THE HUBBLE SPACE TELESCOPE (HST) CONTAMINATION CONTROL PROGRAM

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ABSTRACT

Over the past two decades, the Hubble Space Telescope (HST) Contamination Control Program has evolved from a ground-based integration program to a space-based science-sustaining program. On-orbit, the telescope's primary contamination requirement was maintaining a low contamination flux in the telescope's optical path. In addition, to maintain the scientific capability of the telescope, the contamination requirements and specific contamination controls from the second- and third-generation Scientific Instruments and Orbital Replacement Units were captured within the HST Contamination Control Program. Contamination controls were developed for on-orbit operations and four Servicing Missions (Orbiter, Astronauts, and mission). Long-term on-orbit scientific data has shown that these contamination controls successfully protected the HST from contamination.

KEY WORDS: Hubble Space Telescope, HST, contamination, servicing mission, Shuttle

INTRODUCTION

The Hubble Space Telescope (HST) Contamination Control Program evolved over the past 15 years going from a ground-based integration program to a space-based science-sustaining program. Since its deployment in 1990, the telescope has had four successful servicing missions occurring approximately every 3 years (see Table 1) during which critical systems and science capabilities have been upgraded during extra-vehicular activities (EVAs) or "space walks". During these servicing missions, the telescope's capability was upgraded with the installation of new Orbital Replacement Units (ORUs), most of which allowed the telescope to operate more efficiently. As shown in Table 2, the telescope's science capability was upgraded with the installation of five second- and third-generation Scientific Instruments (SIs) and two Fine Guidance Sensors (FGSs). These servicing mission activities presented an inherent risk to the cleanliness of the telescope. For each servicing mission, the existing HST Contamination

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Control Program was assessed for its applicability to the new mission complement and adjustments were made depending on the sensitivity of the SIs and other ORUs and the demands of the servicing tasks.

Table 1. HST Servicing Missions

Servicing Mission	Flight Number	Date	Duration On-Orbit
1	STS-61	December 1993	3.7 years
2	STS-82	February 1997	6.8 years
3A	STS-103	December 1999	9.7 years
3B	STS-109	March 2002	11.9 years

Table 2. Scientific Instrument/Orbital Replacement Unit Installation

Scientific Instrument/Aft Shroud Orbital Replacement Unit	Date of Installation
Wide Field and Planetary Camera II (WFPC2)	December 1993
Corrective Optics and Space Telescope Axial Replacement (COSTAR)	December 1993
(2) Rate Sensor Unit	December 1993
Space Telescope Imaging Spectrometer (STIS)	February 1997
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)	February 1997
Fine Guidance Sensor R-1	February 1997
Fine Guidance Sensor R-2	December 1999
(3) Rate Sensor Unit	December 1999
Advanced Camera for Surveys	March 2002

Due to the contamination sensitivity of the HST, SIs, and FGSs to molecular and particulate contamination, all aspects of a servicing mission were assessed for potential and subsequent contamination effects to the specific HST contamination-sensitive surface (optical and thermal). The assessment began with the basic requirements for the telescope and extended to each mission component. Multi-mission hardware, including the servicing mission carriers, Scientific Instrument Protective Enclosures (SIPEs) and Orbital Replacement Unit Protective Enclosures (OPEs), were unique as they themselves are not contamination sensitive, but provide a "safe haven" for hardware that was extremely sensitive to molecular and particulate contamination. This multi-mission hardware essentially isolated the contamination-sensitive hardware from the Orbiter payload bay and its contamination environment.

However, because of the large surface area of the servicing carriers, both outgassing levels and surface cleanliness levels were controlled during all aspects of integration, test, launch activities, and servicing mission activities.

A comprehensive contamination control program addressing the Orbiter, the Astronauts, and the carrier hardware, was developed and implemented for each of the servicing missions. This effort was extremely successful and, to-date, no on-orbit contamination events have been reported. An overview of the HST contamination control program including the ORUs, SIs, the multi-mission carriers, the Servicing Mission activities, and the on-orbit operations is discussed. The details for each of the mission-unique HST Servicing Mission Contamination Control Programs can be found in References 1-8.

HUBBLE SPACE TELESCOPE

The HST contamination requirements were driven by the primary mirror and secondary mirror throughput requirements to maintain ultraviolet (UV) wavelength capability. The HST Pre-Launch Contamination Program was comprehensive and all internal outgassing sources that could have affected the primary mirror and secondary mirror UV throughput underwent thermal-vacuum conditioning.

