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CLEAN ASSEMBLY AND INTEGRATION TECHNIQUES FOR THE HUBBLE SPACE TESLESCOPE HIGH FIDELITY MECHANICAL SIMULATOR

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ABSTRACT

A mechanical simulator of the Hubble Space Telescope (HST) Aft Shroud was built to perform verification testing of the Servicing Mission Scientific Instruments (SIs) and to provide a facility for astronaut training. All assembly, integration, and test activities occurred under the guidance of a contamination control plan, and all work was reviewed by a contamination engineer prior to implementation. An integrated approach was followed in which materials selection, manufacturing, assembly, subsystem integration, and end product use were considered and controlled to ensure that the use of the High Fidelity Mechanical Siumulator (HFMS) as a verification tool would not contaminate mission critical hardware. Surfaces were cleaned throughout manufacturing, assembly, and integration, and re-verification was performed following major activities. Direct surface sampling was the preferred method of verification, but access and material constraints led to the use of indirect methods as well. Although surface geometries and coatings often made contamination verification difficult, final contamination sampling and monitoring demonstrated the ability to maintain a class M5.5 environment with surface levels less than 400B inside the HFMS.

INTRODUCTION

It has been well established within the contamination control community that clean assembly and integration are essential elements in the creation of a clean test or manufacturing facility. This principle applies to aerospace test equipment (also called ground support equipment, or GSE) because of the large size and complex interaction of the GSE with flight hardware; cross contamination of sensitive thermal and optical surfaces can cause deleterious effects. An alignment and envelope verification tool, the HFMS, was built for the HST Servicing Missions. The HFMS was manufactured, assembled, and tested within the cleanliness constraints imposed by the HST contamination control program for use with contamination sensitive Scientific Instruments (SIs).

This paper reports on the unique contamination problems associated with creating a mock-up of a large structure for use in testing sensitive hardware. The HFMS and its cleanliness requirements will be described, and the approach to HFMS contamination control will be presented. The practical aspects of implementing this approach and some lessons learned during the construction and certification of the HFMS will be discussed.

HIGH FIDELITY MECHANICAL SIMULATOR

Physical Description

The HFMS is a mechanical mock-up of the HST Aft Shroud and contains a support system for 5 SIs, 3 Fine Guidance Sensors, electrical harnesses, thermal blankets, and an equipment shelf for electronics. The HFMS is comprised of four major parts. The Aft Shroud Mock-up (ASM), a 5 meter high, 5 meter diameter cylinder, supports the Main Ring Simulator (MRS) (Figure 1). In the HST, the Primary Mirror is supported by the Main Ring (Figure 2). Suspended from the MRS is the Focal Plane Deck (FPD) and Scientific Instrument Support Structure (SISS) (Figure 3). Light collected by the HST is directed into SI apertures in the Hub area of the FPD. Access to the SISS is through three sets of doors in the ASM; an opening above one of these doors provides access into the FPD for a radial SI. Three sets of doors allow access to the other radial bays. Within these bays are guiderails and latches for insertion and capture of SIs. As a "high fidelity" simulator, the interior finish and astronaut interfaces have the same appearance and function as the HST Aft Shroud interior (Figures 4-6).

Developmental Stages

In order to understand the sequential imposition of contamination constraints, the HFMS developmental stages must be delineated. The HFMS was assembled and integrated at Goddard Space Flight Center (GSFC). Certain subassemblies were received from the manufacturer already assembled; these were the FPD, the MRS, and the ASM. Other parts were fabricated at GSFC and transferred to the Spacecraft Systems Development and Integration Facility (SSDIF) for assembly. The SSDIF is a class M5.5 cleanroom capable of supporting the integration of two Shuttle payloads concurrently. Integration of the HFMS began with disassembly and cleaning of the MRS, and mating of the MRS with the FPD. After SI latches were installed and aligned on the FPD, the SISS was added to the assembly. Again, latches were installed, and alignment and metrology verification activities occurred. The equipment shelf and blankets were added to the structure, and the structure was integrated with the ASM. Cables were routed and final blanket closeout was performed. A significant milestone in the contamination control program was the integration of the HFMS interior parts with the ASM. This integration virtually eliminated access to the Hub area, and greatly restricted access to the FPD and MRS underside. As access to various surfaces became more restricted, the contamination requirement became more stringent.

