United States General Accounting Office

GAO

Report to the Chairman, Subcommittee on Science, Technology, and Space, Committee on Commerce, Science, and Transportation, U.S. Senate

September 1991

SPACE PROJECT TESTING

Uniform Policies and Added Controls Would Strengthen Testing Activities

GAO/NSIAD-91-248

GAO

United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

B-245141

September 16, 1991

The Honorable Albert Gore, Jr.
Chairman, Subcommittee on Science,
Technology, and Space
Committee on Commerce, Science,
and Transportation
United States Senate

Dear Mr. Chairman:

As requested, we reviewed the National Aeronautics and Space Administration's (NASA) testing activities. Specifically, we assessed the adequacy of NASA's testing policies and practices, NASA's oversight of contractor testing, and the adequacy of resources available for testing.

We are recommending that the NASA Administrator (1) issue testing policies defining NASA's testing goals, establishing minimum requirements, and specifying organizational roles and responsibilities for ensuring that tests are properly planned, conducted, and reported; (2) develop agencywide test standards; and (3) make specific improvements in oversight of contractor testing.

Unless you publicly announce its contents earlier, we plan no further distribution of this report until 30 days after its issue date. At that time, we will send copies of the report to the Administrator, NASA, and appropriate congressional committees. Copies will also be made available to others on request.

Please contact me on (202) 275-5140 if you or your staff have any questions concerning this report. The major contributors to the report are listed in appendix II.

Sincerely yours,

Mark E. Gebicke

Mark E. Gebicke
Director, NASA Issues

Executive Summary

Purpose

In April 1990, NASA deployed its $1.5 billion Hubble Space Telescope to an orbit 380 miles above the earth. Soon after, the agency discovered that the telescope's primary mirror was manufactured in the wrong shape, severely degrading its scientific capabilities. The flaw was not detected before the telescope was launched because the mirror was not adequately tested.

The Chairman, Subcommittee on Science, Technology and Space, Senate Committee on Commerce, Science, and Transportation, asked GAO to review NASA's testing activities. Specifically, GAO's objectives were to assess the adequacy of testing policies and practices and the agency's oversight of contractor testing and to determine whether sufficient resources existed for testing.

Background

Because space missions are inherently risky, systems cannot be easily repaired while in orbit, and failures are widely publicized, it is especially important that the systems' performance be thoroughly tested before launch. These complex systems are usually acquired in very limited quantities, and test programs are specifically tailored for each project.

According to a NASA team appointed to investigate the Hubble failure, mirror tests were inadequately planned and poorly analyzed. The team further noted that NASA did not provide adequate oversight of the contractor's test program.

Results in Brief

Testing has varied from project to project. The success of many of NASA's recent space projects indicates that, in many cases, testing was adequate. Tests were not effective, however, in detecting the Hubble mirror flaw. In other cases, launch schedules have been adversely affected because tests did not identify problems soon enough.

Testing practices vary because NASA has no uniform policies governing testing. Existing guidance is fragmented, not well defined, and varies from one NASA field center to another. In some cases, hardware designed for the same mission may be tested to different standards.

All centers have oversight controls to help ensure that contractors properly plan and conduct tests and report the results. Controls at some centers, however, could be further strengthened. Also, according to a recent National Academy of Public Administration study, NASA needs to retain more of its research and development work in-house to give civil service personnel the experience necessary to adequately oversee agency contractors.

No standard exists for determining the amount of resources that should be devoted to testing, but according to NASA officials, resources are normally sufficient to conduct essential tests. However, project managers must sometimes make cost-risk tradeoffs when defining the scope and extent of testing programs. Further, some in-house test facilities and equipment need upgrading.

GAO's Analysis

Testing Effectiveness Varies

An effective test program demonstrates the capability of a space system to perform its intended function under realistic environments and identifies problems early so that corrective action can be taken. Many of NASA's recent space projects have accomplished or are expected to accomplish their mission objectives. In those cases, GAO can conclude that the tests have been adequate. For example, of the 10 NASA-developed payloads placed in orbit between January 1986 and December 1990, 7 have met their initial mission objectives. One of the 10 has not been in orbit long enough to accomplish its objective and the remaining two—the Hubble telescope and the Astro-1 payload—experienced mission-limiting failures. In some cases, however, tests have not revealed problems early enough. For example, launch of a 1990 shuttle mission was delayed by over 4 months because earlier acceptance tests did not identify defects in seals where the external tank and orbiter fuel lines join.

Testing Guidance Is Inadequate

NASA does not have uniform, agencywide policy guidance for testing space systems. Testing policies and procedures are contained in various documents relating to specific programs or activities, and field centers have developed their own policies and procedures. As a result, the guidance is fragmented and not well defined. For example, current policies do not require a comprehensive test plan on each project to (1) show how performance requirements are to be validated, (2) define responsibilities for testing, and (3) identify any limitations in the testing program. Because testing criteria differ from center to center, hardware designed for the same mission may be tested to different standards. For example, until recently, the four centers developing space station hardware each planned to use its own testing standards on that program.

NASA's Office of Safety and Mission Quality has recognized the need for additional testing guidance and is taking action to provide it. The Office is drafting a policy statement on mission quality that will require comprehensive test plans and will better define roles and responsibilities for assuring mission quality. The Office has also established a technical standards division to work toward agencywide test standards.

Improved Contractor Oversight Is Possible

Most civilian space systems are designed and built by aerospace firms under contract to NASA. For the most part, the contractors plan, conduct, and interpret the results of tests. In this environment, a high degree of oversight of contractor testing activities is needed. NASA field centers have developed various oversight controls, which are implemented differently at each center. Oversight controls are stronger when NASA (1) approves contractor-prepared plans and procedures for all critical tests, (2) conducts independent reviews of testing on major programs, and (3) provides adequate staff with the requisite skills to monitor contractor testing.

A January 1991 report by a panel of the National Academy of Public Administration concluded that hands-on experience in designing, fabricating, and testing space systems was essential to developing scientists and engineers with the level of knowledge needed to adequately oversee contractors. According to the study, which consisted primarily of interviews with NASA managers, scientists, and engineers, the agency should retain more of its research and development work in-house to provide the needed hands-on opportunities. NASA's Associate Deputy Administrator told GAO that the agency concurs in the need for hands-on opportunities and will take that need into consideration when deciding whether to contract out a space project or develop it in-house. Also, NASA has asked to convert some positions from support contractor to civil service in order to perform more work in-house.

Resource Limits Have Not Precluded Essential Tests

Officials at all five field centers GAO visited said that sufficient resources are available to perform essential tests. On six of eight projects GAO examined, officials said that funding limits did not constrain the amount or scope of testing. In the remaining two cases, officials said that testing was constrained primarily because project funds were not available for proof test models or prototypes. In those cases, tests were conducted under less demanding conditions to avoid damaging the actual flight hardware. According to these officials, the tests provided less confidence in design margins. Officials at several centers also told us that staffing limits and old and outdated facilities and equipment caused delays and increased costs for some tests conducted in-house.

Recommendations

GAO recommends that the NASA Administrator issue testing policies that define NASA's testing goals, establish agencywide minimum requirements for space system test programs, and define organizational roles and responsibilities for ensuring that tests are properly planned and conducted and the results accurately reported. The policy should require each project to have a comprehensive test plan that includes (1) the means to be used for validating each performance requirement; (2) the controls established to ensure that validation activities are properly planned, conducted, and reported; and (3) the disclosure of any significant testing limitations and actions taken to reduce increased technical risks associated with the limitations.

GAO also recommends that NASA develop agencywide test standards to ensure consistent qualification and acceptance testing for all space hardware.

