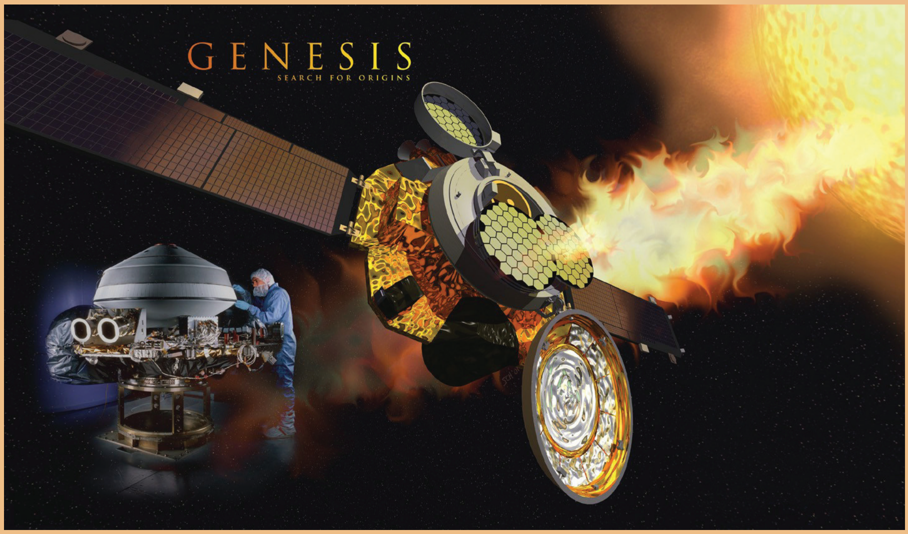
GENESIS

Mishap Investigation Board Report

Volume I



National Aeronautics and Space Administration

GENESIS Mishap Report
Volume I

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

NOV 30 2005

Reply to Attn of:

Solar System Division

MEMORANDUM FOR THE RECORD

FROM: Associate Administrator for Science Mission Directorate (SMD)

SUBJECT: Endorsement Letter for Genesis Mishap Investigation Board Report, Volume I

After SMD review of the subject report, and receipt and review of endorsements from the Office of Procurement and the Office of Safety and Mission Assurance (OSMA), I approve the Genesis Mishap Investigation Board (MIB) Report, Volume I.

I note in particular the comments in the OSMA endorsement memo that call specific attention, as does the MIB report, to the treatment of heritage design and hardware as a significant factor in the cause of the mishap. I concur with the recommendations listed in the MIB report, and agree that the corrective action plan should ensure proper emphasis is placed in the systems engineering process on heritage issues.

My office intends to work with the Office of the NASA Chief Engineer on the process to develop the corrective action plan, as the recommendations apply more broadly than just to programs within the SMD, noted as well in the OSMA endorsement memo.

I will add my voice to that of the NASA Chief of Safety and Mission Assurance in commending the MIB on the excellent report they produced.

In keeping with NASA policy, this endorsement, as well as the endorsements from the Office of Procurement and the Office of Safety and Mission Assurance, will be attached to the top of the mishap report and will be published and distributed as a part of the report.

Mary L. Cleave

cc:
Associate Administrator/Mr. Geveden
Chief Engineer/Mr. Scolese
Safety and Mission Assurance/Mr. O'Connor
Science Mission Directorate/Dr. Hartman

- Mr. Luther
- Mr. Ledbetter
- Mr. Dantzler
- Mr. Brody

GSFC/Mr. Ryschkewitsch
GSFC/Mr. Spidaliere
JPL/Dr. Elachi

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

October 12, 2005

Reply to Attn of:

Safety and Assurance Requirements Division

TO: Associate Administrator for Science Mission Directorate

FROM: Chief, Safety and Mission Assurance

SUBJECT: Endorsement Letter for Genesis Mishap Investigation Board Report

I have reviewed the Mishap Investigation Report of the Genesis Failure and recommend the report for approval. I concur that the report has been prepared as directed by the appointment letter and meets the requirements specified in NPR 8621.1 with the following comments and recommendations:

The mishap report provides a detailed description of the analysis techniques used to evaluate all the potential causes of the mishap. The report clearly articulates that the proximate cause of the mishap is the 'inverted orientation of the G-switch sensors on the relay cards of the Sample Return Capsule-Avionics Unit boxes.' The report provides an excellent event and causal factor tree that traces this proximate cause, and other failed controls that would have detected this design error to their corresponding root causes. In some cases (e.g., Root Cause #1.1, 2.3, and 5.1), the analysis falls a little short, and stops at an intermediate cause rather than a root cause. However, overall, the depth of the root cause analysis is adequate to understand the underlying causes of the mishap so that they can be addressed in the corrective action plan. For each cause/finding, the mishap report includes sufficient facts to adequately substantiate the findings. The report provides a table that clearly illustrates how each finding is addressed by one or more recommendations.

I concur with the recommendations listed in the report and ask that they all be included in the corrective action plan with the following changes:

MIB's Recommendation 1: *"Institute a Systems Engineering Plans, Progress, and Processes Review for all Science Missions Directorate projects as part of the normal Project Design Review process."*

Since the failure to detect the design error occurred because of assumptions made that heritage hardware required less vigilance and review than new hardware, it would make sense to emphasize additional reviews that focus specifically on the use and verification of heritage hardware. Specifically, systems engineering analysis and updated failure modes and effects analysis should be done for modifications to the hardware or software regardless of the scope or size of the change. This recommendation should be extended to encompass projects managed by the Exploration Systems Mission Directorate (ESMD), requiring host centers to develop a process to ensure that "heritage software and hardware" used in the Crew Exploration Vehicle (CEV)/Crew Launch Vehicle (CLV) is adequately verified, validated and tested.

MIB's Recommendation 10: *"Reverification of all requirements should be required until existing heritage verification can be certified as adequate by the responsible engineer and demonstrated to be adequate at the appropriate box-level review. Likewise, testing requirements should specifically target all configuration changes from the heritage design unless adequate detailed rationale can be developed."*

The reverification should not be limited to the box level. All changes need to be analyzed at the systems level as well. The acceptance of detailed rationale should also be subjected to a complete review/assessment. Additionally, use of the terms "as adequate" and "detailed rationale" in this recommendation are vague and difficult to verify. The corrective action plan should be more specific so that it can be effectively implemented and closed.

As many of the recommendations of this report apply to all NASA Programs, Jet Propulsion Laboratory and the Science Mission Directorate should work with the Chief Engineer's office in the development of the corrective action plan. The Chief Engineer's office should work with all centers and Mission Directorates to improve systems engineering, design reviews, the verification processes, and evaluation of the composition engineering teams that support programs and projects.

Overall, this was an excellent report and the Mishap Investigation Board should be commended on a job well done.

In keeping with NASA policy, please attach this endorsement to the top of the mishap report and publish/distribute it as a part of the report.

Resp/ O'C

Bryan O'Connor

cc:
Associate Administrator/Mr. Geveden
Chief Engineer/Mr. Robinson (Acting)
Jet Propulsion Laboratory/Dr. Elachi

Volume I Contents

Signature Page (Board Members)

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Acknowledgements

The Mishap Investigation Board would like to acknowledge the support of a number of groups and individuals who contributed to completing the investigation in an effective and timely manner.

A special commendation goes to the Genesis Project Team who functioned as an Interim Response Team in performing the initial recovery and securing of the crashed sample return capsule. Their timely and quality response not only preserved the critical hardware for MIB examination but more importantly, provided the opportunity for the Mission Curation and Science Teams to preserve and process the scientific samples. Recent reports indicate that most or all of the science goals of the mission will be achieved. In addition, early collection of detailed notes from each member present at the crash site were invaluable in reconstructing the post-recovery timelines.

The MIB received exemplary support from many members of the Genesis Project Team from Lockheed Martin Space Systems and from the Jet Propulsion Lab. The personnel from both organizations and their respective line management cooperated fully and proactively supported the MIB in doing its work. It was clear that everyone on both teams had been strongly personally committed to achieving Genesis mission success and that the crash was a strong personal blow to each one. Each and every team member contacted by the MIB was completely open and tried in every way to help reconstruct events over the life of the Genesis mission. It was clear that people involved felt personally responsible for the failures but, despite significant emotional stress, participated with a high degree of professionalism. Of special mention are Joe Villenga, Nick Smith, Dave Perkins and Al McKinney of LMSS and Don Sweetnam, Tom Wahl and Ed Hirst of JPL. Each of these people did everything possible to help the Board and in every way worked to make sure that the best possible knowledge was gained from the investigation.

The Jet Propulsion Laboratory convened an internal Failure Review Board which operated in parallel with the NASA MIB. This team cooperated fully with and provided additional support for the MIB in many ways. Mark Underwood and Jerry Dalton made particularly strong contributions in the battery and avionics investigations respectively and the Board is indebted for their expertise and their dedication. Of special mention are John Klein, the FRB Chairman and Gen. Ed Barry for their overall insights and work in investigating the team and developmental history of the Genesis Project and Rob Manning for his systems engineering and design insights and for his strong leadership in building a free flow of information between the project and the JPL FRB.

Mr. Pat Martin and Ms Faith Chandler of the NASA Headquaters Office of Safety and Mission Assurance provided invaluable help and guidance in keeping the investigation focused and in helping to organize the results in the clearest possible way. Mr. Don Savage was of great help in preparing and supporting the public release of information. The NASA Engineering and Safety Center provided invaluable assistance to the investigation, both in supplying key personnel and in supporting the transfer of funding to allow a quick start-up of the investigation. The US Air Force provided excellent support to the investigation both in providing two members to the Board as well as through the staff at the Utah Training and Test Range. The National Transportation Safety Board provided irreplaceable expertise and support to the Board in the person of Clint Crookshanks. His advice allowed early and timely action to be taken by the Board at the crash site, greatly expediting the investigation and minimizing the impact of the investigation on the preservation of the science payload.

Ms. Yvonne Kellogg of the NASA Headquarters Office of the Chief Engineer had the challenging job of translating engineering language into clear English. The readability of the final report is due to her efforts. Any remaining issues are areas in which she was not able to convince the engineers to mend their ways. Mr. Ron Zellar and Mr. Pat O'Rear served as advisors to the MIB. They provided excellent technical support as well as handling a great deal of the coordination of activities and the organization of information to allow the Board to do its work. Without them, the work of the Board would have been a great deal more difficult to bring to completion. Chuck Holloway served as our quality assurance lead for all of the hardware investigations at the LMSS in Denver. He did an admirable job of keeping everyone on the straight and narrow in dealing with the Genesis hardware and in documenting our results. Last but certainly not least, Peter Spidaliere and Stacey Nakamura stand out as the chief stewards for Volumes I and II of this report respectively. They also led the interview and analysis processes necessary for understanding "how" the mishap occurred. The rest of the Board members are indebted to them.

Executive Summary

Genesis was one of NASA's Discovery missions, and its purpose was to collect samples of solar wind and return them to Earth. The Jet Propulsion Laboratory was the managing Center; the California Institute of Technology was designated the principal investigator and project team leader. Los Alamos National Laboratory provided the science instruments, and Lockheed Martin Corporation (acting through its Lockheed Martin Space Systems company) was the industrial partner and provided the spacecraft and sample return capsule. The Jet Propulsion Laboratory and Lockheed Martin Astronautics conducted mission operations.

Launched on August 8, 2001, Genesis was to provide fundamental data to help scientists understand the formation of our solar system. Analysis of solar materials collected and returned to Earth will give precise data on the chemical and isotopic composition of the solar wind.

On September 8, 2004 the Genesis sample return capsule drogue parachute did not deploy during entry, descent, and landing operations over the Utah Test and Training Range. The drogue parachute was intended to slow the capsule and provide stability during transonic flight. After the point of expected drogue deployment, the sample return capsule began to tumble and impacted the Test Range at 9:58:52 MDT, at which point vehicle safing and recovery operations began. Section 2.0 provides a description of the mishap.

On September 10, 2004, the Associate Administrator for the Science Mission Directorate established a Type A Mishap Investigation Board as defined by NASA Procedural Requirements 8621.1A, NASA Procedural Requirements for Mishap Reporting, Investigating, and Recordkeeping, to determine the cause and potential lessons from the incident. The Board was chartered to determine the proximate cause of the failure, identify the root causes, and develop recommendations to strengthen processes within NASA's Science Mission Directorate to avoid similar incidents in the future. Section 3.0 describes the method of investigation used by the Board.

Additionally, the Board was to determine the adequacy of contingency response planning and the appropriateness of the actual contingency response, to include the safing and securing of the spacecraft and the science payload, and the protection of response personnel. The results of this second inquiry are documented in Volume II of this report.

The Board determined the proximate (or direct) cause of the mishap to be that the

G-switch sensors were in an inverted orientation, per an erroneous design, and were unable to sense sample return capsule deceleration during atmospheric entry and initiate parachute deployments. Section 4.0 describes the proximate cause and lists other candidates that the Board investigated.

The Board found that deficiencies in the following four pre-launch processes resulted in the mishap:

- the design process inverted the G-switch sensor design;
- the design review process did not detect the design error;
- the verification process did not detect the design error; and
- the Red Team review process did not uncover the failure in the verification process.

The Board identified several root causes and major contributing factors that resulted in the design inversion of the G-switch sensors and the failures to detect it. The root causes and contributing factors fall into six categories, some of which contributed to more than one of the above process errors. Each category is briefly explained below and in more detail in Section 5.0. Recommendations to avoid future reoccurrences are provided in Section 6.0.

- Inadequate Project and Systems Engineering Management.

A lack of involvement by JPL Project Management and Systems Engineering in Lockheed Martin Space Systems spacecraft activities led to insufficient critical oversight that might have identified the key process errors that occurred at Lockheed Martin Space Systems during the design, review, and test of the spacecraft. This process was consistent with the Faster, Better, Cheaper philosophy of the time and approved of by the Discovery Program.

- Inadequate Systems Engineering Processes.

Multiple weaknesses within the Genesis Systems Engineering organization resulted in requirements and verification process issues that led to the failure. The Board recommends adding a thorough review of all project Systems Engineering progress, plans, and processes as part of existing major milestone reviews. This recommendation was written to enforce discipline and critical assessment in the Systems Engineering organizations of future projects. Recommendations regarding Systems Engineering also address the issues raised by the Inadequate Project and Systems Engineering Management root causes by compelling a commitment by Project Management to support an adequate Systems Engineering function.

- Inadequate Review Process.

All levels of review, including the Genesis Red Team review, failed to detect the design or verification errors. It is the Board's position that technical reviews have become too superficial and perfunctory to serve the needs of the Science Mission Directorate. The technical review recommendations in this mishap report are targeted at significantly strengthening the Science Mission Directorate review process beyond its current state.

- Unfounded Confidence in Heritage Designs.

Genesis Management and Systems Engineering and the Genesis Red Team made a number of errors because of their belief that the G-switch sensor circuitry was a heritage design. Further, the prevalent view that heritage designs required less scrutiny and were inherently more reliable than new designs led to the mishap. The Board addresses the systemic problem of inappropriate faith in heritage designs in the Science Mission Directorate by recommending review and verification of heritage designs to the same level expected of new hardware/software.

- Failure to 'Test as You Fly.'

Several issues led to the lack of proper testing of the G-switch sensors, including a failure to treat the G-switches as sensors, which ultimately led to the mishap. The Board's recommendations to strengthen the review process within the Science Mission Directorate will partially address this issue, as well as a recommendation to require a "test as you fly" plan and a "phasing test plan" for all Science Mission Directorate projects.

- Faster, Better, Cheaper Philosophy.

As demonstrated by several failures, NASA's use of the Faster, Better, Cheaper philosophy encouraged increased risk taking by the Projects to reduce costs. Although NASA Headquarters had solicited and selected Genesis under the Faster, Better, Cheaper paradigm, the way JPL chose to implement the Genesis Mission substantially reduced their insight of the technical progress of the project. This precluded them from ensuring that the Project was executed within the range of previously successful mission implementation practices, thereby adding additional risk. The Discovery Program Office accepted these arrangements implicitly by way of the selection and subsequent management review processes.

The potential pitfalls of this approach became clear when the Mars Climate Orbiter and Mars Polar Lander missions failed. Although much has been done within Science Mission Directorate to correct Faster, Better, Cheaper issues, the Board recommends that when establishing appropriate levels of budgetary and schedule reserve that the Science Mission Directorate gives greater consideration to the overall maturity; launch constraints (e.g., short window planetary vs. others), and complexity.

Board members based several of the recommendations on their experience with on-going Science Mission Directorate Systems Engineering and technical review issues. The Board also considered previous failure investigations when generating several of the recommendations. Most of the recommendations center on improving the technical review process of new designs, heritage designs, and Systems Engineering. Instead of creating more reviews, the Board recommends establishing more effective reviews that identify requirements, design, verification, and process issues early to avoid costly overruns or tragic failures.

It appears highly likely to the Board that due to the dedicated efforts of the Genesis Recovery and Curation Teams and the nature of the sample collection materials most of the Genesis science goals will be met. However, the Board believes that this fortunate outcome should not reduce the importance of the lessons learned from the Genesis mishap to future missions.

Other significant observations and recommendations not directly related to root causes or contributing factors are provided in Section 7.0. Recommendations of the Board regarding actions the Stardust Project should consider are provided in Section 8.0.

1.0 Summary of the Genesis Project

a. Mission Description

Genesis was the fifth in NASA's series of Discovery missions, and the first U.S. mission since Apollo to return extraterrestrial material to Earth for study. The purpose of the mission was to collect samples of solar wind and return them to Earth. The California Institute of Technology (CIT) provided the principal investigator and project team leader. The Jet Propulsion Laboratory (JPL) was the managing agency and provided the science canister. Los Alamos National Laboratory (LANL) provided the electrostatic concentrator for the science canister and the electron and ion monitors. Lockheed Martin Corporation (LMC), acting through its Lockheed Martin Space Systems (LMSS) company, was the industrial partner and provided the spacecraft and sample return capsule (SRC). JPL and LMSS conducted mission operations.

Genesis was to provide fundamental data to help scientists understand the formation of our solar system, reinterpret data from past space missions, and provide focus to many future missions. Analysis of the collector materials will give precise data on the chemical and isotopic composition of the solar wind. Once analysis is complete, the Genesis mission will provide:

1. a major improvement in our knowledge of the average chemical composition of the solar system;
2. isotopic abundances of sufficient precision to address planetary science problems;
3. a reservoir of solar material to be used in conjunction with advanced analytical techniques available to 21st century scientists; and
4. independent compositional data on the three solar wind regimes.

Launched August 8, 2001, Genesis was positioned approximately one million miles from the Earth orbiting the Earth-Sun libration point L1 which is outside Earth's magnetosphere. It remained in a libration point orbit for 28 months. The mission trajectory is shown in Figure 1.1. The capsule lid was closed on April 1, 2004 and the spacecraft returned for a daytime Earth entry.

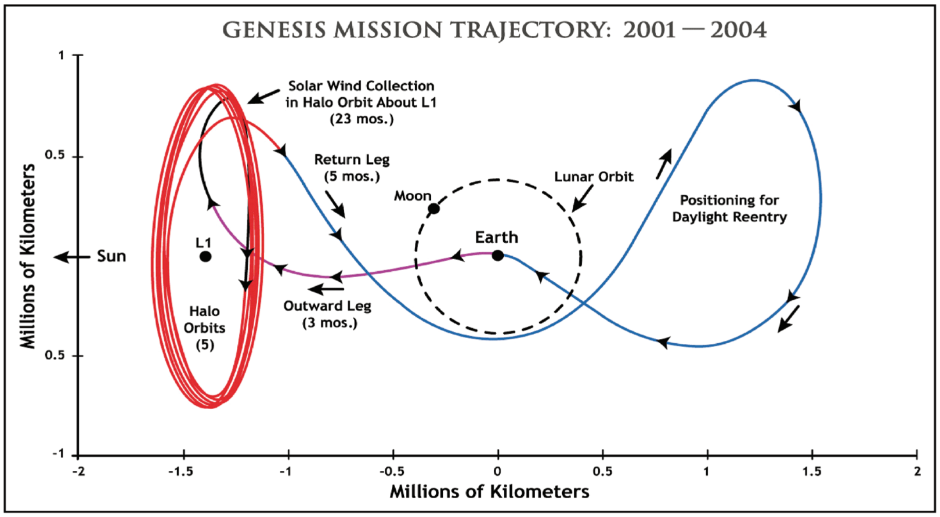


Figure 1.1. Genesis Mission in Earth coordinates.

b. Project Management Structure and Responsibilities

Under the Discovery Program Announcement of Opportunity (AO), the Discovery Program policy was to solicit missions that maximized the partnership between implementing NASA organizations, academia, and industry. The objective was to develop high-content missions at lower costs and with shorter schedules than the norm, i.e., 'Faster Better Cheaper' (FBC). The solicitation and selection required a principal investigator (PI)-mode mission in which all decision making authority was granted to the PI, who was responsible for mission scientific, technical, and programmatic success. For Genesis, programmatic and technical management authority was delegated by the PI to a JPL Project Manager with the lead JPL Mission Engineer (Systems Engineer) as his key technical staff and the LMSS Flight System (spacecraft and SRC) Program Manager as the deputy to the JPL Project Manager. The project organization is shown in Figure 1.2. It was also proposed that LMSS use its own technical and programmatic processes with JPL review and approval limited to systems-level requirements and verification. The Discovery Program Office accepted these arrangements implicitly by way of the selection and subsequent review process.

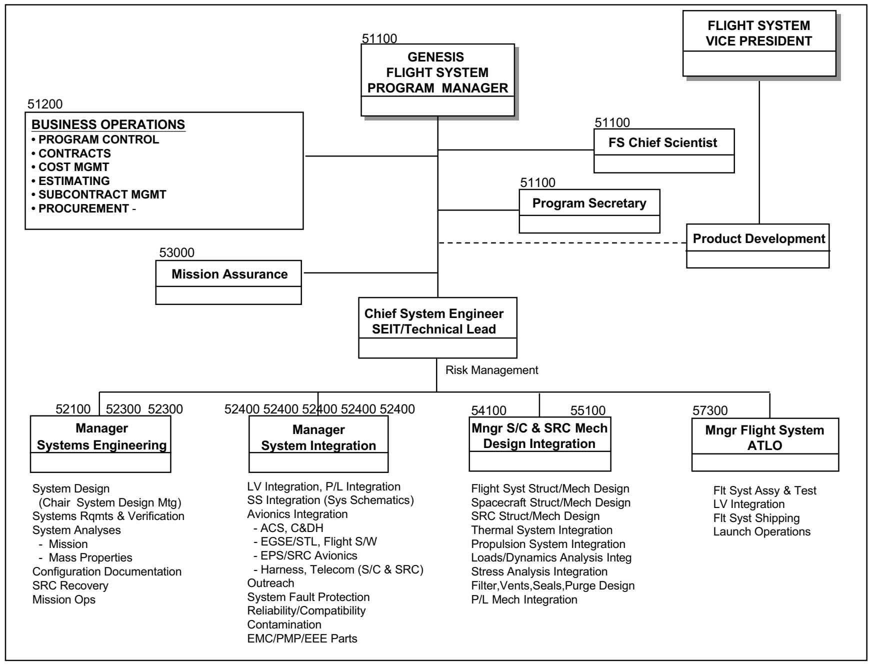


Figure 1.2. Genesis Project organization in 1998.

The Lockheed Martin organization in 1998 is shown in Figure 1.3. The LMSS Flight System Program Manager (also the Genesis Deputy Project Manager), had a Chief System Engineer who managed the technical aspects of the program and the supporting System Engineering, System Integration, Spacecraft and SRC Mechanical Integration, and Assembly, Test, and Launch Operations (ATLO) teams. The System Integration and Mechanical Integration Managers were members of the program team. Subsystem leads reported to the Integration Manager and were dedicated to Genesis but were members of the Product Development Organization (PDO). This “home shop”–type organization within LMSS’s Flight System Organization provided hardware products for multiple LMSS Programs.

The PDO provided standardized products to the extent possible while still meeting program requirements. The PDO developed requirements for their products from the Flight System specification with Integration Manager approval, developed their products, verified them in accordance with the verification requirements documented in their product spec, and delivered their products to the Integration Managers and the Genesis ATLO Team for integration into the spacecraft or SRC. The lead PDO members were Cost Account Managers for their products and were responsible for meeting the agreed cost and delivering on the agreed schedule. PDO lead personnel supported the ATLO Team throughout the system-level testing and launch preparations and some of these personnel moved into the Mission Operations Team at launch.

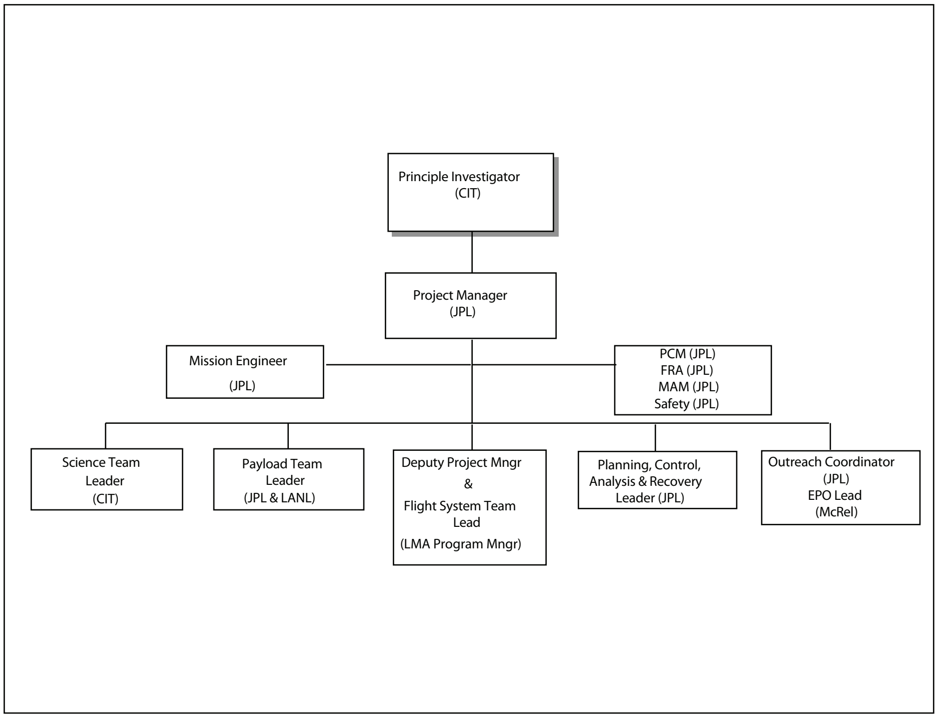
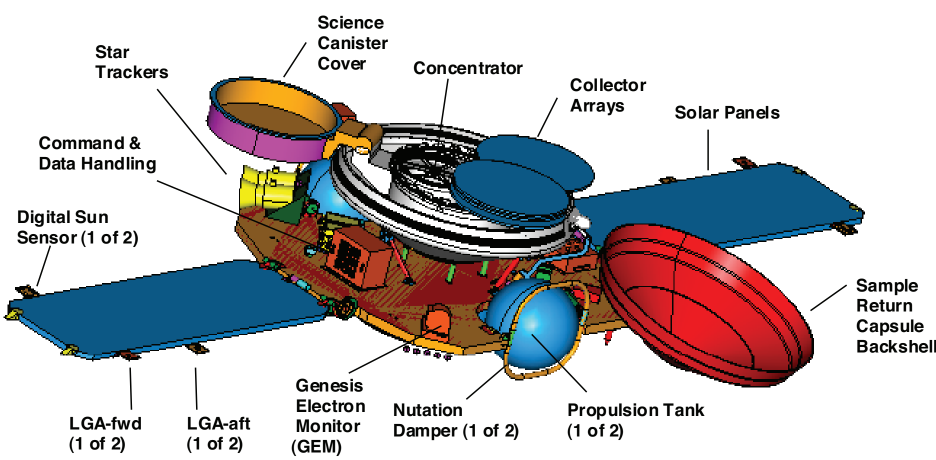


Figure 1.3.
Lockheed Martin Genesis organization in 1998.

c. Space Segment

The spin-stabilized spacecraft was composed of a main spacecraft with an attached SRC. As part of the sample return sequence the SRC was separated from the main spacecraft, which was diverted to a disposal orbit. The main spacecraft and SRC are shown in the science collection configuration in Figure 1.4. The flight configuration is shown in Figure 1.5.



* Genesis Ion Monitor (GIM) is caddy corner GEM, on +Xsv deck (fwd)
* MGA and thrusters on -Xsv deck, towards -Xsv-axis (aft)

Figure 1.4.
Spacecraft in science collection configuration, sun view.

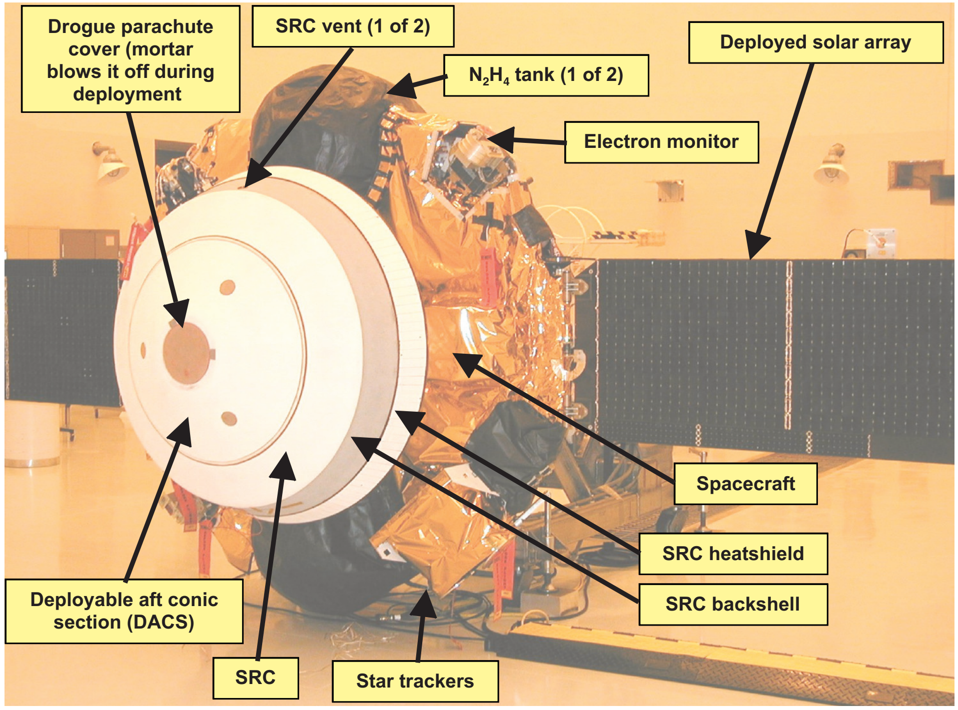


Figure 1.5. Flight configuration with thermal blankets installed.

d. Sample Return Capsule Detail

A cross section of the SRC design is shown in Figure 1.6. The science canister is in the center with the SRC avionics units (AU) and the SRC primary $LiSO_2$ battery mounted in the annulus around the science canister. The canister and the avionics decks are mounted to the heatshield structure. The backshell contains the drogue parachute on the centerline and the parafoil main parachute is packed around the drogue canister. A mortar is fired inside the drogue canister to propel the drogue parachute out through the mortar cover. The deployable aft conical section (DACS) is released by firing three frangible pyrotechnic bolts (DACS Retention and Release Mechanism) and the drag load on the drogue parachute pulls the parafoil out, taking the DACS with it. Before releasing the DACS, the cable to the drogue mortar is cut with a pyrotechnic cable cutter.

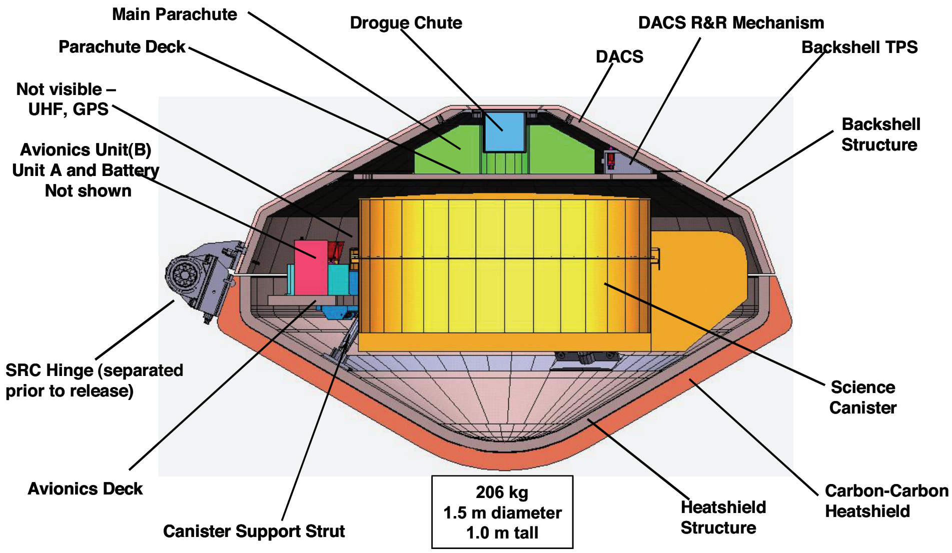


Figure 1.6.
SRC cross section
(SRC hinge is separated from SRC prior to release).

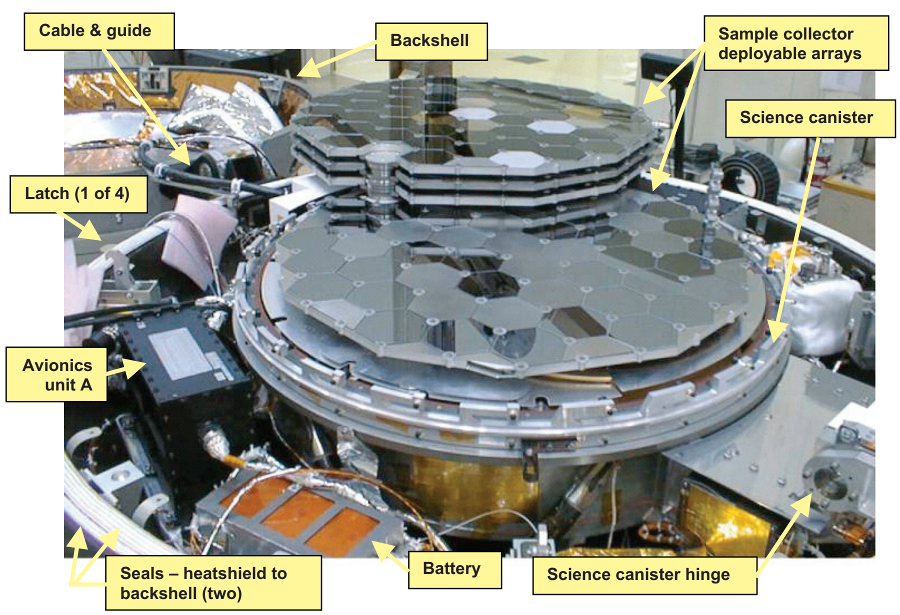


Figure 1.7.
SRC prior to installing thermal closures – avionics box A and the $LiSO_2$ battery in foreground.

Figure 1.7 shows the avionics unit A and the flight battery prior to installing the thermal close outs. The collectors are partially deployed. Also visible in the upper left is the cable management system that restrained the cable between the heatshield and backshell during backshell opening and closing.

e. Drogue and Parafoil Parachute Deployment System Description

A parachute system is deployed in a sequence of timed pyrotechnic events. The Genesis parachute deployment sequence is illustrated in Figure 1.8, and includes the activation of post-landing location aides, namely, a GPS transceiver and a UHF beacon transmitter.

The timing for each pyrotechnic event in the sequence is shown in Table 1. Redundancy of the critical pyrotechnic devices was achieved by incorporating a firing circuit in each of the two AU's. The critical devices are the first three listed in Table 1. A simplified block diagram of the SRC pyrotechnic firing circuit is shown in Figure 1.9.

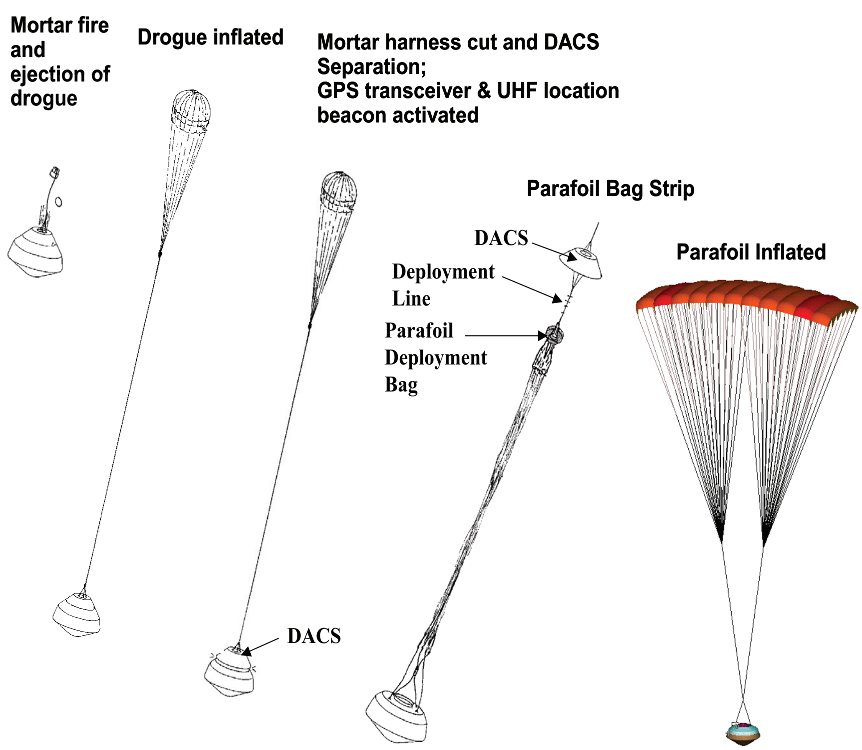


Figure 1.8. Parafoil deployment sequence.

Table 1. SRC Sequence Timing.

Pyrotechnic Device	Time of Fire Command after Start of Event Sequencer, sec	Redundancy
Drogue mortar	5.7	Two firing circuits in each of the two avionics boxes
Drogue harness cable cutter	80.6	Two firing circuits in each of the two avionics boxes
DACS bolts, 3 fired simultaneously	259.6	Two firing circuits in each of the two avionics boxes
GPS transceiver	261.4	One firing circuit in each of the two avionics boxes
UHF beacon transmitter	261.4	One firing circuit in each of the two avionics boxes

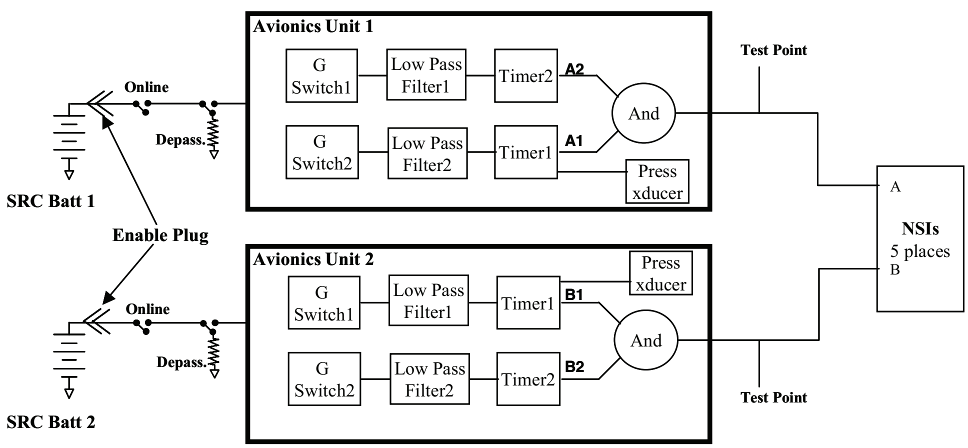


Figure 1.9.
SRC pyrotechnic firing circuit layout.

The firing circuit is activated by the G-switch sensors, which are ANDed together to preclude a single switch failure from prematurely issuing a fire signal. A low-pass filter was added to prevent inadvertent G-switch sensor activation due to atmospheric transients (buffeting) during re-entry. The pressure transducer is not a backup to the G-switch sensor and is only used once the event sequence timer (EST) is running to ensure that parafoil deployment occurs at the desired altitude. A positive firing signal from the firing circuit in either AU was sufficient to fire the respective pyrotechnic device.

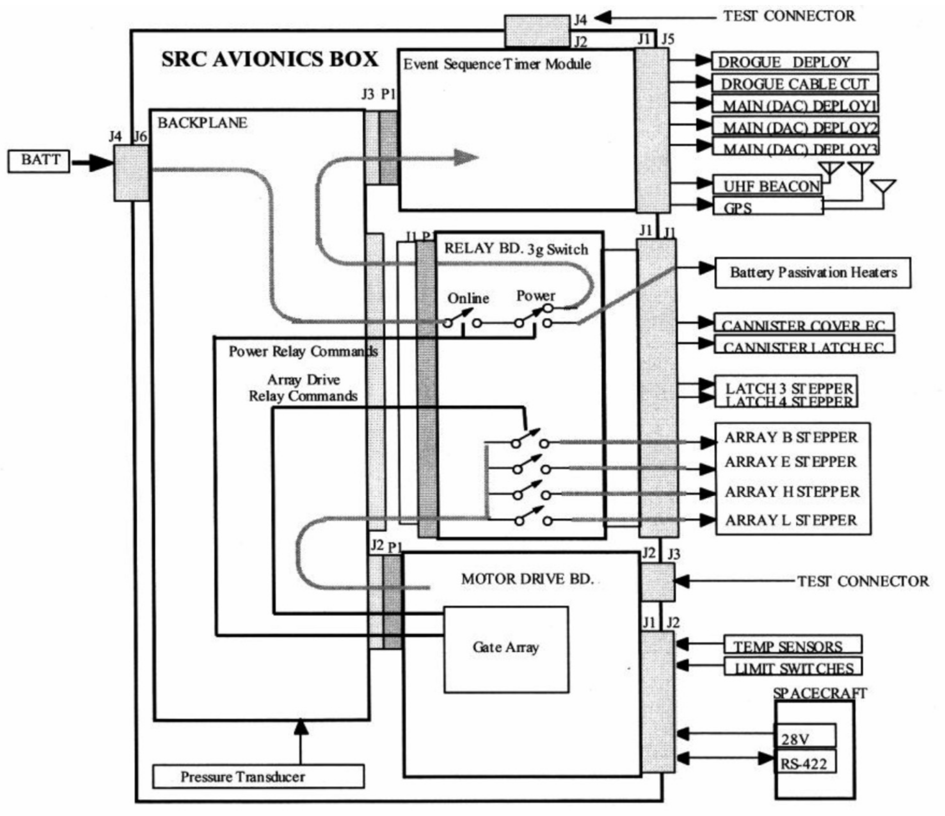
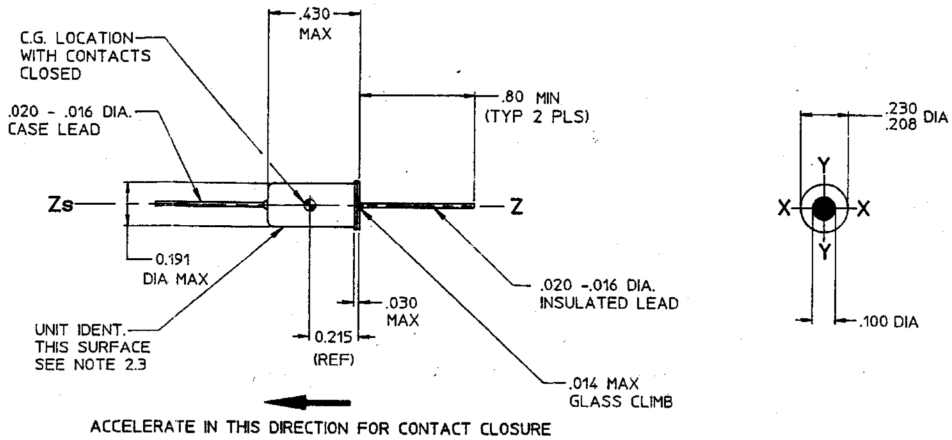


Figure 1.10.
SRC avionics unit.

