LEWIS SPACECRAFT MISSION FAILURE INVESTIGATION BOARD

FINAL REPORT

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LEWIS SPACECRAFT MISSION FAILURE INVESTIGATION BOARD

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LEWIS SPACECRAFT MISSION FAILURE INVESTIGATION BOARD REPORT

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EXECUTIVE SUMMARY

The Lewis Spacecraft Mission Failure Investigation Board was established to gather and analyze information and determine the facts as to the actual or probable cause(s) of the Lewis Spacecraft Mission Failure. The Board was also tasked to review and assess the "Faster, Better, Cheaper" Lewis spacecraft acquisition and management processes used by both NASA and the contractor in order to determine if they may have contributed to the failure. The investigation process used by the Board was to individually interview all persons believed to have had a substantial involvement in the Lewis spacecraft acquisition, development, management, launch, operations and the events that may have led to the eventual loss. These interviews were aimed at not only understanding the facts as they occurred but also at understanding the individual perceptions that may have been instrumental in the decisions and judgments as made on this Program.

The Board found that the loss of the Lewis Spacecraft was the direct result of an implementation of a technically flawed Safe Mode in the Attitude Control System. This error was made fatal to the spacecraft by the reliance on that unproven Safe Mode by the on orbit operations team and by the failure to adequately monitor spacecraft health and safety during the critical initial mission phase.

The Board also discovered numerous other factors that contributed to the environment that allowed the direct causes to occur. While the direct causes were the most visible reasons for the failure, the Board believes that the indirect causes were also very significant contributors. Many of these factors can be attributed to a lack of a mutual understanding between the contractor and the Government as to what is meant by Faster, Better, Cheaper. These indirect contributors are to be taken in the context of implementing a program in the Faster, Better, Cheaper mode:

- Requirement changes without adequate resource adjustment
- Cost and schedule pressures
- Program Office move
- Inadequate ground station availability for initial operations
- Frequent key personnel changes
- Inadequate engineering discipline
- Inadequate management discipline

The Board strongly endorses the concept of "Faster, Better, Cheaper" in space programs and believes that this paradigm can be successfully implemented with sound engineering, and attentive, and effective management. However the role changes for Government and Industry are significant and must be acknowledged, planned for and maintained throughout the program. Since these roles are fundamental changes in how business is conducted, they must be recognized by all team members and behaviors adjusted at all levels. The Board observed an attempt during the early phase of the Lewis Program to work in a Faster, Better, Cheaper culture,

but as the Program progressed the philosophy changed to business as usual with dedicated engineers working long hours using standard processes to meet a short schedule and skipping the typical Government oversight functions.

Based on observations from the Lewis Program, the Board offers the following recommendations in order to enhance mission success in future programs performed under this new paradigm:

Balance Realistic Expectations of Faster, Better, Cheaper.
Meaningful trade space must be provided along with clearly articulated priorities. Price realism at the outset is essential and any mid-program change must be implemented with adequate adjustments in cost and schedule. This is especially important in a program that has been implemented with minimal reserves.

Establish Well Understood Roles and Responsibilities.
The Government and the contractor must be clear on the mutual roles and responsibilities of all parties, including the level of reviews and what is required of each side and each participant in the Integrated Product Development Team.

Adopt Formal Risk Management Practices
Faster, Better, Cheaper methods are inherently more risk prone and must have their risks actively managed. Disciplined technical risk management must be integrated into the program during planning and must include formal methods for identifying, monitoring and mitigating risks throughout the program. Individually small, but unmitigated risks on Lewis produced an unpredicted major effect in the aggregate.

Formalize and Implement Independent Technical Reviews
The internal Lewis reviews did not include an adequate action response and closure system and may have received inadequate attention from the contractor’s functional organizations. The Government has the responsibility to ensure that competent and independent reviews are performed by the Government, the contractor, or both.

Establish and Maintain Effective Communications
A breakdown of communications and a lack of understanding contributed to wrong decisions being made on the Lewis program. For example the decision to operate the early on orbit mission with only a single shift ground control crew was not clearly communicated to senior TRW or NASA management. The Board believes that, especially in a “Faster, Better, Cheaper” program these working relationships are the key to successful program implementation.

Although this report necessarily focused on what went wrong with the Lewis Program, much also went right due to the skill, hard work, and dedication of many people. In fact, these people completely designed, constructed, assembled, integrated and tested a very complex space system within the two-year goal and probably came very close to mission success.

INTRODUCTION

The Lewis Spacecraft was procured by NASA via a 1994 contract with TRW, Inc., and launched on 23 August 1997. Contact with the spacecraft was subsequently lost on 26 August 1997. The spacecraft re-entered the atmosphere and was destroyed on 28 September 1997.

The Lewis Spacecraft Mission Failure Investigation Board was established to gather and analyze information and determine the facts as to the actual or probable cause(s) of the Lewis Spacecraft Mission Failure. All pertinent information concerning the failure, and recommended preventive measures to preclude similar failures on future missions, were to be addressed in a report to the NASA Associate Administrator for Earth Science Programs. Because of the programmatic experimental nature of the Small Satellite Technology Initiative (SSTI) Program, the Board was also tasked to review and assess the Lewis spacecraft acquisition and management processes used by both NASA and the contractor in order to determine if they may have contributed to the failure.

The investigation process used by the Board was to individually interview all persons believed to have had a substantial involvement in the Lewis spacecraft acquisition, development, management, launch, operations and the events that may have led to the eventual loss. These interviews were aimed at not only understanding the facts as they occurred but also at understanding the individual perceptions that may have been instrumental in the decisions and judgments as made on this Program.

The Board wishes to acknowledge the contributions of all of those interviewed. To a person, all were open, forthright and professional. The Board also wishes to acknowledge the Failure Review Board, chartered by TRW and chaired by Vice Admiral David Frost (Retired), to perform an independent internal investigation, for their help by sharing their technical findings.

BACKGROUND

SSTI Program Description

The SSTI Program was intended to validate a new approach to the acquisition and management of spacecraft systems by NASA and to simultaneously produce an implementation that leverages U.S. technology investments. The stated objectives were to reduce costs and development time of space missions for science and commercial applications. Specifically, the Program was to demonstrate new small satellite design and qualification methods and proactively promote commercial technology applications while producing valued science data that was based on new technologies. This effort was to use a new approach of "Faster, Better, Cheaper" acquisition and management by NASA and the contractor. This provided for minimal oversight involvement by the Government in the implementation of the effort and shifted a larger responsibility role to the contractor than was standard practice at that time. The concept was to implement the Program using Integrated Product Development Teams (IPDT) that included industry, the science community, academia and the Government.

The development of the SSTI Program was initiated through a Government sponsored workshop with industry, the science community and academia participation. The workshop, titled the Small Spacecraft Technology Workshop, was held in Pasadena, California in September 1993. This workshop included participation by NASA Headquarters, several NASA Centers, numerous industry teams and representatives from academic and research organizations. All principal participants in the Lewis Program, including NASA Headquarters Code X, the Goddard Space Flight Center, the Langley Research Center and the ultimately selected Lewis Contractor, TRW, were represented at this workshop. One of the goals of the SSTI Program was to allow teams comprised of representatives from the Government, industry and academia to work together to help develop the program. The Workshop provided a forum for Integrated Product Development Team formation to occur.