GAO further recommends that NASA require all of its field centers to (1) approve all contractor-prepared test plans and procedures for critical tests, (2) implement procedures for independent reviews of testing on all major programs, and (3) review its space projects to ensure that adequate personnel with needed skills are available to monitor critical contractor tests.

Agency Comments

NASA agreed that it needs an overall testing policy and noted initiatives to address test differences among its field centers and the development of agencywide test standards. NASA also generally agreed with GAO's observations and said that several actions have already been initiated within the agency to effect the recommendations but NASA did not specifically comment on each recommendation.

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Abbreviations

GAO	General Accounting Office
NASA	National Aeronautics and Space Administration

Introduction

Importance of Testing

Because space missions are carried out in the public spotlight, any failures are magnified. Thus, the objective of the National Aeronautics and Space Administration (NASA) is to achieve a 100-percent mission success rate, according to the Associate Administrator for Safety and Mission Quality. According to the Commission on the Future of the U.S. Space Program, "there can be no acceptable objective among those who would challenge the vastness of space other than perfection."[1]

Unfortunately, as the Commission's report points out, the objective of perfection is not readily met, especially since space missions, whether manned or unmanned, are fundamentally difficult and demanding undertakings that depend upon some of the world's most advanced technology and opportunities for error are formidable. For example, the Saturn V rocket required the integration of some six million components manufactured by thousands of separate contractors. Processing a Space Shuttle for flight requires the accomplishment of 1.2 million separate procedures.

To ensure that space systems can accomplish their intended missions, their performance should be thoroughly tested before launch. The purpose of testing is to gain confidence that the systems will operate properly in their intended environments.

An effective testing program is especially important for space systems since spacecraft with flaws cannot be easily repaired once they are launched. According to a Marshall Space Flight Center handbook on project management, the testing philosophy should be based on the idea that failures on the ground are usually much less costly to correct than those in flight.

Tests should be directed toward (1) verifying the capability of the design, (2) evaluating the susceptibility of the hardware and software to failure, (3) verifying the adequacy of workmanship, and (4) validating the ability of the hardware and software to function together to accomplish mission requirements. Each performance requirement should be validated through tests or analyses, but according to NASA, testing is the preferred method of verifying space system performance.

Limits of Testing

While important, testing cannot be relied upon to identify all possible problems in space systems design and operation. Tests must be used in

[1] Report of the Advisory Committee on the Future of the U.S. Space Program, Dec. 1990.

conjunction with other systems engineering activities. When testing is not feasible due to cost, time, complexity, or other factors, performance should be verified by analyses or a combination of test and analyses. An analysis is a technical evaluation that uses a mathematical model to predict performance. To the extent possible the model should be validated by test data.

A 1984 study of in-flight satellite failures by the Goddard Space Flight Center concluded that only about 56 percent of the failures could have been caught in the test program; the remaining 44 percent had little chance of being detected in tests. The undetected failures would have to be found and corrected during the design review process, according to the study.

The Deputy Director of Goddard's Flight Assurance Office told us that failure of that center's Solar Maximum Mission spacecraft in 1981 could not have been predicted or prevented by a test program of any reasonable length. Satellite fuses malfunctioned earlier than expected due to an inadequate electrical system design. However, according to a Goddard analysis, about 9 or 10 months of continuous ground testing would have been necessary to detect the failure.

In some cases, it is not possible to achieve test conditions on earth that duplicate the space environment. In other cases, testing could pose unacceptable risks to the flight system. For example, it is not always possible to test deployment of spacecraft antenna and solar arrays in ground tests because of limitations in simulating a microgravity environment. Unfurling the arrays in earth's gravity could cause them to break.

Types of Tests

The test program for a typical hardware component, subsystem, and system begins with development testing, normally at the component level, progresses through qualification testing of both components and systems, the most rigorous step, and ends with acceptance testing.

The purpose of development testing is to determine the viability and value of continued work on a new or modified design approach. These tests are relatively inexpensive and make use of replicas, subscale or mock-up hardware.

The purpose of qualification testing is to ensure that the hardware component, subsystem, or system functions in accordance with its performance specification. These tests are usually conducted under simulated launch and space operating environments. To reveal deficiencies in design and methods of manufacture, qualification tests are usually conducted under environmental conditions that are even more severe than those expected to be encountered in launch and orbital operations.

Acceptance testing, typically a less exhaustive version of qualification tests, is to demonstrate that the hardware is acceptable for flight. The process also serves as a quality control screen to detect deficiencies and, normally, to provide the basis for delivery of an item under terms of a contract. Environmental conditions used in the tests generally do not exceed those expected to be encountered in the mission.

When a "protoflight" approach is used, elements of qualification and acceptance tests are combined. Under the protoflight approach, qualification test hardware is refurbished and used as the flight article.

Tests may be performed at all levels of assembly from components such as transmitters and batteries, to entire systems. A test of the entire system is called an "end-to-end" test. End-to-end tests are performed on an integrated ground and flight system to demonstrate that it can fulfill all mission requirements and objectives.

Figure 1.1 shows testing of the water recovery systems for Space Station Freedom.

Figure 1.1: Space Station Freedom Water Recovery Systems Testing

Source: National Aeronautics and Space Administration

When NASA contracts for the design and development of a space project, the contractor typically plans, conducts, and interprets the tests. When NASA develops a project in-house, the responsible NASA field centers also conduct the test program.

Testing Programs Must Be Tailored

Space flight hardware is almost always unique and acquired in very limited quantities. Therefore, testing approaches developed for mass-produced items and weapons are not applicable. A testing program must be specifically tailored for each space system.

Cost and risk are the basic variables in defining a testing program. Costs for testing increase inversely with the acceptable risk or probability of failure. Recognizing this principle, NASA has established four classes of payloads based on the degree of acceptability of mission failure. Payload class is determined by factors such as cost, complexity, mission priority, and the ability to recover from in-flight failures.

Class A payloads are those for which all affordable measures are taken to achieve minimum risk. The highest practical product assurance standards are to be used on these spacecraft. Class A payloads are characterized by high national prestige, long hardware life, high complexity, high cost. Usually the payload cannot be recovered or repaired if problems occur after it is launched. The Hubble Space Telescope, Magellan mission to Venus, and the Galileo mission to Jupiter are all class A payloads.

Class B payloads are those for which compromises are permitted to reduce costs while still maintaining a low risk to the overall mission success and a medium risk of achieving only a partial mission success. Class B payloads are characterized by high priority, high cost, medium hardware life, and high to medium complexity. Class B payloads usually can be retrieved or repaired in-flight if problems occur, although the repairs may be costly and difficult to accomplish. The Gamma Ray Observatory, launched in April 1991 to study the universe in an invisible, high-energy form of light known as gamma rays, is a class B payload.

Class C payloads are those for which a moderate risk of not achieving mission success is accepted to permit significant cost savings. Class C payloads are characterized by medium cost, short program duration, and the ability to retrieve the payload and fly it again later, or perform in-orbit maintenance if it fails. The tethered satellite system, a reusable satellite that can be extended on a tether from the shuttle to study the earth's upper atmosphere is a class C payload.

Class D payloads are those for which a significant risk of mission failure is accepted to permit minimum costs. Class D payloads are characterized by low cost, low complexity, and the ability to retrieve them or repeat the mission if they fail. Experiments launched on suborbital rockets are typically class D payloads.

According to payload classification guidelines, test programs should be tailored to the payload class. For example, separate test and flight hardware is suggested for class A payloads, while protoflight hardware is suggested for other payload classes.