The AU block diagram is shown is Figure 1.10. The primary functions performed by the motor drive electronics (MDE) board were completed when the science canister and the SRC were closed on April 1, 2004. During the SRC release sequence, the relay card and the field programmable gate array (FPGA) on the MDE board are used only to connect the SRC $LiSO_2$ batteries to first the depassivation resistors and then to the EST board to power it through entry and post-entry operations. G-switch sensors, used to sense atmospheric entry and initiate a pyrotechnic events timer, were mounted on the relay card although voltage was applied for the pyrotechnic events from the EST card.

The G-switch sensor is an acceleration-sensitive sensor, which is somewhat smaller than the metal ferrule of a common wooden pencil (Fig. 1.11).



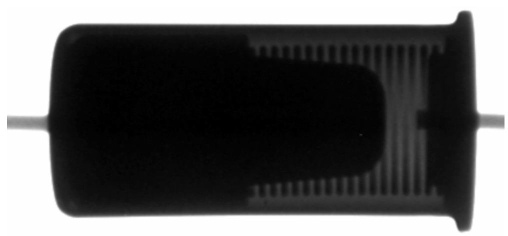


Figure 1.11. Aerodyne 7200-6-000 acceleration switch (G-switch sensor) drawing and X-ray.

The acceleration direction required to close the switch is shown in Figure 1.11. An X-ray of the G-switch sensor shows how the spring mass and contact are oriented inside the cylinder (Fig. 1.11). The closure lip provides a good orientation reference between the photograph of the exterior and the X-ray of the interior of the G-switch sensor. When the G-switch sensor is mounted in the correct orientation, the internal plunger compresses against its spring as the *g*'s are increased, making electrical contact. The *g* profile for the Genesis entry, shown in Figure 1.12, was close to the pre-launch prediction.

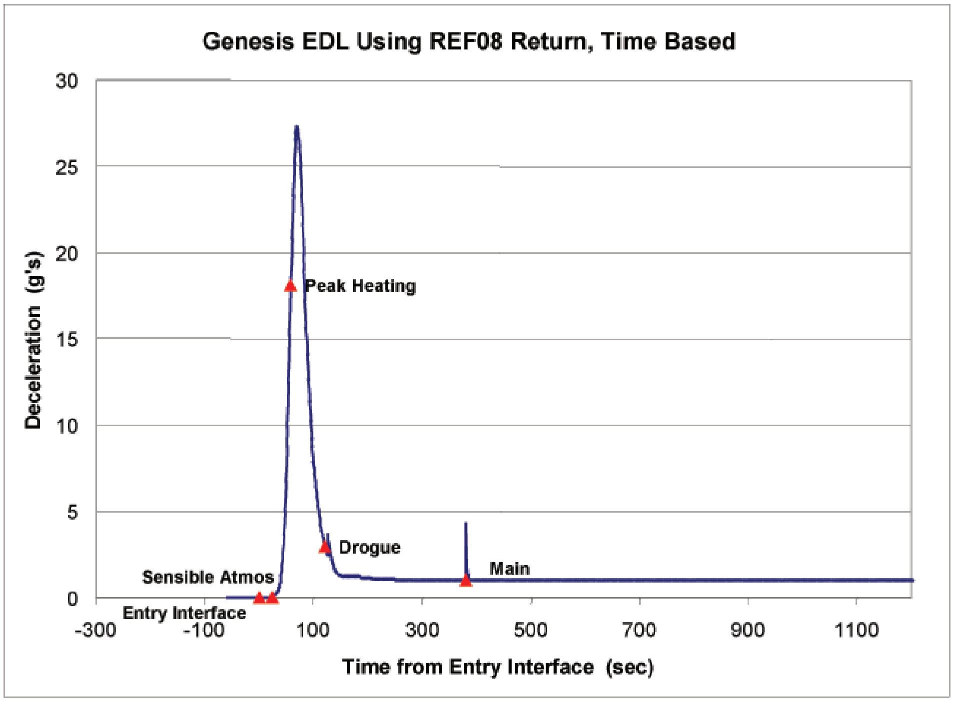


Figure 1.12. Genesis entry g profile.

As seen in Figure 1.12, the *g*'s build up due to the increased drag in the atmosphere. Upon reaching 3 *g*'s, the plunger touches an electrical contact in the end of the G-switch sensor, closing the circuit and arming the sequencer. When the SRC slows down and the *g*'s drop below 3 *g*'s, the plunger in the G-switch sensor pushes away from the contact, which breaks the circuit and starts the sequencer.

2.0 Genesis Mishap Description – Sequence of Events and Timeline

This section describes the events leading up to the impact of the Genesis SRC vehicle at the Utah Test and Training Range (UTTR). Figure 2.1 illustrates the nominal timeline from the SRC release enable/no-go decision through landing. A detailed description of the post-impact ground recovery operations and timeline is in Volume II of this report.

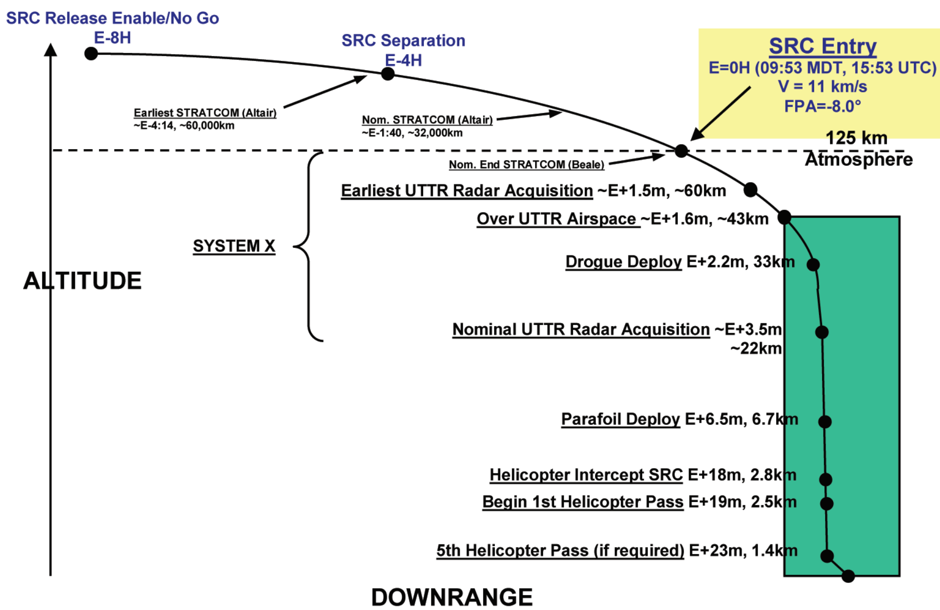


Figure 2.1. Entry timeline.

During the science portion of the mission, which had no significant anomalies, the SRC functioned as an integrated element of the Genesis spacecraft. The SRC was oriented to face the sun and was configured to expose the collector surfaces to the solar wind. At the completion of the planned science mission, the SRC was closed to avoid contamination of the collector surfaces during the return flight to Earth and the spacecraft flew a trajectory designed to permit a daytime landing at the target site.

Approximately 8 hours prior to landing, the SRC was prepared for separation and entry by activating (depassivating) its dedicated batteries, severing umbilicals, and increasing the spacecraft rate of rotation. A 4-hour period had been designed into the timeline to permit response to any observed contingency, but none occurred and the SRC separated from the parent Genesis spacecraft as planned. The Genesis spacecraft was subsequently diverted to a disposal orbit.

Following separation, the SRC continued on a ballistic trajectory to its entry interface with the Earth's atmosphere. Entry occurred on time and at the nominal location to support a landing as designed in the UTTR. Operation of the spacecraft appeared nominal until the expected deployment of the drogue parachute at approximately 108,000 ft (33 km) altitude. No drogue or parachute was observed, and the SRC impacted the desert floor at 9:58:52 MDT.

The navigation team reconstructed the trajectory of the entering spacecraft and verified that the spacecraft was on the desired reference trajectory. Entry-phase tracking systems acquired the SRC over Oregon at an altitude of about 300,000 ft (90 km), only about 32 sec after encountering sensible atmosphere. Hypersonic entry deceleration was nominal until well after the drogue parachute should have deployed.

Following impact, the recovery helicopters located and surveyed the impact site, and landed to permit recovery personnel to approach the SRC. The activities of the recovery personnel involved potential exposure to toxic gasses that could be released from a shorted battery and potential danger from the drogue mortar if it were unfired. This is described in detail in Volume II.

Following safing activities, the SRC hardware was transported to a holding facility at the Michael Army Airfield complex, where it was secured pending the arrival of the Genesis Mishap Investigation Board (MIB).

3.0 Genesis Mishap Method of Investigation

On September 10, 2004, the Associate Administrator for the Science Mission Directorate established the NASA Genesis MIB and designated Dr. Michael Ryschkewitsch, Goddard Space Flight Center (GSFC) Director of Applied Engineering and Technology, as chairman. The Board was directed to:

- obtain and analyze whatever evidence, facts, and opinions it considered relevant;
- conduct tests, and other actions it deemed appropriate;
- take testimony and receive statements from witnesses;
- impound property, equipment, and records as considered necessary;
- determine the proximate cause(s), root cause(s), and contributing factors relating to the Genesis Mishap;
- generate and prioritize findings;
- determine the adequacy of contingency response planning and the appropriateness of the actual contingency response, to include the safeing and securing of the spacecraft and the science payload, and the protection of response personnel;
- develop recommendations to prevent recurrence of similar mishaps; and
- provide a final written report with contents as specified in NPR 8621.1A.

The letter establishing the Genesis MIB is provided in Appendix A.

LMSS investigation of the close out documentation provided to the Board gave strong indication of the likely cause of the failure. However, due to potential implications for other flight systems the Board elected to continue with a more thorough investigation (Appendix B).

The Genesis MIB Chair and Executive Secretary received initial briefings from the Genesis Project (JPL and LMSS) and took responsibility for the recovered hardware at the UTTR crash site, beginning Sept. 10, 2004. The Genesis MIB held initial team organizational meetings on Sept. 14-15, 2004. The Genesis Project held overview briefings for the complete MIB team at UTTR on Sept.14-15 and at LMC on Sept. 22-23 and Sept. 29, 2004. The briefing included material on the Genesis spacecraft, subsystems, development, test, operations, navigation, and spacecraft health status up to the incident. On

Oct. 27, 2004, the Discovery Program provided an overview briefing of the FBC environment, including the Discovery Program culture at that time.

During these initial meetings, the Board established seven sub-teams to investigate specific focus areas. The seven sub-teams and their summary charters are listed in the following.

- Systems, Operations, and Environments
  - Lead development of the failure timeline and fault tree for the Genesis deployment failure.
  - Coordinate the development, review, approval, and disposition of the fault tree closure plans and records.
- 'Test as you Fly'
  - Determine the adequacy of the Genesis verification program as it relates to the Genesis failure.
  - Determine if the verification process for each relevant event on the Fault Tree is adequate to absolve it as the cause of the failure (through coordination with the Systems, Operations, and Environments sub-team).
  - Identify any inadequate verification of downstream event (as part of the investigation of possible failures subsequent to the failure to initiate the deployment sequence).
- Entry Dynamics and Descent
  - Determine if the Genesis SRC entry and descent performance, prior to the failure, were abnormal and may have caused the failure.
  - Determine if the descent environment, after the pyro initiation failure, might have been sufficient to trigger the pyro initiation sequence.
- Battery
  - Determine if the batteries caused or contributed to the Genesis pyro initiation failure.
  - Determine the cause and associated timeline for the low state-of-charge exhibited by the batteries after the accident.
  - Identify, plan, and execute, with the MIB chair's concurrence, any testing, data, and/or analyses required to answer these questions.

- Avionics/Pyrotechnics/EEE Parts
  - Determine if a failure in the design, implementation, or flight of the Genesis avionics and pyrotechnic subsystems may have caused the failure.
  - Identify, plan, and execute, with the MIB chair's concurrence, any testing, data, and/or analyses required to answer these questions.
- Recovery and Ground Safety – (Volume II)
  - Determine the adequacy of contingency response planning and the appropriateness of the actual contingency response, to include the safing and securing of the spacecraft and the science payload, and the protection of response personnel.
- Project Environment and Decision Making Processes
  - Identify any shortfalls in the project implementation/decision making process that may have led to the Genesis failure.

After discussions with the MIB and FRB, in lieu of conducting a formal internal investigation LMSS management elected to make available their extensive resources to the MIB and FRB and to use the findings and recommendations to shape their internal actions and responses. LMSS provided a consultant to the Board; a senior manager with whom to consult and to help expedite LMSS actions.

In addition to root cause determination of the mishap, the MIB charter also included an assessment of the adequacy of contingency response planning and the appropriateness of the actual contingency response. The Recovery and Ground Safety Sub-Team focused on safety, contingency planning, and ground communication issues. This team was led by Mr. Stacey Nakamura, Chief of the NASA JSC Safety and Test Operations Division, and focused on these issues at the request of the NASA Chief Medical Officer. Volume II of this report contains the assessment, findings, and recommendations for the Recovery and Ground Safety aspects of the Genesis mishap.

Under the guidance of the Systems, Operations, and Environments Sub-Team, the MIB used fault tree analysis to identify and analyze a comprehensive range of possible failure scenarios to provide a systematic process to track possible causes to closure. The Systems, Operations, and Environments Sub-Team assigned the other sub-teams various fault tree branches/items based on areas of expertise. The sub-teams documented and tracked the analysis and information gathering necessary to disposition each identified fault tree event. The Genesis MIB fault tree process is provided in Appendix C-1, the fault tree diagram is in Appendix C-2, and Fault Tree Closeout Plans and Records are in Appendices C-3 and C-4 (on DVD).

To provide the information required to disposition the fault tree failure scenarios, the Board requested specific inspections, tests and analyses to be conducted. The analyses, which included SRC tumble analysis and aerodynamic stability analysis, were performed by experts selected by the Board. The inspections and tests were performed by MIB and FRB members and monitored by an MIB Quality Engineer or LMSS technicians under the guidance of MIB and FRB members, using procedures built by LMSS experts and approved by the MIB. Inspections performed on the recovered hardware included inspections of the TPS, pyrotechnics, batteries, avionics boxes, and harnesses. Tests were conducted on the SRC avionics Engineering Development Unit (EDU) and recovered avionics units, including functional tests of cards from one of the recovered avionics units. The results of the inspection, tests, and analyses are summarized in the fault tree discussions in Appendix C and associated reports in Appendix D.

The Systems, Operations, and Environments Sub-Team held fault tree closure meetings and telecons during October and November 2004 where the sub-teams reviewed and reached consensus on each fault tree closure. Following completion of the Board fault tree reviews, the Board concurred on the likely credible cause for the loss of Genesis; they also agreed upon the explanation of potential causes considered, but determined to be unlikely or non-credible. Appendix E contains the root cause and contributing factor narrative and the event and casual factor tree. JPL formed its own Failure Review Board (FRB), which worked closely with the MIB. FRB members worked with MIB sub-teams to maximize efficiency. The JPL FRB final report is included in Appendix F.

The Project Environment and Decision Making Processes Sub-Team conducted extensive interviews with current and former JPL and LMSS employees, as well as other members of the Genesis Red Team. Privileged interviews were offered; however, all interviewees requested non-privileged status. Because the interviews were non-privileged, FRB members participated in all interviews.

The Board typically held teleconferences twice a week to track the status of sub-team activities and discuss special areas of interest. Throughout the investigation there were regular requests made of JPL and LMSS for information and data in support of the Board. JPL and LMSS provided full and open communication in response to all Board requests and provided specialized technical expertise when requested. The list of contractors supporting the MIB is in Appendix G. During the investigation, several meetings were dedicated to special topics. These meetings ensured that all Board members had similar understanding or exposure to key data. Minutes are provided in Appendix H.

The Board assembled observations concerning the Genesis design, verification, and review processes; identified root causes and contributing factors; and then developed a set of recommendations. The MIB Chair provided a briefing of the report to JPL and LMC personnel prior to release of the final MIB report to confirm accuracy.

4.0 Proximate Cause

NPR 8621.1A, NASA Procedural Requirements for Mishap Reporting, Investigating, and Recordkeeping, defines a proximate cause as "The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome." It is also known as the direct cause.

The Board determined the Genesis mishap proximate cause to be that the G-switch sensors did not activate the EST due to the improper orientation on the relay cards of SRC-AU boxes. In the wrong orientation, it was impossible for the sensors to detect atmospheric entry and initiate the EST, which was required to fire the pyrotechnics.

The MIB researched the proximate cause of the failure of drogue parachute to deploy during entry through a fault tree analysis. During this analysis, the Board reviewed all aspects of the mission to identify potential contributors to the entry failure. The fault tree analysis focused on four main failure scenarios (or fault tree branches). These include:

- avionics systems failures
- electrical power system failures
- electrical harness/connectors failures; and
- drogue system failures.

These four fault tree branches were then extended to a total of 103 fault tree elements, or specific failure scenarios, as part of the MIB's fault tree development effort. Details of the fault tree are shown in Appendix C. The MIB thoroughly investigated each element of the fault tree by examining design documents, preflight test data, closeout photos, in-flight data, computer commands, telemetry, and by physical examination and testing of the recovered SRC, and through assorted special analyses. The data collected either supported or refuted each specific fault tree element's contribution to the mishap. Conclusions were then formulated and the MIB as a whole concurred on the credibility of each possible failure mode.

Each of the four fault tree branches are described in more detail in the following, along with its requisite impact to the proximate cause.

4.1. SRC Avionics Unit Failure

During entry, the SRC-AU was responsible for detecting entry and invoking specific commands in the proper sequence to deploy the drogue chute, cut the drogue chute harness, deploy the main chute, and activate the UHF and GPS systems. During the Genesis entry, none of these occurred. The Avionics System fault tree branch consisted of 13 sub-branches. These included:

1. The G-switch sensors did not activate the EST.
2. The low-pass filter in the EST was not designed properly for the anticipated aerodynamic braking profile.
3. After the EST started, an inadvertent reset would stop the EST.
4. Incorrect timing of the EST oscillator prevented the release of the drogue.
5. Latent electronic fault resulting from a potential high-voltage discharge from the scientific concentrator grid circuit.
6. Mortar initiator circuit's current limiting ballast resistor damaged in pre-fight testing which prevented drogue pyro firing.
7. Logic circuits out of phase.
8. EST jumpers set incorrectly, resulting in wrong event sequence.
9. Electromagnetic interference (EMI) disrupted avionics circuit operation.
10. Space or entry environment adversely impacted avionics.
11. Pressure transducers, if improperly wired, interfered with the fire command.
12. The Avionics System internal short during flight or entry.
13. An open fuse prevented the Avionics Systems from operating properly.

As noted earlier, it was determined that the G-switch sensors were improperly oriented on the SRC-AU relay card, making it impossible to initiate the EST circuitry and fire the pyrotechnics (item number 1 above).

MIB review of the board assembly drawings, flight board closeout photographs, and the flight A and B side AU's indicates that the switches were installed in accordance with the design drawings. However, the relay cards, which contained the G-switch sensors, were designed with the G-switch sensors in an inverted orientation as compared to how they were planned for Stardust (the heritage design).

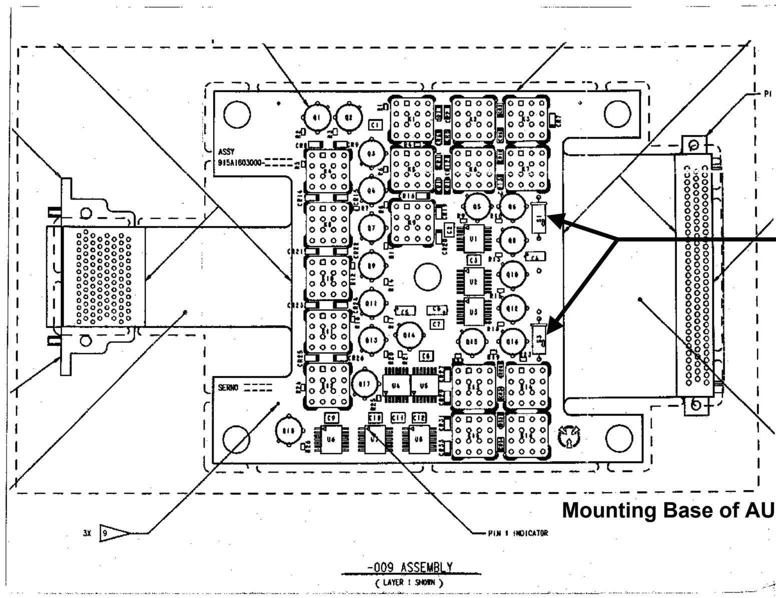


Figure 4.1.
Relay card
assembly drawing.

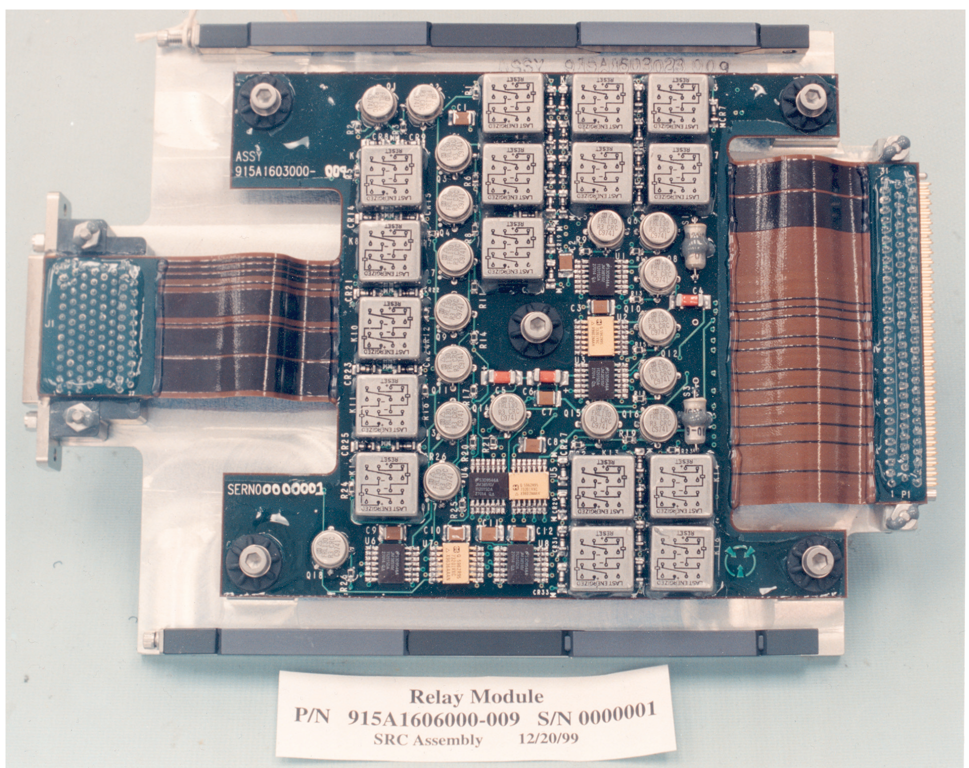


Figure 4.2.
Relay card
close-out photograph.

Figures 4.1 and 4.2 show an assembly drawing and close out photograph of a flight relay card with G-switch sensors, respectively.

The inversion of the G-switch sensors made it impossible for the masses in each sensor to compress their restraining springs, and activate the switch. As a result, the circuit to the EST could not be closed, preventing the timer that controlled the pyrotechnic firings from being initiated. Since the drogue pyrotechnic firing did not occur, the SRC continued its descent at a high rate of speed, lost stability, and struck the desert floor at 193 mph (311 kph).

4.2. Electrical Power System (including the Battery) Failure

The electrical power system fault tree is comprised of the batteries as well as the heaters and electrical loads that affect the power available to the avionics and drogue systems during entry. The batteries powering this entry system are dedicated to entry alone and were activated only hours before entry.

There were six fault-tree sub-branches associated with the electrical power system.

1. Sequence that activated and conditioned the batteries was incorrect.
2. Power relays incorrectly configured.
3. Power system design flaw resulted in premature draining of battery.
4. The batteries or battery connectors jarred loose in-flight or during entry.
5. The entry conditions caused the batteries or cables to overheat, or short/open circuits to develop.
6. Insufficient battery capacity prevented deployment of the drogue parachute (included assessment of battery over temperature event during the mission).

The MIB investigated these possible failure modes and found each to be unlikely or not credible. Appendix C documents the fault tree closeouts for each. Further, Appendix D-1 contains a copy of the Battery Post-Flight Investigation Report, which addressed item 6 above in detail.

4.3. Electrical Harness/Connector Failure

The wiring harness within the SRC must connect all the electrical elements of the SRC. In addition, this harness crosses a hinge and must be correctly routed and secured to ensure hinge operation and keep all electrical connections intact.

There were three primary failure scenarios for the electrical harness/connector system.

1. Pyro circuits not connected.
2. One or more harness wires open during flight.
3. Harness wires shorted to each other or to ground.

The MIB dispositioned each failure mechanism as unlikely or not credible. Documentation for each is provided in Appendix C.

4.4. Drogue System Failure

The Genesis parachute system is deployed in a sequence of timed pyrotechnic events. The first event is to fire redundant NASA standard initiators (NSI's). The initiators then ignite the mortar propellant. The mortar ejects the drogue parachute out of the mortar into the air stream where it inflates, slows, and stabilizes the vehicle. At the appropriate time, the mortar harness is cut and separation bolts are fired to release the DACS and drogue from the vehicle and ultimately deploy the parafoil.

For Genesis, the G-switch sensors were used to start the EST, which would fire the NSI's to start the parachute system deployment. If the sequencer had started and the NSI's fired, the drogue should have been deployed. Because the drogue was not deployed, the remaining events in the parachute sequence could not be accomplished.

Therefore, the sub-branches of fault tree for the Parachute System were limited to the events associated with:

1. pyro firing
2. drogue deployment

The MIB dispositioned these failure mechanisms as not credible; they are documented in Appendices C and D.

5.0 Genesis Mishap Root Causes and Contributing Factors

NPR 8621.1A, NASA Procedural Requirements for Mishap Reporting, Investigating, and Recordkeeping, defines a root cause as "one of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome."

Further, NPR 8621.1A defines a contributing factor as "an event or condition that may have contributed to the occurrence of an undesired outcome but, if eliminated or modified, would not by itself have prevented the occurrence."

Using a bulleted format, Section 5.1 describes the four process-level failures that led to the mishap and their associated root causes and contributing factors. Section 5.2 provides a brief presentation of the major findings associated with each root cause and contributing factor. Appendix E describes in narrative form each root cause and contributing factor in greater detail. Section 6.0 provides recommendations to avoid the reoccurrence of the issues identified by the Board, and Table 6.1 provides a cross reference of root causes and contributing factors to recommendations.

Distinctions between JPL and LMSS Project Management and Systems Engineering are not generally made in this section. The Genesis Deputy Project Manager was the LMSS Program Manager; as a result errors made by the LMSS Program Manager cannot be – and the Board believes should not be -- separated from JPL Genesis Project Management. Further, the lead JPL Systems Engineer agreed, with Project Management concurrence, not to monitor or cross-check LMSS Systems Engineering activities or processes. This intentional omission leaves JPL Systems Engineering equally responsible for errors committed by LMSS Systems Engineering and for that reason distinctions between the two are made only when necessary to explain the events.

5.1 Process-Level Errors: Root Causes and Contributing Factors

The Genesis Project had a number of interrelated issues that led to the inversion of the G-switch sensors -- the proximate cause that resulted in the drogue parachute deployment mishap. After extensive review of the data and numerous interviews, the MIB determined that deficiencies in the following four pre-launch, top-level processes resulted in the incident, each involving multiple root causes and contributing factors:

1. the design process inverted the G-switch sensor design;
2. the design review process did not detect the design error;
3. the verification process did not detect the design error; and
4. the Red Team review process did not uncover the failure in the verification process.

Under each process failure were multiple root causes and contributing factors. Appendix E provides the Event and Causal Factor Tree depicting the hierarchy of events from the root causes through to the proximate cause. The Board used root cause analysis to develop six major categories of root causes and contributing factors; many of these were common to two or more of the above mentioned process failures. The six categories and their associated root causes and contributing factors are listed below.

1. Inadequate Project and Systems Engineering Management
    - Contributing Factor 1.1: Insufficient JPL Project Management and Systems Engineering insight into LMSS activities.
    - Contributing Factor 1.2: SRC not treated as a separate spacecraft.
    - Root Cause 1.1: Genesis Project Management and Systems Engineering did not perform due diligence with regard to reviewing briefing materials.

2. Inadequate Systems Engineering Process
    - Root Cause 2.1: Inadequate requirements generation.
    - Root Cause 2.2: Systems Engineering did not define detailed verification requirements for subsystems.
    - Root Cause 2.3: Lack of documentation of changes made to verification methods.
    - Root Cause 2.4: Systems Engineering verification process did not require consideration of a verifier's qualifications nor incorporate multiple verifiers.
    - Root Cause 2.5: Systems Engineering was not required to review subsystem test procedures or verification results.

- Root Cause 2.6: Inadequate execution of System-level verification.
- Contributing Factor 2.1: Lack of a Systems Engineer assigned to the end-to-end entry, descent, and landing (EDL) function.
- Contributing Factor 2.2: Inadequate Systems Engineering staffing level.

3. Inadequate Technical Review Process
    - Root Cause 3.1: Key individuals' attendance was not required at project technical and drawing reviews.
    - Root Cause 3.2: SRC-AU Critical Design Review (CDR) was too high-level to adequately assess the design.
    - Root Cause 3.3: JPL SMO gave the Red Team too little time to perform an adequate assessment.
    - Root Cause 3.4: Inadequate Red Team management of focus groups.

4. Unfounded Confidence in Heritage
    - Root Cause 4.1: Inappropriate confidence in heritage designs.

5. Failure to 'test as you fly'
    - Root Cause 5.1: G-switch sensor was not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Plan).

6. FBC Issues
    - Root Cause 6.1: The Faster, Better, Cheaper (FBC) philosophy: 'cost-capped' mission with threat of cancellation, if overrun.

5.2 Root Causes/Contributing Factors: Facts and Findings

The following section describes in a bulleted list format the individual root causes and contributing factors identified in Section 5.1. More detail is provided for each root cause and contributing factor in Appendix E-2.

In several cases the top-level process errors mentioned in Section 5.1 shared common root causes. To simplify the discussion, the root causes and contributing factors are discussed in terms of the six categories of root causes and contributing factors.

<u>Root Cause Category No. 1: Inadequate Project and Systems Engineering Management</u>

Contributing Factor 1.1: Inadequate JPL Project Management and Systems Engineering insight into LMSS activities.

Facts:

- Insufficient JPL Project Management and Systems Engineering participation resulted from the FBC philosophy of pushing responsibility to the lowest level and not interfering with the contractor's processes.
- JPL Project Management assumed that LMSS management was performing all necessary spacecraft Systems Engineering functions and required no JPL support.
- Discipline-specific engineering interaction did not occur on a regular basis between the JPL and LMSS teams.
- JPL Project Management and Systems Engineering limited its active support primarily to science instrument activities on the SRC.
- JPL Project Management and Systems Engineering did not actively support or thoroughly review the spacecraft or SRC, including the SRC-AU functions.
- The JPL Systems Engineering lead was not experienced in this type of project.

Findings:

- Inadequate JPL Project Management and Systems Engineering insight into LMSS spacecraft activities played a significant role in the Genesis mishap.
- Insufficient involvement by JPL Project Management and Systems Engineering in spacecraft activities resulted in total dependence on LMSS for its mission success.
- The lack of involvement by JPL Project Management and Systems Engineering at the lower levels did not directly cause the failure, but made it difficult or impossible for them to identify the process failures that led to it.

Contributing Factor 1.2: SRC was not treated as a separate spacecraft.

Facts:

- Project Management addressed the SRC as an integral part of the Genesis spacecraft, not as a separate spacecraft.
- This reduced costs by avoiding the additional management structure needed if the SRC had been treated as a separate element.

Finding:

- While not unsound or uncommon, this approach diminished focus on the critical mission success elements unique to the entry phase and may have contributed to the failure.

Root Cause 1.1: Genesis Project Management and Systems Engineering did not perform due diligence with regard to reviewing briefing materials.

Facts:

- A centrifuge test to verify the directionality of the G-switch sensors had been planned, but was deleted in favor of drawing inspections.
- The only documentation indicating that Genesis Project Management or Systems Engineering had been informed of a centrifuge test deletion was a single bullet presented at two management reviews that read, *"SRC AU 3-g test approach validated; moved to unit test; separate test not required."*
- The "unit test" did not verify orientation, only continuity.
- No one recalled any discussion occurring regarding the bullet.
- Project Management and Systems Engineering assumed that a functional replacement for a centrifuge test was to occur that would determine G-switch sensor orientation.

Finding:

- Had Project Management or Systems Engineering questioned the meaning of the cryptic bullet, the inadequacies of the approach would most likely have been discovered.

<u>Root Cause Category No. 2: Inadequate Systems Engineering Process</u>

Root Cause 2.1: Inadequate requirements generation.

Facts:

- There was a requirement at the SRC avionics subsystem-level to deploy a drogue. This requirement included the phrase *"descending X axial deceleration,"* without a System- or AU-level coordinate system or figure to indicate the direction of the deceleration (acceleration) vector.
- LMSS Systems Engineering assumed the wording of the requirement would be understood, based upon Stardust experience where the requirement was implemented properly and verified with a centrifuge test.
- The process of importing the Stardust design implementation did not include orientation information or sensitivities.
- The critical step of interpreting the AU design and layout in an integrated operational environment was not performed adequately due to the lack of systems engineering support.

Finding:

- The inversion might not have occurred if the direction of the acceleration vector had been written in SRC avionics coordinates, or if a coordinate system figure had been included with the acceleration vector noted.

Root Cause 2.2: Systems Engineering did not define detailed verification requirements for subsystems.

Facts:

- Consistent with the FBC philosophy, the component verification function was delegated to the subsystem organizations with limited oversight from System Engineering.
- Systems Engineering assigned a type of verification (test, analysis, etc.) and a verification event (performance test, functional test, etc.) to each subsystem requirement, reviewed spacecraft-level verification results, and performed verification bookkeeping.
- System Engineering did not establish detailed expectations for the verification of requirements.

Findings:

- The SRC-AU design and verification approach never demonstrated an integrated understanding of how the SRC system was intended to function.
- Absent this understanding, the design was incorrect and the verification testing was ineffective in detecting the design error.
- The G-switch sensor inversion might have been avoided had either the design engineer understood the integrated functionality of the system or the verification approach ensured an effective performance test of the AU.

Root Cause 2.3: Lack of documentation of changes made to verification methods.

and

Root Cause 2.4: Systems Engineering Verification Process did not require consideration of verifier's qualifications or incorporate multiple verifiers.

These two root causes are closely related and are presented together in the following discussion.

Facts:

- The verification matrix for the Genesis spacecraft specified a performance test be used to verify the integrated performance of the SRC-AU.
- The actual method used to verify the G-switch sensor orientation was to inspect the Stardust SRC-AU G-switch sensor drawings for similarity to the Genesis drawings.
- The inspection was performed incorrectly due to the SRC-AU PIE's lack of experience inspecting mechanical drawings.
- The SRC-AU Specification was under LMSS Level 3 Change Control; therefore, the SRC-AU PIE should have processed a Change Request before changing verification methods.
- The PIE did not process this Change Request or generate a Technical Memorandum documenting his approach and findings.

Findings:

- The PIE, an electrical engineer, performed the verification without the necessary mechanical engineering background to review complex mechanical drawings.
- Either a Change Request or Technical Memorandum would likely have resulted in a critical assessment of the inspection approach and possibly detected the error.

Root Cause 2.5: Systems Engineering was not required to review subsystem test procedures or verification results.

Facts:

- Systems Engineering was not viewed as responsible for subsystem verification activities and as a result, did not review test procedures or test/analysis results performed at the Subsystem level.

- Systems Engineering did not review the 'unit test' procedure or results that Project Management and Systems Engineering erroneously believed would verify G-switch sensor orientation.

Finding:

- No effective Systems Engineering review of the SRC entry system verification occurred. Had Systems Engineering critically reviewed verification activities, it is likely the incorrect orientation of the G-switch sensors would have been detected.

Root Cause 2.6: Inadequate execution of System-level verification.

Facts:

- The lower-level SRC-AU requirement was derived from the System-level drogue chute deployment requirement, which had two requirements in one statement. The first requirement was to deploy a drogue between Mach 1.6 to 2.0 and the second was to provide transonic/subsonic stability.
- Review of the verification analysis for this requirement indicated that no actual verification was performed, only a discussion of the intent of the design.
- Two engineers reviewed the verification analysis as a cross-check; however, the lack of any actual verification was not recognized.
- Based on an interview with the LMSS Chief Systems Engineer, although the title of the requirement was "drogue Chute deploy," the focus of the verification analysis review was on the drogue stability issue alone, not the drogue deployment.

Finding:

- No verification of the relevant System-level drogue deployment requirement was performed. Absent such verification and associated unit tests, the verification process did not identify the design error.

Contributing Factor 2.1: Lack of a Systems Engineer assigned to the end-to-end Entry, Descent, and Landing (EDL) function.

Facts:

- No one on the Systems Engineering Team had been assigned individual Responsibility, Accountability, and Authority (RAA) for the entire EDL sequence and for oversight of the system design and operations plans to execute that phase.
- A number of Systems Engineers had responsibilities that might have logically included the G-switch sensor function, but did not.

- These Systems Engineers thought that another person had responsibility for the G-switch function.

Findings:

- Verification of the SRC AU G-switch sensor function should have been a responsibility of Systems Engineering, shared with the SRC-AU PIE, since it crossed subsystem boundaries.
- The lack of a Systems Engineering Team member responsibility for this critical integrated function did not directly cause the mishap, but did contribute to its occurrence.

Contributing Factor 2.2: Inadequate Systems Engineering staffing level.

Facts:

- Based on MIB interviews, JPL and LMSS Project Management and Systems Engineering thought that the LMSS Systems Engineering Team had an adequate staff.
- The LMSS Chief Systems Engineer was required to hold three positions (Chief Systems Engineer, Systems Engineering Manager, and Contamination engineer).
- Interviews indicated that the Systems Engineering Team had difficulty meeting their stated responsibilities, which were already reduced from traditional Systems Engineering responsibilities in accordance with Genesis' implementation of the FBC philosophy.

Finding:

- The MIB found that LMSS Systems Engineering staffing levels were inadequate, and numerous traditional Systems Engineering responsibilities were not performed, (e.g., detailed subsystem verification requirements not established, subsystem test procedures not reviewed, and subsystem verification results not reviewed).

<u>Root Cause Category No. 3: Inadequate Technical Review Process</u>

Root Cause 3.1: Key individuals' attendance was not required at project technical and drawing reviews.

Fact:

- It appears that no one with a System-level perspective of the drogue chute deployment participated in the lower-level peer review of the SRC-AU.
- No one from Systems Engineering participated or was required to participate in the drawing signoffs.

Finding:

- Had someone with a System-level perspective participated in these reviews, the G-switch sensor design inversion might have been detected.

Root Cause 3.2: Design Reviews were too high level to assess the design adequately.

Facts:

- The AU CDR consisted of a 4 hour, 148-page chart review with little technical content and was insufficient to support a box-level CDR.
- There were no noteworthy discussions of the G-switch sensor. No action items regarding the G-switch sensors were assigned.

Finding:

- The design error might have been discovered had the design reviews been conducted in significantly more detail.

Root Cause 3.3: JPL Systems Management Office (SMO) gave the Red Team too little time to perform an adequate assessment.

Facts:

- For the June 2000 Red Team review, the JPL SMO gave the Red Team only 3 days to review data products and meet with the project teams.
- This abbreviated review period was intended to avoid impacting the project's schedule.

Findings:

- An inadequate review period resulted in a review of insufficient depth to meet its chartered goals, which were in part to evaluate the spacecraft and SRC design, implementation, and test.
- Had the JPL SMO allocated adequate time to the Red Team for a thorough review, the error (either the specific verification error or the overall verification process failures) might have been discovered.

Root Cause 3.4: Inadequate Red Team management of focus groups.

Facts:

- The EPS Focus Group was a power system discipline-oriented team, not a cross-cutting, multidiscipline-oriented team. This group reviewed the SRC-AU at the June 2000 review.
- Red Team management formed an EDL Focus Group for the October 2000 Red Team cycle. This group was to take responsibility for AU parachute deployment functions from the EPS Focus Group.
- The EDL Focus Group did not address the SRC-AU, except to recommend

an action to coordinate with the Avionics Focus Group to review issues relative to the parachute deployment initiation system.

- The action was never completed because the Red Team system did not require actions to be closed.

Findings:

- EDL and EPS Focus Group failures were ultimately failures of the Red Team chairman to manage the Red Team properly.
- If the EDL Focus Group had pursued the EDL sequence completely, it is likely this group would have questioned the G-switch sensor implementation or verification. Instead, this group focused almost exclusively on entry aerodynamics.
- Had the EDL Focus Group followed up, or the Red Team action item process forced a follow up with the Avionics Focus Group, the design and verification errors might have been found.

<u>Root Cause Category No. 4: Unfounded Confidence in Heritage Design</u>

Root Cause 4.1: Inappropriate confidence in heritage designs.

Facts:

- The Genesis Project was based on an assumption of considerable reuse of heritage designs from Stardust.
- The view was extensive throughout the Genesis Project, although not universal, that heritage hardware should be considered inherently more reliable than non-heritage hardware.
- An erroneous belief that the SRC-AU was a heritage, or partially a heritage design, and unfounded confidence in heritage designs in general led to five errors that contributed to the mishap:
  (1) Systems Engineering recycled the key drogue deployment requirement in the SRC-AU specification from Stardust without reconsideration;
  (2) the SRC-AU PIE used Stardust schematics without reconsideration;
  (3) the design reviews focused less attention to the details of the pyro firing circuitry design because the presenters and reviewers placed greater confidence in it than was justified;
  (4) the SRC-AU PIE used the similarity of the Stardust heritage design to perform verification of the G-switch sensor orientation, which was performed incorrectly; and
  (5) the EPS Red Team Focus Groups that reviewed the SRC-AU did not review the design or the verification methodology because they considered the likelihood of a design or verification problem with a heritage design to be unlikely.