Request For Proposal (RFP)

NASA Headquarters issued a planning RFP in January 1994 with industry comments received two weeks later. The actual RFP was then revised according to the information learned and reissued in February 1994. The contractors were given an option to propose either a two-years-to-launch or a three-years-to-launch program depending upon the technology infusion methodology selected. The RFP specified severe fee penalties for cost or schedule overruns. There were no Government directed Contract Deliverable Requirements List (CDRL) items and no Government specified technical requirements. Additionally there were no performance, quality assurance, or other Government standards imposed.

Contract Award

The contract for the Lewis spacecraft was awarded at a price of $57,940,026 to TRW at Redondo Beach, California on 8 June 1994. The contract was a Cost Plus Award Fee (CPAF) type that included the acquisition of the total system: the spacecraft, the ground operations system, spacecraft on orbit operations for one year, payload, systems integration, data applications, commercialization outreach, and the launch vehicle. A source evaluation board using the NASA streamlined evaluation process and managed by NASA Headquarters evaluated this proposal. TRW won the contract on the strength of their proposed implementation, technology infusion, cost and schedule. Their proposal was incorporated into the Contract by reference and TRW's Chantilly facility was established as the executing agent. The schedule from contract start to launch was two years.

As implemented by TRW, Lewis was a significantly complex, small size spacecraft. The requirements were driven by the accommodations needed for the scientific payload that included the first spaceflight version of a hyperspectral imager. The spacecraft subsystems, for the most part, had challenging performance requirements, in such areas as pointing accuracy and thermal control, resulting in a relatively complex design. The proposed launch vehicle was to be the Pegasus XL built by Orbital Sciences Corporation in Chantilly, Virginia. The spacecraft was completed in two years but launch vehicle delays caused a launch slip of over a year to August 1997.

Significant Contract Changes

The Government, with TRW concurrence, made significant contractual changes in the on-going Lewis program that changed technical and performance requirements despite the ambitious fast track schedule and the premise that no changes would be allowed. These were a change to increase the on-orbit life of the SSTI Lewis Spacecraft from a three year requirement to a five year goal and a change in the launch vehicle from a Pegasus XL to the Lockheed-Martin Launch Vehicle (LMLV). Additionally, another contract change was made in May 1996. This change established a cost cap of $64,800,000 on the program.

Spacecraft Flight Operations and Failure

Launch. The Lewis Spacecraft was launched into a 300-km parking orbit on 23 August 1997 with nominal performance by the launch vehicle. The spacecraft acquisition timer was autonomously initiated, and the solar arrays appeared to have deployed successfully. This deployment was to have been followed by an autonomously initiated sun acquisition maneuver. The parking orbit had high atmospheric drag and was intended to be transitional. The final mission orbit of 523 km was to have been achieved during the first 30 days by using the satellite's own propulsion system.

Ground operations recorded approximately twelve anomalies during the first four days following launch. The operations team resolved all but four of these anomalies. The rest of this section describes these four anomalies, the last of which led directly to the loss of the mission.

First Anomaly: Autonomous Switch Over to the B-Side Processor. An unexpected event occurred when an autonomous switch over placed the spacecraft under the control of the B-side processor. The spacecraft was launched in the A-side configuration but when first contacted after launch, it was already under B-side control. The reason for this switch over could not be ascertained from available launch event data but the possible causes of this unexpected condition include:

- an unrealistically short time-out flag set before launch;
- failure of the A-side processor;
- failure of gyro 1 or gyro 2 during launch;
- unforeseen interaction involving the solar array drive clocking position interlock with the sun acquisition position loop closure.

A limited set of simulation runs and a lack of launch event simulation fidelity may have contributed to the failure to anticipate this event. Additionally any real-time telemetry that might have been available was lost because the communication transmitter "on-off" table is zeroed-out whenever an autonomous processor switch over occurs. Therefore telemetry was lost until the on-off table was loaded into the B-side processor by ground command.

Second Anomaly: Solid State Recorder Failure. A second anomaly precluded a more meaningful understanding of the actual sequence of events. This anomaly was the inability to playback the solid state recorder (SSR) data taken during the launch event. Early attempts at playback were unsuccessful because incorrect command sequences were sent to the spacecraft. Later attempts using the command sequences from the Operations Manual were also unsuccessful. The attempted data playbacks were unsuccessful using both the A and the B-side of the spacecraft processor. Use of the redundant side of the SSR was never attempted because of a desire to preserve the data that had already been recorded. This data would have been lost if the SSR had been switched over to the redundant side. TRW has since demonstrated that the incorrect command sequence does not cause the engineering model (EM) SSR to lock up, and they were able to achieve data playback from the EM recorder when the incorrect command sequence was followed by the correct sequence. The reason for this failure has not been determined, but possible causes that have been identified are listed below.

- The command sequence used from the Operations Manual may not have been correct. This possibility arises because the Operations Manual contained a different command sequence than was used for Acceptance Testing.
- The operations team assigned to troubleshoot the anomaly was not sufficiently experienced in failures of the SSR unit. A similar problem occurred frequently during testing of the SSR unit in the factory but the acceptance test team was able to move a sequence of data pointers and then execute the read command, resulting in a successful read out of data.
- A hardware or firmware failure may have occurred within the SSR itself.

Note that throughout the initial checkout period, only one crew, serving extended shifts, conducted all of the Lewis on-orbit operations. The entire crew was given a rest period each night, only the first seven hours of which were coincident with a period when ground station coverage was unavailable. This staffing approach will be discussed later in more detail.

Third Anomaly: Contact Lost for Two Orbits, Spacecraft Reappeared in Uncontrolled Attitude Mode. A third anomaly occurred after the spacecraft had been in the normal Attitude Control System (ACS) Earth Hold mode uneventfully for approximately 45 hours using the B-side processor hardware. When the crew started operations on the morning of 25 August, they reconfigured the spacecraft back to the A-side processor which enabled the electrical power subsystem fault triggers, turned on the A-side propulsion catalyst bed heaters and turned on the reaction wheel electronics. Then came a period of about three hours when the next attempted station acquisition was unsuccessful. On the following available acquisition opportunity, orbit links were established but the spacecraft was found to be not in the expected Earth Hold mode, but was instead in an uncontrolled attitude mode with its battery partially discharged. Subsequent telemetry analyses showed that the spacecraft was off pointed from the sun about 28 degrees in pitch and yaw with its battery at a 43% depth of discharge (DOD). This is significant because this DOD implies that the battery had not received adequate charge for a substantial portion of the two orbits during which no contact was achieved. Normal spacecraft operation was then restored in the sun point thruster operated mode in which the intermediate moment of inertia axis is aligned toward the sun. This mode is the built in spacecraft “Safe Mode” but is inherently unstable without the proper active control. On the Lewis spacecraft this mode is controlled by a single 2-axis gyro that provides no rate information about the intermediate axis that is pointed toward the sun.

After verifying that the spacecraft had been stable in the sun mode for four hours of operation with its battery fully charged and operating on the A-side, the operations crew entered approximately a nine-hour rest period and ceased operations for the day. This was done in spite of the serious nature of the “cause unknown” anomalies that had already occurred, and in spite of the fact that the control center had been unsuccessful in their numerous attempts to retrieve any of the data that was locked within the solid state recorder.