Roles and Responsibilities

NASA headquarters program offices are responsible for assigning the class designation for each payload or payload element. Headquarters program offices are also responsible for establishing a set of mission success criteria for each payload.

NASA project managers are the key individuals charged with the development of space systems. The project manager is responsible for the planning and implementation of project resources, schedule, and performance objectives. The project manager plans, organizes, staffs, directs, and controls all project activities. Project managers are responsible for defining or approving test programs for their systems.

NASA's Office of Safety and Mission Quality[2] and its field center safety and mission quality organizations are responsible for ensuring that safety, reliability, maintainability, and quality assurance policies, plans, procedures, and standards are established. It is also responsible for monitoring the status of equipment, software, validation of design, problem analyses, and system acceptability.

Most civilian space systems are designed and developed by private firms under contract to NASA. Historically, NASA contracts out between 85 and 90 percent of its congressionally approved annual budget. NASA's fiscal year 1989 contracts, for example, were over $10 billion—88 cents of every dollar appropriated. Within NASA guidance, contractors plan, conduct, and interpret almost all tests. NASA provides oversight by reviewing test plans and results and, in some cases, monitoring the tests.

[2]This office was formerly known as the Office of Safety, Reliability, Maintainability, and Quality Assurance.

Hubble Space Telescope Investigation Results

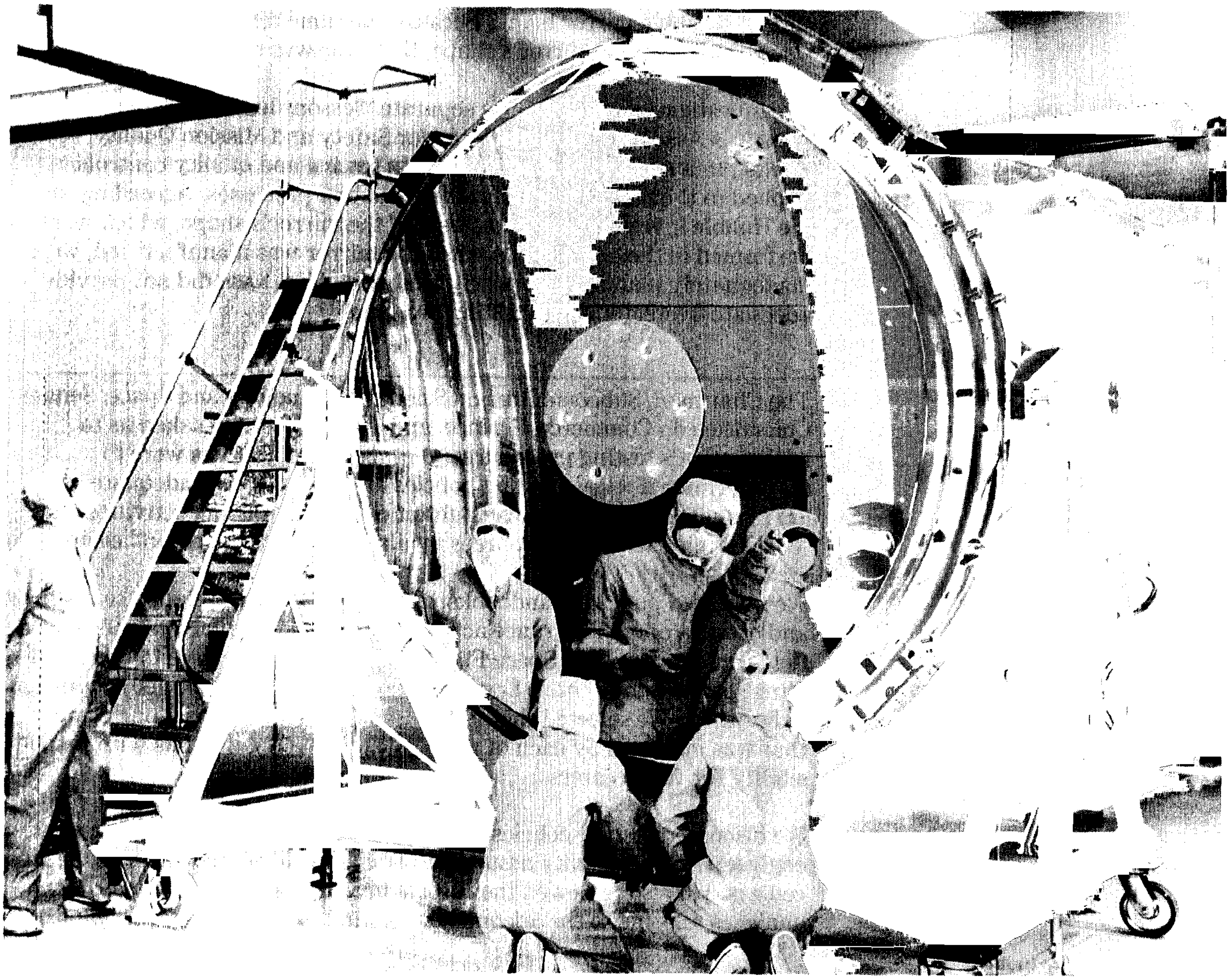
On April 24, 1990, after over 12 years of design, development, and test, NASA launched the Hubble Space Telescope. The observatory, estimated to cost over $1.5 billion was to use a 2.4 meter primary mirror to focus light onto scientific instruments such as cameras and spectrographs.[3] The Hubble, orbiting about 380 miles above the earth, was designed to see objects 7 times farther away and 50 times fainter than any existing ground-based telescope.

Approximately 2 months after launch, on June 21, 1990, the Hubble Space Telescope Project Manager announced that there was a major flaw in one or both of the telescope's mirrors. A team appointed by NASA's Associate Administrator for Space Science and Applications to investigate the problem, found that the telescope's primary mirror was manufactured in an incorrect curvature or shape.

Figure 1.2 shows the telescope's primary mirror immediately after it was coated at the contractor's manufacturing facility.

[3]A spectrograph is an instrument that separates light into various bandwidths or colors and records the result.

Figure 1.2: Hubble Space Telescope Primary Mirror



Source: National Aeronautics and Space Administration

According to the investigation team, the mirror was manufactured incorrectly because a reflective null corrector—the instrument used both to guide the processes for shaping the mirror and to test its shape—was itself incorrectly assembled.[4] Because the reflective null

[4]A null corrector is a device that projects the desired shape onto a mirror blank.

corrector was improperly assembled, it projected an incorrect shape onto the Hubble mirror blank. Because the same reflective null corrector was used to test the mirror's shape, the error was not detected.

The investigation report and a separate "lessons learned" report issued by NASA's Associate Administrator for Safety and Mission Quality pointed to a number of inadequacies in testing and quality controls applied to the mirror manufacturing and test processes. According to the Hubble investigation team, tests of the mirror's shape, which were performed in the early 1980s when the mirror was manufactured, were inadequately planned and poorly analyzed. Also, NASA did not provide adequate oversight of the testing program.

Objectives, Scope, and Methodology

The Chairman, Subcommittee on Science, Technology and Space, Senate Committee on Commerce, Science, and Transportation, asked us to review NASA's testing procedures. Our specific objectives were to (1) determine if NASA's testing policies and practices are adequate (2) evaluate the agency's oversight of contractor testing activities; and (3) determine whether resources available for testing are sufficient.

We reviewed policies, handbooks, and other guidance relating to testing and other product assurance activities at NASA headquarters and five field centers: Marshall Space Flight Center, Johnson Space Center, Goddard Space Flight Center, Lewis Research Center, and the Jet Propulsion Laboratory. We selected the five centers to include at least one center that was managed by each of NASA's headquarters divisions with responsibility for field centers.