The HST science observations are accomplished through five science instruments (four axial and one radial) and three FGSs, as shown in Figure 1. The FGSs are installed in three of the four "radial SI" bays. The Primary and Secondary Mirrors are primarily exposed to the Optical Telescope Assembly, the baffles of the Light Shield Assembly, and the Aperture Door. Not shown in Figure 1, is an area referred to as the "Hub Area". The Hub Area is bound by the three FGSs, the Radial SI, the four Axial SIs, and the backside of the primary mirror. It is the light path and the area where the electro-

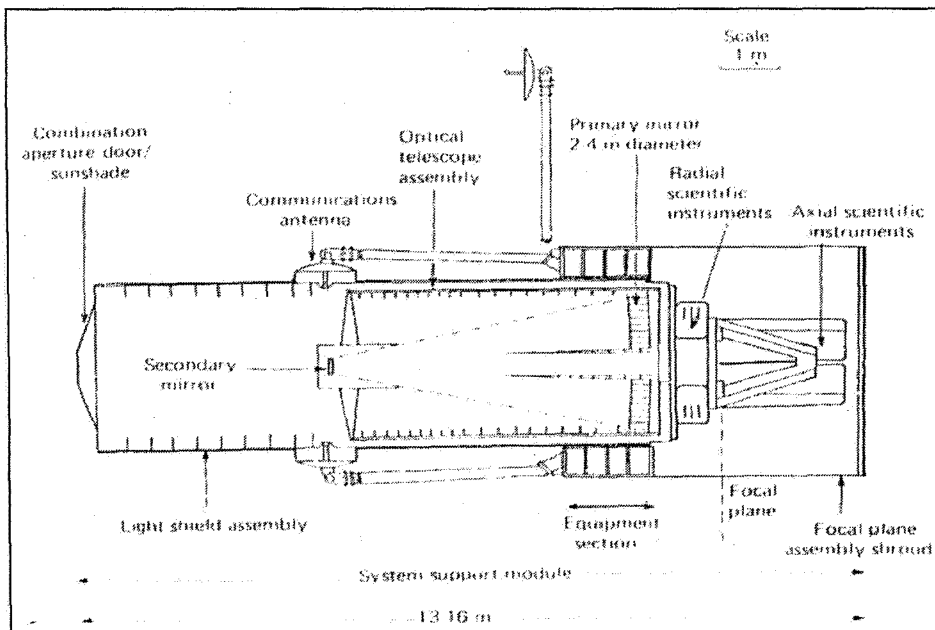

Figure 1. The Hubble Space Telescope Schematic. The Radial and Axial Scientific Instruments are shown in relationship to the primary and secondary mirrors.

magnetic spectrum enters the SIs. This is the central region of the Optical Telescope Assembly and as such is the most contamination sensitive area of the HST. The four Axial SIs were housed within the telescope's Aft Shroud. For the Servicing Missions, the emphasis is to control and quantify all contamination which has the potential to enter the hub area, and subsequently the SIs.

Primary and Secondary Mirrors

The particulate contamination requirements were less than five percent maximum area coverage for the summation of the Primary and Secondary Mirrors at end-of-life (EOL). This was determined pre-launch by measuring the obscuration ratio of optical witness samples. Prior to launch, the accumulated mirror loss (summed over all ground-based activities) was 1.1 percent (9). The molecular contamination requirement was less than a 10 percent decrease in reflectance at Lyman-Alpha (1216 Å) wavelengths on the Primary and Secondary Mirrors after five years on-orbit. This was determined pre-launch by measuring optical witness mirrors. Neither integrated nor periodic measurements indicated that this requirement had been violated prior to the telescope's deployment. During ground integration and test activities, the optical witness samples indicted a reflectance loss less than one percent (9).

The initial outgassing criteria for the telescope assemblies was 4.33×10^{-13} g/cm^2-s flux as measured with the primary and secondary mirrors at nominal operating temperatures and the collector at -20°C. The optical witness mirror reflectance degradation was also required to be less than three percent at three ultraviolet wavelengths (1216 Å, 1608 Å, and 2000 Å) (10).

To date (post- Servicing Mission 3B) no scientific instrument data has indicated that the Primary and Secondary Mirror contamination requirement has been violated. The instrument data will be discussed later in this paper.

Hub Area

The light path of the telescope is referred to as the "hub area". The four axial and one radial SI apertures, the three FGS apertures and the back of the Primary Mirror define this area. To control the amount of contamination entering this area and to prevent cross contamination, contamination requirements were derived for the SIs and FGSs. The outgassing rate from an SI aperture or FGS aperture into the hub area could not exceed 1.32×10^{-9} g/sec. For the upgraded FGSs which were installed during the Servicing Mission 2 and Servicing Mission 3A, the FGS's outgassing rate was measured with the instrument at worse case hot operational temperatures (approximately 25°C) and the collector at -65°C. Similarly, the surface level contamination requirements for any item entering the telescope were Level 400B per MIL-STD-1246 (currently IEST-STD-CC1246D; Reference 20).

