Published: <Washington, D.C.> : Office of Safety and Mission Quality, National Aeronautics and Space Administration, <1990>

HUBBLE SPACE TELESCOPE

SRM&QA OBSERVATIONS AND LESSONS LEARNED

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1. INTRODUCTION

The Hubble Space Telescope (HST) Optical Systems Board of Investigation was established on July 2, 1990 to review, analyze, and evaluate the facts and circumstances regarding the manufacture, development, and testing of the HST Optical Telescope Assembly (OTA). Specifically, the Board was tasked to ascertain what caused the spherical aberration and how it escaped notice until on-orbit operation.

The error that caused the on-orbit spherical aberration in the primary mirror was traced to the assembly process of the Reflective Null Corrector, one of the three Null Correctors developed as special test equipment (STE) to measure and test the primary mirror. Therefore, the Safety, Reliability, Maintainability and Quality Assurance (SRM&QA) investigation covers the events and the overall Product Assurance environment during the manufacturing phase of the primary mirror and Null Correctors (from 1978 through 1981).

This report summarizes the SRM&QA issues that were identified during the HST investigation. The crucial Product Assurance requirements (including nonconformance processing) for the Telescope are examined. The history of Quality Assurance (QA) practices at Perkin-Elmer (P-E) for the period under investigation are reviewed. The importance of the information management function is discussed relative to data retention/control issues. Metrology and other critical technical issues also are discussed. The SRM&QA lessons learned from the investigation are presented along with specific recommendations. Appendix A provides the NASA Marshall Space Flight Center (MSFC) SRM&QA report. Appendix B provides supplemental reference materials. Appendix C presents the findings of the independent optical consultants, Optical Research Associates (ORA). Appendix D provides further details of the fault-tree analysis portion of the investigation process.

2. BACKGROUND

2.1 Synopsis of the Optical Problem

On-orbit data from the HST revealed an imaging problem with the Wide Field Planetary Camera (WF/PC), indicating a deficiency in either the telescope or camera. The Faint Object Camera (FOC) indicated the same imaging problem, which made the telescope optics the primary suspect. Since the HST has only two optical components (a large primary mirror and a small secondary mirror), the problem could have been in either component.

Additional orbital data revealed that the imaging problem was a spherical aberration that did not vary with field angle. Based on knowledge of how telescopes image, the data suggested that the problem was in the primary mirror. Previous tests of the primary mirror against the Reflective Null Corrector (a precision instrument used to test the mirror during manufacture), yielded final test data that appeared "perfect." Therefore, characteristics that would cause spherical aberration in the Reflective Null Corrector became suspect. A tolerance analysis of the Reflective Null Corrector assembly indicated that the error was in either the index of refraction of the field lens (improper glass) or the field lens was spaced incorrectly. To ensure that all possible sources of the aberration were identified, a fault-tree analysis of the OTA was developed by the Hughes-Danbury Optical Systems (HDOS) organization.

2.2 Fault-tree Analysis Description

The fault-tree analysis defined the potential causes of the spherical aberration, ultimately focusing on longitudinal spacing errors that could produce the aberration (or a condition such as an incorrect index that would appear as a spacing error). The preliminary analysis efforts included several tests to eliminate potential fault-tree paths. The first test performed on the Reflective Null Corrector measured the effective focal length (and, therefore, the index of refraction) of the field lens, confirming that the correct glass type had been used. Concurrent with the first test, two spare field lens were located that had been manufactured in the same lot as the one actually used in the Reflective Null Corrector. The spares were measured for figure and back focal length, which also confirmed that the correct lens material had been used. The second test measured the spacing of the field lens to the lower mirror of the Reflective Null Corrector. This measurement showed that the spacing between the field lens and the lower mirror was about 1.3 mm too long, which was sufficient to cause the on-orbit spherical aberration.

Once the Investigation Board had agreed on the cause of the on-orbit spherical aberration, the extensive fault-tree analyses (Appendix D) were halted; and the Board chose not to extend the analyses to cover other, less viable causes of spherical aberration.

2.3 QA Role in the Investigation

The investigation of the SRM&QA issues involved the cooperative efforts of several QA organizations, including: HDOS Product Assurance Group, NASA MSFC and Headquarters personnel, and the Defense Contract Management Command (DCMC) (formerly the Defense Contract Administration Services--DCAS).

- *Hughes-Danbury Optical Systems*. The HDOS Product Assurance Group was tasked by the Investigation Board to gather all relevant documentation and hardware for impoundment by DCMC. (The document search is continuing to locate records that pertain to specific issues.) Additionally, this group reviewed and contributed to the test plans and procedures developed during the Board investigations, and then witnessed the actual tests. The group also assisted in identifying data sources, organizing the impounded data, and locating specific information for the investigators.

- *NASA*. The MSFC QA organization provided daily oversight of the test plans/procedures and the use of impounded hardware during actual testing for the investigation. This effort was supported by the MSFC SRM&QA Payloads Assurance Office personnel, who recommended technical QA changes to the test plans/procedures developed during the testing phase, and then witnessed the actual tests. NASA Headquarters SRM&QA contract support personnel served as the on-site representative of the Associate Administrator for the Office of Safety and Mission Quality (the NASA organization responsible for SRM&QA oversight of all NASA programs). This individual provided technical oversight for the SRM&QA-related aspects of the investigation; including functions such as: reviewing test plans and procedures; witnessing tests; and searching for pertinent data, as needed. In addition, he functioned as the on-site technical interface for the optical consultants, ORA, who were temporarily employed by NASA Headquarters SRM&QA to provide independent optical expertise relative to the HST investigation.

ORA conducted an independent review of the original design and QA processes for the HST optical components, both to support this investigation and to assist in fulfilling the current NASA SRM&QA mandate to provide independent assessments of technical issues. ORA also conducted independent analyses for other Board members, as required; for example, to cross-check the current HDOS analyses. (The ORA Report is included in its entirety in Appendix C.) Their independent conclusions were summarized in the following seven points:

1) The field lens position error (FLPE) can account for the entire HST error.

2) Our results agree with HDOS and the University of Arizona results within factors inherent in the different analytical tools used, given that

3) Inputs to each optical design program can be varied enough to cause output variations exceeding the variations between programs, and

4) The analytical error is in the noise of normal hardware error.

5) The reflective null corrector was the logical choice, if only one of the two null correctors were to be used.

6) Cross checking the reflective and refractive null correctors through tests with inverse null and primary mirror would have shown discrepancies too large to ignore.

7) Inserting windows of different thicknesses into the reflective null corrector may aid in verifying the magnitude of the conic constant error without requiring disassembly of the null corrector.

- *Defense Contract Management Command.* The DCMC organization impounded all documents and hardware related to the HST investigation. Additionally, DCMC preserved the HST hardware in the as-found condition as of July 6, 1990; and ensured that the hardware was not altered during testing. Much of the hardware was found to be in the same condition as when manufacturing ended (1982–1983 timeframe.) DCMC personnel ensured the traceability of calibration data; controlled all investigation-related documents generated by HDOS; attended technical reviews of test plans/procedures and witnessed the actual tests; and provided access to impounded data/hardware, as required.