Findings:

- A major misconception existed within much of the Genesis leadership and within the Red Team that heritage hardware meant a lower standard of review and verification was acceptable.
- It is likely that the design error would not have occurred or would have been discovered during verification had the same standards as those applied to new hardware been applied to the SRC-AU.

Root Cause Category No. 5: Failure to "Test as You Fly"

Root Cause 5.1: G-switch sensor not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Test Plan).

Facts:

- The Pointing Budget and Alignment Criteria Document (Phasing Test Plan) did not identify the G-switch sensor as having a critical alignment.
- The G-switch sensors may not have been included because such plans are typically produced by engineers concerned with hardware that has precise alignment requirements, such as star trackers or science instruments.
- Members of the Genesis Systems Engineering team approved the document.

Finding:

- Had the G-switch sensors been identified as alignment-critical and been included in the Pointing and Alignment Document, the verification of the sensors would have been performed properly.

Root Cause Category No. 6: Faster, Better, Cheaper (FBC) Issues

Root Cause 6.1: Faster, Better, Cheaper (FBC) philosophy: Cost-capped mission with threat of cancellation if overrun.

Facts:

- As proposed, selected, and confirmed on Genesis, the FBC philosophy had the following effects:
  (1) Maximal science scope and focus on payload issues at the expense of the spacecraft, SRC, and ground systems.
  (2) Low schedule and dollar reserves leading to significant adverse pressure on decision making.
  (3) Focus on a low-risk implementation led to a reliance on heritage hardware which gave a false sense that mission risk was controlled and allowed the risks associated with the lower standards for heritage to go unrecognized.
  (4) Very lean Systems Engineering team with heavy un-checked reliance on the subsystems teams for requirements and verification functions.
  (5) Near total reliance by JPL on the LMSS team and processes with little cross-checking outside of payload and payload interface activities.
- Genesis was selected with only 11-percent budget reserve at confirmation and had only 7.2 percent at CDR. All involved (NASA, JPL, and LMSS) were convinced that because of the assumed heritage design, this was an acceptable position.
- JPL asked LMSS to give up fee to cover other non-LMSS risk issues and avoid a project overrun of the cost cap.

Findings:

- The project maintained the cost-cap, in part at the expense of adequate technical insight by JPL into the LMSS Flight System and at the expense of a complete and robust Systems Engineering function.
- The Agency was at fault for encouraging and accepting the FBC philosophy as described above.

6.0 Recommendations

The following 12 recommendations address the root causes and contributing factors identified in Section 5.0.

The Board did not make recommendations at the direct root cause or contributing factor level since they were generally at too low a level to provide meaningful solutions. For example, the Root Cause 2.1 regarding inadequate requirements generation could be addressed directly by recommending requirements training for all Systems Engineers. However, although such training is widely available, poor requirements are still common. The same can be said for almost any of the other identified Project Management, Systems Engineering, or technical review root causes and contributing factors. The Board chose to address issues at a higher level. For example, in the case of inadequate requirements generation, the Board recommends addressing this problem at the Systems Engineering level, not the requirements level alone. When the causes of inadequate Systems Engineering are corrected, the various Systems Engineering failures uncovered in this mishap investigation will be addressed simultaneously.

The primary recommendations have to do with correcting systemic failures within the technical review process that have led to inadequate technical reviews of SMD Projects. In addition to correcting the constituents of the traditional review process, Systems Engineering products and processes must be reviewed in significantly greater detail than is common today. The Board did not intend the recommendations to add additional reviews; they propose to execute the correct reviews and make them effective in probing a design and its processes.

Although there will be increased project-level costs associated with implementing these recommendations, it is the Board's view that any project-level cost increase should be offset by Agency-level savings resulting from fewer mission failures.

Table 6.1 provides a mapping of root causes and contributing factors to the proposed recommendations.

6.1 Recommendations to Address Project Management and Systems Engineering Failures:

The following recommendations address the System Engineering process failures and the Management issues raised in Section 5.2. The first recommendation proposes a review process to force discipline and completeness into the Systems Engineering process for all future Science Mission Directorate projects. The second recommendation is directed at those projects that are later in their project lifecycle and where the first recommendation may no longer be feasible. The third recommendation addresses overall strengthening of Systems Engineering within NASA's contractors. The fourth recommendation addresses the issue of failure to clearly define responsibility through a complex spacecraft system. The fifth recommendation identifies the need to assign adequate Systems and Subsystems Engineers to projects. The final recommendation addresses the question of considering organizational structures that segregate separable elements of spacecraft, such as the SRC.

Recommendation 1: Institute a Systems Engineering Plans, Progress, and Processes Review for all Science Missions Directorate projects as part of the normal Project Design Review process.

<u>Discussion of Recommendation 1:</u>

The Genesis mishap occurred mainly because of failures in NASA's Systems Engineering process. This issue is recognized within the Science Mission Directorate community and is known to be a cause of several of the Directorate's recent failures (MCO, MPL, TIMED, and CONTOUR). Given this, the Board believes it is necessary for NASA to develop a strategy to significantly strengthen that process. Although not a complete strategy, this recommendation should significantly increase the rigor of project Systems Engineering.

Future projects should hold the proposed review as part of a project's normal control gates. The project would be required to focus on the detailed Systems Engineering processes employed, review the detailed Systems Engineering results that led up to the control gate, and review the detailed Systems Engineering plans for reaching the next control gate. This review should be a multi-day event -- similar to a standard Subsystem review. Focus should not be solely on process and plans, such as the Systems Engineering and Management plan and the Configuration Management plan, but also on review of the technical products (reports, trade studies, requirements, verification results, etc.) that the Systems Engineering team has produced. Having to explain to a group of experienced peers one's plans and progress in significant detail is the best method of ensuring an improved Systems Engineering function within the Science Mission Directorate.

Successful implementation of this recommendation requires Project management buy-in, which will be evidenced by requiring that the forward plan at each control gate include a resource-loaded, detailed implementation schedule for Systems Engineering activities.

The Systems Engineering lead for the Mission Design Review should chair the recommended review and it should be staffed by experienced Systems Engineers and Project Managers. A set of standards for the review team and project team should be developed, as well as training to assure compliance with these standards.

Recommendation 2: Hold a tailored version of the review for current Science Mission Directorate projects that are late in their lifecycle and for which a complete Systems Engineering Plans, Progress, and Processes Review may not be feasible.

Discussion of Recommendation 2:

Projects that are late in their lifecycle may not be able to support a detailed review of all of their preceding Systems Engineering activities; however, a review of the adequacy of the Systems Engineering processes and selected products leading to the recommended review could identify significant weaknesses. If a significant Systems Engineering failure were identified as part of the tailored review, a more detailed review of any issues uncovered should be performed.

Recommendation 3: The Science Mission Directorate should place increased emphasis on a contractor's Systems Engineering processes and teams when making contract and award fee decisions.

Discussion of Recommendation 3:

The size and scope of the Genesis Systems Engineering Team was reduced largely to minimize costs. By increasing the emphasis on Systems Engineering in the award of contracts and award fee, the Agency should be able to raise the level of Systems Engineering staffing contractors apply to NASA projects.

Recommendation 4: The Science Mission Directorate should require projects to consider having Mission Mode Engineers from the Systems Engineering organization assigned to each mission mode (ascent, coast, entry, etc.) as a means of guaranteeing complete coverage of all system functions.

Discussion of Recommendation 4:

Mission Mode Engineers would be responsible for all functions associated with their assigned mode of operation; including requirements and verification, insight into hardware and software designs, and operations. For example, the Genesis system operated in several ways, each exercising distinct subsets of the hardware and requirements in different ways and carrying distinct risks. For Genesis these included launch and commissioning in orbit; science operations; return to Earth; and entry, descent, and landing.

It is not atypical for NASA or its contractors to assign Systems Engineers responsibility for particular subsystems -- tracking requirements, design, test, and operations of those subsystems. Typically, modes of operations are addressed by Operations Engineers. Although it is still appropriate to maintain Operations Engineers who are responsible for modes of operations, there may be advantages to assigning responsibility for a mode of operation to a member of the Systems Engineering team, on a part or full-time basis. Since most modes of operation involve multiple subsystems performing a system-level function, defining responsibilities by mode will better allow Systems Engineers to view the subsystems/boxes from a System-level perspective, instead of a stove-piped subsystem perspective. Also, by assigning responsibilities for each mode of operation, coverage of each function within the spacecraft will, by definition, be covered by a Systems Engineer.

Implementation of this approach should be left to individual projects; however, the MIB recommends that the Science Mission Directorate require its consideration. Regardless of the methodology chosen for implementation, it is essential that Systems Engineering functions be applied to each of the major modes.

Recommendation 5: NASA and JPL should assign System and Subsystem/Discipline Engineers to projects to maintain insight into the contractor's activities.

Discussion of Recommendation 5:

In the Genesis case, JPL assigned too small a staff of System and Subsystem/Discipline Engineers to this contractor-managed project. The advantages that a NASA or JPL team bring to contractor-run projects are that they:

- allow for viewing problems from different perspectives/cross-checking,
- allow for identifying problems that the contractor alone may not recognize,
- force the contractor to defend its technical decisions more thoroughly, with the result that decisions are more thoroughly considered,
- provide a continuous review process to the project, identifying and correcting problems earlier and at a lower cost, and
- allow for insight into processes to ensure their adequacy or allow identification of needed changes.

In determining the proper NASA/JPL staffing, consideration must be given to the team's skill sets and training.

Recommendation 6: Future Science Mission Directorate projects that contain separable spacecraft elements within a single system should consider organizing the elements as a separate spacecraft. All projects should ensure that separable spacecraft elements are analyzed and evaluated fully for their free-flight functions and mission success, whether or not this is implemented organizationally.

Discussion of Recommendation 6:

Although there may be sound reasons to organizationally treat a separable spacecraft elements as part of a single spacecraft, these reasons should be justified.

6.2 Recommendations to Address Inadequate Reviews:

Recommendation 7: The Science Mission Directorate should institute a significantly more rigorous and more probing Design Review process than currently exists.

Discussion of Recommendation 7:

That improved design review process should include the following items.

- A greater involvement in the planning and managing of reviews at all levels of the system by the Systems Review Team.
- A process that includes System Review Team ownership of all reviews of Subsystems and instruments, the above-mentioned Systems Engineering Review, and of all box-level and software reviews.
- Mandatory membership at each review that accounts for all disciplines appropriate to the system, subsystem/instrument, box, or software under review.
- Significantly greater level of detail than has become typical at all levels of review – less concentration on chartsmanship and more review of design details, analyses, and other products over a multi-day period.
- Continuity and coordination of membership at the different levels of review throughout the project lifecycle to maximize review team effectiveness.
- Notification of review chair of all substantive changes after each review.

An ineffective technical review process in the Science Mission Directorate also contributed to the Genesis mishap. This issue, like the weakness of Systems Engineering, is commonly recognized within the Science Mission Directorate community and has been a cause of several recent failures (MCO, MPL, TIMED, and CONTOUR). The Board recommends significantly strengthening the technical review process by raising the quality of technical reviews. Efforts to strengthen the review process are underway at GSFC and JPL, and must be completed and extended to all Centers and contractors executing Science Mission Directorate projects.

Recommendation 8: Separate Red Teams, or other comparable review teams, should not be routinely depended upon to conduct design and verification reviews of projects. As part of instituting a more rigorous review process, standing independent review teams should be given the charter across the lifecycle of the project and the membership necessary to avoid having to appoint additional Red Teams late in the project lifecycle.

Discussion of Recommendation 8:

If a project's independent System Review Team cannot be staffed properly or trusted to perform the functions asked of Red Teams, then what purpose do the System Review Teams serve and why do they exist? The charter of technical Red Teams, such as the Genesis Red Team, is not generally outside the scope of a project's System Review Team. With advanced consideration of any special staffing required, and a sufficient charter, there should be no reason to assign Red Teams to review the design and verification of a project. A System Review Team does not generally contain business support, but if this is required an augmentation to the team could be made to fill that need.

Red Teams require a significant amount of time to become technically conversant with a project, more time than they are generally given, and as a result, they are unable to productively contribute and their impact is typically small or negative. This can be avoided by relying on the Systems Review Team to perform that function.

6.3 Recommendations to Address Heritage Design Issues:

Recommendation 9: Give the heritage hardware and software used in Science Mission Directorate projects the same level of review as new designs, to include requirements, design, manufacturing, and test reviews.

Discussion of Recommendation 9:

Generally throughout the Agency, heritage hardware (and software) are given less scrutiny than new hardware because of an often unfounded faith that heritage designs are qualified and will perform properly in a new application. There are two weaknesses with this approach. First, few heritage designs meet all requirements associated with a new application and almost invariably require some level of modification or reverification to meet their new requirements. Second, the designer of the heritage hardware is typically not available to support a new application, so the level of understanding of the heritage design is generally lower than it is for a new hardware designs – a risky position in which to place a project.

Although cost, schedule, and technical risks for heritage hardware and software may be lower than for new hardware, that can only be the case if there is a full engineering understanding of the heritage design and the configuration maintained. To reach that level of understanding, for a new set of requirements and without the original designer, the heritage design must be reviewed as thoroughly as new hardware. Since the design, analysis, production, and verification products already exist for heritage designs, there should be no additional costs associated with producing these products. An incremental cost to develop a full understanding of the products and to present them at a detailed box-level review should be more than offset by a reduced likelihood of failure.

In general, heritage elements may reduce detail design costs, but project managers should not expect the use of heritage elements to reduce the work in requirements management, verification planning, and review. It should not be expected that a high heritage system will require significantly less Systems Engineering resources and contradictory statements should be carefully evaluated.

Recommendation 10: Reverification of all requirements should be required until existing heritage verification can be certified as adequate by the responsible engineer and demonstrated to be adequate at the appropriate box-level review. Likewise, testing requirements should specifically target all configuration changes from the heritage design unless adequate detailed rationale can be developed.

Discussion of Recommendation 10:

Inadequate verification of heritage hardware is common on many projects due to the assumption that since it has been previously been qualified that it requires less scrutiny than new hardware designs. This is often not the case, since the applications are almost always somewhat different and/or the design has been modified to operate in a new application. This recommendation is intended to enforce a rigorous treatment of heritage hardware verification by requiring the same level of verification as is applied to new hardware.

6.4 Recommendation to Address "Test As You Fly" Issues:

Recommendation 11: Include a requirement to review 'test as you fly' and 'phasing test' plans and deviations specifically as part of the improved design review process. This should occur at every level of assembly as part of the verification discussion.

Discussion of Recommendation 11:

Test as you fly exceptions and phasing test plans are commonly presented at design reviews, but not always. The Science Directorate should apply this practice universally and the System Review Team should review it thoroughly.

6.5 Recommendations to Address Faster, Better, Cheaper Issues:

Recommendation 12: The process leading to project confirmation should identify the appropriate level of reserves for a project based upon its overall maturity, launch constraints (e.g., short window planetary mission vs. low-Earth orbit), complexity, and all identifiable cost, schedule, and technical risks.

Discussion of Recommendation 12:

The Discovery Program (and other competitively selected science missions programs) has evolved significantly since the time of the Genesis selection and confirmation. In particular, the AO's now require significantly larger reserves and emphasize the identification and management of risk. However, it is not clear that the current selection and confirmation process adequately assess the unique risk levels for each mission to ensure that reserve levels are adequate for that mission.

Table 6.1 Cross Reference of Root Causes and Contributing Factors to Recommendations.

Mapping of Genesis MIB Recommendations to Root Causes and Contributing Factors (P = Primary mapping; S = Secondary mapping)	Project Management and Systems Engineering Recommendations	R1) Institute a Systems Engineering Plans, Progress, and Processes Review for all Science Missions Directorate projects as part of the normal Project Design Review process.	R2) Hold a tailored version of the review for current Science Mission Directorate projects that are late in their lifecycle and for which a complete Systems Engineering Plans, Progress, and Processes Review may not be feasible.	R3) The Science Mission Directorate should place increased emphasis on a contractors Systems Engineering processes and teams when making contract and award fee decisions.	R4) The Science Mission Directorate should require projects to consider having Mission Mode Engineers from the Systems Engineering organization assigned to each mission mode (ascent, coast, entry, etc.) as a means of guaranteeing complete coverage of all system functions.	R5) NASA and JPL should assign System and Subsystem/Discipline Engineers to projects to maintain insight into the contractor's activities.	R6) Future Science Mission Directorate projects that contain separable spacecraft elements within a single system, should consider organizing the elements as a separate spacecraft. All projects should ensure that separable spacecraft elements are analyzed and evaluated fully for their free-flight functions and mission success, whether or not this is implemented organizationally.
1. Inadequate Project and Systems Engineering Management							
Contributing Factor 1.1: Insufficient JPL Project Management and Systems Engineering insight into LMSS activities.		P	P	P		P	
Root Cause 1.1: Genesis Project Management and Systems Engineering did not perform due diligence with regard to reviewing briefing materials.		P	P	P			
Contributing Factor 1.2: SRC not treated as a separate spacecraft.		S	S	S			P
2. Inadequate Systems Engineering Process							
Contributing Factor 2.1: Lack of a Systems Engineer assigned to the end-to-end Entry, Descent, and Landing function.		S	S	S	P		
Root Cause 2.1: Inadequate requirements generation.		P	P	P			
Root Cause 2.2: Systems Engineering did not define detailed verification requirements for subsystems.		P	P	P			
Root Cause 2.3: Lack of documentation of changes made to verification methods.		P	P	P			
Root Cause 2.4: Systems Engineering verification process did not require consideration of a verifier's qualifications nor incorporate multiple verifiers.		P	P	P			
Root Cause 2.5: Systems Engineering was not required to review subsystem test procedures or verification results.		P	P	P			
Root Cause 2.6: Inadequate execution of System-level verification.		P	P	P			
Contributing Factor 2.2: Inadequate Systems Engineering staffing level.		P	P	P		P	
3. The Review Process at All Levels Failed to Identify the G-Switch Inversion							
Root Cause 3.1: Key individuals' attendance was not required at project technical and drawing reviews.		S	S	S			
Root Cause 3.2: SRC-AU Critical Design Review was too high-level to adequately assess the design.		S	S	S			
Root Cause 3.3: JPL SMO gave the Red Team too little time to perform an adequate assessment.							
Root Cause 3.4: Inadequate Red Team management of focus groups.							
4. Unfounded Confidence in Heritage							
Root Cause 4.1: Inappropriate confidence in heritage designs.							
5. Failure to 'test as you fly'							
Root Cause 5.1: G-switch sensor was not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Plan).							
6. FBC Issues							
Root Cause 6.1: The Faster, Better, Cheaper (FBC) philosophy: 'cost-capped' mission with threat of cancellation, if overrun.							

																								Technical Review Recommendations
		S		S		S	S	P	P													S		R7) The Science Mission Directorate should institute a significantly more rigorous and more probing Design Review process than currently exists
						P	P																	R8) Separate Red Teams, or other comparable review teams, should not be routinely depended upon to conduct design and verification reviews of projects. As part of instituting a more rigorous review process, standing independent review teams should be given the charter across the lifecycle of the project and the membership necessary to avoid having to appoint additional Red Teams late in the project lifecycle.
																								Heritage Hardware Recommendations
				P																				R9) Give the heritage hardware and software used in Science Mission Directorate projects the same level of review as new designs, to include requirements, design, manufacturing, and test reviews.
				P																				R10) Reverification of all requirements should be required until existing heritage verification can be certified as adequate by the responsible engineer and demonstrated to be adequate at the appropriate box-level review. Likewise, testing requirements should specifically target all configuration changes from the heritage design unless adequate detailed rationale can be developed.
																								Test as you Fly Recommendations
		P																						R11) Include a requirement to review ‘test as you fly’ and ‘phasing test’ plans and deviations specifically as part of the improved design review process. This should occur at every level of assembly as part of the verification discussion.
																								FBC Recommendations
P																								R12) The process leading to project confirmation should identify the appropriate level of reserves for a project based upon its overall maturity, launch constraints (e.g., short window planetary mission vs. low-Earth orbit), complexity, and all identifiable cost, schedule, and technical risks.

7.0 Other Observations and Recommendations

The following observations were made during the course of the MIB activities. They do not relate directly to the incident; however, the Board believed they were significant enough to document and to make recommendations to the Science Mission Directorate.

7.1. Recording Key Engineering Telemetry

Observation: The Genesis SRC collected temperature strip data that indicated the effectiveness of the heat shield. These data could be useful for future applications or return capsules and were used to eliminate certain heat shield breach faults that might have led to the incident. The temperature strip data, which did not require any data recording devices, were the only entry data gathered on board the SRC.

The Board believes that it might have been useful to the community at large to have gathered more information during the entry -- information that could be applied to other return capsule concepts -- including Exploration System vehicles.

Project Managers who are not required to gather data for other future missions make logical, pragmatic decisions based on their science requirements and funding limitations. As a result, the need to maximize science yield and minimize cost drive Project Managers to collect no more than is required for their specific mission.

Recommendation: The Board recommends that the Agency determine for each mission what, if any, ancillary engineering data should be gathered that might have applicability to other NASA applications. The results should be provided to a Project Manager as a requirement with the understanding that there will be a cost, and probably a science return, impact of such a requirement.

7.2. Missing Resistor

Observation: One of the Genesis fault tree items was number 2.8, Timer Jumpers Wrong, Causing Excess Delay. The following observations were made during the inspections and test performed to close out this fault tree item.

To implement each timing circuit, a constant clock signal of a 10-Hz frequency is input to one 12-bit (12 output lines) binary counter integrated circuit for each of the different timing circuits (drogue chute deploy; drogue harness cut; main chute deploy; etc). Each circuit is independent of each other with the exception of the 10-Hz oscillator.

The required timing is then selected by connecting some or all (depending on the desired time) of the counter outputs to a series of logic AND gates.

The AND gate inputs are either connected to the counter outputs or to 5 V through installation of one (but not both) of a pair of resistors/jumpers (one pair for each AND input/counter output pair). One resistor of the pair, if installed, would connect the AND gate input to 5 V making that particular AND gate input a logic '1' all of the time and thus not affected by, or connected to, its paired counter output (see resistors 1B and 2B in Fig. 7.1). However, if the other resistor of the pair were installed instead, it would connect the counter output to the AND input causing that AND gate input to follow the logic state of the counter output (see resistors 1A and 2A in Fig. 7.1). Only one of the pair should be installed (i.e., 1A or 1B but not both). By systematically choosing which of the resistors are installed, the 10-Hz input clock can be divided down to achieve the desired timing.

The Avionics/Pyrotechnics/EEE Parts Subteam reviewed the base-lined drawings and subsequent changes, made with respect to the placement of the timing resistors and the respective signal timing expected from those resistor positions.

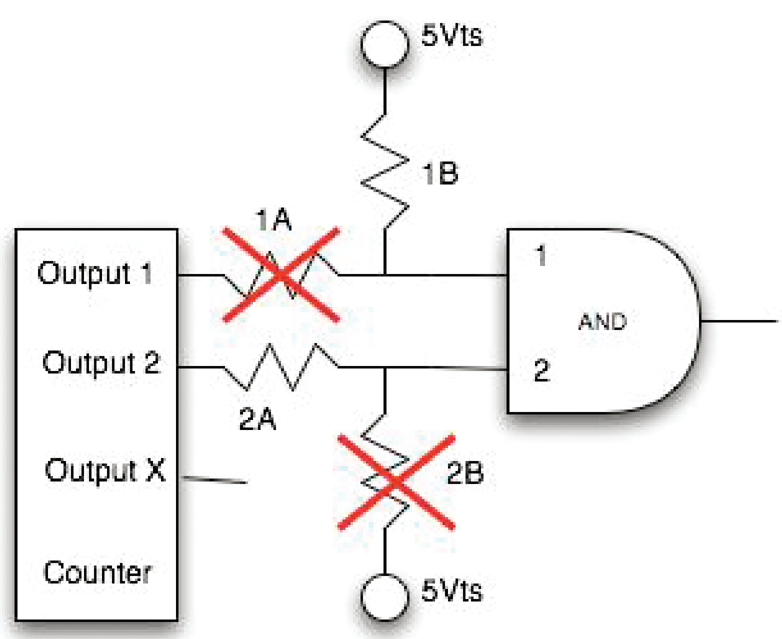


Figure 7.1. Example of EST timing circuit and timing jumper/resistor placements.

During the inspection of the EST board from avionics box B, all the resistors were determined to be installed in the proper configuration to achieve the stated signal timing.

During the inspection of the EST board from avionics box A, one pair of resistors, R185 and R186, was found to be missing (i.e., one of the two (R186) should have been installed but neither one was). This particular pair of resistors is in the timing circuit for the drogue chute harness cable cutter. Figure 7.2 shows some of the resistor pairs and the missing resistors intended location.

With neither resistor installed, the input to one of the AND gates is left 'floating' in an indeterminate state. When a CMOS logic input, such as the AND gate is left floating, the chip can sometimes read that input as a logic '1' and at other times as a logic '0'. Which logic level this input floats to (1 or 0) can be affected by several factors including humidity and surrounding electrical fields and cannot be predetermined.

For example, this particular board went through its testing program and never showed a failure of this timer.

What this floating input means for the timing circuit is that if the input happened to 'float' to a logic '1' during the timing sequence, the circuit would have worked as expected. However, if the input 'floated' to a logic '0', that particular timing circuit would have failed to send a 'fire' signal to its pyro. Since there was a redundant

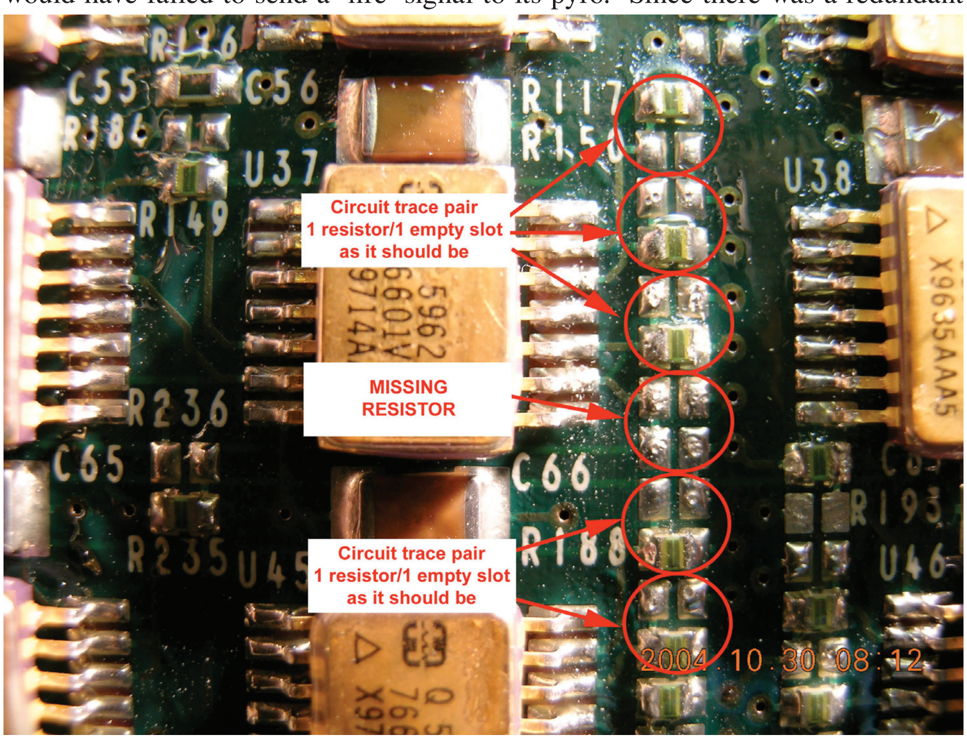


Figure 7.2
Example of resistor pairs and the intended location of the missing resistors.

circuit in the other AU, this missing resistor could have resulted in a loss of redundancy but not a loss of pyro function.

An inspection was then made to determine if there had been a resistor installed but knocked loose upon impact. Inspection inside the box showed no loose pieces and a review of the close-out photos for the EST board confirmed that the resistor was missing prior to flight.

LMSS designers and Quality Assurance then reviewed paperwork to determine if the component had been installed and then removed under direction.

A review of the 'pick list', which is the list of components input into an automated part insertion machine, showed that R186 was programmed into the machine for insertion. There was no indication that a post-assembly inspection noticed a missing resistor.

Later in the project cycle, LMSS changed some of the jumper resistors to modify some of the pyro firing timings. Changes were made on three separate occasions under three different Redline Record Sheets (RRS). There were also two resistors replaced as a precautionary measure due to visual damage (scratches).

A review of change papers indicates that neither R186 or R185 were to be moved; however, resistors R187 and R188 had been moved -- the most recent move had been during the last set of changes. Resistor 187 is within approximately 0.1 inches of the R185/R186 pair. In addition, only R188 has a reference designator on the circuit board, which makes if difficult to locate the correct components on the board. There is a possibility that R186 was inadvertently removed during the modifications of R187/R188.

A microscopic view of the solder pads showed evidence of re-solidification of the solder on the R186 pads, which indicates that the solder had been melted, most likely when R186 was removed.

Whatever the reason for the missing resistor, the fact that it was not noticed indicates a breakdown in the quality inspection process.

While MIB members were inspecting the flight hardware, three issues became evident that made the inspections of the timing resistors difficult.

1. The assembly drawings did not show the placement for all of the timing resistors (i.e., a graphical representation that would help locate particular components).
2. The assembly drawings were not updated to reflect the changes to the resistor

placement called out in the Redline Record Sheets (RRS); nor did the RRS paperwork have any graphical representation of the new resistor locations that could be used in a visual inspection.

3. Only a portion of the resistors actually had a reference designator (i.e., R123, R43, R11, etc.) printed on the printed wiring board (PWB). Therefore, it was very difficult to verify which resistor was which without using an Ohm meter and probing the board (something that would have been frowned upon during the assembly and testing of new 'flight' quality boards).

The visual inspection could have been made easier if the assembly drawings (or at least the RRS paperwork) had shown graphically, the new resistor locations and these drawings had been kept up to date.

Recommendation 1. - Documentation

Assembly drawings should show, graphically, the location of all components. Any subsequent changes should be reflected in the graphical representation, preferably on the actual assembly drawings, but at the very least in the change paperwork. Text instructions are not sufficient for a proper inspection by themselves. The one exception would be for changes that are simply part number or value exchanges that do not require moving, removing, adding, orientation changes, or change in physical size.

Recommendation 2. – Documentation and Design

While it is not always practical to silk screen the reference designator for every component on to a PWB due to part density, a concerted effort must be made to use as many designators as possible and to provide references for all Select-At-Test components or jumpers that are subject to change. For those designators not printed on the PWB, the assembly drawing should be annotated in such a manner that the missing designators on the PWB can be easily identified on the drawings (bold or italicize those designators on the drawing).

Recommendation 3. – Requirements Maturity and Flight Electronics Hardware Build-up

By building the flight electronics and then making repeated changes, as the requirements matured, an environment was established that increased the likelihood of a mistake being made, especially given the verification and systems engineering problems identified in the Genesis program. When a design must be made more complex to provide flexibility to meet changing requirements, re-verification of the hardware after incorporating changes must be rigorous. Building up the final flight hardware should be avoided until the requirements have been finalized and verified on an Engineering (or development) unit.

7.3. LMSS Mission Success

Observation: The LMSS Mission Success Organization in Space Exploration Systems was separated from LMSS Product Assurance in December 1999, but did not become active on Genesis until approximately March 2000, due to the Mars Polar Lander (MPL) loss investigation. LMSS Mission Success was formed too late and was too understaffed to have contributed to the Genesis mishap, either positively or negatively. However, it was the Board's view that this organization could be strengthened to help avoid future mission failures.

Recommendation: Strengthen the LMSS Mission Success organization to provide a strong, independent technical review capability for future LMSS missions.

8.0 Stardust Mission Recommendations

The Board suggests that the Stardust Mission implement the following recommendations. During the Genesis mishap investigation, the Board identified areas of investigation beyond the scope of their inquiry that will improve the understanding of Stardust components and mission risks. These items are listed below and organized into three broad categories: Hardware Test and Analysis, Contingency Planning, and Engineering Reviews.

The Board suggests that these recommendations, especially the six Hardware Test and Analysis recommendations, are carefully coordinated to ensure optimum use of the Genesis flight hardware.

Hardware Test and Analysis

1. Perform Destructive Physical Analysis (DPA) of Flight G-Switch Sensor

The G-switch sensor performs a critical function by sensing the conditions that start the recovery sequence. Post-flight spin tests indicated that the switch should have functioned given the actual entry conditions for Genesis. However, the G-switch sensor specification is not detailed enough to be able to validate the function of the switch for space application. The Board recommends that a DPA be performed on the Genesis flight switches to evaluate the condition of the switch, to determine the space and flight environment effects on the switch's function, and to determine if the switches will function properly during the Stardust entry conditions. The DPA should encompass the standard suite of EEE part evaluation, including a test of hermeticity.

2. Evaluate Effects of G-Switch Sensor Side Load

During spin table tests of the Genesis flight G-switch sensors, an anomaly with one of the switches was detected during the 30° off-axis test. (Note: The 30° off-axis test represented a severe side load condition not indicative of the actual Genesis entry conditions.) During this test one of the G-switch sensors stayed in the closed position after the test was completed and the spin table had stopped. The switch released only after a very slight vibration was applied to it. The Board recommends that the Stardust reentry environment be evaluated to determine the G-switch sensor side load. Further, G-switch sensor performance should be characterized over a range of acceleration conditions and combined with the side load data to ensure proper G-switch sensor behavior in the anticipated environment.

3. Determine Effects of Space Exposure on Parachutes and Pyrotechnics

The Genesis SRC was exposed to the space environment for 3 years, providing an excellent opportunity to evaluate the effects of long-duration space exposure on parachute materials and pyrotechnics. The results of such an evaluation program would directly benefit the Stardust Mission because Stardust used similar hardware. Furthermore, future space programs that use parachute systems, such as the Crew Exploration Vehicle Program, would also benefit from these data. The Board recommends that the Genesis parachute and pyrotechnic systems undergo a thorough test and evaluation program to determine the effects of long-duration space exposure on these systems. The results of this program should be used to assess the condition of the Stardust hardware. The evaluation program should include materials used in construction of the parachutes and spare parachutes to provide a baseline for comparison with the Genesis flight hardware. A detailed plan should be developed to guide the test and evaluation of the Genesis materials and pyrotechnics to ensure maximum effectiveness of the test program. Deliberations regarding the test of the pyros should include knowledgeable JSC personnel.

4. Investigate SRC Latch Operability

The Genesis SRC latches are a scaled-up copy of the Stardust latch mechanisms. Although Genesis telemetry indicated that the SRC latches were closed, post-flight inspections revealed that one latch was open. The Board recommends that Stardust investigate whether the latch opened on impact or if it failed to operate in flight. Results of the investigation should be used to assess the risk to Stardust. In addition, the investigation should attempt to determine the source of the deposit on the exposed bare metal of the latches.

5. Determine Ablation Margin For Heatshield and Backshell

The Genesis and Stardust heatshield and backshell use similar material and design characteristics. The Genesis ablation performance can be used to evaluate the predicted Stardust reentry performance margin. The Board recommends that Stardust update ablation models of the heatshield and backshell using Genesis core samples if necessary. The updated ablation models should then be used to assess Stardust performance margins.

6. Determine Effects of Space Exposure on Seals, Vents, and Science Canister Filter

The Stardust seals between the heatshield and backshell and the backshell vents are critical components of the reentry capsule that help prevent high-temperature gas penetration. The science canister filter prevents contamination of the science samples after recovery. Since the Genesis seals and filter are very similar to the Stardust design, Stardust performance can be predicted from analysis of the Genesis flight hardware. The Board recommends that the Genesis heatshield to backshell seals, the Genesis backshell vents, and the Genesis science canister filter be evaluated to assess degradation due to the space environment. Results of this evaluation should be applied to the Stardust seals, vents, and filter to predict their condition and performance characteristics.

Contingency Planning

7. Adopt an Incident Command System Process for Recovery Contingency Planning

The Board recommends that Stardust adopt an Incident Command System (ICS) process into its planning and execution of recovery ground contingency operations - this includes specifically those recovery ground contingency operations managed by JPL/LMSS. If a Stardust mishap were to result in the activation of a recovery ground contingency, the ICS process provides for effective command, control, and coordination of emergency response operations. ICS would have helped the Genesis Project with (1) identification, containment, and barrier control of "hot zones", (2) hazardous material awareness training and personnel protective equipment provisioning, (3) clear contingency operations command structure, and (4) effective internal and external communications management. The ICS process is well established in the United States and is used by municipal, state, civilian federal, and military federal agencies:

http://www.fema.gov/nims/
http://www.fs.fed.us/fire/operations/niims.shtml
http://www.osha.gov/SLTC/etools/ics/what_is_ics.html
http://www.911dispatch.com/ics/ics_describe.html

Stardust recovery ground contingency plans should incorporate UTTR Safety protocols as well as clearly articulate the roles and responsibilities of the UTTR organization during contingency response operations.

8. Review Recovery Contingency Scenarios

For the Genesis Project, recovery contingency planning and training were not sufficient to ensure an adequate response to the incident that occurred (i.e., more detailed planning and training for the "hard landing" scenario should have been performed). The Board recommends that the Stardust Project review all possible recovery contingency scenarios in coordination with the UTTR organization, prioritize the scenarios for planning and resource allocation and training, and subject them to an independent review.

9. Provide Sufficient Schedule for Recovery Contingency Review and Personnel Training

The Genesis Project experienced schedule compression in the 3-month period prior to SRC return. The Board recommends that the Stardust Project create a recovery contingency planning schedule in coordination with the UTTR organization that allows sufficient time for (1) development of detailed procedures, (2) independent reviews (and associated follow up actions), and (3) contingency training.

10. Review Consistency and Adequacy of Recovery Contingency Requirements

Genesis utilized multiple documents at various organizational levels to identify and plan for recovery contingency scenarios. These documents led to requirement inconsistencies and operational missteps. The Board recommends that the Stardust Project perform internal reviews to assure consistency and adequacy of requirements (including UTTR requirements) throughout the documentation tree.

11. Assemble One Binder for Recovery Contingency Plans

The Genesis Project did not maintain one main binder containing all recovery contingency plans. Also, written recovery contingency procedures were not available to all elements of the recovery team. The Board recommends that Stardust assemble and maintain all recovery contingency documentation in a single binder with configuration-controlled copies deployed to appropriate elements of the recovery team. This recovery contingency documentation should include detailed procedures for field recovery personnel.

Engineering Reviews

12. Evaluate Stardust System Phasing

During the Board's investigation, LMSS personnel described a Stardust G-switch sensor spin table test. The description of the G-switch sensor test helped the Board to understand and mitigate concerns regarding Stardust G-switch sensor phasing. However, definitive test plans, procedures, and results were not presented to the MIB since this was outside the scope of the MIB investigation. To ensure that Stardust G-switch sensor phasing is correct, the Board recommends that an independent evaluation be performed of the Stardust G-switch spin table test. This evaluation should include a review of the Avionics schematics and close-out photos, as well as spin table test plans, test procedures, and test results. This independent team should also review any other system phasing aspects of Stardust that are deemed mission critical and are not already validated during flight. This will provide additional assurance to NASA that all aspects of system phasing are addressed for the Stardust Mission lifecycle.

13. Review Stardust Requirements and Verification Procedures

The Board's investigation uncovered important gaps in Genesis requirement verification plans and practices. To ensure similar gaps do not exist in the Stardust requirement verification program, the Board recommends an in-depth review of the Stardust requirements decomposition and verification program. The scope of this review should include actual verification test procedures, data, and analyses. In addition, traceability of requirements to verification tests and evaluation of test program coverage should also be reviewed to show that all requirements are properly verified.

14. Review Recovery Parachute System

The MIB identified a weakness in the verification and review process during the investigation of Genesis. Review teams, such as the Red Team, failed to examine the pyro and parachute hardware requirements and verification/qualification plans. Also, very little data on the Genesis pyros were provided in the packages presented to the review teams. The MIB focused limited resources on issues surrounding the G-switch sensors and did not perform a detailed investigation on the pyros or parachute system. Because the Genesis mishap prevented a flight demonstration of the pyro and parachute hardware and because little data exist to validate the Genesis design, the Board recommends that the Stardust pyro and parachute requirements verification and hardware qualification program be reviewed.

9.0 Nomenclature and Dictionary

ACS	Attitude Control Subsystem
AFT	allowable flight temperature
AO	Announcement of Opportunity
ATLO	Assembly, Test, and Launch Operations
ATP	Acceptance Test Procedure
AU	avionics unit
BOL	beginning of life
C&DH	command and data handling
CCA	circuit card assembly
CDR	Critical Design Review
CEB	concentrator electronics box
CFD	Computational Fluid Dynamics
CIT	California Institute of Technology, Pasadena, CA
CMIC	command module interface card
DACS	deployable aft conical segment
DCNS	Digital Communications Network System
DGB	disk gap band
DPA	Destructive Physical Analysis
DSI/O	dual slave input/output
DSMC	Direct Simulation Monte Carlo
DSN	Deep Space Network
DSS	digital sun sensor
EDAC	error detection and correction
EDL	Entry, Descent, and Landing
EDU	Engineering Development Unit

EEPROM	electrically erasable programmable read-only memory
EGSE	Electrical Ground Support System
EI	entry interface
EMC	electromagnetic compatibility
EMF	electromagnetic force
EMI/EMC	electromagnetic interference/electromagnetic compatibility
EMIC	EPS module I/F card
EOL	end of life
EPI	EaglePicher, Inc., Phoenix, AZ
EPS	Electrical Power Subsystem
EPS/PCA	Power Control Assembly in EPS
EPS/PIU	Power Initiation Unit in EPS
EST	event sequence timer
ET	Ephemeris Time
FAT (or AFT)	flight allowable temperature (or allowable flight temperature)
FBC	faster, better, cheaper
FET	field effect transistor
FFRDC	Federally Funded Research Development Center
FPGA	field programmable gate array
FRB	Failure Review Board
FSRD	Flight System Requirements Document
FSW	flight software
FTA	Fault Tree Analysis
GEM/GIM	Genesis Electron Motor/Genesis Ion Monitor
GPS	global positioning system
GSE	ground support equipment
ICD	Interface Control Document

ICS	Incident Command System
I/F	interface
I/O	input/output
IR	infrared
ISA	incident, surprise, anomaly
IX	interface connector
JPL	Jet Propulsion Laboratory, Pasadena, CA
KSC	Kennedy Space Center, FL
LANL	Los Alamos National Laboratory, NM
LGA	low-gain antenna
LMC	Lockheed Martin Corporation
LMSS	Lockheed Martin Space Systems, Denver, CO
LOI	Lissajous Orbit Insertion
LSC	load switch card
MAAF	Michael Army Air Field, Dugway Proving Ground, UT
MAD	motor articulation drive
MAR	mid-air recovery
MDE	motor drive electronics
MCSPF	mission critical single point failures
MGA	medium-gain antenna
MGO	Mars Global Orbiter
MIB	Mishap Investigation Board
MOS	Mission Operations (team)
MPL	Mars Polar Lander
MSRD	Mission System Requirements Document
MSVDD	Mission System Verification Description Document
MTF	Multi-Function Test Facility
MVM	master verification matrix

NAV	Navigation (team)
NSI	NASA standard (pyro) initiator
PARL	precess to attitude on rhumb line
PCA	Planning, Control, and Analysis Team
PDR	Preliminary Design Review
PDO	Product Development Organization
PFR	Problem Failure Report
PIE	Product Integrity Engineer
PIM	pyro initiation module
PIRS	Product Integrity Reporting System
PIU	pyrotechnical initiator unit
PMP	Project Management Plan
PPIC	payload & pointing I/F card
PRS	Problem Reporting System (LMSS)
PTH	plate through hole
PWB	printed wiring board
R&R	retention & release
RF	radio frequency
S/C	spacecraft
SCID	spacecraft ID
SCLK	spacecraft clock
SE	Systems Engineer
SEE	single event effects
SEU	single event upset
SKM	station keeping maneuver
SMO	Systems Management Office
SMT	surface mount technology
SNL	Sandia National Laboratory, Albuquerque, NM

SOC	state of change
SPG	single point ground
SRC	sample return capsule
SSF	Space Systems Factory
SSS	spinning sun sensors
STRATCOM	Strategic Command
STR	system test requirement
STU	special test unit
TCM	trajectory correction maneuver
TLM	telemetry
TPS	Thermal Protection Subsystem
TVAC	thermal vacuum
UHF	ultra high frequency
UTC	Universal Coordinated Time
UTTR	Utah Test and Training Range, Dugway Proving Grounds, UT
VIS	Verification Information Sheet
WCA	worst-case analysis

Genesis Dictionary

ACS	Attitude Control Subsystem (on S/C bus). The ACS is primarily responsible for the pointing of a spacecraft during on-orbit operations.
AFT	Allowable flight temperature (max allowable in flight operations, usually derated from the design qualification flight temp.
ATLO	Assembly Test and Launch Operations. LMSS term for all pre-launch flight hardware (FSW) operations at the flight system level. Starts after box-level, subsystem, and assembly-level delivery to initial S/C assembly process and completes at launch. Usually only covers flight equipment operations and does not typically cover assembly and system-level engineering-model (qual) hardware testing.
AU	Avionics unit. There are two AU's in the Genesis SRC (redundant – AU1 and AU2). They contain the science motor controllers (array and canister hinge control used during the science mission) as well as a relay card and the entry event sequencer timers. The dual (logically AND'ed) G-triggers (roughly 3-*g* threshold) are on the relay card in the SRC and trigger the event sequence timer.
Backshell	The back (aft body) of the SRC aeroshell. Used SLA-561V (Viking Mars Entry) ablative TPS.
C&DH	Command and Data Handling Subsystem (on S/C bus). This is the main (and only) general-purpose computer on board the S/C bus and it is a standard dual redundant design (fail-stop and resume) that is used on several operational LMSS spacecraft. It includes a RAD6000 single board computer with 256 MB of EDAC memory and VME I/O. It also includes FLASH memory, I/O cards (including interfaces to the S-band RF command and telemetry), and local power supplies.