We discussed testing policies and practices with program management, engineering, and quality assurance officials at headquarters and the five centers. We also reviewed the Hubble investigation report and other analyses relating to the adequacy of testing.

To help determine how NASA assures that performance requirements are verified on space systems before they are launched, we reviewed test plans and activities on specific projects at each of the five field centers. These projects were the Aeroassist Flight Experiment and Space Shuttle Main Engine Alternate Turbopump Development at Marshall; the Upper Atmosphere Research Satellite at Goddard; the Extravehicular Activity Development Flight Experiments at Johnson; the Galileo program at the Jet Propulsion Laboratory; and the Advanced Communications Technology Satellite project at Lewis.

In assessing the adequacy of testing resources, we relied primarily on the opinions of NASA field center personnel since there is no criteria for how much money should be spent on a test program. We asked the centers to provide their assessments of the impact of resource constraints on testing in general and the effects of any resource constraints on eight specific projects. The eight projects included the six previously listed, the Magellan mission to Venus, and an upgraded version of the Hubble telescope's wide field planetary camera. We did not verify the centers' assessments.

We performed our review from August 1990 through May 1991 in accordance with generally accepted government auditing standards.

Uniform Testing Guidance Is Needed

NASA testing practices and their adequacy vary from project to project. While the success of many recent flight programs indicates that much of the testing is adequate, in some cases tests have not revealed problems early enough in the development process to prevent schedule problems.

NASA does not have uniform, agencywide policies, procedures, and standards to guide its field centers' testing programs. Policies and other testing guidance are contained in various documents, some of which are limited to certain programs and activities. As a result, guidance is fragmented and not well defined.

Field centers have developed their own policies, procedures, and standards. Some centers have more comprehensive guidance than others, and policies and standards vary from one center to another. As a result, hardware intended for the same space mission may be tested using different criteria.

NASA has recognized the need for agencywide guidance and has initiated efforts to provide it.

Adequacy of Testing Varies From Project to Project

According to NASA, the purpose of testing is to identify design and workmanship deficiencies as early as possible and to demonstrate that the system will operate properly in space. As a Marshall Space Flight Center manual on project management points out, the ultimate test of a system is its performance in space. Thus, one measure of the adequacy of testing is whether or not the space system accomplishes its intended mission.

Table 2.1 shows that most of the NASA-developed payloads placed in orbit between January 1986 and December 1990 have achieved their original mission objectives.

Table 2.1: NASA-Developed Payloads Launched January 1986 - December 1990[a]

		Original mission objectives		
Launch date	Payload	Achieved	Not achieved	Pending
9-17-86	National Oceanic and Atmospheric Satellite-G[b]	X		
2-26-87	Geostationary Operational Environmental Satellite-7[b]	X		
9-24-88	National Oceanic and Atmospheric Administration-H[b]	X		
9-29-88	Tracking and Data Relay Satellite System-C	X		
3-13-89	Tracking and Data Relay Satellite System-D	X		
5-04-89	Magellan	X		
10-18-89	Galileo			X
11-18-89	Cosmic Background Explorer	X		
4-24-90	Hubble Space Telescope		X	
12-02-90	Astrophysics Spacelab-1		X	

[a]Does not include the joint NASA-European Ulysses and Rosat missions because those payloads were developed primarily by the European Space Agency.

[b]These weather satellites were developed by NASA for the National Oceanic and Atmospheric Administration.

Seven of the 10 payloads had achieved all of their initial mission objectives by June 1991. For example, the objective of the Magellan mission launched in May 1989 was to map 70 percent of the surface of Venus. That objective was met in May 1991, and the mission was extended to map the remainder of the planet.

The Galileo mission has not been launched long enough to have accomplished its objective. The Galileo spacecraft, on a mission to Jupiter, has experienced problems with its high gain antenna which, if not corrected, will severely limit the amount of data that can be transmitted from Jupiter and could preclude the satellite from achieving its mission. However, NASA is optimistic that the problem can be resolved and that the satellite will accomplish its mission objective.

The remaining two payloads—the Hubble Space Telescope and the Astro-1 mission—both experienced mission-limiting failures. The Hubble mirror problem restricts the telescope's ability to see faint and low contrast objects. The objective of the Astro-1 mission was to observe more than 200 astronomical objects in the ultraviolet and x-ray wavelengths. Because of operational and pointing system problems, only about 68 percent of the planned 200 targets were observed.

Even though many of the space systems have accomplished their missions, several have experienced in-orbit problems. For example, one of three gyroscopes used in the guidance and control system of the Cosmic Background Explorer spacecraft failed about 5 days after launch. The disabled gyroscope, however, did not keep the spacecraft from accomplishing its mission of mapping cosmic background radiation with which to study the origin and dynamics of the universe, especially the "Big Bang" theory. NASA has not analyzed all in-flight problems to determine the extent to which inadequate testing contributed to the problems.

In some cases, tests have not detected problems early enough to prevent costly schedule slips. For example, a flight of the Shuttle Atlantis was delayed from July 9, 1990, to November 15, 1990, because tests at the launch pad detected a dangerous hydrogen leak from a defective seal where the external tank and orbiter fuel lines join. The defective seal was not discovered in earlier acceptance tests, and NASA subsequently concluded that the acceptance tests were not sufficiently realistic. A major reason for this conclusion was that NASA used liquid nitrogen instead of hydrogen to test the components. The nitrogen did not cool the metal and seals sufficiently to detect possible leaks. According to a Johnson Space Center official, NASA has recently revised the acceptance test criteria to address these deficiencies and is conducting new tests of existing seals.

In another instance, a flight of the Shuttle Columbia was delayed for about a week in May 1991, when NASA became aware of structural cracks in temperature probes within the vehicle's main propulsion system. Investigation revealed that the probe's design was defective and susceptible to cracking. According to the manager of the shuttle orbiter engineering office at the Johnson Space Center, testing to qualify the probe's design did not reveal the problem because the tests were not conducted at the cold temperatures indicative of their actual operating environment. Subsequent investigation revealed cracks in probes installed in two other shuttle vehicles, indicating that shuttles had flown with cracked probes. The probes could have broken off and contaminated turbopumps in the shuttle's main engines.

Also, according to the contractor developing instruments for a new generation of weather satellites, technical problems on that program could have been detected and resolved earlier and at less cost if the project had built and tested engineering models early in the program. The weather satellite program is about 3 years behind schedule.

Current Policy Guidance Is Fragmented and Not Well Defined

NASA does not have uniform, agencywide policy guidance for testing space projects. Some testing guidance is contained in documents that prescribe reliability and quality assurance policies for contractors. In some cases, programs such as the Space Transportation System and the Space Station Freedom have developed their own testing policies and guidance. No policies currently exist to guide NASA's involvement in the testing of commercially developed, expendable launch vehicles and upper stages.

Current policies do not (1) adequately define NASA's testing goals, (2) require test plans showing that all critical aspects of performance are systematically validated, or (3) define roles and responsibilities for assuring that tests are properly planned, conducted, and reported.

Testing Goals Not Defined

Because NASA has no agencywide testing policies, it has not adequately defined its testing goals. According to the Associate Administrator for Safety and Mission Quality, NASA's available testing guidance does not properly define the agency's quality objectives or provide an overall policy to link available tools and techniques for use to meet the objectives. For example, NASA does not currently require end-to-end tests of space systems or major subsystems before launch or some means of independently testing all of the components that define critical system performance parameters. According to the Hubble investigation team, either of these would have surfaced the defect in the telescope's mirror. All five field centers we visited expressed a preference for end-to-end testing. Center officials told us that end-to-end tests are performed whenever feasible, but only one center had a written policy requiring such tests.