3. PRODUCT ASSURANCE REQUIREMENTS

The SRM&QA findings relative to the P-E OTA Product Assurance Plan and requirements for the HST Program are as follows:

- *The initial Product Assurance Plan contained all of the basic requirements to ensure the quality of the end-item.*

- *The nonconformance requirements in the Product Assurance Plan and the formal reporting system were sufficient to raise critical issues, if utilized.*

- *The critical program/design reviews and SRM&QA survey processes did not surface the major problems and concerns that led to the spherical aberration.*

- *Formal disclosure of testing/tooling nonconformance reports would have forced a more visible assessment of the problems by both P-E and NASA.*

- *Test data sheets were signed off by QA; however, the Primary Mirror Phase II Metrology Test Plan and the OTA Verification Report for Primary Mirror lacked a QA signature.*

- *There was minimal participation by P-E design engineering during the mirror operations.*

3.1 <u>Basic SRM&QA Requirements</u>

The NASA contract contained an adequate set of SRM&QA requirements based on the criteria specified in NASA Handbook (NHB) 5300.4(1D-1), "Safety, Reliability, Maintainability and Quality Assurance Provisions for Space Shuttle Program." [NHB 5300.4(1D-1) was superceded in October 1979 by NHB 5300.4(1D-2).] To meet NASA contractual requirements, the HST plans and procedures that implemented the SRM&QA requirements were defined in the P-E OTA Product Assurance Plan (PA-01), PR-114. This Plan was originally released in January 1978.

The basic SRM&QA requirements were expanded and refined during a series of design reviews. A Product Assurance Preliminary Work Element Audit Review (P-WEAR), PA-07, PR-287, was presented to NASA in March 1979 to summarize the status of the Plan. The disposition of Review Item Discrepancies (RIDs) for the P-WEAR (PR-283) was documented in April 1979. A Product Assurance Critical Work Element Audit Review (C-WEAR), PR-496, was presented to NASA in June 1980 to provide the final status of the Plan. C-WEAR RIDs, PR-531, were documented and dispositioned in August 1980.

The Quality Engineering provisions of the Product Assurance Plan were designed to control the fabrication and inspection sequences, including tooling, jigs, fixtures, and other fabrication equipment to ensure the quality of the end-item. Thus, basic SRM&QA requirements that governed the processing of critical tools, testing, and the manufacture of the OTA components were in place prior to the start of the work.

The Product Assurance Plan was designed to assure a rigid and conventional approach to engineering, manufacturing, and quality. OTA manufacturing efforts were governed by the Plan's Quality Engineering requirements, which addressed the "requirements appropriate to the design, procurement, fabrication, assembly, acceptance test, and on-orbit verification and maintenance phases" (paragraph 6.2.1). Typical tasks cited in this paragraph included:

"a. Review the functional, equipment, design and interface specifications and drawings for incorporation of Quality requirements...

b. Determine the critical processes and develop special training programs, certification requirements, and process controls where required.

c. Ascertain inspectability of the design approach and determine the special inspection, inspection tests, tools, equipment, and facilities required.

d. Participate in test planning and verify that test requirements are defined and adequate.

e. Review test equipment design criteria to ensure that test data requirements will be met."

3.2 Nonconformance Requirements

The NASA contract contained an adequate set of nonconformance requirements as specified in NASA Handbook (NHB) 5300.4(1D-1). The intent of the contract in meeting NHB 5300.4(1D-1) requirements, was well defined and amplified in the Product Assurance Plan. Subsequent revisions to the Plan enhanced the basic requirements governing the critical tooling, testing, and manufacturing processes. Revision A to the Plan was issued on May 28, 1978, and included one pertinent change related to nonconformance testing. The overall Plan was generic in nature and did not have any specific references to mirror operations. For example, paragraph 6.6.7.2(e) originally stated:

> "Nonconformances and their dispositions are fully documented. The specific type of QA coverage for each particular test will be identified on the applicable documentation. All test data sheets will include a QA sign-off margin."

Revision A added the following statement to the above paragraph:

> "Selected tests, as the iterative testing of the mirror figuring, will be audited and validated by a review and verification of the recorded data."

It is interesting that this revision indicates a recognition of the importance of the iterative mirror figure testing.

Additional paragraph changes in Revision A addressed general requirements of nonconformance control (6.7.1), and nonconformance reporting and corrective action (6.7.2). The control-related change added a requirement for the Criticality classification to all OTA Malfunction Reports (MRs). The reporting change added the requirement to report any malfunction to NASA within 48 hours of occurrence. The corrective action process was changed to ensure that analysis and closure occurred within 21 days of the event. Since the final iterative testing of the mirror figuring was the only acceptance test of the mirror figure, it certainly should have been covered by these reporting provisions.

Revision B was issued on August 12, 1980, and addressed the basic technical requirements for quality control of subcontractors. The Detailed Quality Requirements section (6.4.5) was revised to use the term "subcontractor" in place of "supplier."

While Revision A and B changes enhanced the nonconformance requirements sections of the Product Assurance Plan, these changes did not substantively alter the basic nonconformance requirements. Testimony indicated that the MSFC Science and Engineering (S&E) optical experts reviewed and approved the in-process interferogram data. However, P-E and NASA on-site SRM&QA personnel were not directly involved in the review and approval of the in-process interferogram data.

3.3 Nonconformances - Testing/Tooling

The OTA Verification Report for the Primary Mirror (Ref. 1) lists three types of nonconformance documents: Material Review Board (MRB) Reports, Nonconforming Material Notices (NMNs), and Vendor Material Review Requests (VMRRs). [Three of the MRB reports were listed as remaining open and one NMN was listed as lost. Although the open MRB reports were closed by the end of 1984, no attempt was made to revise the OTA Verification Report to reflect closure.] The nonconformances addressed OTA issues, focusing on imperfections in the manufacture and coating of the primary mirror glass. However, none of these documents addressed the critical STE used to measure mirror quality.

Formal nonconformance reporting was not applied to test data or test tooling hardware (including STE) discrepancies. The requirement for nonconformance reporting of anomalies resulting from end-item acceptance test operations was clear and specific that it would be part of the formal flight hardware nonconformance reporting system. The requirement for STE anomaly reports is less specific, requiring the contractor to have quality surveillance of STE build in lieu of utilizing formal nonconformance system for the flight hardware. The common industrial practice is to utilize some form of in-house discrepancy report rather than using the formal system for test equipment.

A properly functioning reporting system at the Wilton and Danbury divisions would have documented at least the following discrepancies:

- Final Refractive Null interferogram fringe anomalies
- Fringe anomalies with use of the Inverse Null Corrector (INC) in combination with the Reflective Null Corrector
- Purported anomalies in the INC build process.

