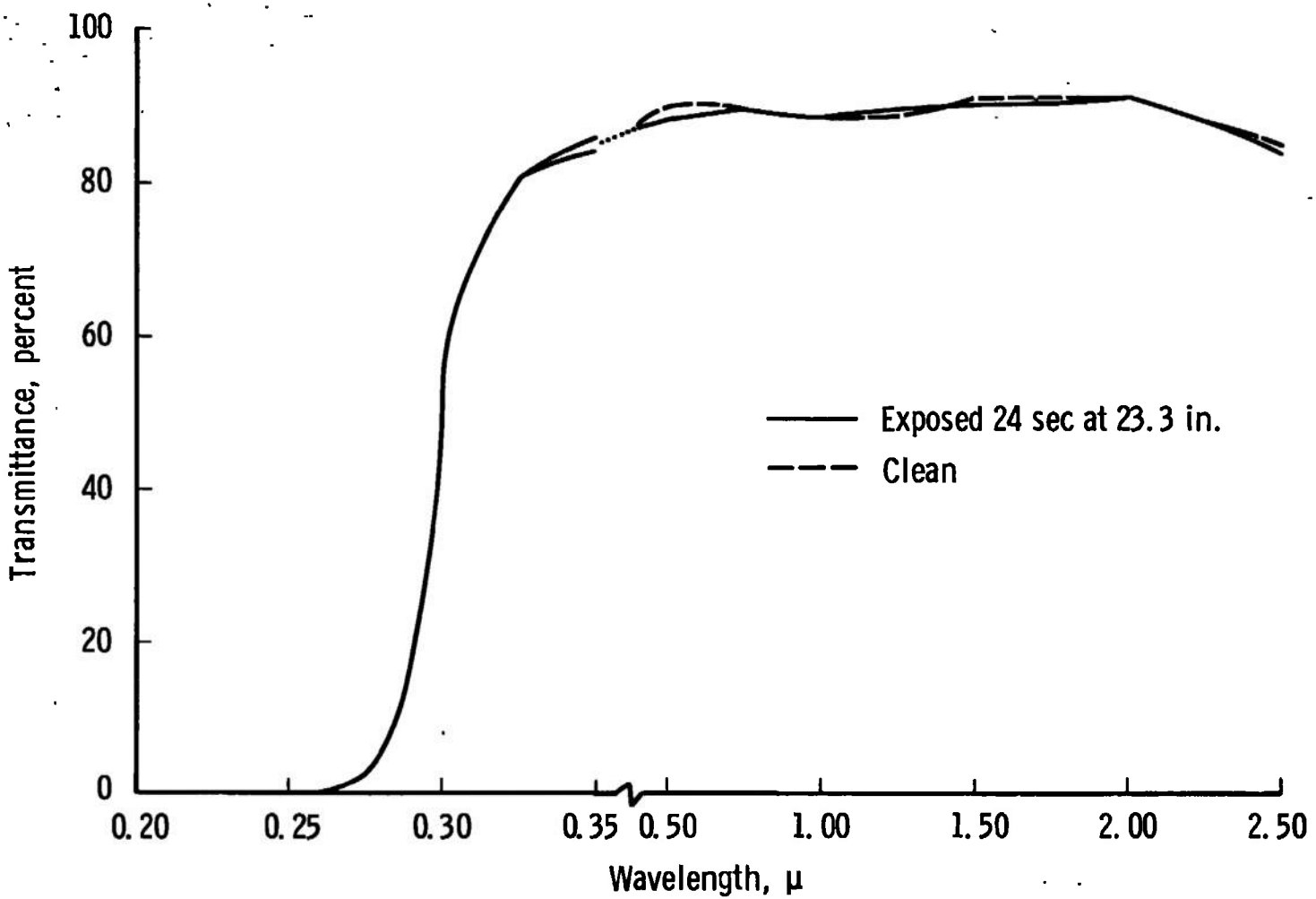


Fig. 15 Pyrex Transmission - Typical Long Duration Exposure

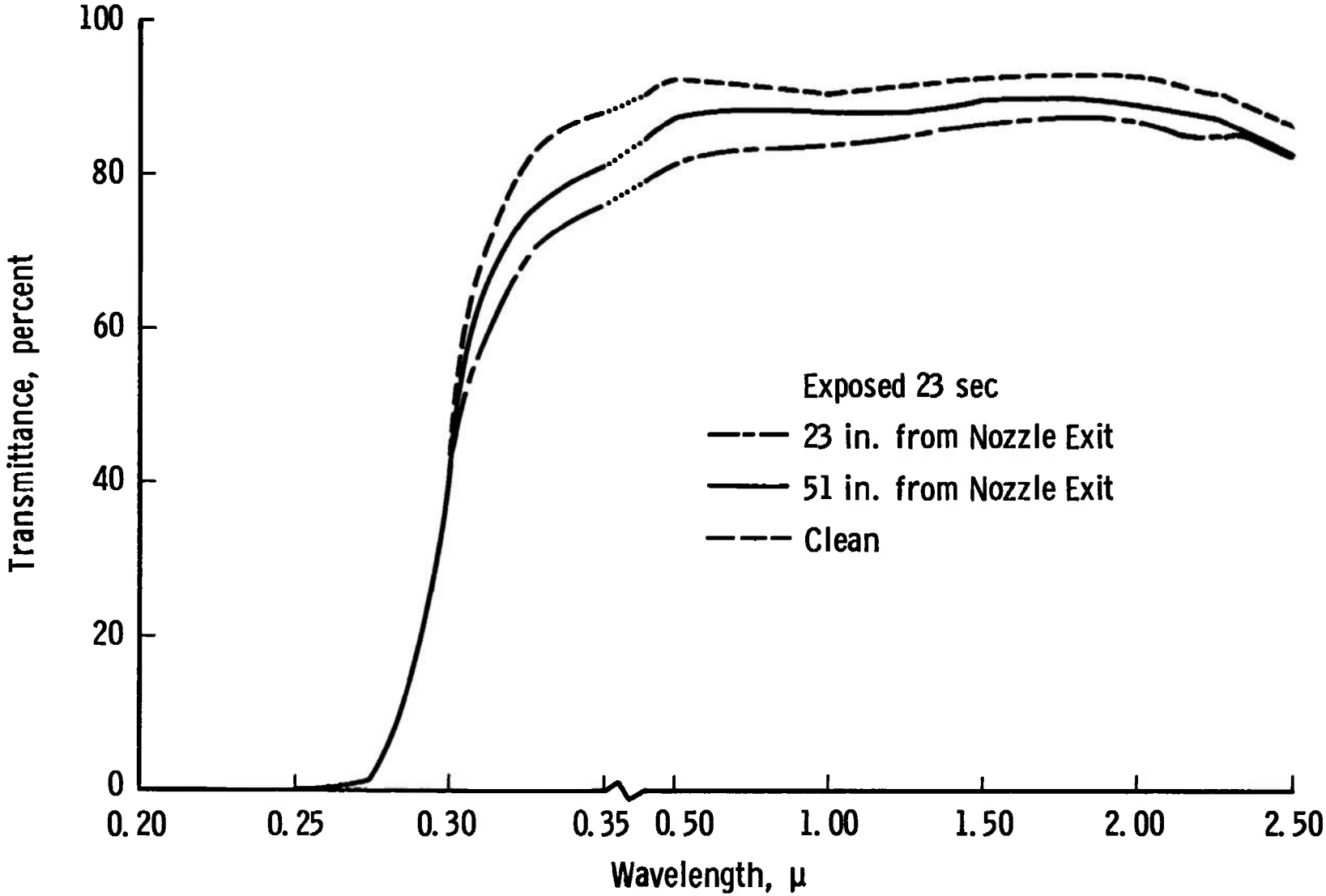


Fig. 16 Pyrex Transmission - Pulse Exposure

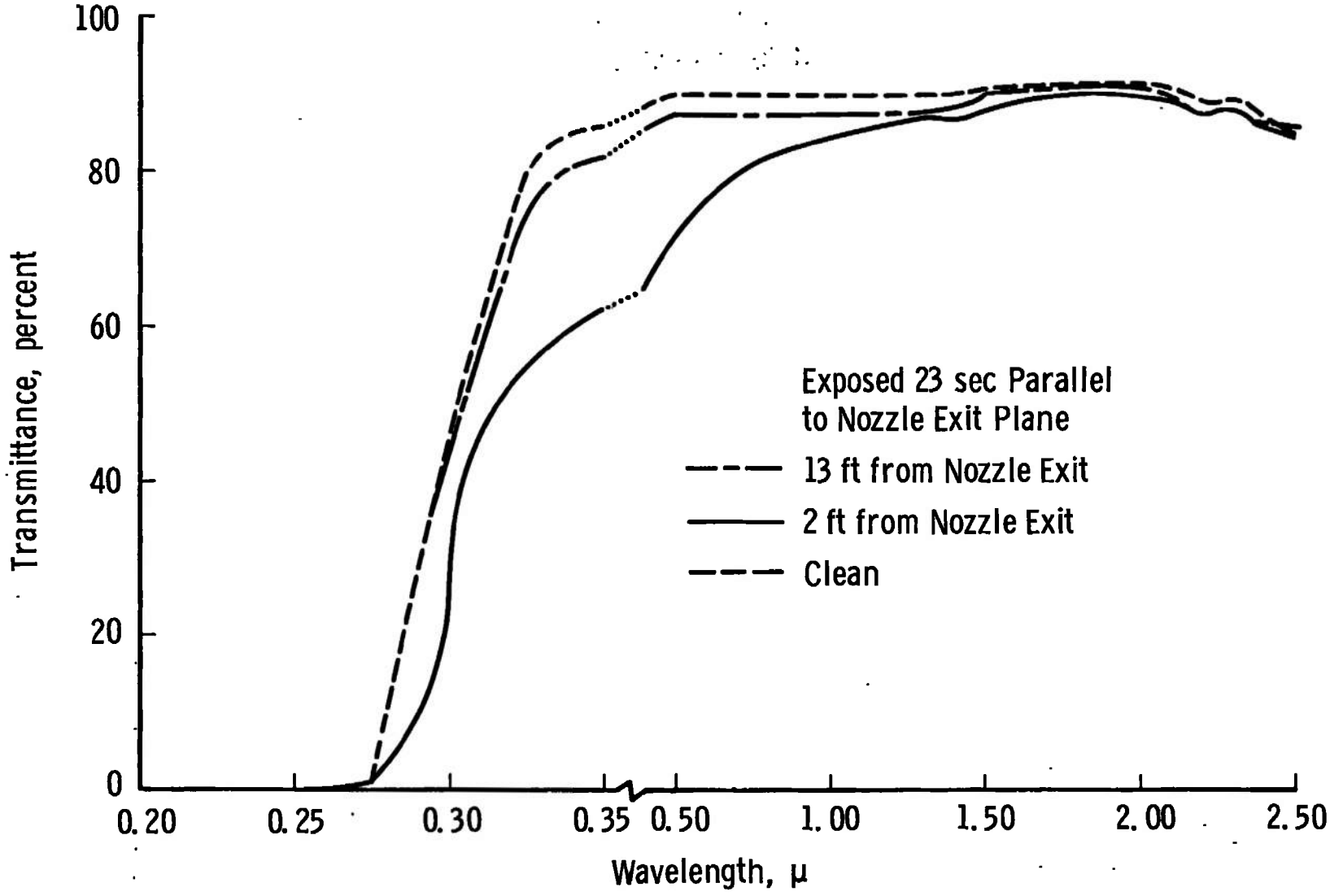


