National Aeronautics and
Space Administration

Office of Inspector General
Headquarters
Washington, D.C. 20546-0001

Reply to Attn of: Office of Inspector General

June 5, 2000

The Honorable F. James Sensenbrenner, Jr.
Chairman, Committee on Science
U.S. House of Representatives
Suite 2320, Rayburn House Office Building
Washington, DC 20515-6301

Dear Mr. Chairman:

In response to your March 28, 2000, letter (Appendix A), my office has reviewed issues raised in a press report alleging misconduct during the testing of the Mars Polar Lander (MPL). We found the press report's allegations of misconduct during the testing of MPL braking thrusters to be unfounded. The story's description of the problem with MPL landing legs is somewhat more accurate but, again, we found no evidence of misconduct.

I. BACKGROUND

MPL was a robotic spacecraft intended to land near the South Pole of Mars for a planned 90-day mission to study the planet's layered polar terrain. Attached to MPL was the Deep Space 2 mission—two small probes designed to separate from the lander prior to atmospheric entry and penetrate at high speed into the Martian soil. Lockheed Martin Astronautics was the prime contractor for MPL. NASA's Jet Propulsion Laboratory (JPL) managed the program for NASA's Office of Space Science.

MPL was one of two NASA spacecraft intended to reach Mars in late 1999. The other was the Mars Climate Orbiter (MCO), which was intended to observe Mars's seasonal climate and daily weather from a low orbit around the planet. Two months before MPL's arrival at Mars, a navigation error caused MCO to burn up in Mars's atmosphere. The MCO Mishap Investigation Board, in cooperation with two other review teams, determined the cause of the MCO mission's failure and recommended a number of changes to the MPL mission to improve its chances for success.[1]

Following the loss of the MCO, NASA began acting upon the recommendations of the various MCO review boards. With the help of a MPL Mission Safety and Success Team

[1] Mars Climate Orbiter Mishap Investigation Board. *Phase I Report*. November 10, 1999.

comprised of over 50 senior JPL technical experts, the MPL team conducted detailed fault tree analyses for pending mission events, and took steps to prevent potential failures. When MPL arrived at Mars on December 3, 1999, the spacecraft's final communications with Earth before entering the Martian atmosphere suggested that all systems were functioning properly. Communications were expected to resume after MPL and the Deep Space 2 probes had landed, but no further messages were ever received. Because there were no communications between MPL and Earth during the spacecraft's descent, the reason for the MPL's loss cannot be known with certainty.

NASA convened two committees to examine the loss of MPL. On December 16, 1999, JPL appointed a Special Review Board to examine the loss of MPL and Deep Space 2. On December 17, 1999, the NASA Administrator created the Mars Program Independent Assessment Team to review the Agency's approach to robotic exploration of Mars in the wake of the MPL loss. In March 2000, one week before the release of these teams' reports, a United Press International (UPI) article (Appendix B) was published alleging that the MPL failed critical acceptance tests before launch, that this failure had been discovered by NASA just prior to MPL's arrival at Mars, and that NASA had not publicly disclosed this information.

II. REVIEW METHODOLOGY

We reviewed numerous documents concerning MPL testing, the MPL failure, and the MPL investigation. In addition, we contacted individuals involved in the MPL program, the UPI article, and the MCO and MPL failure investigations.

Documents reviewed included:

- The UPI article
- NASA's initial response to the UPI article[2]
- The report of the JPL Special Review Board[3]
- The report of the Mars Program Independent Assessment Team[4]
- The report of the MCO Mishap Investigation Board[5]
- NASA's response to Congressional inquiries about MPL and the UPI story[6]
- Portions of the contracts between JPL and Lockheed Martin and between Lockheed Martin and its subcontractors

[2] NASA's Response To UPI's March 21 Mars Polar Lander Story. NASA Press Release 00-43. March 22, 2000.

[3] JPL Special Review Board. *Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions*. Report JPL D-18709. March 22, 2000

[4] Mars Program Independent Assessment Team. *Mars Program Independent Assessment Team Summary Report*. March 14, 2000.

[5] *Phase I Report*. Mars Climate Orbiter Mishap Investigation Board. November 10, 1999.

[6] Letter from the NASA Associate Administrator for Legislative Affairs to the Honorable John McCain et al. (with enclosures). April 6, 2000.

- Test data reports for the MPL propulsion system and related systems

Individuals contacted in the course of our investigation included:
- The author of the UPI article
- A primary source for the UPI article
- Members of the MCO Mishap Investigation Board, the JPL Special Review Board on MPL and Deep Space 2, and the Mars Program Independent Assessment Team
- NASA/JPL officials associated with the MPL program

III. FINDINGS

The UPI article made three major claims related to the Mars Polar Lander failure:

1. MPL's braking thrusters failed acceptance testing during the spacecraft's construction. When the catalyst beds used in the engine were tested at the low temperatures that would be experienced at Mars, the ignition failed or was too unstable to be controlled. Rather than begin an expensive and time-consuming redesign, an unnamed space official altered the conditions of the testing until the engine passed.