Fourth Anomaly: Spin about the Principal Axis. The fourth and final (catastrophic) anomaly occurred approximately four hours after the seven-hour ground station planned unavailability period. The anomaly manifested itself as a spacecraft flat spin (a spin about its principal axis) that pointed the solar arrays edge-on to the sun. The start of the flat spin was in a period when the ground stations were available but the operations crew had not yet returned to work and therefore went initially unnoticed. By the time of the discovery of the anomaly, the battery was in a deep depth of discharge (approximately 72%). Subsequent analyses of the situation concluded that excessive thruster firings, caused by the spacecraft autonomous attempts to control in the intermediate axis mode, were sensed by the spacecraft processor which then disabled the A-side thrusters and had switched control from A-side processor to B-side processor. Excessive thruster firings on the B-side then caused the B-side thrusters to also be disabled by the processor, leaving the spacecraft uncontrolled. The single two-axis gyro was saturated, and the spacecraft was then in free drift that resulted in rotation about the principal axis, off pointing the solar array from the Sun.

At the next and final contact pass (in this low earth orbit the ground station contact times are on the order of about five minutes each), the depth of battery discharge was 82%. In preparing for this pass, the operations crew working under extreme time pressure developed what was hoped to be a recovery plan. At the start of the contact pass the B-side thrusters were enabled by ground command, and three, one-second thruster pulses were commanded in an attempt to arrest the spacecraft rotation rate. As it turns out only the first of the three commands was executed by the dying spacecraft because the operations crew had addressed the second and third commands incorrectly. The spacecraft went out of ground station contact and was subsequently never reacquired.

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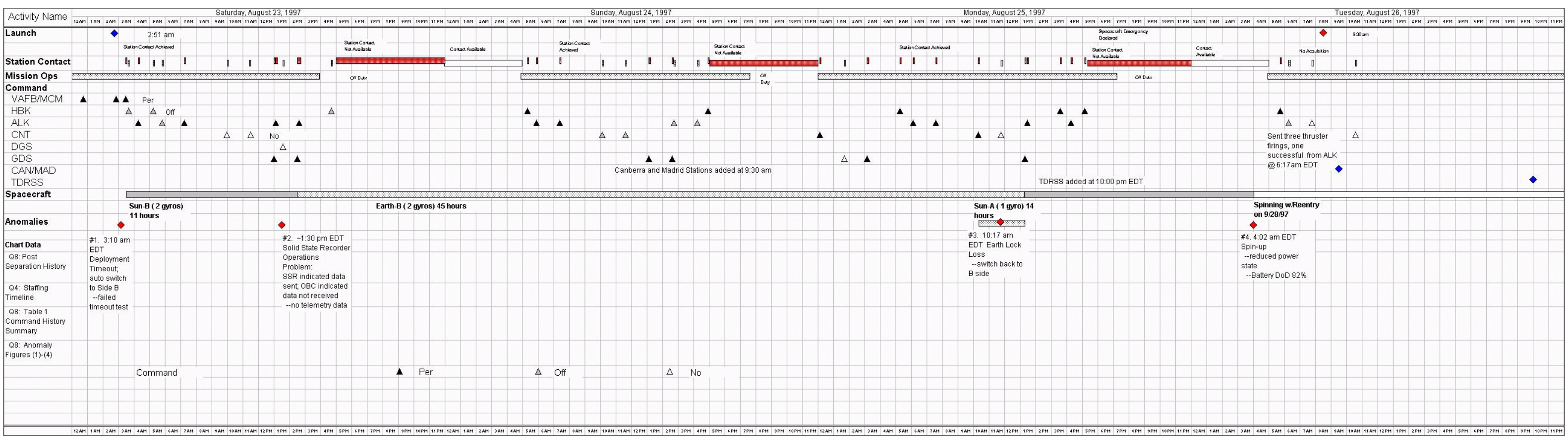


FACTORS DIRECTLY CONTRIBUTING TO FAILURE

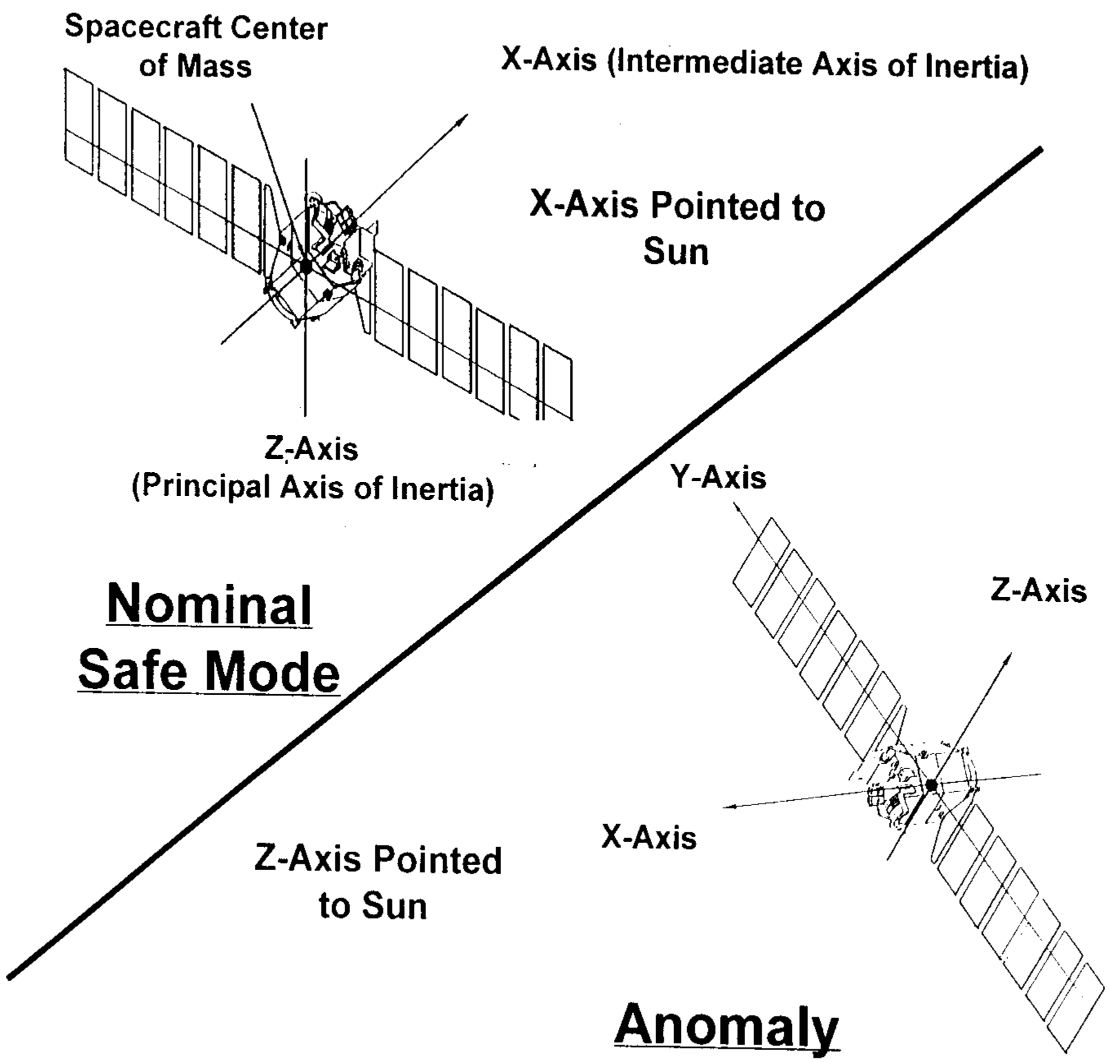
The Board believes that the loss of the Lewis Spacecraft was the result of an implementation of a technically flawed Safe Mode in the Attitude Control System. This error was made fatal to the spacecraft by the reliance on that unproven Safe Mode by the operations team and the failure to adequately monitor spacecraft health and safety during the critical initial mission phase.