CDR	Critical Design Review. A review of a design (at any level of assembly) typically held at the completion of the detailed design phase and prior to hardware build (or software coding). A standard NASA control gate.
CMIC	Command module interface card. Provided cross-string prime selection and cross-strapped memory inside the C&DH. This is the key internally dual-redundant cross-strap interface between the two C&DH strings. This card selects the prime string and holds the data that is "handed off" to the string that takes control after a swap.
Concentrator	The portion of the science payload that electro-statically focused solar ions onto the concentrator's four small targets.
Contributing Factor	NPR 8621.1A defines a contributing factor as "an event or condition that may have contributed to the occurrence of an undesired outcome but, if eliminated or modified, would not by itself have prevented the occurrence."
DACS	Deployable aft conical segment. The aft-most part of the SRC backshell that is separated via three frangible bolts and is pulled off by the drogue chute. The DACS pulls out the main parafoil parachute as it separates.
Depassivation	The process used on board the vehicle to remove (burn off) the passivation (oxide) layer that chemically accumulates in primary battery cells over days and months. This layer is useful for long missions when the battery must be stored as it prevents self-discharge but if not removed or reduced, it excessively limits the current that is provided from the battery. The SRC battery (LiSO2) must be (and was) depassivated prior to use by discharging through a high-wattage/low-impedance resistance for several minutes starting a few hours before entry (see official timeline).

DGB	Disk gap band drogue parachute configuration. Top of chute is the disk (with a vent hole in the center), an air gap and a band of fabric on the outer-most perimeter. This configuration is directly derived from the Mars Viking DGB parachute design and qualification program (in particular the full-scale supersonic high-altitude Balloon-launched Deployment Test program in the 1970's and the PEPP and SHAPE parachute test programs).
Discovery	A NASA program that funds a series of principal investigator-lead, cost-capped, low-cost small missions. Genesis is the 5th Discovery Mission (after NEAR, Mars Pathfinder, Stardust, etc).
Divert	The TCM that the S/C bus executes after SRC release so that the bus does not impact Earth.
Drogue	A 6-ft DGB supersonically deployed parachute used for dynamic stability in the transonic phase and used to assist DACS pull-out and parafoil deploy.
DSN	Deep Space Network. The ground system run by JPL for NASA that communicates with JPL deep space missions (X, S, and Ka-band stations at Canberra Australia, Goldstone CA, and Madrid Spain)
DSS	Digital sun sensor – has a modest field of view of the sun, but is more accurate.
Dual initiator	Pyro initiators that contain dual bridge wires. Used by the cutters and other R&R interfaces. Although similar, they are not NSIs.
E-4 hrs	Entry minus 4 hours.
EDL	Entry, descent, and landing phase of the mission.
EEPROM	electrically erasable programmable read-only memory (on S/C Bus).

Entry ellipse	The ellipse-shaped area at the entry radius that covers all *a priori* dispersions (navigation errors, S/C execution errors, estimated atmosphere density variations, estimated winds, etc), in a 99-percent sense. The *a priori* size of this ellipse was estimated to be 40x28 km and centered on our agreed-to target based on end-to-end Monte Carlo simulations.
EST	Event sequence timer. The card in (each of) the AUs in the SRC that takes the G-trigger signals and times the various pre-programmed descent events (drogue deploy, DACS cutter, DACS and parafoil separation and power up of the GPS and beacon).
ET	Ephemeris Time. A UTC-like time standard used by navigators.
FBC	Faster, Better, Cheaper. A philosophy espoused during the 1990's within NASA to develop spacecraft (typically small spacecraft) faster than was typical prior to that time. These missions were to be better in terms of technical performance and less expensive.
FFRDC	Federally Funded Research Development Center. The Jet Propulsion Laboratory (JPL) is NASA's only FFRDC. NASA provides funding for JPL, which is operated by the California Institute of Technology.
FSW	Flight software (only on the Spacecraft in the case of Genesis)
GEM/GIM	Genesis Electron Monitor/Genesis Ion Monitor. Los Alamos experiment. Used in flight to determine which solar wind regime the vehicle was in to control collection arrays. FSW autonomously used that knowledge to select which collector array was to be exposed (the algorithm was resident in the C&DH FSW on the S/C bus).

Global SeqVariables	Software variables used by on-board sequences (such as the SRC release sequences) to test the status of autonomously controlled states such as ACS event completion or fault protection as well as to "mark" its place in the sequence ("mark and roll-back" function). These allowed the sequence to make key decisions to cancel or proceed with the critical actions. These variables are stored in the CMIC so that in the event of a C&DH side swap, the backup string can resume where the prime string left off.
GPS/DCNS	Global Positioning System-based commercially procured locator used by the SRC.
Heatshield	The front (fore body) of the SRC aeroshell. Used carbon-carbon composite TPS.
Heritage	A design with significant reuse of previously qualified hardware and/or software.
Inheritance Review	Used by LMSS to indicate a review of a heritage design for applicability to a new mission for which the hardware/software had not been originally intended.
I/O	Input/output (e.g., electronic hardware between sensors and actuators and the computer).
ISA	Incident, surprise, and anomaly. The closed-loop problem reporting system used by JPL and LMSS during the post-launch operational phase.
L-1	First Lagrangian Point. A point between the Earth and the sun where the gravity of each is equal. Genesis' location for approximately 2 years during science operations.

Landed ellipse	The ellipse-shaped area on the ground at UTTR that covers all *a priori* dispersions (navigation errors, S/C execution errors, estimated atmosphere density variations, estimated winds, etc), in a 99-percent sense. The *a priori* size of this ellipse was estimated to be 40x28 km and centered on our agreed-to target based on end-to-end Monte Carlo simulations.
LGA	Low-gain antenna for S-band 2-way communication at low data rate or when near Earth (there is one pointed aft and another pointed forward)
LOI	Lissejous Orbit Insertion. The TCM that placed the S/C (and SRC) into a looping "halo orbit" about the first Lagrangian point (also called L-1).
MAR	Mid-air recovery. The Genesis SRC was intended to be captured during its descent on a parafoil by a waiting helicopter.
MGA	Medium-gain antenna for S-band 2-way communication used during science mission.
Mortar	The pyrotechnically activated pressurized drogue chute launcher. Had dual redundant NSI inputs each driven by one of the dual AU's.
NAV	Navigation (team). Primarily performed at JPL.
NSI	NASA standard (pyro) initiator (used to ignite the mortar).
Parafoil	The subsonic rectangular lifting SRC parachute that facilitates helicopter mid-air capture.
PARL	Precess to attitude on rhumb line. An ACS turn mode for large off-sun turns that closes the loop using the sun sensor's sun cone angle only. The Star Tracker is not used. Sun clock angle is not explicitly controlled during the turn due to the limited field of view of the Star Tracker.

Patch	Commands that contain FSW overlays that correct or augment the loaded FSW code. These are very rarely used and are usually added to correct design flaws in the loaded FSW.
PCA	Planning, Control and Analysis Team (JPL & LMSS). Essentially the Genesis Mission Operations Team.
PDR	Preliminary Design Review. A review of a design (at any level of assembly) typically held after design requirements have been flowed down to the lowest level and preliminary design solutions have been generated. A standard NASA control gate.
PFR	Problem Failure Report. The closed-loop problem reporting system used by JPL during the development phase.
PIE	Product Integrity Engineer – An LMSS term for the engineer with responsibility (cost, schedule, and technical) for a specific item of hardware.
PIM card	Payload interface module card. Controlled hinge separation and SRC separation on S/C side.
Proximate cause	NASA NPR 8621.1A, NASA Procedural Requirements for Mishap Reporting, Investigating, and Recordkeeping, defines a proximate cause as "The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome." It is also known as the direct cause.
PRS	LMSS Problem Reporting System used during development. Significant problems were copied into the JPL PFR system during development.
Qual	The process (test and analyses) that prove that the design is qualified for the mission (typically environmental, but also functional and system-level interactions).

R&R	Retention and release devices (e.g., pyro cutting of frangible bolts, cable cutters, pyro separation nuts, etc.)
RAA	Responsibility, Accountability, and Authority.
Root cause	NPR 8621.1A defines a root cause as “one of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.”
S/C	Spacecraft – The space vehicle on which the SRC was the payload.
Sabot	The piston inside the drogue mortar that pushes the drogue out of the mortar canister. Once free of the vehicle, the sabot has its own square 14-inch wide parachute that is intended to keep it separate from the drogue.
SCLK	Spacecraft clock (time). A monotonic time count maintained on board the spacecraft (bus) that corresponds to a UTC value that is interpreted on the ground and used to drive command execution times.
SE	Systems Engineer. An engineer responsible for system design, requirements, and verification. SE’s may have all or part of these responsibilities, depending on the organization of the SE team.
Semaphore (FSW)	A mechanism typically implemented via the real-time operating system that is used to serialize multi-task access to shared resources (like I/O).
Semaphore (telecom)	A discrete signal that, when issued, indicates that a particular state has been achieved.
Sequence block	A list of commands that are stored on board (as a file) that may be “called” by other sequences. Typically sequence blocks implement commonly used functions.

Sequence (seq)	A list of timed commands that are stored on board (as a file) that can be initiated by a real-time command and will execute serially based on the time tag of that command or based on time relative to the previous command.
SKM	Station-Keeping Maneuver. Small maneuvers that maintained the vehicle's position and attitude during the science collection phase of the mission.
SOC	State of charge (of a battery). Typically represented as a percent of a rechargeable (secondary) battery capacity or as an absolute amp-hr value. The S/C bus Ni-H battery can be charged above 100 percent. The SRC's $LiSO_2$ is not rechargeable (and is therefore called a primary battery).
SMO	Systems Management Office
SRC	Sample return capsule. The portion of the spacecraft that held the science collection materials and was returned to Earth.
SSS	Spinning sun sensors. Off-sun angle estimate and spin rate. Has wide field of view (to allow large off-sun attitude excursions) but is not as accurate as the DSS.
Star Trackers	Dual redundant star scanning imagers. Centroiding and star identification are done in the C&DH by ACS FSW.
TCM	Trajectory Correction Maneuver. Used to invoke significant changes in the trajectory of the bus. While there were only 11 TCMs needed in the Genesis mission, there were many different modes of TCM operation that were possible depending on what direction and magnitude of TCM was needed relative to the sun and Earth.

Thrusters	The Genesis thrusters on the S/C bus are used to perform turns (e.g., to precess the S/C to a new spin attitude) and burns (e.g. for major maneuvers) as well as to control the spin rate. Since there is an asymmetry in the thruster arrangement, whenever the S/C performs a spin change or an attitude turn, a change in the vehicle's velocity occurs as a side effect.
TLM	Telemetry.
TPS	Thermal Protection Subsystem.
UTC	Universal Coordinated Time. The time standard used for controlling and defining MOS and S/C events.
UTTR	Utah Test and Training Range (Genesis landing site), near US Army Dugway Proving Ground.
x/D (entry)	Ratio of center-of-mass distance from nose to entry body diameter. Should be small for dynamic stability during entry.
x/D (Parachute)	Ratio of DGB drogue trailing distance to entry body (blunt body) diameter. Viking tests of DGB chutes mandates x/D = 8.5 or more. This is to ensure that parachute deployment occurs sufficiently far away from the wake of the entry body to inflate safely.

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Appendix A

Letter Establishing the Genesis Mishap Investigation Board

September 10, 2004

Science Mission Directorate

TO: Distribution

FROM: Associate Administrator, Science Mission Directorate

SUBJECT: Investigation Board for the Genesis Mishap

This memorandum is in reference to NPR 8621.1A "NASA Procedural Requirements for Mishap Reporting, Investigating, and Recordkeeping" and establishes the Genesis Mishap Investigation Board (MIB) and sets forth its responsibilities and membership. The Chairperson, Members of the Board, and supporting staff are listed in the enclosure.

I am establishing the Genesis MIB to gather information, analyze the facts, identify the proximate cause (s), root cause (s) and contributing factors relating to the Genesis, and to recommend appropriate actions to prevent a similar mishap from occurring again as specified in the referenced NPR.

The Chairperson of the Board will report to me.

The Board will

- Obtain and analyze whatever evidence, facts, and opinions it considers relevant.
- Conduct tests, and other actions it deems appropriate.
- Take testimony and receive statements from witnesses.
- Impound property, equipment, and records as considered necessary.
- Determine the proximate cause (s), root cause (s) and contributing factors relating to the Genesis Mishap and document.
- Generate and prioritize findings.
- Determine the adequacy of contingency response planning and the appropriateness of the actual contingency response, to include the safing

and securing of the spacecraft and the science payload, and the protection of response personnel.

- Develop recommendations to prevent recurrence of similar mishaps.
- Provide a final written report to me with contents as specified in the referenced NPR.

The Chairperson will:

- Conduct Board activities in accordance with the requirements in NPR 8621.1A and other pertinent NASA documents.
- Establish and document, as necessary, rules and procedures for organizing and operating the Board, including any subgroups, and for the format and content of oral or written reports to and by the Board.
- Designate any representatives and advisors, 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.
- Keep all concerned Genesis and support Center officials informed of the Board's plans, progress, and findings.
- Designate another member of the Board to act as Chairperson in his or her absence.
- Document all meetings and retain records.

All Genesis program and support Center personnel must cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that the Board may request.

The Board will begin its investigation during the week of September 13, 2004, and will provide a final report within 75 calendar days of this letter.

I will dismiss the Board when it has fulfilled its requirements.

A.V. Diaz

Enclosure

Distribution:

Deputy Administrator/Mr.Gregory
Executive Officer, Integrated Financial Management Program/Mr. Ciganer
Associate Deputy Administrator for Systems Integration/Ms. Kicza
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Jet Propulsion Laboratory/Dr. Elachi
Johnson Space Center/Gen. Howell
Kennedy Space Center/Mr. Kennedy
Langley Research Center/Gen. Bridges
Marshall Space Flight Center/Mr. King
Stennis Space Center/Adm. Donaldson
Air Force Safety Center/Major Gen. McFann
Air Force Safety Center/SES Alston

Appendix B

Genesis Project Description, Narrative

a. Mission Description

Genesis was the fifth in NASA's series of Discovery missions, and the first US mission since Apollo to return extraterrestrial material to Earth for study. The purpose of the mission was to collect samples of solar wind and return them to Earth. Professor Don Burnett of the California Institute of Technology was the principal investigator and project team leader. The Jet Propulsion Laboratory (JPL) was the managing agency and provided the science canister. Los Alamos National Laboratory (LANL) provided the electrostatic concentrator for the science canister and the Electron and Ion Monitors. Lockheed Martin Corporation (LMC), acting through its Lockheed Martin Space Systems (LMSS) company, was the industrial partner and provided the spacecraft and sample return capsule (SRC). JPL and LMSS conducted mission operations.

Genesis was to provide fundamental data to help scientists understand the formation of our solar system, reinterpret data from past space missions, and provide focus to many future missions. Analysis of the collector materials will give precise data on the chemical and isotopic composition of the solar wind. Once analysis is complete, the Genesis mission will provide:

(1) a major improvement in our knowledge of the average chemical composition of the solar system;

(2) isotopic abundances of sufficient precision to address planetary science problems;

(3) a reservoir of solar material to be used in conjunction with advanced analytical techniques available to 21st century scientists; and

(4) independent compositional data on the 3 solar wind regimes.

Launched on August 8, 2001, Genesis was positioned approximately one million miles from the Earth orbiting the Earth-Sun libration point L1 which is outside Earth's magnetosphere. It remained in a libration point orbit for 28 months. The mission trajectory is shown in Figure B-1. The capsule lid was closed on April 1, 2004 and the spacecraft returned for a day-time Earth entry.

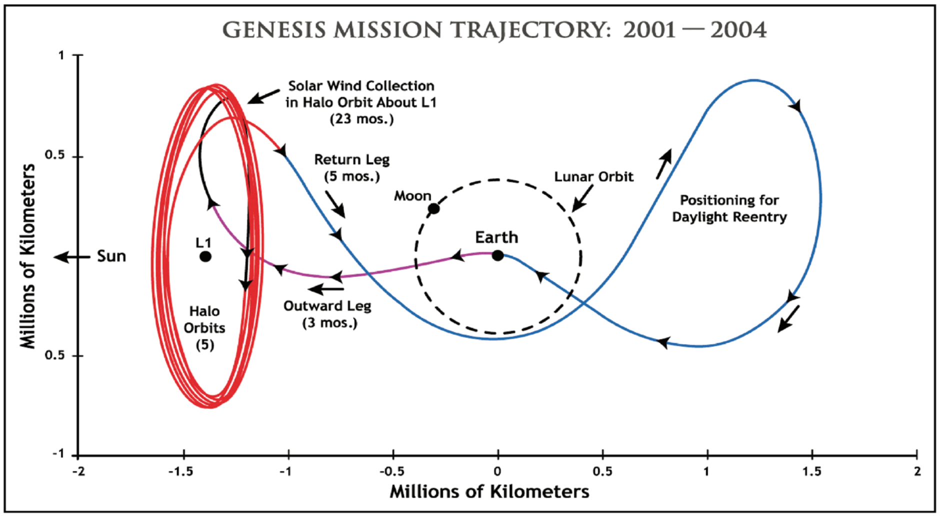


Figure B-1. Genesis Mission in Earth coordinates.

b. Space Segment

The spacecraft was spin stabilized, nominally spinning at 1.6 rpm. The spacecraft was a honeycomb disc with the sample return capsule (SRC) mounted toward the sun and the launch vehicle adapter below. Electronics were on the sun side of the disc outside the SRC. Star trackers were mounted on the perimeter viewing near radially but away from the sun. Two bladder propellant tanks were mounted at the perimeter with nutation dampers just outboard. Thrusters, 5 lbf for major maneuvers and 0.2 lbf for precessions and minor maneuvers, were mounted on the anti-sun side of the spacecraft to minimize potential for contamination of the collectors. The rechargeable nickel hydrogen spacecraft battery was mounted inside the launch vehicle adapter. The science collection configuration is shown in Figures B-2a and B-2b. Thermal control was provided by multi-layer insulation blankets that covered all of the components, as shown in the flight configuration picture, Figure B-3.

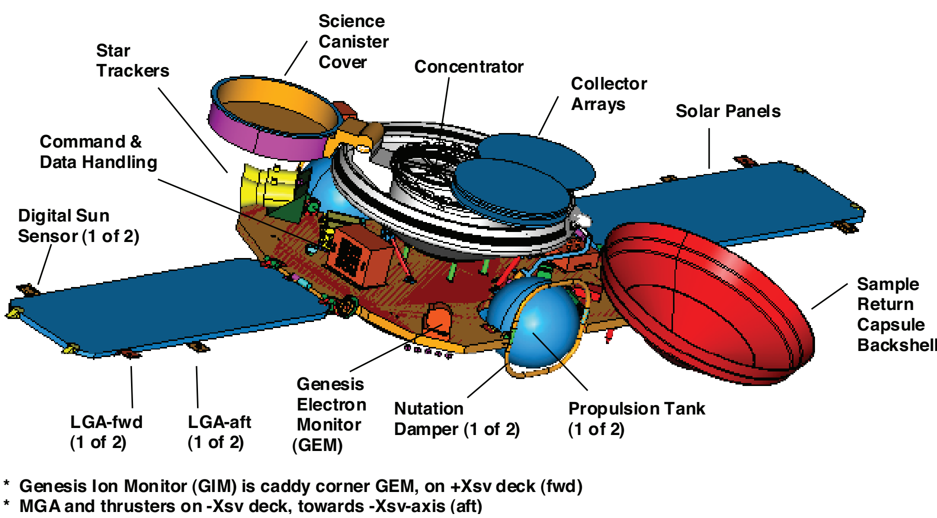


Figure B-2a. Spacecraft in science collection configuration, sun view.

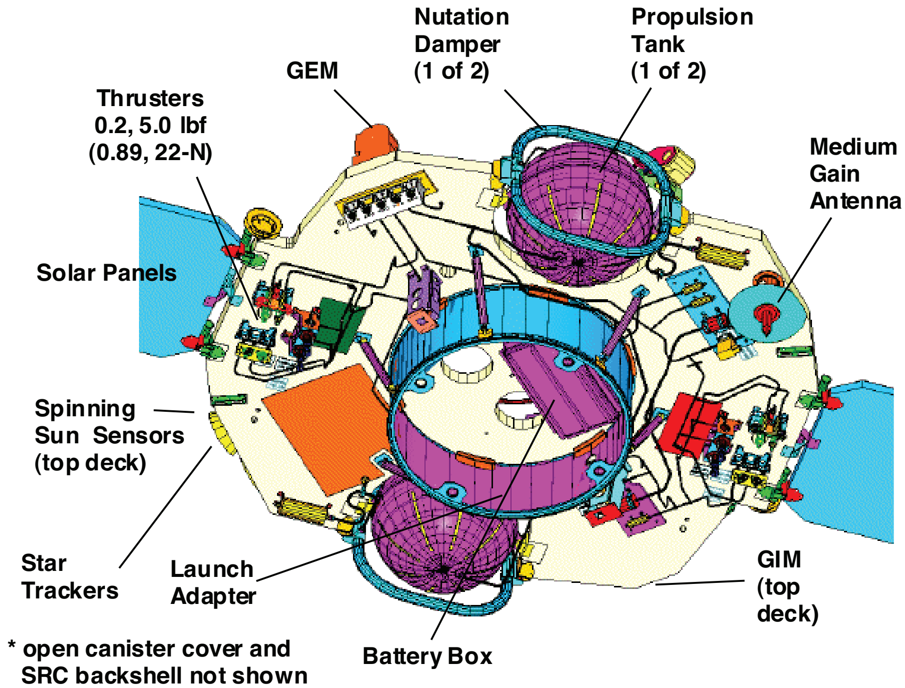


Figure B-2b. Spacecraft in science collection configuration, anti-sun view.

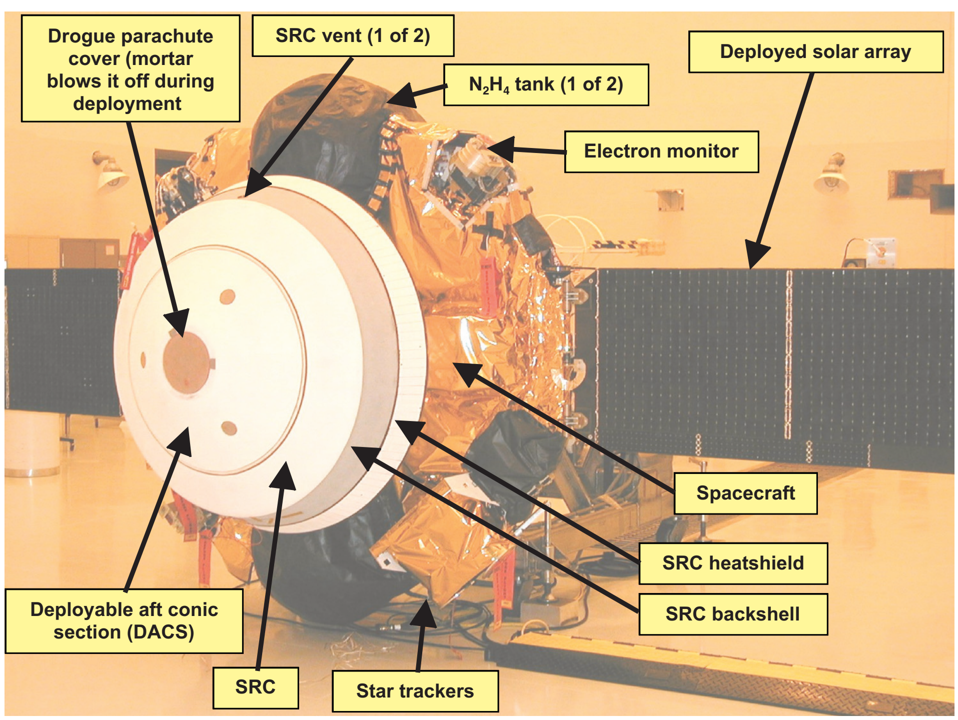


Figure B-3. Flight configuration with thermal blankets installed.

c. Sample Return Capsule Detail

A cross section of the SRC design is shown in Figure B-4. The science canister is in the center with the SRC Avionics Units (AUs) and the SRC primary $LiSO_2$ battery mounted in the annulus around the science canister. The canister and the avionics decks are mounted to the heatshield structure. The SRC hinge opens the backshell off of the heatshield. The hinge is bolted to the heatshield and backshell with pyrotechnic bolts to separate the hinge from the SRC after pyrotechnic cable cutters sever the connection to the spacecraft power and control electronics. The backshell contains the drogue parachute on the centerline and the parafoil main parachute is packed around the drogue canister. A mortar is fired inside the drogue canister to propel the drogue parachute out through the mortar cover. The Deployable Aft Conical Section (DACS) is released by firing three frangible pyrotechnic bolts (DACS Retention & Release Mechanism) and the drag load on the drogue parachute pulls the parafoil out, taking the DACS with it. Prior to releasing the DACS, the cable to the drogue mortar is cut with a pyrotechnic cable cutter. The SRC is protected from entry heat loads by a carbon-carbon heatshield insulated from the structure by carbon foam and on the backshell by Super Light Ablator material.

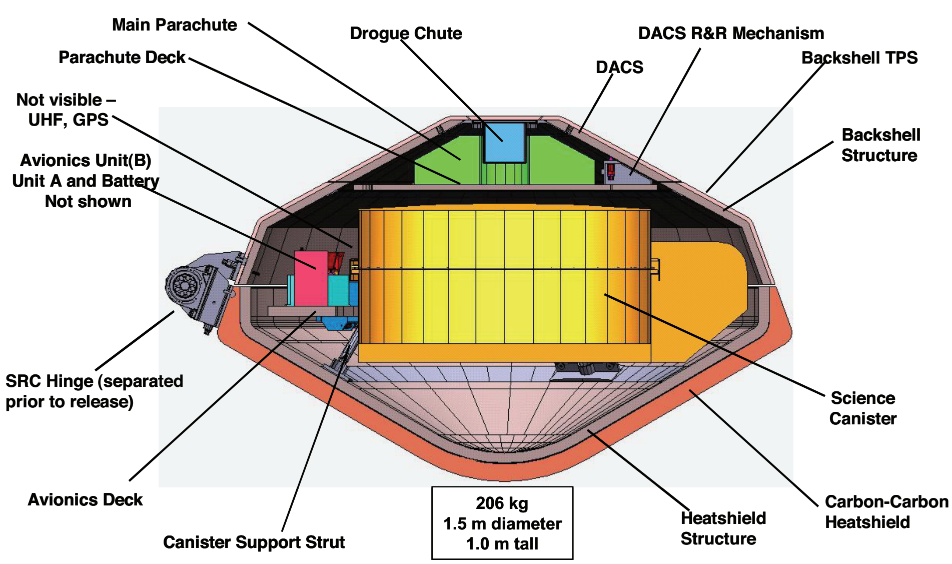


Figure B-4.
SRC cross section
(SRC hinge is separated from SRC prior to release).

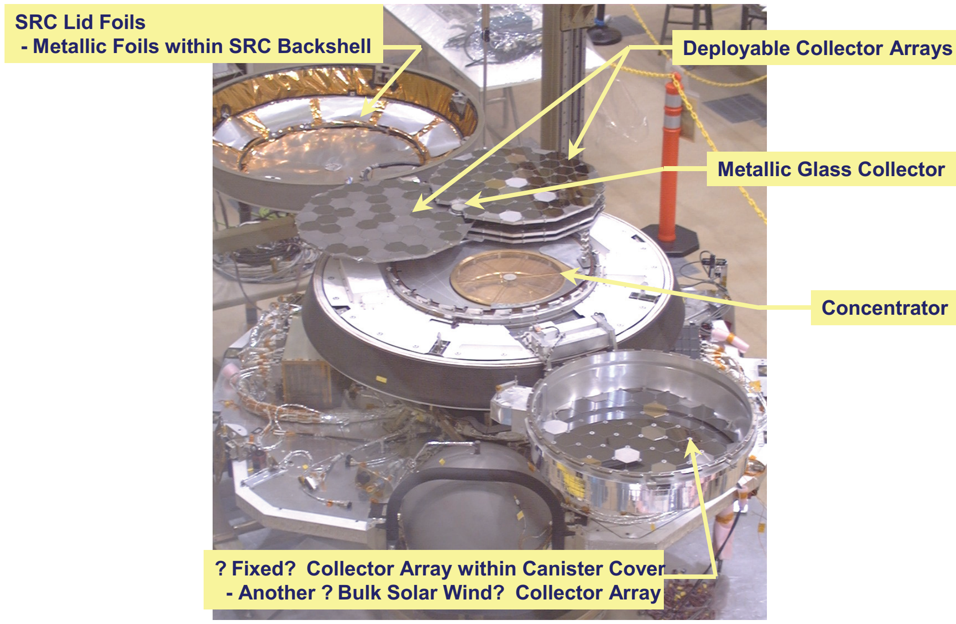


Figure B-5.
SRC open in science collection configuration.

The canister is shown in the science collection configuration with the SRC backshell open and the science canister open with the arrays deployed in Figure B-5. Thermal closure panels cover the avionics and battery.

Figure B-6 shows the AU A and the flight battery prior to installing the thermal closures. The collectors are partially deployed. Also visible in the upper left is the cable management system that restrained the cable between the heatshield and backshell during backshell opening and closing.

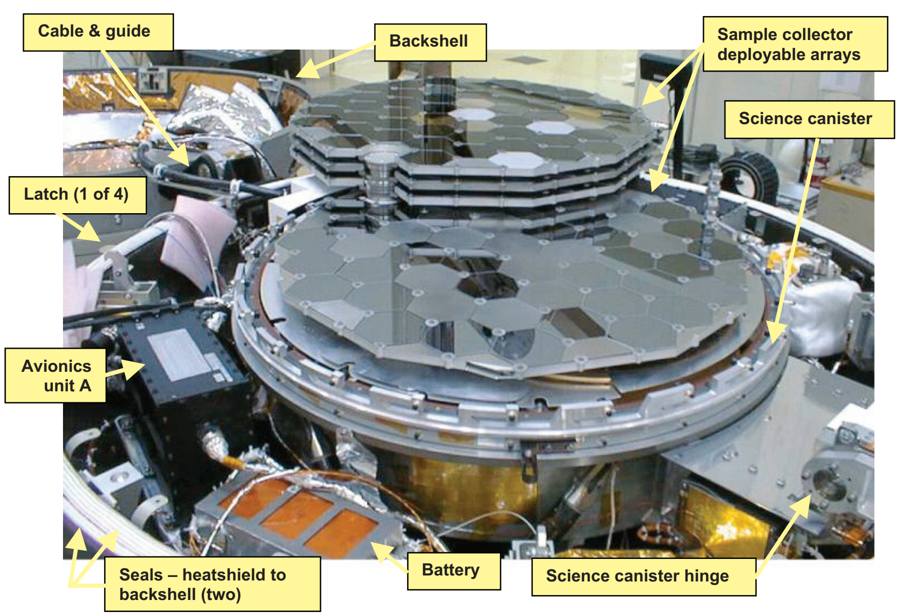


Figure B-6.
SRC prior to installing thermal closures – avionics box A and the $LiSO_2$ battery in foreground.

Temperature strips were attached to the inside honeycomb structure of the heatshield and backshell to record the maximum temperature reached during entry and heat soak back.

d. Entry, Descent, and Landing Nominal Timeline

Figure B-7 shows the entry and descent timeline for the mission. Trajectory correction maneuver (TCM) 10 was the first to move the targeting of the flight system from off-Earth to the Utah Test and Training Range (UTTR). TCM 11 was performed at Entry (E) –52 hours to establish a target, or instantaneous impact point, in NE Nevada so that the velocity increments added by the spin up and precession maneuvers and the push off of the SRC would put the target mid-air capture spot at the desired target point on UTTR. TCM 11 accurately established the target point so that TCM 12, a contingency maneuver that could have been performed at E --28 hours, was not needed.

Figure B-7 also summarizes the decisions that had to be made to verify that safe return was highly probable. The Green button decision was based on targeting, spacecraft, and ground systems all being "go" for entry at E --8 hours. Spacecraft fault protection was constantly checking performance of all subsystems and would have autonomously proceeded through component fixes, rebooting, and even side swap to restore the spacecraft to operation if any fault had occurred. The ground control team could have signaled termination just before the release (the Red button) if a problem occurred

Earth Entry Decision Mechanisms:

1. SRC Release Enable (ground command)
2. SRC Release Fault Protection (spacecraft flight software)
3. SRC Release Disable (ground command)
4. Divert Maneuver Disable (ground command)

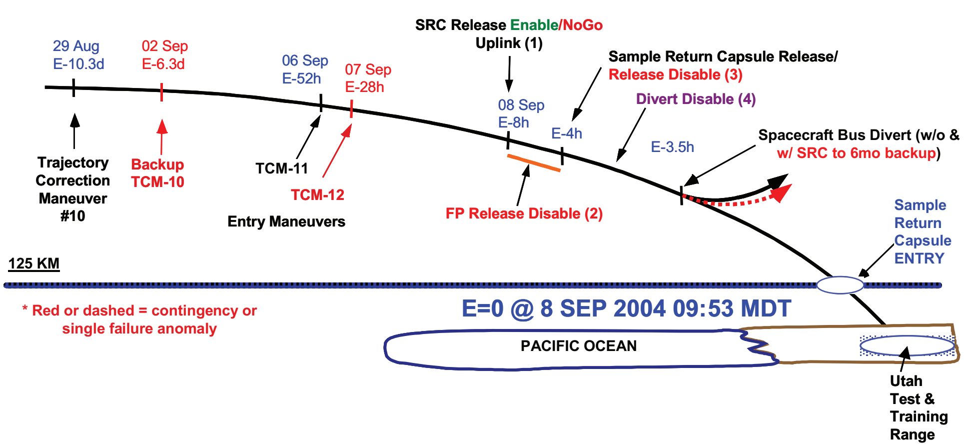


Figure B-7. Entry timeline.

that would jeopardize safe entry into UTTR airspace. If termination had occurred after cable cut the SRC would have been on internal battery power and would have been dead in hours. Prior to cable cut the divert maneuver already on board and ready for execution would have placed the spacecraft with SRC into a backup orbit that would return to Earth for a second entry attempt in about 6 months.

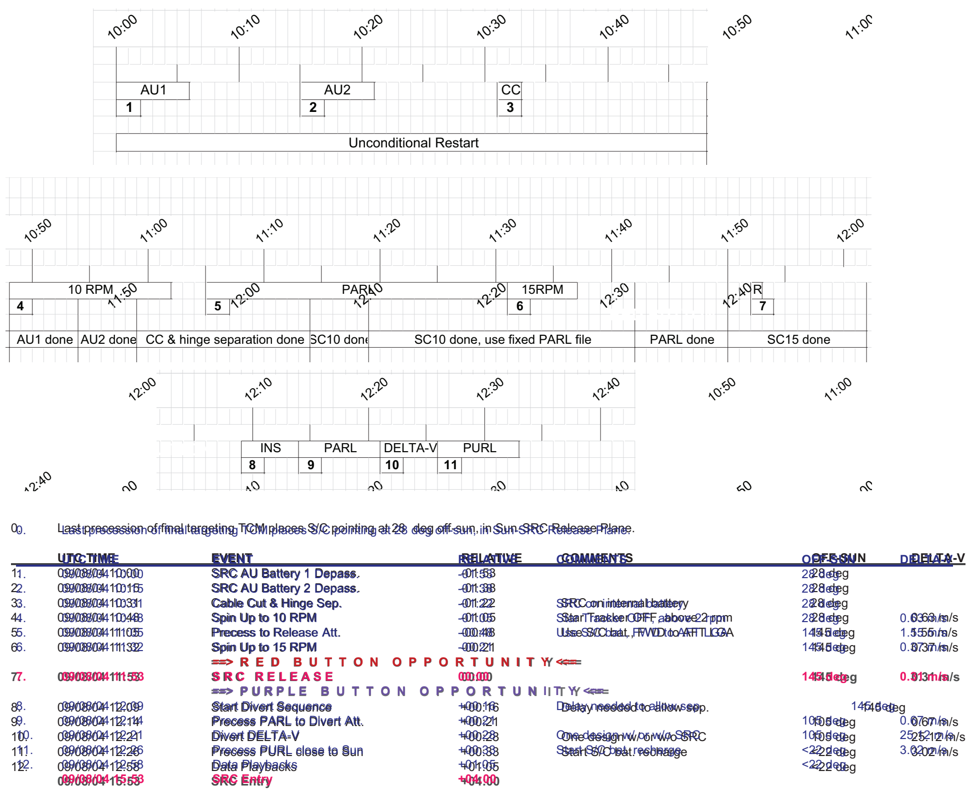


Figure B-8.
SRC release sequence timeline in Universal Time.

The final decision (Purple button) was the command to enable the spacecraft to execute the same divert maneuver to put the spacecraft en route to a safe disposal orbit. If the SRC did not separate from the spacecraft (i.e., if the cable had not fully cut and the two bodies were dangling with a soft connection), this final decision would cover the contingency. The final decision timeline is shown in Figure B-8.

Table B-1 is the summary timeline from the start of SRC battery preheat through post-divert tracking. It shows Deep Space Network (DSN) coverage at Canberra, Goldstone, and Madrid; SRC Release; Spacecraft Divert Timeline; spacecraft event descriptions; what was running in the Spacecraft Test Laboratory (STL); the interfaces in work at the time; and the ground team activities, e.g., polls, that were taking place to make the decisions for entry to proceed.

Table B-1. Summary Timeline, SRC Battery Preheat Through Post-Divert Tracking.