Aft Shroud

The first-generation SIs (i.e., those deployed with the telescope) were considered a contamination source to the telescope's primary and secondary mirrors and as such were thermal-vacuum conditioned to meet acceptable outgassing rates. In addition, the SIs were treated as potential contamination sources to other SIs. The SI allowed outgassing rate was derived from the allowed deposition on the telescope's primary and secondary mirrors. The SI outgassing rate was measured and verified at the SI's vent and/or aperture (the largest vent path) and at the coldest temperature in the Aft Shroud which was the operating temperature of the Faint Object Sepctrograph (FOS) detector (-20°C). The SIs and ORUs inside the Aft Shroud portion of the HST or components that have a direct line-of-sight into the Aft Shroud were certified with a Quartz Crystal Microbalance (QCM) temperature of -20°C.

Four axial SIs were installed in the Aft Shroud. To control the amount of contamination entering this area and to prevent cross contamination, the SIs met minimum surface levels cleanliness and outgassing requirements. The SI exterior surface cleanliness level did not exceed Level 400B per MIL-STD-1246 (currently IEST-STD-CC1246D). The outgassing requirement measured at the SI aft vent could not exceed an equivalent rate of 4.33×10^{-13} g/cm^2-s based on the exterior surface area of the instrument. This outgassing rate was measured with the SI ten degrees above the worse case predicted hot operational temperatures and the collector at -20°C. While the largest percentage of the outgassed products from the SIs was vented through the telescope's aft vents, there was a small probability that a SI could increase the contamination flux in the hub area, thus affecting the telescope's performance. These requirements also controlled cross-contamination between the SIs and Rate Sensor Units (gyroscopes).

The Rate Sensor Units resided in one of the Aft Shroud Bays (between two axial SIs). Although not inherently contamination sensitive (as a Rate Sensor Unit versus individual gyroscopes), the Rate Sensor Units were subjected to the same stringent contamination requirements as the SIs. This included outgassing and surface cleanliness levels which minimized cross-contamination between the SIs and the Rate Sensor Units.

ON-ORBIT OPERATIONS

The primary on-orbit contamination controls are pointing constraints that limit bright object viewing and relatively warm Optical Telescope Assembly temperatures (~ 10°C), including the primary and secondary mirrors.

The Aperture Door also provides shading to the forward end of the telescope tube allowing for a 50-degree field-of-view. The pointing constraints during telescope normal operations as described in the proposer's guide (11) are that the SIs do not observe targets that are within 50 degrees of the Sun; within 20 degrees of any illuminated portion of the Earth; within 6 degrees of the dark limb of the Earth; or within 9.5 degrees of the Moon.

Servicing Mission Observatory Verification (SMOV)

A telescope recommissioning program following each Servicing Mission called the Servicing Mission Observatory Verifications (SMOV) consists of pre-planned coordinated tests. As described in Reference 12, the typical SMOV, lasting several months, includes three phases: "1) spacecraft subsystem recovery and initial instrument checkout; 2) recommissioning of existing instruments; and 3) commissioning of new instruments." Additional constraints, to the nominal pointing constraints were developed to limit viewing of the bright Earth for the first 12 days following the telescope's release from the Orbiter to preclude high UV flux into the telescope during the highest outgassing period following servicing mission activities.

ON-ORBIT SERVICING

The HST was designed to be periodically serviced on-orbit using the Space Transportation System (STS). Servicing carriers provided an interface from the Orbiter to the SIs, ORUs, and the captured telescope. The servicing carriers were configured for each mission to accommodate mission-unique ORUs; the basic carrier (structure and support airborne flight equipment) remained unchanged.

The servicing missions were complex and required that the telescope be exposed to the Orbiter (including servicing carriers) environment during the installation of the SIs and FGSs into the HST Aft Shroud. This exposure was typically from one to seven hours during an EVA. Over the duration of all the servicing missions the telescope was exposed for approximately 60 hours. During the SI installation, one EVA crew member (i.e., an astronaut) entered the Aft Shroud to guide both the old instrument out of the telescope and the new SI into the telescope. Because of this exposure and to maintain the UV capabilities of the telescope, the contamination requirements placed on both the Orbiter and carriers were quite stringent. While one might argue that the SI was the most contamination sensitive element, in reality, maintaining the low contamination flux in the telescope's optical path was the servicing mission's primary contamination requirement.