Flawed ACS Design and Simulation

Flawed ACS Design. The Safe Mode was required by TRW specification to maintain the spacecraft in a safe, power positive orientation. This mode was to drive the solar panels to a predetermined clock position, to orient the spacecraft intermediate axis (the x-axis) toward the sun and to maintain that orientation autonomously using thruster firings without ground station intervention for a minimum of 72 hours in mission (523km altitude) orbit. This was implemented using a single two-axis gyro that was unable to sense rate about the spacecraft intermediate (x-axis). Therefore, when the spacecraft tried to maintain attitude control, a small imbalance, perhaps in thruster response, caused the spacecraft to spin up around the not-sensed x-axis. Because the spin was about an intermediate axis, the spin momentum started to transfer into the controlled principal axis (z-axis) causing the thrusters to fire excessively in an attempt to maintain control. The ACS processor was programmed to shut down the control system if excessive firings occurred. When both the A-side and the B-side thrusters had been shut down sequentially, the spin momentum that had been built-up in the intermediate (x) axis transferred into the principal (z) axis. This had the effect of rotating the spacecraft up to 90 degrees in inertial space causing the solar arrays to be pointed nearly edge-on to the sun. The spacecraft then drained its battery at a significantly fast rate because of the power subsystem and thermal subsystem Safe Mode design.

Flawed ACS Simulation. The operations crew, relying on the ACS Safe Mode, as validated by simulation, allowed the spacecraft to go untended for a 12-hour period. This reliance was ill founded because the simulation that was used to validate the ACS Safe Mode was flawed. The ACS design heritage was initially based on the proven Total Ozone Mapping Spacecraft (TOMS) design. The expected system performance was then analyzed using tools developed for the TOMS program. In fact, the Lewis control subsystem design was significantly more complex than TOMS because the Lewis spacecraft aligned its x-axis (intermediate/unstable), rather than its z-axis (principal/stable) of inertia toward the sun in Safe Mode. When a Lewis design modified version of the TOMS simulation was run, neither a thruster imbalance nor an initial (albeit small) spin rate about the intermediate (roll) axis was modeled. The simulation was run for about twice the 72 hour requirement and demonstrated stability under the programmed conditions. An additional factor was that the simulation was done using mission mode parameters, not low earth transfer mode parameters that represented the condition that the spacecraft was actually in at the time of these operations. The mission mode represented a more stable attitude control condition because of lower drag forces. This simulation was subsequently “validated” during a fixed base test involving spacecraft hardware. Unfortunately this validation test was done for only a 100-minute period and did not model a thruster-imbalance-on-orbit scenario. In the absence of disturbance torque that would have been imparted had thruster imbalance been modeled, the fatal flaws remained undetected.

Lewis Flawed ACS Design



- Safe Mode points x-axis to sun; x-axis spin rate not sensed; thruster imbalance caused spin about x-axis, x is intermediate/ unstable axis; thruster firings required to keep x-axis pointed to sun
- X-axis spin rate caused disturbance torques to build in other axes-resulted in excessive thruster firings; caused automonous shut down of thrusters
- Momentum vector remains fixed; in absence of active control, s/c transfers spin from X to Z axis
- Points solar array nearly edge on to sun

Inadequate Spacecraft Monitoring

Single Crew Operations. The contractor implemented single crew operations as a cost saving measure, even in the initial on orbit operations before the spacecraft was characterized and put into the more stable mission orbit. The single shift operation prevented a timely recognition of the final anomaly since no one was manning the operations at the time of the actual occurrence. This single shift operation concept was developed shortly after, and as a direct result of, the emphasis put on cost control by NASA. This emphasis on cost control was indicated to TRW by the issuance of the show cause notice in March 1995. Significantly the NASA management team did not know about the planned single shift operations, at least the planned single shift during the first 30 days operations, until after the fatal anomaly had occurred.

Failure to declare an emergency. The spacecraft exhibited several anomalies, any of which should have been enough justification to declare a spacecraft emergency and call-up additional ground station coverage and additional people. Non-recognition of the significance of these anomalies by the operations team, especially the third anomaly, was the fatal flaw.

The first anomaly was that the spacecraft was discovered, immediately after launch, in an unexpected condition. When first observed by the ground station the B-side processor was in control of the spacecraft. This signified an autonomous change from the initial launch condition that had the spacecraft under the A-side processor control. Furthermore, this B-side status was maintained for the next two days without requesting additional ground station coverage through the declaration of a spacecraft emergency. When operating on the B-side, the spacecraft is on a single string operation since an autonomous fail over back to the A-side is not a feature of this design. Therefore had the B-side processor failed during that time, the Safe Mode, flawed though it was, would have not been autonomously enabled.

The second anomaly was discovered when the solid state recorder would not play back the data previously recorded. This included all launch data that could have been helpful in analyzing the first anomaly.

The third anomaly was discovered after a two-orbit failure to acquire the spacecraft telemetry signal. The spacecraft reappeared in an uncontrolled attitude with the battery partially discharged. The operations crew again failed to declare a spacecraft emergency and, after implementing a ground commanded recovery and seeing that the spacecraft operated nominally in the Safe Mode for four hours, allowed the spacecraft to go untended for a 12-hour period.

The fourth and catastrophic anomaly occurred after the spacecraft had been left in Safe Mode with its intermediate axis of inertia pointed toward the sun with the roll rate not sensed. When the operations crew returned from a rest period, they discovered that the spacecraft was spinning at approximately two revolutions per minute about its principal axis of inertia with its solar arrays pointed nearly edge on to the sun.

The Board strongly believes that these actions were not in keeping with accepted NASA and industry practices of paying close attention to a newly launched, not-yet-checked-out asset, especially one in a low, unstable earth orbit.

FACTORS INDIRECTLY CONTRIBUTING TO FAILURE

Although the Board believes that the loss of the Lewis Spacecraft was directly due to a flawed ACS design and the failure to adequately monitor the on orbit spacecraft, during the investigation the Board also discovered numerous factors that contributed to the environment that allowed the direct causes to occur. While the direct causes were the most visible reasons for the failure, the Board believes that the indirect causes were also very significant contributors. Many of these factors can be attributed to a lack of a mutual understanding between the contractor and the Government as to what is meant by Faster, Better, Cheaper.

Requirement Changes without Adequate Resource Adjustment

A basic premise of the SSTI program was to do a fast track program from start to finish in 24 months. This was to have been facilitated by incorporating no design changes after contract award. However, the Lewis spacecraft program was to suffer two significant changes in requirements, with consequential design changes, without adequate adjustment in resources. The first requirements change involved a change of launch vehicles. The original Lewis launch vehicle, the Pegasus XL, failed shortly after Lewis contract award and the Lewis development started exhibiting weight growth. Both NASA and TRW agreed that a move to a different vehicle was an appropriate response under the circumstances. However, NASA took this opportunity to make another much more significant change. Responding to both congressional staff and science community pressure, the Lewis Program Office decided to extend the on orbit life from a three year requirement to a five-year goal. This change required some redesign due to a need to increase spacecraft consumables.