DOW	DOY	UTC	PDT	MDT	E-hrs	DSN G	DSN C	DSN M	SPACECRAFT/*DSN* EVENT DESCRIPTION	STL	INTERFACE	GROUND (FLIGHT) EVENT DESCRIPTION
Tue	251	09/07 16:00	09/07 09:00	09/07 10:00	23:55		D		**Start Preheat Sequence**			
Tue	251	09/07 17:00	09/07 10:00	09/07 11:00	22:55		D			SRC RLS		
Tue	251	*09/07 18:15*	*09/07 11:15*	*09/07 12:15*	21:40		D		DSS-34 EOT			
Tue	251	*09/07 18:15*	*09/07 11:15*	*09/07 12:15*	21:40				DSS-66 BOT			
Tue	251	*09/07 18:30*	*09/07 11:30*	*09/07 12:30*	21:25				DSS-46 EOT			
Tue	251	*09/07 18:30*	*09/07 11:30*	*09/07 12:30*	21:25			D	DSS-54 BOT			
Tue	251	09/07 20:00	09/07 13:00	09/07 14:00	19:55			D	**noop**			
Tue	251	09/07 23:00	09/07 16:00	09/07 17:00	16:55			D			OD	OD CUTOFF - Eval #2
Tue	252	09/08 00:00	09/07 17:00	09/07 18:00	15:55			D			NAV -> SRC	Deliver Entry Dispersions - Eval #2
Tue	252	09/08 00:30	09/07 17:30	09/07 18:30	15:25			D	**noop**			
Tue	252	09/08 01:00	09/07 18:00	09/07 19:00	14:55			D			All	Go/No-Go Evaluation #2 Meeting
Tue	252	*09/08 01:45*	*09/07 18:45*	*09/07 19:45*	14:10			D	DSS-24 BOT			
Tue	252	*09/08 01:45*	*09/07 18:45*	*09/07 19:45*	14:10	D		D	DSS-16 BOT			
Tue	252	*09/08 02:05*	*09/07 19:05*	*09/07 20:05*	13:50	D		D	DSS-66 EOT			
Tue	252	*09/08 02:05*	*09/07 19:05*	*09/07 20:05*	13:50	D			DSS-54 EOT			
Tue	252	09/08 03:00	09/07 20:00	09/07 21:00	12:55	D						
Tue	252	09/08 05:00	09/07 22:00	09/07 23:00	10:55	D					OD	OD CUTOFF - Eval #3 (FINAL)
Wed	252	09/08 06:00	09/07 23:00	09/08 00:00	09:55	D					NAV -> SRC	Deliver Entry Dispersions - Eval #3
Wed	252	*09/08 06:40*	*09/07 23:40*	*09/08 00:40*	09:15	D			DSS-34 BOT			
Wed	252	*09/08 06:40*	*09/07 23:40*	*09/08 00:40*	09:15	D	D		DSS-46 BOT			
Wed	252	09/08 07:00	09/08 00:00	09/08 01:00	08:55	D	D				All	SRC Release Go/No-Go Briefing
Wed	252	09/08 08:00	09/08 01:00	09/08 02:00	07:55	D	D				All	SRC Release Go/No-Go Poll
Wed	252	09/08 08:05	09/08 01:05	09/08 02:05	07:50	D	D		**Uplink Divert/SRC Release Start**			
Wed	252	**09/08 10:00**	**09/08 03:00**	**09/08 04:00**	05:55	D	D		**SRC Release Sequence Start**			
Wed	252	09/08 10:00	09/08 03:00	09/08 04:00	05:55	D	D		SRC RLS: AU1 Depassivation			
Wed	252	09/08 10:15	09/08 03:15	09/08 04:15	05:40	D	D		SRC RLS: AU2 Depassivation			
Wed	252	*09/08 10:20*	*09/08 03:20*	*09/08 04:20*	05:35	D	D		DSS-24 EOT			
Wed	252	09/08 10:31	09/08 03:31	09/08 04:31	05:24		D		SRC RLS: Cable Cut & Hinge Sep			
Wed	252	09/08 10:48	09/08 03:48	09/08 04:48	05:07		D		SRC RLS: 10RPM Spin Control Start			
Wed	252	*09/08 10:50*	*09/08 03:50*	*09/08 04:50*	05:05		D		DSS-16 EOT			
Wed	252	09/08 11:03	09/08 04:03	09/08 05:03	04:52		D		SRC RLS: PARL Start			
Wed	252	09/08 11:08	09/08 04:08	09/08 05:08	04:47		D					SRC RLS: POLL #1
Wed	252	09/08 11:32	09/08 04:32	09/08 05:32	04:23		D		SRC RLS: 15RPM Spin Control Start			
Wed	252	09/08 11:37	09/08 04:37	09/08 05:37	04:18		D					SRC RLS: POLL #2
Wed	252	09/08 11:45	09/08 04:45	09/08 05:45	04:10		D					SRC RLS: POLL #3
Wed	252	**09/08 11:53**	**09/08 04:53**	**09/08 05:53**	04:01		D		**S R C R E L E A S E**			
Wed	252	09/08 12:00	09/08 05:00	09/08 06:00	03:55		D					SRC RLS: POLL #4
Wed	252	09/08 12:08	09/08 05:08	09/08 06:08	03:47		D		**Divert Start**	Divert		
Wed	252	09/08 12:08	09/08 05:08	09/08 06:08	03:47		D		DIV: 15RPM Spin Control Start			
Wed	252	09/08 12:15	09/08 05:15	09/08 06:15	03:40		D		DIV: PARL Start			
Wed	252	09/08 12:21	09/08 05:21	09/08 06:21	03:34		D		DIV: DELTA-V Start			
Wed	252	09/08 12:26	09/08 05:26	09/08 06:26	03:29		D		DIV: PURL Start			
Wed	252	09/08 12:33	09/08 05:33	09/08 06:33	03:22		D		DIV: Divert Complete			
Wed	252	*09/08 15:10*	*09/08 08:10*	*09/08 09:10*	00:45		D		DSS-34 EOT			
Wed	252	*09/08 15:15*	*09/08 08:15*	*09/08 09:15*	00:40				DSS-46 EOT			
Wed	252	09/08 15:20	09/08 08:20	09/08 09:20	00:35				Helicopters Take Off			
Wed	252	**09/08 15:55**	**09/08 08:55**	**09/08 09:55**					**ENTRY - 125km EIP**			
Wed	252	09/08 16:01	09/08 09:01	09/08 10:01	+00:06				SRC Main Chute Deploy (22,000 ft)			
Wed	252	09/08 16:10	09/08 09:10	09/08 10:10	+00:15				Helicopters to Furtherst Intercept			
Wed	252	09/08 16:17	09/08 09:17	09/08 10:17	+00:22				**SRC Capture (approximate)**			
Wed	252	09/08 16:30	09/08 09:30	09/08 10:30	+00:35				Intermediate Landing			
Wed	252	09/08 17:00	09/08 10:00	09/08 11:00	+01:05				Return to MAAF			
Wed	253	09/09 00:00	09/08 17:00	09/08 18:00	+08:05							
Wed	253	*09/09 00:40*	*09/08 17:40*	*09/08 18:40*	+08:45				DSS-34 BOT			
Wed	253	09/09 01:00	09/08 18:00	09/08 19:00	+09:05				Divert Epilogue			
Wed	253	09/09 02:00	09/08 19:00	09/08 20:00	+10:05				Spacecraft Reconfiguration			
Thu	253	*09/09 17:20*	*09/09 10:20*	*09/09 11:20*	+25:25				DSS-34 EOT			

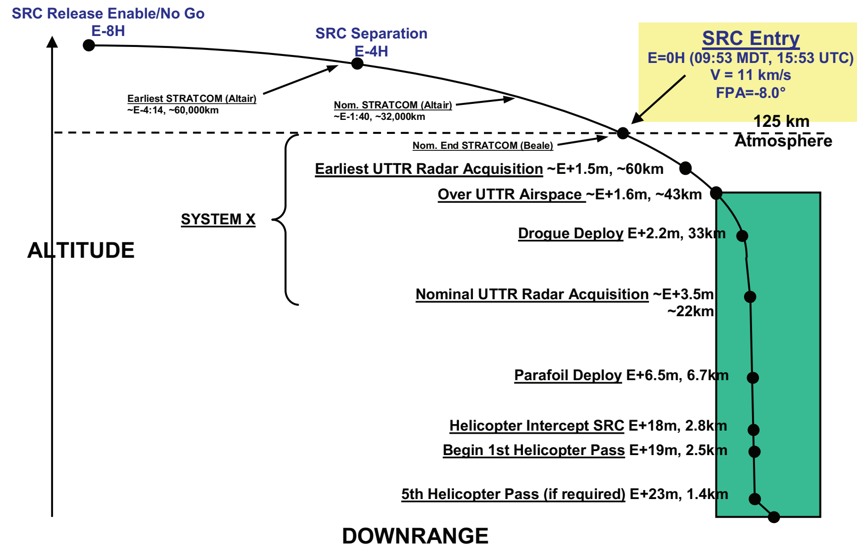


Figure B-9.
Entry profile and timeline..

The green bar in Figure B-9 shows the fault protection options that became more restricted as release was approached and time to execute complete recovery was no longer available. Also shown in the right column are the velocity increments imparted during the final maneuvering of the spacecraft to set up the proper attitude for SRC release and the spacecraft maneuvers for divert.

The entry interface is defined as occurring at 125 km shortly before the sensible atmosphere is encountered. The entry, descent, and post-capture timeline is shown in Table B-2. Specific heating, acceleration, range, and location plots are shown in Figure B-10.

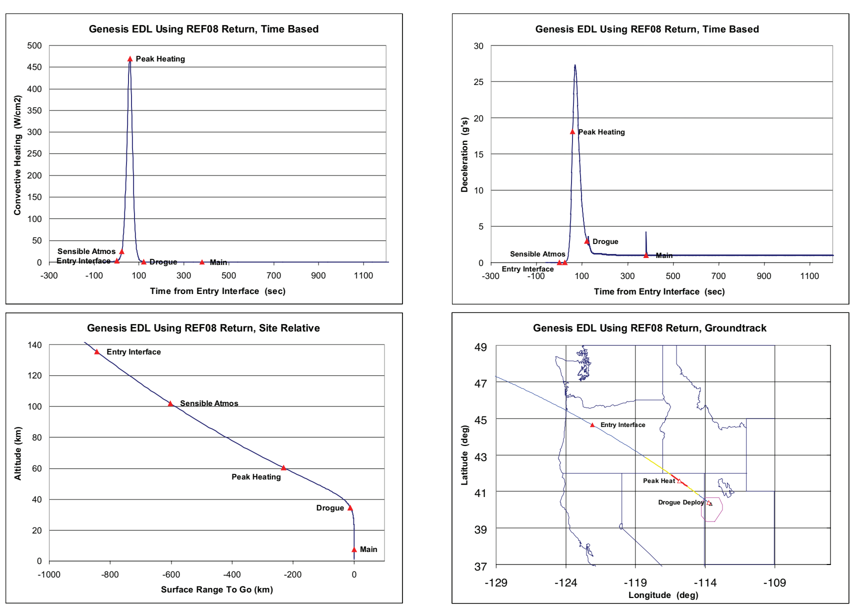


Figure B-10.
Atmospheric entry profile.

Table B-2. Entry, Descent, and Post-Capture Timeline.

Time	Event Description
E – 4 hrs	USAF Strategic Command begin tracking
E - 2 hrs	Collect weather data on wind velocity and azimuth, temperature, pressure, and density vs. altitude
Entry	Defined at 125 km above 6378 km spherical radius (848 km uprange)
E + 40 sec	Begin UTTR infrared and cine tracking [if clear skies] (80 km MSL altitude, 430 km uprange, 7° elevation)
E + 59 sec	Peak heating (60.4 km MSL altitude, 266 km uprange)
E + 71 sec	Peak *g*'s (51 km MSL altitude, 137 km uprange, 20° elevation)
E + 121 sec	3 g's timer trigger (34.4 km MSL altitude, 12 km uprange, 71° elevation)
E + 127 sec	Drogue chute mortar deploy at Mach 1.8 (33 km MSL altitude, 9 km uprange, 75° elevation)
E + 140 sec	SRC decelerated to Mach 1 (30 km altitude, 4 km uprange, 82° elevation)
E + 220 sec	Enter UTTR airspace from above (17.7 km MSL altitude, 0 km uprange, 90° elevation)
E + 381 sec	Deploy main chute by releasing DACS/drogue (6.7 km MSL altitude), begin DCNS and UHF tracking
E + 20 min	Mid-Air Retrieval (first pass) (2.4 km MSL altitude)
E + 24 min	Latest MAR opportunity (1.3 km MSL altitude)
MAR+12 min	Intermediate landing touchdown
MAR+20 min	min Lift-off and fly to MAAF
MAR+44 min	min Nominal landing at MAAF
MAR+2 hrs	hrs Purge established on canister
MAR+5 days	Canister and other hardware delivered to JSC
	Science assessment begins

The post-mid-air capture timeline was driven by getting a nitrogen purge on the science canister within 2 hours. The timeline was dependent on where in the range the capture was made which could significantly change the time to reach Michael Army Air Field (MAAF). Intermediate landing was expected to take 10 to 12 minutes to reach the ground and about 5 to 8 minutes on the ground but the low-speed transit to the landing site could vary depending on the On-Site Range Commander's assessment of the safety of prospective landing sites.

Once the SRC had touched down at MAAF on the apron north of Building 1012, the SRC was to be rolled into the entry area, the vent covers installed during intermediate landing lifted, and safety experts from LMSS and NASA Johnson Space Center (JSC) would check the SRC interior gas for HCN, CO, and SO_2. Before lifting the backshell, the safety team would sample the interior gases again. If toxic gases were present, LMSS and JSC personnel wearing Self Contained Breathing Apparatus (SCBA) would open the backshell and establish the nitrogen purge while other personnel maintained a safe distance from the SRC. The safety team was to saw the latches attaching the backshell to the heatshield. The SRC could then be opened by lifting the backshell.

After the safety team purged the nitrogen from the science canister, the timeline was more relaxed. The recovery team would remove the thermal closeout panels to gain access to disconnect and remove the battery, which was the next time-sensitive item to be accomplished before completing operations on September 8.

e. Drogue and Parafoil Parachute Deployment System Description

As shown in Figure B-10, the deceleration of atmospheric entry first builds with increased drag on the capsule as the ambient atmosphere becomes more dense, reaches a peak deceleration of 22 *g*'s, and then decreases as the capsule slows. It was intended that the SRC avionics G-switch sense when the increasing deceleration reached 3 *g*'s to arm the pyrotechnic initiation circuitry. After reaching the peak deceleration, the avionics were to sense the decreasing transition to initiate the timers leading successively to the firing of the drogue mortar, drogue harness cable cutter, drogue aft conical section retention bolt cutters leading to the release of the parafoil, and turn on of the GPS transceiver and UHF beacon transmitter. The timing of these events is shown in Table B-3. Redundancy was designed into the AU by incorporating firing circuits in each unit for the critical pyrotechnic events.

A positive firing signal from the timing chain in either AU was sufficient to fire the respective pyrotechnic device.

Table B-3. SRC Pyrotechnic Device Firing Times.

Pyrotechnic Device	Time of Fire Command after G-switch opening, sec	Remarks
Drogue mortar	5.7	Two circuits each in AU A and B
Drogue harness cable cutter	80.6	Two circuits each in AU A and B
DACS bolts, 3 fired simultaneously	259.6	Two circuits each in AU A and B
GPS transceiver	261.4	One circuit each in AU A and B
UHF beacon transmitter	261.4	One circuit each in AU A and B

Note: Each of the "ANDed" timer signal outputs is replicated four times to produce the distinct timing events.

Figure B-11 is a simplified block diagram of the SRC avionics system pyrotechnic firing system. The low-pass filter is designed to prevent inadvertent G-switch circuit atmospheric transients (buffeting) as the increasing deceleration passes through 3 *g*'s . The G-switch sensors are 'ANDed' to preclude a single switch failure from prematurely issuing a deploy signal. The AUs are referred to in development phase documentation as 1 and 2 or A and B alternatively with 1 = A and 2 = B.

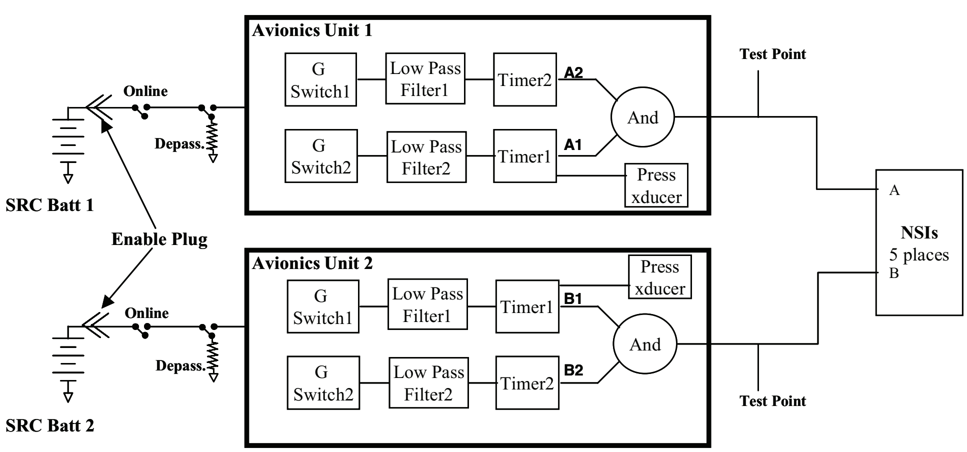


Figure B.11. SRC avionics pyrotechnic firing system.

The AU block diagram is shown is Figure B-12. The primary functions performed by the Motor Drive Electronics (MDE) board were completed when the science canister and the SRC were closed on April 1, 2004. During the SRC Release Sequence, the relay card and the FPGA on the MDE board are used only to connect the SRC $LiSO_2$ batteries to the depassivation resistors attached to the interior of the heatshield first and then to the Event Sequence Timer (EST) board to power it through entry and post entry operation of the GPS transceiver and the UHF beacon. The G-switch sensors were mounted on this relay card for entry, although voltage was applied from the EST card.

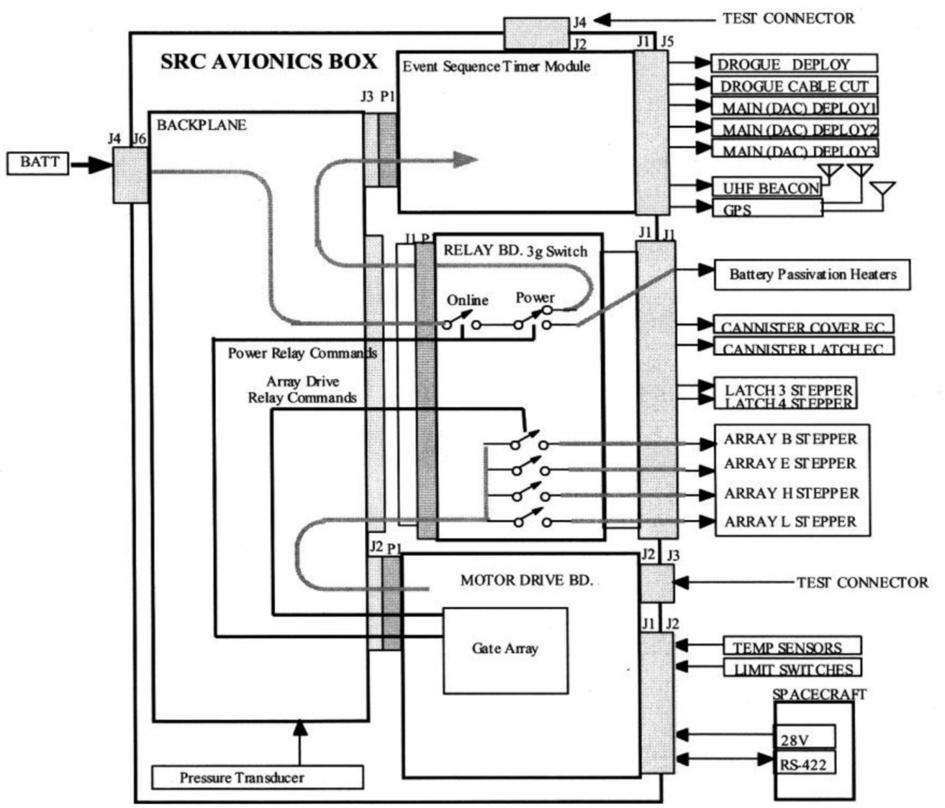


Figure B.12.
SRC avionics unit.

The EST block diagram is shown in Figure B-13. The G-switch sensor initiates all the R-C timer circuits set to fit the entry profile (see Table B-3 event times). The drogue parachute stabilizes the capsule during the passage through transonic velocities, nominally being deployed at Mach 1.8. The drogue cable cut could be done anytime between drogue deploy and DACS firing. The DACS firing is timed to correspond to about 22,000 ft (72 km) above MSL. The pressure transducer is a back-up to timed parafoil deployment but is switched on by a timer sequence initiated by the G-switch sen

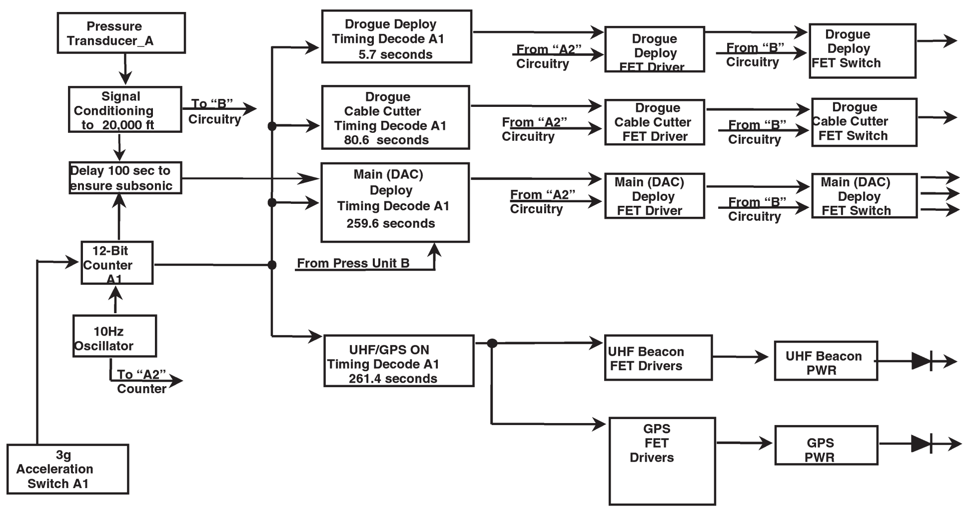
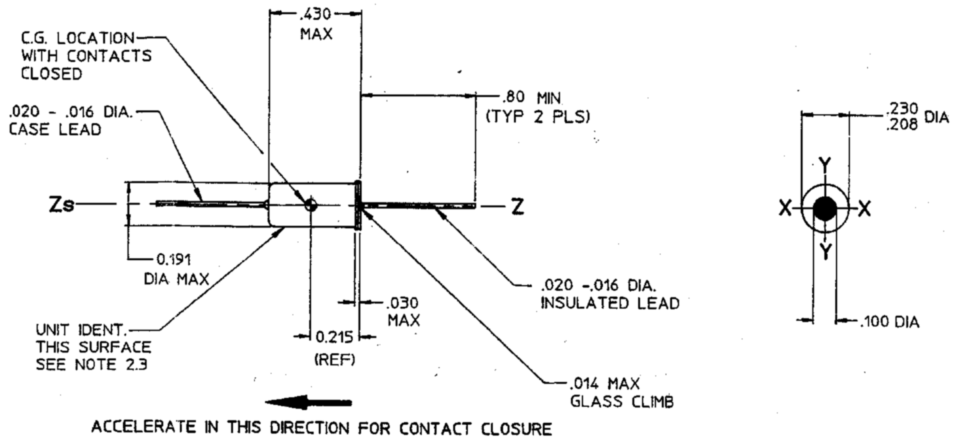


Figure B-13. Event sequence timer.

sor. It is intended for back-up initiation for parafoil deployment in case the estimated timing of the descent sequence was incorrect. It is not intended as a back-up to the G-switch sensor. The redundant AU circuits are cross strapped and the boxes are cross strapped, as shown in Figure B-13. The UHF beacon and the GPS transceiver provide location information in case of a failed Mid-Air Retrieval.

The component of interest is the Aerodyne 7200-6-000 3-*g* acceleration switch, referred to herein as the G-switch sensor. The G-switch sensor drawing is shown in Figure B-14. The acceleration direction required to close the switch is marked on the drawing. An X-ray of the G-switch sensor is included in Figure B-14 showing how the spring mass and contact are oriented inside the cylinder. The closure lip provides a good orientation reference between the photograph of the exterior and the X-ray of the interior of the G-switch sensor. When mounted in the correct orientation, the internal plunger would be compressed against its spring during SRC deceleration upon entering the atmosphere. When the deceleration reached approximately 3 *g*'s , the plunger would have touched an electrical contact in the end of the switch, closing the circuit and arming the EST. When the deceleration dropped below 3 *g*'s as the capsule slowed, the plunger would have been pushed away from the contact, breaking the circuit and causing the EST to start, leading to the successive deployments of the drogue and parafoil.



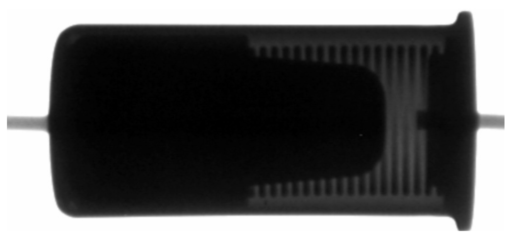


Figure B-14. Aerodyne 7200-6-000 acceleration switch (G-switch sensor) drawing and X-ray.

Appendix C-1

Fault Tree: Process and Diagram

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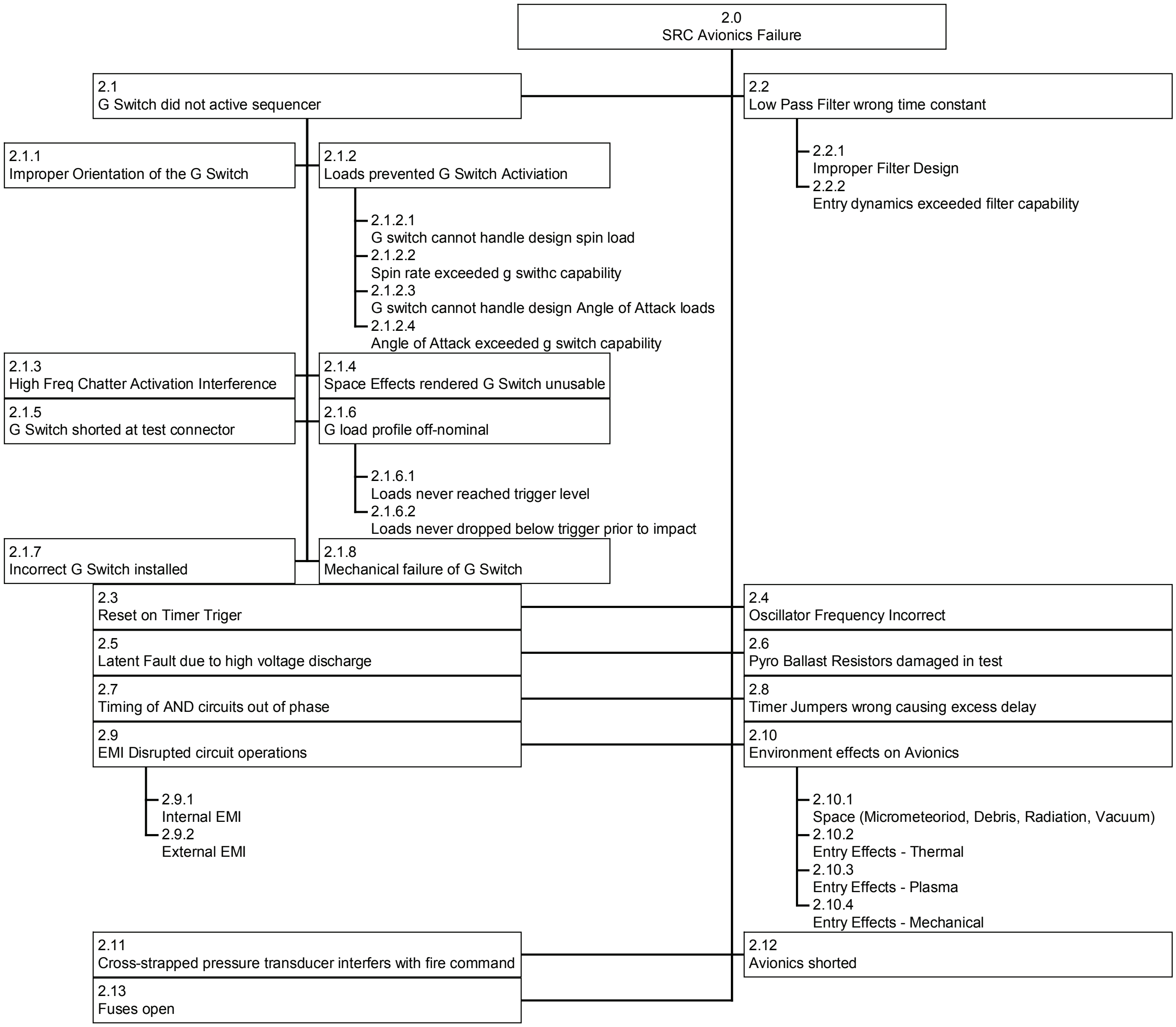
Appendix C-2.a
Fault Tree Diagram

Drogue Not Deployed

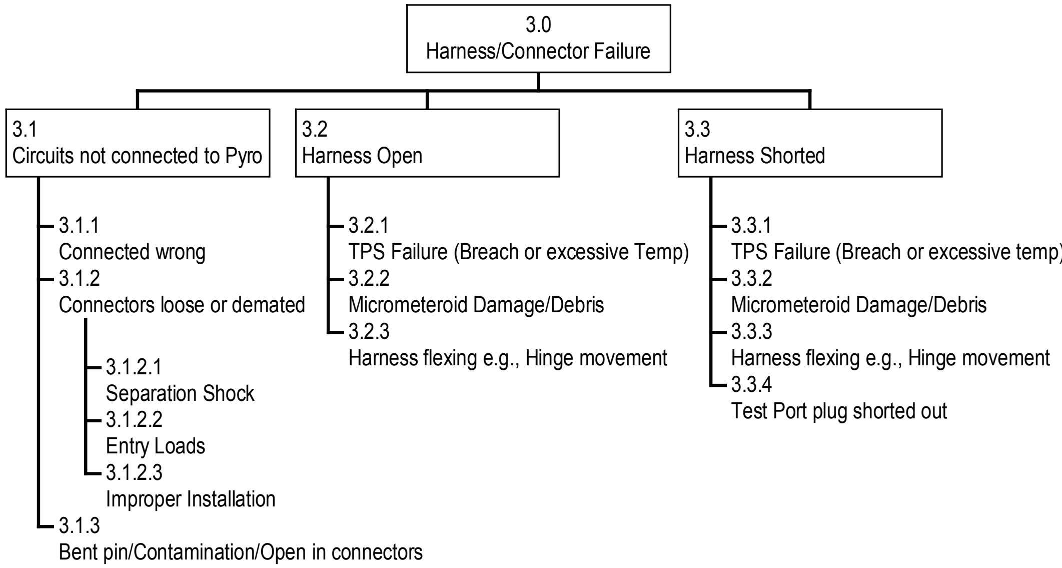
- **1.0 Electrical Power Failure in SRC**
  - 1.1 Spacecraft Bus Sequence Wrong
  - 1.2 Power State of Circuits Incorrect (Relays)
  - 1.3 Power Electronics Design Flaw
  - 1.4 Power Disconnected on Entry
  - 1.5 Entry Thermal Environment Effects
  - 1.6 Inadequate Battery Voltage and Power
- **2.0 SRC Avionics Failure**
  - 2.1 G Switch did not active sequencer
  - 2.2 Low Pass Filter wrong time constant
  - 2.3 Reset on Timer Triger
  - 2.4 Oscillator Frequency Incorrect
  - 2.5 Latent Fault due to high voltage discharge
  - 2.6 Pyro Ballast Resistors damaged in test
  - 2.7 Timing of AND circuits out of phase
  - 2.8 Timer Jumpers wrong causing excess delay
  - 2.9 EMI Disrupted circuit operations
  - 2.10 Environment effects on Avionics
  - 2.11 Cross-strapped pressure transducer interfers with fire command
  - 2.12 Avionics shorted
  - 2.13 Fuses open
- **3.0 Harness/Connector Failure**
  - 3.1 Circuits not connected to Pyro
  - 3.2 Harness Open
  - 3.3 Harness Shorted
- **4.0 Drogue System Failure**
  - 4.1 Pyro Failed
  - 4.2 Drogue parachute did not deploy

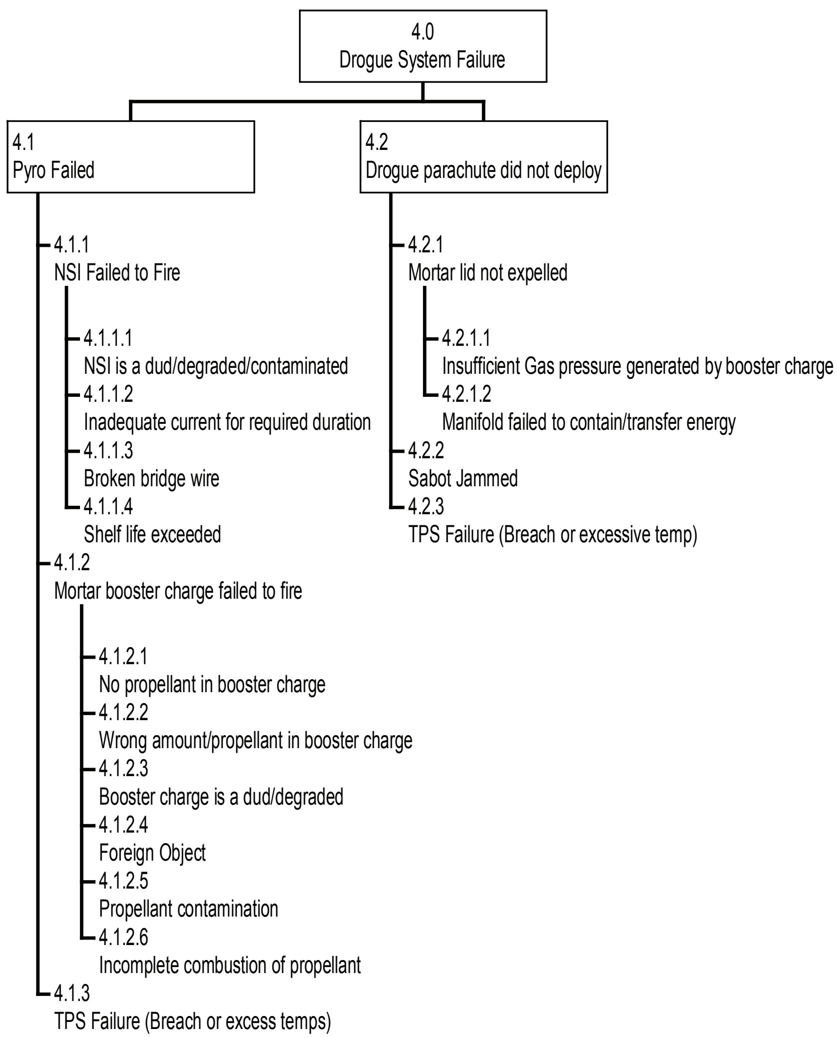
1.0 Electrical Power Failure in SRC

- **1.1 Spacecraft Bus Sequence Wrong**
  - 1.1.1 Battery online command incorrect
- **1.2 Power State of Circuits Incorrect (Relays)**
  - 1.2.1 Cable cut effects
  - 1.2.2 Spin Up effects
  - 1.2.3 Separation Shock Effects
  - 1.2.4 Entry Load effects
  - 1.2.5 Power off Transient in MDE toggles power relays
  - 1.2.6 Relay did not connect to EST position
- **1.3 Power Electronics Design Flaw**
- **1.4 Power Disconnected on Entry**
  - 1.4.1 Battery Enable plug came loose
  - 1.4.2 Entry loads disconnecteed Power Connectors
- **1.5 Entry Thermal Environment Effects**
  - 1.5.1 Entry Plasma effect on cut cables
  - 1.5.2 Overheating and shorting of cables
  - Overheating and damage of battery
- **1.6 Inadequate Battery Voltage and Power**
  - 1.6.1 Excessive Electrical loads
    - 1.6.1.1 Extrernal Shorts Drained Battery
    - 1.6.1.2 Battery Drained before Entry - Excess Avionics Load
    - 1.6.1.3 Deadface drained battery
  - 1.6.2 Inadequate battery
    - 1.6.2.1 Battery Drained before Entry - bad power model
    - 1.6.2.2 Battery Temp too low in flight
    - 1.6.2.3 Battery stored at too high a temp in flight
  - 1.6.3 Mechannically damaged battery
  - 1.6.4 Battery thermostat open on EDL
  - 1.6.5 Depassivation not complete



2.0
SRC Avionics Failure
2.1
G Switch did not active sequencer
2.2
Low Pass Filter wrong time constant
2.1.1
Improper Orientation of the G Switch
2.1.2
Loads prevented G Switch Activiation
2.2.1
Improper Filter Design
2.2.2
Entry dynamics exceeded filter capability
2.1.2.1
G switch cannot handle design spin load
2.1.2.2
Spin rate exceeded g swithc capability
2.1.2.3
G switch cannot handle design Angle of Attack loads
2.1.2.4
Angle of Attack exceeded g switch capability
2.1.3
High Freq Chatter Activation Interference
2.1.4
Space Effects rendered G Switch unusable
2.1.5
G Switch shorted at test connector
2.1.6
G load profile off-nominal
2.1.6.1
Loads never reached trigger level
2.1.6.2
Loads never dropped below trigger prior to impact
2.1.7
Incorrect G Switch installed
2.1.8
Mechanical failure of G Switch
2.3
Reset on Timer Triger
2.4
Oscillator Frequency Incorrect
2.5
Latent Fault due to high voltage discharge
2.6
Pyro Ballast Resistors damaged in test
2.7
Timing of AND circuits out of phase
2.8
Timer Jumpers wrong causing excess delay
2.9
EMI Disrupted circuit operations
2.10
Environment effects on Avionics
2.9.1
Internal EMI
2.9.2
External EMI
2.10.1
Space (Micrometeoriod, Debris, Radiation, Vacuum)
2.10.2
Entry Effects - Thermal
2.10.3
Entry Effects - Plasma
2.10.4
Entry Effects - Mechanical
2.11
Cross-strapped pressure transducer interfers with fire command
2.12
Avionics shorted
2.13
Fuses open


3.0
Harness/Connector Failure
3.1
Circuits not connected to Pyro
3.1.1
Connected wrong
3.1.2
Connectors loose or demated
3.1.2.1
Separation Shock
3.1.2.2
Entry Loads
3.1.2.3
Improper Installation
3.1.3
Bent pin/Contamination/Open in connectors
3.2
Harness Open
3.2.1
TPS Failure (Breach or excessive Temp)
3.2.2
Micrometeroid Damage/Debris
3.2.3
Harness flexing e.g., Hinge movement
3.3
Harness Shorted
3.3.1
TPS Failure (Breach or excessive temp)
3.3.2
Micrometeroid Damage/Debris
3.3.3
Harness flexing e.g., Hinge movement
3.3.4
Test Port plug shorted out


4.0
Drogue System Failure
4.1
Pyro Failed
4.1.1
NSI Failed to Fire
4.1.1.1
NSI is a dud/degraded/contaminated
4.1.1.2
Inadequate current for required duration
4.1.1.3
Broken bridge wire
4.1.1.4
Shelf life exceeded
4.1.2
Mortar booster charge failed to fire
4.1.2.1
No propellant in booster charge
4.1.2.2
Wrong amount/propellant in booster charge
4.1.2.3
Booster charge is a dud/degraded
4.1.2.4
Foreign Object
4.1.2.5
Propellant contamination
4.1.2.6
Incomplete combustion of propellant
4.1.3
TPS Failure (Breach or excess temps)
4.2
Drogue parachute did not deploy
4.2.1
Mortar lid not expelled
4.2.1.1
Insufficient Gas pressure generated by booster charge
4.2.1.2
Manifold failed to contain/transfer energy
4.2.2
Sabot Jammed
4.2.3
TPS Failure (Breach or excessive temp)

Appendix C-2.b
Fault Tree Spreadsheet

Appendix D Contents

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Appendix D-9
Human Factors and Organizational Analysis

Patricia M. Jones

Executive Summary

This report is a detailed analysis of human and organizational factors that contributed to the Genesis mishap. It focuses on decision making, management, and communication issues. Through detailed analysis of interview transcripts and an organizational communication survey, four layers of contributions have been identified: individual human error in engineering and design; preconditions relating to team coordination and individual readiness; flaws in project management and systems engineering practices; and organizational factors related to the pervasive influence of the Faster-Better-Cheaper corporate culture at the time of the Genesis design.

1. Introduction

This report provides a detailed account of the human factors and organizational analysis that provided data and results for the Genesis MIB. Because of the nature of the Genesis mishap as a "design error", attention was not focused on many "classic" human factors issues such as display design, usability of controls, and the like, but more focused on decision making, management processes, and organizational climate issues.

The goal of the analysis was not to blame individuals but to systematically examine a range of issues, beginning with various types of "design error" and working backwards in time to preconditions, management operations, and organizational influences (Reason, 1990; see Shappell and Wiegmann (2001) for an alternative characterization). Figure D-9.1 illustrates the conceptual idea.

A more detailed characterization of "designer acts" is that designers may make errors or perform violations. Errors are related to perception, cog-

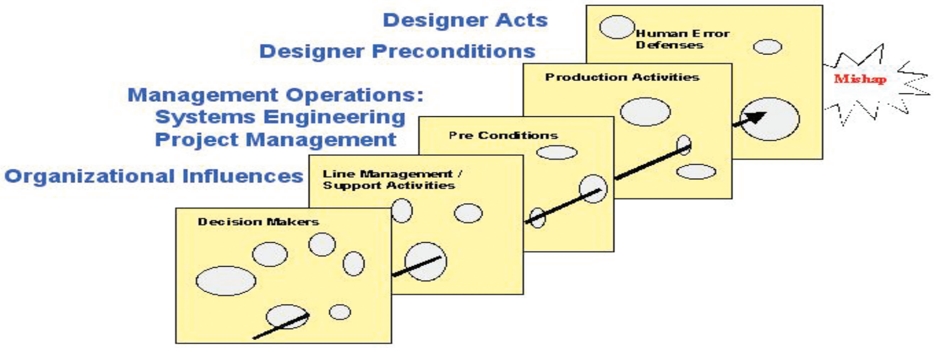

Figure D-9.1. Conceptual framework for analysis.

nition, and motor performance. A perceptual error is that the designer "didn't see it". A cognitive error takes several forms such as "forgot it", "didn't attend to it", "didn't use the rule", "made the wrong decision". A motor error is that the designer did not actually perform the skill or technique appropriately. A violation refers to carrying out a known procedure – the person may violate a procedure routinely (e.g., as in often driving over the speed limit), may violate a procedure 'somewhat' (infraction), or may knowingly perform a blatant violation (exception).

If we then ask why a designer may perform an error or violation, then the next layer of analysis is "precondition" related to that designer as an individual or as part of a team. There are three major types of preconditions: medical, team coordination, or readiness. A person may err because he or she is in an adverse state either mentally (e.g., mental fatigue) or physically (e.g., physical fatigue, drunk) or may be limited in some other way (e.g., is not strong enough to perform a physical task). A second type of precondition related to team coordination issues. Three specific types of coordination issues are those related to communication processes, to assertiveness, and to flexibility/adaptability. Inadequate communication can take many forms (e.g., communication gaps, lack of shared vocabulary). Assertiveness refers to the likelihood or ability of people to speak up to make their views and issues known. Flexibility/adaptability in a team context refers to the willingness of the team to adapt to new demands. For example, a team that insists on using a design process that no longer fits the current situation could be diagnosed as having a flexibility/adaptability problem. Finally, readiness of an individual or team refers to training and certification issues. Readiness also refers to 'workload' in the sense of the number of concurrent task demands placed on the person or team.

Again, if we ask why such preconditions exist, we turn next to issues related to management operations. In the case of a design mishap such as Genesis, our focus is specifically on systems engineering and project management issues. Systems engineering as defined within NASA includes major activities related to requirements, verification, risk management, and documentation. Project management issues include oversight, decisions about local resources such as staff assignments, schedule and costs, and problem reporting systems and practices. For completeness, the category of supervisory misconduct is also included.

Finally, if we ask why those management operations problems might exist, we turn to the broader category of organizational influences. Two major classes of organizational influence are resource management (staffing, funding, equipment) and organizational climate (organizational structure, organizational culture, and organizational processes). Examples of organizational risk factors include lack of staff, staff turnover, lack of funding, poor equipment, ineffective organizational structures, poor organizational culture, and unclear or cumbersome organizational processes.

This set of categories was used to analyze organizational data from Genesis. These categories are summarized in Table D-9.1.

Table D-9.1. Detailed Set of Analytical Categories

Category	Sub-Category	Detailed Category
Designer Acts	Error	Attention/Memory
		Knowledge/Rule
		Skill/Technique
		Judgment/Decision
		Perception
	Violation	Routine
		Infraction
		Exception
Preconditions	Medical	Mental State
		Physical State
		Limitation
	Team Coordination	Communication
		Assertiveness
		Adaptability/Flexibility
	Readiness	Training/Preparation
		Certification/Qualification
		Concurrent task demands
Management Operations	Systems Engineering	Requirements
		Verification
		Risk Management
		Configuration Control / Documentation
	Project Management	Supervision/Oversight
		Local Resources
		Problem Reporting
		Supervisory Misconduct
Organizational Influences	Resource Management	Staffing
		Funding
		Equipment/facilities
	Organizational Climate	Culture
		Structure
		Policies

Within the context of this framework, several specific issues related to Genesis emerged as special topics of study. These were:

1. Requirements, design, and test issues. In particular, how the requirements were written, interpreted and used in design, and how verification activities were planned and carried out.
2. Communication and role issues. In particular, how information was communicated and how roles were perceived.
3. Heritage issues. In particular, the extent to which it was perceived that Genesis inherited hardware from Stardust, which therefore might influence decisions about requirements, testing, and communication.
4. Organizational climate issues related to the "Faster-Better-Cheaper" emphasis within NASA's Discovery Program at that time. In particular, emphasis on cost and schedule, the use of cost caps, and how those factors influenced decision making.