Neither the Orbiter nor the Extravehicular Mobility Unit (space suit) contamination levels was verified by methods other than visual examination. Outgassing levels were not measured and by the nature of the Orbiter, many materials generally not used around contamination-sensitive hardware were used for performance. Where possible, materials which were verified to be high outgassing, which would not impact the Orbiter performance were removed for the HST servicing missions. In addition, a best effort was made to control contamination during Orbiter processing activities.

The Orbiters undergo periodic maintenance during which extensive mechanical and electrical system inspection, upgrades, and/or refurbishment are performed. These maintenance periods are referred to as Orbiter Maintenance Down Periods (OMDPs). The STS, *Discovery*, OV-103, had an OMDP from October 1995 until June 1996. Over 67 modifications were planned. The HST Second Servicing Mission was the first flight of OV-103 after its OMDP. Due to the extensive nature of the modifications and upgrades, and addition of high outgassing materials to the midbody (payload bay) area, there were concerns of quantifying the payload bay environment during this servicing mission. A list of the OV-103 OMDP activities which had the potential to produce contamination was analyzed to determine which activities could cause potential molecular or particulate contamination of HST, the SIs, and FGS. As a result of this assessment, monitoring of the midbody (payload bay) area with nonvolatile residue (NVR) plates and airborne particle levels was performed from December 1995 until June 1996. A detailed discussion of the OMDP and monitoring program can be found in Reference 13.

Ground processing activities, Orbiter integration and the overall mission activities were assessed for subsequent contamination to the HST, the SIs, and FGSs for each servicing mission. The assessment began with the basic requirements for the HST and extended to each mission component. An overall contamination budget was established allocating acceptable degradation among mission phases. The servicing mission cleanliness requirements and budgets were set with respect to hardware line-of-sight views of sensitive surfaces, purging of the SIs for sustaining critical element functional lifetimes, Orbiter and EVA effects, Orbiter cleanliness, cleanroom protocol, and launch site (Kennedy Space Center) integration activities.

Prior to each servicing mission, the HST contamination control philosophy was reviewed to determine its applicability to reflown servicing carrier hardware, new SIs, new ORUs, and HST optical performance. The current contamination control program evolved over four servicing missions. The new servicing carriers, SIs, FGSs, ORUs, and significantly reworked contamination-sensitive hardware, such as the SIPEs, were certified to the required outgassing rate prior to a servicing mission.

Scientific Instruments and Fine Guidance Sensors

The SIs and FGSs had individual contamination requirements based on their optical sensitivity. For example, SIs viewing in the UV wavelength regions would have the most sensitivity to molecular contamination. However, SIs viewing in the infrared wavelength regions would have the greatest sensitivity to particulate contamination. The SI contamination requirements and contamination control programs have been reported elsewhere (1-8). The SIs and FGSs were delivered to NASA with verification of internal contamination levels. These levels were maintained throughout the integration, test, and launch activities through contamination controls such as a gaseous Nitrogen purge.

Servicing Carriers

Six servicing carriers were designed, built and flown during the four servicing missions. The servicing mission carrier manifest is illustrated in Table 3. As can be seen the Flight Support System (FSS) and the Orbital Replacement Unit Carrier (ORUC) were manifested most often, requiring the most number of configuration changes to support specific hardware manifested for a specific servicing mission. For the ORUC, this primarily involved the reconfiguration of its shelves and the OPEs. The other carriers – Multi-Use Lightweight Explorer, Rigid Array Carrier, Second Axial Carrier, and Solar Array Carrier – were manifested for specific hardware elements and as such were flown less often. The servicing carriers manifested for the First Servicing Mission are shown in Figure 2. Discussion of the carrier design and contamination control program can be found in References 4 -6.

Table 3. Carrier Mission Manifest

Carrier	Servicing Mission 1	Servicing Mission 2	Servicing Mission 3A	Servicing Mission 3B
Flight Support System	✓	✓	✓	✓
Multi-Use Lightweight Explorer				✓
Orbital Replacement Unit Carrier	✓	✓	✓	
Rigid Array Carrier				✓
Second Axial Carrier		✓		✓
Solar Array Carrier	✓			