Cost and Schedule Pressure

Significant emphasis was placed on cost performance that led to the decision to go to one ground control crew operation and also limited independent reviews . Concerns about escalating cost also led to strained, if not openly adversarial relations between NASA and TRW management. Discussions on the requirement changes began in August 1994. In October, weeks before the first technical design audit (review), NASA received a previously requested Not to Exceed (NTE) proposal from TRW for the life extension. As a result, TRW received a contract change direction with a value not to exceed $3.4M on 28 October 1994, although the Government never subjected the TRW NTE to a rigorous cost analysis. However, between that October and the following March, TRW realized that a much larger impact would be caused by these changes and withdrew their proposal on 17 March 1995 suggesting significant cost increases. NASA's response was a "Show Cause and Cure" letter on 28 March 1995. NASA urged TRW to live within the constrained budget. It was at this time that TRW made the decision to go to one shift ground control crew operations even for early on orbit operations – a decision that was not known to NASA until after the on orbit failure. The TRW change proposal submitted in January 1996 unfortunately was sufficiently vague so that this decision was not readily apparent to either NASA or upper TRW management. This proposal read:

> The TRW engineers will perform shift operations in conjunction with Allied during the initial orbital subsystem and payload checkout phase and during the initial payload operations phase. Following this month period the flight operations team will transition to 1 shift/5 days/week coverage. This reduces the workload requirements to less than two persons (TRW) with the remaining tasks performed by Allied personnel. One shift per day is consistent with acquisition of 1 image per working day taken over NASA prescribed U.S. test sites.

Move from Chantilly to Redondo Beach

In January 1995, following a change in TRW Division Managers, a decision was made to move all but the ACS efforts and the Ground Operations from Chantilly to Redondo Beach. The Board believes the move itself was justified in order to meet the required schedules. However, the Board also believes that TRW erred in leaving the ACS and the Ground Operations in Chantilly, separated from the rest of the spacecraft development, integration and testing and most importantly, the ACS functional discipline support system in Redondo Beach. The ACS did not undergo sufficient independent reviews by functional experts in Redondo Beach as the other subsystems enjoyed. The Board believes that inadequate technical design review of the ACS design, simulation and test allowed the lethal ACS design flaws to be implemented on the Lewis spacecraft and go unnoticed. The ACS design flaw appears to have resulted from three things: (1) a lack of realization that a thruster imbalance could exist; (2) a belief that it was unnecessary to measure rate about the array normal/sun pointed axis; and (3) a belief that multi-gyro operation in safe mode would be compromised in the case of gyro failure. The analysis that was done should have been challenged by a technical review. In fact the Board discovered that a spacecraft of very similar ACS design was concurrently implemented on a commercial program but with the added feature of multi-gyro operation in the safe mode. This was based on an analysis that revealed that ACS instability was present due to thruster imbalance. The implementation of multi-gyro operation could have also been done for Lewis had the problem been surfaced by an adequate technical review.

The move to Redondo Beach also left the Ground Crew separated from the Integration and Test Group. This situation was further exacerbated by not having a crew-training simulator, which was originally not bid, since it was assumed the two groups would be working side by side. When the Lewis launch was delayed by over one year, the lack of a simulator resulted in inadequate contingency training.

Inadequate Ground Station Availability for Initial Operations

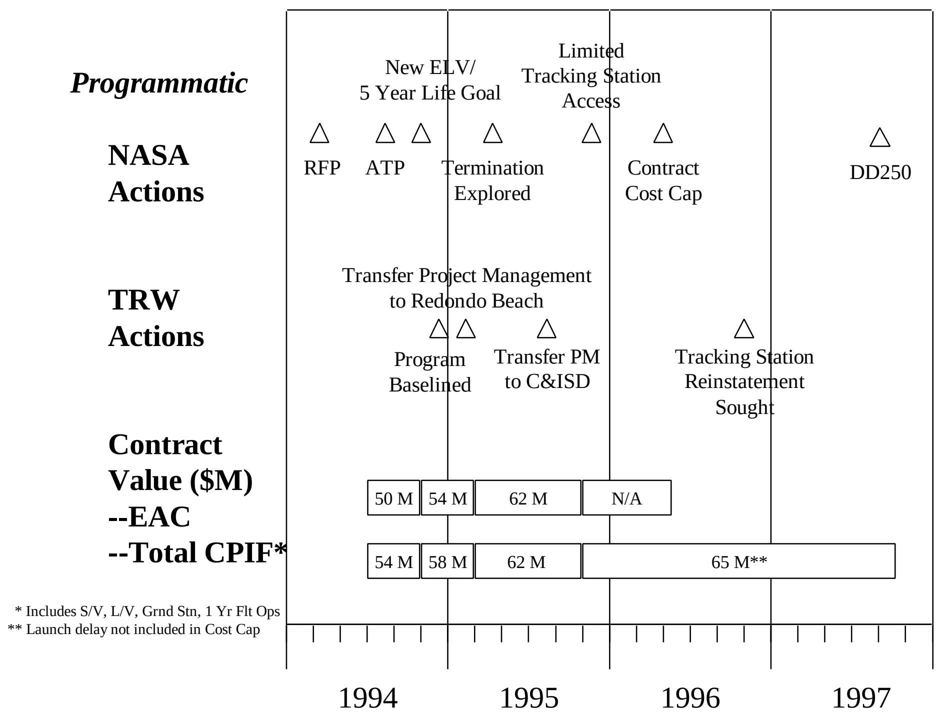
As proposed, the Lewis Program was to have a ground station pattern of coverage that provided a maximum period of on orbit non-contact of less than three hours. This situation was changed part of the way into the program because of mutual frequency interference with a classified program. The NASA ground network notified the NASA Lewis Program office that due to this conflict, coverage to be provided by the ground station network was such that a seven-hour period of non-contact with the spacecraft would occur on a daily basis. NASA and TRW management accepted this coverage, albeit with some protest and initial reservation. The coverage was accepted on the basis that the required science data would be able to be collected in spite of this reduced coverage. What apparently was not sufficiently addressed was the initial 30-day on orbit time period when the operations would be more critical due to the unstable low earth orbit and due to the unknown factors usually always associated with a newly launched, complex satellite. The Lewis upper management, on both the Government and contractor sides was apparently unaware of either the limited ground station coverage available during initial on orbit operations or of the potentially serious consequences of this reduced coverage during the early on orbit period.

The Board believes that a team more experienced in launch and early low earth orbit operations would have penetrated this issue and raised the limited coverage concern to the highest levels of management until a more acceptable solution was achieved. This lack of coverage during initial operation does not meet industry and Government accepted practice.

Frequent TRW Personnel Changes

The Lewis Program experienced a large turnover in key TRW personnel. There were four Division Managers and four Program Managers in a 14-month period. Each Division Manager had a different management philosophy with regard to achieving success. The most significant change occurred in August 1995 when Lewis was moved from the Space & Technology Division (S&TD) to the Civil & International Systems Division (C&ISD). Not only did the program management change but also numerous other personnel changes occurred including the loss of the Systems Engineer, and the Integration and Test lead engineer. A NASA perception was that a major change in philosophy also occurred at this time due largely to the move to the C&IS Division. It was believed that this shift signaled a move from “innovative processes” to “business as usual”. Informal integrated product development team meetings were stopped and focus on controlling cost became paramount. Program management relations between NASA and TRW deteriorated to an adversarial state. There are no indications that NASA management took corrective action based on this perception to assure that their Faster, Better Cheaper objective would continue to be a part of the program. This lack of action is of concern to the Board because it raises the question of how the Government viewed its role in the Faster, Better, Cheaper implementation of the program.