Comprehensive Test Plans Not Required

NASA does not currently require that each project have a comprehensive test plan showing how performance requirements will be validated or specify the content of test plans. We believe that comprehensive test plans should be prepared and reviewed by management.

The investigation team found that inadequate test planning was one of the factors which contributed to the problems on the Hubble program. According to the team, a project test plan that considered the various ways of measuring the mirror's shape, the possibilities of error in each, and the feasibility of independent checks should have been prepared and externally reviewed.

As a result of the Hubble investigation, the Associate Administrator for Safety and Mission Quality recommended that more attention be placed on detailed specification compliance and validation of the overall system as a part of its formal acceptance. A detailed test plan is necessary to trace the validation of all performance parameters, according to the Associate Administrator.

According to NASA's Office of Safety and Mission Quality, a test plan should be prepared for each project to outline the testing to be conducted at every level and phase of the program. The test plan should

- provide a clear audit trail showing how each performance requirement will be validated;
- describe test concept objectives and the requirements to be satisfied, test methods, and responsible NASA functions associated with the testing;
- include flow diagrams, milestones, locations, and schedules for the tests; and
- describe the roles and responsibilities of contractor and government quality assurance personnel in the tests.

While all but one of the projects we reviewed had test plans, sometimes called verification and validation plans, none of the plans included all of the information that the Office of Safety and Mission Quality said was needed. For example, some of the plans did not provide a clear trail showing how each performance requirement would be validated. Also, the plans did not show who would monitor the tests or when government witnesses would be required.

Roles and Responsibilities Not Defined

Current policies do not clearly define the role of NASA's Safety and Mission Quality organizations in ensuring that tests are properly planned, conducted, and reported. According to the Hubble investigation report, none of the formal plans and reports for optics fabrication included signature approval from the quality assurance organization or any NASA element. For example, the primary mirror test plan was not signed by either the contractor's or NASA's quality assurance personnel indicating their review and approval.

NASA's Deputy Associate Administrator for Safety and Mission Quality told us that, in his view, the mission quality organization at each field center should be responsible for approving test plans and procedures. However, a March 1990 NASA headquarters survey of Marshall Space Flight Center's Safety and Mission Assurance office reported that the organization did not have personnel with the expertise to independently assess functional and environmental test requirements or results. Marshall's response to the survey observation was that these activities are the responsibility of the design engineering organization rather than safety and mission quality.

Safety and mission quality officials at the other centers told us that their offices approve test plans. In assessing lessons learned from the Hubble incident, however, the Director of the Lewis Research Center's Office of Mission and Safety Assurance concluded that the centers need to concentrate more on test and verification activities through an increased focus on system engineering. According to this official, each center should begin to establish a focused test and verification function within its safety and mission quality organization. This function would address component, subsystem and system level test and verification requirements and activities and provide independent test assessments at major program milestones.

Testing Guidance Varies From Center to Center

Without headquarters guidance, some field centers have developed their own policies, procedures, and standards for testing. Three of the five centers we visited had center-wide testing guidance, but these guidance documents differed considerably.

The Goddard Space Flight Center had the most comprehensive testing guidance. Goddard's Guidelines for Standard Payload Assurance Requirements describes required tests and the content of planning documents such as verification plans, test specifications and procedures.

The Goddard guidelines require comprehensive tests to demonstrate that space hardware meets its performance requirements within allowable tolerances. It also requires end-to-end tests of the integrated ground and flight system, including all elements of the payload, its control, communications, and data processing to demonstrate that the entire system can fulfill all mission requirements and objectives. The guidelines further require that at the conclusion of the performance verification program, payloads shall have demonstrated failure-free performance testing for the last 100 hours of operation.

Guidance documents prepared by the Jet Propulsion Laboratory and the Marshall Space Flight Center provide less detail. These guidelines do not prescribe the content of test plans, procedures, or specifications. Neither of the guidance documents require comprehensive or end-to-end tests. The Johnson and Lewis centers have no center-wide testing guidelines.

Some field centers have also developed their own criteria or standards for the environmental conditions to be used in qualification and acceptance tests. The environmental test criteria differ from center to center, even though in some cases the centers are developing hardware for the same space missions. In such cases, the differences in test criteria could lead to disparate test conditions for hardware on the same mission.

The Goddard Space Flight Center, the Johnson Space Center, and Jet Propulsion Laboratory have already published environmental criteria for projects developed at their centers. The Marshall Space Flight Center has a draft handbook specifying environmental test conditions. Officials at the Lewis Research Center told us that they plan to begin drafting environmental criteria in the near future.

We found that the criteria at the four centers differ in several areas. For example, all four require that hardware be tested in temperature extremes but the test methods differ. Three of the four centers require that hardware be cycled through hot and cold extremes a number of times, but the criteria differ as to the number and duration of cycles. Temperature cycles are to range from the minimum expected flight temperature less about 10 degrees centigrade to the maximum expected flight temperature, plus about 10 degrees centigrade. The Goddard standard requires that payloads be held at the temperature extremes for a minimum of 16 hours during each cycle, while Marshall's draft document suggests a 12-hour minimum exposure and Johnson requires a minimum of 1 hour.

The Jet Propulsion Laboratory does not require temperature cycling for space hardware it develops. Rather, this center requires longer periods of constant exposure to temperature extremes. The Jet Propulsion Laboratory requirement is to expose the hardware to a minimum of 144 hours at 75 degrees centigrade and a minimum of 24 hours at minus 20 degrees centigrade.

Environmental test standards for the centers also differ in other areas such as vibration and acoustic, humidity, and electrostatic discharge tests. The Johnson Center's standards do not address acoustic, humidity, or electrostatic discharge testing.

In some cases, different standards are used to qualify and accept hardware for the same mission. For example, four NASA centers are responsible for developing space station flight hardware. In early 1990, a Space Station program verification review team expressed concern that environmental test criteria were not standardized across the program. According to Space Station program officials, each center planned to conduct qualification and acceptance tests using its own environmental criteria. The Space Station program office, however, has now drafted environmental criteria for use by all program participants in testing station hardware.

NASA Plans to Improve Testing Guidance

NASA has recognized the need for agencywide testing guidance. According to the Deputy Associate Administrator for Safety and Mission Quality, NASA is drafting a policy statement on quality that will include testing policies. In addition, the Office of Safety and Mission Quality has established a technical standards division to begin work on agencywide engineering and test standards.

The Office of Safety and Mission Quality is drafting a policy statement on mission quality. According to the Deputy Associate Administrator, the policy statement, to be issued by December 1991, will specify that each performance requirement must be validated through analysis or test. Validation matrices will be developed for all performance requirements to identify the method of validation and provide traceability to implementing documents such as test plans, procedures, and reports. The policy statement will also require project test plans showing how and when tests are to be conducted and the controls that will be established to ensure that they are properly conducted and reported. According to the Deputy Associate Administrator, the policy statement also will better define the responsibility of mission quality organizations at the various field centers for assuring that performance requirements are verified.

The Office of Safety and Mission Quality has also established a technical standards division. One of the division's functions is to develop and maintain a consistent set of NASA-wide standards, guidelines, and processes to support the design, manufacture, and qualification of hardware and flight systems. According to the Division Director, agencywide environmental test criteria are needed to ensure consistent hardware qualification and acceptance.

Conclusions

Testing varies from one space project to another, due in part to NASA's lack of uniform, agencywide policy guidance and standards to govern testing at its field centers. Current guidance is fragmented and incomplete. Some field centers have developed their own policies, procedures, and standards. As a result, in some cases, hardware intended for the same mission may be tested to different criteria. NASA's Office of Safety and Mission Quality has recognized the need for uniform policies and criteria and has initiated efforts to provide the needed guidance.

