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Report to the Chair, Subcommittee on VA, HUD, and Independent Agencies, Committee on Appropriations, U.S. Senate

February 1992

SPACE PROJECTS

Status and Remaining Challenges of the Advanced X-ray Astrophysics Facility

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Washington, D.C. 20548

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National Security and
International Affairs Division

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February 28, 1992

The Honorable Barbara A. Mikulski
Chair, Subcommittee on VA, HUD,
and Independent Agencies
Committee on Appropriations
United States Senate

Dear Madam Chair:

As requested, we reviewed the National Aeronautics and Space Administration's (NASA) Advanced X-ray Astrophysics Facility (AXAF) program in terms of its phased development status. Our objectives were to assess (1) program cost and schedule status, (2) results of tests of the observatory's outer mirrors, and (3) remaining technical challenges.

Although the information contained in this report is current, subsequent to commenting on the report, NASA instructed the AXAF development contractor to study options for reducing program costs. One option being studied is a redesign of the observatory that includes fewer mirrors and science instruments and launch on an expendable launch vehicle. If adopted, such a redesign would impact the observatory's cost, schedule, and performance. NASA does not expect to make a decision on the options before late March 1992.

Unless you publicly announce this report's contents earlier, we plan no further distribution 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

The Advanced X-ray Astrophysics Facility is being designed for the National Aeronautics and Space Administration (NASA) at an estimated cost of about $2.0 billion. It is to be one of the mainstays of this nation's space science program for the next decade.

The Chair of the Subcommittee on VA, HUD, and Independent Agencies, Senate Committee on Appropriations, requested that GAO review the program's status. The specific objectives were to assess (1) program cost and schedule status and risks, (2) results of mirror tests to date, and (3) remaining technical challenges.

Background

The facility is to be the third in NASA's series of four "great observatories." Operating in the X-ray band of the electromagnetic spectrum, it is to complement the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Space Infrared Telescope Facility. The Congress authorized NASA to begin facility development in fiscal year 1989 but mandated a phased development approach. Under this approach, NASA was required to first verify the observatory's mirror concept by fabricating and testing the largest of six pairs of concentric mirrors. Through December 1991, NASA had expended $302.2 million on the program.

Results in Brief

Since fiscal year 1989, the program's estimated cost has increased by about 23 percent and its launch schedule has been delayed by 2 years primarily because of budget cuts imposed by NASA and the Congress. To keep program costs from increasing even further, NASA used a portion of cost reserves being held for future unanticipated changes and reduced the number of spare parts it plans to purchase. Reducing spare parts increased the program's schedule risk. Further cost increases could result if NASA decides to launch the observatory on an expendable launch vehicle rather than the space shuttle.

Test results to date show that the first pair of mirrors has met the requirement for mirror resolution mandated by the Congress. On the basis of those results, NASA expects overall mirror performance to meet contractual standards. However, a number of challenges remain for NASA to successfully launch and operate the observatory.

Principal Findings

Unanticipated Effort and Budget Constraints Cause Cost and Schedule Increases

In fiscal year 1989, NASA estimated the program's cost at about $1.614 billion. NASA now estimates the facility will cost about $1.994 billion, an increase of $380 million, or about 23 percent. Although there has been some cost growth in the program, most of the increase to date can be attributed to schedule stretchouts caused by budget cuts.

About $85 million of the increase resulted because NASA (1) underestimated work required to fabricate the mirrors and (2) changed the design of the facility used to test the mirrors. The remaining $295 million increase resulted primarily from two budget cuts. NASA cut the program's budget for fiscal year 1991 by about $25 million and the fiscal year 1992 budget by about $75 million. As a result, many of the activities planned for fiscal years 1991 and 1992 had to be delayed, and NASA slipped the observatory's scheduled launch from April 1997 to March 1998. The impact of these cuts would have been greater, but NASA reduced the scope of the development program and used reserves to offset some of the increase. The second budget cut occurred when the Congress appropriated $60 million less for the program in fiscal year 1992 than NASA requested and required NASA to limit the fiscal year 1993 funding request. Program officials told GAO that these cuts will cause another schedule stretchout that will delay the launch about 1 more year—to early 1999—and increase development costs by another $205 million. The cost increases are attributed to inflation and an additional year of fixed development costs such as salaries for contractor project engineers.

Schedule Risks Increase

To partially offset cost increases resulting from the budget cuts, NASA now plans to purchase fewer spare components than originally planned. NASA officials believe that fewer spares will not result in unacceptable risk; however, the officials acknowledge an increased schedule risk because certain parts, if damaged in testing, cannot be replaced quickly.

Further Cost Increases Possible

Costs will increase even more if NASA decides to launch the observatory on an expendable launch vehicle rather than the space shuttle. NASA estimates that it would cost up to $286 million to redesign the observatory and an additional $250 million for a Titan IV launch vehicle.

The current estimate contains reserves to cover the cost of future unanticipated changes. While NASA considers the current reserves to be adequate, they have been reduced to offset program cost increases. Before the budget cuts, the reserves equaled about 43 percent of estimated future program costs. Following the cuts, NASA reduced the reserves to about 31 percent of remaining costs.

Mirrors Pass Feasibility Demonstration Test

When the Congress authorized NASA to begin the program, it required the Agency to fabricate and test the largest pair of mirrors to an exact standard for mirror resolution before beginning other tasks. After correction for test effects, data from tests completed in September 1991 showed that the mirrors met the requirement. In addition, NASA believes test results to date provide confidence that all pairs of mirrors, when assembled, will meet the contractual standard for collecting and focusing X-rays.

Difficult Challenges Remain

While NASA is satisfied with mirror development to date, many challenges remain before the observatory can be launched. They include developing additional test equipment, other observatory components, and science instruments, in addition to coating and aligning the mirrors.

Recommendations

GAO is not making any recommendations.