The thruster manufacturer, Primex Aerospace (Primex), viewed the MPL thrusters as sufficiently similar to existing thrusters so as to not require extensive testing. Only a few qualification tests were conducted on a prototype thruster in 1996.[7] These tests focused on determining whether the thruster could produce the correct thrust and survive the vibration environment it would experience in the mission. Primex did not conduct low-temperature tests (the lowest planned test temperature was 70^{o} F) because it felt that the thrusters were similar enough to other thrusters that had been qualified to work at low temperatures.[8]

The twelve thrusters actually used in the MPL were acceptance tested prior to flight. The primary goal of these tests was to verify the workmanship of the thrusters. Consistent with industry practice, no low-temperature tests were conducted. Minor problems were found with some of the thrusters, but those were either accepted as meeting requirements or fixed with rework.[9]

Finding 1: MPL's braking thrusters did not fail acceptance testing due to low temperatures. The situation described in the UPI article could not have occurred because no low-temperature acceptance or qualification tests were conducted.

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[7] The tests and results are detailed in *MR-107 Thruster Demonstration Test Report*. Report No. 96-R-2045 submitted to Lockheed Martin Technologies, Inc. by Olin Aerospace Company.

[8] The NASA/Lockheed/Primex review team responding to questions about the thruster testing stated that this qualification process "lacked the full formality and rigor that would have been desirable" but was "accepted by Lockheed Martin Astronautics and was not arbitrary and capricious."

[9] None of the problems were related to the temperature at which the test was conducted. Detailed reports of each acceptance test are included in Primex Aerospace Company End Item Data Packages P/N 33095-301 S/N 005, 006, 009, 010, and 011, and in P/N 33095-303 S/N 007, 008, 013, and 014.

2. Prior to MPL's arrival at Mars, a review board identified a temperature-related design flaw within the braking thrusters that doomed the mission. By the time the problem was discovered, it was too late to do anything about it and NASA made no public disclosure of the problem.

The MCO Mishap Investigation Board identified a potential problem with the operation of MPL's descent thrusters in cold temperatures during an October 1999 review of the MPL propulsion system. The Board found that the propulsion system might be too cold to operate successfully by the time MPL got to Mars.

The Board's Phase I report, which was released to the public at a press conference (and made available on the web) on November 10, 1999, discussed the problem and recommended a solution.[10] Even before the release of the report, NASA, Lockheed Martin, and Primex performed analyses and conducted a series of thermal tests of the thruster (including its connection to the spacecraft)[11] to better understand the problem. By November 22, 1999, NASA and its contractors determined that the problem could be solved by turning on the heaters attached to the propellant feed lines five and a half hours prior to use. This solution was successfully tested on the ground and implemented.[12] Available evidence suggests that the solution worked.[13]

Finding 2: More than a month before MPL's arrival at Mars, the MCO Mishap Investigation Board identified a potential problem with the operation of the MPL descent thrusters due to cold temperatures. This information was made available to the public 23 days before MPL reached Mars. NASA and its contractors moved rapidly to analyze the problem, conduct tests, and develop a solution. Data from MPL prior to its entry in the Martian atmosphere suggests that the solution was effective.

3. MPL's three landing legs contained small microswitches that send a signal when the legs touch down. The signal tells the probe's engines to cease firing. Post-accident tests

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[10] One of the report's recommendations was that "the MPL team examine the [propulsion system's] thermal analysis and determine when the heaters on the lines feeding the thrusters should be turned on to ensure adequate, stable liquid flow with sufficient positive margins."

[11] Details of the test are contained in *Mars Polar Lander Descent Thruster MR-107N Cold Start Verification Test Report*. Report MSP-99-4070. November, 1999.

[12] *Mars Polar Lander Descent Thruster MR-107N Thermal Analysis Verification Test Report*. Mars Surveyor Operations Document MSOP-00-0003. February, 2000.

[13] There were very few temperature sensors in MPL's propulsion system, so it is impossible to be 100 percent sure that the solution sufficiently warmed all critical parts of the thruster. However, the ground tests of the propulsion system indicated that if the heaters were turned on at the correct time and operated normally, the propulsion system would work properly. Telemetry sent from MPL just prior to Mars entry verified that the heaters were turned on at the correct time and were operating normally.

showed that the switches accidentally trigger when the legs unfold during final descent. At Mars, this would have caused MPL's computer to shut off the engines while the probe was still high above the surface. An integrated end-to-end test that would have detected the problem was not performed due to budget and time constraints.