Requirements

The contamination requirements are derived from the intended uses of the HFMS: envelope verification of SIs, astronaut familiarization with HST interfaces and Orbital Replacement Unit (ORU) installation, SI confocality and alignment verification, and SI thermal vacuum operational tests. The intimate contact between the SIs and the HFMS imposes a surface cleanliness requirement upon the HFMS interior equal to the most stringent of the SI external surface requirements: Level 400B per Mil-Std 1246. Contact between the astronauts and the exterior surfaces of the HFMS provides the opportunity for cross contamination of the interior during crew familiarization; therefore, all external hand rails and astronaut interfaces must also be Level 400B. Other exterior surfaces are Visibly Clean, Highly Sensitive (VCHS) per JSC-SN-C-0005. During some operations, SI optics are exposed to the Hub area for extended periods of time without a direct purge or covering. The most stringent cleanliness requirement imposed to protect the First Servicing Mission (FSM) SI optics was Level 200A in the Hub area. Although the HFMS was not used in a vacuum for the FSM, a requirement exists not to preclude outgassing certification at the SI requirement of 1 Hz/hr on a 15 Mhz Quartz Crystal Microbalance at -20° C with the hardware at the maximum on-orbit temperature. An unusual requirement for GSE, internal air cleanliness of class M5.5 or better, is mandated by the enclosed nature of the HFMS and the class M5.5 environmental requirement of all HST SIs and Aft Shroud ORUs.

These primary requirements led to the development of secondary requirements which were not applicable to the flight HST: materials used inside the ASM must not generate particles when contacted by cleanroom garments, interior surfaces must be sufficiently static dissipative to prevent the attraction of particles, and the Hub area must be purgeable to prevent contamination of the SI optics in the unlikely event the cleanroom goes out of specification. To maintain the class M5.5 air cleanliness, constraints were placed on the orientation of the HFMS in the cleanroom air flow, HFMS door opening, and the number of persons permitted inside the ASM. Implementation of these requirements is discussed below.

IMPLEMENTATION

An early management commitment to contamination control facilitated implementation of contamination controls. Concurrence from the contamination control engineer (CCE) was required for all work authorizations, and the CCE was involved in daily test team meetings. With this guidance, the test team personnel were able to implement the spirit of the contamination control program during all phases of development. Standard operating procedures and contamination status memos were issued as necessary to communicate the level of cleanliness to which the hardware was being maintained. These documents proved to be a valuable addition to the contamination control plan because they were specific to the work at hand.

Because of resource limitations and surface morphology constraints, not every surface could be verified to Level 400B after each operation. HFMS surfaces were categorized according to the cross contamination risk they posed to the SIs, and verification requirements consistent with these risks were established. The contamination risks were assessed by evaluating the pontential for SI contamination due to the following transfer mechanisms: direct contact, airborne mobility of contaminants, vacuum outgassing, and indirect transfer by personnel contact. Although surface cleanliness cleanliness requirements differed, the precision cleaning procedure by which all surfaces were cleaned was invariant. This procedure had been previously proven capable of producing surfaces meeting Level 250A; Quality Assurance audits demonstrated the repeatability and consistency of the results. Molecular verification of HFMS surfaces, because of the geomety and access constraints, required the development of techniques other than the standard solvent rinse.

Materials selection was also considered an important aspect of the integrated approach to contamination control. Selection of materials which would not generate particles or cause static discharge during testing of SIs required an elaborate test program.

Personnel Management

Personnel constraints formed the basis of success for the HFMS contamination control program. Because the integration team personnel were all experienced in cleanroom assembly and testing, it was possible to concentrate on specific work patterns and priorities rather than general cleanroom behavior. Issues that were addressed included personnel access to the HFMS interior, when to notify contamination engineering of an operation requiring support, and how to minimize cross contamination between surfaces. The cooperation of the integration personnel in following the standard operating procedures was essential for the success of the contamination control program.

Standard Operating Procedures

During contamination generating activities, active involvement by contamination control technicians limited the accumulation of contaminants. All obvious contamination generating operations, such as drilling, cutting, or reaming, required simultaneous vacuuming and a follow-up wipe with isopropyl alcohol (IPA). In addition, any time fasteners were installed or removed, tape or optical targets were removed, or a subassembly was integrated with the HFMS, the areas involved were wiped with IPA. To minimize particle fallout accumulation on difficult to clean surfaces, such as the SI latches, bagging material was used to cover the hardware when access was not required.

In addition to the cleaning already mentioned, maintenance cleaning was performed bi-weekly at the subassembly level and weekly at the assembly level. Routine cleaning was mandated by the high activity levels in the cleanroom and the large surface area of the HFMS.

Verification Requirements

The verification requirements for HFMS parts during assembly and integration are shown in Table 1. Temporary mating surfaces, such as surfaces mated for match drilling, could be cleaned after the part was removed. Reflecting the cleanable nature of these surfaces, verification to VCHS was considered acceptable. Similarly, non-mating surfaces that were accessible for cleaning were verified to VCHS. Using a VCHS requirement instead of a 400B requirement allowed operations to continue without waiting for tapelift data. Surfaces which would become inaccessible for verification due to the HFMS geometry were a concern because of airborne contaminant transport. Both direct and indirect contamination transfer mechanisms were a concern because these surfaces could be contacted by personnel or hardware. Accordingly, these surfaces were verified to Level 400B. Because mated surfaces are not a source for direct contact, indirect contact, or particle transport under ambient conditions, particulate cleanliness was not required to be verified prior to mating. The possibility of volatile condensible contaminants from mated surfaces cross contaminating other surfaces under ambient conditions was considered negligible due to the lack of a transport mechanism. To minimize future outgassing due to surface Non Volatile Residue (NVR), each mating surface was wiped with IPA prior to mating. Mating surfaces which could be de-mated during crew familiarization in the HFMS had to meet the same requirements as surfaces which were inaccessible. The modifications to the verification requirements which were necessary to accommodate the different surface finishes and geometries are discussed further in the Verification Methods section.