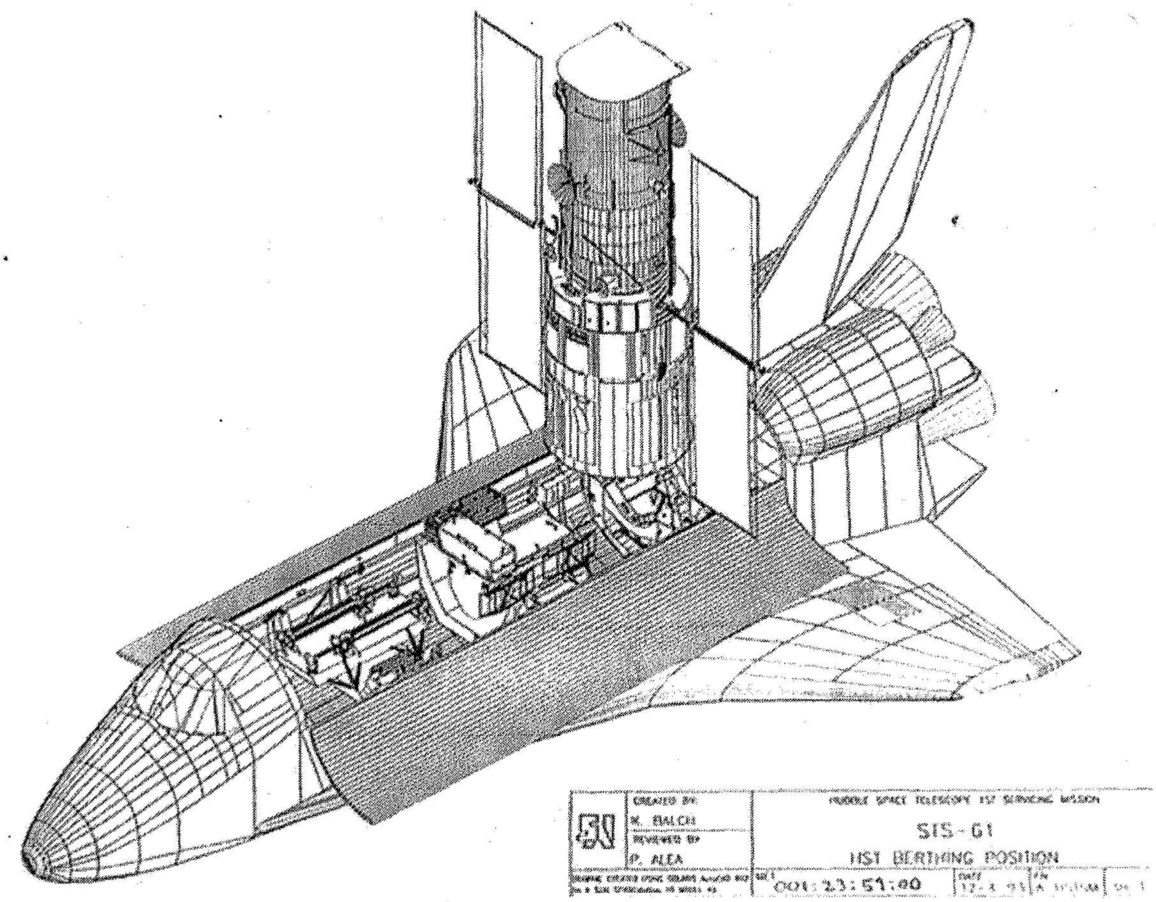

Figure 2. Servicing Mission 1 Hardware Configuration. The servicing carrier hardware is shown manifested in the Orbiter payload bay. The Solar Array Carrier is shown in the foreground, followed by the Orbital Replacement Unit Carrier. The HST is shown berthed on the Flight Support System.

Unique to the servicing mission was the development of the SIPE. Two designs were used for the radial SI and FGSs and two designs were used for the Axial SIs. The SIPEs provided a contamination- and thermally-controlled environment for stowed scientific instruments while the servicing carrier provided load isolation from the Orbiter.

The SIPEs provided a thermal environment equivalent to that inside the HST. The warm thermal environment ensured that the SIs and FGSs remained within their temperature limits during the EVA. This also ensured that any outgassing inside the SIPEs, which would otherwise have affected the optical performance, would not condense on the Scientific Instruments or Fine Guidance Sensors. The SIPEs also provided a purge interface, which allowed the Scientific Instruments and Fine Guidance Sensors to be purged until launch (T-0). To inhibit particulate contamination of the SIs or FGSs during all ground and launch activities, a “vent restrictor plate” (37 μm mesh mounted within a frame) was mounted over the SIPE vent. Additional details about the SIPE design, test, and qualification for flight can be found in References 4-5.

