

Third Quarterly Technical Report
PROPULSION BEAM DIVERGENCE EFFECTS

Contract No. 952350

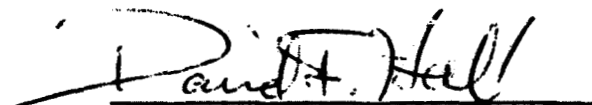
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A handwritten signature in dark ink, appearing to read "David F. Hall", is written over a horizontal line.

David F. Hall
Program Manager

This work was performed for the Jet Propulsion
Laboratory, California Institute of Technology,
under Contract No. 952350.

TRW Systems
One Space Park
Redondo Beach, California
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ABSTRACT

The second phase of a program to develop understanding of and tolerance-level criteria for the deleterious effects of electrostatic rocket exhaust (Cs , Cs^+ , Hg , Hg^+) impinging on typical classes of spacecraft (S/C) surfaces is proceeding. Prior work was done under Contract No. NAS7-575. This phase includes fabrication of necessary experimental fixtures and exploratory experiments. The current status of fixture design, fabrication, and testing is reported along with experimental and analytical results obtained during the quarter. Sputtered accelerator grid material is an important thruster effluent to spacecraft surfaces, but is negligible in the experimental configuration. Atomic Hg beams did not significantly affect the absorptivity (α) or emissivity (ϵ) of ten typical S/C coatings under conditions where at most one monolayer of Hg could be adsorbed. Very high fluxes and large doses of 3 Kev Hg^+ produced marked increases in α of white paints and RTV samples, but not of black paints, Al, Au, and glasses. Emissivities of all samples remained relatively constant. Addition of up to 10% Ag to soft solder apparently does not improve its resistance to Hg attack. Ultimate tensile strength of pure Ag samples is not sensitive to surface coatings of Hg, even following four weeks of reaction time.

This report contains information prepared by TRW Systems under JPL subcontract. Its content is not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or the National Aeronautics and Space Administration.

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I. INTRODUCTION

A. Program Goals

Electrostatic rockets emit propellant particles into at least 2π steradians. Spacecraft (S/C) designers therefore require tolerance-level criteria for the almost inevitable interception of propellant particles by S/C surfaces. Under contract NAS7-575 a systematic analytical study was made of the deleterious effects of Hg, Hg^+ , Cs, and Cs^+ on spacecraft surfaces⁽¹⁻⁵⁾ Erosion of non-metallic surfaces by sputtering, degradation of thermal control coatings, chemical degradation of non-metallic surfaces, and condensation on solar cell cover glasses are expected to pose the most restrictive design constraints. Of the above areas, quantitative constraints have been generated for condensation; the others are at the qualitative stage and require experimental study.

The program goals of the present effort are 1) to fabricate experimental fixtures required to make these measurements, and 2) perform exploratory experiments to determine in which areas future emphasis should lie.

B. Program Organization

The program contains four work units: Metallurgy, Chemistry, Thermophysics, and Electric Propulsion Technology. The metallurgy group is charged with elucidating reactions between the propellants and S/C metals. The chemistry group is responsible for elucidating reactions between the rocket efflux and non-metallic S/C materials. The thermophysics group will determine the surface thermal changes which occur in various thermal control coatings. The electric propulsion group is responsible for sputtering experiments, operation of the primary facility in which most exposures are made, and program management.

The structure of this report reflects this program organization.

C. Program Status

The chemical and metallurgical immersion tests, and the mercury surface thermal tests have been completed. Fabrication of the multipurpose sample holder is complete, but it awaits testing.

II. TECHNICAL DISCUSSION

A. Electric Propulsion Technology

1. Summary. Fabrication of the multipurpose sample holder was completed. Additional samples were prepared. A new engine shutter was fabricated. A journal manuscript was prepared. Analysis was made of sputtered accelerator grid material. It is an important thruster effluent to S/C surfaces, but is negligible in our experiments.

2. Multipurpose Sample Holder. Fabrication of the multipurpose sample holder was completed during the quarter. The photograph in Fig. 1 was taken prior to connecting the fluid pipes to the port plate feedthroughs. One lower track roller and both upper track guide pins can be seen in the photograph. Fabrication of the associated glovebox table was begun. Remaining tasks are leak checking the system, precision adjustment of the holder behind the collector cut-out, exterior plumbing, and completion of the table. Sample holding screws must also be machined.

A Haake Model No. 1280-1 constant temperature circulator was purchased on capital funds as a source of high temperature fluid. The circulator specifications indicate $\pm 0.01^{\circ}\text{C}$ temperature control accuracy, a 2 KW stepless heater, and 28 l/min discharge capacity. It has passed tests for malfunction.

3. Samples. Effort was spent during the reporting period on the preparation of samples for the multipurpose sample holder. Current status of each type is shown below.

4. Engine Shutter. Initial data from exposure of thermal control coatings to Hg^{+} indicated that much shorter beam exposures than previously anticipated would be desirable. The then existing engine shutter, which operated approximately 1 inch in front of the thruster, did not permit thruster start-up when closed. Neither was the approximately 10 minute engine start-up period permissible with the surface holder in the measurement position.