Agency Comments

The program manager generally concurred with GAO's report. In its written comments on a draft of this report (see app. I), NASA said that successful fabrication of the observatory's largest mirrors in conjunction with previously constructed smaller mirrors established a thorough understanding of the mirror fabrication process. According to NASA, important manufacturing performance assumptions were verified and significant risk was removed from the development program.

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Abbreviations

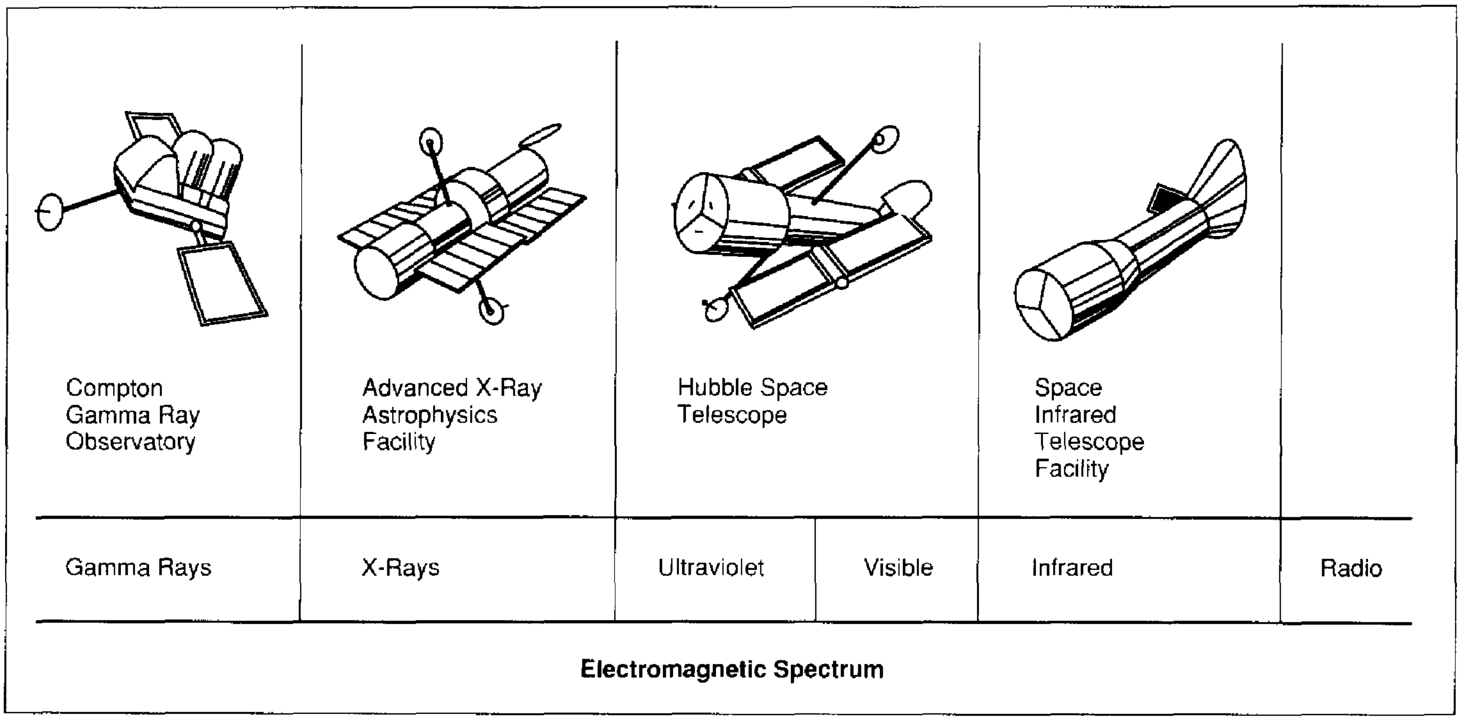
AXAF	Advanced X-ray Astrophysics Facility
GAO	General Accounting Office
NASA	National Aeronautics and Space Administration

Chapter 1

Introduction

The Advanced X-ray Astrophysics Facility (AXAF) is to be the third in the National Aeronautics and Space Administration's (NASA) planned "Great Observatory" series. Each observatory is designed to view the universe through a different band of the electromagnetic spectrum.[1] The Hubble Space Telescope, which is designed to study visible and ultraviolet light, and the Compton Gamma Ray Observatory, which collects and analyzes gamma rays, have been launched. AXAF, which is being designed to study X-ray emissions, is now expected to be launched about 1999. The fourth observatory—the Space Infrared Telescope Facility—is to study infrared radiation. It is currently unfunded. The observatories, when operational, will permit NASA to study a range of cosmic phenomena and will form the backbone of the U.S. space sciences program for the next decade. (See fig. 1.1 for the role of each observatory.)