SSTI Lewis Program Timeline



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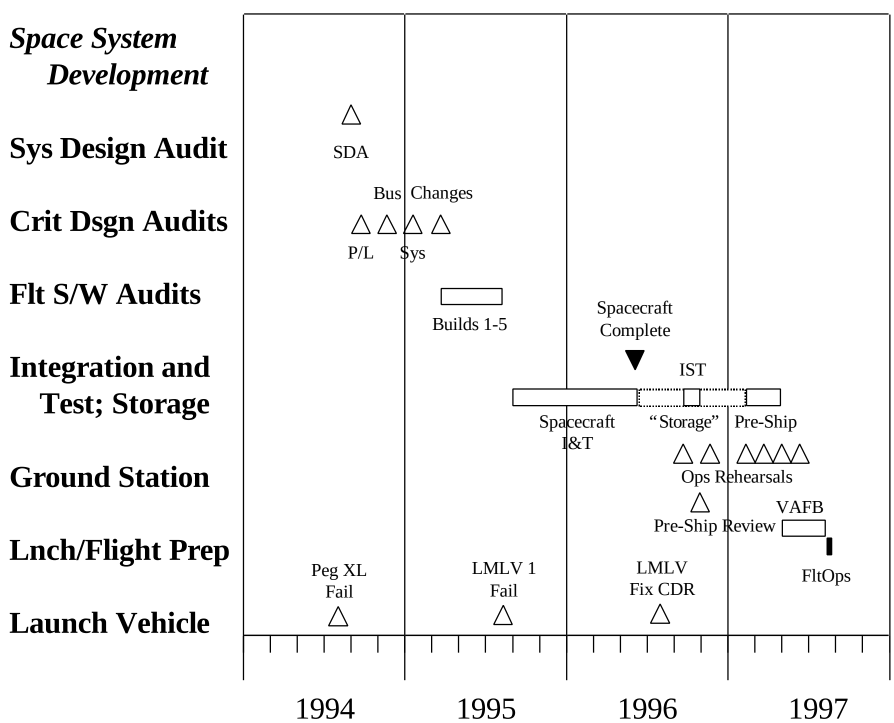
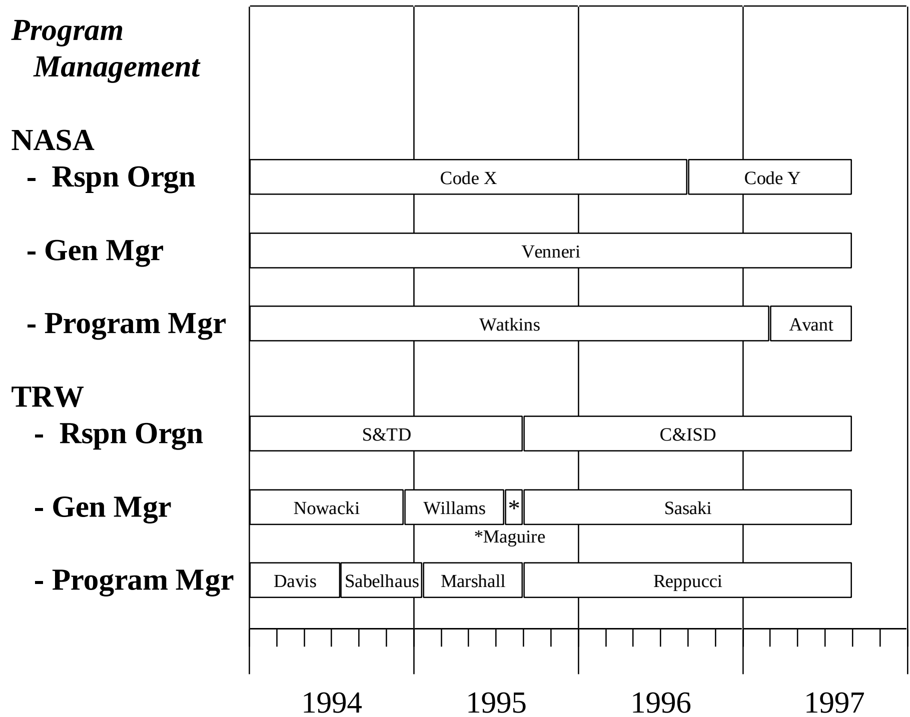


SSTI Lewis Program Timeline



Inadequate Engineering Discipline

The Board noted several deviations from the engineering rigor that is essential for successful space system development. The causes can only be speculated: cost pressures, physically separated teams, and sudden contractor empowerment through lack of Government oversight. Internal reviews by functional managers did not occur in all areas. Action items were considered closed when the person assigned to do the action believed it to be complete. Independent checks were rarely performed. Informal peer reviews were largely abandoned after August 1995. There was little evidence of in-depth contingency planning, and launch rehearsals failed to reveal the need for more than one operations crew for the first 30 days. TRW's approach to operations was that only one primary mission payload image per working day was required and that, coupled with the 72 hour Safe Mode, permitted single crew operations even for the initial 30 days.

Inadequate Management Discipline

In managing the Lewis program, the NASA management team stepped into a new role of minimal Government oversight. Their expectation was that TRW management would fill in, with internal oversight and management processes, to assure successful implementation of this relatively complex spaceflight program. However, sufficient resources were not applied from the Government side to assure that the contractor was indeed properly accepting the faster, better, cheaper challenge and implementing a program consistent with expectations. Indeed a clear definition of expectations by either side was not established. On the TRW side, their numerous changes in program and cognizant corporate management personnel had the effect of imparting small but significant changes in the philosophy of implementing this new innovative concept. In some instances the TRW management allowed implementations that were not in keeping with what the company believed to be best practice for their business. Both NASA and TRW management failed to assure that the best industry practices, appropriate to this job, were imposed and operating effectively.

The Board believes that the engineering and management discipline exhibited by NASA and TRW on the Lewis Program was not in keeping with accepted NASA and industry practices of quality, engineering rigor and program management.

IMPLICATIONS ON "FASTER, BETTER, CHEAPER"

The acquisition approach embodied in the "faster, better, cheaper" philosophy achieves essential reforms in the traditional business approach to space systems development. Major change rarely comes without some experimentation and adjustment. NASA intended Lewis, in part, to be such an experiment. The Lewis spacecraft acquisition and program implementation was a bold attempt at jump-starting this new paradigm in the Agency.

The Board strongly endorses the concept of "faster, better, cheaper" in space programs and believes that Faster, Better, Cheaper can be implemented with sound engineering and good management. However the role changes for Government and Industry are significant and must be acknowledged, planned for and maintained throughout the program. Since these roles are fundamental changes in how business is conducted, they must be recognized by all team members and behaviors adjusted at all levels. The Board observed an attempt during the early phase of the project to work in a Faster, Better, Cheaper culture. But as the project progressed the philosophy changed to business as usual with dedicated engineers working long hours using standard processes to meet a short schedule and skipping the typical Government oversight functions.

Based on observations from the Lewis Program, the Board offers the following recommendations in order to enhance mission success in future programs:

Balance Realistic Expectations of Faster, Better, Cheaper.
Meaningful trade space must be provided along with clearly articulated priorities. Price realism at the outset is essential and any mid-program change should be implemented with adequate adjustments in cost and schedule. This is especially important in a program that has been implemented with minimal reserves.

Establish Well Understood Roles and Responsibilities.
The Government and the contractor must be clear on the mutual roles and responsibilities of all parties, including the level of reviews and what is required of each side and each participant in the Integrated Product Development Team.