Fig. 17 Pyrex Transmission - Pulse Exposure in Nozzle Exit Plane

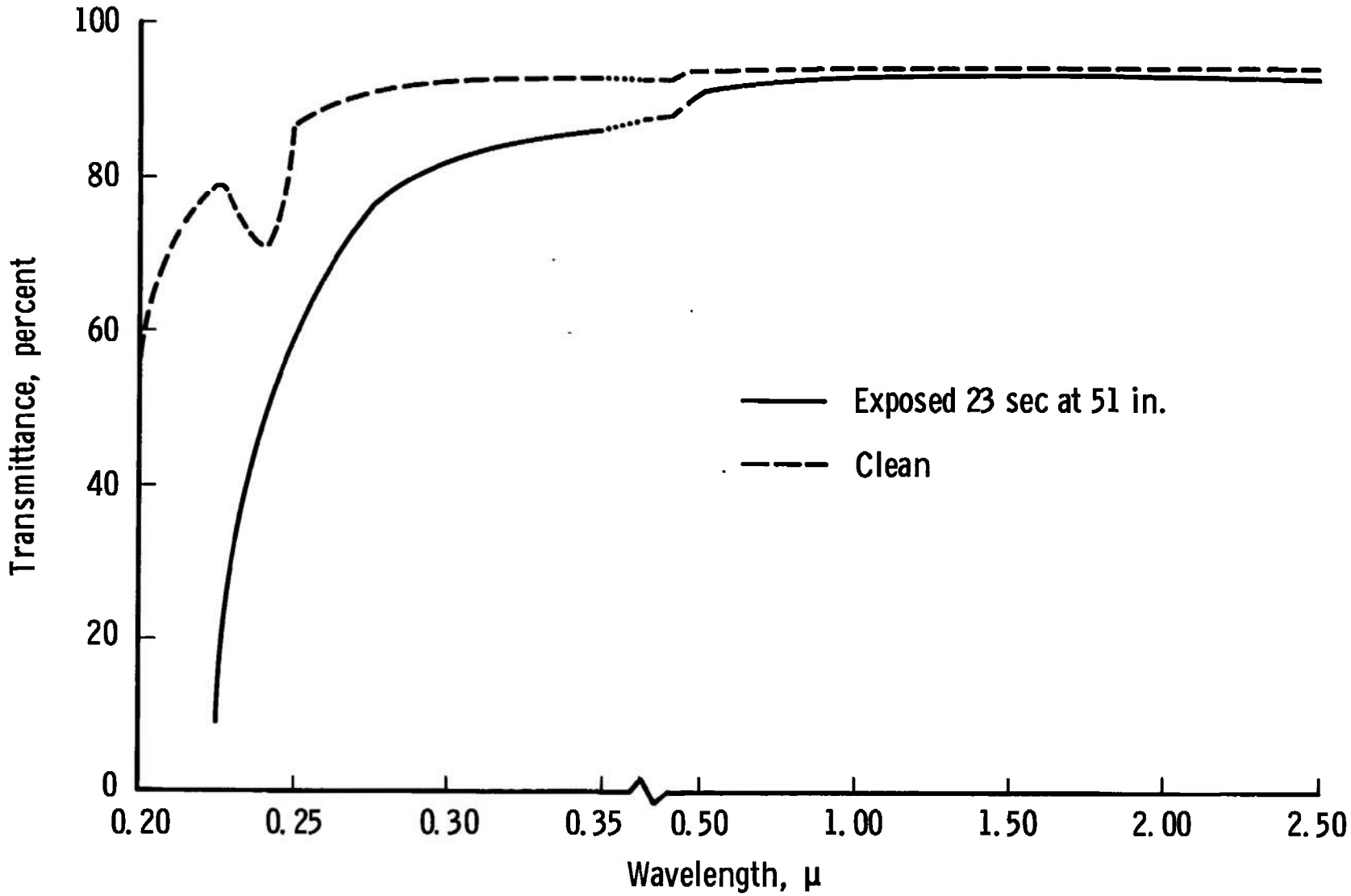


Fig. 18 Silica Transmission - Pulse Exposure

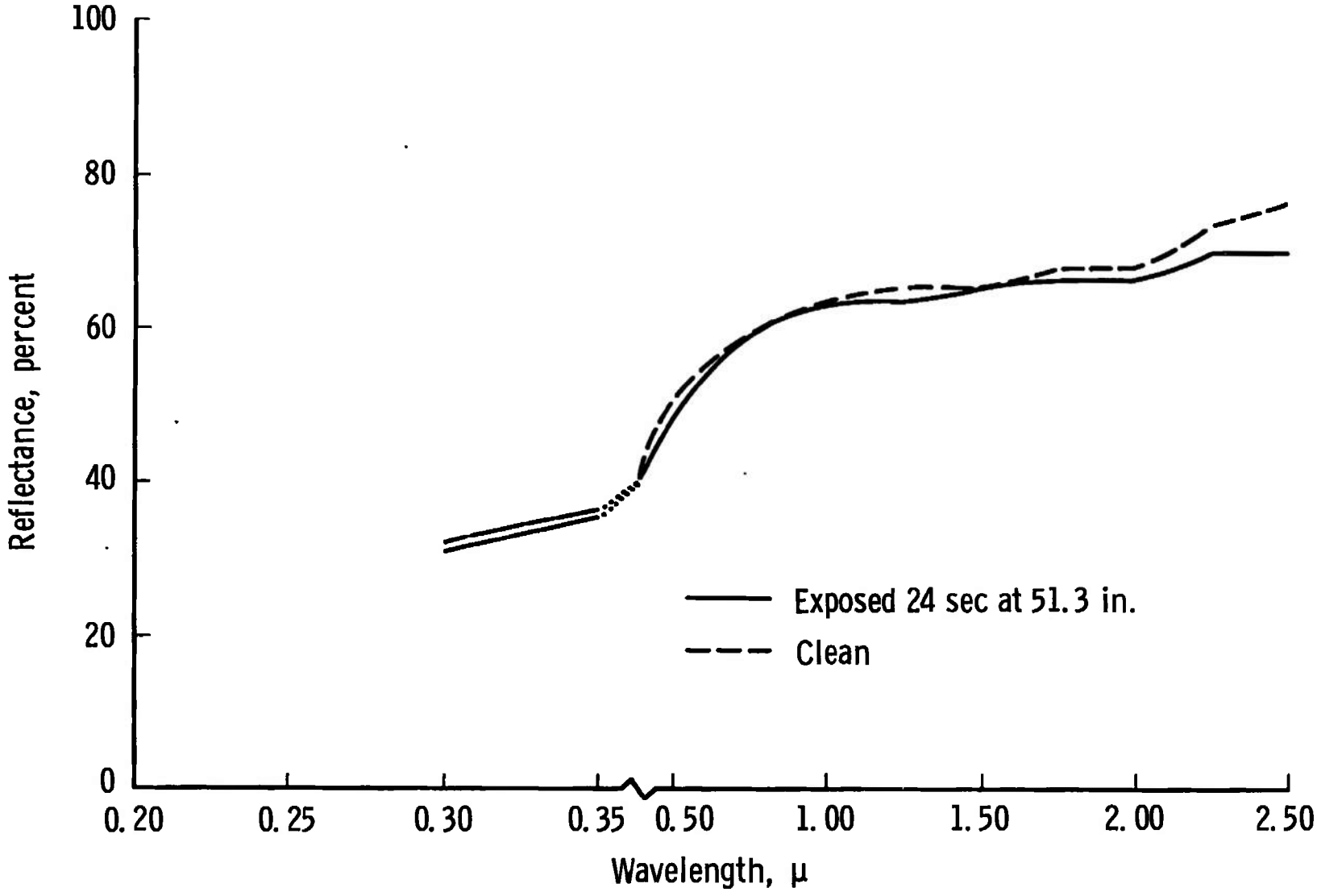


Fig. 19 Platinum Mirror Reflectance - Typical Long Duration Exposure