Figure 1.1: NASA's Great Observatories

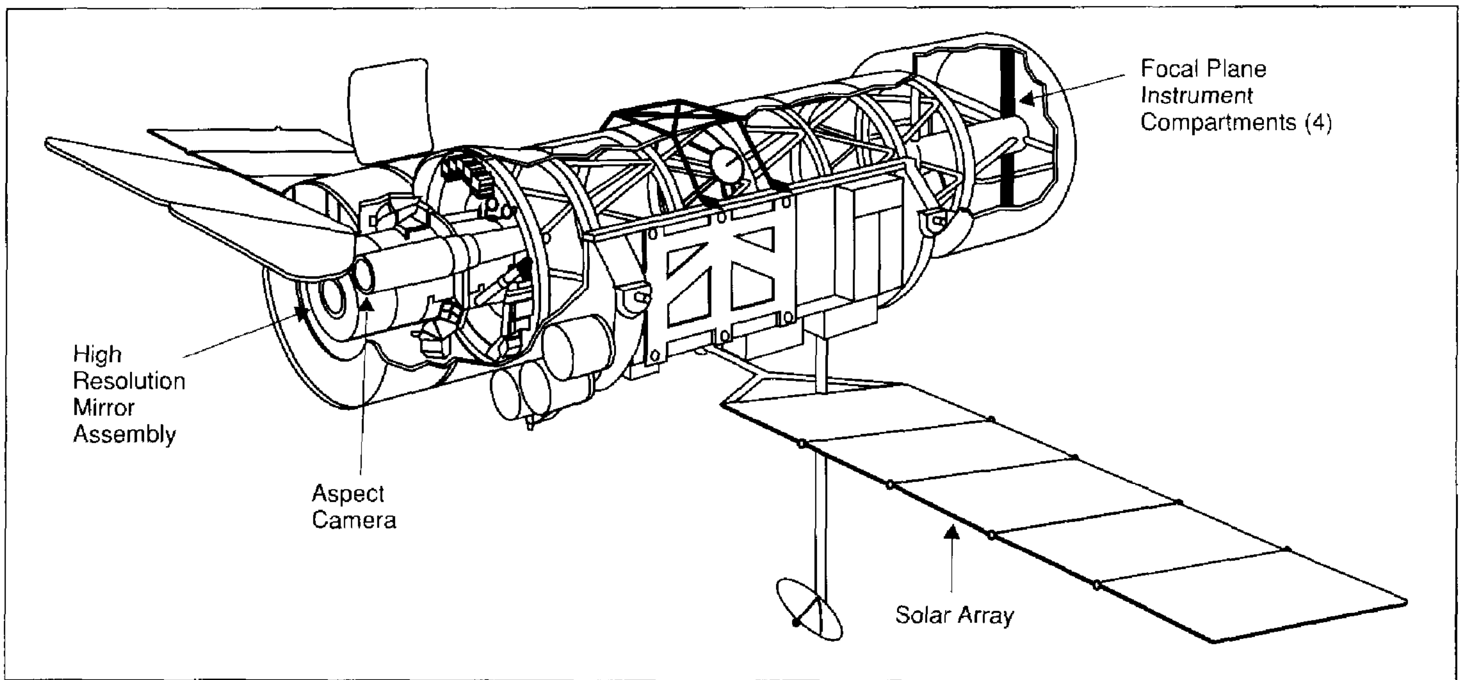


[1] The electromagnetic spectrum is the entire array of energy wavelengths as a continuum, from gamma rays to radio waves. The four observatories cover the spectrum from gamma rays to infrared.

Description

The objective of the AXAF project is to orbit a high quality X-ray telescope system for use by the astronomical community. The observatory (see fig. 1.2) is to be 45 feet long, weigh about 32,000 pounds, and fly at an altitude of 320 nautical miles. The objectives for the program are to (1) determine the nature of celestial entities ranging from normal stars to quasars,[2] (2) understand the nature of the physical processes that take place in and between astronomical objects, and (3) add to the scientific community's understanding of the history and evolution of the universe.

Figure 1.2: AXAF Configuration



The three major elements of the program's space segment are the spacecraft system, the telescope system, and the science instruments. The spacecraft system will include the electrical, mechanical, communications, command and control, and observatory pointing and image reconstruction subsystems. The telescope system is to be comprised primarily of the High Resolution Mirror Assembly, which will consist of six pairs of concentric mirrors. According to NASA, the mirror assembly is to be the heart of the AXAF system. The outer mirrors will be primarily responsible for focusing

[2]Quasars are the most distant and luminous objects known in the universe. They can have hundreds of times the power of an entire galaxy.

low energy X-rays, while the inner mirrors will focus high energy X-ray emissions. The science instruments are to be designed to provide research data in two broad categories—X-ray imaging and spectroscopy. The imaging instruments will provide pictures of X-ray emissions, and the spectroscopic instruments will analyze the emissions in terms of their wavelength.

The core instrument payload is to include an AXAF Charge Coupled Device Imaging Spectrometer, a High Resolution Camera, and High and Low Energy Transmission Gratings. In addition to the core payload, NASA is now developing both an X-ray Spectrometer and a Bragg Crystal Spectrometer, and it plans to include one or both of these instruments in the observatory.

The key components of the program's ground segment will include a Payload Operations Control Center and an AXAF Science Center. The control center is to be located at Marshall Space Flight Center, and it will perform day-to-day mission operations. The science center, which will be located in Cambridge, Massachusetts, will provide science planning, data analysis, and dissemination, and it will be a focal point for interaction with the science community.

Scientific Priority

In 1982, and again in 1991, National Research Council astronomy and astrophysics committees recommended new ground and space-based programs for development. The committees considered large and expensive development efforts, as well as smaller, more focused experiments. Both committees strongly recommended AXAF.

The 1982 committee report identified AXAF as its top priority among major new astronomy and astrophysics programs. In recommending AXAF development, the committee spoke of an "urgent scientific need...for a long-lived satellite observatory with capabilities for X-ray astronomy ..." The committee urged NASA to begin development in time to have the observatory operational by the end of the decade.

The 1991 committee report reaffirmed the earlier conclusion. It stated, in part, that AXAF "... will return the United States to preeminence in X-ray astronomy ..." In reaffirming AXAF's priority, the 1991 report also stressed "... the importance to all astronomy of deploying AXAF as soon as possible."

Prior X-ray Observatories

AXAF is to build on the discoveries of earlier programs. The last NASA mission to study X-ray emissions was the High Energy Astronomy Observatory-2, or Einstein Observatory. It operated from 1978 to 1981, and it was designed to focus X-rays from celestial objects into images. According to NASA, this observatory revealed many new and different X-ray sources.

In 1990, Roentgensatellit—a U.S., British, and German X-ray observatory commonly known as ROSAT—was launched to further study and catalog X-ray emissions from a variety of celestial sources. AXAF is being designed to (1) provide significantly greater mirror resolution and (2) analyze a wider range of energy levels than either the Einstein Observatory or ROSAT.