Due to the diversity of the ORUs and SIs manifested for each flight, the servicing carriers provided the most flexible stowage capability for the servicing mission hardware. Because of the planned multiple mission use of the ORUC and the FSS over a decade, the HST contamination control program looked at the "big picture" to determine the most cost-effective contamination control approach that provided the needed contamination controlled environment for the SIs and FGSs. Because of the excessive cost and schedule required to recertify the molecular outgassing levels of the individual carriers for each servicing mission, the HST contamination control program looked at innovative methods to alleviate the recertification of the servicing carriers for each mission. Controlling the material added to the servicing carriers and individually certifying new hardware prior to integration onto the servicing carrier accomplished this. The storage, integration and test environment was also controlled, with the servicing carriers spending the majority of these activities in a Class 10,000 (ISO Class 7) cleanroom. When not in a cleanroom, the servicing carriers were double bagged. During storage, the servicing carriers were cleaned periodically to maintain the surface cleanliness levels.

Orbiter and EVA Effects

In addition to many hardware cleanliness requirements, numerous analyses were performed for the Orbiter environment and EVA contamination impacts. These analyses provided critical assessments for controlling on-orbit contamination generating activities and provided the necessary quantitative details for imposing ground processing requirements for the Orbiter. The major analyses included plume impingement, waste/water dumps, SIPE, Extravehicular Mobility Unit (space suit), Orbiter reboost, and HST configuration changes including deployed solar arrays (14). These analyses represent the core of the cleanliness concerns associated with the shuttle and EVAs.

In addition to the analyses for the Orbiter, cleaning requirements were assessed and levied on the Orbiter payload bay. To quantify the effects of the crew compartment on subsequent EVAs relative to the particulate environment, two witness plates were flown on STS-51 to characterize the particle transfer from the Extravehicular Mobility Unit during Astronaut translation through the Orbiter payload bay and during EVA activities. These results were used to determine the crew cabin and Extravehicular Mobility Unit cleanliness requirements (15).

Plume Impingement

The analyses of the Orbiter plume impingement assessed the degradation of the HST surfaces due to gaseous and liquid droplet impingement from thruster firings during maneuvers and station-keeping operations. Byproducts from the incomplete combustion, such as monomethyl hydrazine (MMH)-nitrate, could have had detrimental effects on contamination-sensitive optical and thermal control surfaces. The station-keeping and attitude adjustments considered were low-Z and norm-Z modes. Because the byproduct mass flux in the norm-Z thruster firing case was significant, limitations were imposed for Orbiter operations.

Waste/Water Dumps

Significant droplets were formed during the Orbiter waste/water exhaust. These droplets may have posed a potential threat to the HST during EVA operations when the telescope's Aft Shroud doors were open. The estimation of the maximum effluent released during these dumps was approximately 320-lbm for each dump. Since this represented a significant amount of released material during the HST servicing operations, restrictions were placed in the flight rules for all of the servicing missions. All dumps were constrained 120 minutes prior to and during EVAs to preclude potential impingement on critical areas of the HST.

Scientific Instrument Protective Enclosure

Because the SIPEs provided cleanliness protection during launch, ascent, and on-orbit operations for the SIs, a separate analysis was performed to assess contamination impacts. The primary objective was to examine impacts due to particle redistribution within the SIPEs, molecular flow, and moisture control with the SIPEs. All of the elements of this analysis accounted for any degradation to the SIs during these phases. The results of these analyses are discussed in References 4-5.

Extravehicular Mobility Unit

During an EVA, the amount and type of contamination emitted by an astronaut was considered a threat to optical surfaces on the HST. In addition, the astronaut was in close proximity (e.g., line-of-sight) to the SIs and Aft Shroud. The main concern was contamination contributions from the Extravehicular Mobility Unit (space suit). The Extravehicular Mobility Unit exhaust was analyzed and assessed for molecular and particulate contributions. The main byproduct of the Extravehicular Mobility Unit exhaust was estimated to be 1 to 1.5 lb/hr of water vapor and/or ice. Because the sensitive HST and SI surface temperatures were above the water condensation temperature for a low-pressure environment, no contaminant depositions from the Extravehicular Mobility Units were expected.

Orbiter Payload Bay Cleanliness Requirements

The Orbiter payload bay liner and thermal control blankets (forward and aft bulkheads; Bays 12 and 13) provided thermal control to the payload and may be flown on many missions. A reflown liner section or thermal control blankets could have been a large outgassing source to a payload if contaminated by a previous payload or another mission. As this potential outgassing source could not be quantified (the outgassing species and rate), a new unflown payload bay liner was requested for the entire payload bay. The thermal blankets could not be replaced due to excessive cost; however, they were cleaned with an isopropyl alcohol (IPA)/deionized (DI) water mixture and verified to have no significant fluorescing molecular contamination. Small amounts of molecular contamination could have been tolerated, but were evaluated on a case-by-case basis and were dependent on their location within the payload bay.