The MPL's three landing legs were kept in a stowed position during launch and the spacecraft's journey to Mars. They were designed to deploy into position for landing when the MPL had descended to 1,500 meters above the surface of Mars. Each leg had a magnetic sensor to detect when it touched the planet's surface. When the sensors detected touchdown, the flight software would send a signal to shut down the MPL's thrusters.

During MPL development, tests of the landing legs found that the magnetic sensors usually generated a false touchdown signal when the legs were deployed. To solve the problem, MPL systems requirements stated that all touchdown signals generated before the spacecraft descended to 40 meters above the surface should be ignored. However, the flight software requirements did not properly implement this system requirement. The result was that when the spacecraft descended to 40 meters above the surface, the touchdown signal from leg deployment was still in the system, causing the engine to shut off. At Mars, this would have resulted in the MPL hitting the surface at approximately 22 meters per second (50 mph), causing the loss of the spacecraft. Review teams have determined that this was the most probable cause of the loss of the MPL. [14]

This failure mode was not easy to detect analytically. The software error was not detected during software "walkthroughs" or when the software was presented to the review teams created after the loss of the MCO. According to the JPL Special Review Board, the problem was only found during a test run of the similar Mars 2001 Lander when, early in a landing test, a test engineer accidentally pushed a button sending the "touchdown" signal, resulting in the premature shutdown of the thrusters later in the test. [15]

The failure mode, however, probably could have been detected with additional testing. An end-to-end test of the MPL landing legs was conducted on June 4, 1998. During the test, the magnetic sensors did not generate a false touchdown signal during leg deployment and thus the command to shut down the engine early was not sent. The leg sensors also failed to detect touchdown during this test. After the test, the sensors were found to be incorrectly wired and thus incapable of sending any signals. After the wiring was repaired, the ability of the sensors to detect a touchdown was verified, but the full test (including leg deployment) was not repeated.

If the end-to-end leg test had been repeated after the sensor wiring was repaired, the problem should have been found. One of the "lessons learned" in the report of the JPL Special Review Board was: "When important tests are aborted or are known to be flawed due to configuration

[14] JPL Special Review Board. *Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions.* Report JPL D-18709. March 22, 2000

[15] JPL Special Review Board. *Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions.* Report JPL D-18709. March 22, 2000

errors, they must be rerun after the configuration errors are fixed. If any software or hardware involved in a test are changed, the test must be rerun to demonstrate the correct functionality."

Finding 3: Premature engine shutdown caused by a software error related to the landing leg touchdown sensors has been found to be the most likely cause for the loss of the Mars Polar Lander. An end-to-end test that should have detected the error was conducted, but a hardware problem during the test prevented the error from being found. The test was not rerun after the hardware problem was fixed. If the test had been rerun after the fix, the error would probably have been detected.

We hope this information fully responds to your inquiry. Should you or your staff want to discuss these issues further, please feel free to call me at (202) 358-1220.

Sincerely,

Roberta L. Gross
Inspector General

2 Enclosures:
Appendix A: Letter requesting OIG review
Appendix B: UPI Article on Mars Polar Lander

Appendix A

Letter Requesting OIG Review

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE
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March 28, 2000

The Honorable Roberta Gross
Inspector General
National Aeronautics and Space Administration
300 E Street, S.W.
Washington, D.C. 20546

Dear Ms. Gross:

A recent press report published by UPI asserts that Lockheed Martin engineers were unable to successfully fire the Mars Polar Lander's braking thrusters during acceptance testing. When the thrusters did not perform as expected, the test conditions were altered until the thrusters passed.

The same story also asserts that a second engineering design flaw was found to exist on extension of the landing legs. Microswitches apparently were triggered erroneously by the legs' deployment, causing the computer to prematurely shut down the thrusters. According to the story, the Mars Polar Lander landing system was never ground tested in an integrated manner that would have produced this result.

I ask that your office initiate an investigation of this episode to determine the merits of this story (attached). If it proves true, can you identity any responsible individuals and determine whether they may have violated any federal laws or statutes?

I look forward to your response.

Sincerely,

F. JAMES SENSENBRENNER, JR.
Chairman

FJS/egf
Attachment

Appendix B

UPI Article on Mars Polar Lander

NASA knew Mars Polar Lander doomed

United Press International - March 21, 2000 15:01

By James Oberg, UPI Space Writer
HOUSTON, March 21 (UPI)

The disappearance of NASA's Mars Polar Lander last December was no surprise to space officials, UPI has learned.

Prior to its arrival at Mars, a review board had already identified a fatal design flaw with the braking thrusters that doomed the mission, but NASA withheld this conclusion from the public.

The probe was lost while attempting to land near the martian south pole on December 3. Two small microprobes which had deployed separately also were never heard from again. It was the second expensive setback for American interplanetary exploration in less than three months. On September 23, a companion probe had been destroyed when a navigation error sent it skimming too deeply into the atmosphere of Mars.