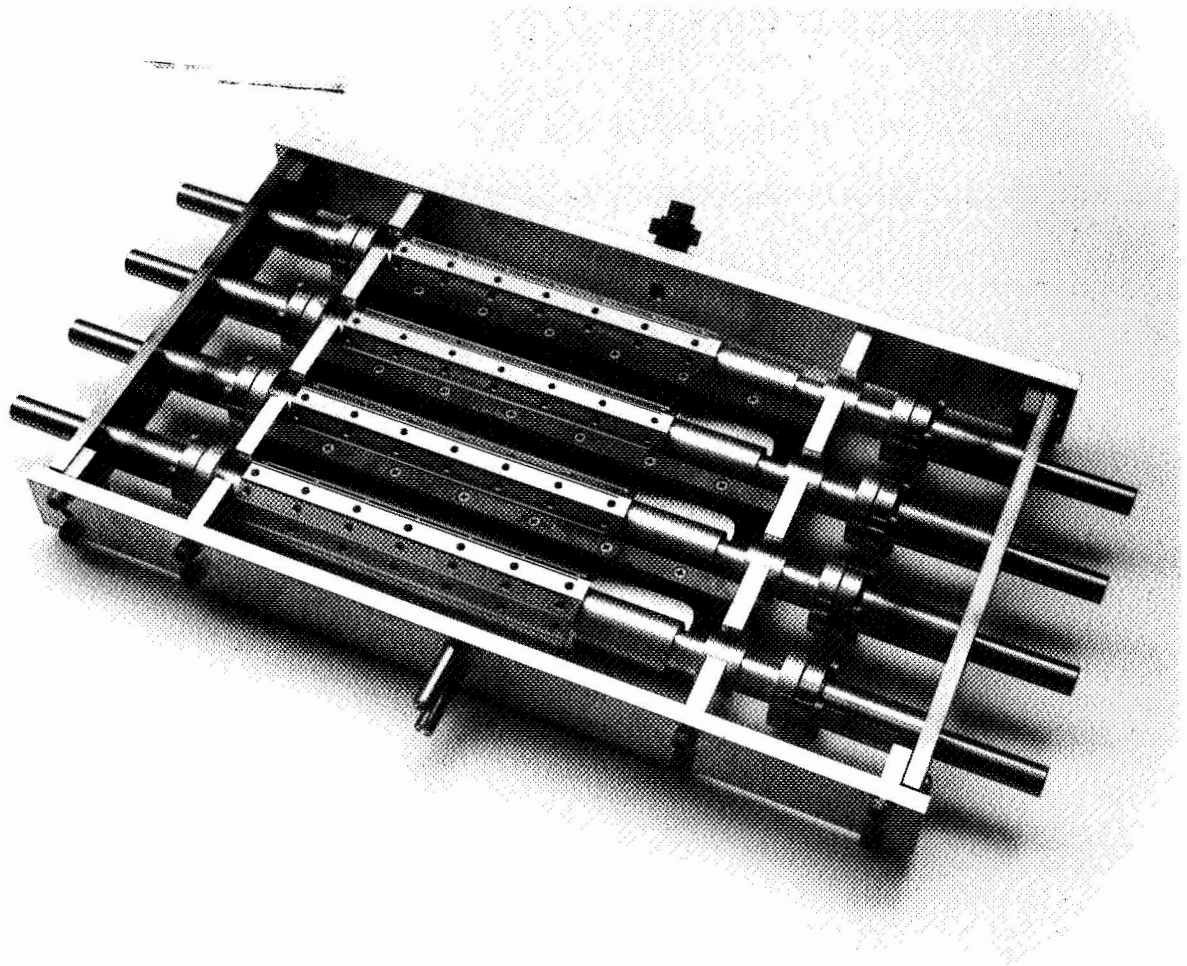


Figure 1. Photograph of completed
multipurpose sample holder.

STATUS OF MULTIPURPOSE SAMPLES

<u>TYPE</u>	<u>STATUS</u>
3M401-C10	50 mounted for spraying
PV100	" " " "
Cat-a-Lac	" " " "
RTV-41	40 mounted for coating
RTV-566	40 prepared
Teflon FEP	have 2 and 5 mil sheet stock
Kapton	have 3 mil sheet stock
Copper	60 prepared
6061-T6 Al	18 polished
Silver	30 plated (2-3 mil thick) on 6061-T6
Solder	70 mil billet rolled
Gold	30 plated on 6061-T6
7940 Quartz	have 20 mil sheet for approximately 5 samples
0211 Glass	have 6 mil sheet for approximately 8 samples
Z-93	60 prepared
S13G	60 prepared

Therefore a new shutter was designed, fabricated, and installed. It operates a few inches in front of the sample plane, and its thermal design permits thruster operation when closed without significant outgassing in the direction of the samples. Open and closure operations are less than 2 seconds in duration.

5. Support of Thermophysics Experiments. A significant amount of time was expended providing the mercury beams for the experiments described in Section B.

6. Preparation of AIAA Manuscript. Reference 5 was revised and submitted for publication in the Journal of Spacecraft and Rockets. In addition to editorial changes, the section on propellant condensation was rewritten along the lines of Section 3 of Reference 4, and current experimental results were summarized. The figure showing bulk accumulation regions for mercury and cesium was modified to cover a wider range in surface temperatures, as shown in Figure 2. The chemical effects table was simplified and updated, as shown in Table 1.

7. Analysis of Sputtered Accelerator Grid Material. To date, contract reports have not included analysis of sputtered accelerator grid material, either as a potential S/C surface contaminant or as a source of experimental error in ion beam exposures of samples. It will be shown that the former may be a matter of some concern, but that the latter is negligible.

Accelerator grid sputtering is done by (Class 3) charge exchange ions. The impinging ions appear as accelerator "drain" current, and after a few hundred hours of operation, sputtering patterns are clearly visible on the downstream face of this molybdenum electrode. The magnitude of the resulting flux of Mo atoms may be estimated from the drain current and sputtering yield data:

$$\Gamma_o = S \Gamma_+ = S I_+(qA)^{-1} \quad (1)$$

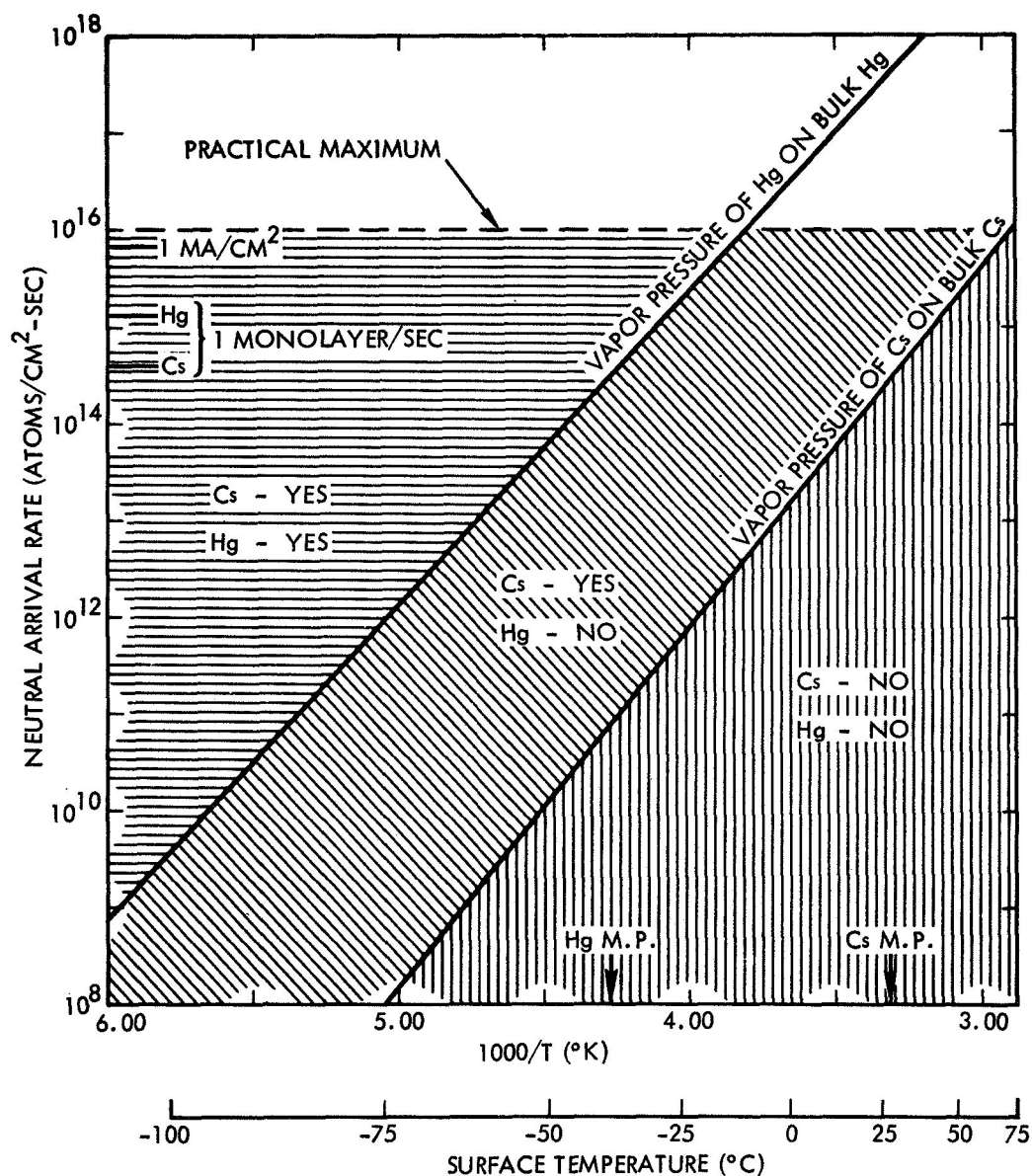


Figure 2. Bulk accumulation regions for mercury and cesium atoms on surfaces where adsorbed monolayers already exist.

