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Contamination-induced degradation of optics exposed to the Hubble Space Telescope interior

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ABSTRACT

After the first Hubble Space Telescope (HST) servicing mission, the WFPC-1 and HSP instruments were returned to earth. Three optical surfaces from these instruments were analyzed in detail. They were the WFPC-1 pickoff mirror, the WFPC-1 aperture window, and the HSP filter assembly, all of which faced the central hub area of the HST. Hub-facing optics were of particular interest because any degradation in their performance might indicate a changed environment within the telescope itself. The pickoff mirror reflectance and aperture window transmittance were both found to be severely degraded in the far UV. The cause of the reflectance loss was contamination; the pickoff mirror was covered with a contaminant film about 450Å thick, and the aperture window and HSP filters each had about 150Å. The contamination contained multiple chemical species, some of which had been photopolymerized by exposure to earth-albedo UV. A UV-stimulated deposition and polymerization mechanism was posited. This contamination process is not expected to happen, however, for current and future instruments in HST. The HST components outgassed for 3.5 years before the first servicing mission, so the contaminants are no longer present in any appreciable quantity. Steps are being taken to ensure that any new equipment installed in the HST will not outgas. Over 2.5 years of operation, neither the WFPC-2 instrument nor the corrective optics module (COSTAR) has shown performance degradation in the UV. There is also no evidence that the primary or the secondary mirror of the HST has changed.

Keywords: optics, contamination, degradation, reflectance, ultraviolet, photopolymerization, albedo, HST

1. INTRODUCTION

In December 1993, seven astronauts aboard the space shuttle Endeavour rendezvoused with the Hubble Space Telescope (HST) in order to install corrective optics and replace other components. As part of this mission, the Wide Field and Planetary Camera I (WFPC-1) was replaced by the Wide Field and Planetary Camera II (WFPC-2), and the High Speed Photometer (HSP) was replaced by the corrective optics module (denoted COSTAR). The WFPC-1 and HSP instruments were brought back to earth.

Optical and thermal surfaces of these "returned" instruments were measured and analyzed in detail in order to understand the effects of space environment exposure on HST hardware. Of particular interest were the instrument surfaces which faced into the central "hub" area of the HST, because any degradation in these surfaces might be indicative of conditions within the telescope itself (to which all scientific instruments are exposed), as opposed to conditions internal to one instrument. There were three hub-facing optical surfaces on the WFPC-1 and HSP instruments:

- The WFPC-1 pickoff mirror, which was mounted on an arm that extended from the WFPC-1 instrument into the hub region,
- The WFPC-1 aperture window, a magnesium fluoride window that sealed the aperture of the WFPC-1 instrument,
- The HSP filters.

2. REFLECTANCE AND TRANSMITTANCE MEASUREMENTS

Reflectance or transmittance measurements were made on the items listed below. Each item was measured at several locations on the surface to check for consistency.

- The aperture window,
- The flight pickoff mirror,
- A spare pickoff mirror, which was identical to the flight mirror in every way except that it did not go into space,
- A reference mirror which had the same coating as the two pickoff mirrors, and whose absolute reflectance was known. This was used as a standard from which to calculate the absolute reflectance of the pickoff mirrors.

Reflectance measurements were performed[1] at wavelengths of 1216Å to 6500Å. The visible and near UV measurements were done in air, and the far UV measurements were done in a tent under a continuous dry nitrogen purge. The purge was needed to displace air which absorbs the shorter wavelengths.

The normal procedure was to perform UV reflectance measurements in vacuum; however in this case there was a concern that exposing the pickoff mirror and aperture window to vacuum might cause the optics to change (by evaporating off a contaminant, for example). Later, after the flight pickoff mirror had been exposed to vacuum with no noticeable change, the reflectance and transmittance measurements were repeated in vacuum to verify the accuracy of the results. The vacuum and nitrogen measurements agreed well.

The results for the far UV are shown in Figures 1-3 In addition to the usual measurements at normal incidence, measurements at a 45° angle of incidence were also performed because the pickoff mirror was used at a 45° angle during the HST mission. The flight pickoff mirror showed a dramatic loss of reflectance in the far ultraviolet compared to the spare pickoff mirror and compared to preflight measurements of both the flight and spare mirrors. No significant reflectance change was seen in the visible and near UV.