Following these failures, NASA commissioned several expert panels to review the accidents and recommend improvements in NASA procedures.

A source close to the panel probing the second accident has told UPI that its conclusions are "devastating" to NASA's reputation. Unlike the previous accident, where management errors merely prevented the recognition of other human errors, in this case it was a management misjudgment which caused the fatal flaw in the first place.

"I'm as certain as I can be that the thing blew up," the source concluded.

As explained privately to UPI, the Mars Polar Lander vehicle's braking thrusters had failed acceptance testing during its construction. But rather than begin an expensive and time-consuming redesign, an unnamed space official simply altered the conditions of the testing until the engine passed.

"That happened in middle management," the source told UPI. "It was done unilaterally with no approval up or down the chain of command."

The Mars Polar Lander employed a bank of rocket engines which use hydrazine fuel. The fuel is passed through metal grates which cause it to decompose violently, creating the thrust used by the engines.

These metal grates are called "catalyst beds," or "cat beds." Their purpose is to initiate the explosive chemical reaction in the hydrazine.

"They tested the cat bed ignition process at a temperature much higher than it would be in flight," UPI's source said. This was done because when the cat beds were first tested at the low temperatures predicted after the long cruise from Earth to Mars, the ignition failed or was too unstable to be controlled.

So the test conditions were changed in order to certify the engine performance. But the conditions then no longer represented those most

likely to occur on the real space flight. Following the September loss of the first spacecraft due to management errors, NASA had initiated a crash review of the Mars Polar Lander to identify any similar oversights. According to UPI's source, the flaws in the cat bed testing were uncovered only a few days before the landing was to occur on December 3. By then it was too late to do anything about it.

Garbled rumors of some temperature-related design flaw circulated in the days before the landing attempt. However, as in the September case when space officials possessed terrifying indications of imminent failure even before the arrival at Mars, NASA made no public disclosure of these expectations.

The Mars Polar Lander investigation team has also reportedly identified a second fatal design flaw that would have doomed the probe even if the engines had functioned properly. The three landing legs of the probe contain small microswitches which are triggered when the legs touch the surface. This signal commands the engines to cease firing. Post-accident tests have shown that when the legs are initially unfolded during the final descent, springs push them so hard that they "bounce" and trigger the microswitches by accident. As a result, the computer receives what it believes are indications of a successful touchdown, and it shuts off the engines. Since this false signal actually occurs high in the air, the engine shutdown automatically leads to a free fall and destructive high-speed impact. Ground testing prior to launch apparently never detected this because each of the tests was performed in isolation from other tests. One team verified that the legs unfolded properly. Another team verified that the microswitches functioned on landing. No integrated end-to-end test was performed due to budget and time constraints. But UPI has been privately told that "this has been reproduceable on a regular basis" in post-flight tests. Perhaps by coincidence, in a safety memo to NASA employees distributed on March 20, NASA administrator Dan Goldin stressed "the importance of adequate testing." Reliability, he said, "requires well-thought-out verification and test activities." Goldin explicitly described the adverse impact of "our difficulties with recent failures in late stages of development -- such as system integration and testing -- and during mission operations." The memo did not specifically attribute these problems to the Mars failures.

The Mars Polar Lander also deployed two small "penetrator" probes, both called Deep Space 2. They were designed to fall freely through the thin atmosphere, hit the ground at about 200 meters per second (400 miles per hour), and come to rest deep in the soil. All attempts to pick up radio signals from these probes, relayed via another spacecraft already orbiting Mars, also failed. Reportedly, the review board believes that the probe radio equipment could not have survived the impact.

Alternately, the probes may simply have hit ground too rocky for survival. Engineers also suspected that their batteries, which had been charged before launch almost a year earlier and not checked since then, might not have retained sufficient power. "Nobody in the know really expected either of the penetrators to work," UPI's primary source said.

Dr. Carl Pilcher, head of NASA's planetary program, talked with space scientists at last week's Lunar and Planetary Science Conference in Houston. While expressing disappointment at the setbacks and skepticism of ambitious flight schedules -- "Our ambition exceeded our grasp," he

told the scientists -- he would not discuss the results of the accident investigation.

The conclusions, he did admit, "make sober reading." The investigation was led by Tom Young, a former manager at NASA's Jet Propulsion Laboratory which runs most of NASA's deep space probes.

"Goldin recently told his managers that the Young report will be the Rogers Commission of space science," Andrew Lawler wrote in the March 10 issue of Science magazine, "referring to the devastating critique delivered by a panel that examined the 1986 Challenger disaster." And in a March 9 internal memo from JPL director Ed Stone, which UPI has obtained, space workers are warned that "the days ahead may at times be difficult." According to Lori Garver, NASA's associate administrator for plans, the report on NSA's failures will be reviewed internally and then will be sent to the White House before being released to the public.