Table 1. Chemical effects of Cs, Cs⁺, Hg and Hg⁺ on typical spacecraft materials.

MATERIAL	TYPE	EXTENT OF DEGRADATION ^a BY				
		Cs	Cs ⁺ , Hg ⁺ ⁺²⁰	CsOH ^b , 21	Hg ²²	
H-FILM ^c	POLYIMIDE	Turns deep violet due to one electron oxidation-reduction product probably highly conductive and photoconductive) ²²	(MODERATE) ^d	(SEVERE HYDROLYSIS WITH CHAIN SCISSION)	NONE	
TEFLON FEP ^e	POLY (PERFLUORO-ETHYLENE PROPYLENE)	Turns black; C & CsF forms at surface ²²	(SEVERE, LOSS OF FLUORINE) ^f	(NONE)	NONE	
RTV 40	AMINE CURED SILICONE	(LITTLE OR NONE) ²³	(MODERATE) ^d	(MODERATE BY HYDROLYSIS)	(NONE)	
CAT-A-LAC BLACK	AMINE CURED EPOXY	(LITTLE OR NONE)	(MODERATE) ^d	(MODERATE)	(NONE)	
PV-100	SILICONE-ALKYD RESIN; TiO ₂ PIGMENT	(LITTLE OR NONE OF RESIN; ²³ POSSIBLE PIGMENT DISSOLUTION) ²⁴	(MODERATE, WITH DARKENING) ^d	(MODERATE TO SEVERE DUE TO HYDROLYSIS)	(NONE)	
DELRIN ^c	POLYACETAL	LITTLE OR NONE ²²	(MODERATE) ^f	(NONE)	NONE	
SYLGARD 182 ^c	SILICONE	LITTLE OR NONE ²²	(MODERATE) ^d	(MODERATE)	NONE	
SMRD 745 ^c	EPOXY	LITTLE OR NONE ²²	(MODERATE) ^d	(LITTLE OR NONE)	NONE	
GT-100 ^c	POLYESTER	LITTLE OR NONE ²²	(MODERATE) ^d	(SLIGHT TO SEVERE DUE TO HYDROLYSIS)	NONE	
S-13	METHYL SILICONE +ZnO	(LITTLE OR NONE OF RESIN ²³ POSSIBLE DARKENING OF PIGMENT) ²⁴	(MODERATE, PROBABLE DARKENING DUE TO PIGMENT REACTION) ^f	(MODERATE)	(SLIGHT OR NONE)	
Z-93	POTASSIUM SILICATE + ZnO	(SLIGHT AT STRAIN POINTS, ²⁵ MODERATE DARKENING)	(MODERATE, WITH DARKENING)	(MODERATE ETCHING)	(SLIGHT OR NONE)	
Al ₂ O ₃		(SLIGHT TO MODERATE AT STRAIN POINTS) ²⁴⁻²⁶	(SLIGHT)	(SLIGHT ETCHING)	(SLIGHT OR NONE)	
BeO		(SLIGHT TO MODERATE AT STRAIN POINTS) ²⁴	(SLIGHT)	(SLIGHT ETCHING)	(SLIGHT OR NONE)	
CORNING 7740	PYREX	(SLIGHT TO MODERATE AT STRAIN POINTS) ²⁵	(SLIGHT TO NONE)	(SLIGHT ETCHING)	(SLIGHT OR NONE)	
CORNING 0211	PYREX	(SLIGHT TO MODERATE AT STRAIN POINTS) ²⁵	(SLIGHT TO NONE)	(SLIGHT ETCHING)	(SLIGHT OR NONE)	

a. INFORMATION IN PARENTHESES IS POSTULATED, BASED ON ANALOGOUS LITERATURE DATA; INFORMATION WITHOUT PARENTHESES IS DATA FROM LITERATURE AND IMMERSION TESTS.

b. CsOH IS ANTICIPATED WHEN Cs ARRIVES AT SURFACES HAVING ABSORBED WATER VAPOR.

c. IMMERSION TESTED IN Cs AND Hg FOR 48 HOURS.

d. SURFACE CHAIN DEGRADATION AND CROSS-LINKING.

e. SURFACE CHAIN SCISSION.

Mercury electron bombardment thrusters typically have $1 \text{ to } 3 \times 10^{-5} \text{ A/cm}^2$ drain current density. The sputtering yield of polycrystalline Mo by 2 Kev Hg^+ is ~ 2.6 . Therefore $\Gamma_o \simeq 2 \times 10^{14} \text{ Mo cm}^{-2} \text{ sec}^{-1}$.

To first order, the spatial distribution of this flux should be cosine. Thus the Mo flux arriving at any location may be directly compared to neutral propellant flux, and it is seen that the Mo flux will be $\sim 1/10$ the Hg flux. However, Mo has a very low vapor pressure, so virtually all atoms arriving at a surface will be deposited there. Layer thickness will grow at the rate

$$\frac{dx}{dt} = \frac{\Gamma_{ar}}{n} = \frac{\Gamma_o a^2}{n r^2} \cos \theta \quad (2)$$

where

- Γ_{ar} = arriving Mo flux density, $\text{atoms cm}^{-2} \text{ sec}^{-1}$
- a = thruster radius, cm
- n = atomic density of Mo, atoms cm^{-3}
- r = radial distance from center of thruster, cm
- θ = angle between thrust vector and radius vector, degree

For a 15 cm-diam thruster, for instance, a layer thickness growth rate of 1 Å/hr would occur at a surface normal to the 80° radius vector at 1 meter. In order for a mercury layer to grow more rapidly than this, the surface temperature would have to be less than $\sim -75^\circ\text{C}$. At greater distances, corresponding temperatures for equivalent growth rates are even lower. Thus, for solar distances less than $\sim 3 \text{ AU}$, deposition of Mo will usually be of more concern than condensation of Hg. Note, too, that the layer growth rate employed in this example is significant: at 1 Å/hr it would only take a few hundred hours to produce an opaque Mo layer.

Evaluation of significance of this Mo flux in the experimental situation requires calculation of the Mo arrival rate at the sample location and comparing it to the Hg^+ arrival rate. The thruster-sample distance is 71 cm, so the flux of Mo arriving at the surface is $2 \times 10^{12} \text{ atoms cm}^{-2} \text{ sec}^{-1}$. The Hg^+ arrival flux is typically 1×10^{15} , 500 times greater; therefore the Mo flux is negligible.

8. Future Work. During the forthcoming reporting period, preparation for the quartz crystal microbalance experiments will begin.

B. Thermophysics

1. Summary. RTV 41 and RTV566 samples were prepared. Five more sample materials were measured in situ before and after exposure to mercury atoms (neutrals). Results were similar to those reported in the Second Quarterly Report for the first five samples tested in that no large changes were detected. All samples (except barrier layer anodize aluminum which is being eliminated from the current test program due to unavailability) were also exposed to various large doses of 3 Kev Hg^+ . Marked increases were observed in the absorptance of white paints and RTVs. Emissivities remained relatively constant. In addition to the normal tests, a series of post ion exposure measurements were made before and after exposure to an oxygen environment. A slight oxygen-linked recovery of α_{xe} was observed.