The aperture window showed a transmittance loss in the ultraviolet. Some transmittance roll-off was expected for a thick magnesium fluoride window; however additional degradation was apparent compared to the preflight data.

Figure 1. UV Reflectance at Normal Incidence

Flight and Spare Pickoff Mirrors

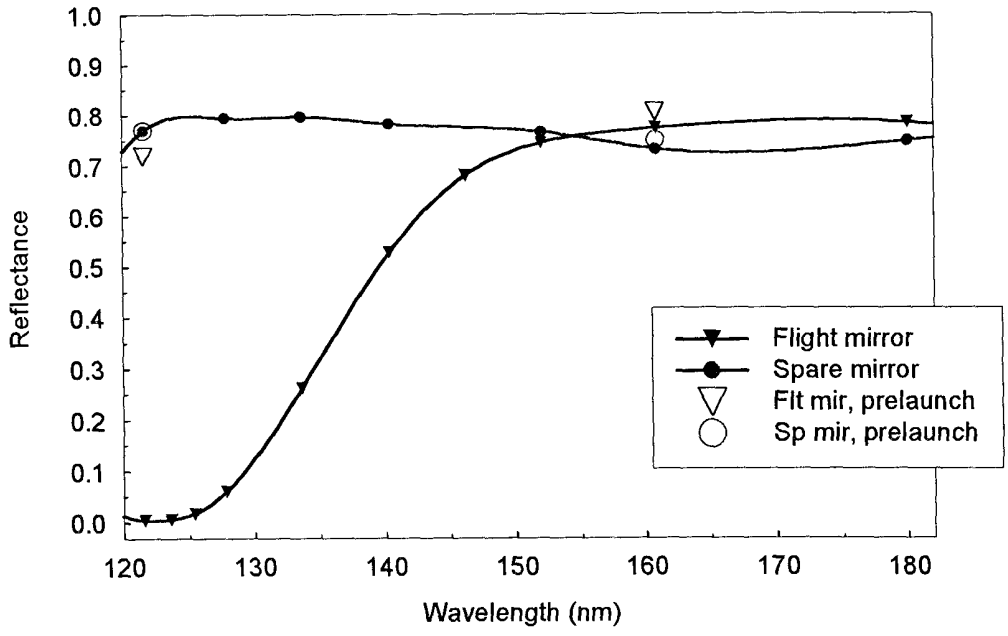


Figure 2. UV Reflectance at 45 Degrees

Flight and Spare Pickoff Mirrors

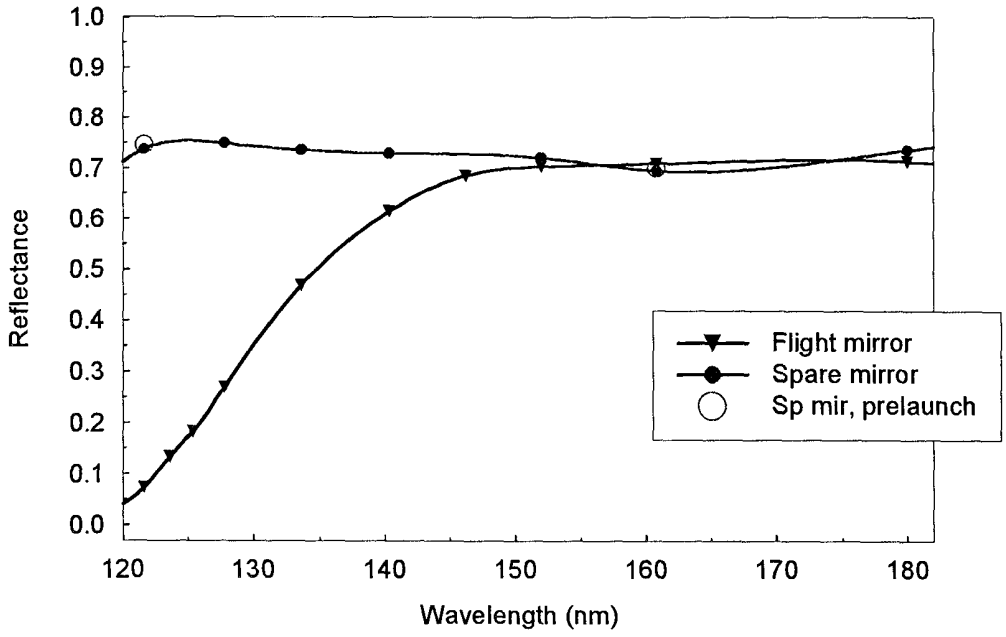
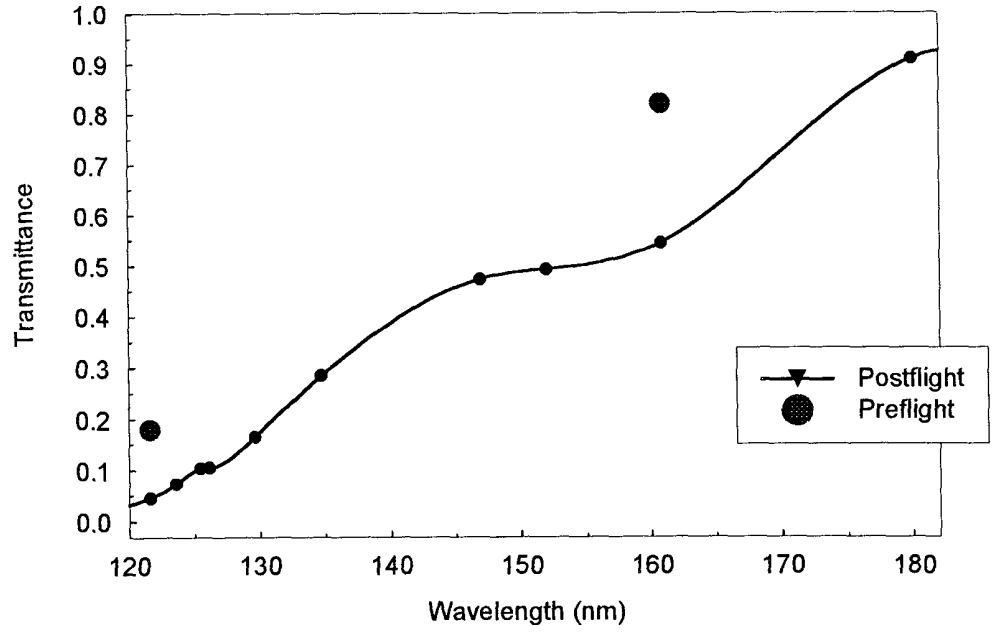


Figure 3. UV Transmittance of Aperture Window



3. MICROSCOPIC EXAMINATION

The observed degradation in the UV was cause for great concern, so further testing was pursued to find the cause of the degradation. First, non-destructive tests such as visual inspection, microscopic inspection, and microphotography were performed.

The flight pickoff mirror showed a blue haze to the naked eye. The haze was not uniform; it was more pronounced near the center and less visible in a narrow region at the edges of the pickoff mirror. No such haze was visible on the spare pickoff mirror, the aperture window, or the HSP filters.

These optics were then examined and photographed under a high-power microscope in phase-contrast (Nomarski) mode at magnifications up to 400X. The aperture window did not appear contaminated or damaged, except for a crystalline defect in the exact center. This defect was present prior to launch. The HSP filters had a rough surface finish and several features which appeared to be manufacturing defects, but showed no visible contamination. The haze on the pickoff mirror was revealed to consist of numerous circular droplet-like features 1 to 2 microns in diameter.

The presence of the blue haze and droplet-like features suggested that the UV degradation was caused by contamination on the mirror. Contamination does not generally deposit as a uniform film, but rather forms small droplets (or sometimes droplets on top of a film.) However, the microscopic examination alone did not preclude the possibility that the reflectance degradation was caused by damage to the optical coating, since the circular features could have been blisters or pits in the coating. Additional analyses were necessary to verify conclusively that the problem was contamination, not coating damage.