Once documented, the formal disclosure of the testing/tooling anomaly reports would have forced a more visible assessment of the problems by both P-E and NASA.

3.4 Critical Reviews

Formal design reviews were held for the whole OTA system but not for the elements. These reviews provided NASA with a current status of the various program operations. P-WEARs were held prior to preliminary design reviews (PDRs) and C-WEARs were held prior to critical design reviews (CDRs). ORIs were primarily safety reviews conducted prior to each major processing function to ensure that the mirror and OTA components were handled in a safe manner. These reviews should have discovered most or all of the deficiencies that have been surfaced by this investigation.

Other than the formal program reports, the complete records of meetings, comments, and rejected/accepted RIDs for these reviews have not been found. However, there is little evidence that any of the cited discrepancies (RIDs) raised specific concerns related to the current investigation. The ORIs were based on NASA requirements, served as the primary SRM&QA review, and focused on detailed safety evaluations of manufacturing processes, tooling, and handling to prevent potential in-process damage to the mirror. In this regard, the ORIs were generally successful. In contrast, the WEAR process (driven primarily by internal P-E requirements with NASA involvement) failed in its primary objective of assessing the ability of the primary mirror polishing and testing operation to meet design objectives.

Apparently, there were early concerns within NASA about the effectiveness of the P-E quality operation; however, the Review Board found virtually no documented evidence of these concerns during the time period in question. A MSFC Safety, Reliability, and Quality Assurance (SR&QA) survey (which included one NASA Headquarters SR&QA representative) was conducted on February 26-29, 1980. The survey produced only three findings pertinent to the investigation (two related to quality and one to safety):

a. The Assembly and Verification Plan, AV-01, lacked the required identification of test/inspection/contamination control points and associated procedures (Q-1).

b. The apparent absence of a formal system at Perkin-Elmer to survey principal suppliers (Q-8).

c. No formal closure method for action items generated from ORIs (S-2).

(Note that the investigation did not locate any records or documentation to verify closure of these items.)

These findings reflect a general concern about the apparent fragmentation and informality related to certain areas of the OTA Quality and Safety Programs that were not in compliance with the OTA Product Assurance Plan. The MSFC survey team emphasized to Perkin-Elmer at the exit interview that the P-E programs should require "proper visibility" of corrective actions, delineation of accountability for each action, and closure traceability. In addition, the Summary of Findings section in the survey report (Ref. 2) included the following statement:

> "The review of the QA planning and documentation, configuration control and training revealed that the current method of operation does not always agree with that stated in the QA documentation. It was recommended that a review and update of the PA Plan and Manual be made to reflect the actual method of operation."

On June 9, 1980, the Head of the MSFC System Safety Office wrote a Memorandum for Record (Ref. 3) concerning the P-E Computer Control Polisher (CCP) II and the OTA Chamber ORIs. Regarding the overall ORI process as originally conducted by P-E, he stated:

> "Their original approach was very informal with little documental *[sic]* of training personnel involved in critical operations, little or no hazard analysis of the operation. (They were simply looking at the results of rudimentary FMEA's of the equipment involved.) A survey in February also raised questions about the methods and documentation of the closure of hazards and the support being provided by the company industrial safety organization."

Additionally, he noted in the memorandum that:

> "Data reviewed at PE during the ORI's indicated a marked improvement in PE's ORI technique. There was some concern that MSFC employees were asking most of the questions during the reviews. (This was especially true during the CCP II when several members of the PE upper management were present.) Apparently, there had been a "dress rehearsal" earlier where the PE questions had been addressed. PE either provided answers during the reviews or made the questions action items for closure before operations could take on the equipment under review."

On June 11, 1982, the MSFC Director, Reliability and Quality Office, issued a letter concerning HST R&QA support (Ref. 4) to the Director of Science and Engineering (S&E) and the HST Program Director. This letter in part stated:

"We believe, as expressed to you, that the effectiveness of the DCAS at P-E can be improved and we are committed to work toward that end. In view of the weaknesses in the overall P-E operation, including the institutional R&QA performance, we concur in the need for additional TDY support to supplement the Resident Representative. We plan to provide this additional support through a rotational TDY plan starting in the mid-August time frame depending on the scheduled events and improvement progress with DCAS.

Also, as expressed to you, we believe the loss of Mr. Dave Burch, the P-E Product Assurance Manager, to the program can only adversely impact an already questionable QC operation. As you discuss other aspects of the ST Project with top P-E management, please convey our concerns and the need for a strong individual in this area."

Based on the date of the letter, these observations probably were directed to activity that occurred after the primary mirror grinding/polishing operations; and thus after the Reflective Null Corrector was assembled.

The recurring theme in the above examples is a concern about inherent "weaknesses" in the overall P-E approach to quality assurance/control during the optical fabrication. Subsequent operations on other portions of the space telescope assembly at Perkin-Elmer (such as the Fine Guidance System and integration of the structural elements with the Lockheed organization) were controlled more thoroughly by NASA. In-flight performance data has confirmed that these very complex systems are functioning as designed.

3.5 Quality Documentation Requirements

The formal design reviews discussed in the preceding section rely on documented quality criteria to ensure that the design incorporates SRM&QA requirements. The technical documentation requirements related to quality are specified by NHB 5300.4(1D-1), and supplemented by additional MSFC contractual data requirements and guidelines. For example, 5300.4(1D-1), Section 1D501, paragraph 1, Technical Documents, states:

"a. The contractor shall establish, document, and ensure compliance with design control requirements and quality criteria during all phases of contract work. The contractor shall ensure enclusion *[sic]* of quality characteristics and design criteria necessary for procurement, fabrication (including assembly), inspection and test operations.........as applicable in specifications, procedures, drawings, and fabrication and planning documents.

b. The contractor shall utilize a system which identifies hardware characteristics requiring verification. This identification should be based on the use of the hardware involved and shall be utilized in developing quality inspection and test surveillance planning, as an input to the.........development of quality criteria, workmanship and inspection standards, and inspection procedures.

c. Contractor quality assurance personnel shall conduct a timely review of technical documents that affect quality and changes thereto. Reviews shall ensure that all necessary information has been included and that requirements are clear and unambiguous. The reviews shall be documented and action shall be taken to ensure correction of deficiencies. These reviews shall also be an integral part of the quality planning function to ensure timely planning of quality activities and facilities associated with subsequent procurement, fabrication, assembly, inspection, testing, delivery.......activities."

NHB 5300.4(1D-1), Section 1D505, paragraph 2, states that the contractor (P-E) must document inspection and test plans to provide for: availability of calibrated inspection and test equipment, and coordination of inspections and tests conducted by the designated Government (MSFC) quality representative.

Baseline design criteria used in the final design phase (PDR through CDR) served as the basis for special inspections (critical source, receiving, in-process, and final). These requirements should have encompassed all of the STE such as the Null Correctors used to define critical performance parameters.