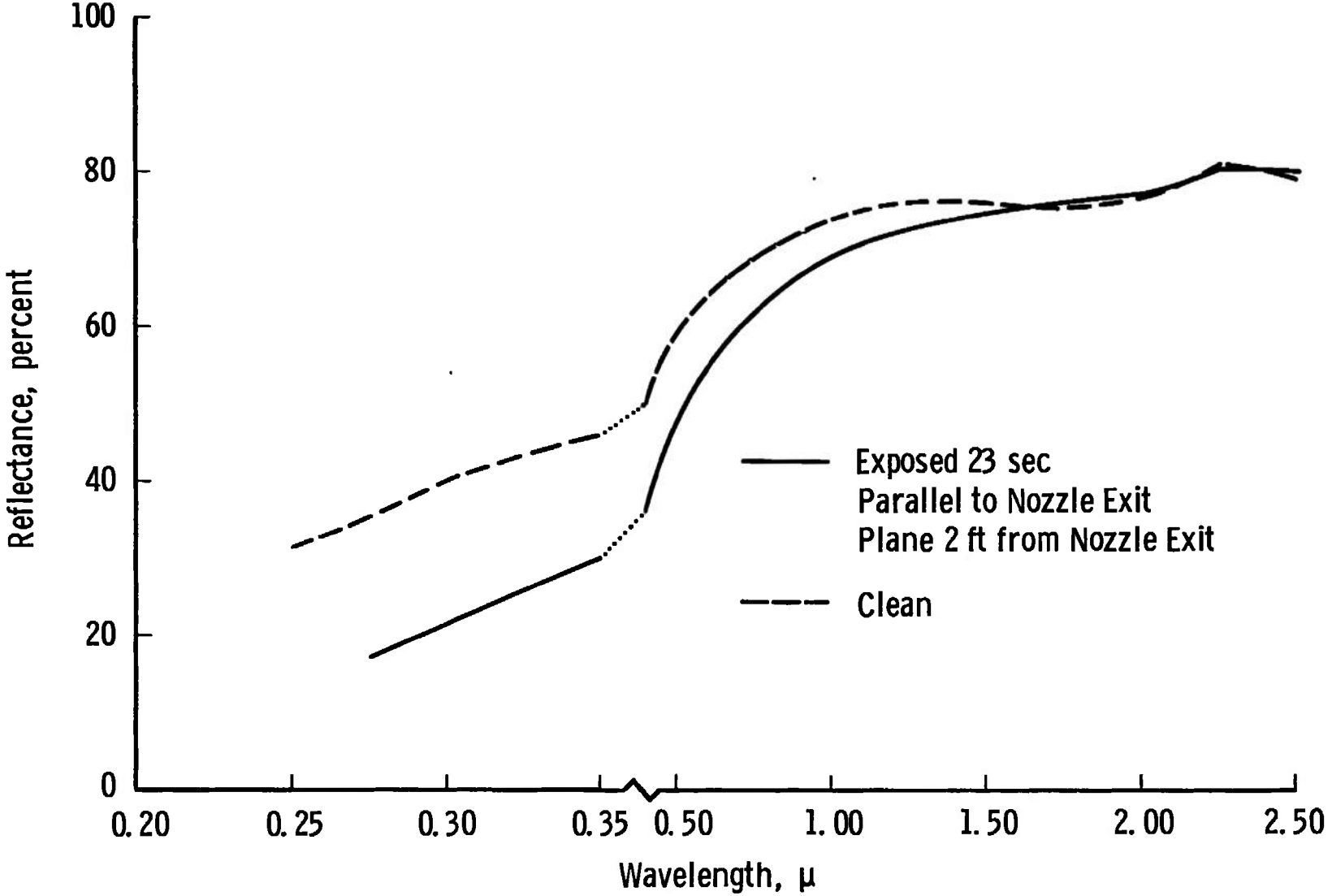


Fig. 20 Platinum Mirror Reflectance - Pulse Exposure in Nozzle Exit Plane

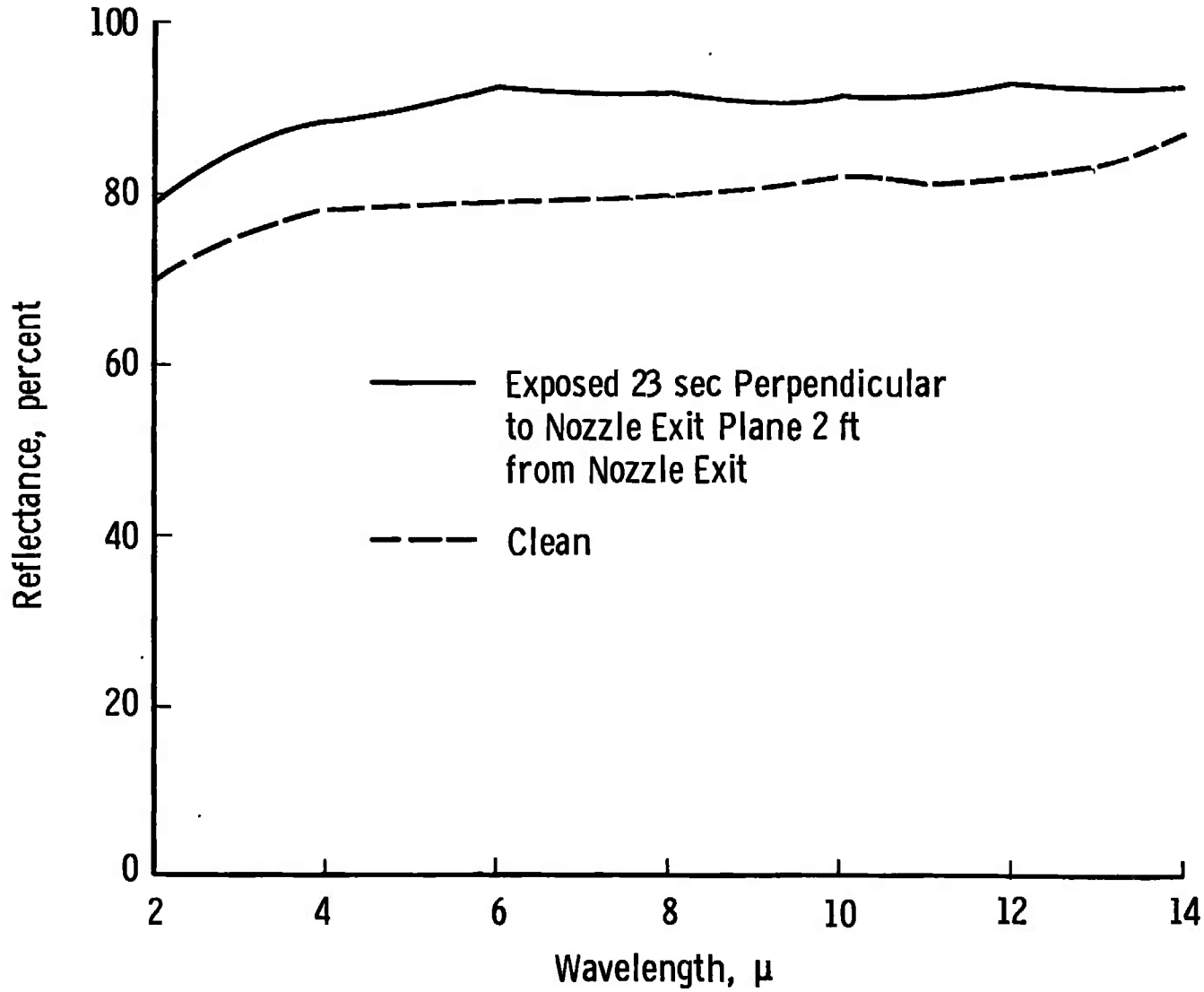


Fig. 21 Infrared Reflectance of Platinum Mirror - Pulse Exposure in Nozzle Exit Plane