Recommendations

We recommend that the NASA Administrator issue testing policies that define NASA's testing goals; establish agencywide minimum requirements for space system test programs; and define organizational roles and responsibilities for ensuring that tests are properly planned, conducted, and reported. The policy should require officials to prepare a comprehensive test plan for each project showing how each performance requirement will be validated and the controls established to ensure that validation activities are properly planned, conducted, and reported.

We also recommend that NASA develop agencywide test standards to ensure consistent qualification and acceptance testing for all hardware.

Further Improvements in Contractor Oversight Are Possible

Most of NASA's space systems are designed and built by private companies under contract to the agency. In these cases, the contractors are responsible for verifying that the systems meet performance requirements and can accomplish their missions. The contractors plan, conduct, and interpret most tests, including qualification and acceptance tests. Since, in many cases, the same contractor organization that designed the space system is also responsible for testing its performance, it is especially important that NASA provide strong oversight to ensure that performance is adequately tested.

According to the Hubble investigation team, NASA's oversight of the mirror manufacturing and testing was inadequate. Since the mirrors were built, NASA has enhanced its safety and mission quality activities to provide better oversight, but the agency still has no standardized approach to contractor oversight. We found that each center has oversight controls to help ensure that tests are properly planned, conducted, and reported. However, the controls operated differently at each center. Some approaches appear to provide stronger controls than others. Among the most significant controls are (1) NASA's review of contractor test plans and procedures, (2) formal design or milestone reviews, and (3) government monitoring of tests.

All of the controls depend on the capabilities of NASA's staff to spot problems before they occur. According to a recent study by the National Academy of Public Administration, NASA needs to provide its science and engineering staff more hands-on work experience to, among other things, better train the staff to oversee contractor performance. Because NASA contracts out so much of its research and development work, the agency's ability to adequately critique contractor designs, tests, and operations has deteriorated.

NASA's Oversight of Hubble Testing Was Inadequate

The Hubble investigation team identified deficiencies in NASA's oversight of the testing. For example, from 1978 through 1981 when the mirrors were manufactured, neither NASA nor the contractor's quality assurance organizations had an independent chain of command that would have permitted program decisions to be appealed to higher management. NASA headquarters quality assurance oversight for all NASA programs, including the Hubble Space Telescope, consisted of two or three engineers assigned to the Office of Chief Engineer. At Marshall Space Flight Center, the NASA center responsible for the Hubble program, quality assurance personnel reported to the Director of Science and Engineering, who was responsible for space systems designs. Neither the contractor nor NASA quality assurance staff had expertise in optics, according to the investigation report.

When the mirror was being manufactured, NASA had only one quality assurance person at the contractor's plant. This official had to cover essentially an around-the-clock, 7-day a week operation at two manufacturing facilities. Due to a management decision, neither NASA nor the contractor's quality assurance personnel provided surveillance of critical functions during the assembly of the reflective null corrector or the testing of the primary mirror. According to the Hubble investigation report, the decision probably resulted from schedule and cost pressures and a belief that engineering coverage was an adequate assurance.

NASA Has Improved Safety and Mission Quality Organization

Since the Hubble mirror was manufactured and tested, NASA has substantially improved its safety and mission quality activities. The changes resulted primarily from the January 1986 Challenger accident. NASA created independent safety and mission quality organizations, both at headquarters and in its field centers, and increased the resources allocated to safety, reliability, maintainability, and quality assurance. For example, the number of civil service personnel dedicated to these functions increased by 58 percent, from 845 to 1,330, between 1986 and 1990. Also, according to the Associate Administrator for Safety and Mission Quality, the number of contractors supporting the safety and mission quality civil service work force more than doubled, from 711 to 1,453, between 1986 and 1990.

Safety and mission quality organizations now provide active oversight of development projects. For example, the Office of Safety and Mission Quality provides independent assessments and hazard analyses for a wide variety of NASA programs and projects. Some recent assessments include studies of the structural adequacy of space shuttle solid rocket booster aft skirts and hazards and safety concerns associated with the tethered satellite system. Safety and mission quality personnel also participate in launch decisions. For example, the Associate Administrator for Safety and Mission Quality co-chairs all shuttle flight readiness reviews. These reviews are conducted to address safety concerns and to decide if the shuttle and its payload are ready to fly.

Some Oversight Controls Can Be Strengthened

All of the field centers we visited had oversight controls to help ensure that contractors properly plan, conduct, and report tests. Among these were government review and approval of contractor-prepared test plans and procedures, formal reviews of design and testing activities at various milestones, and government monitoring of critical tests. However, the controls were implemented differently at each center.

NASA Does Not Approve All Plans and Procedures for Critical Tests

According to the Hubble investigation report, mirror test planning documents were inadequate. The primary mirror test plan was, at best, a cursory overview of the testing to be performed. Test procedures did not provide criteria for the correct results of testing and thus did not provide guidance toward identifying unexpected out-of-limits behavior of the optical tests. According to the investigation team, neither the test plan nor the procedures were approved by the contractor's quality assurance organization or any NASA element.

NASA has no policy requiring government approval of contractor-prepared test plans and procedures. The agency's handbook on reliability program requirements for space system contractors identifies documents that contractors normally prepare and indicates the action NASA is to take on those documents. According to the handbook, NASA reviews specifications and procedures for reliability tests but does not formally approve them.

Project management and quality assurance personnel at all five field centers told us they review contractor-prepared test planning documents. At some centers, decisions about review and approval of test plans and procedures are made on a contract-by-contract basis.

Of the five centers we visited, only the Goddard Space Flight Center had a written requirement for government review and approval of contractor test plans and procedures and this requirement was limited to class A and class B payloads. Officials from the other four centers told us that their normal practice is to approve test plans, but that they approve test procedures only under special circumstances.

According to Goddard's Office of Flight Assurance, a requirement for government approval and sign-off of critical contractor test plans and procedures provides a stronger control over the adequacy of test planning, because it helps ensure discipline in the review of the documents. According to this office, where approval of test planning documents is required, formal approval adds discipline to the review process and helps prevent problems that could result from poor test procedures.

Independent Reviews Not Required for All Major Programs

Officials at the five centers we visited identified design and other milestone reviews as an important means of helping to ensure that verification activities are properly planned and conducted. However, the reviews are different at each center. At some centers, the reviews are conducted by people independent of the project's management and design activities; at other centers, project managers conduct the reviews.

The reviews provide the mechanism by which NASA assesses program performance, enforces technical and programmatic discipline, and conveys requirements and progress. Additionally, the reviews are to establish a technical baseline for controlling requirements and configurations as the program evolves through the development phase.

According to the Chairman of NASA's Engineering Management Council, the objective of the review program is to provide documented assurance to NASA and contractor management that the design satisfies the program requirements. The design review activity should direct program management's attention to design or testing deficiencies while they can still be corrected.

According to the Hubble investigation report, design reviews conducted on that program should have identified problems with the mirror manufacturing and testing, but they did not. The reviews did not penetrate the contractor's activities to sufficient depth, nor did they discuss any issues that might have adversely affected cost and schedule.

Although NASA acknowledges the importance of design and milestone reviews, the agency has no uniform definition of the reviews or the approach to conducting them. Of the five centers we visited, only three—Marshall, Goddard, and the Jet Propulsion Laboratory—had center-wide policies to guide the review process.