Thus, all planned preliminary thermophysical experiments on mercury propellant have been completed. Recommendations are made for future mercury experiments.

2. Sample Preparation. Thirty samples each of RTV41 and RTV566 were prepared by a strike-off technique that produced an RTV thickness of about 10 mils on the 6061-T6 substrate. The substrate was primed with SS4155 silicone primer to improve adhesion.

3. Ex Situ Measurements. This quarter, spectral distributions of two samples each of RTV41, RTV566, and Cat-a-lac black were measured between .28 and 2.5 microns on the modified Beckman DK2A double beam ratio recording photospectrometer and between 2.0 and 26.0 microns on the Gier Dunkle Heated Cavity Reflectometer. In addition, two samples each of the 6-mil and 20-mil second surface aluminized mirrors were measured on the Beckman. One of each was then broken to obtain a piece small enough to be run in the heated cavity reflectometer.

All ex situ spectral data taken during the program was manually reduced during the quarter. Values for α_{xe} were obtained by using a 25-band overlay based on the computer-reduced spectral distribution of the Christie xenon lamp unit. In order to obtain a sufficiently low thermal flux density, high α/ϵ samples such as gold and polished aluminum must be run in situ with the Christie lens system removed. Since the spectral distribution with the lens out is somewhat different from that with the lens in, a separate overlay was made for each of the two optical configurations. The two spectral distributions (lens in and lens out) as well as their integral curves are shown in Figures 3 and 4. Values for α_s were obtained by using a 25-band overlay based on the Johnson zero-air-mass solar curve. Table 2 gives a summary of results from the ex situ measurement and data reduction effort.

4. Mercury Atom Beam Experiments. Five sample materials (polished aluminum, gold plated aluminum, 6-mil second surface aluminized microsheet, 20-mil second surface aluminized fused quartz, and RTV41 on aluminum) were tested in situ during the Quarter.

Table 3 shows in situ values of α_{xe} and ϵ_H after various periods of accumulated exposure compared to the ex situ measurements. The impinging beam was mercury atoms (neutrals) at a constant rate of about 1×10^{14} atoms $\text{cm}^{-2} \text{sec}^{-1}$ and the sample temperatures were about 22°C.

In general, it can be said that the absolute values of α_{xe} and ϵ_H as determined in situ for all five samples are in excellent agreement with the corresponding ex situ values. The apparent scatter of in situ values for any given sample is approximately of the same magnitude as scatter observed in the ex situ measurements. Therefore the effect of beam exposure on sample optical properties may be examined.

A comparison in Table 3 of in situ measurements of α_{xe} or ϵ_H after various exposure times indicates that no significant change occurred with up to 3.366 hours of exposure. Pre and post-exposure ex situ measurements of ϵ_H tends to substantiate this conclusion. Post exposure α_{xe} was not measured on the Beckman for this set of samples because of time limitations so that comparison is unavailable.

TABLE 2
SUMMARY OF RESULTS OF PRE-EXPOSURE
EX SITU MEASUREMENTS ‡

SAMPLE NO.		α_s (a)	α_{xe} (a)	ϵ_N (b)	ϵ_H (c)
454-69	Gold Plated Aluminum	.220	.160*	.010	.013
455-69	Gold Plated Aluminum	.196	.140*	.010	.013
456-69	SI3G White Paint	.190	.148	.903	.853
457-69	SI3G White Paint	.188	.142	.899	.850
458-69	PV100 White Paint	.188	.142	.866	.823
459-69	PV100 White Paint	.190	.139	.864	.820
460-69	Z93 White Paint	.159	.117	.918	.869
461-69	Z93 White Paint	.162	.117	.923	.873
462-69	Polished Aluminum	.181	.166*	.018	.023
463-69	Polished Aluminum	.169	.155*	.021	.027
464-69	3M Black Paint	.982	.982	.909	.858
465-69	3M Black Paint	.986	.986	.918	.866
554-69	6-mil Microsheet [†]	.138	.133	.817	.785
555-69	6-mil Microsheet [†]	.142	.135	--	--
556-69	20-mil Quartz [†]	.118	.114	.779	.751
557-69	20-mil Quartz [†]	.118	.114	--	--
613-69A	Cat-a-lac Black	.956	.956	.872	.828
613-69B	Cat-a-lac Black	.954	.954	.868	.825
672-69	RTV 41	.305	.265	.892	.846
673-69	RTV 41	.327	.291	.887	.843
794-69	RTV 566	.652	--	--	--
795-69	RTV 566	.652	--	--	--

‡Third figure included to show data trends; not fully significant.

[†]Vacuum deposited aluminum on second surface.

*Based on lens-out spectrum.

(a) Measured on modified Beckman DK2A.

(b) Measured on Gier Dunkle Heated Cavity Reflectometer.

(c) Calculated from normal emittance and theoretical correction given in Eckert and Drake, "Heat and Mass Transfer," 2nd Edition.