A similar analysis was performed for the HFMS GSE. Small tools were cleaned to the level of the hardware with which they interfaced. Larger GSE, such as the Optical Telescope Assembly (OTA) dolly, were cleaned according to the cross contamination risk that was posed. Surfaces in contact with the HFMS were verified to 400B or VCHS, depending on the requirement of the surface with which they interfaced. Surfaces not in direct contact with the HFMS were cleaned to VCHS (the same requirement as the HFMS exterior), except for those surfaces which were not accessible to personnel. Because of the difficulty in reaching and verifying inaccessible surfaces, those surfaces were cleaned for entry into the cleanroom or covered with bagging material and verified to Visibly Clean on a periodic basis. These requirements are summarized in Table 2.

Verification Methods

The principle surface verification methods were the tapelift and solvent rinse. Unfortunately, not all surfaces were amenable to these methods. Alternative verification methods were developed for painted surfaces, surfaces with geometries that prohibited rinsing, and parts with less than the appropriate sampling area.

The solvent rinse technique often is not compatible with painted surfaces because the solvent will extract paint components from the surface or react with the paint. In some cases, this can be solved by the choice of solvent; however, for the HFMS only IPA was used to perform rinses. Rather than attempt to verify that no contamination was present, the approach taken was to monitor incremental changes. This allowed the use of solvent swabs, which do not contain enough solvent to endanger the paint integrity. The species detected were compared with previous swab samples to ensure that no new source of contamination had impacted the surface. This approach was dependent upon confidence in the initial cleanliness level. Maintenance of the painted surfaces in controlled environments following painting provided this confidence.

Some surfaces and assemblies could not be rinsed because the geometry of the part prohibited collection of a solvent rinse. These parts were swab sampled to determine qualitatively if any contaminant species were present. Once the cleanliness of the part was established, routine cleaning was used to maintain the surfaces. Monitoring of nearby parts confirmed the absence of volatile condensible contamination. Personnel training with respect to cross contamination mechanisms assisted in maintaining the cleanliness of the surfaces.

Small parts, such as fasteners, shims, and standoffs, presented less surface than the standard sampling area. To rinse these items, similar parts were grouped together after cleaning and rinsed as a batch. Once the parts were integrated with a larger structure, the structure became the controlling surface for rinse sampling.

To improve confidence in the cleanliness of the surfaces which were not amenable to standard rinse techniques, the entire HFMS was regularly inspected using an ultraviolet (UV) light. Many hydrocarbons fluoresce when illuminated with UV light. To ensure that the critical Hub area, to which the SIs would be exposed, was free from condensible hydrocarbons, a real-time NVR deposition monitor was installed: a Temperature Controlled Quartz Crystal Microbalance (TQCM) with a magnesium fluoride (MgF_2) coating operating three degrees centigrade below room temperature was used to record NVR deposition. To eliminate possible unkonwn surface effects, the MgF_2 coating was used to mimic the coating on the SI optics. Although MgF_2 coated TQCMs are sensitive to humidity (surface water mass is indistinguishable from hydrocarbons), the assumption that all accumulation is caused by hydrocarbons was conservative. Analysis of the TQCM response indicates a 1 Hz increase for a 2% relative humidity increase. Relative humidity was usually 45% at 68 °F. The use of the TQCM in ambient conditions is discussed in detail in reference 1.

Materials Selection

Materials used inside the HFMS had to be cleanable to 400B, low outgassing, static dissipative, and abrasion resistant. Verification of these criteria required an extensive test program. The test procedures were customized for each material based upon the use and location of the material. The HST structure is a graphite-epoxy composite covered with aluminum tape on the outside and multi-layer insulation (MLI) on the inside. The test process is depicted in Figure 7. After screening the material for low outgassing properties (less than 1% TML and 0.1% CVCM per ASTM E595) and the ability to meet Level 400 by tapelift before and after cleaning, the material entered a concurrent test period. Static dissipation, NVR rinse, and dry abrasion testing were performed concurrently. Static dissipation was checked for single layer and overlapped layers of tape. Abrasion testing was performed using a dry wipe; both the wipe and the sample were microscopically examined. Finally, a vacuum outgassing test was performed in the Molecular Kinetics (Molekit) facility.

Two materials, the aluminum tape used on the exterior of the HFMS and the beta cloth blankets intended for the interior of the HFMS, illustrate the necessity for a comprehensive test program. The HST flight aluminum tape was tested for use on the exterior and certain parts of the interior of the HFMS. In general, bare aluminum is a particle generating material because the oxide is easily abraded from the surface. Although most failed to meet the criteria for internal use, certain tape samples met Level 400 when tapelifted; this may be due to mechanical hardening during the tape fabrication process. Because the samples which passed were from the same roll as samples which failed, the tape was rejected for use inside the ASM. The samples were inspected to VCHS and approved for use on the exterior of the HFMS.