According to the Chairman of the Engineering Management Council, each program has a different set of reviews. While reviews such as the preliminary and critical design reviews[1] are common to all programs, the

[1]The preliminary design review is to assess the basic design approach to ensure that it is compatible with requirements and can be produced, integrated, and verified. The purpose of the critical design review is to determine if the completed design complies with NASA requirements.

Apollo, Space Transportation System, and Space Station contracts each require a different set of milestone reviews. Also, each program defines the milestones differently and political pressure can force design reviews before the program has reached the necessary level of maturity. For example, in the case of the Space Station Freedom, the preliminary design review was held even though significant controversy as to the feasibility of the entire station concept still existed, according to the Chairman.

At two of the five centers we visited, design reviews are usually conducted by people independent of the project's management and design teams. At the other three centers, review boards included people outside the management and design organizations; however, project managers normally chair reviews of their projects. One of the three centers used independent reviews in some cases, and project manager chaired reviews for others.

NASA recognizes the importance of independent reviews and recently revised its regulations to require independent reviews on its class A payloads. However, independent reviews are not required for launch systems and major class B payloads such as the Advanced X-ray Astrophysics Facility. This facility is estimated to cost about $1.8 billion in development.

On-Site Test Monitoring Staff Not Always Sufficient

For major programs, NASA has safety and mission quality personnel located at contractor plants. In some cases, NASA also delegates quality assurance oversight to other government agencies such as the Defense Contract Management Command. Among other things, the government quality assurance personnel are to help ensure that tests are conducted in accordance with approved procedures and results are accurately reported.

According to the Director of Safety and Mission Quality at the Johnson Space Center, to be effective, the oversight organizations must be adequately staffed by fully qualified individuals. In the case of Hubble, neither NASA nor the contractor's quality assurance personnel were optical experts and, therefore, were not able to distinguish the presence of inconsistent data results from the optical tests. According to a Marshall Space Flight Center report on the Hubble investigation, operations that require specialists should be independently assessed by other personnel of equal skill to provide adequate check and balance. This check and balance should normally be performed by quality assurance personnel.

Safety and Mission Quality officials at several of the centers told us that the quantity and skill of safety and mission quality staff in residence at contractor plants are less than desirable for some projects. For example, until recently, Marshall Space Flight Center's oversight of its contractor's optics testing on the Advanced X-ray Astrophysics Facility program was constrained because Marshall quality assurance personnel were not experienced in optical design and testing. In January 1991, the Center employed a consultant to monitor the contractor's design and testing activities. In May 1991, the Center hired a permanent optics expert and placed him in residence at the facility where the x-ray mirrors are being manufactured.

According to one field center, when contractor plants are located in high-cost areas, it is often difficult to hire technically competent people at civil service salaries. Civil service staffs can be augmented with support contractor personnel. Also, according to the National Academy of Public Administration, recently enacted pay reform that provides for geographic pay adjustments may help resolve this problem.

Study Concludes That More Hands-On Experience Is Needed

According to a recent study by the National Academy of Public Administration, the fact that NASA contracts out such a large percentage of its research and development activities may detract from the agency's ability to adequately oversee contractor performance. In March 1990, the NASA Administrator asked the Academy to study the allocation of technical work and responsibility between NASA and its support contractors, within the agency itself, and the effects of that allocation on NASA's in-house technical capability to effectively accomplish its assigned activities.

The Academy study addressed questions such as whether (1) NASA had contracted out too much of its technical work to remain a "smart buyer" of technical products and services from industry, (2) NASA's in-house engineering and scientific work was truly important to the development of fully competent scientists and engineers, and (3) NASA has enough hands-on work opportunities available. The study consisted primarily of interviews with current and former senior NASA and contractor managers and a survey questionnaire issued to a sample of 2,243 NASA scientists and engineers at Grades 12 and 15.[2]

According to the study, there was almost unanimous agreement that hands-on science and engineering work experience is essential (1) to developing civil service staff with a level of knowledge that provides a "sixth sense" for spotting problems early, (2) for being a smart buyer of technical products and services, and (3) for being able to astutely oversee the work of technical contractors. Officials at three centers expressed the same opinion. Hands-on experience is essential not only for new engineers and scientists, but to keep current skills of those more senior.

According to the Academy's study, many NASA personnel believe that the agency has turned over critical tasks to contractors and has lost the ability to critique contractor designs, tests, and operations. For example, over 57 percent of the respondents believe that NASA's in-house scientific and engineering capabilities have eroded. Respondents from all centers noted that NASA's ability to be a smart buyer and to make independent judgments about the quality of the work has declined as the number of contractors has grown. Thirty-four percent of the respondents said they did not believe that NASA still has in-house competence to make responsible decisions in all programs for which it is responsible. According to the study, there was a general feeling that as NASA managers have turned over critical tasks to contractors, they have lost the ability to critique contractor designs, tests, and operations. Over 65 percent said the public interest would be best served if less technical work were contracted out to the private sector.

Several NASA centers have programs underway to provide more hands-on opportunities. For example, at the Marshall Space Flight Center, young engineers are trained on in-house projects such as the technology test bed for liquid engine research and development. At the Kennedy Space Center, new engineering hires are assigned to the payload integration program for a time. This program requires the engineers to understand flight experiments; design, develop, build, and test the apparatus required to install experiments into the shuttle; and support shuttle operations. At the Goddard Space Flight Center, managers keep one or more projects in-house to provide hands-on training to young engineers.

[2] A total of 1,615, or 72 percent, of those surveyed responded. The respondents represented 42 percent of all NASA engineers and scientists at the two grade levels.

For example, the $200-million Cosmic Background Explorer project was designed, built, and tested in-house at Goddard.

According to most respondents to the Academy study, however, NASA still is not doing enough. More than 80 percent of the respondents said that NASA needs to do more to provide hands-on opportunities to its engineers and scientists.

The Academy panel concluded that the value of and the need for hands-on science and engineering work is essential to the professional development of NASA scientists and engineers to effectively perform the work of the agency, and that the agency needs to provide more of it. The panel recommended that NASA provide policy guidance to the centers to retain in-house sufficient project, experiment, advanced development, and research activities to provide more hands-on technical work by civil service scientists and engineers.

According to NASA's Associate Deputy Administrator, the agency concurs in the need for its scientists and engineers to have hands-on experience. NASA considers this need when deciding whether to contract out a space project development effort or to develop the project in-house, according to the Associate Deputy Administrator. In addition, in its fiscal year 1992 budget request, the agency is seeking authority to convert some support contractor positions to civil service positions so that the agency can perform more work in-house.

Conclusions

All field centers have internal controls designed to help ensure that contractors properly plan, conduct, and report tests. The controls are applied differently at the centers and, in our opinion, are stronger at some centers than others because the controls at those centers are more focused and provide for more independent assessments of the adequacy of testing. NASA is attempting to provide its engineers and scientists with more hands-on experience in designing, developing, and testing space systems to further enhance their capabilities to oversee the work of the agency's contractors.

Recommendation

We recommend that the NASA Administrator require that all centers (1) approve contractor-prepared test plans and procedures for critical tests, (2) implement procedures for independent reviews of testing on all major programs, and (3) review each project to determine if adequate personnel with needed skills are available to monitor critical contractor tests.

Resource Limits Have Not Precluded Essential Tests

As officials at the Lewis Research Center pointed out, testing must compete for resources with all other project activities such as engineering, design, and manufacturing. No standard has been set for the amount of a project's resources that should be devoted to testing.

Although limited, in most instances, resources have not significantly constrained testing and essential verification activities are always performed, according to project and testing officials we interviewed. In some cases, however, project managers have had to make cost-risk tradeoffs when planning testing programs. Also, officials at several centers told us that additional staff and facilities are needed for in-house testing. As a result of these conditions, tests are sometimes abbreviated, or schedules are delayed, and costs are increased.