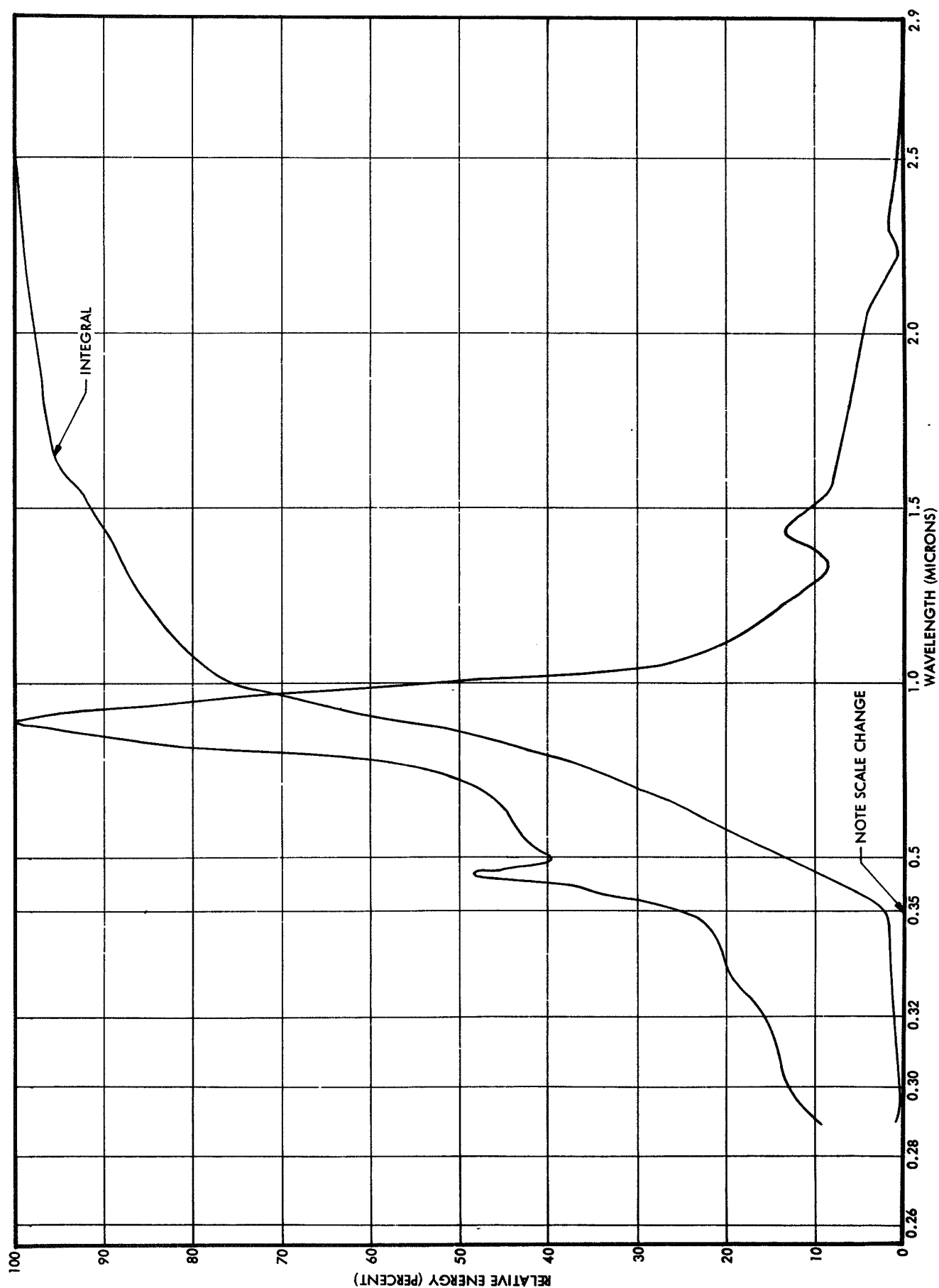


Figure 3. Normalized spectral distribution provided at the sample by the Christie Xenon Arc System with the lens in place.

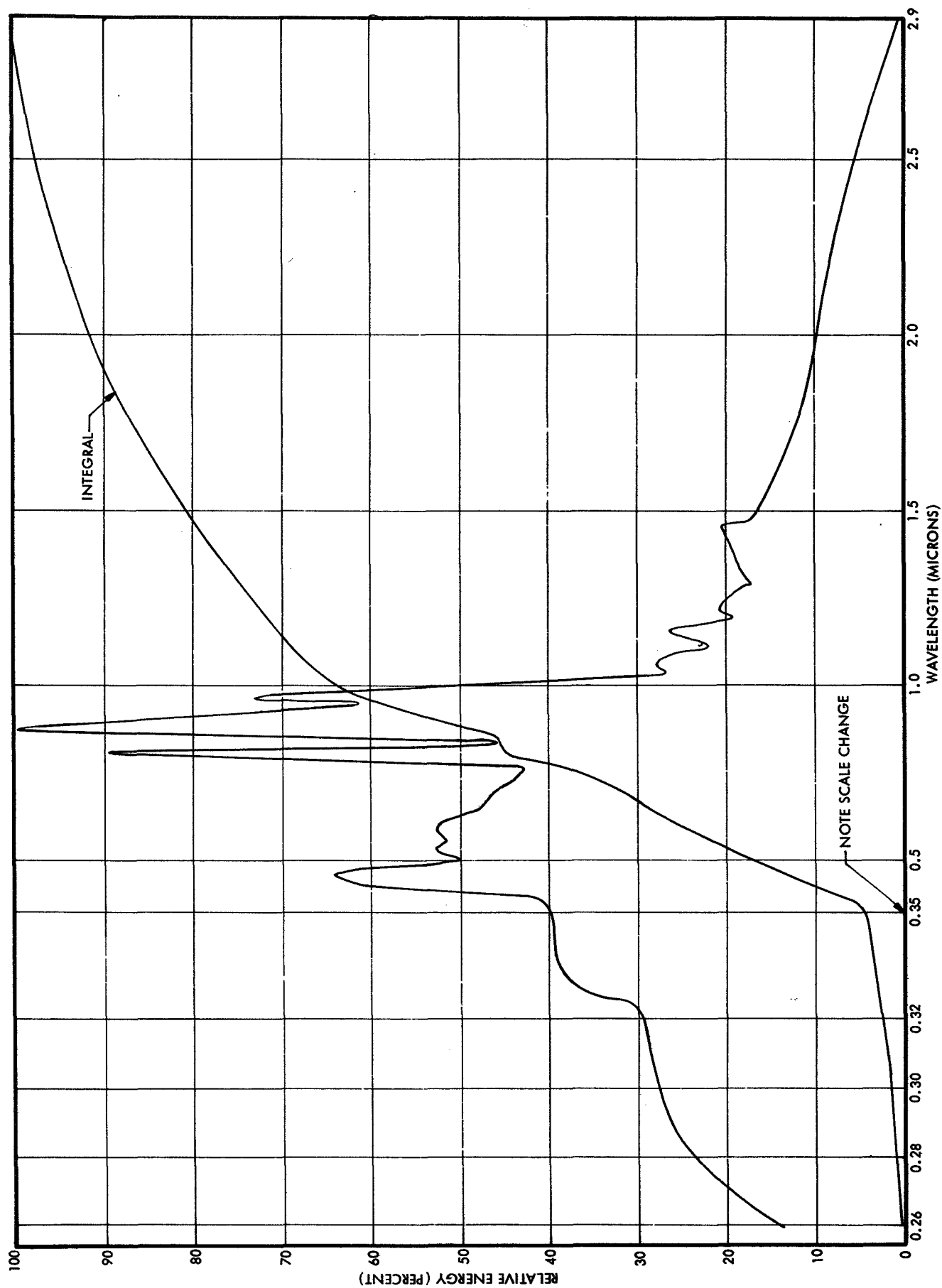


Figure 4. Normalized spectral distribution provided at the sample by the Christie Xenon Arc System with the lens removed.

TABLE 3.
COMPARISON OF THERMAL PROPERTIES MEASURED AFTER VARIOUS PERIODS OF 22°C EXPOSURE TO MERCURY
ATOMS AT A BEAM FLUX DENSITY OF APPROXIMATELY 1×10^{14} ATOMS/CM² SEC.

SAMPLE MATERIAL	EX SITU PRE EXPOSURE				IN SITU MEASUREMENTS [†]												EX SITU POST EXPOSURE			
	α_{xe}	$\epsilon_N(a)$	$\epsilon_N(b)$	$\epsilon_H(c)$	t = 0			t = 0.333hr			t = 2.366hr			t = 3.366hr			α_{xe}	$\epsilon_N(a)$	$\epsilon_N(b)$	$\epsilon_H(c)$
					α_{xe}	ϵ_H	α_{xe}	ϵ_H	α_{xe}	ϵ_H	α_{xe}	ϵ_H	α_{xe}	ϵ_H	α_{xe}	ϵ_H				
Polished Aluminum	.161*	.035		.045	.146	.058	.121	.056	.147	.058	.157	.060	.137	.059	---		---	.029	.037	
Gold Plating on Polished Aluminum	.150*	.025		.032	.130	.053	.110	.056	.170	.063	.152	.069	.147	.068	---		---	.018	.023	
6-mil Microsheet (Aluminized on Back)	.134	.842		.800	.153	.790	.151	.789	.157	.795	.148	.798	.153	.798	---		---	.845	.804	
20-mil Fused Quartz (Aluminized on Back)	.114	.811	.779		.139	.765	.139	.766	.139	.773	.142	.776	.140	.775	---		---	.809	.775	
RTV 41 on Aluminum	.278	.909	.860		.237	.877	.236	.874	.245	.883	.245	.888	.239	.887	---		---	.909	.859	

[†]Third figure included to show data trends; not fully significant.