4. SURFACE CHEMISTRY ANALYSES

A variety of surface analytical techniques were employed, beginning with X-ray Photoelectron Spectroscopy (XPS) XPS allows the chemical elements present in the top 50Å of surface to be identified. The chemical bonds between an atom and its nearest neighbors can also be identified. Chemical elements present below the surface can be identified by sputtering away the top 50Å, then analyzing by XPS again. By repeating this process many times, a depth profile of the surface is obtained.

XPS analyses were performed on the pickoff mirror, aperture window (both sides), HSP filters, and reference samples. The data are summarized in Table 1 and Table 2. Depth profiles of the pickoff mirror revealed that the MgF_2 and Al coatings were intact, but that the mirror was heavily contaminated with hydrocarbons, esters, and silicones. Depth profiles of the aperture window and an HSP filter showed similar contaminants as were on the pickoff mirror. Only the hub-facing side of the aperture window was contaminated; the side facing into the WFPC-1 instrument was clean. The absolute thickness of the contamination layers could not be determined from the depth profiles alone, because the sputtering rate of the contaminant was unknown. However, the relative thicknesses on the 3 samples could be determined by comparing the sputtering times. This comparison showed that the thickness of the contamination layer on the pickoff mirror was three times that on the aperture window and HSP filter Since all these optical elements proved to be contaminated with the same chemical species, many of the later tests were performed on only one optical element, and the results were generalized to all the optical elements.

The abolute thickness of the contaminant was measured by sputtering a "square well" through the contamination layer on an HSP filter, then using an Atomic Force Microscope to measure the depth of the well. The result was 150-160Å The ratio of sputter times was then used to deduce that the aperture window contained approximately 150Å of contamination and the pickoff mirror contained about 450Å.

Various types of mass spectroscopy were performed next, to better identify the chemical species of contaminants and to determine whether the contaminants had been photopolymerized by exposure to ultraviolet radiation. Photopolymerization was suspected because the contamination had not evaporated in vacuum over time, and because the severe degradation in UV reflectance was typical of polymerized contaminant films. Unpolymerized hydrocarbon contaminants have generally produced a much less prounounced drop in UV reflectance[2].

Table 1
Results of XPS Analyses
Atomic Concentration of Elements Detected

Sample	Analysis area	Depth (Å)	C	O	Mg	F	Si	N
Pickoff mirror	Area #1	0	63	30	0	1.6	2.3	2.6
		30	67	28	0	0.6	2.2	2.3
		60	67	26	0	0.5	3.2	3.0
		90	69	24	0.7	1.1	2.4	2.8
		150	71	23	0.8	0.4	1.7	3.7
		210	74	19	0	1.0	2.4	3.3
		300	76	17	0.7	1.1	2.6	2.6
		400	77	14	2.1	1.4	3.2	2.6
		600	79	8.7	4.0	3.9	2.5	2.2
		800	74	8.5	7.6	5.2	2.6	2.3
		1000	71	7.4	7.7	7.5	3.0	3.3
		1400	68	7.9	10	10	2.6	0.9
	Area #2	0	63	32	0	1.2	2.4	2.4
		60	70	27	0	0.5	2.1	0.7
		120	71	24	0	1.2	1.8	1.8
		240	74	19	0.8	0.4	2.2	4.4
		400	78	13	2.5	0.3	2.5	3.3
		800	73	7.2	7.1	9.0	2.4	1.0
		1400	71	7.7	8.6	9.8	2.0	1.3
	Area #3	0	64	31	0	1.1	2.5	1.9

Table 1, cont.
Results of XPS Analyses
Atomic Concentration of Elements Detected

Sample	Analysis area	Depth (Å)	C	O	Mg	F	Si	N
Aperture window	Outside position #1	0	67	28	0	1.4	2.8	1.6
	Outside postion #2	0	66	28	0	1.3	2.5	1.7
		100	52	13	14	22	0	0.3
		150	18	17	27	39	0	0
	Outside position #3	0	67	28	0	1.3	2.7	1.7
	Inside position #1	0	32	6.4	23	38	0	0.5
	Inside position #2	0	33	6.7	23	37	0	0.5
		50	8.8	6.1	25	60	0	0
		100	7.3	7.5	29	57	0	0
		150	3.1	11	30	56	0	0
HSP filter #1	Outside surface	0	66	24			7.9	0.9
		50	67	16			15	1.9
		100	36	34			28	2.1
		150	13	51			35	1.3
	Inside surface	0	41	36			22	0.7
HSP filter #2	Outside, before AFM & TOF-SIMS	0	61	25	0	0.7	12	0.9
	Outside, after AFM & TOF-SIMS	0	67	25	0	1.7	4.7*	1.4