Adopt Formal Risk Management Practices
Faster, Better, Cheaper methods are inherently more risk prone and must have their risks actively managed. Disciplined technical risk management must be integrated into the program during planning and include formal methods for identifying, monitoring and mitigating risks throughout the program. Individually small but unmitigated risks on Lewis produced an unpredicted major effect in the aggregate.

Formalize and Implement Independent Technical Reviews
The internal Lewis review process was inconsistent, and reviews did not include an adequate action response and closure system and may have received inadequate attention from the contractor's functional organizations. The Government has the responsibility to ensure that competent and independent reviews are performed by either the Government or the contractor or both.

Establish and Maintain Effective Communications
A breakdown of communications and a lack of understanding contributed to wrong decisions being made on the Lewis program. For example the decision to operate the early on orbit mission with only a single shift ground control crew was not clearly communicated to senior TRW or NASA management. The Board believes that, especially in a "faster, better, cheaper" program these working relationships are the key to successful program implementation.

SUMMARY

This report necessarily focused on what went wrong with the Lewis Program though much also went right due to the skill, hard work, and dedication of many people. In fact, these people completely designed, constructed, assembled, integrated and tested a very complex space system within the two-year goal. While, the new “Faster, Better, Cheaper” acquisition approaches help unburden Government and industry of accumulated layers of low value added processes, it’s important that we retain and fine tune the best practices contributing to program success. The Lewis experience reinforces the importance of scrupulous attention to detail, rigorous test process application, and the role of independent audits with engineering discipline in successful space system development. Also essential to achieving success in this new environment is mutual understanding and clarity of responsibilities in the new working relationships and innovative teaming mechanisms. Making the effort remains worthwhile because the gains in lower cost and faster time to market will rapidly pay back the investment.

APPENDICES

APPENDIX A

ASSIGNMENT LETTER

1. PURPOSE

This establishes the Lewis Spacecraft Mission Failure Investigation Board and sets forth its responsibilities and membership.

2. ESTABLISHMENT

a. The Lewis Spacecraft Mission Failure Investigation Board (hereinafter called the Board) is hereby established in the public interest to gather information, analyze, and determine the facts as well as the actual or probable cause(s) of the Lewis Spacecraft Mission Failure in terms of (1) Primary Cause, (2) Contributing Cause(s), and (3) Potential Cause(s), (pertinent observations may also be addressed) and to recommend preventive measures, and other appropriate actions to preclude recurrence of a similar mishap. In view of the experimental nature of the SSTI Program and its objectives to validate new ways of doing business in space systems acquisition, the Board is also asked to review and assess the Lewis spacecraft acquisition process (from start of program definition through on-orbit operations) and program management philosophy, including risk management approaches and to develop recommendations to enhance mission success in future programs.

b. The chairperson of the board will report to the NASA Associate Administrator for Mission to Planet Earth.

3. AUTHORITIES AND RESPONSIBILITIES

a. The Board will:

1) Obtain and analyze whatever evidence, facts, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions it deems appropriate. In so doing, it may take testimony and receive statements from witnesses.

2) Impound property, equipment, and records to the extent that it considers necessary.

   Note: Impoundment may not necessarily preclude release of information. General information which would normally be released or had been released previously can continue to be released.

3) Determine the actual or probable cause(s) of the Lewis Spacecraft Mission Failure, and document and prioritize their findings in terms of (a) the primary cause(s) of the mishap, (b) contributing cause(s), and (c) potential cause(s). Pertinent observations may also be made.

4) Develop recommendations for preventive and other appropriate actions. A finding may warrant one or more recommendations or it may stand alone.

5) Provide periodic interim reports to the appointing authority, the NASA Associate Administrator for Mission to Planet Earth as requested and a final written report to same by Jan 12, 1998. The requirements in NASA Management instruction 8621.1F will be followed.

b. The Chairperson will:

1) Conduct board activities in accordance with the provisions of NMI 8621.1F and any other instructions that the appointing authority may issue or invoke.

2) Establish and document, to the extent considered necessary, rules and procedures for the organization and operation of the board, including any subgroups, and for the format and content of oral or written reports to and by the board.

3) Designate any representatives, consultants, experts, liaison officers, or other individuals who may be required to support the activities of the board and define the duties and responsibilities of those persons.

4. MEMBERSHIP

The chairperson, members of the board, and supporting staff will be government employees designated in Attachment A.

5. MEETINGS

The chairperson will arrange for meetings and for such records or minutes of meetings as considered necessary.

6. ADMINISTRATIVE AND OTHER SUPPORT

a. The Director of Goddard Space Flight Center will arrange for office space and other facilities and services that may be requested by the chairperson or designee.

b. All elements of NASA will cooperate fully with the board and provide any records, data, and other administrative or technical support and services that may be requested.

7. DURATION

The NASA Associate Administrator for Mission to Planet Earth will dismiss the board when it has fulfilled its requirements.

8. CANCELLATION

This appointment letter is automatically canceled 1 year from its effective date otherwise specifically extended by the establishing authority.

William F. Townsend
Acting Associate Administrator for
Mission to Planet Earth

ATTACHMENT:

Members and supporting staff for the Lewis Spacecraft Mission Failure Investigation Board

Chairperson:
Ms. C. Anderson, Director, Space Vehicle Directorate, USAF, Phillips Laboratory, (505-846-6243), email: anderson@plk.af.mil

Executive Secretary:
Mr. Charles Vanek, Director, Office of Flight Assurance, NASA GSFC, 301-286-6086, email: vanek@pop300.gsfc.nasa.gov

Membership:
NASA-GSFC: Mr. Richard Freeman 301-286-6422, email: richard.freeman@gsfc.nasa.gov

NOAA: Mr. Dave Furlong, 301-427-2084 ext 160, email: dfurlong@ipo.noaa.gov

NRO: Mr. Robert Pattishall 703-808-1615

USAF-SMSC: Col. Robert Preston, 310-363-5440, email: robert.preston@losangeles.af.mil

NAVY-NRL: Mr. Peter Wilhelm, 202-767-6547, email: wilhelm@ncst.nrl.navy.mil

(Ex-Officio)
NASA/HQ/QE: Mr. Steve Wander, NASA Office of Safety and Mission Assurance, 202-358-4612, email: steve.wander@hq.nasa.gov

Advisors:
NASA/HQ/AF: Mr. Sam Venneri, NASA Chief Technologist, 202-358-4600, email: sam.venneri@hq.nasa.gov

NASA/HQ/AF: Dr. Roger L. Avant, SSTI Prograrn Executive, 202-358-0690 or 301-286-0660, email: roger.avant@gsfc.nasa.gov

NASA Office of Chief Council: Mr. Greg La Rosa, 301-286-8092. (GSFC), email: glarosa@pop100.gsfc.nasa.gov

Public Affairs Office: NASA HQ, Mr. Doug Isbell, 202-358-1753, emai1: doug.isbell@hq.nasa.gov

Cousultants/Observers:
NASA/Air Force Senior NASA representative at SMC: Mr. Marcus Watkins, 310-363-5451, email: marcus.watkins@losangeles@af.mil

NASA/JPL/Mars Pathfinder Project Office, Mr. Anthony Spear, 818-393-7868, email: anthony.spear@jpl.nasa.gov

NOAA Integrated Program Office: Dr. James Duda, 301-427-2121x126, email: jduda@ipo.noaa.gov