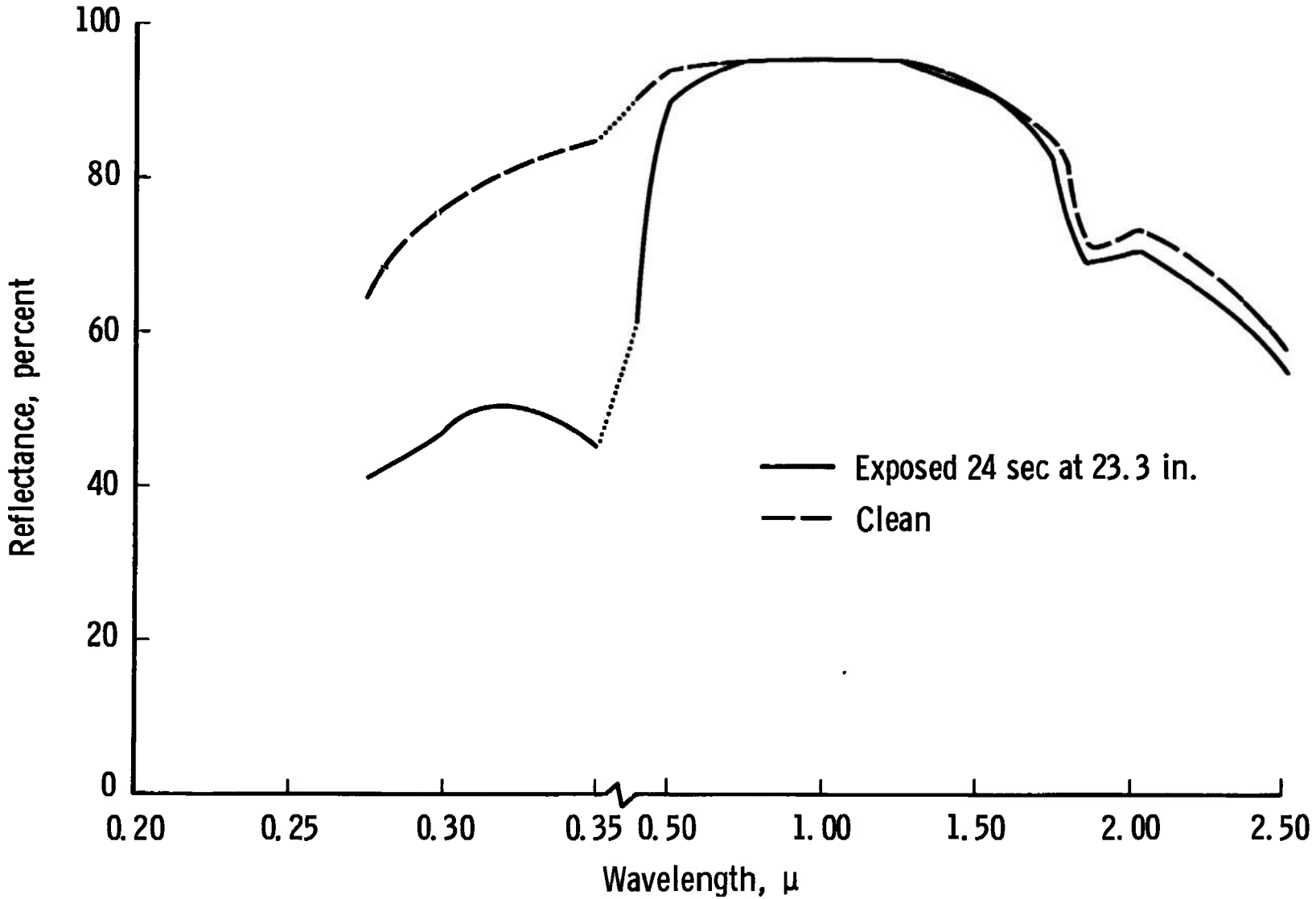


Fig. 22 LP40A Reflectance - Typical Long Duration Exposure

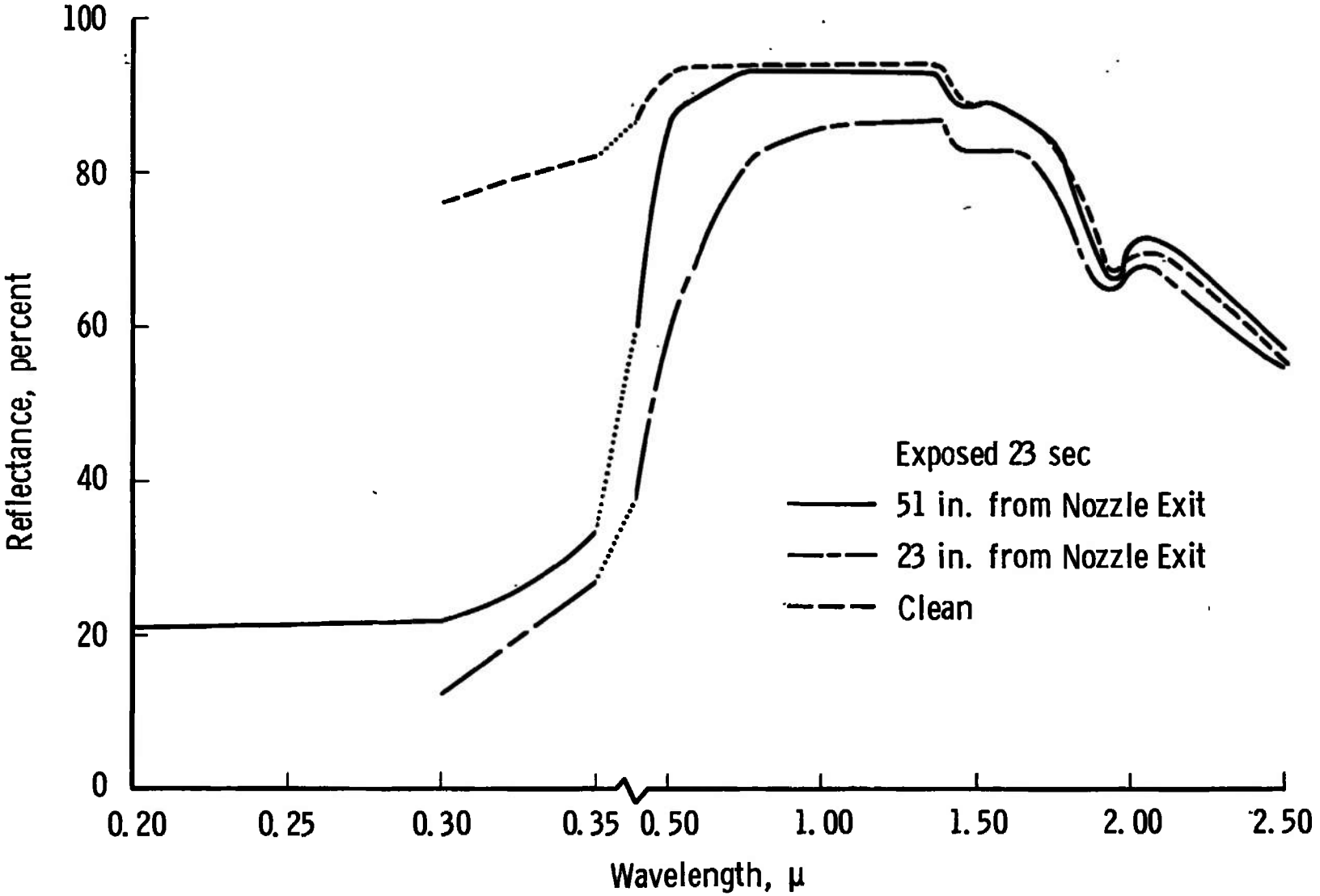


Fig. 23 LP40A Reflectance - Pulse Exposure

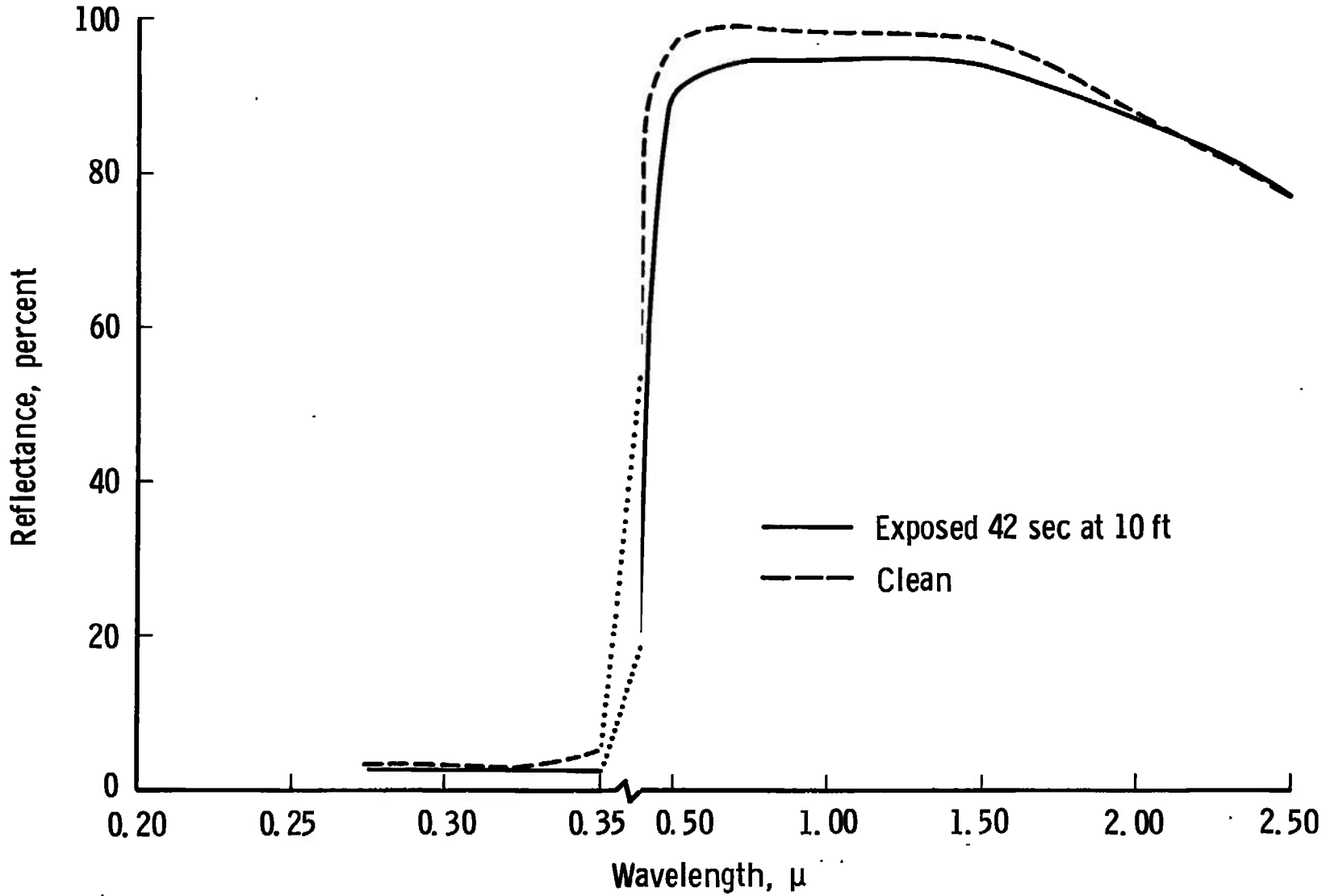


Fig. 24 Z93 Reflectance - Typical Long Duration Exposure

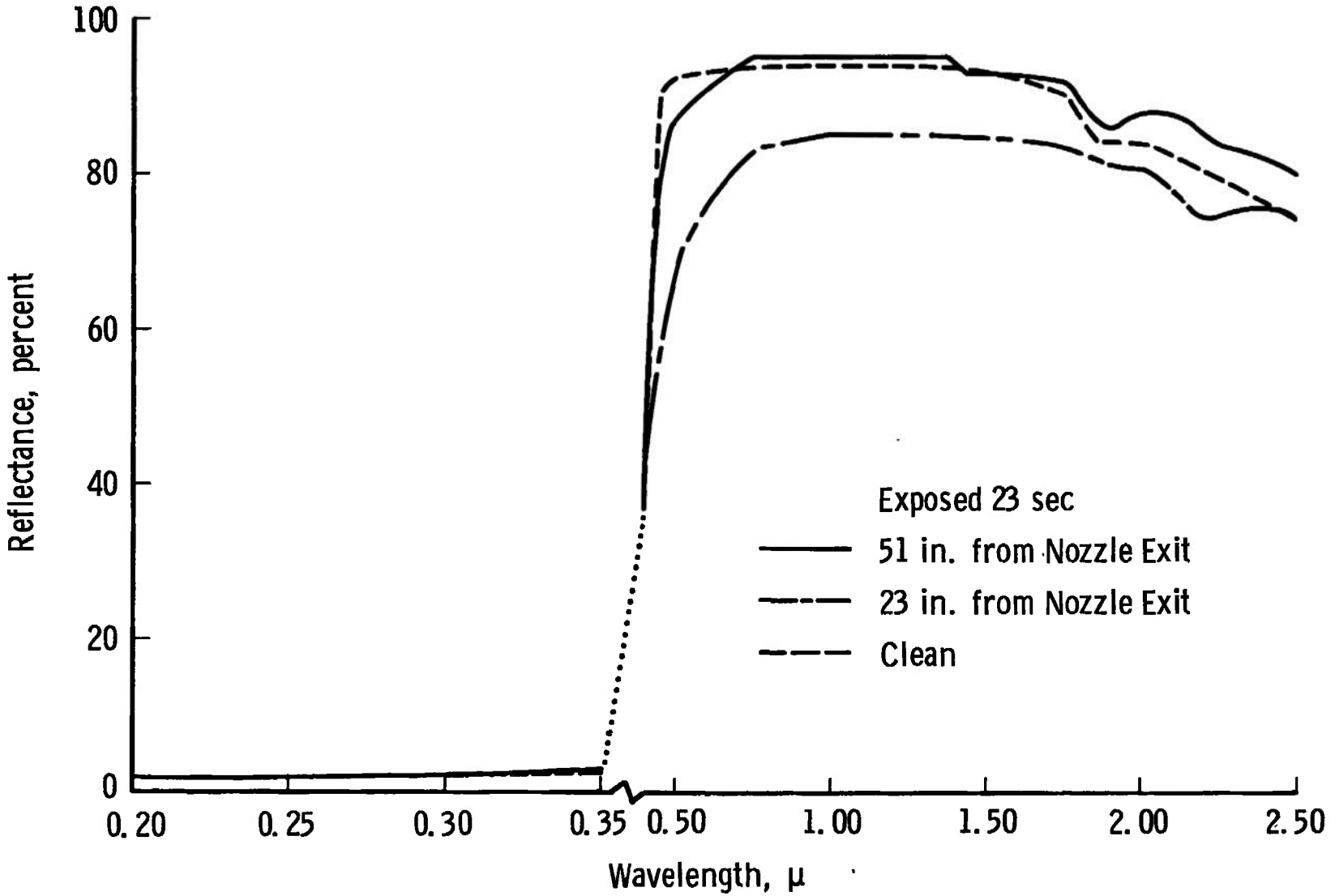