Based on the hardware cleanliness requirements, for the servicing missions a new payload bay liner was cleaned to visibly clean highly sensitive (VCHS) per Johnson Space Center Document Number SN-C-0005C, with an IPA/DI water mixture. During Orbiter servicing in the Orbiter Processing Facility (OPF), the payload bay liner and thermal blankets, including the bilge area and wire trays, were vacuumed every three days. The payload bay was cleaned to VCHS at the Payload Changeout Room (PCR), with the Orbiter in the vertical configuration. Vertical cleaning at the Pad provided both the best access to all levels and a top-down cleaning approach so that any particles cleaned from the level above, but not captured, would fall to a level which would be subsequently cleaned. Again, the thermal blankets were verified to have no significant fluorescing molecular contamination.

Cleanroom Protocol

The biggest contamination threat to the servicing mission carriers, SIs, and FGSs was the personnel working on or around them. To control this threat, the servicing mission carriers spent the majority of their time in a Class 10,000 (ISO Class 7) cleanroom. The cleanroom protocol, detailed in Reference 7, was derived from the hardware requirements, contamination control practices, and data from previous missions. Personnel constraints, cleanroom operating procedures, and site management issues were addressed for each facility in which the servicing mission hardware was assembled, integrated or tested. Activities which had the potential to contaminate hardware were identified and controlled by procedure. These activities included crew familiarizations, alignment and envelopment measurements with the High Fidelity Mechanical Simulator and SI to SIPE fit-checks and integration.

Launch site integration activities also presented a challenge to maintaining the servicing carriers, SI and FGS contamination levels. Because of the servicing mission carriers' physical size, the launch site could only provide Class 100,000 (ISO Class 8) facilities. However, Class 10,000 (ISO Class 7) cleanroom protocols were used which resulted in significantly lower operating levels – Class 10,000 to Class 20,000 during typical integration activities. During the Scientific Instrument insertion into the SIPE, the cleanroom was run at Class 10,000 (ISO Class 7) cleanroom with strict personnel limits. For the servicing missions, these cleanroom protocols resulted in hardware contamination levels significantly below required limits (7).

SCIENTIFIC INSTRUMENT DATA

The SIs provide an indirect measurement of the contamination environment within the telescope. All SIs, except for the WFPC1, had open apertures and thus were directly influenced by the contaminant flux within the HST Aft Shroud. The deposition of contaminants causes the largest losses in sensitivity at UV wavelengths. Thus only the on-orbit data from SIs with UV capability is discussed.

Post-Mission Data

Each of the SIs returned from orbit underwent extensive post-mission inspection and testing. The most significant findings, from a contamination perspective, were from the Wide Field and Planetary Camera I (WFPC1). These results reported elsewhere (16-18), significantly impacted the Servicing Mission Contamination Control Program and are summarized for completeness.

The WFPC1 was one of the original SIs deployed on HST. It was replaced with the Wide Field and Planetary Camera II (WFPC2) during the First Servicing Mission, which provided upgraded science capability. Post-mission inspection of the WFPC1 pick-off mirror showed some haziness when viewed with a bright light. A Failure Review Board was convened to determine the cause of the haziness and to recommend remedial action to the HST Project to preclude contamination of other optical surfaces.

The WFPC1 pick-off mirror's reflectance was severely degraded in the far UV region when compared with pre-launch measurements and measurements from the flight-spare pick-off mirror (16-18). Subsequent testing of the mirror indicated that there was a partially photopolymerized contaminant layer which was approximately 450 Å thick (16). It was theorized that the photopolymerization of contaminants occurred when the pick-off mirror was exposed to Earth-albedo UV radiation. Most interesting, was the fact that this contaminant layer caused no change in reflectance at wavelengths above 2000 Å. See References 16-18 for a complete discussion of the WFPC1 post-mission analyses. It should be noted that for the SIs installed during the Second Servicing Mission, WFPC2 and Corrective Optics and Space Telescope Axial Replacement (COSTAR), there was no subsequent degradation of their optical performance in the UV wavelength region (1216 Å – 2000 Å).

The WFPC1 (Magnesium Flouride) window, which sealed the WFPC1 instrument, also had a partially photopolymerized contamination layer on the outside surface (facing the HST optical path). Its thickness was approximately 150 Å thick. Filters from the returned High Speed Photometer (HSP) also had a 150 Å thick contaminant layer.