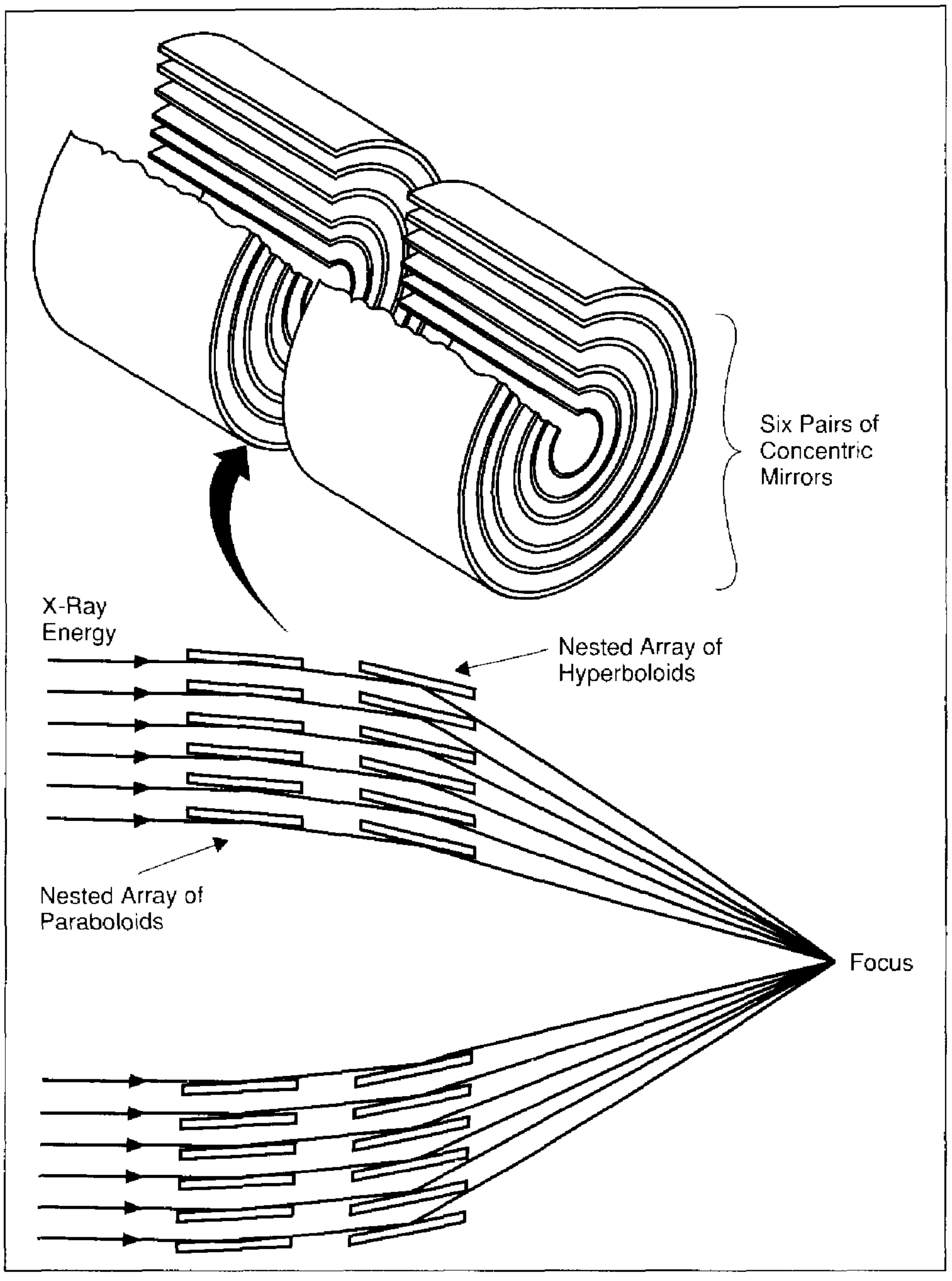
Phased Approach To AXAF Development

NASA's fiscal year 1989 budget submission included a request to begin AXAF development. In response, the Congress appropriated funds to begin developing the High Resolution Mirror Assembly (see fig. 1.3 for AXAF mirrors). The House required NASA to first demonstrate that the mirrors could perform to a resolution of one-half arc second[3] before beginning the spacecraft development program in fiscal year 1992. The House recommended a phased development approach because of the technical risk associated with fabricating and testing the mirrors. The Senate also provided for a phased approach as a means of avoiding some of the technical interface problems that the Hubble Space Telescope program experienced.

On the basis of this guidance, NASA completed fabrication and testing of AXAF's two outer mirrors in September 1991. The tests, which involved actual X-ray emissions, were performed at Marshall Space Flight Center's X-ray test facility. Through December 1991, NASA had expended $302.2 million on the AXAF program.

[3]An arc second is 1/3600th of one degree. AXAF is being designed to distinguish between two energy sources 0.5 arc seconds apart in space.

Figure 1.3: AXAF Mirrors



The slighly curved surfaces of the mirror intercept X-rays at a grazing angle and focus them into a single image.

Objectives, Scope, and Methodology

The Chair, Subcommittee on VA, HUD, and Independent Agencies, Senate Committee on Appropriations, asked us to review the AXAF program. Our objectives were to assess (1) AXAF cost and schedule status and risks, (2) results of mirror tests to date, and (3) remaining technical challenges.

We reviewed budget submission documentation, cost estimates, test plans, test results, legislative language, and project planning documents at Marshall Space Flight Center and NASA headquarters. We then discussed cost, schedule, and performance issues with program management, engineering, quality assurance, and procurement officials. We also discussed program status with members of the AXAF user community.

In assessing cost issues, we used official NASA estimates to the extent possible. However, in examining the potential impacts of fiscal year 1992 budget cuts, we relied primarily on our discussions with NASA officials because negotiations on these impacts were not final at the completion of our work.

To assess AXAF mirror performance, we reviewed test results to the extent that they were available. Since test data were emerging throughout our review, we relied extensively on the opinions of those officials involved in the test program, including NASA quality assurance officials. We did not, however, independently verify the results.