Fig. 25 Z93 Reflectance - Pulse Exposure

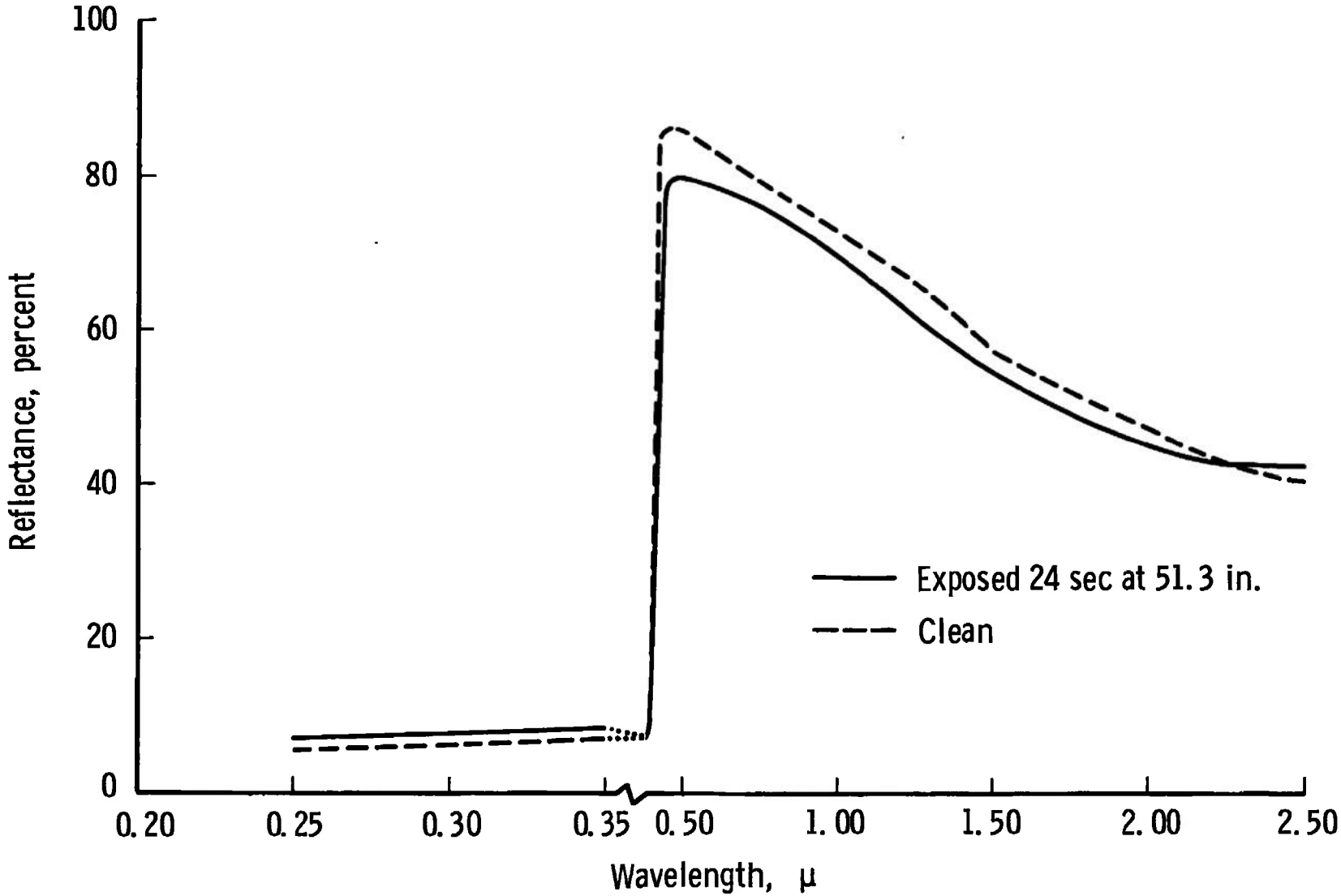


Fig. 26 AL2082 Reflectance - Typical Long Duration Exposure

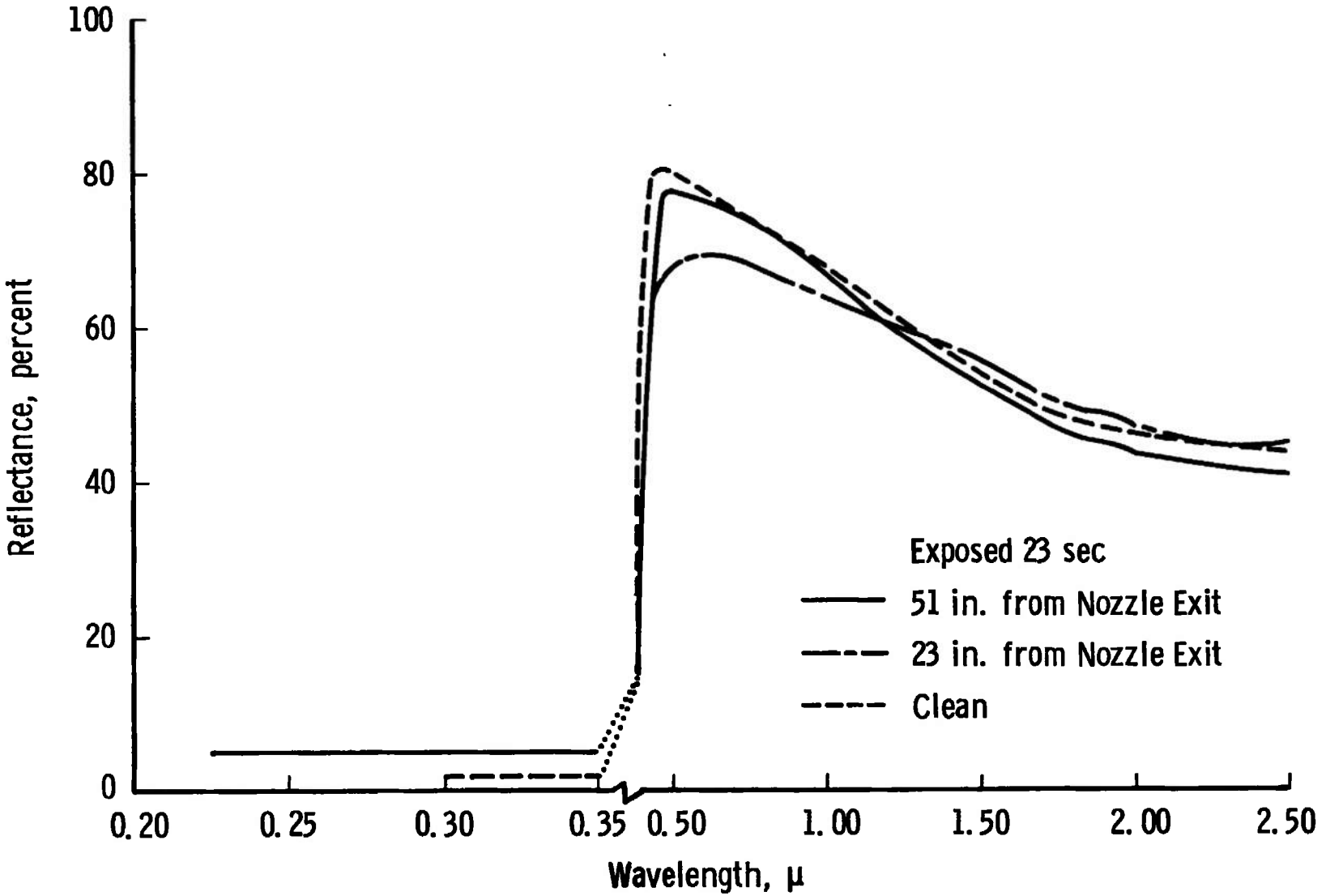


Fig. 27 AL2082 Reflectance - Pulse Exposure

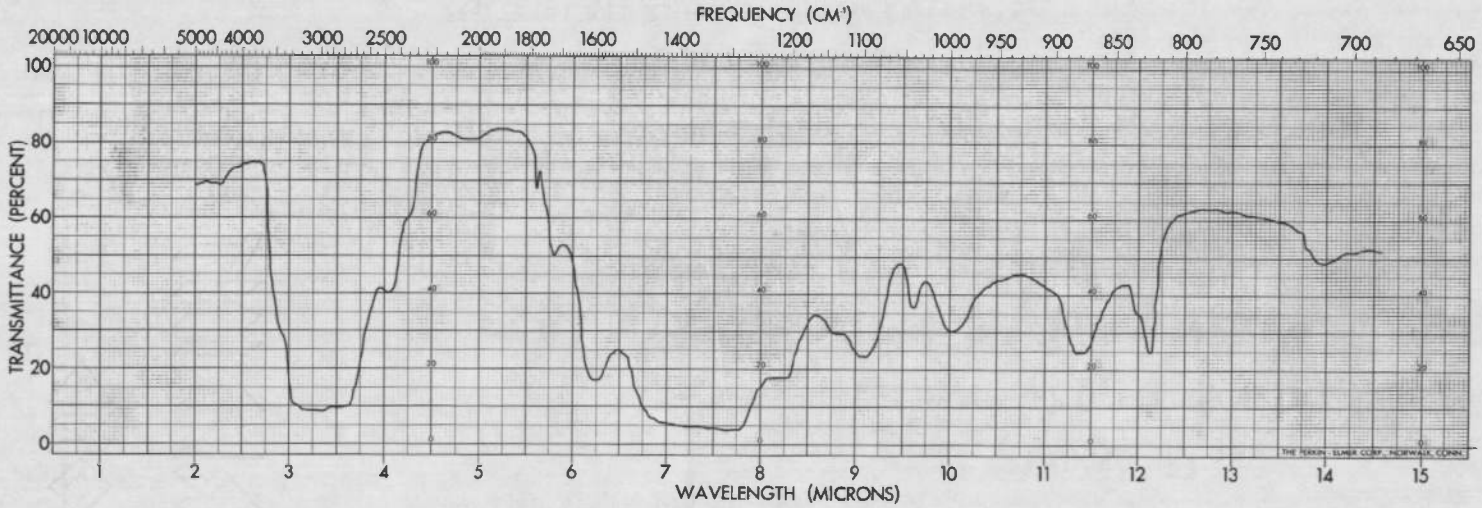