Forensic evidence of the HST build and contamination control program indicated that three FGSs deployed with the telescope were not held to the same rigorous materials screening criteria, outgassing rate, or surface cleanliness levels as the SIs. This was an oversight that was subsequently corrected for all replacement FGSs. The Failure Review Board concluded that the FGSs were most likely responsible for most of the contamination seen on the WFPC1 pick-off mirror (16). However, telescope surfaces (structural members supporting the Aft Shroud and Primary Mirror) were also a contributor (16). The original SIs were not considered likely sources of contamination to the WFPC1 pick-off mirror as they all underwent extensive thermal-vacuum testing and their outgassing rates were well characterized.

On-Orbit Data

Goddard High Resolution Spectrometer

The Goddard High Resolution Spectrometer (GHRS) was one of the original HST SIs and the only SI that measured at Lyman-Alpha (1216 Å) wavelengths. Over its life (1990-1997) it did not measure a decrease in sensitivity greater than its three percent uncertainty at 1216 Å. However, its channel at 1150 Å, showed decreases in sensitivity slightly above its 10 percent uncertainty (19). A post-SM1 (1993-1997) loss of sensitivity at 1150 Å was reported at about two percent per year (20).

Corrective Optics and Space Telescope Axial Replacement

The Corrective Optics and Space Telescope Axial Replacement (COSTAR) was installed during the First Servicing Mission and provided corrective optics to the three remaining axial SIs. No degradation of the corrective optics performance was reported (1993-2002).

Wide Field and Planetary Camera II

The Wide Field and Planetary Camera II (WFPC2) was installed during the First Servicing Mission, replacing the WFPC1. Due to the instrument design, contaminants within the WFPC2 gradually built-up on the cold CCD faceplates of the camera resulting in a decrease in the UV throughput. Monthly decontamination procedures were developed to warm the camera to +20°C which restores the normal UV throughput (21-22). The contamination accumulation rate has decreased about 50 percent from December 1993 to May 2002 (23).

Space Telescope Imaging Spectrograph

The Space Telescope Imaging Spectrograph (STIS) was installed into the HST during the Second Servicing Mission (February 1997). On-orbit calibration data, taken after each servicing mission (SM2, SM3A, and SM3B) indicated that the STIS CCD (Charge-Coupled Device) sensitivity at Lyman-Alpha (1216 Å) wavelengths has changed on-average approximately one percent per year. In 2002, during the SM3B post-servicing mission calibration cycle, the wavelength-averaged sensitivity loss remained at approximately one percent per year (24).

Advanced Camera for Surveys

The Advanced Camera for Surveys (ACS) was installed into the HST during the Fourth Servicing Mission (March 2002). On-orbit calibration data indicated that the UV sensitivity of the ACS Solar Blind Channel detector at 1150 Å has declined on-average two to four percent per year (25-26). At longer UV wavelengths (2220 Å) the High Resolution Camera has declined about one percent (25).

SUMMARY

The HST Contamination Control Program evolved over the past 15 years going from a ground-based integration program to a space-based science-sustaining program. This program captured the contamination requirements and contamination controls necessary to meet the requirements which provided continuity and consistency from the First Servicing Mission (1993) through the Fourth Servicing Mission (2002). Starting with the design of the telescope, extensive analysis, contamination modeling, bakeouts and outgassing verification were performed for all hardware elements which had the potential to contaminate and subsequently degrade the performance of either the telescope optics or SI optics. The HST Contamination Control Program has been a successful approach to maintaining long-term science capability while controlling costs through the reuse of multi-mission hardware and mission-unique trade studies and contamination controls. By maintaining the cleanliness of the hardware between missions, and by controlling the materials added to the hardware during modification and refurbishment, both project funding for contamination recertification and schedule were significantly reduced.

The HST Contamination Control Program utilized detailed contamination modeling and trade studies to compare the risk of potentially contaminating the HST and its SIs during servicing mission activities. The results were used to craft the Flight Rules for each servicing mission. Modeling was also used to perform trade studies for the SIs, starting at the design stage through the test and integration phase to compare such things as the preferred venting path which produced the least deposition to the contamination-sensitive optics.

Feedback, through the periodic on-orbit calibration of the Scientific Instruments and post-mission inspections and testing for the returned SIs, allowed the HST Contamination Control Program to incorporate new contamination controls as necessary to preserve the HST science capability. Data from the SIs, such as GHRS, STIS, and ACS provided indirect measurements of the HST contamination levels. The contamination levels within the GHRS, STIS, and ACS instruments themselves were low and most likely, were due to monolayer contamination depositions. The data also indicated that the sensitivity losses remained relatively constant for these SIs from their deployments (1990-2005) also indicating that the contamination levels within the HST Aft Shroud were low. This data was in turn used to determine the best contamination control approach for new hardware (SIs and ORUs).

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