* (HSP filter #2) For the TOF-SIMS analysis, a wash with hexane was performed to remove silicones at the surface.

The aperture window and the pickoff mirror were analyzed by Gas Chromatography/ Mass Spectroscopy. In this technique, an area of the surface is rinsed with a strong solvent (methylene chloride), then the solution is injected into a gas chromatograph to separate the molecular types, then sent into a mass spectrometer for identification. This technique features high sensitivity, but can only detect methylene-chloride-soluble contaminants of relatively low molecular weight.

The pickoff mirror was analyzed by Direct Probe Mass Spectroscopy and Pyrolysis Mass Spectroscopy. In these techniques, a small area of the mirror surface is scraped off, and the scrapings are heated to several hundred degrees Celsius to evaporate the sample The evaporated molecules are then directed into a mass spectrometer for identification. The advantage of this is that chemical species with high molecular weights can be detected.

An HSP filter was analyzed by Time-of-flight Secondary Ion Mass Spectroscopy. This technique consists of bombarding the surface with ions to knock molecules out of the surface, then sending the molecules into a mass spectrometer for identification. The advantage of this technique is that it is not necessary to previously remove or dissolve the contaminant from the surface. However, only the top few monolayers can be detected.

The four mass spectroscopy techniques yielded results that were roughly consistent with each other. The most abundant chemical species found were:

A high-molecular-weight polymeric hydrocarbon,
Poly dimethyl siloxane
Di ethyl phthalate
Di octyl phthalate
Palmitic acid
Palmitic acid polymers
Caprolactam
Polyamides (generic Nylon)
Tri phenyl phosphine oxide
Numerous low-molecular-weight hydrocarbon fragments

Table 2. XPS Carbon Peak Curve Fits

Sample	Analysis area	Percent of Peak Area			
		C-(C,H)	C-(O,N)	C=O	O-C=O
Pickoff mirror	Area #1 (hazy)	60	21	8	11
	Area #2 (reference)	60	21	9	10
	Area #3 (scratched)	59	21	9	11
Aperture window	Outside position #1	61	22	8	9
	Outside postion #2	61	21	8	10
	Outside position #3	60	23	9	8
	Inside position #1	87	8	3	2
	Inside position #2	87	9	2	2
HSP filter #1	Outside surface	71	17	7	5
HSP filter #2	Outside surface	74	15	7	4