*Based on lens out spectrum

- (a) Average of two control samples measured on Beckman (modified DK2A)
- (b) QED (measured on Gier Dunkle Inspection Device)
- (c) Calculated from normal emittance and theoretical correction given in Eckert and Drake, "Heat and Mass Transfer," 2nd Edition.

These results (and those reported for 5 additional sample materials in the Second Quarterly) should be examined in light of Figure 2, which indicates that bulk condensation of mercury will not occur under the conditions of exposure employed. Thus, if an effect had been observed on any of the samples, it would have been the result of a partial monolayer coverage, either as an adsorbed film or through reaction with the sample material. Reaction of mercury with the paint samples was not expected in light of the previously reported chemical immersion tests. It is common knowledge that glass and mercury do not react at 22°C. A most interesting result of these measurements is that gold was affected only slightly if at all, since gold's affinity for mercury is well known.

Thus it appears on the bases of these first experiments that either the 10 materials tested do not react with mercury in a manner which produces significant change in thermophysical properties, or that even fractional monolayer mercury adsorption did not occur. The obvious next step in this investigation is to expose these sample materials to mercury atoms under conditions which result in bulk mercury condensation, reevaporate the bulk mercury, and then look for sample property changes. If none are found, it will then be possible to dismiss mercury atom damage to these (and perhaps similar) thermal control coatings as a deleterious effect to be considered in spacecraft design.

Such an experiment might provide a secondary but interesting opportunity: rough in situ measurement of ϵ_H and α_{xe} of the mercury layer before it is reevaporated. The experimental difficulty of maintaining a constant sample temperature well below room temperature and accounting for heat of sublimation would probably preclude a really accurate measurement. It would be valuable, however to see how a rough measurement compared with the semi-theoretical values developed under the previous contract.

5. Mercury Ion Beam Experiments. Ten sample materials were exposed to various doses of 3 Kev mercury ions and the properties were measured in situ. The ion flux used in these tests was approximately 1×10^{15} ions $\text{cm}^{-2} \text{sec}^{-1}$ and the samples were maintained at approximately 22°C. The results are presented in Table 4. The experimental sequence employed was to measure

TABLE 4.
Ion Engine Mercury Ion Test Results[†]

	Pre Exp.		Exp.		Post 1 Min Exp.		Post 10 Min Exp.		Post 40 Min Exp.		Post 40 Min Exp. Rerun		Post 3.249 Hr. Exposure		Post Oxygen Exposure	
	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H	α_x	ϵ_H
6 mil usheet	.152	.805	.170	.804			.187	.805	.186	.804	.182	.811	.142	*	.169	.865
20 mil Quartz	.151	.779	.179	.777			.165	.779	.165	.780	.159	.803	.155	.811	.147	.807
3M Black	.888	.889	.877	.885			.884	.883	.876	.886	.878	.887	.900	.895	.861	.889
RTV-41	.244	.881	.253	.878			.450	.873	.446	.874	.420	.878	.486	.865	.451	.857
Z-93	.147	.924	.148	.904			.660	.915	.762	.915	.763	.916	.841	.912	.808	.912
Gold	.135	.067			*	*	.131	*	.126	*						
Cat-a-Lac	.881	.862			.826	.852	.868	.882	.852	.890						
PV-100	.165	.808			.573	.802	.663	.804	.632	.816						
RTV-566	.575	.853			.626	.848	.655	.845	.649	.851						
SL3G	.163	.880			.309	.872	.344	.877	.338	.876						

[†] Third figure included to show data trends; not fully significant. Exposure times are accumulative.

* Data unreliable due to instrumentation instability.

the sample properties following an overnight pump down and approximately 2 hours of LN_2 cooling of the shrouds (labeled "Pre-Exp." in Table 4), turn the samples 180° for a timed beam exposure, return the samples to the measurement position (labeled "Post x min. Exp." in Table 4), turn and expose again, turn and measure again, and repeat this sequence until the samples had received 3 Hg^+ doses. The "Post 40 min Exp Rerun" readings were taken approximately 18 hours after the "Post 40 min Exp." readings. Throughout these measurements tank pressure was typically less than 2×10^{-7} torr and consisted of gases not condensed at LN_2 temperatures (mainly CO and H_2). The most significant change in properties was exhibited by the Z-93 sample; after a 10 minute exposure the absorptance had increased to 0.66. A check on oxygen-linked recovery was performed by raising the chamber pressure to near atmospheric with oxygen, soaking the samples, re-evacuating and taking another set of data. Pressurization took approximately 15 minutes; a vacuum of approximately 1 in. Hg was held for approximately 15 min.; 48 minutes were consumed in repumping. Throughout the entire procedure the LN_2 liners were kept cold to prevent desorption of Hg and H_2O , but above LN_2 temperature to limit condensation of O_2 . At the higher pressures a thick oxygen fog was produced within the chamber.

As seen in Table 4, there are significant changes in some of the test surfaces, notably the Z-93. Two other white paints, PV-100 and S13G, and both RTV samples also showed increase in α_x when exposed to Hg^+ , a trend which was also confirmed by visual inspection. The α_x of the black paints and the ϵ_H of all samples were not significantly affected. Both the quartz and microsheet second surface mirrors exhibited stable properties (within the limits of measurement accuracy). The gold sample underwent a visual color change - post test appearance could best be described as "coppery". Post exposure spectral measurements (Fig. 5a) however, indicate no significant change in absorptance and the spectral data still exhibits the gold characteristics. The surface is most likely a gold-mercury amalgam, but primarily gold. The post exposure Z-93 spectral data, (Fig. 5b), is interesting in that the absorptance edge of ZnO is still evident at 0.37 microns even though