NASA/HQ/QE (contractor): Mr. Mike McDermott: George Washington University, 202-994-8178, email: mmcderm@seas.gwu.edu

APPENDIX B

Lewis Spacecraft Failure Investigation Board Composition

Ms. Christine Anderson, Chair	Director, Space Vehicles, Air Force Research Laboratory
Dr. Richard Freeman	Chief Engineer, NASA Goddard Space Flight Center,
Mr. David Furlong	Deputy Associate Director for Acquisition, Integrated Program Office, National Polar-Orbiting Operational Environmental Satellite System (NPOESS)
Col. Alan Kirschbaum	Director, Systems Engineering, Air Force Space and Missile Systems Center
Mr. Rich Roy	Associate Deputy Director, Future Imagery Architecture Program, National Reconnaissance Office
Mr. Charles Vanek, Executive Secretary	Director, Office of Flight Assurance, NASA Goddard Space Flight Center
Mr. Steve Wander, Ex-Officio	Aerospace Engineer, NASA Headquarters, Office of Safety and Mission Assurance
Mr. Peter Wilhelm	Director, Naval Center for Space Technology, Naval Research Laboratory

APPENDIX C

Individuals Interviewed

TRW, Chantilly

Parry, Paul	Guidance, Navigation and Control Subsystem Manager
Sabelhaus, Tony	SSTI Program Manager
Zion, Phil	Operations Manager
Niemela, Lee	Mission Assurance Manager
White, Jerome	Software Engineer

TRW, Space Park

Biber, Klaus	Spacecraft Bus Manager
Brooks, Bob	Spacecraft Integration and Test Manager
Chory, Mary Ann	Avionics Systems Center Manager
Frost, David E.	AST Engineering Services, Consultant, Chair, Internal Review Board
Hannemann, Tim	Executive Vice President and General Manager, Space and Electronics Group
Lane, Linda	Configuration Control, Redundancy Management, and Test Engineer
Marshall, Don	Lewis Deputy Program Manager and Program Manager
McShane, Peter	Responsible Design Engineer for Data Management System
Nowacki, Ed	Vice President and General Manager, Space and Electronics Group
Reppucci, George	Lewis Program Manager
Reeves, Emery	Aerospace Consultant, Member, Internal Review Board
Roesler, Maribeth	GNCS Analyst (MTS Senior)
Sarina, Jim	Ground Segment Manager
Sasaki, Paul	Vice President and General Manager, Civil & International Systems Division
Schmeichel, Harry	Attitude Control & Determination Subsystem Manager on ROCSAT
Smith, Bob	Flight Software Manager
Stafa, John	Flight Software Subsystem Engineer
Susskind, Craig	Spacecraft Integration and Test Manager
Williams, Gordon	Deputy General Manager, Space & Electronics Group and Acting Vice President & General Manager, Space and Technology Division
Woods, Dick	System Engineer

HQ NASA, Washington

Avant, Roger	Program System Engineer and Program Manager
Lupis, Jeffery	Contracting Officer
Watkins, Marcus	Lewis Program Manager, NASA Program Executive
Venneri, Sam	SSTI Program Manager

APPENDIX D

Meetings Conducted

4 November 1997	NASA HQ, Washington, DC	Charter and Introduction
5 December 1997	TRW/Chantilly, VA	Interviews
11,12, 15 December 1997	TRW/Redondo Beach, CA	Interviews
16 December 1997	Los Angeles AFB, CA	Deliberations
18, 19 December 1997	NASA HQ, Washington, DC	Interviews and Deliberations
9 January 1998	NRO HQ, Westfields, VA	Report Preparation
22 January 1998	Los Angeles AFB, CA	Report Preparation

APPENDIX E

Additional Detail on the Direct Cause of the Anomaly

Inappropriate Use of Heritage Contributed to a Flawed ACS Design. The Safe Mode was required by TRW specification to maintain the spacecraft in a safe, power positive orientation. This mode was to drive the solar panels to a predetermined clock position, to orient the spacecraft intermediate axis of inertia (the x-axis) toward the sun and to maintain that orientation autonomously using thruster firings without ground station intervention for a minimum of 72 hours in mission (523km altitude) orbit. This mode utilized a single two axis gyro that measured rates about the two axes orthogonal to the spacecraft x-axis, but not about the spacecraft x-axis (the intermediate axis) itself. The control system design was claimed to have been based on a Space Park TOMS heritage design, and was analyzed using tools developed for the TOMS program in spite of significant differences that existed between the TOMS and Lewis configurations and requirement sets. The Lewis control subsystem design was more complex than TOMS. Lewis aligned its intermediate/unstable axis of inertia toward the sun while TOMS pointed it principal/stable axis of inertia toward the sun in safe mode. TOMS measured rates in 3 axes, while rate information about the intermediate axis was deemed unnecessary for Lewis. Additionally, time out logic was used to disable the Lewis thruster electronics whenever the processor detected an "excessive" string of thruster firings. This autonomous shut down would occur whenever thruster firings exceeded 225ms, in any axis, in any 61.4 second period. This feature was included to preclude an inadvertent vehicle spin-up and to preserve fuel. This feature however, would leave the spacecraft in an uncontrolled state whenever the thrusters were disabled, and a rotation about an intermediate axis of inertia is unstable whenever control authority is disabled in the other axes. In retrospect, it was determined that the use of a single gyro and the resultant failure to sense rate about the spacecraft intermediate axis in safe mode allowed thruster imbalance to spin up the spacecraft about its intermediate axis; the axis that had been pointed toward the sun. If the thrusters fired to arrest the disturbances caused by a rate build-up, the thruster drive electronics disable would trip. Because the momentum vector must remain fixed in space, the spacecraft would transfer its spin from its intermediate axis, to its maximum axis of inertia. This 90 degree rotation would have put the solar arrays nearly edge-on to the sun.

The TOMS sensitivity to thruster imbalance was evaluated using an analytic tool other than the TOMS simulation; consequently, thruster imbalance had not been modeled in the TOMS analytic simulation tool. Accordingly, the Lewis safe mode sensitivity to thrust imbalance was never evaluated.

A False Sense of Security. The Safe Haven mode was designed to provide safe and autonomous control for a minimum period of 72 hours in mission orbit. The project team fully relied on the safety and the autonomy of this mode. Because of this unfounded reliance, the project management team failed to emphasize the review process; operations training and contingency planning; and they staffed the control center with only one crew per day and left the spacecraft unattended for 12 hours per day even during the early orbit, critical phase of the mission. Finally, TRW management had not included a training simulator in its proposal because it had proposed that the integration and test activity, and its control center training would be collocated in Chantilly. This decision was never revisited once the integration and test activity was moved to Space Park.

Inadequate Validation Process. An analysis had been used to validate the safety of the Safe Haven mode for twice its 72 hour requirement, and a hardware-in-the-loop "fixed base test was used to provide additional confidence. However, the control law was verified using the TOMS analytic simulation with an abbreviated set of initial conditions, the fixed base test had been run for only 100 minutes, and both the analysis and fixed base test had assumed that the spacecraft was in its mission (rather than in its transfer) orbit. In the absence of disturbance torques that would have been imparted had thruster imbalance been modeled, the fatal flaws remained undetected. A post anomaly simulation run, with thruster imbalance disturbance torques modeled, resulted in the spin-up of the intermediate axis and a loss of control. This conclusion closely replicated the failure signature that was observed in orbit. A peer review of the validation process would probably have identified the flaws.