In addition, several categories were quickly dismissed as irrelevant (e.g., medical issues, supervisory misconduct). Therefore, the resulting analysis focused on the subset of categories shown in Table D-9.2.

Table D-9.2. Focus of Genesis Analysis.

Category	Sub-Category	Detailed Category	Examined for Genesis
Designer Acts	Error	Attention/Memory	
		Knowledge/Rule	How knowledge was applied and used
		Skill/Technique	
		Judgment/Decision	Who made what decisions
		Perception	
	Violation	Routine	
		Infraction	
		Exception	
Preconditions	Medical	Mental State	
		Physical State	
		Limitation	
	Team Coordination	Communication	Informal communication network
		Assertiveness	
		Adaptability /Flexibility	
	Readiness	Training /Preparation	Years of experience; educational background
		Certification / Qualification	
		Concurrent task demands	Number of simultaneous roles held by individuals
Management Operations	Systems Engineering	Requirements	Clarity vs. ambiguity; common view vs. different views
		Verification	Clarity vs. ambiguity; common view vs. different views
		Risk Management	Central or peripheral
		Configuration Control / Documentation	
	Project Management	Supervision /Oversight	Degree of oversight
		Local Resources	
		Problem Reporting	
		Supervisory Misconduct	
Organizational Influences	Resource Management	Staffing	As related to FBC climate
		Funding	As related to FBC climate
		Equipment/facilities	
	Organizational Climate	Culture	FBC climate
		Structure	Formal roles and responsibilities; informal communication network
		Policies	

2. Methods

Data were collected through two major activities: interviews and an organizational communication survey. In addition, some archival documents from the Genesis mission were used as data sources, such as rosters, organizational charts, and documents from design reviews.

2.1. Organizational Communication Survey

The purpose of the organizational communication survey was twofold: to clarify roles and tenure on the Genesis project that were not clear from the interviews, and to gather systematic data about communication patterns among the 23 people selected as relevant to the Genesis mishap investigation. These 23 included all those who were interviewed plus those from other functions who were selected as relevant by the Board. Two names were added from an original roster of 21 from the JPL and LMSS assistants to the investigation. The final roster of 23 participants is shown in Table D-9.3 below.

Table D-9.3. Roster of the Survey Participants.

ID Label	General Role	Institutional Affiliation	Technical Specialty for Engineering Roles
MGL1	Manager	LMSS	N/A
MGL2	Manager	LMSS	N/A
MGJ1	Manager	JPL	N/A
PML1	Project manager	LMSS	N/A
PMJ1	Project manager	JPL	N/A
SEJ1	Systems engineer	JPL	N/A
SEJ2	Systems engineer	JPL	N/A
SEJ3	Systems engineer	JPL	N/A
SEL1	Systems engineer	LMSS	N/A
SEL2	Systems engineer	LMSS	N/A
SEL3	Systems engineer	LMSS	N/A
MAL1	Mission assurance	LMSS	N/A
MAJ1	Mission assurance	JPL	N/A
LEL1	Lead engineer	LMSS	SRC Recovery
LEL2	Lead engineer	LMSS	Mechanical
LEL3	Lead engineer	LMSS	ATLO
LEL4	Lead engineer	LMSS	Operations
LEL5	Lead engineer	LMSS	Payload Integration
LEL6	Lead engineer	LMSS	EPS and SRC avionics
LEL7	Lead engineer	LMSS	Entry systems
LEJ1	Lead engineer	JPL	Payload
ENL1	Engineer	LMSS	SRC electronics
ENL2	Engineer	LMSS	SRC electronics and C&DH

A standard communication network-style survey was used in which each person provided a subjective rating (from a fixed set of choices) of how often he or she communicated with each other person in the network. The six rating categories are shown in Table 4 below, along with the numeric scores later used to analyze the data. This rating was intended to capture the memory of "average" communication during Phases B, C, and D of the Genesis project, where communication includes all modes such as face-to-face individual or group meetings, email, telecons, etc. Contractor (2004, personal communication) confirmed that in social network analysis research, it is acceptable to ask people about networks they belonged to some years ago, provided that "average" behavior is requested rather than behavior in a specific time period. A copy of the organizational communication survey, with actual names of the 23 people omitted, is shown in Section 6 of this report.

Table D-9.4. Rating Categories for Communication Frequency.

Category	Numeric Score Later Used in Analysis
None	0
Once a year or less	1
Several times a year	2
Several times a month	3
Several times a week	4
Once a day	5
Several times a day	6

The communication network survey was disseminated by email, along with an offer by the analyst to gather data via telephone interview or fax. All participants used email. In a few cases, participants left part of the communication network survey blank. In most cases, this was resolved through emails to discuss if the participant had actually intended to rate "none" on communication or if the participant had simply forgotten to check an item. In four cases, one or two items remained unchecked, the situation was not resolved, and these missing data were left blank and taken to be "zero" for analytical purposes.

The analysis of the ratings of communication frequency is an example of social network analysis (Wasserman and Faust, 1994). Social network analysis is a specialized field that uses graph theory and multivariate statistics to examine social network data – ranging from communication networks, as in this study, to studies of friendship and advice between individuals, information sharing between organizational groups, and trade relations among nations. Whatever the context, the basic idea of social network analysis is that you have data that can be represented as a graph: that is, a set of nodes and arcs that connect the nodes. In this study, a node represents a person and the arc represents the rating of communication frequency. In particular, because the survey participants are all rating each other on a scale of 0 – 6 for communication frequency, the graph in this investigation is an example of a directed and valued graph. It is directed because it has a direction: an arc between two nodes originates from one (the 'source') and goes to another (the 'recipient'). This arc is an 'outdegree' of the source and an indegree of the recipient. It is valued because it has a value: a score of 0 to 6. All these data can be represented as a 'sociomatrix', which is a matrix where the rows represent the people who did the rating, the data in the matrix represent those ratings, and the columns represent the people who were rated. Thus, the rows show outdegrees from each person and the columns show indegrees into each person.

For example, consider a network of three individuals – Alpha, Bravo, and Charlie – who did ratings as follows: Alpha said "I talk with Bravo once a day" (5) and "I talk with Charlie several times a month" (3). Bravo said "I talk with Alpha several times a week" (4) and "I talk with Charlie not at all" (0). Charlie said "I talk with Alpha several time a day" (6) and "I talk with Bravo not at all" (0). The resulting sociomatrix is shown in Table D-9.5.

Table D-9.5. Example Sociomatrix of Alpha, Bravo, Charlie.

	Alpha	**Bravo**	**Charlie**
Alpha	----	5	3
Bravo	4	----	0
Charlie	6	0	----

There are numerous types of analyses that can be done on social network data. In this investigation, we will restrict our attention to the following specific questions:

1. Basic descriptive statistics about the network: number and strength of indegrees and outdegrees, density.
2. Centrality and prestige of the people in the network:
3. Cohesion: Are there distinct subgroups or cliques? If so, how many and who are members?

2.1.1. Descriptive Statistics

A variety of simple descriptive measures can be used to characterize sociomatrix data. These include

- Counting the number of indegrees and outdegrees for each node in a directed graph. In the usual sociomatrix format as shown in the Alpha-Bravo-Charlie example, this simply means counting up the number of non-zero entries in each column (for indegrees) and row (for outdegrees).
- Calculating the mean strength of the indegrees and outdegrees for each node in a directed valued graph.
- Calculating the density of a directed graph, which is the percentage of arcs that exist (i.e., are non-zero) out of the total possible number of arcs. Thus, the density measure varies between zero and one.
- Examining mutuality: in a directed graph, each pair of nodes may or may not have arcs of the same strength.

In the Alpha-Bravo-Charlie example, we obtain the results for indegrees and outdegrees shown in Table D-9.6.

Table D-9.6. Descriptive Statistics from Alpha-Bravo-Charlie Example.

Node	Indegrees	Indegree Strength	Outdegrees	Outdegree Strength
Alpha	2	5	2	4
Bravo	1	5	1	4
Charlie	1	3	1	6

The density of the Alpha-Bravo-Charlie graph is 4/6 = 0.67.

2.1.2. Centrality and Prestige

A basic question in social network analysis is how to identify the most "important nodes in the network". Here, "importance" is taken to mean "most prestigious" and "most central". The simplest measure of node prestige is the relative indegree: the number of indegrees divided by the total number of indegrees possible (g-1 where g is number of nodes). In this example, Alpha is the most prestigious (or 'popular') node with a relative indegree of 1, the maximum possible because both other nodes in the network have chosen Alpha. Bravo and Charlie both have a relative indegree of 0.5.

A more complicated measure of node prestige takes into account not just nodes that are directly connected to that node, but also to all the other nodes reachable by that node. In our small example, this is irrelevant – both Bravo and Charlie are directly connected to Alpha. See Wasserman and Faust (1994) for further discussion.

Centrality of a node in a network can be calculated in a variety of ways. The formula for closeness centrality given by Equation 5.22 in Wasserman and Faust (1994) is to calculate the reciprocal of the average 'distance' of each node from the node of interest. A variety of other measures of centrality exist; see Wasserman and Faust (1994) for more discussion.

In our simple Alpha-Bravo-Charlie example, we can calculate closeness for each node as follows in Table D-9.7. However, note that in our example, big numbers mean "more frequent communication" and thus larger numbers are 'closer'. Therefore, because the closeness centrality measure is a reciprocal, a smaller closeness centrality score would mean greater closeness. Alternatively, we could recode our original sociomatrix to be more intuitive with the notion of "distance".

Table D-9.7. Closeness Centrality of the Alpha-Bravo-Charlie Network.

Node	**Closeness Centrality = (g-1) / [Sum of distances from other nodes] Where g = 3**
Alpha	2 / [5+3] = 0.25 This is the most central node
Bravo	2 / [4+0] = 0.5 This is the least central node
Charlie	2 / [6+0] = 0.33 This is the second most central node

Mutuality is a concern with directed graphs. Mutuality refers to the idea that any dyad (group of two nodes) may or may not reciprocate the relationship between those nodes. In our Alpha-Bravo-Charlie example, both Bravo and Charlie report that they do not talk at all. Thus the Bravo-Charlie dyad is mutual. However, the other dyads are not mutual; they are asymmetric. In other words, the Alpha-Bravo-Charlie sociomatrix is asymmetric. For most real data sets, this is the case. An index of mutuality can be computed to show the degree to which the network contains mutual dyads.

2.1.3. Cohesion

Another common concern in social network analysis is to identify cohesive subgroups. A variety of mathematical definitions exist that distinguish cliques from groups and other similar concepts; these are based on the identification of paths, trails, geodesics, and so on in graph-theoretic terms. In the case of a directed graph, we can choose a threshold value above which to analyze what nodes are reachable from what other nodes. In our Alpha-Bravo-Charlie example, the group of three nodes is cohesive because all nodes are reachable from every other node.

2.1.4. Other Structural Phenomena

Identifying other interesting structural features of a social network relies on automated statistical packages and visualization. For example, one phenomena of interest is to identify "bridges" in the network – an arc that connects two subgroups that otherwise would not be connected. A node that connects two groups that otherwise would not be connected is called a cutpoint. In our example, Alpha is a cutpoint. If Alpha was removed from the network, Bravo and Charlie would remain as isolated nodes.

Other larger-scale questions have to do with hypothesis testing. A number of techniques exist for comparing a hypothesized sociomatrix to an actual sociomatrix data set and performing statistical goodness-of-fit tests. For the purposes of this investigation, such detailed hypotheses were not explored.

2.2. Interviews

Interviews were conducted as part of the main Genesis investigation and are documented elsewhere in Volume 1. Four different analyses of interview data were performed. The general method for each analysis was the same: interview comments that were judged relevant to the issue at hand were selected and separated into "thought units" which usually corresponded to individual sentences, but in some cases a "thought unit" consisted of a sentence fragment and in some cases consisted of several sentences. After a comprehensive selection of "thought units" was derived, each unit was coded. This coding activity was the systematic interpretation of each unit into one of a mutually exclusive set of codes designed to capture relevant features of the question of interest.

Four different coding systems were developed related to four major areas of interest from the interview data. These four areas of interest were (1) Heritage, (2) Design and Test, and (3) FBC and Organizational Climate. An additional qualitative assessment was done of Roles and Communication to supplement the organizational network data.

2.2.1. Heritage Coding Systems

From the interview data, “thought units” were collected in which the word ‘heritage’, ‘common’, ‘commonality’, or ‘reuse’ was used to refer to common features between Genesis and Stardust.

Two different coding systems were developed. The first focused on the level of detail that ‘heritage’ was described and how it related to decision making or action. In particular, in this coding system, each unit was assigned a triple code <Object, Explicitness, Action>. The mutually exclusive options for each item in this triplet are shown in Table D-9.8 below.

Table D-9.8. Heritage Coding System for Object-Explicitness-Action.

Code Type	Code	Numeric Code
Object	Mission	1
	System	2
	Subsystem	3
	Avionics (“box”)	4
	SRC avionics box	5
	G-switches	6
	Other	7
Explicitness about design or test impact	N/A	1
	Implicit	2
	Explicit	3
Action/Impact	N/A	1
	Less scrutiny needed because assumed same as before	2
	More scrutiny needed because change identified	3

For example, a statement such as “We knew the G-switch was heritage from Stardust so we didn’t have to test it” would be coded as <6, 3, 2>, while a statement such as “Genesis had Stardust heritage” was coded as <1, 1, 1>.

A second set of codes was developed to examine the extent to which different people in various roles did or did not perceive heritage. Selected thought units were coded as the tuple <ROLE, BELIEF> using the system shown in Table D-9.9 in the following. The coding of person to role was straightforward based on the person’s formal affiliation as given in the interview and/or survey data.

Table D-9.9. Heritage Coding System for <ROLE, BELIEF>.

Code Type	Code	Numeric Code
Role	Project Management (PM)	1
	Systems Engineering (SE)	2
	Red Team	3
	Engineering	4
	Other	5
Belief	Heritage	1
	Not Heritage	2

For example, if a person in a project management role said, "We knew that the hardware design was different than Stardust", that unit was coded as <1, 2>.

2.2.2. Design and Testing Coding System

The interview data varied widely in how design and verification issues were characterized. For example, "verifying the G-switch" referred to a variety of potential kinds of verification types (verification by test or similarity or by analysis) and various different kinds of tests (functional, performance, continuity, directionality) and test techniques (centrifuge, drop, lift).

Interview data were collected into relevant "thought units" in which the words "design", "verification", "test", "centrifuge", and related items were identified.

Each of these units was coded into the tuple <ROLE, OBJECT, LEVEL, VERIFICATION-TYPE, TEST-TYPE, TEST-DETAIL> as shown below in Table D-9.10. Role was straightforward to identify from each person's job title or function as described in the interviews.

Table D-9.10. Design/Test Coding System for <ROLE, OBJECT, LEVEL, VERIFICATION-TYPE, TEST-TYPE, TEST-DETAIL>.

Code Type	Code	Numeric Code
Role	Project Management (PM)	1
	Systems Engineering (SE)	2
	Red Team	3
	Engineering	4
	Other	5
Object of discussion	Philosophy	1
	System	2
	Avionics	3
	SRC	4
	SRC Avionics	5
	G-switch	6
	G-switch circuitry	7
	FPGA	8
	Packaging	9
	Other	10
Level of design or verification discussed	None/NA	0
	Science	1
	Mission	2
	Flight	3
	Subsystem	4
	Box	5
	Component	6
	Circuitry	7
	Other	8
Verification Type	None	0
	Analysis	1
	Similarity	2
	Test	3
Test Type	None	0
	Functional	1
	Performance	2
	Continuity	3
	Other	4
Test Detail	None	0
	Spin/centrifuge	1
	Drop	2
	Lift	3
	Other	4

For example, if an engineer stated "We planned to do a centrifuge test on the G-switch", that would be coded as <4, 6, 6, 3, 4, 1>.

2.2.3. Roles and Communication Analysis

Interview notes were analyzed to examine the extent to which self-reported roles differed from others' perception of that role.

2.2.4. FBC and Organizational Climate Coding System

The Board was interested in the extent to which the well-documented climate of Faster-Better-Cheaper would have affected decision making on the Genesis mission. In particular, this meant significant pressures to meet cost and schedule goals that could put technical goals at risk. A related question of organizational climate is the extent to which people perceived that the Genesis project climate was open and that teamwork was effective.

Interview data were collected into relevant "thought units" in which the words "schedule", "cost", "faster-better-cheaper", "teamwork", and related items were identified (e.g., "people weren't shy about speaking up").

Each of these units was coded into the triplet <ROLE, BELIEF, STRENGTH> as shown below in Table D-9.11. Role was straightforward to identify from each person's job title or function as described in the interviews.

Table D-9.11. FBC Coding System for <ROLE, BELIEF, STRENGTH>.

Code Type	Code	Numeric Code
Role	Project Management (PM)	1
	Systems Engineering (SE)	2
	Red Team	3
	Engineering	4
	Other	5
Belief	No schedule pressure	10
	Schedule pressure	11
	No cost pressure	20
	Cost pressure	21
	Open communication/good teamwork	30
	Lack of communication/poor teamwork	31
	No resource issues	90
	Resource issues	91
	General statement about resources	99
Strength	Mild	0
	Moderate	1
	Strong	2

For example, if a Systems Engineer said, "Well yeah we had some schedule pressure but it was no different than any other project", that was coded as <2, 11, 0>. As another example, if an Engineer said, "I couldn't run that test because it was too expensive", that was coded as <4, 21, 1>.

3. Results

Two sets of results are presented: those for the organizational communication survey and those for the interview data.

There are several important caveats to keep in mind with all these results. First, these data are based on participants' memory of events from approximately six years ago. It is well known that memory is reconstructive in various ways and may not always be reliable (e.g., Loftus, 1979; 1980). For example, people may reconstruct events as they "must" have happened but not necessarily as they did happen. Furthermore, there are well-known social effects to be noted, such as people's general tendency to say socially acceptable answers. Finally, few conclusions can be drawn from the absolute frequency counts in the data. These counts are obviously related to the nature of the interview questions and follow-up probes asked; therefore, frequency of behavior alone is confounded with the nature of the interview. However, relative frequencies may be diagnostic.

Nevertheless, interviews and surveys contain valuable data that can be analyzed systematically.

3.1. Organizational Communication Survey Results

The demographic part of the organizational communication survey helped to clarify the roles, experience, and tenure of the 23 selected participants in the Genesis project. From these data, the following observations are noted:

Observation: The team was experienced. The mean number of years of experience at the home institution (JPL or LMSS) prior to Genesis was reported to be 15.5 years.

Observation: Turnover was not a significant issue. A detailed look at 12 key participants (two project managers, six systems engineers, two lead engineers, and two engineers) showed that eight of them worked on Genesis before the System Requirements Review (March 1998) and worked continuously through to launch (August 2001). One worked before the SRR and continuously through May 2000, then transitioned to part-time status until August 2001 when Genesis launched. One participant joined after the Preliminary Design Review (July 1998) and worked through launch. The remaining two of these 12 represented the only significant turnover in the project that occurred October/November 1998. The first engineer for the SRC avionics left the organization after 5 months on Genesis, with a 1-2 week turnover period with his successor.

Observation: Most people had multiple roles. This meant heavy concurrent task demands on most of the key people on the Genesis project. For example, systems engineers would typically have four or five roles such as System Design Lead, Requirements Lead, Verification Lead, Contamination Control Lead, Payload Integration Lead, or Launch Vehicle Integration Lead.

3.1.1. Descriptive Statistics of the Communication Network

The communication network contained 23 nodes. Thus, the maximum number of indegrees or outdegrees is 22. The rating scale was numerically coded as 0 to 6, where 6 represented the most frequent communication as show in Table 4 previously. Thus, the highest mean value of an indegree or outdegree would be 6 as well, if every rating received was a 6.

Figure D-9.2 shows a frequency histogram of indegrees. This shows that many people in the network were "popular"; in fact, 14 of them had either 21 or 22 indegrees.

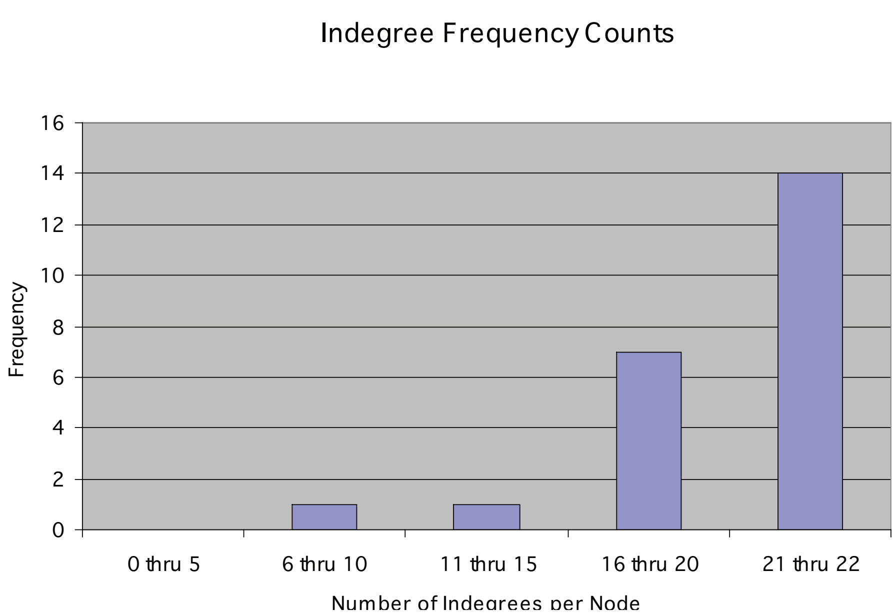

Figure D-9.2. Frequency histogram for indegrees.

Figure D-9.3 shows a frequency histogram of outdegrees. This shows that most people were "expansive" in that they rated having at least some communication with most everybody else in the network. In fact, 22 of the 23 people in the network rated themselves as communicating with 16 or more other people.

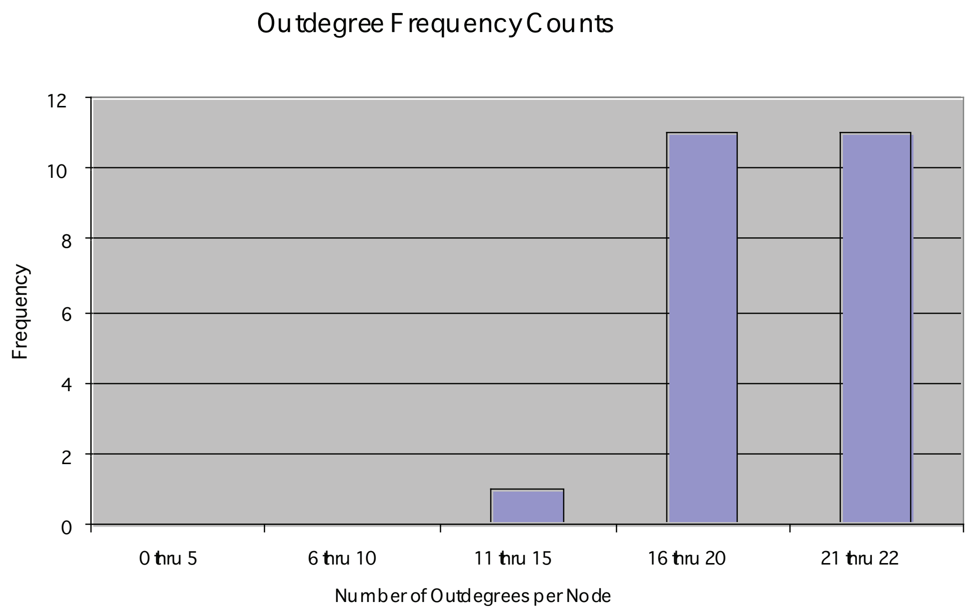

Figure D-9.3. Frequency histogram for outdegrees.

For the entire network, the mean number of indegrees, which equals the number of outdegrees by definition (i.e., we are simply counting all the arcs that exist in two different ways) is 19.91. The mean value or "strength" of the indegrees was 3.15 and the mean value of outdegrees was 3.19. Thus, we can say the "average communication" as reported in this network was slightly more than "several times a month". The density of the network (which only examines the presence or absence of mutual dyads, not considering their strength) is 0.91, which is quite high (the maximum is 1). Therefore, even though many ratings of communication frequency were not identical between two people, it was almost always the case that people did reciprocate on the simpler question of "did we communicate at all or not".

3.2.1. Centrality and Prestige

For each person in the network, prestige was calculated as relative indegree (number of indegrees divided by 22, the maximum number of indegrees). In this network of 23 people, 10 of them are "most prestigious" in that the prestige score is 1.0. The relatively low rating for ENL1, the first SRC avionics engineer on Genesis, is most likely due to his short tenure on the project.

MGL1 is in a job function that is not actually part of the Genesis project but in a related matrix organization. Otherwise the range of prestige scores is quite narrow and high – from 0.82 to 1.0.

A closeness centrality measure was calculated for each network node also. This used the same formulation as in the previous example: the reciprocal of the sums of distances of adjacent nodes. Again, in this formulation, smaller numbers are 'closer' because the inverse of larger numbers for communication frequency results in smaller scores. In addition, the closeness centrality measures were ranked smallest to largest to also help highlight the "top" scorers for closeness. Ties were represented using the standard midrank method. For example, a score of 0.34 occurred twice and those numbers would have been ranked 11 and 12 if they were distinct; therefore the mean rank of (11 + 12) / 2 = 11.5 was assigned to both those values.

The resulting scores for prestige and centrality are shown in Table D-9.12.

Table D-9.12. Prestige and Closeness Centrality of the Network.

ID Label	General Role	Institutional Affiliation	Prestige (relative indegree)	Closeness Centrality	Rank of Closeness Centrality
MGL1	Manager	LMSS	0.68	0.54	22
MGL2	Manager	LMSS	1.0	0.34	11.5
MGJ1	Manager	JPL	0.86	0.39	16
PML1	Project manager	LMSS	1.0	0.28	3.5
PMJ1	Project manager	JPL	0.95	0.39	16
SEJ1	Systems engineer	JPL	1.0	0.33	9
SEJ2	Systems engineer	JPL	0.86	0.42	21
SEJ3	Systems engineer	JPL	0.86	0.32	7
SEL1	Systems engineer	LMSS	1.0	0.22	1
SEL2	Systems engineer	LMSS	1.0	0.27	2
SEL3	Systems engineer	LMSS	1.0	0.31	6
MAL1	Mission assurance	LMSS	0.82	0.39	16
MAJ1	Mission assurance	JPL	0.82	0.41	18.5
LEL1	Lead engineer	LMSS	0.95	0.28	3.5
LEL2	Lead engineer	LMSS	1.0	0.3	5
LEL3	Lead engineer	LMSS	1.0	0.41	18.5
LEL4	Lead engineer	LMSS	1.0	0.34	11.5
LEL5	Lead engineer	LMSS	0.95	0.33	9
LEL6	Lead engineer	LMSS	0.95	0.38	14
LEL7	Lead engineer	LMSS	1.0	0.33	9
LEJ1	Lead engineer	JPL	0.86	0.42	20
ENL1	Engineer	LMSS	0.36	0.59	23
ENL2	Engineer	LMSS	0.86	0.36	13

From Table D-9.7 we can see that in addition to many prestigious nodes in the network, the most central nodes were two of the systems engineers from Lockheed Martin, the Lockheed Martin project manager, and two of the lead engineers from Lockheed Martin.

3.2.2. Cohesion

The next kind of analysis is to look at cohesion, and in particular the presence of subgroups in the network. This type of analysis can be very sophisticated, but for the purposes of this investigation, visual inspection of the sociomatrix was used as a simple way to gauge the presence of independent subgroups (cliques – those groups that are not connected). In this type of network (a valued directed graph), the value of 5 was used as a threshold and the analysis examined both the upper half and the lower half of the sociomatrix (which was not symmetric).

The choice of the value of 5 (representing communication of at least "once a day") as a lower threshold for examining cohesion is because all the nodes in the network are connected at the value of 4 and lower. That is, in looking at communication of "several times a week" or less, every node was eventually reachable by every other node. In that sense, this entire network is very well-connected or "one big clique".

Using a threshold value of 5, the lower half of the sociomatrix was examined to see what nodes were reachable by what other nodes. That analysis showed the following:

- two nodes were not connected to anybody: MAL1 and LEL7
- one cohesive subgroup was: MGL1, LEL6, ENL1, and ENL2.
- The other cohesive subgroup consisted of everybody else

Similarly, a visual inspection of the upper half of the sociomatrix was performed and found almost identical results, with the one difference that MGL1 became an isolate and was not part of the LEL6-ENL1-ENL2 group.

3.3. Interview Results

The results from coding the interview data are presented in this section.

3.3.1. Heritage Results

The issue of heritage was discussed at a variety of levels in the interviews. Fifty-three units were categorized as <OBJECT, EXPLICITNESS, ACTION>.

Figure D-9.4 shows the distribution of units related to the level of discussion. A discussion of heritage was usually explicitly related to design and test as shown in Figure D-9.5. The number of units of whether heritage meant less scrutiny or lack of heritage meant more scrutiny, or neither, was approximately equal with a slight advantage to "neither" as shown in Figure D-9.6.

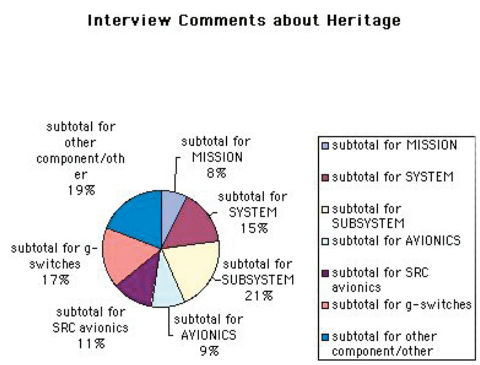

Figure D-9.4. Distribution of units for OBJECT of heritage.

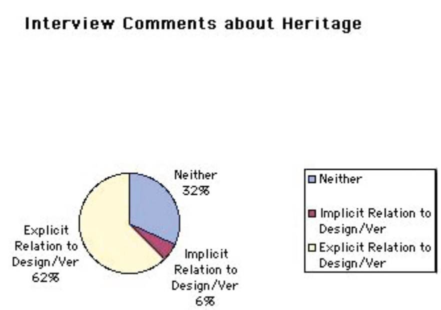

Figure D-9.5. Distribution of units about EXPLICITNESS of heritage.

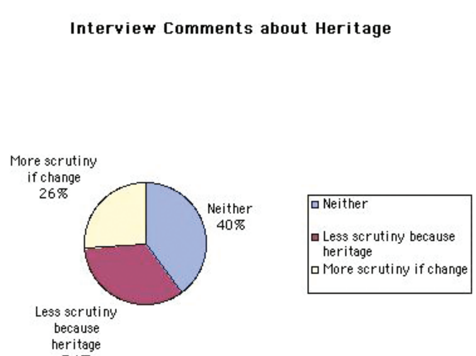

Figure D-9.6. Distribution of units about ACTION related to heritage.

Examining the relation of role and belief, forty-eight units were categorized as <ROLE, BELIEF>. It was found that project managers and systems engineers had comments both about how Genesis was heritage and how Genesis was not heritage. Engineering staff focused most of their comments on how Genesis differed from Stardust heritage. Members of the Red Team did not recognize that Genesis differed in heritage from Stardust. These results are shown in Figure D-9.7.

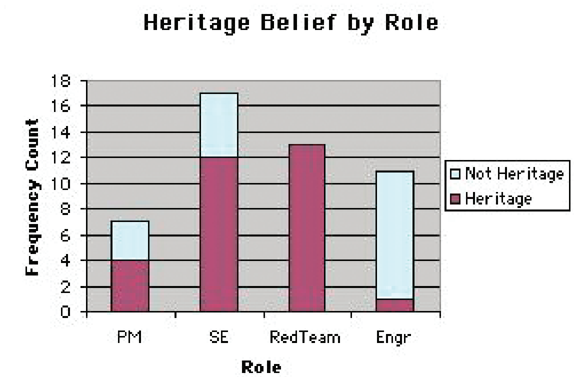

Figure D-9.7. Belief in heritage by organizational role.

3.3.2. Design and Test Results

A total of 154 'thought units' were extracted from the interviews that related to design and test issues.

Figure D-9.8 shows the distribution of units by role.

Figure D-9.9 shows the distribution of units by object, where rare categories were all collected into "Other".

Figure D-9.10 shows the distribution of units about the level of the design or test activity. Rare items were all collected into the category "Other".

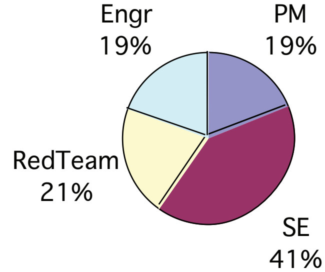

Figure D-9.8. Distribution of units by role.

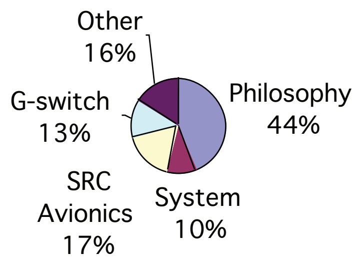

Figure D-9.9. Distribution of units about "Object" of design or test.

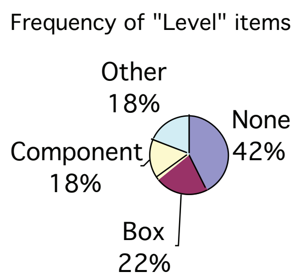

Figure D-9.10. Distribution of units about the "Level" of design or test.

The frequency counts for the categories of verification type, test type and test detail are show in Table D-9.13.

Table D-9.13. Percent Frequency for Units of Verification Type, Test Type, and Test Detail.

Code Type	Code	Percentage of Units
Verification Type	None	71
	Analysis	1
	Similarity	1
	Test	27
Test Type	None	81
	Functional	4
	Performance	1
	Continuity	4
	Other	10
Test Detail	None	83
	Spin/centrifuge	6
	Drop	3
	Lift	0
	Other	8

These data in Table D-9.13 illustrate that most of the units from the interviews were very general remarks about verification and testing. Most of the time there was not a detailed articulation of what kind of test was under discussion.

The data in this section show that in general there was a lack of clarity about design and testing. There were no systematic patterns of specific tests being consistently discussed for specific components.

3.3.3. Roles and Communication Results

A qualitative analysis of the interview transcripts provided deeper insight into potential issues related to roles, responsibilities, and communication in the Genesis project.

In general, the project managers and systems engineers had a common view of a formal hierarchical process for defining design requirements and verification requirements. For example, the JPL Project Manager explained in some detail the different levels of organization – mission, system, subsystem etc. – and the related formal processes of requirements flow-down and roll-up. Similarly, the systems engineers discussed the process of verification flow-down and roll-up. The project managers and systems engineers emphasized that they would probably not know the details of particular test types – at their level, they would need to know that adequate testing was done, and they trusted the engineering staff to use its best judgment to accomplish design and verification goals.

The interviews also highlighted some disconnects between people's perceptions of their own roles versus others' perceptions of their roles. For example, one of the systems engineers spoke of the Recovery Operations Team Chief as "the EDL lead" and therefore by implication a good check-and-balance for all matters related to entry, descent, and landing, including the G-switch. Another systems engineer stated that he thought the SRC avionics engineers would go to that Chief for matters related to the G-switch; but he did recognize that the Chief's interest began with the SRC separation from the spacecraft. The Recovery Operations Team Chief himself defined his role as an end-user of "the box", primarily concerned with trajectory analysis and modeling, safety, and operational planning for the actual capture of the SRC, and was not involved in any detailed testing of the G-switch or other mechanisms.

3.3.4. FBC and Organizational Climate Results

A total of 66 'thought units' were extracted from the interviews that related to cost, schedule, teamwork and other resource and organizational climate issues. The distribution of the comments by role is shown in Figure D-9.11. It is easily seen that most statements were made by people in project management and systems engineering roles.

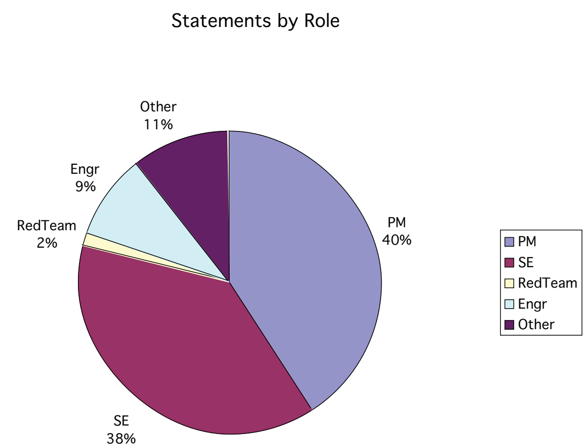

Figure D-9.11. Distribution of "FBC" statements by role.

If we then take the 66 statements and categorize them by the topic – whether schedule was an issue or not, whether teamwork was an issue (i.e., categorize them by the coding scheme shown previously) – we find the results shown in Figure D-9.12. While there was a fair amount of variety, the two

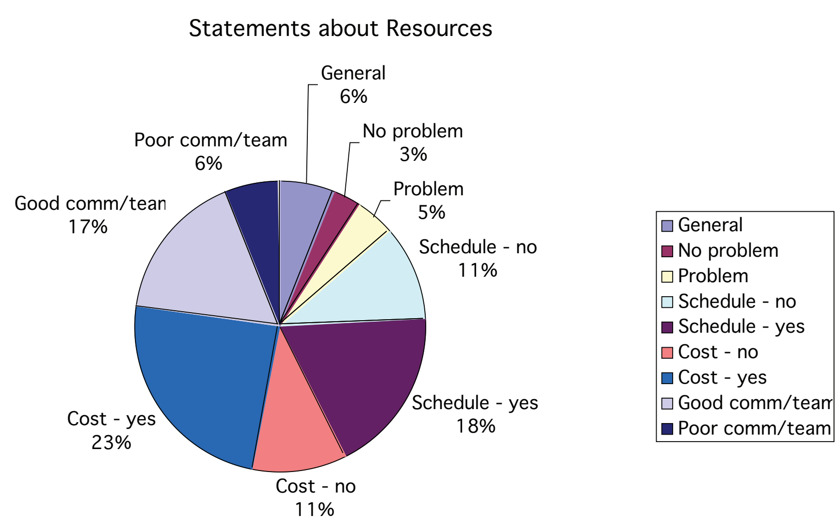

Figure D-9.12. Distribution of statements by type.

most common kinds of statements were along the lines of "yes there was schedule pressure" and "yes there was cost pressure".

A more detailed examination focused on those categories with relatively high frequency counts: statements by project managers, system engineers, and engineers about cost and schedule. It was found that the distinction between "strong" versus "moderate" or "none" was not very helpful, and so results are collapsed across those categories. The distribution of fre-

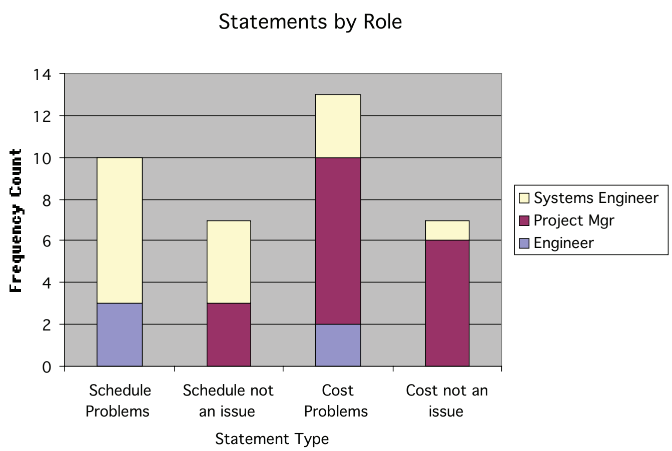

Figure D-9.13. Distribution of statements about cost and schedule by role.

quency counts of the resulting four kinds of statements (there was or was not schedule pressure, there was or was not cost pressure) by role (project manager, system engineer, engineer) is shown in Figure D-9.13.

On the face of it, some of these results are surprising. Did project managers really perceive no schedule problems and claim about half the time that cost was not an issue? To go back to the raw data, there are a variety of very different statements that were categorized in these ways. For example, the statements that the Star Tracker was a recognized risk, "and so schedule was added", and that "after Mars 98…a month of schedule was added" were coded as a "no schedule problem/schedule did not impact quality". Similarly, the statements of how cost was not an issue often involved detailed explanations of the fee structure of the Genesis contract to LMSS. The fee was not based on having an on-time launch but was based on science return. In that sense, cost did not overwhelm the scientific purpose of the mission.

4. Discussion and Conclusions

Returning to Table D-9.2, we may now shed some more light on the details that emerge from the analysis. "Designer error" includes both the ambiguity about the G-switch drawings and proper methods for verification of the G-switch function. Preconditions relate somewhat to team coordination issues (as evidenced by some role confusion and some rigidity in the systems engineering and project management processes seen in the interviews), although the organizational communication survey generally shows a strong social network among all the major parties. Another precondition discussed in Volume 1 is the issue of personal readiness, particularly that an electrical engineer alone is ill-equipped to cope with some of the mechanical issues that would arise with a G-switch implementation. Yet another layer deeper are the systems engineering and project management issues. The data here suggest, and detailed comments in the interview corroborate, that the formal requirements and verification processes tended to prevent appropriate 'drill-down' into issues that should have been examined in detail. In other words, the formal and hierarchical processes acted as a barrier to some extent, perhaps leading to a false sense of security that issues had been properly raised and resolved at some other level. This is not to say that formal hierarchical processes are bad, but that it still takes appropriate judgment and action to wield them effectively. The ambiguity about the notion of 'test' itself leads systematically to assumptions that can often go unexamined. Finally, the organizational climate of reliance on heritage and the values of "Faster" and "Cheaper" tending to trump "Better" are another set of latent factors behind the mishap.

5. References

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Organizational Communication Survey: As given to 23 members of the Genesis team except that actual names from the roster are omitted.

Genesis MIB
Organizational Communication Survey

Purpose: The purpose of this survey is to gather systematic data about organizational communication patterns. These data will be based on your own individual recall of "average" communication with different people related to the Genesis project. The data will be used for aggregate analyses of communication patterns. Similar to non-privileged interview data, these "raw" data will not be used in the Board's final report.

Instructions: This survey is in two parts. Part 1 asks you for demographic data about how long you worked on Genesis and what jobs you held during that time. "Job title" refers to an official title like "Systems Engineer". "Major duties" refer to major activities you remember being responsible for, such as "avionics box design" or "Level 2 requirements documentation".

Part 2 of the survey asks you to recall the "average" frequency of communication with each other person in the given roster during your time with the Genesis project. Frequency of communication includes face-to-face conversations, any kinds of meetings (tabletop, weekly status, PDR, etc.), telephone/telecons, and email. A rating scale is provided and you just need to check the item on the rating scale that most closely matches your recall.