Many of the HFMS internal surfaces are covered by blankets. To simulate the HST, black betacloth blankets were baselined for use. The betacloth is a teflon coated fiberglass which is etched to produce the black color. This etching process weakens the betacloth such that the material was easily abradable by personnel contact. A test plan similar to the tape test plan was followed for several candidate blanket materials. In the case of the tape testing, the only cleaning that was tested was solvent wiping with IPA. For the blanket samples, different cleaning methods were tested, including non-contact vacuuming and solvent rinsing. The material which was chosen was manufactured without the use of silicone oil lubricant and was the only one which was non-porous. The non-porous aspect improved rinsability, cleanability, and abrasion resistance, and permitted verification to Level 400B.

DISCUSSION

Cleanliness Data

During assembly and integration of the HFMS, cleanliness samples were required whenever contamination generating activities were completed. While the HFMS interior assembly was separate from the ASM, access for cleaning was not precluded. Following integration with the ASM in April 1993, access for cleaning was restricted. From that point forward, maintaining cleanliness was paramount. Cleanliness levels found during routine sampling of the HFMS showed that the interior of the HFMS was better than Class 200. During heavy activity, cleanliness levels increased slightly, but stayed below Level 400. Rinses taken from the FPD during integration and closeout were in the tenths of milligrams per square foot. Selected routine sampling data is shown in Table 3; the July data was taken during operation of the HFMS.

In May 1993, after the HFMS was integrated, a TQCM was installed in the hub area to monitor contamination generated by cable routing and blanketing operations. The data from May through the end of June is shown in Figure 8. Two interesting items are evident on the graph: a 12 Hz jump in mid-May and a sudden increase in the contamination rate in June. An investigation of the 12 Hz jump indicated that the jump was not caused by contamination but was intrinsic to the TQCM.[1] The sudden increase around June 21 was caused by final closeout activities. Though not shown, the rate of contamination remained low once the HFMS was operational; the TQCM frequency at the end of SI testing was 935 Hz, compared with 930 Hz at the beginning. From the time of integration until commissioning, the total NVR accumulation in the Hub area was 4.3×10^{-2} mg/ft^2 (30 Hz at 1.56×10^{-9} g/cm^2/Hz). Optical witness mirrors placed near the TQCM showed no degradation at 121.6 nm during this period. Because swab samples of the Hub taken before integration showed no materials other than the swab background, confidence was high that the Level B requirement was maintained in the Hub area.

Lessons Learned

Several significant contamination lessons were learned during the HFMS program. Some of these are related to surface treatment, and others are relevant to cleanroom management.

It was found during assembly of the MRS that brush irridited aluminum does not possess the same resistance to particle generation as dip irridited aluminum. Tapelifts from the brush irridited surface ranged from Level 500 to Level 750, whereas dip irridited surfaces were better than Level 300. Bare aluminum surfaces produced particles too numerous to count.

Tape coverings for surfaces which will be used in vacuum are often perforated to prevent air bubbles. The direction of perforation of paper backed tape is important; perforating from the backing side through to the tape surface causes fibers to be trapped in the perforations. The ASM was covered with perforated tape, and efforts to remove the fibers by cleaning failed. The only solution was to re-cover the surface with unperforated tape.

Black beta-cloth is sometimes used as a thermal blanket on flight hardware. When ground simulators are used, the temptation is to use the same material for visual fidelity. Etched beta-cloth, however, easily generates particles when contacted because the fiberglass ends are weak. An alternative material which does not generate particles should be used in the cleanroom.

The direction in which the HFMS was oriented was found to have an impact on air flow into and out of the simulator. To minimize particle accumulation, the HFMS was oriented for each activity such that the air flow was tangent to the open doors - thus carying personnel and activity generated contamination downstream, rather than into the HFMS. Related to this phenomenon, the top of the HFMS, between the MRS and the ASM, was open. To prevent cross contamination from other cleanroom activities, this opening was covered with bagging material.

To control particle accumulation in the HFMS, a series of clean zones within the cleanroom were designated. Entrance to the clean zone required passing over a tackymat, and entrance to the HFMS required wiping the soles of one's booties with IPA. By controlling personnel access, the amount of contamination introduced into the HFMS was minimized. This process is discussed in more detail in Reference 2.

SUMMARY

The use of clean assembly and integration techniques is as important for GSE as it is for the flight hardware which that GSE will contact. Using an integrated contamination control approach to materials selection, integration, and use of GSE will minimize the cleanliness impact to sensitive hardware. Cleanliness data collected during the HFMS assembly, integration and use validates this approach.

REFERENCES

1. Mitchell, W. J., "Monitoring Deposition of Contamination on Optics Using a Temperature Controlled Quartz Crystal Microbalance (TQCM)", Presented at SPIE *Optical System Contamination - Effects, Measurement, Control IV Conference*, 25-29 July 1994, San Diego, California.