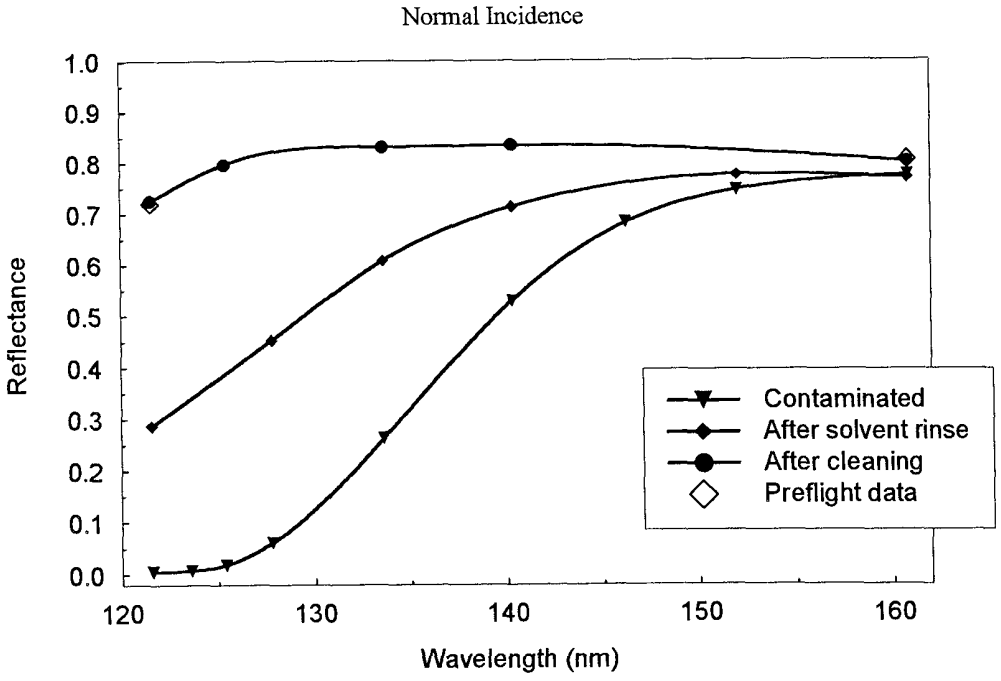
In order to account for the relatively high amounts of oxygen detected by XPS, it was suggested[3] that the polymeric "hydrocarbon" was not actually a purely hydrocarbon chain, but possibly incorporated caprolactam and phthalic acid in the polymer as well. As a final check, non-optical surfaces which faced the hub area but were not in the beam of light (and therefore saw no UV exposure) were tested using the aforementioned techniques No significant contamination was found on these surfaces.

5. REFLECTANCE RESTORATION

During the surface chemical analyses, it was noted that the degraded UV reflectance of the pickoff mirror was partially restored by solvent rinsing. In the process of performing GC/MS, portions of the aperture window and pickoff mirror had been rinsed with methylene chloride. Their reflectance and transmittance were remeasured after this solvent rinsing. The aperture window results were inconclusive, but the pickoff mirror reflectance was partially restored (see Figure 4.) Furthermore, the contamination on the aperture window was measured by XPS before and after the methylene chloride rinse. By comparing the relative strengths of the XPS peaks, it was estimated that 2/3 of the contamination layer was removed by the solvent.

After all the examinations and chemical analyses were completed, a final test was done to determine whether the UV reflectance of the pickoff mirror could be entirely restored by cleaning. If it could, this would conclusively demonstrate that the reflectance degradation was due entirely to contamination, not to a combination of contamination and coating damage. First, the reflectance of the pickoff mirror was remeasured at 3 different locations on the mirror. Then the entire mirror was cleaned using the following procedure: The mirror was immersed in a solution of Alconox and water. A clean piece of cheesecloth was also immersed in the solution. With the mirror and the cheesecloth still under water, the cloth was laid on top of the mirror and dragged/rubbed very gently across the surface several times. Because magnesium fluoride coatings are easily scratched, the pressure applied was not much more than the weight of the cheesecloth. The mirror was then rinsed continuously for about 1 minute with a steady stream of distilled water. The mirror was rinsed again continuously for about 1 minute with a steady stream of distilled acetone. Finally, the mirror was inspected to ensure that there was no visible solvent residue or dust left behind on the surface. The reflectance of the cleaned mirror was then measured at the same 3 spots. The preflight reflectance was completely restored, as shown in Figure 4.

Figure 4. Pickoff Mirror Reflectance Restoration



6. CONTAMINATION MECHANISM

Because the contaminant deposited on room-temperature surfaces, did not come off in vacuum, and produced a reflectance degradation curve typical of that previously seen on optics contaminated with polymerized hydrocarbons, a UV-stimulated mechanism for depositing the contamination was suspected. The HST optical train was exposed to earth-reflected UV for part of each orbit. The UV stimulation hypothesis was also supported by the fact that contamination was not found on hub-facing surfaces which were not exposed to UV.

It seemed questionable, however, that earth-reflected UV radiation could produce enough intensity on the optical surfaces to stimulate the formation of a 450Å contaminant deposit. Therefore, a back-of-the-envelope calculation was done to show that this mechanism is physically (i.e. energetically) possible, and a series of laboratory tests[4] was performed to demonstrate that a contamination deposit could be produced with low-level UV. The calculation is described below.