Part 1: Demographics

Name: **Date:**

Affiliation during your time on Genesis (Choose one): JPL LMA
How many years had you worked there before you worked on the Genesis project?
What is your educational background? (Choose all that apply)
Electrical engineering Mechanical engineering Industrial or systems engineering Business Administration Aeronautical engineering Astronomy Other (please specify):

Please list your each of your positions on the Genesis project. For each position, list start and end dates, your official supervisor, and your major duties. Use the back of this page to continue if you had more than three positions with Genesis.

Position 1:

Start date (month/year): End Date (month/year):

Official Supervisor (name):

Major duties:

Position 2:

Start date (month/year): End Date (month/year):

Official Supervisor (name):

Major duties:

Position 3:

Start date (month/year): End Date (month/year):

Official Supervisor (name):

Major duties:

Part 2: Communication Survey

For each person on the below roster (excepting yourself), please check the box that most closely matches the average frequency of communication that you recall with that person while you were working on the Genesis project. Communication includes face-to-face conversations, any kinds of meetings (tabletop, weekly status, PDR, etc.), telephone/telecons, and email. If any engineering or technical person you recall communicating with at least several times a week is NOT on this roster, please write in the names below and indicate your rating of communication frequency.

Name	None	Once a year or less	Several times a year	Several times a month	Several times a week	Once a day	Several times a day

Appendix E

Root Cause and Contributing Factor Narrative; Event and Causal Factor Tree

This appendix complements Section 5.0 of the report. Section E-1 is a timeline to place the events in a historical perspective; Section E-2 contains the details of each root cause or contributing factor.

Figure E-2 contains the Event and Causal Factor Tree for the Genesis mishap, a visual representation of the causes that led to the mishap. The MIB used a fault tree(see Appendix C-2.A.) to identify the possible causes leading to the mishap and the Event and Causal Factor Tree was then used to further decompose those events by asking why each event occurred. The MIB continued this "why" process until they identified the root causes and causal factors.

E-1. Process-Level Errors: Timeline of Root Causes and Contributing Factors

The Discovery Program selected Genesis for implementation in early November 1997. It was selected as a PI-led Discovery Class mission under a cost cap, following the selections of Mars Pathfinder, NEAR, Lunar Prospector, and Stardust. To be competitive, a high heritage design was proposed, based upon the Stardust SRC and spacecraft bus subsystems. At the time of the proposal, the Project planned the Genesis SRC-AU to be a heritage implementation of the Stardust design.

The project-level Preliminary Design Review (PDR) was held July 20 and 21, 1998. The Project was confirmed on August 19, 1998 with tight schedule and fiscal margins (the Phase C/D schedule margin to launch was 4 months; the Phase C/D/E cost reserve was 11 percent).

Throughout the Project, **JPL Project Management and Systems Engineering had little involvement in LMSS activities.** JPL therefore had no effective insight into the lower-level activities or processes of the LMSS Flight Systems (spacecraft) Team, and no means of cross checking or detecting the LMSS process errors. This lack of involvement, consistent with NASA's FBC philosophy, and approved by the Discovery Program, did not cause the failure directly, but did contribute significantly to its occurrence. Also throughout the Project, the **inadequate Systems Engineering Staffing levels** at JPL and LMSS contributed to the mishap. Staffing was inadequate for the responsibilities that the Systems Engineering organization recognized and for those, such as complete verification roll-up, that it did not recognize as its responsibility.

The Genesis Project had a number of interrelated issues that led to the inversion of the G-switch sensors -- the proximate cause that resulted in the drogue parachute deployment mishap. After extensive review of the data and numerous interviews, the MIB determined that deficiencies in the following four pre-launch, top-level processes resulted in the incident, each involving multiple root causes and contributing factors:

1. the design process inverted the G-switch sensor design;
2. the design review process did not detect the design error;
3. the verification process did not detect the design error; and
4. the Red Team review process did not uncover the failure in the verification process.

Process-Level Error No. 1: Design Process Generated Design Error

Around the time of PDR and Confirmation Review, the Genesis project recognized that the SRC-AU required more functionality than was available from the heritage Stardust SRC-AU, upon which its proposed design had been based. Additional relays and a new motor control board were required to drive the collection arrays and contamination lid used for gathering and isolating samples. To accommodate these requirements, the SRC-AU design was upgraded to six cards, which was well beyond the volume of the original SRC-AU box. The six boards were installed on edge, an orientation 90° from that of the Stardust SRC-AU. To meet SRC center of gravity requirements, the SRC-AU was split into two redundant boxes of three cards each. The G-switch sensor was also moved from the timer card to the relay card, since it was mounted on shock isolators and would help avoid a "spoofing" issue (i.e., inadvertent triggering due to buffeting during the early entry or inadvertent shifting of the relay positions) with which the designers were concerned.

When heritage hardware is used in a new application, LMSS engineers typically conduct an inheritance review of the hardware. With these and other changes to filters and timers, Stardust heritage had been violated, and the project recognized this by not holding an inheritance review. However, many engineers believed that the pyro initiation aspects of the design maintained their Stardust heritage.

The requirement for the SRC-AU to deploy the drogue was flowed down to the SRC-AU Design Team, but the cryptic requirement levied by Systems Engineering on the SRC-AU may have led to confusion among the box-level designers. This requirement drove the deployment of the drogue chute on the "*X axis descending deceleration*," but contained no coordinate system or indication of the direction of the acceleration vector for the Electrical Engineers who were leading the redesign to reference. The requirement was taken from Stardust requirements wording, which also contained no coordinate system or indication of the direction of the acceleration vector. The inadequate requirements statement was a result of **inadequate requirements generation** and an assumption that the Stardust requirement would be understood based on its Stardust heritage **– inappropriate confidence in heritage design**.

The LMSS Flight Systems Product Development Organization (PDO) handled the SRC-AU changes. These changes laid out the relevant portions of the relay card printed circuit boards based on a Stardust heritage schematic that contained no indication of any sensitivity of the G-switch sensors to orientation. It also appears that the G-switch sensor part-level drawing was not understood by the layout engineer, since it contained a clear indication of the required direction of acceleration to close the switch. As a result, the relay card drawing was laid out with the G-switch sensor in an inverted orientation from that necessary for it to function during entry.

During this design process, and throughout the life of the project, there was a **lack of a Systems Engineer assigned end-to-end EDL responsibility**. There were Systems Engineers and others with responsibilities for most functions of the SRC; however, there was a gap in coverage that left the G-switch sensor function unaddressed by Systems Engineering. Had Systems Engineering assigned that responsibility, the MIB believes it is likely that the AU PIE and the relay card designer would have received guidance regarding the orientation of the G-switch sensor, a mechanical sensing device. The SRC-AU designers had insufficient mechanical systems or guidance, navigation, and control systems experience to recognize the orientation issue with their design.

The failure to assign a Systems Engineer end-to-end EDL responsibility may have been due, in part, to a decision by the Project **not to treat the SRC as a separate spacecraft.** Had it been treated as a separate spacecraft, the SRC would have received additional and more dedicated focus. Although this did not cause the failure, it may have been a contributing factor.

Concurrent with the changes already mentioned, the PIE for the SRC-AU left the Project and a new PIE was assigned. During the 1- to 2-week hand-off period, the new PIE faced several pressing issues:

- the SRC-AU motor drive electronics (MDE) card did not fit within its space allocation;
- the FPGA was 20-percent oversubscribed and it was unclear whether the relays could be laid out in the space available; and
- the EST board was also pressing against its layout/volume constraints.

The primary concern of the PIE at this time was the MDE board -- which placed science requirements for the Project in jeopardy – threatening the Project schedule, and therefore, the cost-cap established by the **FBC philosophy**.

Process-Level Error No. 2: Technical Reviews Failed to Identify Design Error

The SRC-AU PIE presented the new SRC-AU design at peer and drawing reviews, and it was subsequently presented at the SRC-AU Critical Design Review (CDR).

Based on MIB interviews, it appears that not all of the key individuals necessary for an adequate peer review were present. An attendance list for the peer review could not be located. Review of the drawing signatures also indicates that no one from Systems Engineering signed the drawings, signifying that the design would meet system-level requirements. This may have been the case because procedure at that time did not require **participation by key individuals at project technical and drawing reviews**. However, as previously noted, there was **no Systems Engineer assigned end-to-end EDL responsibility,** so even if attendance had been required at technical reviews or at drawing sign-offs, it is not clear that a person with the focus on EDL system requirements and performance would have been available.

During the SRC-AU CDR, the SRC-AU PIE presented a short, top-level design review package; however, that **CDR was too high level to adequately assess the design**. This Science Mission Directorate-wide systemic problem of weak technical reviews led to this failure as it did not allow for in-depth probing of the design.

At the SRC-AU CDR the CRD package stated that the SRC-AU would undergo a centrifuge test to verify the functionality of the SRC-AU. The MIB believes it is possible that attendees may have concluded that any error in the G-switch sensor orientation would be identified through testing, and as a result, less scrutiny of the design occurred. As will be discussed below the centrifuge test was deleted after the CDR, so reduced scrutiny could have resulted in failure to identify the design error.

Process-Level Error No. 3: Verification Process Failed to Detect Design Error

The centrifuge test was deleted for four reasons:

1. schedule pressure;
2. an erroneous belief by some in Project Management and Systems Engineering that a box-level continuity test had functionally replaced the centrifuge tests;
3. a possible belief by some in Project Management that verification by inspection of drawings was completed properly; and
4. the G-switch sensor was not identified as having a critical alignment in the Pointing and Alignment Document (i.e., a Phasing Plan).

The centrifuge test was deleted primarily because of schedule pressure. The **philosophy of the time, Faster, Better, Cheaper, created an ever-present threat of cancellation if overruns occurred** on **cost-capped missions.** Delivery of the SRC-AU to spacecraft ATLO slipped by 4 months, due to the design issues with the MDE; the number of changes required to the SRC-AU boards; and increasing scope of the centrifuge test, which threatened the overall project schedule. Project Management and the SRC-AU PIE believed continued slips during ATLO would have consumed the minimal cost reserves available, placing the Project in jeopardy of cancellation.

Two Systems Engineering process failures led to the increase in scope of the centrifuge test that caused the SRC-AU schedule to become untenable:

1. **Systems Engineering did not define the detailed verification requirements for the subsystems,** so the AU Subsystem Team did not have higher-level guidance as to what was necessary to verify, and
2. **no Systems Engineer was assigned end-to-end EDL responsibility**, which led to a lack of involvement by Systems Engineering during key testing discussions.

From the interviews, the MIB also noted that the technical team was very concerned about the possibility of spoofing. It appears that the focus on spoofing issues may have reduced the attention being paid to the G-switch sensor orientation.

Following the decision to delete the centrifuge test, the SRC-AU PIE decided a continuity test was needed for portions of the G-switch sensor circuit that had not yet been tested. The PIE and LMSS Mission Assurance developed a manual "quick-lift" test to verify that the G-switch sensors made contact and that all related circuit card and backplane signals were contiguous. This quick-lift test consisted of raising the box rapidly by hand and observing switch contact through a continuity check. This test was not meant by the PIE to serve as a phasing test (a test to verify orientation/alignment), and therefore it did not address switch orientation. Given the philosophy of pushing responsibility down to the subsystems, Systems Engineers did not participate in designing the test.

Project Management and Systems Engineering believed that the quick-lift test had functionally and adequately replaced the centrifuge test. Key to drawing this erroneous conclusion was a single cryptic bullet, *"SRC-AU 3-G test approach validated; moved to unit test; separate test not required,"* presented to JPL and LMSS Project Management and Systems Engineering. However, **Project Management and Systems Engineering did not question the meaning of the cryptic bullet regarding deletion of the centrifuge testing**. Had it been questioned, the MIB believes it is likely that the weakness of the approach would have been identified. **No documentation of the change in verification methods was generated** in the form of a Change Request or Technical Memorandum. Had this been done it would have resulted in a critical assessment of the change. It remains unclear if a Change Request was required by the Configuration Management process at that time, but a Technical Memorandum was clearly appropriate.

No one above the SRC-AU Team reviewed the test plan or results, which contributed to the belief that the quick-lift test had functionally replaced the centrifuge test (in addition to above-mentioned communications issues). This was because **Systems Engineering was not required to review subsystem test procedures or verification results.** As a result, Systems Engineering continued to believe that the quick lift test had functionally replaced the centrifuge test. It was not identified in the verification roll-up process that normally occurs on projects, but was effectively only a verification bookkeeping process on Genesis.

Because of the schedule pressure, it was decided to delete the centrifuge test in favor of verification by inspection against Stardust drawings. This approach could have been successful if it had been performed by an experienced Mechanical Engineer or guidance, navigation, and control; however, the drawing inspection was performed by the SRC-AU PIE, an Electrical Engineer who lacked the necessary mechanical experience, but apparently did not realize his limitation. While the PIE erroneously concluded that the orientation was correct, he perhaps should have realized that he needed assistance from Systems Engineering or the PDO. In addition, the error was also partially a Systems Engineering failure because the **Systems Engineering verification process did not require consideration of a verifier's qualifications nor incorporate multiple checkers** to verify a requirement**.** Had the background of the verifier been considered or multiple personnel been required to perform the inspection as a cross check, it is likely that the weakness of the inspection approach would have been detected.

The final issue leading to the deletion of the centrifuge test was that the **G-switch sensor was not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Test Plan)**. Had the G-switch sensor been identified as having a critical alignment in the Phasing Plan, it is likely that it would have received the level of scrutiny that other critical sensors typically receive, and the alignment error would have been discovered.

Inadequate execution of System-level verification of the drogue deployment requirement was the final reason for the verification process failure. The requirement for drogue deployment was poorly written and contained requirements for both drogue deployment and aerodynamic stabilizations; however it was interpreted to address only aerodynamic stability – a result of **inadequate Systems Engineering requirements generation**. A System-level verification analysis, the "Recovery Analysis," was performed, but failed to verify actual deployment. The verification failure also occurred because there was no **Systems Engineer assigned end-to-end EDL responsibility** to review the Recovery Analysis results and because Subsystem verification was not considered as part of the System-level roll-up. **Systems Engineering was not required to review subsystem test procedures or verification results,** and as a result the verification roll-up function was performed ineffectively.

Through this series of events, the SRC-AU was delivered for spacecraft assembly having never completed a phasing test and with incorrect, undocumented verification of G-switch sensor orientation.

Process-Level Error No. 4: Red Team Reviews Failed to Identify Verification Error

JPL's Systems Management Office (SMO), under direction from NASA and JPL Senior Management, established a Red Team to review the readiness of Genesis for launch in June 2000, after the second Mars failure. The Red Team chair developed a detailed plan and objectives that JPL Senior Management reviewed and approved. The Red Team chairman then formed 11 focus groups that spent 2 days reviewing material, 1 to 1 1/2 days with their JPL and LMSS counterparts on Genesis, and 1 day preparing a report. Inputs were then assimilated into one report that was briefed to the JPL and LMSS Genesis Project Management.

The Electrical Power Subsystem (EPS) Focus Group reviewed the SRC-AU in June 2000, since an EDL Focus Group had not been formed for the June 2000 review. The EPS Focus Group did not identify any issues regarding the inversion of the G-switch sensor. This oversight appears to have occurred for the following reasons.

- First, the EPS Focus Group was disciplined oriented, not cross-cutting, being interested primarily in power issues, which included power switching (G-switch sensor electrical contact function), but not all EDL functions (G-switch sensor orientation). This resulted from **inadequate top-level Red Team management of the focus groups.**

- Second, the **JPL SMO gave the Red Team too little time to perform an adequate assessment.** Although the EPS Focus Group approached its review conscientiously, it had little chance of performing an adequate review in the time available.
- Finally, given the limited time available and their focus on power issues, when the EPS Focus Group learned that the deployment circuitry was a heritage design, they became part of a longstanding Science Mission Directorate problem i.e., having **inappropriate confidence in heritage designs.**

In October 2000, the Red Team chairman formed an EDL Focus Group and assigned them responsibility for all EDL activities, including those that had been addressed by the EPS Focus Group. However, the EDL Focus Group concentrated on aerodynamic issues and provided no review of drogue or drogue deployment functions. As a result, no findings regarding the G-switch sensor were uncovered during the reviews. The EDL Focus Group took an action to coordinate with the Avionics Focus Group to review pyro initiation circuitry; however, the action was never closed. These failures by the EDL Focus Group were a result of **inadequate top-level Red Team management of the focus groups.**

Late in the Genesis schedule, the Project was responding to the Mars Failure Board recommendations, the Red Team findings that called for significant activities, and a slip in launch date caused by a launch scheduling and personnel resource conflict with the Mars Odyssey Project. As a result, Discovery Program gave the Genesis Project an additional $17M to respond to the Red Team findings and to pay for a 6-month slip caused by the Mars Odyssey conflict. The Project used this time to conduct additional System-level testing. However, since these additional tests used a bypass of the G-switch sensors and focused on higher-level verification and validation, these tests did not identify the G-switch sensor inversion.

E-2. Root Causes and Contributing Factors, Narrative Discussion

The following discussion provides the details associated with each root cause and contributing factor and is intended as a companion document to Section 5.2 of this report.

Root Cause Category No. 1:
Inadequate Project and Systems Engineering Management

Root Cause 1.1: Project Management and Systems Engineering did not question meaning of a cryptic bullet regarding deletion of centrifuge test.

There is some confusion regarding what Genesis Program Management and Systems Engineering knew about the deletion of the centrifuge test, due to the passage of time and a lack of documentation. The SRC-AU PIE's recollection was that he had been directed by LMSS Project Management to delete the centrifuge test; however, the only known documentation indicating that JPL and LMSS Project Management or Systems Engineering had been informed of a centrifuge test plan change was a single bullet presented at the 9/9/99 Bluebook Meeting (LMSS management review) and the 9/14/99 Monthly Management Review (briefing to JPL). That bullet read, *"SRC-AU 3-G test approach validated; moved to unit test; separate test not required."* The unit test that was referred to was a quick lift test that verified G-switch sensor continuity, not orientation.

Because there was no recollection of a conversation regarding the bullet statement mentioned above, the Board decided it was not possible to determine how the brief and cryptic mention of this change was interpreted, although no one recalled any discussion occurring regarding the statement. The Board believes it is reasonable to assume that had the meaning of the cryptic bullet been questioned by JPL or LMSS Project Management/ Systems Engineering then it is likely that the inadequacies of the approach would have been discovered.

Contributing Factor 1.1: Lack of JPL Project Management and Systems Engineering insight into LMSS activities.

The lack of adequate management and oversight by JPL contributed significantly to the Genesis mishap. Of particular importance was the lack of involvement by JPL Project Management and Systems Engineering in LMSS Flight System (spacecraft) activities – stove-piping of the two teams – leaving JPL with effectively no insight into the activities or process of the LMSS team, and therefore no means of detecting the LMSS process errors. The FBC culture of the time encouraged pushing responsibility to the lowest level and not interfering with the contractor's processes.

Although JPL held weekly Systems Engineering telecons with all Project participants, it is apparent to the Board from interviews and briefings that

JPL Project Management and Systems Engineering were assuming LMSS was performing all necessary spacecraft Systems Engineering functions and required no JPL support, involvement, or approval of its processes. JPL provided discipline support but predominantly in response to issues identified via "bubble-up" reporting from LMSS to JPL, not JPL searching for issues within the LMSS effort. Little or no regular discipline engineering interaction occurred between the JPL and LMSS teams. JPL did support SRC payload integration activities, but these focused on the science instrument not the spacecraft or SRC, and did not include the SRC-AU functions. This stove-piped Systems Engineering approach left little opportunity for cross-discipline verification and significantly reduced the safety net that a comprehensive systems engineering process provides. In addition, the JPL Systems Engineering lead was not experienced in this type of project. These shortfalls led to a weak spacecraft systems engineering implementation, which is discussed more thoroughly in the Systems Engineering discussion below.

Although the lack of involvement by JPL Project Management and Systems Engineering at the lower levels did not directly cause the failure, the lack of involvement in the spacecraft made it difficult or impossible for them to identify the process failures that led to it or to find the specific engineering error in question.

Appendix D-7 contains a report by the Test as You Fly Sub-team with observations that provide further indication of the nature and extent of the systems engineering issues within the project.

Contributing Factor 1.2: SRC was not treated as a separate spacecraft.

Although the SRC was managed as an integral part of the Genesis spacecraft, it was not treated as a separate spacecraft -- which it was during the key entry phase. This approach reduced costs by avoiding the overhead of the additional management structure. The approach taken by the Project was not unsound or uncommon, but it may have contributed the failure by producing less focus on the SRC than if it had been treated as a separate spacecraft.

Root Cause Category No. 2: Inadequate Systems Engineering Process

The following discussion identifies the Systems Engineering process root causes and contributing factors that led to the failure. These root causes and contributing factors fall into three major categories.

1. The Systems Engineering Team did not consider several typical and necessary Systems Engineering functions to be their responsibility, such as defining for the subsystems teams expectations for verification of their requirements nor for reviewing the results of verification testing.
2. Some Systems Engineering functions were performed incorrectly, such as requirements that were not clearly documented.
3. A lack of a Systems Engineering team member whose clearly delineated responsibilities included the G-switch sensor function.

The Board believes the JPL and LMSS Systems Engineering Teams were too small to address their defined responsibilities adequately, and those defined responsibilities did not represent the full extent of a comprehensive Systems Engineering process necessary for the Genesis Mission. This contributed to the failure, but did not directly cause it.

Root Cause 2.1: Inadequate requirements generation.

There was a single requirement at the SRC Avionics subsystem level that addressed the issue of G-switch sensor orientation and that may have caused the confusion that contributed to the inversion. The requirement from "SRC Avionics Subsystem Requirements Document GN-55200-200, Rev A" reads, "*3.2.1.4.2.2 Drogue Parachute Release Trigger - The SRC avionics event sequence timer shall initiate the parachute release trigger timer upon detection of a 3.0 g ± 10% descending X axial deceleration.*" Of particular importance are the words, "*descending X axial deceleration,*" which were taken verbatim from requirement 3.2.3.1 of "Stardust SRC AU Requirements Document, 905C5100016, Rev 0."

LMSS Systems Engineering believed that the wording of the requirement would be understood based upon experience from the Stardust Project, where the requirement was implemented properly and verified with a centrifuge test. However, the Stardust and Genesis requirements were difficult to understand since no figures were provided showing the direction of the X-axis or the direction of the 'deceleration' (acceleration) vector.

The SRC drogue deployment requirement was written in terms of a higher-level requirement (e.g., spacecraft-level instead of SRC-AU level), which may have caused confusion at the subsystem level. The Board determined that the inversion might not have occurred had the requirement included a description of the direction of the acceleration vector, or had a coordinate system figure been included with the acceleration vector noted.

Root Cause 2.2: Systems Engineering did not define detailed verification requirements for subsystems**.**

The Systems Engineering Team was performing the requirements flow-down function, but was not performing the entire verification roll-up function that led to the incorrect verification of the G-switch sensor function. Genesis Project Management and Systems Engineering delegated the component verification function to the PDO with limited oversight from the Genesis Project System Engineering in accordance with LMSS/Flight Systems and Systems Engineering practices at the time (Flight Systems Faster/Better/Cheaper (FBC) Program Plan, FS-98-0006, Rev E, Jan. 2000 and the Mission Integration and Test Plan Volume 1 – System Verification Plan, GN-57300-100, Oct. 1999). Systems Engineering assigned a type of verification (test, analysis, etc.) and a verification event (performance test, functional test, etc.) to each subsystem requirement, reviewed spacecraft-level verification results, and performed verification bookkeeping.

Genesis System Engineering responsibilities should have included establishing detailed expectations for the verification of requirements and reviewing the subsystem test plans and verification results, but did not. The G-switch sensor inversion might have been avoided had a detailed statement been provided regarding how the System or Subsystem requirements to deploy the drogue were to be verified. Such guidance to the SRC Avionics Subsystem engineers would have been helpful in establishing expectations for close-out of Subsystem verification requirements. The Board believes that would have led to adequate verification or a change request when another method was proposed.

Systems Engineering assumed that the Subsystem engineers knew what needed to be done to verify their requirements and that no guidance was necessary. This was consistent with the pervasive FBC philosophy within NASA at the time to push responsibility to the lowest level possible. Meant to reduce costs, this approach pushed the responsibility too low, particularly given that the function the SRC-AU performed crossed subsystem boundaries, and was therefore a System-level issue.

Root Cause 2.3: Lack of documentation of changes made to verification methods.

Root Cause 2.4: The Systems Engineering Verification Process did not require consideration of verifier's qualifications or incorporate multiple checks.

These two root causes are closely related and are presented together in the following discussion.

The method used to verify the G-switch sensor orientation was to inspect the Stardust SRC-AU G-switch sensor drawings for similarity to the Genesis drawings. As a result, verification of this one portion of the drogue deployment requirement was actually through inspection, not test, as specified by Systems Engineering for that requirement. The SRC-AU specification was under LMSS Level 3 Change Control; as a result, the PIE should have processed a Change Request for the change in verification methods, but he did not. A Technical Memo or Change Request would have resulted in a critical assessment of the inspection approach, namely that the PIE, an Electrical Engineer, was performing the verification without the necessary mechanical engineering background to review complex mechanical drawings. With a cross check of his work, the G-switch sensor inversion might have been identified.

Since the Stardust AU had undergone a successful centrifuge test to verify its G-switch sensor orientation, inspection of the Stardust drawings and comparison against the Genesis drawings would have revealed the inversion of the Genesis G-switch sensors, if the comparison had been performed correctly. While a direct test is preferable, an inspection of drawings can be an acceptable verification method. Ideally, multiple engineers with the proper experience and knowledge would have performed the inspection independently and compared their results. This was not done.

Root Cause 2.5: Systems Engineering was not required to review subsystem test procedures or verification results.

Systems Engineering did not assign itself responsibility for reviewing subsystem verification activities. As a result, Systems Engineering was not required to review test procedures or to review test/analysis results performed at the Subsystem-level.

The quick-lift test that Project Management and Systems Engineering thought had replaced the centrifuge test as a means of verifying G-switch sensor orientation was intended to test only the continuity of the circuit. Had Systems Engineering reviewed the test procedures or assessed the results of the tests, it is possible that the Systems Engineering staff would have recognized that not all drogue deployment functions were being verified.

Root Cause 2.6: Inadequate execution of System-level verification.

The Flight System Requirements Document (spacecraft-level requirements document) included a requirement that read *"3.2.1.2.8.3.2.2 Drogue Chute Deploy – The SRC shall deploy a drogue parachute capable of providing subsonic SRC stability at a velocity of 1.8 ± 0.2 Mach."* This requirement, from which the SRC-AU requirement was derived, was two requirements in one statement; the first was to deploy a drogue and the second to provide stability between Mach 1.6 to 2.0. The Board determined that the weakness of the process to verify the requirement led to the G-switch sensor inversion, not the weak requirement itself. Analysis was the verification method identified for the requirement, which is generally considered appropriate for stability verification, but not for deployment of a parachute, where test is appropriate.

The verification analysis, provided in Recovery Analysis Report – Document No. GN-000-A-88VR, was based on a top-level discussion of the intent of the design and mention of a stability analysis, without any technical content provided to indicate verification of the requirement. The following is an excerpt from the report.

- "3.2.1.2.8.3.2.2 Drogue Chute Deploy – The SRC shall deploy a drogue parachute capable of providing subsonic SRC stability at a velocity of 1.8 ± 0.2 Mach.
- DISCUSSION The SRC has been designed to deploy a drogue parachute capable of providing transonic SRC stability. The sequence of events is that the g switch reads 3 g's, after coming down from a peak of approximately 40 g's, a period of time elapses (5.6 sec) and the drogue mortar is pyrotechnically actuated. The drogue parachute enters the supersonic slipstream, inflates, and quickly slows the SRC to subsonic speeds. The commanding of the drogue mortar actuation

has been calculated to occur at a velocity of 1.8 Mach based on known atmospheric conditions tied to entry dynamics. Monte Carlo trajectory modeling performed by NASA Langley Research Center, which statistically varies trajectory and atmospheric parameters over 3000 test cases, verifies system performance falls within the required range, and maintains SRC stability as required.

- *This discussion verifies compliance with paragraph 3.2.1.2.8.3.2.2 of the Flight System Requirements Document, no further action is required."*

As a cross check, two engineers reviewed the recovery analysis; however, they did not recognize the lack of any verification in the verification discussion. Further, based on an MIB interview with the LMSS Chief Systems Engineer, the focus of the review was on the drogue stability issue alone, not the drogue deployment, although the title of the requirement was "Drogue Chute Deploy." Regardless of the wording, the analysis author and reviewers interpreted the requirement to address only stability, not deployment. As a result, no one noticed that there was no statement regarding how the deployment sequence had (or had not) been tested. If there had been a statement regarding the deployment sequence and the System-level verification been performed adequately, the Board believes it is likely the weakness of the actual drogue deployment verification approach would have been identified.

The Board realized during an interview with a JPL Systems Engineering team member that the above verification statement was inadequate. Although the interviewee did not recall the specific verification analyses, he did recall that some of the verification analyses reports were similarly inadequate, but he was not aware of any action taken by JPL Systems Engineering to correct the problem.

Contributing Factor 2.1: Lack of a Systems Engineer assigned to the end-to-end EDL function.

The PIE for the SRC-AU was responsible for his box and contributed to the failure, since the unit had functions that crossed subsystem boundaries. However, during the interviews it became clear to the MIB that no one on the Systems Engineering Team had been assigned individual Responsibility, Accountability, and Authority (RAA) for the entire EDL sequence and for oversight of the system design and operations plans to execute that phase.

The RAA function was crucial to achieve complete integration and oversight and to ensure that all SRC functions were properly implemented in design and verified. The Aerodynamics Lead identified the pyro timing requirements used in the AU, but was not responsible for the avionics or G-switch sensor that fired the pyro; the Recovery Lead was concerned with the parachute functions, but not the components in the AU that deployed them; and the Systems Engineering Lead responsible for Avionics considered himself responsible for the electrical function of the AU, but not the system-level function the G-switch sensors performed.

Further, each person thought that someone else had responsibility for the G-switch sensors. The LMSS Chief Systems Engineer, in his additional role as Chief Engineer, considered himself to be responsible for the G-switch sensors. However, this was not understood by the aforementioned engineers, and given that the Chief Engineer was responsible for the rest of the spacecraft and held multiple positions within the project, the Board does not believe it is reasonable to assume he could have maintained direct oversight of such a low-level circuit. In addition, based on MIB interviews, it was not clear to the Avionics PIE to whom he should turn for advice or interpretation of requirements, results, or changes in plan.

In the Systems Engineering organization, an RAA would be responsible for the full end-to-end EDL and thus the G-switch sensor function. Without an RAA, the lack of attention to the G-switch sensors by Systems Engineering manifested itself as a failure to detect the inversion of the G-switch sensor during the design, technical review, and verification processes. Although the SRC-AU PIE was also responsible for that function, had a Systems Engineer also been responsible for oversight of the all interfaces/functions associated with the unit, the Board believes it is likely that the design or verification errors would have been detected.

Contributing Factor 2.2: Inadequate Systems Engineering staffing level.

Based on MIB interviews, JPL and LMSS Project Management and Systems Engineering thought that the LMSS Systems Engineering team had an adequate staff. However, it appeared to the MIB that the staffing levels were not adequate; first, when considering the limited responsibilities that the System Engineering Team had been assigned and particularly if one considers the Systems Engineering responsibilities that were not performed, (e.g., detailed subsystem verification requirements not established, subsystem test procedures not reviewed, and subsystem verification results not reviewed).

The MIB drew its conclusion that the LMSS staff was inadequate by considering that the LMSS Chief Systems Engineer held three positions (Chief Systems Engineer, Systems Engineering Manager, and Contamination Engineer). It became clear from interviews that the Systems Engineering team was hard pressed to meet their stated (although incomplete) obligations, much less the additional obligations that should have been assigned.

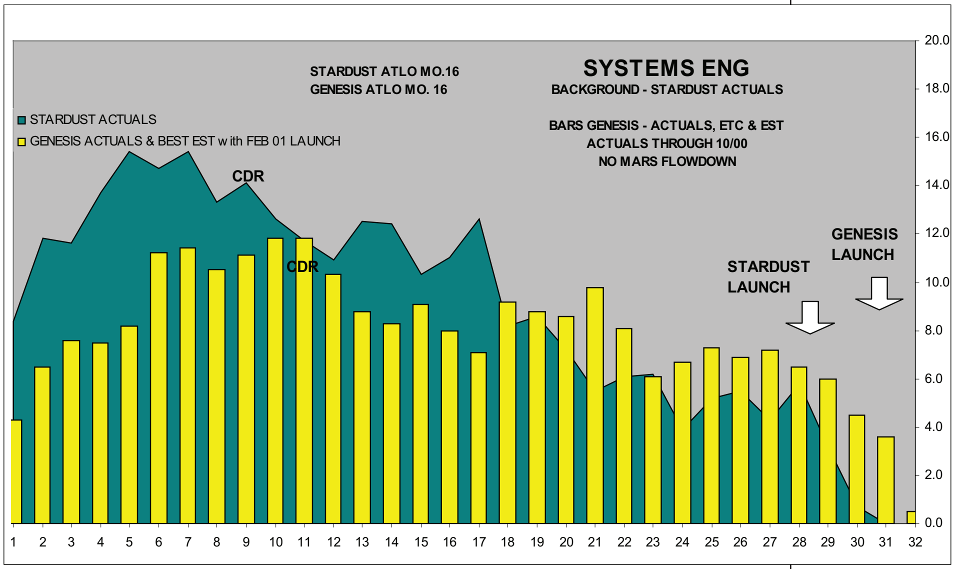

Figure E-1. Comparison of LM Stardust and Gen Systems Engineer staffing profiles ov project life. Genes launch indicates p launch; actual lau delayed late in life to accommodate M Odyssey needs.

Comparison of the LMSS Stardust and Genesis Systems Engineering Teams also indicates that the Genesis Team was too small. The small Genesis Systems Engineering staff was the result of a belief on the part of JPL and LMSS Project Management that leveraging off of Stardust heritage would allow for a smaller, less expensive team. The Board did not believe this to be a sound position, particularly given that heritage assumptions did not hold as the design matured and given that the Genesis SRC was more complex than the Stardust SRC. It was also not sound because the Systems Engineering requirements and verification processes needed to be executed with undiminished rigor.

By comparison, the Genesis actual labor charges show approximately a 26-percent reduction over Stardust levels from inception to the start of ATLO. These were the critical periods when mistakes were made that eventually led to the mishap. Figure E-1 shows this mismatch in staffing between the two projects.

As noted earlier, the JPL Systems Engineering involvement in the spacecraft was limited. Had they been more involved in LMSS activities, their staff of three Systems Engineers would not have been sufficient for the task.

An understaffed Systems Engineering team caused the JPL and LMSS Systems Engineers to devote less time to

- understanding or uncovering subsystem problems (sometimes called "unknown unknowns"),
- melding the spacecraft and mission systems (JPL and LMSS) teams, and
- ensuring a comprehensive verification and validation program was performed at all system levels.

The small staff did not directly cause the failure, but it did significantly contribute to its occurrence.

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Root Cause Category No. 3: Review Process Failure

The Review Process at every level of detail failed to identify the G-switch sensor inversion. The design reviews failed to identify the error in the design, due to a lack of detail in some reviews and a lack of participation in others.

Later Red Team reviews, assigned in the wake of the Mars mission failures, should have identified the deletion of the centrifuge test as an issue and the inadequate method used to verify G-switch sensor orientation (inspection of Stardust heritage drawings). However, the Red Team did not identify these, due in large part to inadequate time to review the project, errors by the focus teams assigned responsibility to review the SRC-AU functions, and inadequate management of the Red Team Focus Groups.

The issue of inappropriate faith in heritage designs by the Red Team is discussed later in this Heritage Section of this narrative.

1. Project Technical Reviews

Root Cause 3.1: Participation by key individuals not required at project technical and drawing reviews.

Based on MIB interviews, it appears that no one with a System-level perspective of the drogue chute deployment participated in the lower-level peer reviews of the SRC-AU. An attendees list could not be located. Additionally, no one from Systems Engineering participated or was required to participate in the drawing signoffs. The Board believes the G-switch sensor design inversion might have been identified had an engineer with a System-level perspective participated in these reviews.

Root Cause 3.2: Design Reviews were too high level to adequately assess the design.

An assessment of the CDR documentation for the AU indicates that it was held at too high a level to identify the G-switch sensor design error. The only references in the CDR presentation to the G-switch sensors were in a functional block diagram, timing description diagram, and a note that centrifuge testing was planned for the switch. The AU CDR, scheduled for only 4 hours, consisted of a 148-page chart package, which contained little technical content and was insufficient to support a box-level Critical Design Review. No action items regarding the G-switch sensors were taken.

Based on interviews, there were no noteworthy discussions of the G-switch sensor. A partial attendance list indicates that the JPL Systems Engineer participated along with other JPL Electrical Engineers and EaglePicher Inc. Battery Engineers. The LMSS attendance list could not be located. The LMSS Chief Systems Engineer chaired the review.

Had the design reviews been conducted in significantly more detail, it is likely the inversion would have been discovered (e.g., detailed walk-throughs of printed circuit board containing the G-switch sensor and discussion of its functions and how they had been or would be verified).

<u>Red Team Reviews</u>

Root Cause 3.3: JPL SMO gave the Red Team too little time to perform an adequate assessment.

A key failing of the Red Team review was that the JPL SMO allowed insufficient time to perform the review adequately. For the June 2000 Red Team review, the JPL SMO gave them only 3 days to review data products and meet with the project teams, which was done to avoid impacting the project's schedule. However, the review was of insufficient depth to meet its chartered goal, which was in part to evaluate the spacecraft and SRC design, implementation, and test. Had JPL SMO allocated adequate time to the Red Team for a thorough review, it is possible that the error, particularly the verification error, would have been discovered.

Root Cause 3.4: Inadequate Red Team management of focus groups.
The EPS Focus Group was a power-system-discipline-oriented team, not the 'cross cutting', multidiscipline-oriented team necessary to review the design adequately. This was not the fault of the EPS Focus Group, but rather the result of an error on the part of Red Team management to structure the teams with all of the necessary support.

For the October 2000 Red Team cycle, an EDL Focus Group was formed. This Group was to take responsibility in part for AU parachute deployment functions from the EPS Focus Group. However, the EDL Focus Group did not address the SRC-AU, except to recommend an action to coordinate with the Avionics Focus Group to review issues relative to the parachute deployment initiation system. The action was never completed because the Red Team system did not require actions to be closed. If the EDL Focus Group had pursued the EDL sequence completely, and not focused almost exclusively on entry aerodynamics, the Board believes it is likely they would have questioned the G-switch sensor implementation or verification. Further, had the EDL Focus Group followed up, or the Red Team action item process forced a follow up with the Avionics Focus Group, the errors might have been found. These EDL Focus Group failures were also ultimately failures to manage the Red Team properly.

Root Cause Category No. 4: Unfounded Confidence in Heritage Design

Root Cause 4.1: Inappropriate confidence in heritage designs.
The Genesis Project was based on an assumption of heavy reuse of heritage designs from the Stardust Project. The unfounded confidence in heritage hardware as being inherently more reliable than new designs helped lead to this mishap. The view that heritage hardware should be considered inherently more reliable than non-heritage hardware was not universally held by Genesis Team members, but was extensive and was voiced as late as the February 2004 Genesis System Recovery Design Review.

Although it was recognized that the final Genesis AU was not strictly a heritage design (since it was extensively modified from the Stardust design), many team members viewed it as maintaining much of its heritage and, hence, requiring less scrutiny in design and verification. An erroneous belief that the SRC-AU was a heritage, or partially a heritage design, and unfounded confidence in heritage designs in general led to five errors that contributed to the mishap.

1. The key drogue deployment requirement in the SRC-AU specification was recycled from Stardust without reconsideration;
2. Stardust schematics were used without reconsideration;
3. the design reviews focused less attention to the details of the design of the pyro firing circuitry, because greater confidence than was justified was placed in it due to its heritage;
4. verification of the G-switch sensor orientation by similarity to the Stardust heritage design was performed (and performed incorrectly); and
5. one of the Red Team Focus Groups that reviewed the SRC-AU did not review the design or the verification methodology, because they considered the likelihood of a design or verification issue with a heritage design to be unlikely.

The FBC philosophy was, in part, based on the assumption that the use of heritage hardware would reduce costs, schedule, and technical risks and reduce verification process requirements. The assumption that heritage hardware could reduce cost and schedule risks was perhaps well founded, but such an argument regarding technical risks could only be made after a thorough technical review of the design and its verification in the Genesis-specific application. In summary, there existed a major misconception within much of the JPL and LMSS leadership and within the Red Team that heritage hardware meant a lower standard of review and verification was acceptable. Had the same standards as those applied to new hardware been applied to the SRC-AU, it is likely that the design error would not have occurred or would have been discovered during verification.

Root Cause Category No. 5: Failure to "Test as You Fly"

The failure of Project Management and Systems Engineering to recognize the importance of the 'test as you fly' philosophy was evidenced by the deletion of the centrifuge test and the replacement of the test with the unsuccessful verification-by-drawing inspection. These issues have been previously presented; however, there was one additional error demonstrating a failure to recognize the importance of testing, which was that the G-switch sensor alignment was not identified as critical in the Pointing and Alignment Document.

Appendix D-7 contains a more complete discussion of the Genesis "test as you fly" issues in report entitled, 'Test as You Fly Observations.'

Root Cause 5.1: G-switch sensor not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Plan)**.**

In addition to deleting the test for schedule reasons, the Pointing Budget and Alignment Criteria Document (Phasing Test Plan) did not identify the G-switch sensor as having a critical alignment and, hence was not included in that plan. The purpose section of the document read in part "*The Genesis Pointing Budget and Alignment Criteria document establishes subsystem component and instrument control and knowledge alignment requirements.*" The document did not include the G-switch sensors as having a critical alignment, so no alignment test was formally planned as part of the document. The possible reason the G-switch sensors were not included in the plan was that such plans are typically produced by engineers concerned with hardware that has precise alignment requirements, such as star trackers or science instruments. Although members of the Systems Engineering Team approved the document, the previously noted issue of a lack of a Systems Engineer with end-to-end EDL responsibility, inclusive of the G-switch sensors, may have contributed to the omission.

Had the G-switch sensors been identified as alignment-critical and included in the Phasing Test Plan, the drogue deployment failure might have been avoided. Testing would have been required and additional attention would have been given to the G-switch sensor orientation.

Root Cause Category No. 6: Faster, Better, Cheaper Issues

Root Cause 6.1: Faster, Better, Cheaper Philosophy: cost-capped mission with threat of cancellation if overrun.

FBC was a concept, under an annual fixed budget, to increase the number of experimental missions from one 'big' billion dollar experiment to a series of smaller cost missions, e.g., ~$200-250M each, with each implemented via streamlined processes. Characteristics of missions selected under the FBC mantle were shortened schedules; lower overall budget, as well as budget reserves; maximum value on heritage systems; and implementation of government-industry partnering rather than the traditional government oversight process. NASA recognized that the risk to mission success would increase, but it was hoped that using the contractors' proven processes, hardware, and software would minimize the risks. Some NASA leaders believed that four out of five successes were better than one billion-dollar mission failure.