Fig. 28 Infrared Absorption Spectrum of the Pulse Generated Contaminants

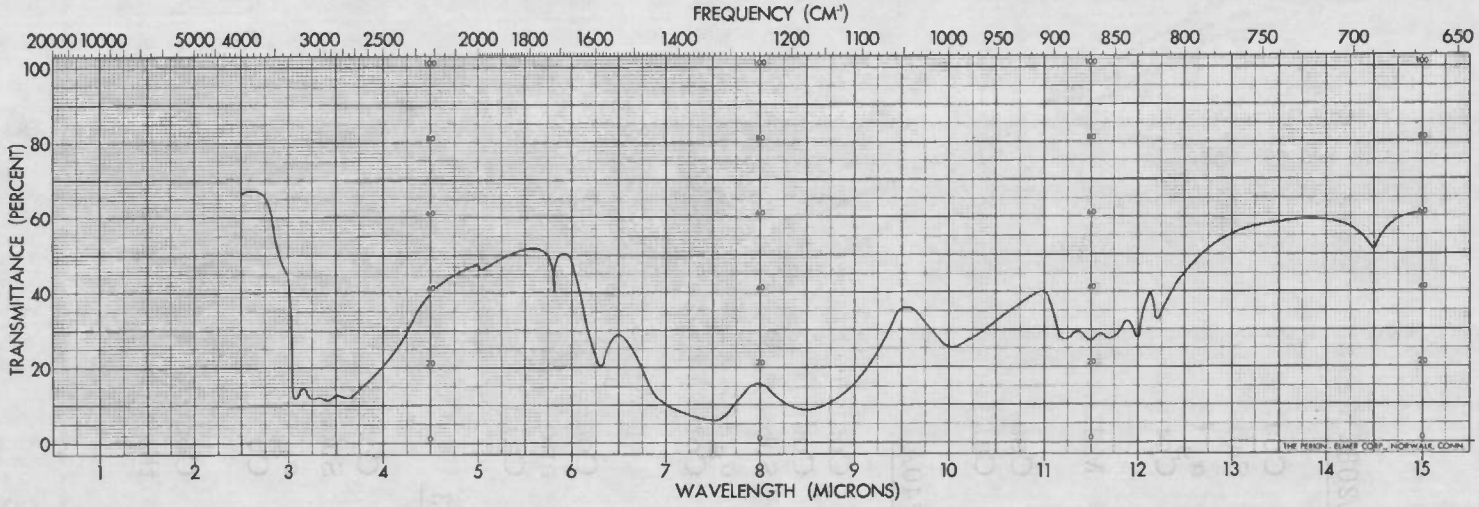


Fig. 29 Infrared Absorption Spectrum of the Adduct Formed by NO_2/MMH Vapors at Subignition Pressure

TABLE I
THERMAL CONTROL COATING SAMPLES
Samples for AEDC Rocket Plume Test

AL2082 Ceramic Enamel

Coating Weight:	0.42 Kg m^{-2} (0.086 lb ft^{-2})
Substrate:	6061-T6 Aluminum, 1.63 mm (0.064 in.) thick
α_s (as applied):	0.35 to 0.33
Composition:	(Frit) SiO_2, Na_2O, Li_2O, BeO, K_2O, TiO_2, PbO, Sb_2O_3
Mill Addition:	TiO_2, H_3BO_3, K_2SiO_3, H_2O

Coating applied by the McDonnell-Douglas Corporation, Santa Monica, California.