For simplicity, a single representative chemical species of contamination was assumed. The contaminant species used was bis (2 ethyl hexyl) phthalate, which is a common plasticizer with a bond energy of 1180 Joules/g The spectral irradiance of the earth albedo had been measured by the International Ultraviolet Explorer (IUE) satellite. Using the IUE data for wavelengths with energies greater than the bond energy, the total energy of reaction-causing UV photons incident on the WFPC-1 pickoff mirror over the 3.5 years in orbit was calculated to be 0.05 Joules/cm^2. Dividing this incident energy by the bond energy gave a predicted contaminant layer thickness of $\approx$ 4200 Å.

There were several assumptions implicit in that calculation:

1. Every incident UV photon with enough energy was absorbed by a contaminant molecule and broke one bond.
2. Once a single bond in the contaminant molecule was broken, the contaminant molecule would chemisorb to the surface.
3. The contamination deposited on the surface as a uniform thin film
4. The mass density of the contaminant film was 1 g/cm^3, so that a surface density of 1 μg/cm^2 corresponded to a film thickness of 100Å.

The last two assumptions have been commonly made in contamination estimates. The first two assumptions amounted to saying that the process of UV-stimulated deposition occurred with 100% efficiency. This was considered highly unlikely; a more reasonable efficiency might have been around 10%. In that case the predicted contaminant film thickness would have been 420Å, which was approximately what did deposit on the pickoff mirror. This rough calculation thus established that UV-stimulated deposition was a plausible hypothesis.

7. CONTAMINATION SOURCES

The first step in locating the source(s) of contamination was to determine when in the mission the contamination occurred. To this end, the handling and performance history of the pickoff mirror was carefully reviewed Table 3 summarizes the possible times when the mirror could have become contaminated, and the likelihood of contamination occurring during each of those times. The evidence strongly supports the conclusion that the optics were contaminated during normal HST mission operations; i.e. the contamination happened in space, not on the ground, and it happened while the WFPC-1 and HSP instruments were inside the telescope, not while the instruments were residing in the space shuttle payload bay for transport back to earth.

Therefore attention was focused on potential contamination sources in or near the hub area of the HST. There were three major possiblilities: the Science Instruments, the Fine Guidance Sensors (FGSs) and the inner surfaces of the telescope itself (called the Optical Telescope Assembly or OTA) The science instruments were considered an unlikely source of contamination because they were subject to far more rigorous bake-outs than were the FGSs and OTA. Also, the apertures of the science instruments, through which contaminants could enter the hub area, were relatively small.

The fine guidance sensors were considered next. An outgassing test was performed on a spare FGS which was still on the ground. In this test, the FGS was installed in a vacuum chamber and heated to its maximum in-orbit temperature

Table 3
Pickoff Mirror History Evaluation

EVENT	LIKELIHOOD of contamination	RATIONALE
Pre-shipment testing at Jet Propulsion Laboratory	Low	• Contamination was consistent with vacuum deposition, and • Post thermal vacuum test data showed pickoff mirror had 72% reflectance at 1216Å.
Pre-launch processing at Kennedy Space Center	Low	• Pickoff mirror was stored in separate container until WFPC-1 installation into HST. • No polymerizing UV present, so contam. would have come off in space, not stayed on mirror as was observed.
HST deployment mission	Low	• Pickoff mirror was inside HST and HST aperture door was closed, thus no UV present. • Hard to explain why 450Å of contamination would accumulate permanently on a warm mirror in absence of UV.
HST operations in space (3.5 years)	High	• Reflectance/transmittance curves were consistent with UV-induced contamination. • Uniform and thick contaminant on warm surface suggests vacuum deposition, assisted by UV. • Correlation found between pickoff mirror contaminants and FGS outgassing products. • Earth albedo was present to provide the necessary UV. • Thickness of contaminant on pickoff mirror, aperture window, and HSP filters corresponded to relative UV energy doses of these surfaces.
HST Servicing mission	Low	• 450Å was thicker than expected for short exposure in space shuttle environment. • HSP contained polymerized contaminant only on hub-facing optics. • Some exposed surfaces did accumulate Si and F during the servicing mission, and there was a rise in pressure at instruments when astronauts opened aft shroud doors, BUT • Witness mirror on radial SIPE (Scientific Instrument Protective Enclosure) showed no UV degradation at 1216Å.
Post-launch processing at Kennedy and Goddard	Low	• Space shuttle payload bay was kept purged within 45 min of landing, purge was maintained to instruments during shipment to Goddard. • Witness samples did not show UV degradation. • No polymerizing UV was present to stimulate contamination deposition on a warm surface.