Essential Tests Have Not Been Eliminated Because of Funding Constraints

Testing and project officials at all five field centers told us that sufficient resources have been available to perform essential tests. According to the Chief of NASA's Cost and Economic Analysis Branch, however, NASA has no standard criterion for judging the adequacy of funds spent on testing. Space system developments are unique, and testing programs must be tailored for each project.

We asked field center officials whether funding limits constrained the scope of testing on eight specific projects.[1] According to officials, funding limits did not constrain testing on six of the eight projects. The officials stated that no additional tests would have been done on these six projects, even if more funds had been available. Also, no tests were subsequently deleted from these projects due to funding constraints.

Cost-Risk Tradeoffs Are Sometimes Necessary

In two of the eight cases—the Galileo spacecraft and the replacement for the Hubble's wide field planetary camera—officials told us that test programs were constrained by the availability of project funds. In both cases, the primary limitation was that sufficient project funds were not available to purchase prototypes or "engineering models" for use in testing and that, as a result, less rigorous tests were performed.

Prototypes are electrically and mechanically equivalent to the flight spacecraft. When available, the prototypes are used to verify system

[1] The six GAO case study projects, plus the Magellan spacecraft and the replacement for the Hubble Space Telescope's Wide Field Planetary Camera.

design requirements and to avoid risk to the flight hardware. The prototypes are used for tests that have potential risk to demonstrate that the performance exceeds requirements by a specified margin.

Additional environmental tests at higher levels would have been performed to establish design margins if prototypes had been available on the two projects, according to Jet Propulsion Laboratory officials. Since the prototypes were not available, design margins had to be established by analysis. Also, design verification tests that were subsequently performed on the flight spacecraft would have been done on the prototypes, reducing risks to flight hardware if the prototypes had been available.

Both Jet Propulsion Laboratory and Johnson Space Center officials told us that decisions about the number and type of test hardware are sometimes based on the amount of funds available rather than on the needs. According to the Chief Engineer at Johnson, programs shortchange themselves when they do not provide sufficient test articles. If sufficient test articles are not available, problems are not detected until after flight hardware is built. The flight hardware then has to undergo costly modifications or repairs.

In-House Testing Resources Are Limited

According to officials at all five centers, staffing, facilities, and equipment available for in-house testing are limited. Although all essential tests are performed, in some cases, the limitations have resulted in abbreviated tests or added cost and time to the test program, according to the center officials. The centers plan to upgrade their test facilities.

Marshall Space Flight Center

According to the Marshall Space Flight Center, staffing and facilities available for in-house testing are limited. Insufficient staffing due to hiring restrictions has resulted in the extensive use of overtime and compensatory time, especially for around-the-clock testing programs.

In addition, annual funding constraints have prevented the repair or replacement of aging equipment and have kept the Center from fully equipping new test facilities, according to the test officials. According to these officials, the environmental test facility and electromagnetic interference facility are operating with equipment that is over 20 years old. Frequent breakdowns of equipment in these facilities cause delays in testing schedules.

The officials also told us that, in some cases, the size and number of in-house test facilities is limited. For example, the Center had no vacuum chamber large enough for acceptance and qualification tests on large flight hardware until 1991, when a large vacuum chamber was installed in the Marshall X-ray Calibration Facility. Similarly, the existing electromagnetic interference facility is limited to smaller- and medium-sized experiments, and larger vibro-acoustic facilities are needed to accommodate larger test items. These larger test facilities, when needed, can be obtained from other government agencies or NASA contractors, according to the officials.

These officials also told us that Marshall has requested additional funding for test facilities. Because of annual funding constraints, however, some of the additional test capabilities have been delayed.

Jet Propulsion Laboratory

According to officials at the Jet Propulsion Laboratory, almost all of that center's testing facilities and equipment are inadequate and obsolete. For example, shielded rooms in the electromagnetic compatibility test laboratory are too small to accommodate entire satellites, or even some subassemblies and instruments. Also, according to the officials, upgraded test instrumentation is needed as new spacecraft testing requirements become more demanding.

According to the officials, the Center has been able to work around the limitations to perform essential tests. In some cases, however, tests were either abbreviated or were performed at other agencies because the Center's electromagnetic compatibility test facilities were not large enough. The Center has plans for a new, larger shielded room in its recently constructed flight hardware development facility.

Johnson Space Center

Johnson officials told us that their laboratories are not all adequately staffed and that much of their test equipment is outdated and in need of repair. For example, some test stands, calibration devices, and pumps currently used in testing are 20 years old and require frequent repair. Some computers are 8 to 9 years old and need to be replaced, according to the officials. The officials told us, however, that they have been able to provide adequate testing services to support current programs.

Lewis Research Center

According to the Director of Mission Safety and Quality Assurance at Lewis, that Center's electromagnetic interference, outgasing, toxicity, and thermal vacuum testing facilities and equipment are limited. According to the Director, however, the Center has access to test facilities at other NASA activities and, in all cases, has satisfied testing requirements.

Goddard Space Flight Center

Goddard officials told us that some of their testing facilities have aged, but the Center has recognized the problem and is in the midst of a 10-year program to modernize the facilities. For example, Goddard recently upgraded and modernized its largest thermal vacuum test chamber. According to the chief of the Center's Environmental Test Engineering and Integration Branch, the test branch's civil service staffing is about nine people short of its needs. The Center has worked around the staffing shortage by augmenting civil service staff with support contractor personnel and using overtime and compensatory time during peak testing periods. According to the branch chief, resource limits have not unduly inhibited testing to date.

Conclusion

Although testing resources are limited, in most cases, officials told us that it does not significantly constrain testing and that essential verification activities are always performed. There are cases, however, where tests have been abbreviated to avoid damage to flight hardware when sufficient funds were not available to purchase prototypes or engineering models for use in testing. While the minimum essential amount of testing is conducted, officials have less confidence that the space system can withstand its launch and operating environments and successfully perform its intended mission. Also, staffing, facilities, and equipment available for in-house testing are limited.

Recommendation

We recommend that the NASA Administrator require that each project test plan fully disclose any testing limitation that increases technical risk and describe actions to be taken to minimize the risk.

Comments From the National Aeronautics and Space Administration

NASA

National Aeronautics and Space Administration

Washington, D.C. 20546

Office of the Administrator

JUL 29 1991

Mr. Frank C. Conahan
Assistant Comptroller General
National Security and
International Affairs Division
General Accounting Office
Washington, DC 20548

Dear Mr. Conahan:

We have reviewed the GAO draft report, "Space Project Testing: Uniform Policies and Added Controls Would Strengthen Testing Activities."

In general, we agree with the observations cited. Initiatives within the NASA Safety and Mission Quality Technical Standards Program will address the test differences existing among NASA Centers and the development of Agency-wide test standards. Although basic requirements can be identified quickly, it should be recognized that detailed implementation will require thorough evaluation and coordination among program, project, and functional area managers.

We also agree that budget limitations have not caused elimination of essential testing. Such limitations do impact test philosophy and planning. Due to escalating costs, the Agency has increasingly relied on a "protoflight testing" approach where the hardware being tested is also the flight hardware. The planned use of flight hardware for testing significantly reduces the price of the program but not necessarily the program life-cycle costs. Testing must be limited to avoid overstressing or severely reducing the life of the flight hardware and thus results in an increased reliance on analysis.

We agree that the Agency needs an overall testing policy. Several actions have already been initiated within the Agency to effect these recommendations.

Sincerely,

John E. O'Brien
Assistant Deputy Administrator

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