LP40A

Coating weight:	0.68 Kgm^{-2} (0.14 lb ft^{-2})
Coating thickness:	0.25 mm (0.010 in.)
Substrate:	6061-T6 Aluminum, 0.81 mm (0.032 in.) thick
α_s (as applied):	0.15 to 0.14
Composition:	Synthetic lithium-aluminum silicate in potassium silicate (LiO_2:$XSiO_2$ + Al_2O_3:$XSiO_2$/K_2O:$XSiO_2$)

Coating purchased from the Lockheed Missiles and Space Company and applied by the McDonnell-Douglas Corporation, Santa Monica, California.

Z93

Coating thickness:	0.11 mm (0.0045 in.)
Substrate:	6061-T6 Aluminum, 0.81 mm (0.032 in.) thick
α_s (as applied):	0.15
Composition:	Zinc oxide in potassium silicate (ZnO/K_2O: $XSiO_2$)

Coating was applied by the Space and Information Systems Division of the North American Rockwell Corporation.

TABLE II
SAMPLE LOCATIONS AND EXPOSURE TIME

Duration of Engine Firing, sec	3.0, 5.0, and 7.0		8.0					0.0225 (Pulse Operation)				
Total Exposure Time, sec	42	27	24	16	24	16	16	23	23	23	23	23
Distance[a], in.	120	120	51.3	49.3	23.3	21.3	10.0	51	23	240[b]	156[b]	24[b]
Pyrex	*	*	*		*	*	*	*	*	*	*	*
Silica				*		*	*	*				
Platinum	*	*	*	**	*	*	*	X	X	*	*	*
Z93	*	*	*		*		*	*	*			
LP40		*	X	*	*		*	*	*			
AL2082	*		*		*		*	*	*			

* - Exposed
X - Damaged

[a]Distance in front of engine exit unless otherwise noted, see Fig. 6.

[b]Distance in nozzle exit plane.

TABLE III
SOLAR ABSORPTION COEFFICIENTS

Sample	Location[a], in./sec	α Clean	α Exposed	α Change[b]	Percent Change[c], Normalized
LP40A	120/27	0.13	0.16	0.03	23
	120/27	0.13	0.17	0.04	31
	51.3/24	0.13	Surface Cracked		
	49.3/16	0.12	0.17	0.05	38
	23.3/24	0.12	0.17	0.05	38
	10.0/16	0.11	0.17	0.06	46
	51/Pulse 24	0.14	0.20	0.06	46
	23/Pulse 24	0.15	0.34	0.19	146
Z93	120/42	0.18	0.18	0.00	0
	120/27	0.17	0.20	0.03	17
	51.3/24	0.19	0.21	0.02	11
	23.3/24	0.19	0.20	0.01	6
	10.0/16	0.18	0.21	0.03	17
	51/Pulse 24	0.19	0.20	0.01	6
	23/Pulse 24	0.18	0.33	0.15	83
AL2082	120/42	0.34	0.38	0.04	11
	51.3/24	0.38	0.38	0.00	0
	23.3/24	0.36	0.33	-0.03	-8
	10.0/16	0.34	0.37	0.03	8
	51/Pulse 24	0.39	0.40	0.01	3
	23/Pulse 24	0.35	0.44	0.09	25

[a]Distance from nozzle exit accumulated exposure time

[b]$\alpha_{change} = \alpha_{exposed} - \alpha_{clean}$

[c]$\text{Percent} = \dfrac{\alpha_{change}}{(\text{avg } \alpha_{clean})}$

TABLE IV
CONTAMINATION DEPOSITION VERSUS POSITION IN PLUME[a]

Position[b]	Chamber Pumpdowns 1	2	3
7.0		-30	
6.0		-40	
5.0		-20	
4.5	-28	-30	-40
4.0		-20	-110
3.5	0		-160
3.0		-20	-110
2.5	-2		-120
2.0		0	190
1.5	232	160	730
1.0		failed[c]	1,290
0.5	failed[c]		16,440
-0.5			1,170
-1.5			130
-2.0			- 90
-2.5			-140
-3.0			-130
-3.5			- 70
-4.5			- 90

[a]Sloan DTM-2 frequency change in Hertz. Negative numbers represent mass deposition.

[b]Distance in feet from centerline of plume in a plane 10 ft from the nozzle exit.

[c]The platinum electrical surface was removed from the quartz crystal.

APPENDIX III

PROPELLENT CONTAMINATION CONTROL SPECIFICATIONS

(From Bell Process Specification BPS 42764, Contamination Control)

6. COMPONENT CONTROL:

A 6.1 Cleaning: Refer to Section 7 for cleaning requirements.

A 6.2 Functional Tests:

6.2.1 Cleanliness Requirements: (See Table I) All functional testing shall be conducted using liquid or gas specified by applicable drawing. All such fluids shall be of the Cleanliness Class required by the applicable component drawing (or cleaner).

6.2.2 Physical and Chemical Properties of Test Fluids: Solvent and functional test liquids in use shall conform to the following requirements. See 8.7 for test methods and 9.1.3 for frequency of tests.

Material	Acidity, (% by wt max)	Water Content (max)	Specific Gravity
Methanol[a]	0.003 as acetic acid	-	0.7932 (max) (20/20C)
Methylene Chloride[b]	0.0005 as HCl	0.020% by wt	1.317 - 1.322 (25/25C)

a) Used as fuel flush for AEDC testing
b) Used as oxidizer flush for AEDC testing

6.2.3 Fluid Cleanliness Classes:

TABLE I - FLUID CLEANLINESS CLASSES

PARTICLE SIZE (MICRONS)	CLASSES (MAX PARTICLES/100 ML LIQUID OR 10 CU FT GAS)					
	1	2	3	4[c]	5	6
5-15	To be estab-	70	700	3500	NL	NL
16-50	lished if a	10	100	500	1000	2000
51-100	class lower	0	10	50	100	200
101-200	than Class 2	NA	1	10	25	50
201-350	is required.	NA	NA	3	5	10

NA - None Allowed
NL - No Limit

NOTE: Particles larger than 350 microns are permissible when specified on the drawing.

c) Class 4 or better cleanliness was used during AEDC testing.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	UNCLASSIFIED
	2b. GROUP N/A

3. REPORT TITLE

EFFECT OF CONTAMINATION ON SPACECRAFT SURFACES EXPOSED TO ROCKET EXHAUSTS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report April 13 through August 4, 1967

5. AUTHOR(S) (First name, middle initial, last name)

B. A. Burch, ARO, Inc.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1968	55	9

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
AF 40(600)-1200 b. Program Element 6340940F/632A	AEDC-TR-68-23
c. d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Air Force (SAFSL-6A) Los Angeles Air Force Station, California 90045

13. ABSTRACT

This report describes the contamination effects caused by rocket exhaust impingement on spacecraft surfaces. A rocket engine with a hypergolic propellant combination was fired at a simulated altitude of 300,000 ft. Thermal control coatings, highly reflective surfaces and transmission samples were exposed to the exhaust plume at various distances. For longer duration firings, reflectance and transmittance changes of less than 10 percent were measured for the exposed samples. A comparison of the effects from pulse operation and longer duration firings indicate that contamination occurs during ignition and shutdown. Samples exposed to the exhaust plume during pulse operation had a 10 to 20 percent decrease in reflectance and transmittance. Solar absorptance changes calculated from the reflectance varied from 10 to 147 percent. The contamination during pulse operation varied inversely with distance. Contaminants will be deposited on spacecraft surfaces exposed to the exhaust from a liquid propellant engine.

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DD FORM 1 NOV 65 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
contamination						
spacecraft						
rocket exhausts						

1. Space vehicles -- Surface Contamination
2. " " -- Contamination
3. " " -- Exhaust effects
4. Exhausts -- Effects
5. " -- Dispersement

17-4

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