3.6 Test Documentation Approval

The Product Assurance Plan required a QA signature on test documents for the primary mirror and the other OTA components, but did not specify a requirement for a QA signature on the final buy-off documentation. While the QA organization reported to engineering, none of the formal plans and reports for optics fabrication included signature approval from the QA organization or any NASA element. The Abstract of P-E document PR-235, "Primary Mirror Phase II Metrology Test Plan," dated July 20, 1979, contained the following statement of purpose:

> "The plan of the Metrology Tests used during the Phase II primary mirror polishing to ensure Quality."

This Plan lacks a QA signature, although it is one of the few reports signed by P-E engineering (in this case, the Deputy Director of Engineering). While the test data sheets were signed off by QA, it is interesting to note that the test procedures and final reports did not have a QA signature. For example, a P-E memorandum on the final Phase I test parameters (used to conclude the Wilton Phase I effort on the primary mirror) had only engineering signatures (Ref. 5).

The Panel found no evidence of continuing design engineering participation during the fabrication and test of the primary mirror. The signature of the Deputy Director of Engineering on the Primary Mirror Phase II Metrology Test Plan was one of the few formal indications of engineering participation. In fact, the designer of the original Reflective Null Corrector and Inverse Null Corrector stated to the Board that he never had been in the tower to see the device in actual operation.

As noted previously, the OTA Verification Report for Primary Mirror finally was released on October 3, 1983, but without a QA signature. This report provides the following conclusion (paragraph 1.2):

> "Since the Primary Mirror complies with design and verification requirements stated in the CEI specification and VRSD, it can be used in the Primary Mirror Assembly."

The Primary Mirror Phase II Metrology Test Plan and OTA Verification Report were the engineering-based quality documentation that allowed the primary mirror to progress to the next assembly stage. It is interesting to note that the Applicable Documents section of the OTA Verification Report did not list the P-E Product Assurance Plan, but only the P-E Contamination Control Program Plan. In addition, the only NASA publication listed was NHB 5300.4(1C), "Inspection System Provisions for Aeronautical and Spare System Materials, Parts, Components, and Services." NHB 5300.4(1D-1) should have been included.

It is presumed that both the P-E and NASA QA organizations used the Primary Mirror Phase II Metrology Test Plan and the OTA Verification Report in formally accepting the primary mirror as part of the final OTA buy-off package.

4. HISTORY OF HST QUALITY ASSURANCE

The findings relative to the HST QA oversight and interfaces by the Government and contractor organizations are as follows:

- *The on-site representatives for the NASA and P-E QA organizations were not specifically trained in optics to provide an informed and independent evaluation of the assembly and manufacturing operations. Only one NASA QA representative was available to cover a 7-day, 3-shift operation at two locations.*

- *None of the P-E QA Monthly Reports indicated concern that their organization was removed from the metrology area during the final grinding/polishing operations; nor did they indicate any concerns with test results.*

- *The NASA and P-E QA organizations lacked a clearly independent chain of command that would have permitted program decisions to be appealed to higher management.*

- *A letter of delegation was not issued to DCAS prior to critical primary mirror/corrector operations.*

Critical to the review process of the HST problem was an understanding of the interactions and interfaces among the QA organizations involved in the manufacture of the primary mirror and Null Correctors from 1978 to 1981. Three distinct organizations provided the overall HST OTA product assurance: P-E Product Assurance Directorate; NASA Headquarters and MSFC SR&QA, including the MSFC Resident Office at P-E; and DCAS (now referred to as DCMC).

Note that the P-E award fee criteria had no specific reference to quality performance, and the NASA award fee board did not have a SRM&QA representative. However, this was common practice at the time.

4.1 Perkin-Elmer QA Organizations

When the OTA contract was awarded to the P-E Optical Technology Division, the existing QA system was organized to comply with MIL-Q-9858A requirements for Department of Defense (DoD) programs. Minor adjustments were made to the OTA QA program to comply with the basic requirements of the NHB 5300.4 (1D-1), and additional guidelines imposed by the MSFC Statement of Work and Data Requirements.

The P-E QA functions (including quality control, quality engineering procurement control, and contamination control analysis) reported to the QA manager. The reliability engineering functions (including materials and processes, safety, reliability, and maintainability) reported to the Reliability Engineering/Assurance manager. The P-E system had one significant organizational difference from a typical NASA program: the Product Assurance Directorate (responsible for reliability and QA functions) reported directly to the OTA Project Manager, who in turn was responsible for schedules, resource allocations, and end-item deliveries.

This reporting structure did not provide the necessary independence for the Product Assurance function. The situation was not rectified until 1982 when, in response to a RID generated during the MSFC survey, the Directorate began reporting to the Assistant General Manager for Operations.

The P-E Product Assurance organization was staffed with well-qualified senior engineering and QA professionals. The management had considerable experience in QA and reliability disciplines, optical manufacturing, and systems test applications. Staffing levels averaged between 10 to 15 percent of the total program contingent, which is typical for Product Assurance programs of this size. Although there were several qualified optical engineers working in QA areas, none were actually assigned to interface with the critical optical tooling operations at either the Danbury or Wilton facility; each facility had a separate QA organization. This arrangement meant that Danbury had contractual responsibility for the work subcontracted to the Wilton division, but Danbury QA (and also MSFC QA) relied on the Wilton QA organization for coverage of critical tooling processes.

After a series of safety-related incidents related to the Phase I manufacture of the primary mirror, the Danbury QA organization expanded their oversight of safety at the Wilton facility. Permanent safety/QA personnel were assigned to Wilton from the Danbury division Product Assurance organization. These individuals were tasked to monitor and provide technical guidance on all safety-related issues concerning the primary mirror.

A major contractual requirement of the OTA QA program was the preparation of regular Product Assurance reports that were issued as part of monthly P-E Program Reviews. These reports covered progress, problems, and plans for the areas of: Quality

Assurance (3.6.1); and Reliability, Safety, Maintainability, Materials-Processes, and EEE Parts (3.6.2).

The HDOS file copies of the monthly PRs are incomplete. The missing data make it difficult, if not impossible, to reconstruct the events identified in these reports. However, the available information does not indicate any specific concerns related to the Reflective Null Corrector. Since the safety of the primary mirror was of paramount concern, more routine QA problems were not considered sufficiently notable to merit inclusion in the monthly reports.

This view may have resulted from the lack of notification to the QA staff that Reflective Null Corrector final assembly operations were in-process or completed; since the QA staff was not involved in these crucial activities, they could not monitor or report QA concerns. The issue of adding spacers to the field lens assembly of the Reflective Null Corrector (possibly via a formal MRB process) also was not discussed.

4.2 NASA Headquarters and MSFC QA

The P-E contract was awarded in October 1977, and primary mirror grinding/polishing operations spanned the period from December 1978 to April 1981. When the contract was initiated, NASA Headquarters QA oversight for all NASA programs, including HST, comprised two to three engineers assigned to the Office of Chief Engineer (which is the predecessor of the Office of Safety and Mission Quality).