We performed our review from April 1991 through January 1992 in accordance with generally accepted government auditing standards.

Unanticipated Effort and Budget Constraints Cause Cost Increases and Schedule Delays

The AXAF cost estimate has increased by about $380 million since fiscal year 1989, and AXAF's scheduled launch has slipped by 2 years. The cost increase resulted from development cost overruns and program rephasing caused by NASA and congressional budget cuts. To hold the increase to this level, NASA reduced reserve funds and the quantity of spare parts it plans to purchase. Also, NASA is considering launching AXAF on an expendable launch vehicle, which will either increase costs or require the project office to further deplete its reserves.

Cost Increases and Schedule Delays

In June 1989, NASA estimated that it would cost about $1.614 billion to develop AXAF. Since then, the cost has increased to about $1.994 billion (see table 2.1) and the launch schedule has been delayed by 2 years. The cost increase of just over 23 percent resulted primarily from mirror fabrication cost growth and program rephasings.

Table 2.1 : AXAF Development Cost Estimates

Date of estimate	Amount[a] (billions)	Reason(s) for change	Program impacts
June 1989	$1.6	-	-
April 1991	1.8	Underestimated effort to fabricate mirrors, and program rephasing due to NASA budget cuts in fiscal years 1991 and 1992	Cost growth, schedule slippage, higher risk, and postponed/canceled procurement
December 1991	2.0	Congressional budget cut in fiscal year 1992 and funding constraints imposed for fiscal year 1993	Cost growth and schedule slippage

[a]Estimates do not include costs for launch, advanced technology development, construction of facilities, activities budgeted by the Office of Space Operations, or civil service salaries.Differences will not equal $380 million due to rounding.

About $35 million of the increase resulted because NASA underestimated the effort needed to fabricate the first pair of mirrors. For example, the number of staff hours required for mirror fabrication was significantly higher than anticipated. Between June 1989 and June 1991, NASA almost doubled the number of staff hours needed by the contractor. Based on that experience, the AXAF program manager estimated that the development cost increased an additional $40 million to fabricate the remaining five pairs of mirrors.

Also, NASA increased its estimate of the total cost for modifying the X-ray test facility at Marshall Space Flight Center by about $10 million—from $2.2 million to $12.2 million. The changes proved to be more extensive than originally anticipated. For example, electrical connections to the test equipment had to be upgraded and the test chamber's temperature control system had to be improved.

The remaining $295 million increase was due primarily to two rephasings of the program as a result of budget cuts. The rephasings also delayed AXAF's planned launch date by 2 years.

To provide funds for the Hubble Space Telescope and other projects, NASA cut the AXAF budget by about $25 million and $75 million in fiscal years 1991 and 1992, respectively. These cuts caused cost increases of about $90 million because the program had to be rephased. The increase would have been even greater, but NASA reduced the scope of the development program by decreasing the number of spare parts it planned to purchase and used some of its cost reserves to partially offset the increase.

In rephasing, NASA postponed many of the activities that were to be performed in fiscal years 1991 and 1992. For example, NASA delayed procurement of the long lead items necessary to ensure a smooth transition to full-scale development. It also delayed a number of contractor activities such as work related to the mirror assembly and other manufacturing and test activities. As a result, NASA changed the observatory's launch date from April 1997 to March 1998, a slip of 11 months.

After this rephasing, the program experienced further cost increases when the Congress reduced AXAF's fiscal year 1992 appropriation. The Congress appropriated $60 million less than NASA requested for AXAF in fiscal year 1992. The Congress also directed NASA to propose funding ceilings on all fiscal year 1993 development activities in anticipation of limited budget resources. Consequently, NASA reduced planned fiscal year 1993 funding for AXAF by about $140 million. As a result of these funding actions, activities scheduled in fiscal years 1992 and 1993 will now be performed later in the program, the launch schedule was further delayed by about 1 year, and overall costs increased by an estimated $205 million. The increased costs result from additional inflation and because fixed development costs such as salaries for contractor engineers must be incurred for an additional year.

AXAF Schedule Risks Increase

Actions taken by NASA to contain AXAF costs have increased the program's schedule risk. However, NASA considers the current risk to be acceptable.

When NASA reduced the fiscal years 1991 and 1992 budgets for AXAF, delaying the launch schedule by 11 months, it also delayed the Preliminary and Critical Design Reviews by 17 months each. The purpose of these reviews is to confirm the observatory's engineering concept before its fabrication, assembly, and launch. The preliminary review was postponed from July 1992 to December 1993, and the critical review was slipped from July 1993 to December 1994. This delay reduced the time interval between the reviews and the launch date by 6 months. NASA recognizes that conducting the reviews 6 months closer to the launch date increases overall schedule risk because it will have less time to incorporate potential changes.

Moreover, NASA reduced the number of spare components it plans to purchase. These components include the solar array panel, power electronics module units, reaction wheel electronics assembly, and instrument switching unit. NASA acknowledges that having fewer spares increases schedule risk because it will not be able to quickly replace certain parts if they are damaged in testing or if problems with these parts occur during launch operations. Nevertheless, project officials believe current risks are acceptable. The deputy project manager noted that the Compton Gamma Ray Observatory had fewer spare components than currently planned for AXAF, but experienced no major schedule problems related to the number or nature of spare parts.

Further Cost Increases Are Possible

Costs will likely increase further if NASA decides to launch the observatory on a Titan IV expendable launch vehicle rather than the space shuttle or to equip AXAF with its own propulsion subsystem. The cost estimate includes reserves intended to cover future program changes, but NASA has already reduced the amount of reserves in the estimate and it is uncertain whether or not the reserves will be adequate to cover all future changes.

NASA currently plans to launch AXAF on the space shuttle. However, the shuttle, as currently configured, cannot lift AXAF to its required orbit. As a result, NASA must first develop and equip the shuttle with an Advanced

Solid Rocket Motor. In addition, some members of the AXAF Science Working Group[1] question if the shuttle will be available when it is needed to launch AXAF. One member noted that AXAF would likely be in direct competition with the space station for shuttle launches.