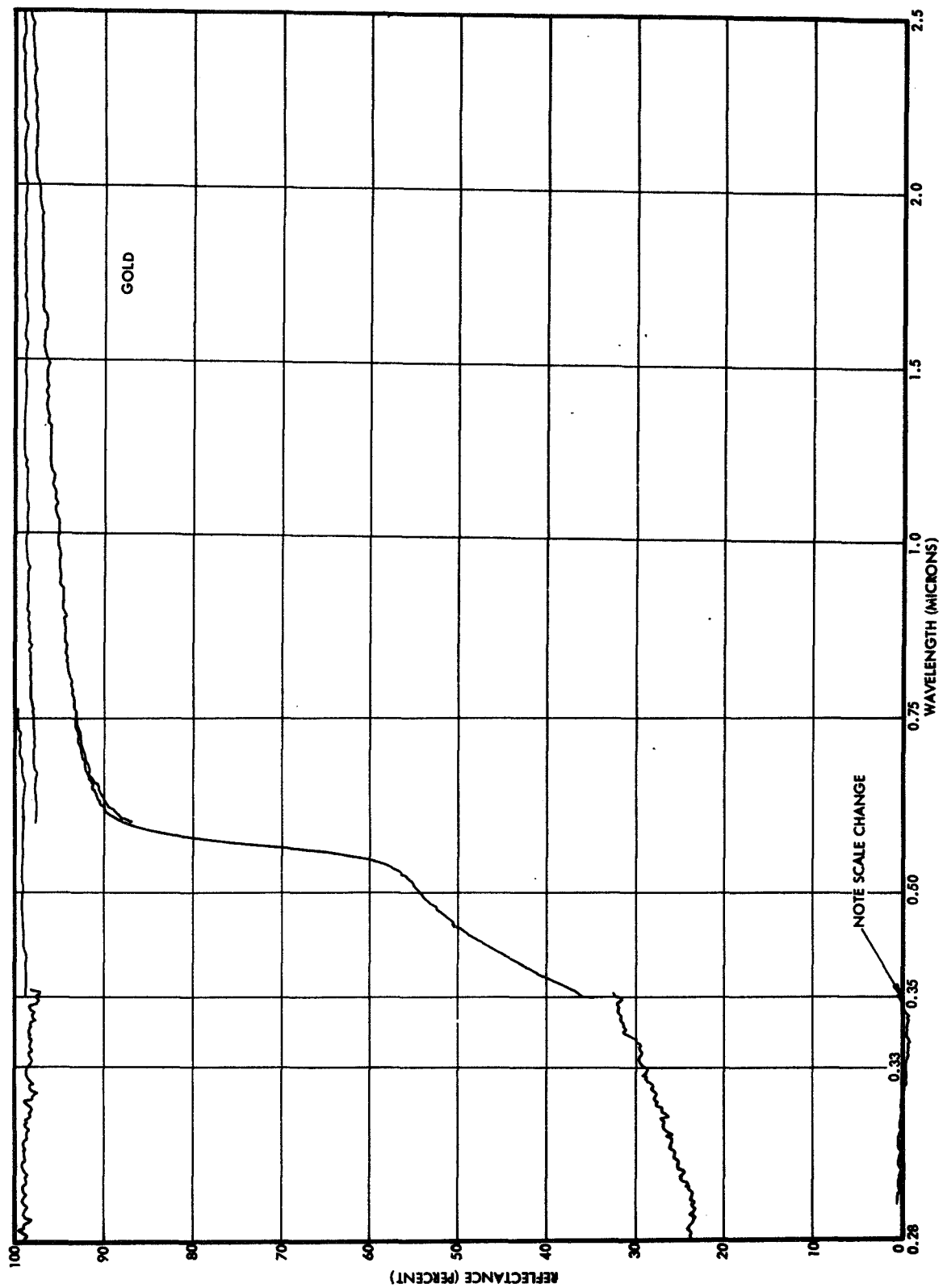


Figure 5a. Spectral reflectance of gold following 40 minutes of exposure to $10^{15} \text{ Hg}^+ \text{ cm}^{-2} \text{ sec}^{-1}$.

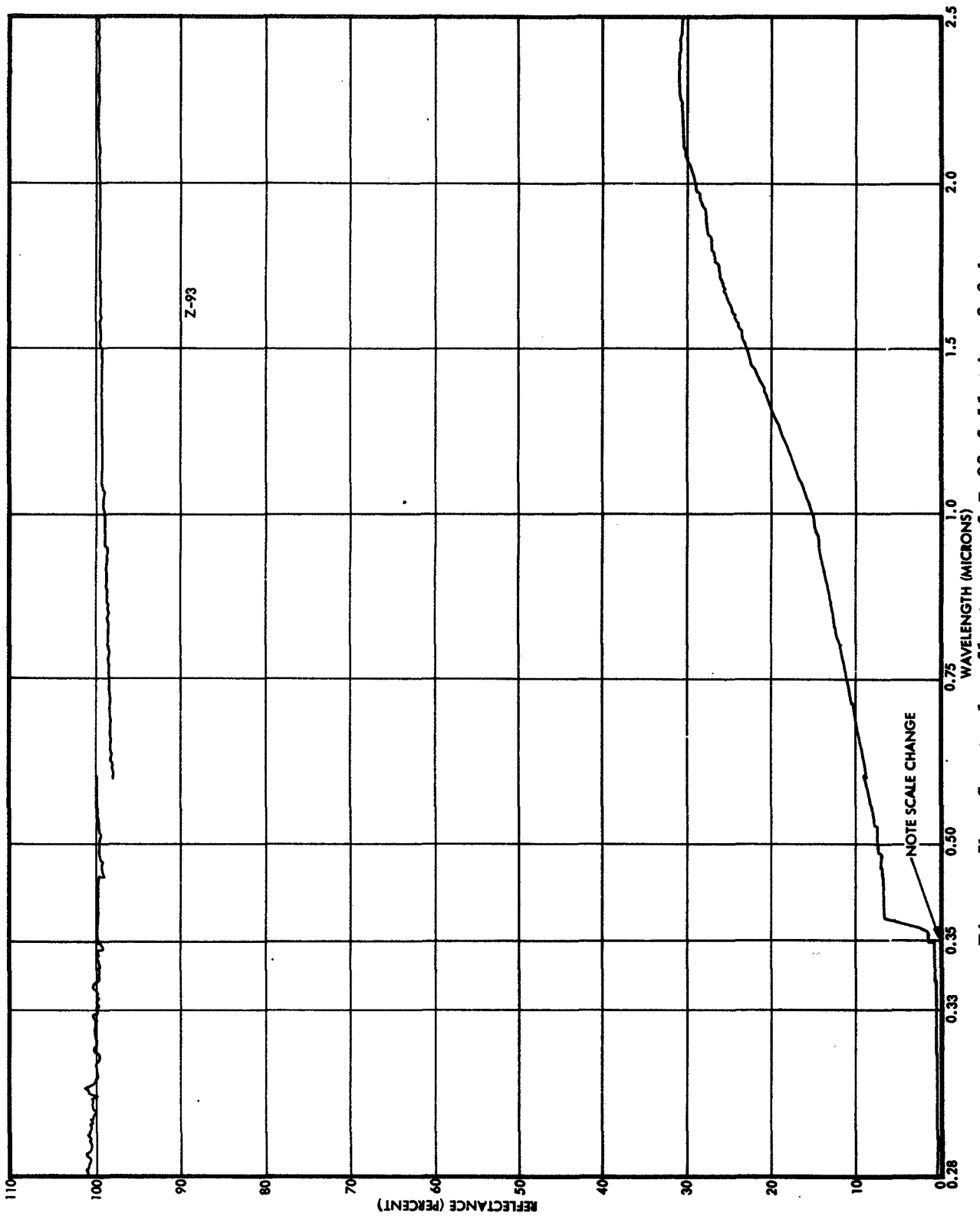


Figure 5b. Spectral reflectance of Z-93 following 3.2 hours of exposure to 10^{15} Hg^+ cm^{-2} sec^{-1} .

the surface is nearly "black" at that wavelength. The oxygen exposure test after the ion exposure did produce a small decrease in absorptance. It is felt that a more significant change would be measured if semi-spectral (i.e. filter) data were taken in the in situ tests. Indeed, attempts at mechanism evaluations must certainly rely on some more sophisticated test procedures than are presently employed.

Note that the test results are for greatly accelerated arrival rates, and flux rate effects have not yet been evaluated. A typical arrival rate of high divergence angle ions to a spacecraft surface would be 10^9 ions cm^{-2} sec^{-1} . Furthermore the Hg^+ dose size is large in comparison to most practical missions. A 10^9 arrival rate during a 10^4 hour thrust period corresponds to a 3×10^{16} ions cm^{-2} dose, whereas in these experiments 6×10^{16} ions cm^{-2} arrive in 1 minute. Clearly, future experiments should include exposing these samples at lower arrival rates and measurements after smaller doses.

Nonetheless some tentative conclusion may be drawn from these severe tests of thermal control coatings with respect to solar-electric spacecraft.