The first full-time NASA quality representative was in place as of March 2, 1979. This single individual constituted the total government QA presence during the period in question to cover what was essentially an around-the-clock, 6 or 7 day-a-week operation at both the Danbury and Wilton facilities. While the representative had over 23 years in Government reliability and QA experience at the time of his assignment to the program, he did not have any formal optics training. The representative indicated that he utilized the optical expertise resident at MSFC whenever such expertise was required. (No file copies of the representative's reports to MSFC have been located at Danbury or MSFC.)

Supporting the NASA representative at P-E Danbury in a collocated function at the MSFC Project Office was another NASA quality representative who served as his direct counterpart. Other members of the MSFC SRM&QA staff provided support to the NASA representative at P-E on an as-needed basis; the time expended by these supporting personnel (at least 12 individuals) varied from 10 to 35 percent. None of the MSFC QA staff had expertise in optics and relied totally on the Engineering organization for this support and insight.

Some of the primary responsibilities of the SRM&QA representative included:

- Providing MSFC SRM&QA interface with the P-E Quality Manager.
- Monitoring quality compliance with contractual requirements..
- Providing technical guidance in establishing subcontractor quality criteria.

- Interfacing with DCAS to establish SRM&QA requirements.
- Serving as the Government MRB representative.
- Monitoring adequacy of nonconformance reporting system.
- Evaluating hardware and system modifications for reinspection and retest.
- Participating in MSFC SRM&QA surveys, design reviews, ORIs, and Configuration Management Audits.

4.3 Defense Contract Administration Services (now DCMC)

The DCAS oversight duties for the HST Program began on December 1, 1980, over 3 years after the contract was awarded to P-E. Thus, they were not involved in the primary mirror grinding/polishing processes nor the manufacture of the Null Correctors at Wilton. (Prior to 1980, DCAS representation consisted of one to two individuals who covered the Danbury and Wilton divisions for DoD programs.) Since the actual letter of delegation was written only 3 months before the completion of the mirror polishing, it is doubtful that DCAS delegation would have had meaningful impact on the design and assembly of the Null Correctors.

During subsequent testing, the DCAS representative indicated a concern for the lack of QA participation in critical processes. He noted in a DCAS Optical Telescope Division (OTD) Quality Control daily log sheet, dated April 29, 1981 (Ref. 6), that the test procedure #679-5017 for the vertex location tests lacked a requirement for QA participation in the data collection/review. The log sheet shows that the DCAS representative related the problem via telecon to the NASA QA representative in compliance with NHB 5300.4(2B), paragraph 2B600, as listed in the letter of delegation (Ref. 7). This indicates how independent DCAS oversight might have benefitted the design and assembly phases of the Null Correctors.

DCAS duties for the HST Program were in accordance with NHB 5300.4(2B), and were typical of similar NASA programs. Normally, DCAS would monitor compliance with calibration requirements, provide an independent verification of test results, and sign for the Government on end-item documents. However, there are only limited references to DCAS activity in the surviving P-E monthly reports. None of the DCAS information in these monthly reports supports any concerns or findings relative to the Null Correctors.

5. DATA RETENTION/CONTROL

The SRM&QA concern about the adequacy of the data management system in retaining critical quality data during the HST program life cycle (from onset to completion) is as follows:

- *There was no formal and centralized information management system to retain and categorize the voluminous data that defined the HST performance characteristics.*

The NASA contractual requirements for control of critical records for programs of this size typically stipulated retention for a specified period of time to support on-orbit anomaly investigations and resolutions. The NASA contract requirements (Ref. 8) stipulated that: "The materials....shall be made available to the Office of the Contractor, at all reasonable times, for inspection, audit, or reproduction, until the expiration of three (3) years from the date of final payment under this contract.....". NASA had assumed that Perkin-Elmer (and now Hughes-Danbury) would be under contract for a minimum period of 15 years during which all HST data would be retained according to standard practice.

There was no separate formal system for retention of HST data by either P-E or NASA during the time period in question (the data were not systematically indexed, filed, or stored). When the Investigation Board requested that Hughes-Danbury impound all relevant data, the available information primarily consisted of final OTA buy-off documentation located at Danbury and individual files of former P-E employees as well as current HDOS employees.

The lack of complete data records on the manufacture and assembly operations during the time period in question seriously hampered the Board investigation as well as the Hughes-Danbury investigation. [Note that the original contract was extended to October 5, 1990; after which the Goddard Space Flight Center (GSFC) assumed the retention/control function for all existing HST data to support on-orbit operations under a 2-year contract.]

It is believed that the documentation stored at the Wilton facility at the time of the final OTA buy-off remained in the possession of the P-E Wilton divisions when the Danbury division was sold to Hughes. Consequently, the tooling/STE data were not retained with the final OTA buy-off documentation. Acquiring that data after a 10-year lapse has been difficult; the Hughes Product Assurance Manager is conducting data searches for the investigation in cooperation with the P-E data management organizations.

6. METROLOGY

The SRM&QA findings relative to the critical metrology operations and the pivotal issue of denial of QA access to these areas are as follows:

- *Due to a management decision, neither NASA nor P-E QA provided surveillance of critical metrology functions/processes during the build of the Reflective Null Corrector or testing of the primary mirror. The decision probably resulted from schedule/cost pressures and a belief that the respective engineering coverage was an adequate assurance.*

- ***The HST Program lacked an independent second means of final testing each critical optical component, which would have surfaced the HST flaw.***

NOTE

Optical metrology has a broader context than typical QA metrology organizations, which deal primarily with instrumentation calibration. P-E optical metrology encompassed the design, build, and testing of special tooling/hardware (such as the Null Correctors), the conduct of the tests, and data analyses required to produce the final optical end-items.

6.1 Surveillance of Critical Metrology Operations

As discussed in Section 3.1 of this report, witness testimony indicated an underlying concern about the formal discipline of the P-E optics/metrology operations. P-E treated the metrology operations as experimental engineering rather than formal manufacturing operations. A 1979 Program Evaluation Review Technique (PERT) chart of 60-inch Null Corrector modifications (Ref. 9) indicates that metrology engineering intended to provide only laboratory certification for the Reflective Null Corrector STE rather than formal certification through an independent QA process.

The metrology area at Danbury (where the HST Reflective Null Corrector was developed from the original 60-inch Corrector and the Inverse Null Corrector was assembled) was secured by a cipher lock door that was accessible only by Wilton metrology engineers; ostensibly, this was to afford complete privacy for these engineers. The Product Assurance Manager stated that his organization was not aware that a modification and final assembly process was occurring until the Reflective Null Corrector Assembly was moved from the metrology area to the OTA test chamber. Since no formal manufacturing process paperwork covering that activity was initiated through the accepted production channels, the QA organization was prevented from providing oversight. He could only recall being asked to provide safety personnel to assist with the transfer of the 60-inch Reflective Null Corrector from Wilton to Danbury, and the final transfer of the HST Reflective Null Corrector to the OTA test chamber.