Based on discussions in June 1991, the group drafted a resolution in support of maintaining the capability of launching AXAF on a Titan IV. If AXAF is launched on a Titan IV, the observatory's design will have to be modified and NASA will have to buy the Titan IV. NASA currently estimates that the cost for modifications will range between $117 million and $286 million, depending on when the launch vehicle decision is made. Much of the modification cost is associated with equipping AXAF with an Integral Propulsion System, which will be needed to boost the observatory to its required orbit. The estimated cost of a Titan IV is $250 million. NASA estimates a 40-month lead time will be needed to purchase an expendable vehicle. To support the planned 1999 AXAF launch date, NASA's decision regarding a Titan IV launch will be required by mid 1995.

NASA's fiscal year 1992 budget request does not include funding for the advanced solid rocket motor development. According to the AXAF program manager, if the advanced motors are not available, NASA will have to incorporate an integral propulsion system into the AXAF design and may have to launch AXAF on a Titan IV.

Even if the advanced motors are available, NASA may equip AXAF with its own propulsion system. AXAF will have to be reboosted at least twice during its lifetime to maintain its orbit. According to the AXAF project manager, the propulsion system could be used for this purpose, eliminating the need for dedicated shuttle missions. Project officials told us that, to prevent expensive redesign, a decision on the propulsion system will have to be made before the Preliminary Design Review, currently scheduled for December 1993. NASA currently estimates the cost of the propulsion system at about $50 to $60 million.

NASA's current AXAF cost estimate includes reserves to cover changes that may occur during development. If NASA chooses to incorporate the modifications necessary to launch AXAF on a Titan IV vehicle or to incorporate the Integral Propulsion System, it may consider using some of the program reserves to cover the cost, according to the program

[1]The AXAF Science Working Group includes the project's principal investigators, telescope scientist, and interdisciplinary scientists. It assists the project in scientific matters, and it is chaired by the AXAF project scientist.

manager. However, that would significantly deplete reserves available for other changes, such as technical problems, that may arise during development.

NASA has already used a portion of the reserves to offset some of the cost increases that have occurred. Prior to the April 1991 program rephasing, the estimate included a reserve of $474.2 million, or about 43 percent of remaining development cost. After the rephasing, the estimate included a reserve of $385.8 million, or about 31 percent of remaining cost. There is no standard for how much reserve should be included in a project's cost estimate. However, during past reviews NASA's cost estimating officials told us that a 30-percent reserve was a good "rule of thumb" for complex programs prior to their critical design reviews.

Outer Mirrors Pass Feasibility Demonstration Test

On the basis of predictive and actual test results, NASA believes AXAF's outer mirrors exceed the requirement of 0.5 arc second resolution. In addition, NASA's preliminary analysis indicates that the mirrors will meet the contractual standard for collecting and focusing X-rays. However, to ensure that the observatory will meet its objectives, five more pairs of mirrors must be fabricated and tested. Tests of the entire mirror assembly are not scheduled until 1997.

AXAF's performance is stated in terms of (1) mirror resolution and (2) the amount of X-ray energy focused into a specified area, or encircled energy. The observatory is being designed to achieve a mirror resolution of 0.5 arc seconds. Encircled energy is the percentage of available energy that the observatory will collect and focus at various X-ray intensity levels. NASA has established contractual standards requiring that AXAF be able to collect up to 90 percent of low-intensity X-ray energy and up to 16 percent at high-intensity energy levels within a circle having a 1 arc second diameter.

Predictive Testing

Before conducting actual X-ray tests, NASA used metrology instruments at the mirror fabrication contractor's facility in Connecticut to assess the quality of the first mirror pair. These instruments included devices to measure the roundness, diameter, and surface roughness of the mirrors. NASA then used the data to predict the observatory's mirror resolution and energy collection capabilities.

NASA's analysis showed that the mirrors would achieve a 0.43 arc second resolution. It also predicted that when all six pairs of mirrors were fabricated and assembled, the contractual requirement for encircled energy would essentially be met.

Each mirror pair includes one paraboloid and one hyperboloid mirror.[1] The preliminary performance predictions showed that the first hyperboloid mirror performed much better than the first paraboloid mirror, but together the pair essentially satisfied overall performance requirements. According to AXAF engineers, the hyperboloid mirror's performance offset the performance of the other mirror. In projecting the performance of all six pairs of mirrors, NASA assumed that the remaining mirrors would be fabricated at least as well as the first hyperboloid mirror. Project engineers and quality assurance officials believed this was a valid assumption