(approximately 40°C). The consequent outgassing products were collected on a liquid-nitrogen-cooled cold plate, and the collected sample was chemically analyzed. The outgassing products correlated well[5] with the contamination species found on the pickoff mirror. Furthermore, the three FGSs in orbit presented a large combined aperture area facing the HST hub. Thus it was concluded that the FGSs were the likely source of a large portion of the contamination.

The FGSs probably did not cause all of the contamination, however A review of handling and test histories revealed that during ground processing, both the FGSs and the OTA were bagged in bagging material that contained caprolactam. Past experience has shown that the caprolactam can "rub off" onto the bagged hardware and attach itself to Chemglaze Z306 paint or to urethanes in an ambient atmosphere in the presence of humidity. The HST OTA and the FGSs both contained a large amount of Z306 and urethanes. Finally, there was a 1 to 2 inch gap above each FGS which had a direct view back to the inner surface of the aft shroud. These gaps could have allowed any outgassing products in the aft shroud direct access to the hub.

Based on the foregoing evidence, it was concluded that the fine guidance sensors were responsible for most of the outgassed contaminants, but that the OTA and aft shroud were also likely contributors. The science instruments were deemed unlikely contamination sources.

8. SUMMARY AND CONCLUSIONS

The pickoff mirror and aperture window from the "returned" WFPC-1 instrument showed severely degraded performance in the UV. Microscopic examination, surface chemical analysis techniques, and the ability to restore the UV reflectance of the pickoff mirror by cleaning indicated that the source of degradation was contamination (as opposed to optical coating damage.) The pickoff mirror accumulated about 450Å of contamination, while the aperture window received about 150Å. Several filters from the other returned instrument, the HSP, were also found to have about 150Å of contaminant on them.

Evidence showed that the contamination happened in orbit during normal HST operations over the 3.5 years that elapsed between deployment of the HST and performance of the first servicing mission. The mechanism posited was that outgassed molecules from hub-facing components (such as the FGSs, OTA, and aft shroud) impinged on optical surfaces and were photopolymerized there by exposure to earth-albedo UV.

Some of the contamination, however, was removable by rinsing with strong solvents, such as methylene chloride. Therefore the contamination layer could not have been entirely photopolymerized. Past flights and laboratory tests[6-8] in which photopolymerization occurred involved high UV intensities, and resulted in total polymerization of the contaminant, such that none of the contamination could be removed by solvent rinsing. This "partial polymerization" observed on the pickoff mirror is thus unusual (to our knowledge it has never been seen before on space optics), and might be a result of the low intensity of the UV exposure. Nevertheless, it is clear that direct exposure of optical surfaces to the UV irradiance from the sunlit earth presents a potential hazard to far UV performance if sufficient polymerizable contaminants are present.

For the current suite of instruments in HST, however, this contamination is not occurring. The HST had 3.5 years to outgas prior to the first servicing mission, so the polymerizable contaminants are no longer present in any appreciable quantity. In their 2.5 years of operation, neither COSTAR nor WFPC-2 has shown performance degradation in the UV. There is also no evidence to suggest that the primary or secondary mirrors of the HST have changed

In principle, this type of contamination could occur again if new high-outgassing components were installed during the next servicing mission. However steps such as bakeouts, outgassing tests, and installation of molecular absorbers where needed have been taken to ensure that any new components installed in the HST do not outgas. Also, exposure of the HST to earth albedo (as well as to the sun) will be minimized during the next servicing mission. Thus this contamination-induced UV degradation is *not* expected to occur for next-generation HST instruments.

9. ACKNOWLEDGEMENTS

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