The P-E Wilton division optical engineering/metrology organization operated with few checks and balances from P-E or NASA program engineering and QA organizations. Thus, P-E and NASA central engineering staff and QA organizations had essentially no effective technical surveillance of the metrology operations. According to witness testimony and written records, the P-E HST optical engineering personnel (under the Manager of Manufacturing Optical Analysis) had minimal contact with the P-E central engineering staff. NASA engineering coverage basically consisted of MSFC Program Office engineering representative, who covered all program aspects and could not provide any detailed surveillance of the operation and data analyses.

Consequently, the QA representatives at the Danbury facility were limited to performing safety functions. According to testimony, the primary duty of the QA representative during the optical measuring process was to enforce the rules concerning loose objects that could fall and damage the mirror. For example, the P-E Danbury QA representative was not allowed access to the top platform in the primary mirror test cell;

therefore, he was not in a position to visually confirm the activities of the optical test personnel. Limited to the intermediate level, he could only control individual access to the tower and tether all loose objects to the optical engineering personnel prior to entry. (In this case, denial of access was at least partially driven by technical considerations that required a minimum number of people at the upper level.)

This resulted in a lack of independent surveillance of the critical metrology area for activities such as:

a. Certification of the STE and equipment being utilized.

b. Technical review/validation of the precise methods and analytical tools being employed.

c. Surveillance to ensure that the repetitive use of these methods were applied consistently.

d. Control of input film quality, as received from the test tower.

The MSFC Resident SRM&QA Representative stated that he was directed by his senior supervisor, the MSFC Director of Quality and Testing, not to cover the metrology area as it would be covered by MSFC engineering. He believed this directive resulted from a meeting at MSFC with the Director of Science and Engineering, and his senior supervisor. (At that time, the QA organization reported to the Director of Science and Engineering.) He believes the rationale given for this arrangement was that the metrology engineers were capable of performing the requisite QA functions without the adverse schedule impact created by additional Government inspections. This decision could have been driven in part by the Resident SRM&QA Representative's lack of qualifications in optics; given his experience (refer to Section 4.2), he could have effectively monitored the discipline of the operation.

There are no written records that either the P-E quality organization or NASA ever contested the denial of QA access to the metrology areas. It was the consensus of both government and contractor witnesses that P-E management had enforced a policy (accepted by both the NASA and P-E HST Program Offices) that limited the NASA and P-E Danbury QA organizations access to the optical metrology operation. Testimony indicated that access was denied—at the request of optical engineering management—to the Danbury metrology areas that involved metrology testing, data reduction/analysis, and the final Null Corrector assembly. Apparently, denial was based on the rationale that much of the HST metrology assembly operations involved Wilton division proprietary functions and DoD-classified sensitive technology. This constraint in effect shielded the operation from NASA and the Danbury division.

The P-E Quality Manager claimed to have verbally protested this arrangement to management (Product Assurance Program Manager and Manager of Manufacturing Optical Analysis) on several occasions but to no avail. He also claimed that in this time period he originally had two qualified optical engineers on his staff; one of whom purportedly resigned because he was not being properly utilized in his field of expertise.

Given that P-E Danbury QA had qualified optical engineering personnel, the management decision to exclude QA appeared to be based solely on the concern about proprietary Wilton division and DoD-classified design technology, rather than on the basis of schedule/cost impacts. Since the Product Assurance Manager was qualified with the appropriate clearances to operate in both P-E proprietary and DoD classified areas, the only rationale remaining for QA exclusion was the anticipated schedule impact of inspections.

P-E internal memoranda produced during the design and manufacture of Null Corrector components indicated that P-E optic engineers had desired the presence of the Wilton QA organization (Refs. 10, 11) during Null Corrector assembly and test phases. However, no data have been found to confirm that any QA personnel witnessed the final assembly of the HST Reflective or Inverse Null Correctors. There are data to confirm that Wilton QA did witness the final assembly of the Refractive Null Corrector.

In theory, QA oversight in the metrology areas should have included: a review of these metrology processes as well as test records (including interferograms), and provided a documentation trail for support of in-flight anomaly investigations. [A set of interferograms was assessed independently by NASA MSFC engineering midway through the operation and appeared to confirm the P-E methods. A later set also was sent to NASA, but no report on their results has been found.]

6.2 Optical Review Environment

In reviewing witness testimony, there is a sense that the optical review environment during the formal design reviews was not conducive to open discussion of problems. The presentation material from the 1978 to 1980 timeframe does not indicate that the differences among interferograms or any other QA concerns about access to metrology were addressed. It appears that these and other issues that might have adversely affected schedules or cost did not surface.

During the 1980s, cost was a major consideration for NASA and its contractors. The cost constraints on the HST Program were reflected in the budget/manpower trade-offs of the P-E QA organization. For example, the investigation uncovered a handwritten P-E memorandum (Ref. 12), dated September 9, 1980, referencing possible changes in the Product Assurance organization to meet the FY 1981 budget level. Given a concern about meeting the QA staffing requirements with a restricted budget, the memo suggests alternatives such as cutting travel for QA staff and eliminating QA positions—including that of the Product Assurance Program Manager. This memo was not formally distributed.

The impact of schedule pressures is reinforced by a P-E memorandum (Ref. 13) that explains why the Phase I portion of the HST primary mirror fabrication at Wilton took so long. This memo addressed the reasons why a planned 50-week fabrication effort became an 86-week effort. By the time the Null Correctors were in final assembly, the program had severe schedule problems.

6.3 Need for Additional Testing

An internal review in 1981 by a P-E team headed by the Assistant Program Director recommended additional testing (Ref. 14). "Another test of the figure using an alternate method such as a Hartmann test or a test utilizing the pattern distribution of a reflected laser beam should be made. The purpose of this test would be to uncover some gross error such as an incorrect null corrector." "After assembly of the primary and secondary in there final configuration a simple autocollimation test using a flat of the order of 12" diameter should be performed to look for gross errors which may have occurred in the very long chain of analyses and tests leading to a complete optical system." No documentation has been found to indicate how this concern was resolved. Witness testimony also remembered private discussions about concerns for a possible need for a second test method for the Reflective Null Corrector. We do know that no other tests were performed.