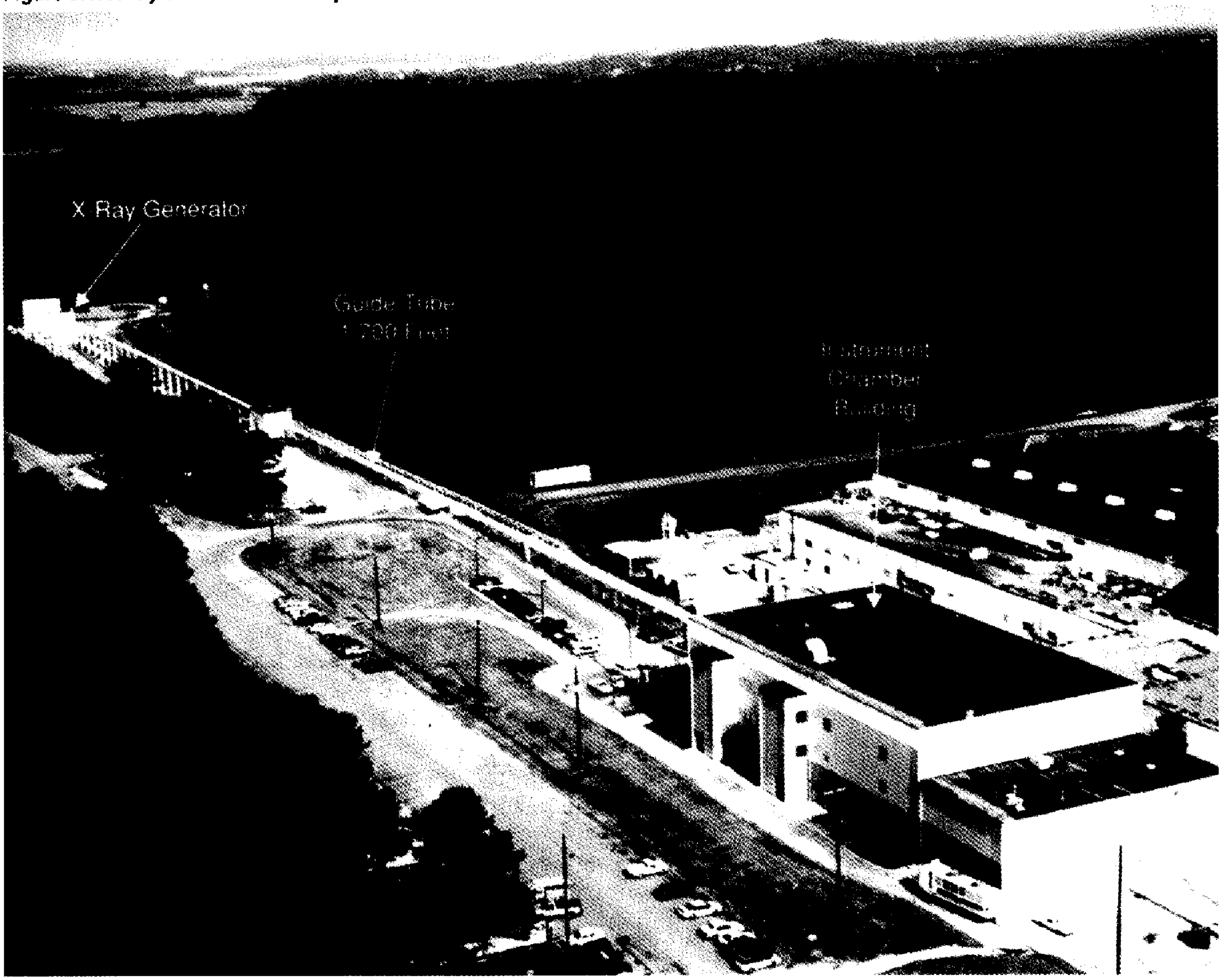
[1]To obtain a precise focus, each X-ray must be reflected by two mirrors, ground to slightly different shapes. They are called paraboloid and hyperboloid, referring to the geometric curvature.

because the paraboloid mirror was polished first and experienced problems that are not likely to occur again.

X-ray Testing

In August 1991, NASA brought the outer mirrors to Marshall Space Flight Center to begin testing at the X-ray Calibration Facility (see fig. 3.1). The facility consists of an instrument vacuum chamber to house the test mirrors, an X-ray generator to produce rays similar to those emanating from distant stars, and a 1,700- foot guide tube that connects the X-ray generator to the vacuum chamber. X-rays are created by the generator and travel down the guide tube to the mirrors. The mirrors then focus the rays onto detectors that are mounted behind them. The detectors sense the incoming X-rays and convert them into information that depicts how well the mirrors focused the rays. The generator, guide tube, and instrument chamber are all kept under a vacuum to prevent air from absorbing the X-rays before they reach the detectors.

Figure 3.1: X-ray Calibration Facility



On September 11, 1991, NASA announced that the outer mirrors had achieved a 0.23 arc second resolution during the X-ray testing, which was better than the congressionally imposed requirement of 0.5 arc second resolution. In announcing the results, NASA explained that the resolution was achieved after adjusting the data for conditions that would not be present in space.

Based on the raw data derived from the X-ray testing, AXAF's outer mirrors achieved a resolution of approximately 0.4 to 0.6 arc seconds. However, NASA identified a number of distorting conditions present in the test configuration. They included gravity, X-ray source distance and size, and mirror spacing. To better predict the mirror performance in space, NASA adjusted the raw data to remove the test effects. After adjusting the data, NASA reported that the mirrors achieved a resolution of 0.23 arc seconds.

After performing initial tests to measure resolution, NASA reconfigured the mirrors, in part, to derive data on encircled energy. This process involved applying pressure to the mirror ring mounts to remove the effects of gravity. As of November 1991, NASA had not completed its analysis of the encircled energy data. Project management officials told us, however, that they expected the final results to be consistent with the earlier metrology predictions.

Mirror Assembly Testing

To date only one mirror pair has been fabricated and tested. Although NASA is satisfied with the performance of that pair, the remaining five pairs of mirrors must be fabricated and tested to ensure that the observatory will meet its objectives.

In contrast to the first mirror pair, the remaining pairs of mirrors will not be tested individually in the X-ray facility. Instead, NASA plans to test the individual mirror pairs without X-rays at the manufacturing facility in Connecticut. Later, the entire mirror assembly and the science instruments together will be tested at the X-ray Calibration Facility in Alabama. To perform the X-ray tests, the mirrors will be mounted and precisely aligned in their operational configuration. Based on this test series, NASA hopes to ensure that the mirrors and the instruments will operate in orbit as designed. The testing is currently scheduled to begin in early 1997 and is to last about 8 months. NASA has not as yet developed the detailed plan for this test series.

Difficult Challenges Remain

While NASA is satisfied with mirror performance to date, many engineering challenges remain before AXAF can be launched. Some challenges relate to developing test equipment, observatory components, and science instruments, while others involve manufacturing processes. For example, test equipment used to predict performance of the largest mirrors must be modified to accommodate the smaller mirrors.

In part, because of problems with the Hubble Space Telescope program, NASA is closely monitoring AXAF's critical performance characteristics. Project officials believe all of the current and foreseeable challenges are manageable.