- With the probable exception of degradation of their optical coatings, if any, ion damage to solar cell cover glass properties will probably proceed at ion erosion rates, i.e., very slowly. Thus, thermo-physical attention regarding the front surface of a solar array should focus on the materials exposed to the thruster exhaust by virtue of cover glass discontinuity and on propellant condensation effects.
- On the rear surface of solar arrays, where only ϵ_H is of interest, ion damage will also proceed slowly for many if not all coatings.

6. Future Work. Work in the thermophysics area has been suspended pending further direction from the JPL contract manager.

C. Metallurgy

1. Summary. Thin solder samples containing silver were prepared and coated with mercury. Sample strength apparently was not improved by the silver additive. Tensile tests were made on thick mercury coated silver bars following various reaction periods. Recorded variations in modulus are not understood, but the bars retained their ultimate tensile strength.

2. Solder Containing Silver and Mercury. Earlier immersion tests of solder in mercury clearly indicated that solder in 7 mil thickness had very low physical strength properties after exposure to mercury. Silver showed some attack after four weeks of immersion but appeared to have sufficient properties to be used in the mercury environment. Furthermore, silver is sometimes employed as a solder constituent in solar array designs. Therefore, two silver solder alloys were made for testing during this reporting period. Both of the alloys made contain 10% silver, but they were made in two different ways. The first alloy contained 57^W/o Pb and 10% Ag while the second was 61.9% Sn, 38.1% Pb to which 10^W/o silver was added. Both of these alloys were melted without flux in an argon atmosphere. After melting, a 7 mil strip was rolled from each of the alloys and tensile samples were cut. These samples were then surface coated with mercury in the manner described in the Second Quarterly Report. These 7 mil alloy samples reacted to the surface mercury coating in the same manner as eutectic solder. That is, the samples would not support their own weight and the longest time period between coating and failure was less than one minute.

3. Tensile Tests of Mercury Coated Silver. Tests on 1/4 x 1/4 inch silver tensile bars were completed. Table 5 presents the data from these tests. Ultimate tensile strength of the bars was unaffected by up to four weeks of reaction time following surface coating with Hg. The modulus of the four-week bar is significantly lower than recorded for the one-week bar and the uncoated bar. This result is not understood in light of the previously reported four week immersion test. That test indicated no more than a 3 mil deep reaction zone with higher microhardness values than the sample interior. Variations in modulus between samples are usually associated with variations in sample composition or structure.

However, the effects of Hg on the mechanical properties of silver do not appear, on the basis of these tests, to exclude the use of silver on spacecraft surfaces which intercept Hg propellant.

Table 5.
Tensile Properties of Silver

Reaction Period	Ultimate Tensile Strength	Modulus
Uncoated Bar	41,050 psi	13.2×10^6 psi
Surface Coated with Hg - 1 week reaction time	40,400	14.4×10^6
Surface Coated with Hg - 4 weeks reaction time	40,600	9.7×10^6

4. Recommendations for Future Work. A review of the immersion and surface coating work done thus far indicates that the environment provided in these tests is too severe for solder and not without affect on solder. Any metallic combination that proved unaffected under the testing conditions would be of little concern in spacecraft design; however, since the materials have been affected, attention should turn to the planned beam exposures of these metals, which will more closely simulate the spacecraft surface environment.

5. Future Work. Work in the metallurgy area has been suspended pending further direction from the JPL Contract Manager.

III. CONCLUSIONS

Analysis of the sputtering of molybdenum from the accelerator electrode of mercury electron bombardment thrusters indicates that this is an important thruster effluent. At solar distances less than 3 AU, the deposition rate of Mo on spacecraft surfaces will usually exceed the net condensation rate of mercury because of surface temperature: The arrival rate of Mo will be $\sim 10^{-1}$ that of Hg^0 , but the reevaporation rate of Hg^0 is $\sim 10^{17}$ higher than Mo.

Exposure of polished aluminum, gold plated aluminum, 6-mil Corning 0211 glass microsheet (back aluminized), 20-mil Corning 7940 fused quartz (back aluminized), RTV41, Cat-a-Lac black paint, 3M 401-C10 black paint, PV100 white paint, Z-93 white paint, and S13G white paint at 22°C to 10^{14} atoms $\text{cm}^{-2}\text{sec}^{-1}$ for periods up to 4 hours did not produce a detectable change in sample hemispherical emittance (ϵ_H) or xenon lamp absorptance (α_{xe}). These exposure conditions could not have produced bulk condensation of Hg. Thus, either fraction monolayer mercury adsorption did not occur, or ϵ_H and α_{xe} are not significantly changed by adsorption of one or less monolayers of Hg at this temperature.

Exposure of gold, 6-mil Corning 0211, 20-mil Corning 7940, RTV41, Cat-a-Lac black, 3M black PV100, Z-93, S13G, and RTV566 at 22°C to 3 Kev Hg^+ at 10^{15} ions $\text{cm}^{-2}\text{sec}^{-1}$ for 40 minutes or more did not produce significant change in sample ϵ_H . This arrival rate is $\sim 10^6$ larger than a typical arrival rate of charge exchange ions to a spacecraft surface and the total ion dose ~ 80 or more larger than will be typical. Therefore, on the rear surface of solar arrays, where ϵ_H is the only thermophysical property of interest, thermophysical ion damage will proceed slowly, if at all, for many if not all thermal control coatings.

These ion exposures produced marked increases in α_{xe} for the RTVs and white paints, but little change in α_{xe} of the other samples. Therefore: 1) with the probable exception of degradation of their optical coatings (when present), ion damage to solar cell cover glass properties will probably

proceed at ion erosion rates, i.e., very slowly; 2) thermophysical attention regarding ion damage to the front surface of silicon cell solar arrays should focus on the materials exposed to thruster exhaust by virtue of cover glass discontinuity, and 3) additional ion exposures of the RTVs and white paints at lower arrival rates and/or smaller ion doses are required. A slight oxygen-linked recovery of α_{xe} was observed with a crude test. Semi-spectral (i.e. filter) data would probably have revealed a more significant recovery, and more sophisticated test procedures must be used if degradation mechanism evaluations are to be made.

Seven-mil-thick solder samples containing ~10% silver were surface coated with mercury. They would not support their own weight after less than one minute. This result is identical to similar tests on silver-free solder samples, indicating that in concentrations of 10% or less silver does not significantly reduce degradation of solder strength by mercury. Tensile tests on mercury coated 1/4 x 1/4 inch silver bars following reaction periods up to 4 weeks showed constant ultimate tensile strength. The 4-week sample showed a ~30% decrease in modulus, which is not understood in light of metallurgical theory and previous experimental results.

IV. RECOMMENDATIONS

It is recommended that:

- 1) Phase III Hg^0 exposures of thermal control coatings under conditions producing bulk Hg condensation be made.
- 2) Phase III Hg^+ exposures of thermal control coatings emphasize RTVs, white paints and non-glass materials typical of the illuminated surface of solar arrays. These experiments should include lower arrival rates and/or ion dose than employed to date, and semi-spectral absorptance measurements should be considered.
- 3) Future work on metallurgical effects emphasize exposure of samples to beams as opposed to immersion tests and surface coating tests.
- 4) Engineering design curves for Mo deposition degradation be constructed.

V. NEW TECHNOLOGY

None

VI. REFERENCES

1. First Quarterly Letter, TRW #08965-6004-R000, Contract NAS7-575.
2. Second Quarterly Letter, TRW #08965-6007-R000, Contract NAS7-575.
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6. G. Carter and J. S. Colligon, Ion Bombardment of Solids, American Elsevier Publishing, Inc., (1968), pp. 310-353.