7. CRITICAL TECHNICAL ISSUES

The SRM&QA-related findings with regard to the circumstances that caused the spherical aberration are as follows:

- *NASA believed that the manufacture of HST optical components was well within the capabilities of P-E and Eastman-Kodak, and thus deferred the critical optical issues to Perkin-Elmer.*

- *In-situ or end-to-end testing of the Reflective Null Corrector was not performed, nor is there evidence of a quantitative certification of this Corrector.*

- *No formal optical acceptance criteria was established to cross-compare Null Corrector test results within the error budget limits.*

- *Warning flags such as conflicting interferogram data and the field lens mounting spacers were ignored.*

Historically, the NASA optical community characterized the manufacture of OTA optical components as being well within the capabilities of optical manufacturers such as Perkin-Elmer and Eastman Kodak. The large investment in the 60-inch mirror program had provided an excellent proof of the capability of the people and systems. It was recognized that the optical figure and smoothness requirements for the primary mirror imposed stringent controls on the manufacturing process to achieve the desired performance. Of greater concern to NASA were the pointing and fine guidance control systems required to fully utilize the on-orbit OTA capabilities, and the extensive system integration efforts needed to place the HST in orbit. Due to these larger concerns, NASA appears to have deferred the critical issues associated with the manufacture of the optical components to the P-E experts. The HST contract specified only the final OTA performance requirements rather than the component-level requirements to ensure that OTA objectives were achieved.

The Investigation Board focused on the development and manufacture of the Refractive, Reflective, and Inverse Null Correctors (INC); and interferograms associated with the grinding/polishing of the primary mirror and Null Correctors. The Null Correctors were designed to achieve specific goals during the two manufacturing phases of the primary mirror. The Refractive Null Corrector was designed to provide a sufficient level of accuracy to meet the objectives of the Phase I grinding and polishing efforts; i.e., to achieve a surface figure equivalent to one wavelength RMS. The basic concept used in the design of the Refractive Null Corrector could not achieve the desired OTA quality level. Therefore, the Reflective Null Corrector was designed to achieve the final surface figure. The INC originally was designed as a calibrator in conjunction with the Reflective Null Corrector. Its purpose was to simulate the primary mirror in the optical path to check either the Reflective Null Corrector or the Refractive Null Corrector. In actual use, the INC functioned as an alignment monitor between the interferometer and the Reflective Null Corrector. The INC never was used in conjunction with the Refractive Null Corrector because it was attached to the base of the Reflective Null Corrector.

7.1 Refractive Null Corrector

The Refractive Null Corrector was used to measure the primary mirror surface figure at the end of Phase I, which was the initial grinding operation at the Wilton facility. The series of measurements confirmed that the surface figure was better than one wavelength. The Refractive Null Corrector also was used to measure the vertex radius at the end of Phase II, which was the final grinding/polishing operation at the Danbury facility. The testimony of the inspectors who witnessed the assembly and signed the inspection sheets, in conjunction with a review of engineering records, indicate that the Refractive Null Corrector was built and certified by the standard Wilton QA process. A slight error in the design of this Corrector that would produce a small amount of fifth-order spherical aberration was confirmed during the current investigation, although the amount is within the design error budgets.

7.2 Reflective Null Corrector

The HST Reflective Null Corrector was based on the existing P-E 60-inch mirror Reflective Null Corrector program. The design objectives and priorities established for the 60-inch Reflective Null Corrector incorporated the concerns relative to the stability and alignment of the components for extended periods under varying environmental conditions. A P-E memorandum (Ref. 15) addressing the design of the Reflective Null Corrector stated:

> "Precision of optical performance must be given the highest priority.....this assembly will be used for the manufacture and inspection of optical components where size and figure tolerance represent the limits of the state-of-the-art. The part of the total error budget that can be assigned to the null corrector must be held to a practical minimum in order that the greatest part of the error budget can be assigned to the critical manufacturing operations.
>
> Stability of optical performance is essential in order that precise optical performance be maintained under all required environmental conditions.

Stability is particularly important in this application because optical performance of the complete assembly cannot be periodically verified by a single test. The performance must be certified by evaluation of separate optical components and monitoring critical alignment procedures under laboratory conditions. Once certified, it is essential that optical performance remain within tolerance within the period of performance under all environmental conditions."

The emphasis on solving the precision design problems as reflected in the careful selection of manufacturing sequences for the original 60-inch Reflective Null Corrector, indicated that the design engineers understood the criticality of optical performance. The QA/build records are available for the 60-inch Null Corrector, which was built with P-E internal Independent Research and Development (IR&D) funds. The detailed build records indicate that a standard QA process was implemented.

The decision was made to develop the HST Reflective Null Corrector by modifying the 60-inch Null Corrector. The HST modifications included: a) building a new field lens; and b) changing the spacing parameters for the Coaxial Reference Interferometer (CORI)-to-upper mirror spacing, upper-to-lower mirror spacing, field lens-to-lower mirror spacing, and new field lens. The original 60-inch design analysis indicated that these modifications could be accomplished with few significant changes to the existing hardware.

In performing the modifications and in particular, the field lens-to-lower mirror spacing, mispositioning of the field lens (commonly referred to as the despace error) occurred. The despace resulted from an inaccurate interferometric measurement because the spherical wave interferometer was focused on an end cap placed over the end of a field lens spacing rod, rather than on the end of the rod itself. The technique using the spacing rod precluded repeated measurements without altering component alignment, since either the field lens or the interferometer had to be removed to extract the spacing rod from the assembly.

Validation/certification procedures for the HST Reflective Null Corrector were documented in PR-237B, Test Configuration Report for Phase II Manufacture of Space Telescope Primary Mirror, which was released in June 1983. Paragraph 4.2.2.6.2, Reflective Null Corrector, stated in part:

"The reflective null corrector was certified by measurement of its components, the field lens and the two null mirrors, and the assembly parameters. This was necessary since null correctors in general cannot be tested as functional units. The reflective design, however, allowed in situ testing of the critical elements."

Lab notes and other documentation of the final assembly process indicated a rigorous effort by the optic engineers to check and cross-check each measurement to eliminate alignment and spacing errors. There is no evidence that either an in-situ or a total end-to-end test of the Reflective Null Corrector was performed. In addition, there is no documentation of a quantitative certification of the Null Corrector hardware. Since the Reflective Null Corrector was the only test device used to accept the primary mirror figure, it should have been certified by an independent or second non-interferometric method such as a Hartmann test as noted by a 1981 P-E Audit Team.

The HST Reflective Null Corrector was used to measure the surface figure at the start and end of Phase II at Danbury, and was the final determiner (measuring device) for acceptance of the primary mirror surface figure. It also was used as an intermediate and in-process check of this mirror figure during the final polishing phase (Phase II) and was the actual source of data inputted to the automated CCP.

7.3 Inverse Null Corrector

The INC apparently had been intended by engineering (according to Abe Offner) to be used as a partial in-situ calibrator of the overall Reflective Null Corrector test system, but never was used for this purpose. It only was used as an alignment monitoring device (Ref. 16). No specific reasons were given as to why the INC was used only as an alignment monitoring device, and the overall pedigree of the device could not be determined from the documentation. Unverifiable testimony raised concerns about a possible dimensional error and/or a possible remelt condition affecting one of the optic elements. During the current investigation, an error in the design calculations was discovered that produced a small amount of spherical aberration in the INC. In comparing the interferogram data between the Reflective Null Corrector and the combination of the Reflective Null Corrector and the INC, the difference in the amount of spherical aberration noted was due to the calculation-based error. Like the Refractive Null Corrector, this unit produced interferograms that indicated possible evidence of a basic problem that never was pursued in detail.