Test Instruments

Metrology instruments used to predict the performance of AXAF's largest mirrors were sufficient to assess that pair, but they will have to be modified to accommodate tests on the smaller mirrors. In addition, instruments capable of measuring mirror performance beyond the contractual specification have not been developed. Those instruments will be necessary to assess whether the mirrors can achieve the maximum performance goals established by NASA.

Project officials do not expect major problems in developing additional metrology instruments since the technology has been demonstrated. Nevertheless, the development program to test AXAF's first mirror pair proved more costly and technically challenging than NASA anticipated. For example, in January 1990 NASA reported that the delivery of some metrology instruments would be delayed because the time required to design, build, and integrate the equipment was longer than originally estimated.

Aspect Camera

To precisely locate X-rays from distant sources, AXAF must first be accurately aligned with celestial reference points. The spacecraft aspect camera will perform this function by monitoring star positions. The camera includes a telescope and charge coupled device technology for processing electronics. Similar cameras have flown on previous space missions, including the Hubble Space Telescope and the Galileo Spacecraft. However, in those cases they were used for imaging rather than precise alignment determinations. As a result, NASA must develop software to demonstrate a new application of existing charge coupled device technology. According to NASA, this application will require precise calibrations, but is not considered to be beyond state-of-the-art technology and methods.

X-ray Spectrometer

The X-ray Spectrometer is one of the science instruments that NASA currently plans to fly on AXAF. To function properly over its planned lifetime, the energy detectors in the spectrometer must operate at an extremely low temperature. NASA is developing a cooling device to achieve and maintain the necessary temperature. According to project management officials, if the cooling device does not work properly, the spectrometer's life expectancy could be reduced from about 4 years to 18 months.

In developing another spectroscopic instrument, NASA recognized the uncertainty associated with the development of the X-ray Spectrometer. NASA originally planned to develop the Bragg Crystal Spectrometer as a replacement if cost or technical obstacles precluded X-ray Spectrometer development. According to AXAF engineers, the Bragg will not need the cooling device being developed for the X-ray Spectrometer. AXAF engineers said that completion of interim technical milestones suggest that the X-ray Spectrometer will be developed as planned. As a result, they believe NASA should consider using both spectrometers on the observatory. NASA has not yet made a final decision on this issue.

Mirror Bonding

After all six pairs of mirrors are fabricated, they will be assembled into the final configuration. Their alignment is critical to ensure maximum system performance. The mirrors will be held in precise alignment with an epoxy bond. According to project officials, bonding technology is not new, and it has been demonstrated on other projects. However, NASA has had difficulties with mirror bonding. For example, during its Technology Mirror Assembly program, which was designed to demonstrate the feasibility of achieving AXAF's mirror requirements, the mirror assembly experienced a loss of alignment. NASA believed the problem was caused by the failure of an internal epoxy bond.

Mirror Coating

Prior to final assembly, NASA will coat AXAF's mirrors to give them the reflectivity necessary to perform properly. To date, NASA has not decided upon a technique or coating material to be used on the mirrors.

The project office is considering two techniques and at least three different coating materials. The coating process is critical to the program's success.

According to AXAF engineers, a substandard coating could affect the smoothness and reflectivity of the mirror surface, which could degrade overall performance.

NASA officials believe mirror coating will not be a problem because it is a process that has been demonstrated on previous projects. However, they acknowledge that past mirror coatings have had mixed results and the process has not yet been mastered.

NASA Is Closely Monitoring AXAF Development

In light of problems with the Hubble Space Telescope program, NASA is closely monitoring AXAF's critical performance characteristics. A Hubble investigation found that NASA had not provided adequate oversight of the testing program that contributed to a defective Hubble mirror.

To avoid repeating this situation, NASA's Associate Administrator, Office of Space Science and Applications, asked the Hubble investigation team to review the AXAF program to "... ensure that the elements inherent in the (Hubble) failure were not going to affect the success of AXAF." The team reported that "... the deficiencies ... which contributed to the ... problem are not present in the AXAF mirror fabrication and testing program..." However, the team also noted that "... the technical challenges posed by the AXAF mirror specifications are formidable ..." The team concluded that schedule and performance risk was inherent in the AXAF program.

To address the schedule and performance risks, the Congress directed NASA to structure AXAF's development program in a way to reduce the risk of a Hubble-type experience. NASA has followed the phased approach, ensuring that the mirror fabrication process was demonstrated before committing to further development.

Project officials told us that they believe all of the current and foreseeable challenges are manageable and that the program will continue to succeed. However, they acknowledge that most of AXAF's development lies ahead and that many areas will require constant monitoring and oversight.

Comments From the National Aeronautics and Space Administration

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

JAN 22 1992

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 General Accounting Office draft report entitled "Space Projects: Advanced X-Ray Astrophysics Facility: Status and Challenges". Achievement of the mirror fabrication milestones in FY 1992 was an important step in this highly visible program. The fabrication of better than one-half arc second Paraboloid 1/Hyperboloid 1 (P1/H1) mirrors in conjunction with the previously constructed and smaller Technology Mirror Assembly (TMA) mirrors established an understanding of mirror fabrication for the smallest and the largest mirror pairs to be used on AXAF. These two programs have, therefore, bracketed the experience needed to fabricate the remaining mirrors for the AXAF High Resolution Mirror Assembly (HRMA). In the process, important manufacturing performance assumptions were verified, important technical and management lessons were learned, and significant risk was removed from the AXAF development program.

There was an approximately $35 million increase in cost above the initial contractor estimates for the P1/H1 mirror fabrication work. NASA had anticipated possible technical and management difficulties during this first phase of the project and had set aside contingency funds to cover the scope and scale of the activity. This amount was sufficient to cover additional costs actually incurred in development of P1/H1.

We have provided, through our technical point of contact, comments to your evaluators.

Sincerely,

John E. O'Brien
Assistant Deputy Administrator

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