2. Hedgeland, R. J., et al; "An Integrated Approach to Contamination Verification and Control for the HST First Servicing Mission", Presented at SPIE *Optical System Contamination - Effects, Measurement, Control IV Conference*, 25-29 July 1994, San Diego, California.

Table 1. Verification Requirements, HFMS Surfaces

Surfaces	Metal or Tape	Painted (Note 1)	Rinse Prohibited
Cleanroom entry	400B	400B + swab	400 + UV
Non-mating or temporary mating	VCHS	400 + swab	VCHS
Prior to becoming inaccessible	400B	400B + swab	400 + UV (Note 2)
Prior to permanent mating	None (Note 3)	None (Note 3)	None (Note 3)
Prior to mating if de-mating may occur with ORUs present	400B	400B + swab	400 + UV

Note 1. Solvent restrictions exist
Note 2. Consult the CCE concerning contamination impact
Note 3. Alcohol wipe prior to mating

Table 2. Cleaning and Verification Requirements, GSE Surfaces

Surfaces	Clean to	Verify to
Contact HFMS non-critical surface	400B	VCHS
Contact HFMS critical surface	400B	400B
No contact with HFMS surfaces	VCHS	VCHS
Not accessible to personnel	Per cleanroom entry requirements	Per cleanroom entry requirements

Table 3. HFMS Cleanliness Data

Date/Activity	Axial Bay	Radial Bay	ASM Interior	Hub Area
4/9 Pre-integration	100B	50B	150	100
4/9 Post-integration	200	(Note 1)	300	(Note 2)
5/17 Routine Inspection	100	(Note 1)	100	(Note 2)
6/5 Routine Inspection	100	100	150	(Note 2)
7/9 Pre-Use	150B	150B	100	(Note 2)
7/9 Post-Use	(Note 1)	200	200	(Note 2)
7/28 Pre-Use	150B	100B	(Note 1)	(Note 2)