7.4 Cross-checks of Conflicting Interferograms

The use of the INC illustrates the lack of a definitive test plan that would have correlated and defined more precisely the interrelationships of the various test elements (Refractive Null Corrector, Reflective Null Corrector, INC, vertex radius measurements, and others). This plan also should have interrelated the various tests to confirm the secondary mirror performance. The elaborate error budget system employed by P-E is an adjunct to test planning but does not represent an adequate plan. The Primary Mirror Phase II Metrology Test Plan, PR-235, is at best a cursory overview of the testing during the polishing phase. PR-237B, Test Configuration Report for Phase II Manufacture of Space Telescope Primary Mirror, dated June 1983, was essentially an as-run test plan that used the error budget as its primary integrating device.

In discussions of why so little credence was placed in the apparent contradictory interferograms taken with the Refractive Null Corrector, the primary thesis given in the testimony was that they had absolute confidence in the pedigree of the Reflective Null Corrector and considerably less in the Refractive unit. Intensive review of the data could not substantiate either of these statements. The lack of formal evidence would seem to indicate that by normal aerospace standards, neither unit had an acceptable pedigree. The formal reports (PR-235 and PR-237B), using references to the 60-inch program to document the pedigree of the HST Reflective Null Corrector, lacked sufficient detail to serve as certification papers.

When the decision was made to modify the 60-inch Corrector for use on the HST primary mirror, the as-built unit should have been formally certified by the quality organization. The design modification may have been done via redlining the 60-inch drawings, since no formally released drawings has ever been found. The investigation found that Wilton QA only participated in rebuilding the Reflective Null Corrector at the component-level involving spacing rods and the field lens assembly.

An optical-based verification/certification test plan for programs of similar size to the HST typically include error budget-driven optical acceptance criteria. The criteria are used to cross-check interferogram data from Null Corrector tests within the tolerances imposed by the error budgets. Without cross-checking the data, the optical engineers missed a series of key indicators (warning flags) that should have evolved from comparisons of interferograms such as:

- Phase I Refractive Null Corrector data compared to initial Phase II Reflective Null Corrector data
- Phase II Reflective Null Corrector data compared to Refractive Null Corrector vertex radius test results
- Data from the Inverse Null Corrector combined with the Reflective Null Corrector compared to Reflective Null Corrector data only

Thus, there are no formal quantitative data to support the pedigree of the Null Correctors. The confidence about the accuracy and pedigree of the Reflective Null Corrector as expressed in witness testimony may be due to the entire design and build operation having involved only a small engineering team who had total confidence in each other's ability to ensure final product quality. In its oversight capacity, NASA S&E (optics) personnel could have imposed the cross-comparison criteria as a requirement for this team to ensure hardware adequacy; particularly since only the Reflective Null Corrector data were used to define the end-item figure quality. An alternative might have been to use round-robin null testing with a common Inverse Null Corrector between Perkin-Elmer and Eastman Kodak.

8. LESSONS LEARNED - RECOMMENDATIONS

As a result of the findings and observations during the investigation, several SRM&QA lessons have been learned relative to the HST Program:

Finding: The on-site representatives for the NASA and P-E QA organizations were not specifically trained in optics that would have enabled them to provide an informed and independent evaluation of the assembly and manufacturing operations.

Recommendation: The NASA SRM&QA organizations should augment their staff to provide independent expertise in special technical areas (such as optics technology) where major program objectives are at stake.

Finding: NASA oversight of critical optical component design/development and manufacture was deferred to Perkin-Elmer, and critical reviews during these phases failed to identify major data anomalies.

Recommendations: NASA should maintain active oversight of all critical program elements, and should ensure that critical review processes are conducted in strict compliance with NASA contractual requirements (Plans, Handbooks, etc.).

Finding: The basic Product Assurance requirements and formal review processes were in place but lacked the control or follow-up to ensure closure of all problems/issues/concerns.

Recommendation: The formal program reviews and SRM&QA survey processes should require the inclusion of a thorough, closed-loop system for resolution of Review Item Discrepancies (RIDs) and Nonconformance Reports.

Finding: Denial of access to critical metrology areas prevented proper QA oversight: final signature authority for QA was subsumed by engineering.

Recommendation: QA organizations with signature responsibility for ensuring that SRM&QA requirements are satisfied for final acceptance of critical components should have full access to the all critical operations.

Recommendation: The QA oversight should be a separate function from program and engineering management.

Finding: The HST Program lacked: 1) an independent second means of final testing each critical component and 2) a complete end-to-end test of the optical system. Either of these independent tests would have surfaced the spherical aberration.

Recommendation: NASA should impose a requirement on each program to incorporate independent means of testing components that define critical performance parameters. Full-up (end-to-end) testing is particularly desireable where individually developed components/modules must be mated for the first time at final assembly (or on-orbit).

Finding: NASA focused its resources on systems integration and guidance control systems, which were considered to be more susceptible to anomalies that could adversely impact on-orbit HST operation. Conversely, the design/manufacture of large mirrors for space applications was considered to be well within the scope of existing state-of-the-art optical technology.

Recommendation: In making the inevitable trade-offs relative to resource allocation, NASA program management must consider the long-range operational impact of each critical program element.

Finding: Lack of complete data seriously hinders relatively long-term investigations (such as for the HST aberration), and renders rapid support for in-flight anomalies virtually impossible.

Recommendation: NASA QA organizations should develop more stringent requirements for the data management. Specifically, critical data should be formally collected, indexed, and stored at regular review intervals for access by both NASA and the contractor.

Finding: For large-scale, complex programs (such as the HST), if system specification compliance and validation requirements are focused at the component level only rather than looking at the components as part of the overall system, then the formal validation of the system may be flawed.

Recommendation: More attention must be placed on detailed specification compliance and validation of the overall system as part of its formal acceptance. Incumbent to this is a detailed test plan that specifically traces the validation of all performance parameters.

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3. Perkin-Elmer memorandum from G. Rogers/A. Slomba to L. Montagnino, dated June 5, 1980 (Log #102); Subj: *Final Test Sequence on ST Primary Mirror.*

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15. Perkin-Elmer memorandum #74-SS-1675, from W. E. Kohman to L. Montagnino; Subj: *Design - Reflective Null Corrector Assembly*; dated November 20, 1974.

16. Perkin-Elmer memorandum, from Chuck Robbert to Sid Greenspan; Subj: *Fabrication Guidelines for ST Inverse Null Corrector Components*; dated October 12, 1979.

[Note that this report makes full use of the HST documentation obtained during the formal investigation. The documents provided in the appendices of this report also contain numerous references to material used.]