Note 1. Not sampled at this time
Note 2. Not accessible for sampling

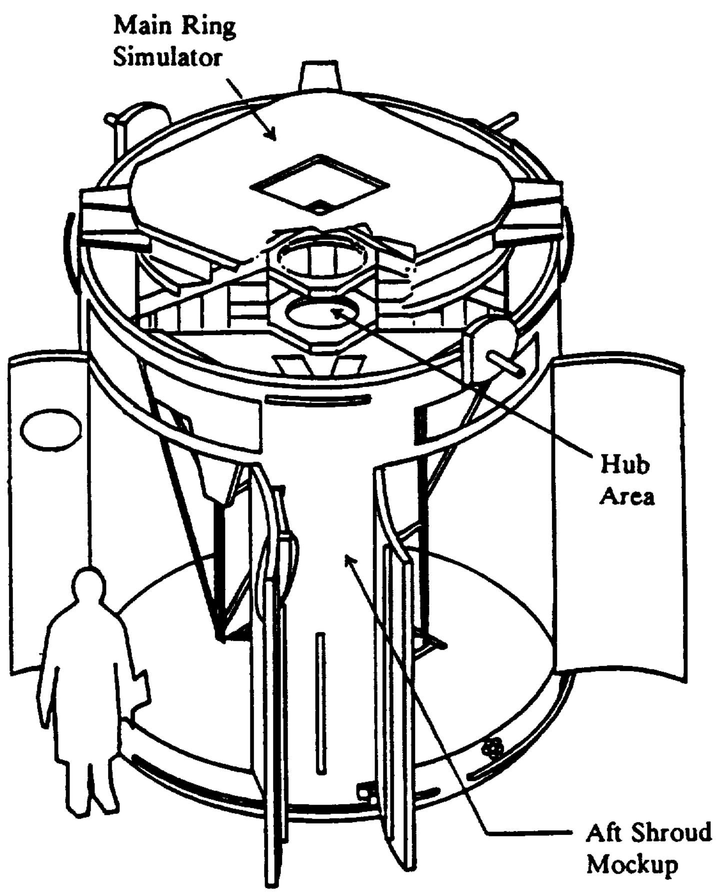

Figure 1 : HFMS Aft Shroud Mockup

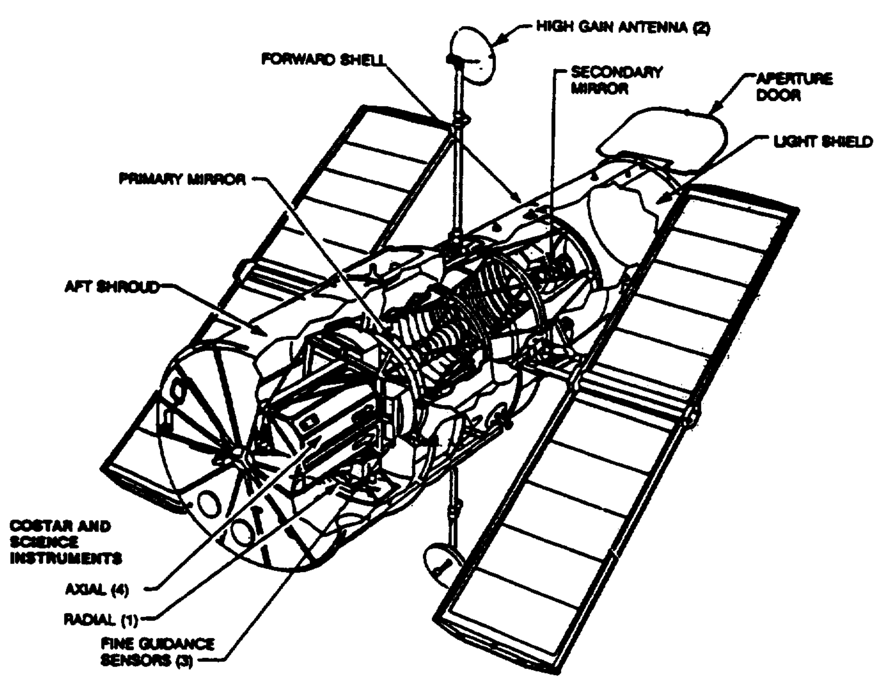

Figure 2 : HST Showing Location of Aft Shroud

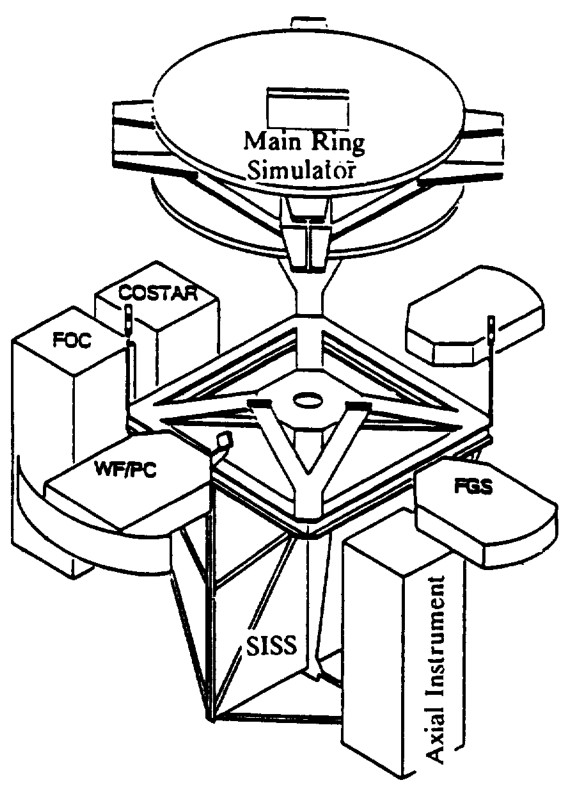

Figure 3 : HFMS Internal Components


Figure 4 : Radial Bay


Figure 5 : HFMS Axial Bay

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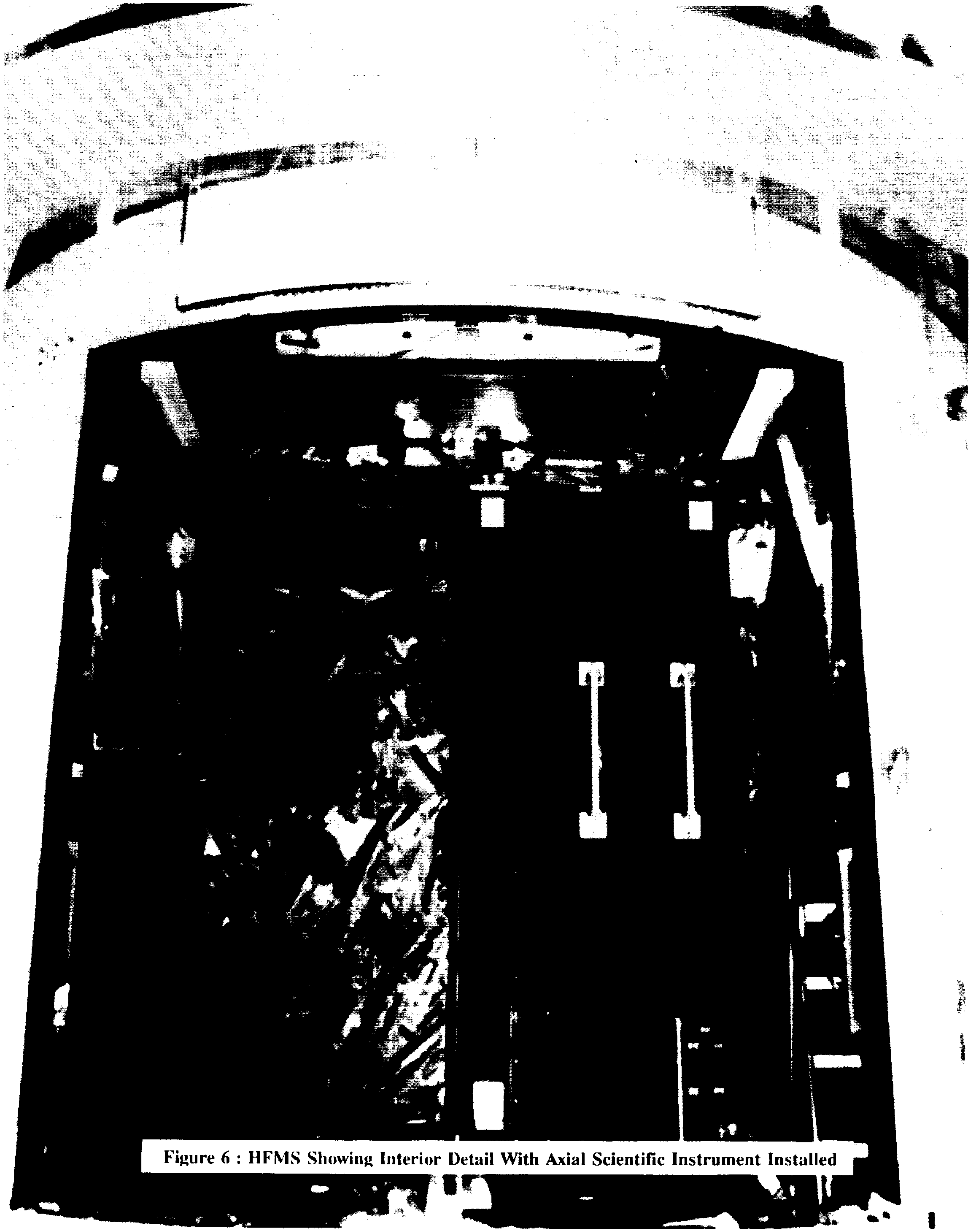

Figure 6 : HFMS Showing Interior Detail With Axial Scientific Instrument Installed

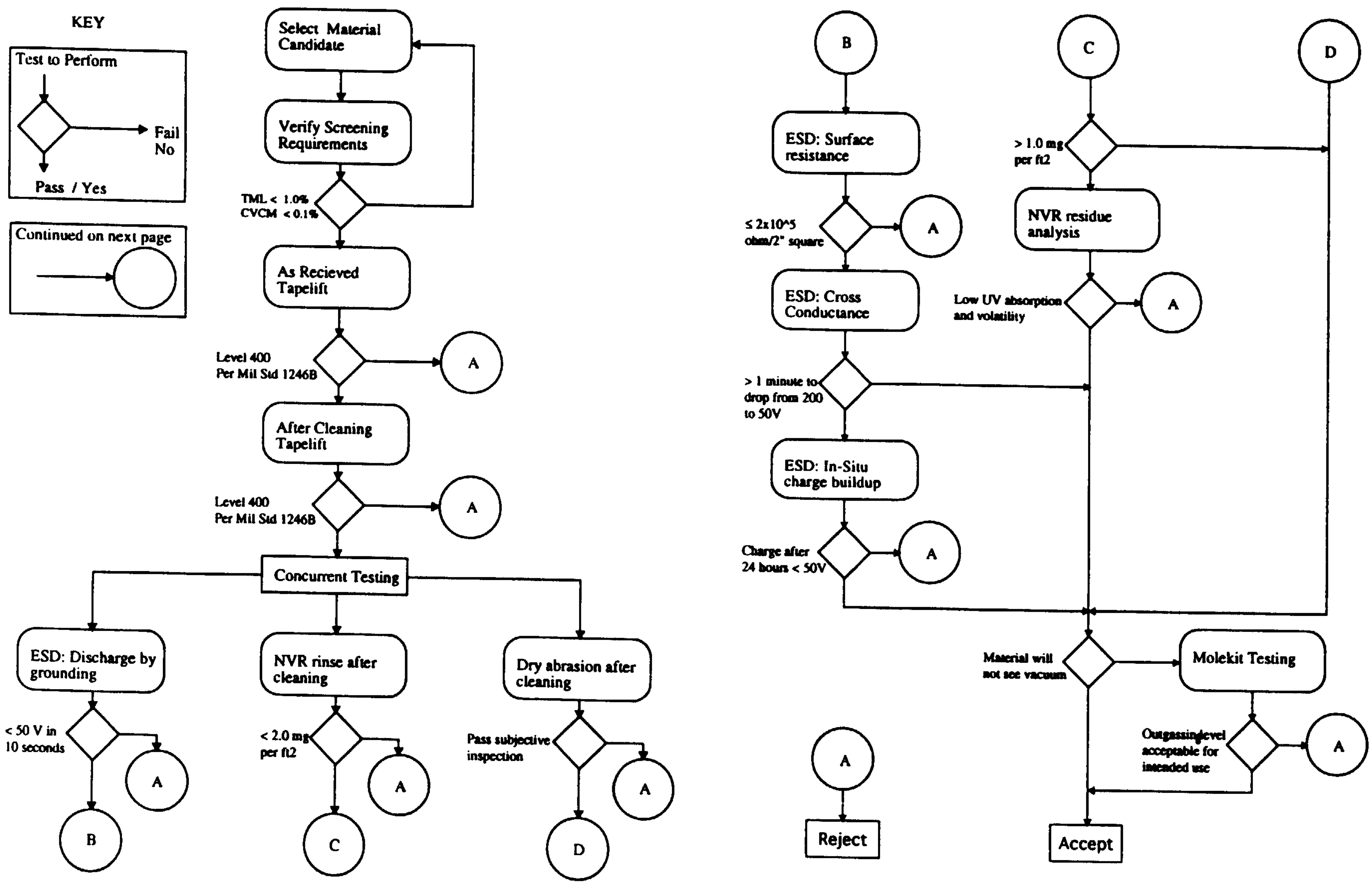

Figure 7 : Materials Testing Flow Chart

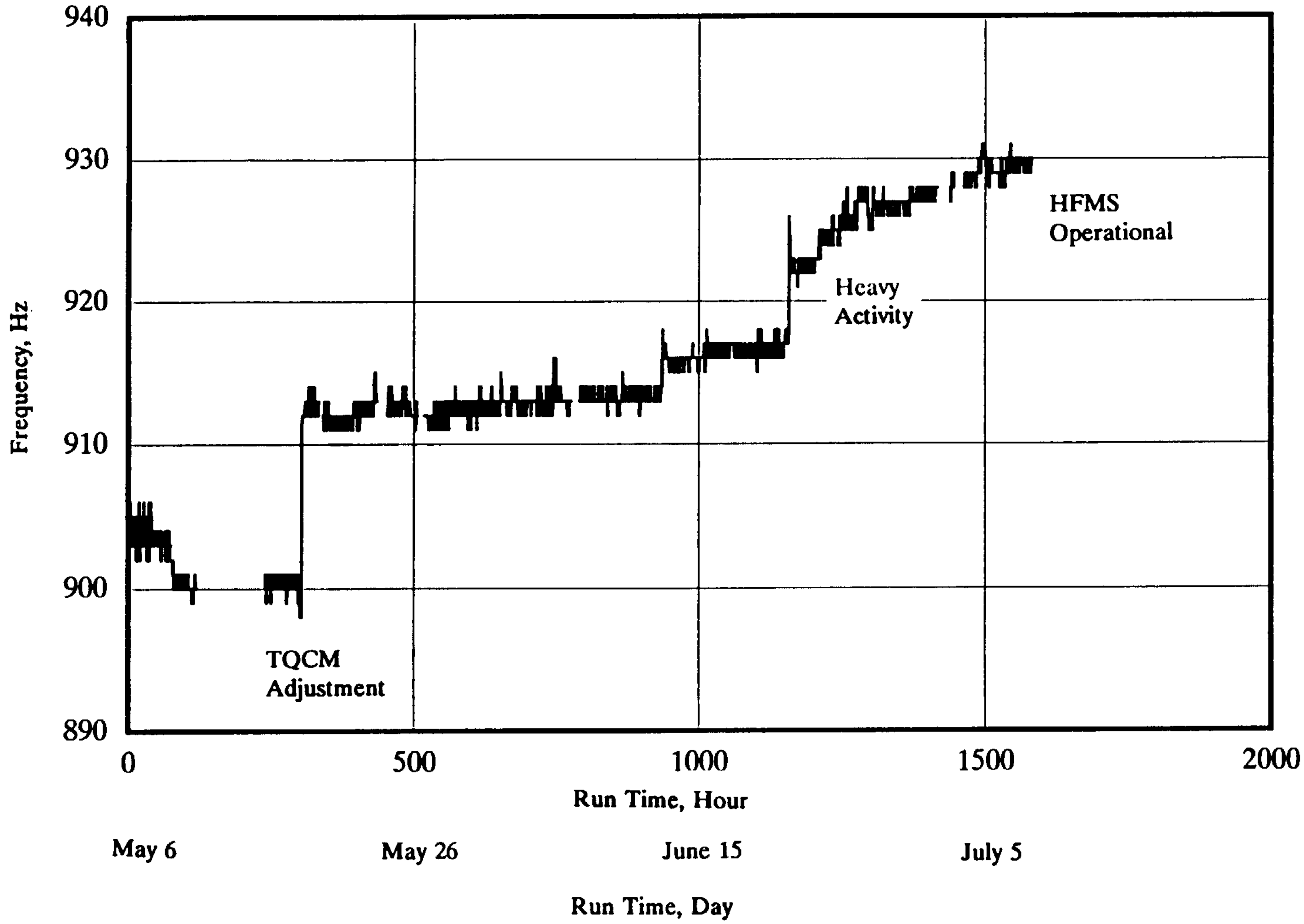

Figure 8 : TQCM data from the HFMS Hub area, May - June 1993