However, FBC missions became synonymous with fixed-price, cost-capped missions. Competitive pressures were intended and did maximize the ratio of science to total dollars expended. With science scope determined early in the project, and with fixed launch windows (fixed schedule) for most deep-space missions, risk was the only variable a project team had to trade to maintain fixed cost and schedule.

As proposed, selected, and confirmed on Genesis, the FBC mantra had the following effects.

- Maximum science scope and focus on payload issues at the expense of the spacecraft, SRC, and ground systems.
- Low schedule and dollar reserves leading to significant adverse pressure on decision making.
- Focus on a low-risk implementation led to a reliance on heritage hardware which gave a false sense that mission risk was controlled and allowed the risks associated with the lower standards for heritage to go unrecognized.
- A very lean Systems Engineering Team with heavy un-checked reliance on the subsystems teams for requirements and verification functions.
- Near total reliance by JPL Project Management and Systems Engineering on the LMSS Team and processes with little cross checking outside of payload and payload interface activities.

NASA was also at fault for encouraging and accepting this concept. They selected this mission with only 11-percent budget reserve at confirmation and had only 7.2 percent at CDR. All involved (NASA, JPL, and LMSS) were convinced that because of the assumed heritage design, this was an acceptable position. However, once heritage was broken and design issues arose, and the limited reserves expended, there was only one place for funds to be found -- the contractor's profits. Eventually, JPL Project Management asked LMSS to give up fee to cover other non-LMSS risk issues and avoid a project overrun of the cost cap. Later, due to a launch slip and NASA-mandated changes the project obtained more money for the JPL Project Team; and was able to re-establish fee for LMSS through incentives to be efficient during flight operations.

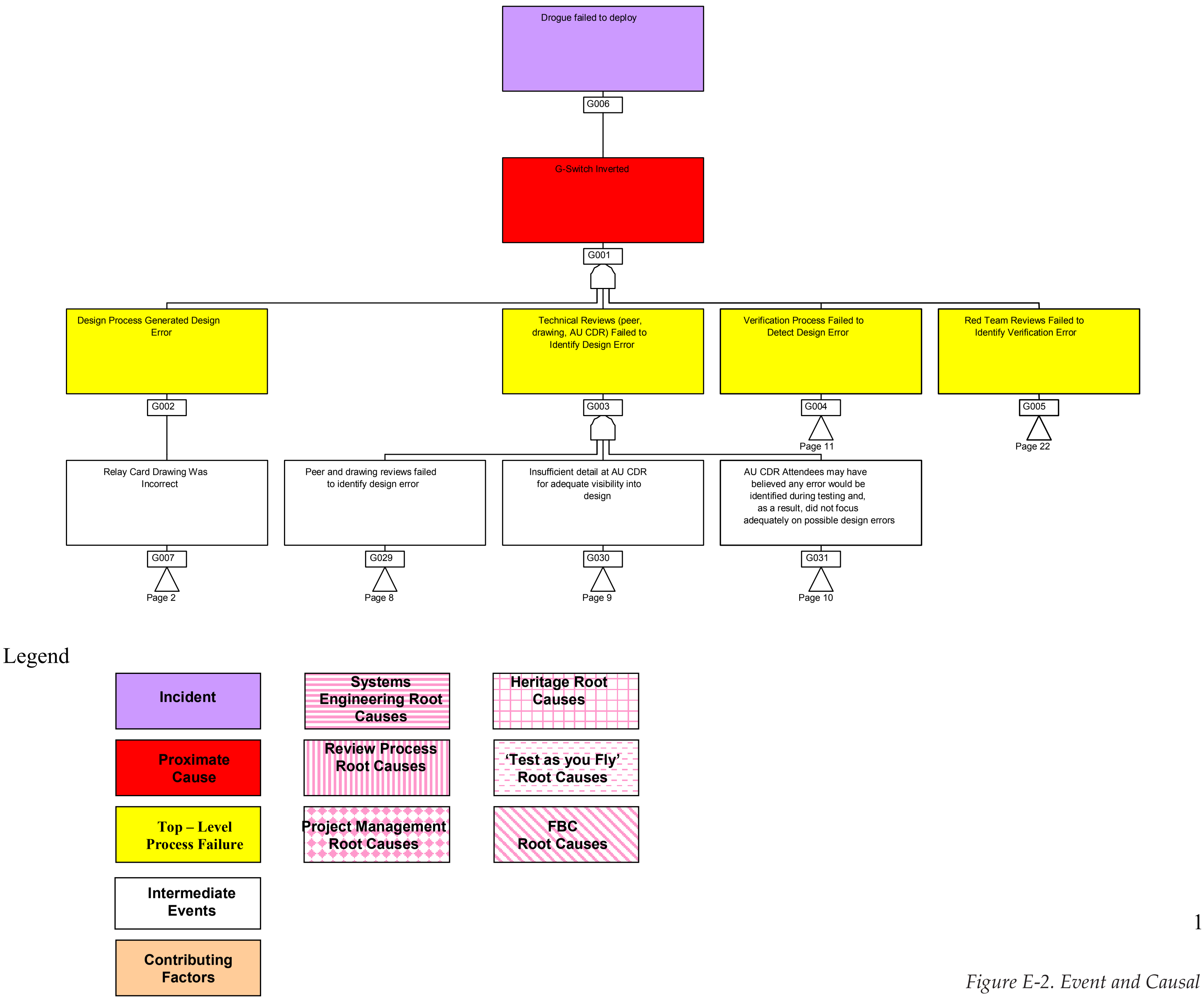
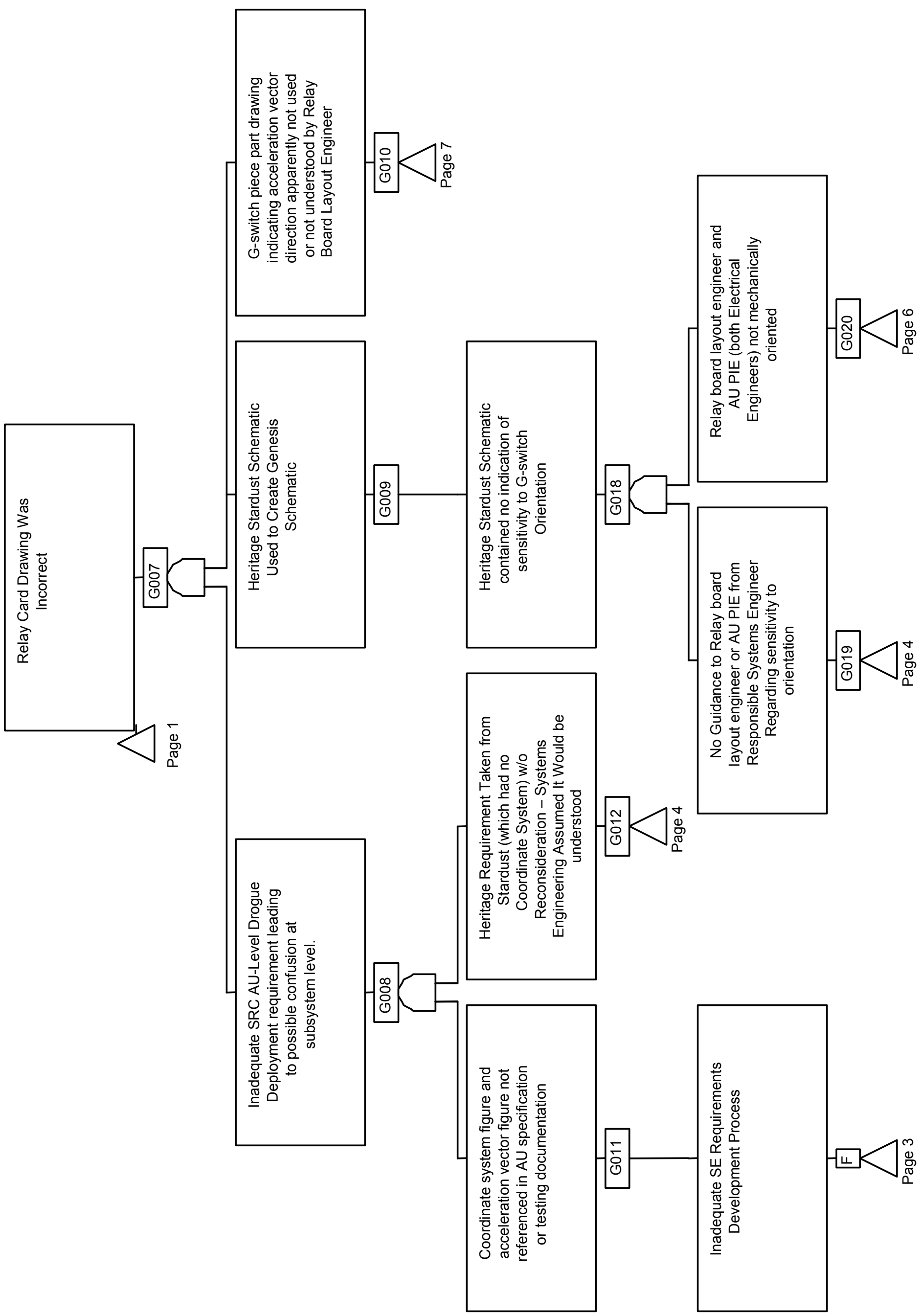
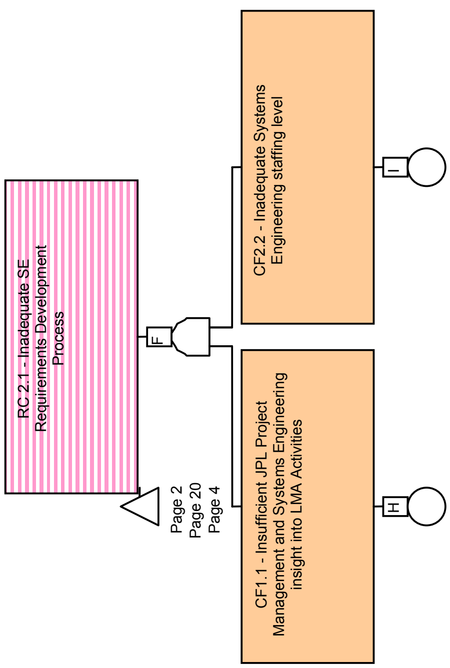


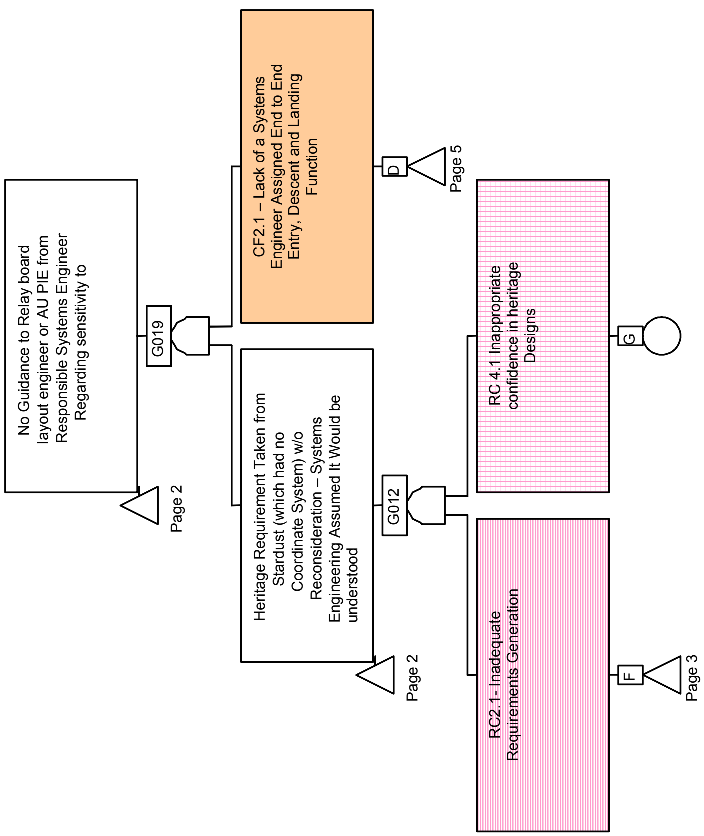
Figure E-2. Event and Causal Factor Tree.

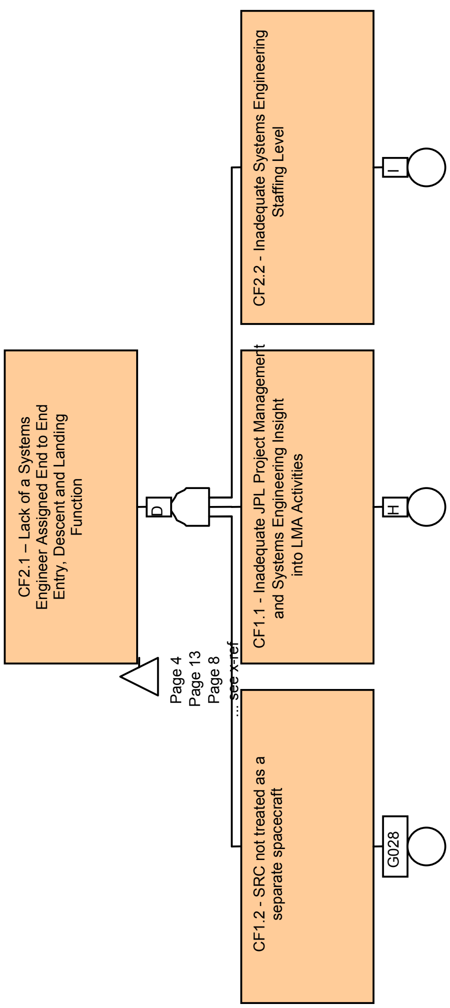
2


Relay Card Drawing Was Incorrect
Page 1
G007
G-switch piece part drawing indicating acceleration vector direction apparently not used or not understood by Relay Board Layout Engineer
G010
Page 7
Heritage Stardust Schematic Used to Create Genesis Schematic
G009
Heritage Stardust Schematic contained no indication of sensitivity to G-switch Orientation
G018
Relay board layout engineer and AU PIE (both Electrical Engineers) not mechanically oriented
G020
Page 6
No Guidance to Relay board layout engineer or AU PIE from Responsible Systems Engineer Regarding sensitivity to orientation
G019
Page 4
Inadequate SRC AU-Level Drogue Deployment requirement leading to possible confusion at subsystem level.
G008
Heritage Requirement Taken from Stardust (which had no Coordinate System) w/o Reconsideration – Systems Engineering Assumed It Would be understood
G012
Page 4
Coordinate system figure and acceleration vector figure not referenced in AU specification or testing documentation
G011
Inadequate SE Requirements Development Process
F
Page 3

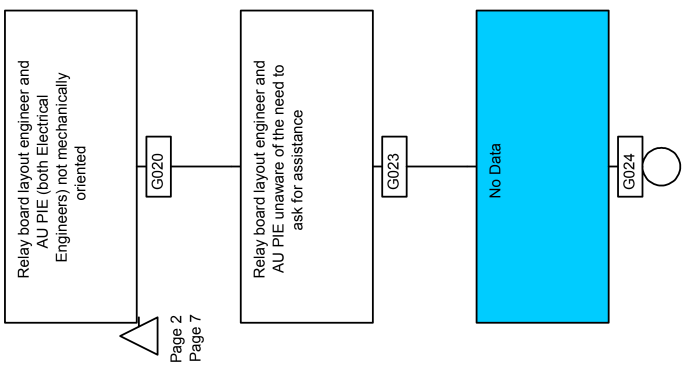
3

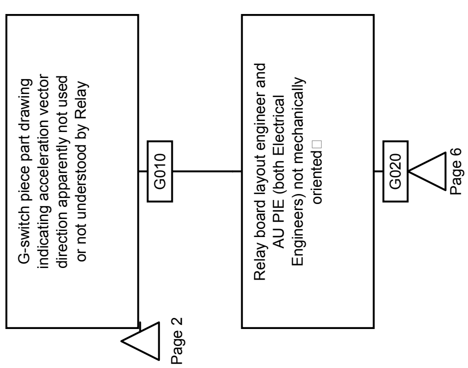

RC 2.1 - Inadequate SE Requirements Development Process
Page 2
Page 20
Page 4
F
CF1.1 - Insufficient JPL Project Management and Systems Engineering insight into LMA Activities
H
CF2.2 - Inadequate Systems Engineering staffing level
I


No Guidance to Relay board layout engineer or AU PIE from Responsible Systems Engineer Regarding sensitivity to
Page 2
G019
CF2.1 – Lack of a Systems Engineer Assigned End to End Entry, Descent and Landing Function
D
Page 5
Heritage Requirement Taken from Stardust (which had no Coordinate System) w/o Reconsideration – Systems Engineering Assumed It Would be understood
Page 2
G012
RC 4.1 Inappropriate confidence in heritage Designs
G
RC2.1- Inadequate Requirements Generation
F
Page 3

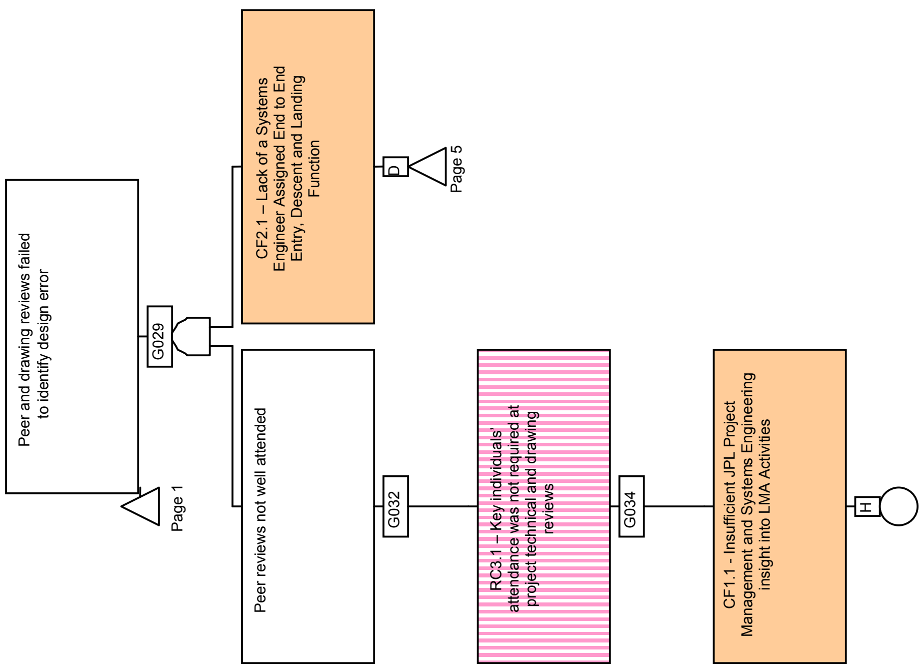

CF2.1 – Lack of a Systems Engineer Assigned End to End Entry, Descent and Landing Function
D
Page 4
Page 13
Page 8
... see x-ref
CF1.2 - SRC not treated as a separate spacecraft
G028
CF1.1 - Inadequate JPL Project Management and Systems Engineering Insight into LMA Activities
H
CF2.2 - Inadequate Systems Engineering Staffing Level
I

6


Relay board layout engineer and AU PIE (both Electrical Engineers) not mechanically oriented
G020
Page 2
Page 7
Relay board layout engineer and AU PIE unaware of the need to ask for assistance
G023
No Data
G024

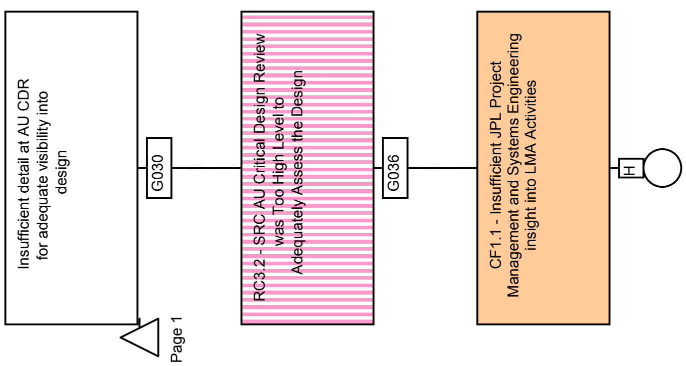

G-switch piece part drawing indicating acceleration vector direction apparently not used or not understood by Relay
G010
Page 2
Relay board layout engineer and AU PIE (both Electrical Engineers) not mechanically oriented
G020
Page 6

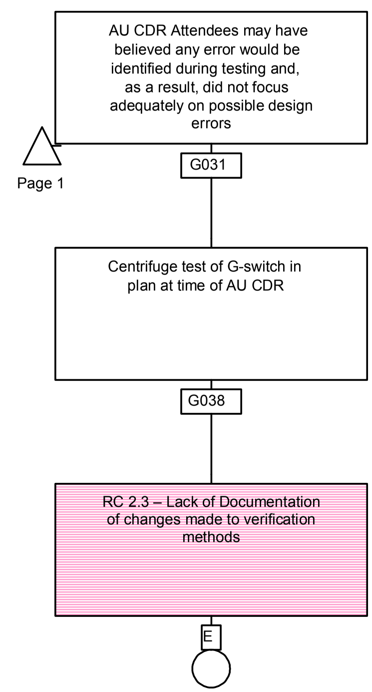
8

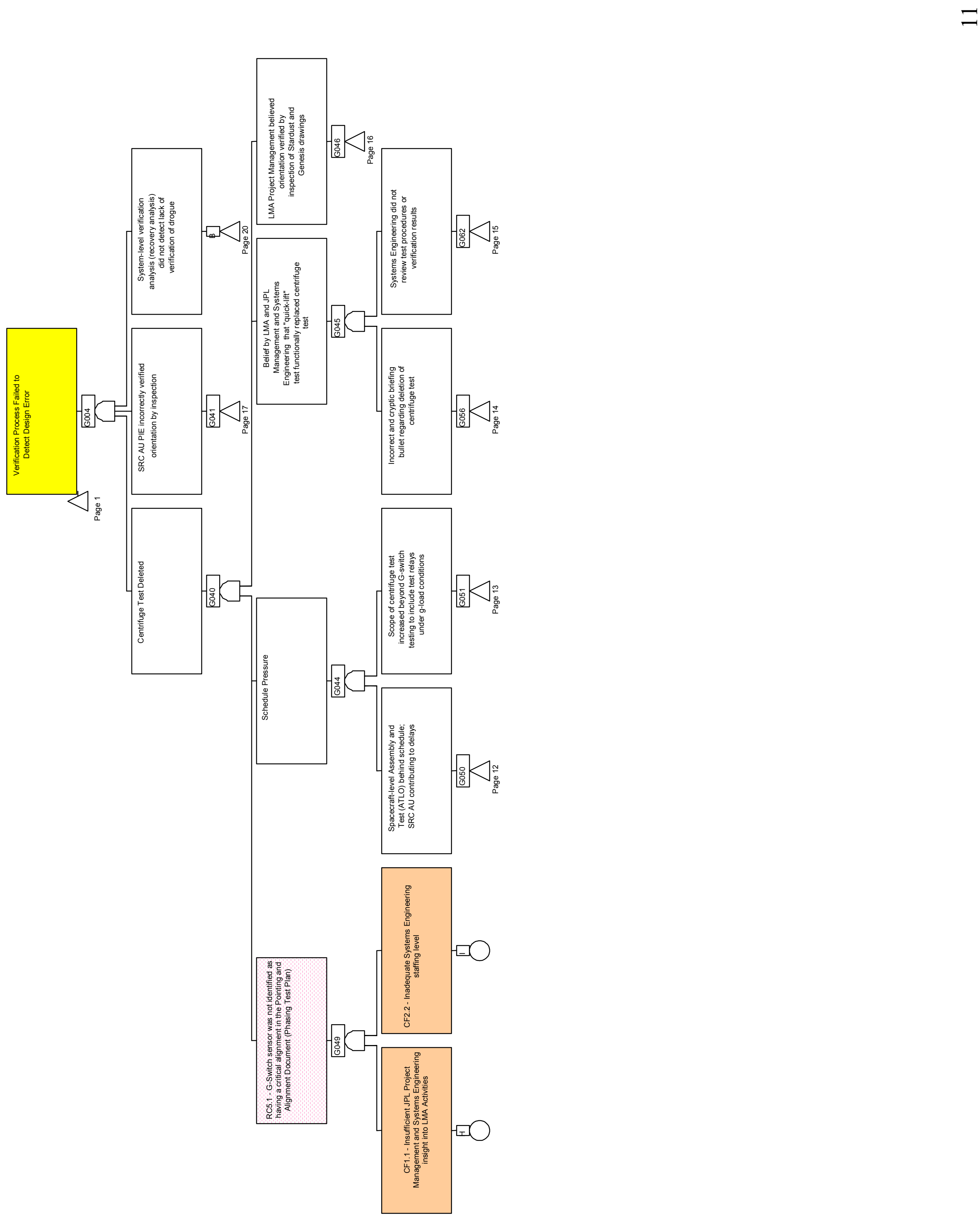


Peer and drawing reviews failed to identify design error
G029
Page 1
CF2.1 – Lack of a Systems Engineer Assigned End to End Entry, Descent and Landing Function
D
Page 5
Peer reviews not well attended
G032
RC3.1 – Key individuals' attendance was not required at project technical and drawing reviews
G034
CF1.1 - Insufficient JPL Project Management and Systems Engineering insight into LMA Activities
H

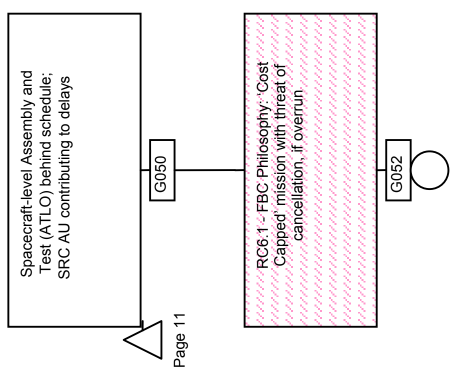
6


Insufficient detail at AU CDR for adequate visibility into design
G030
Page 1
RC3.2 - SRC AU Critical Design Review was Too High Level to Adequately Assess the Design
G036
CF1.1 - Insufficient JPL Project Management and Systems Engineering insight into LMA Activities
H


AU CDR Attendees may have believed any error would be identified during testing and, as a result, did not focus adequately on possible design errors
Page 1
G031
Centrifuge test of G-switch in plan at time of AU CDR
G038
RC 2.3 – Lack of Documentation of changes made to verification methods
E


11
Verification Process Failed to Detect Design Error
Page 1
G004
SRC AU PIE incorrectly verified orientation by inspection
G041
Page 17
System-level verification analysis (recovery analysis) did not detect lack of verification of drogue
B
Page 20
Centrifuge Test Deleted
G040
LMA Project Management believed orientation verified by inspection of Stardust and Genesis drawings
G046
Page 16
Belief by LMA and JPL Management and Systems Engineering that "quick-lift" test functionally replaced centrifuge test
G045
Systems Engineering did not review test procedures or verification results
G062
Page 15
Incorrect and cryptic briefing bullet regarding deletion of centrifuge test
G056
Page 14
Schedule Pressure
G044
Scope of centrifuge test increased beyond G-switch testing to include test relays under g-load conditions
G051
Page 13
Spacecraft-level Assembly and Test (ATLO) behind schedule; SRC AU contributing to delays
G050
Page 12
RC5.1 - G-Switch sensor was not identified as having a critical alignment in the Pointing and Alignment Document (Phasing Test Plan)
G049
CF2.2 - Inadequate Systems Engineering staffing level
I
CF1.1 - Insufficient JPL Project Management and Systems Engineering insight into LMA Activities
H

12



Spacecraft-level Assembly and Test (ATLO) behind schedule; SRC AU contributing to delays
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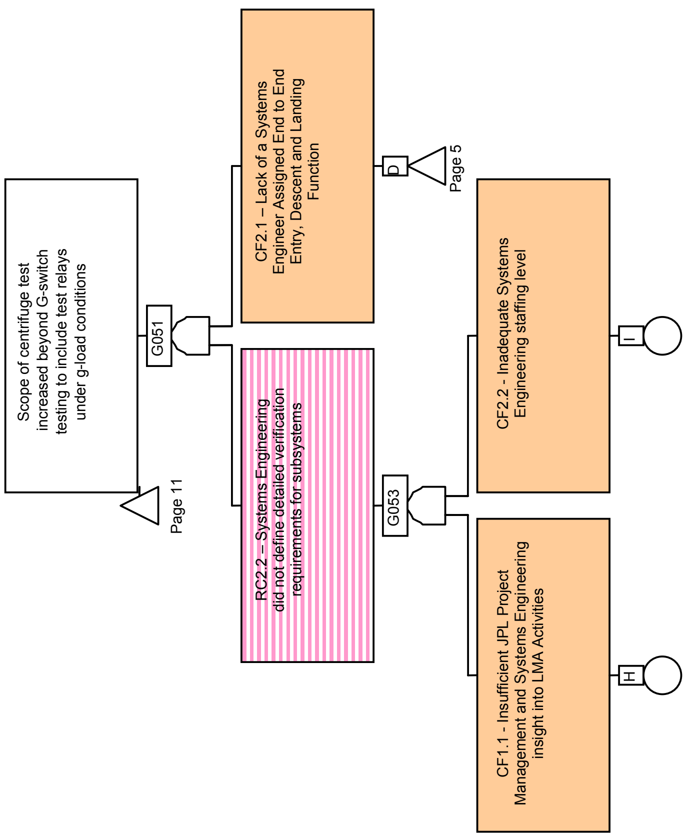
Scope of centrifuge test increased beyond G-switch testing to include test relays under g-load conditions
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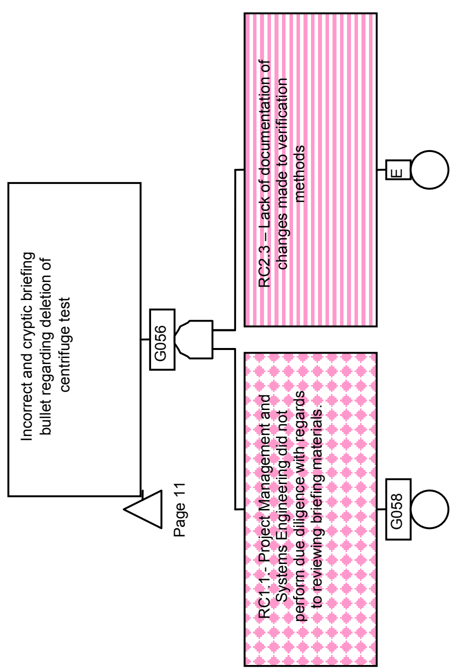
Incorrect and cryptic briefing bullet regarding deletion of centrifuge test
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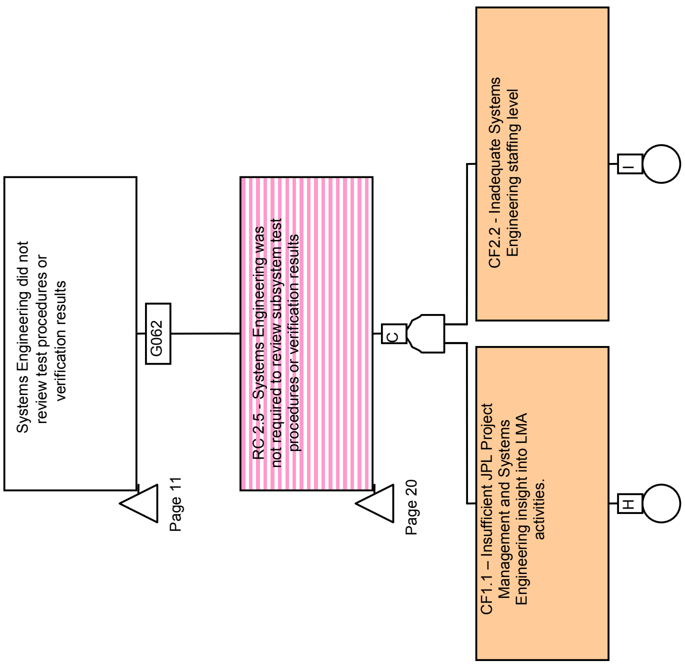
G056
RC1.1- Project Management and Systems Engineering did not perform due diligence with regards to reviewing briefing materials.
G058
RC2.3 – Lack of documentation of changes made to verification methods
E



Systems Engineering did not review test procedures or verification results
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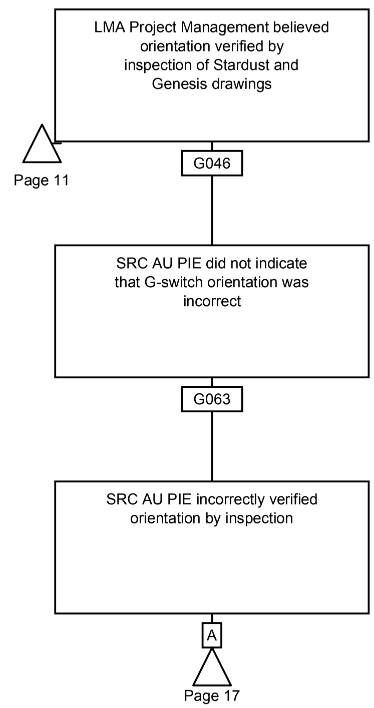
RC 2.5 - Systems Engineering was not required to review subsystem test procedures or verification results
Page 20
C
CF1.1 – Insufficient JPL Project Management and Systems Engineering insight into LMA activities.
H
CF2.2 - Inadequate Systems Engineering staffing level
I


LMA Project Management believed orientation verified by inspection of Stardust and Genesis drawings
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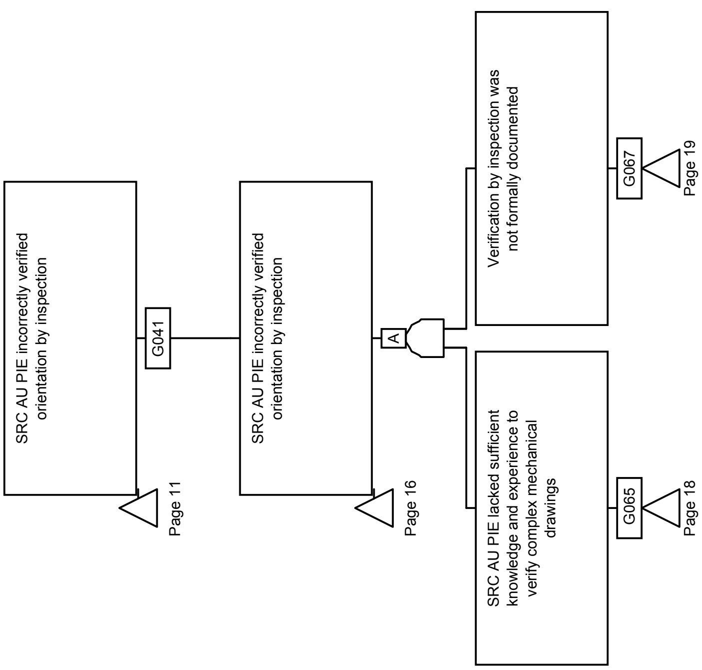
G046
SRC AU PIE did not indicate that G-switch orientation was incorrect
G063
SRC AU PIE incorrectly verified orientation by inspection
A
Page 17


SRC AU PIE incorrectly verified orientation by inspection
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SRC AU PIE incorrectly verified orientation by inspection
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A
SRC AU PIE lacked sufficient knowledge and experience to verify complex mechanical drawings
G065
Page 18
Verification by inspection was not formally documented
G067
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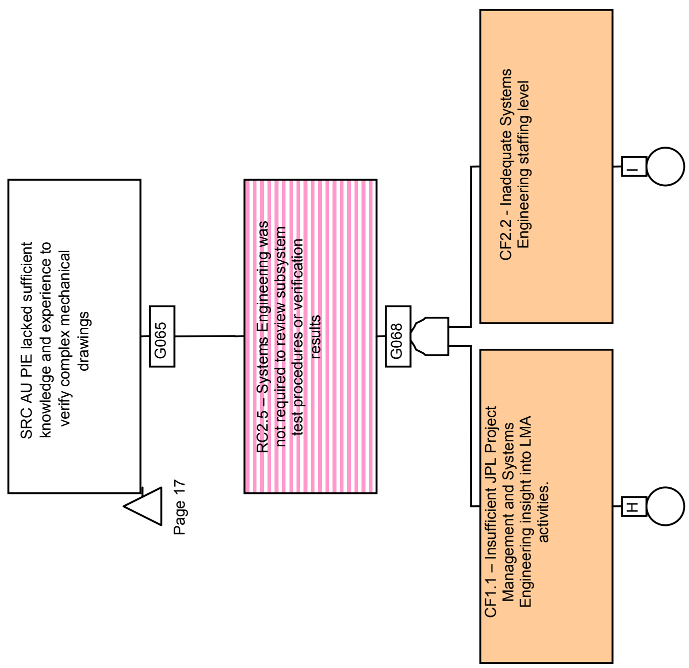
SRC AU PIE lacked sufficient knowledge and experience to verify complex mechanical drawings
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G065
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G068
CF1.1 – Insufficient JPL Project Management and Systems Engineering insight into LMA activities.
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CF2.2 - Inadequate Systems Engineering staffing level
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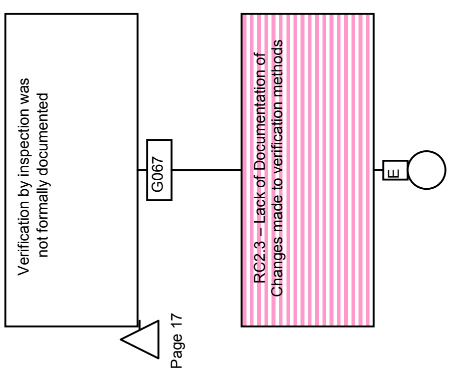

Verification by inspection was not formally documented
G067
RC2.3 – Lack of Documentation of Changes made to verification methods
E
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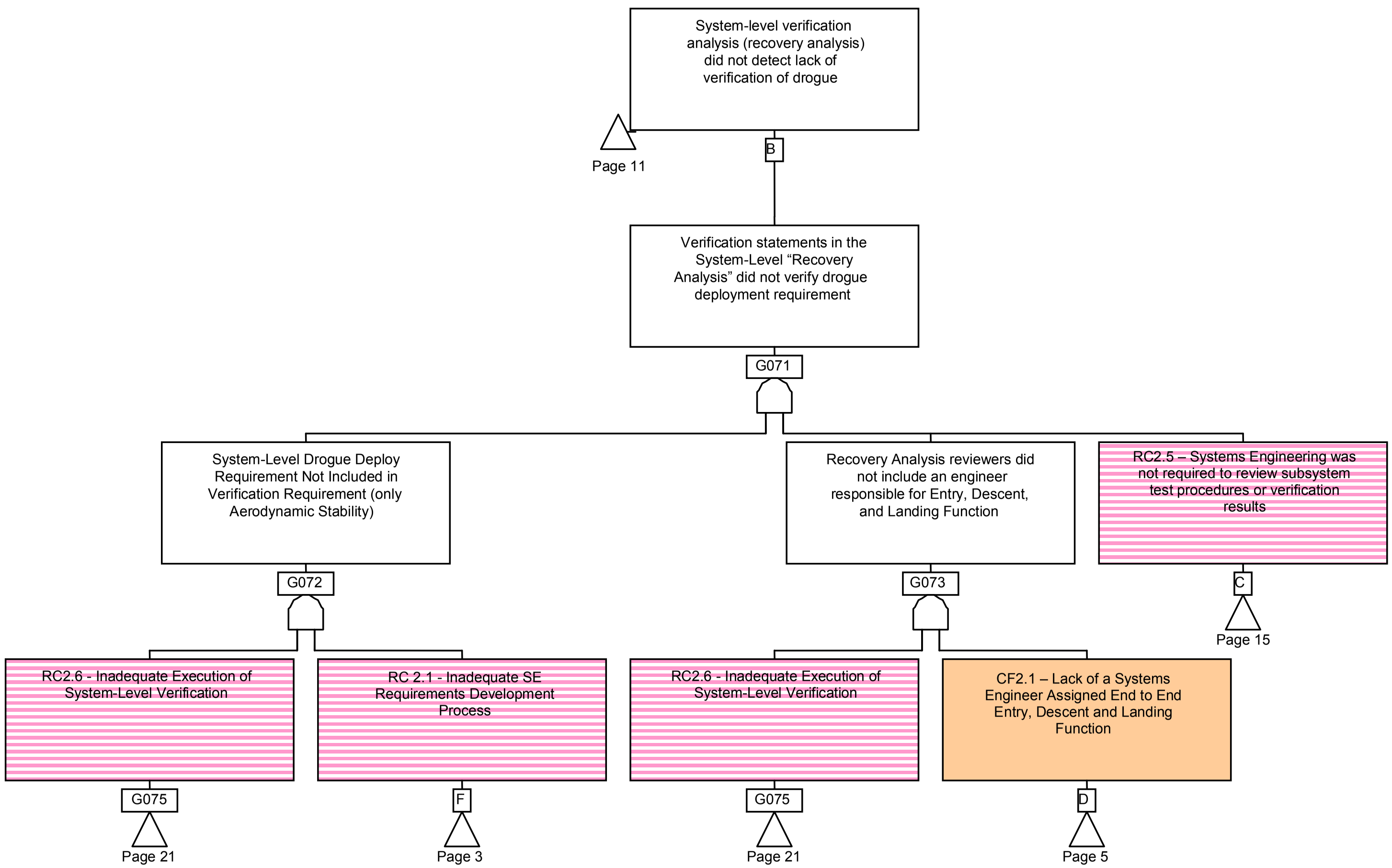
System-level verification analysis (recovery analysis) did not detect lack of verification of drogue
Page 11
B
Verification statements in the System-Level “Recovery Analysis” did not verify drogue deployment requirement
G071
System-Level Drogue Deploy Requirement Not Included in Verification Requirement (only Aerodynamic Stability)
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Page 3
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CF2.1 – Lack of a Systems Engineer Assigned End to End Entry, Descent and Landing Function
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Page 5
RC2.5 – Systems Engineering was not required to review subsystem test procedures or verification results
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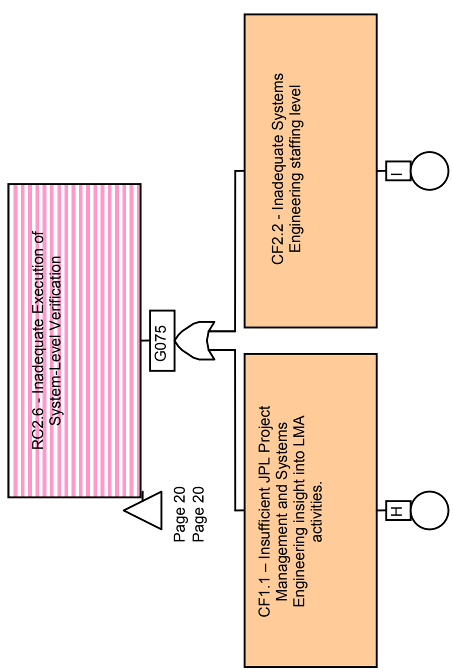
RC2.6 - Inadequate Execution of System-Level Verification
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Page 20
G075
CF1.1 – Insufficient JPL Project Management and Systems Engineering insight into LMA activities.
CF2.2 - Inadequate Systems Engineering staffing level
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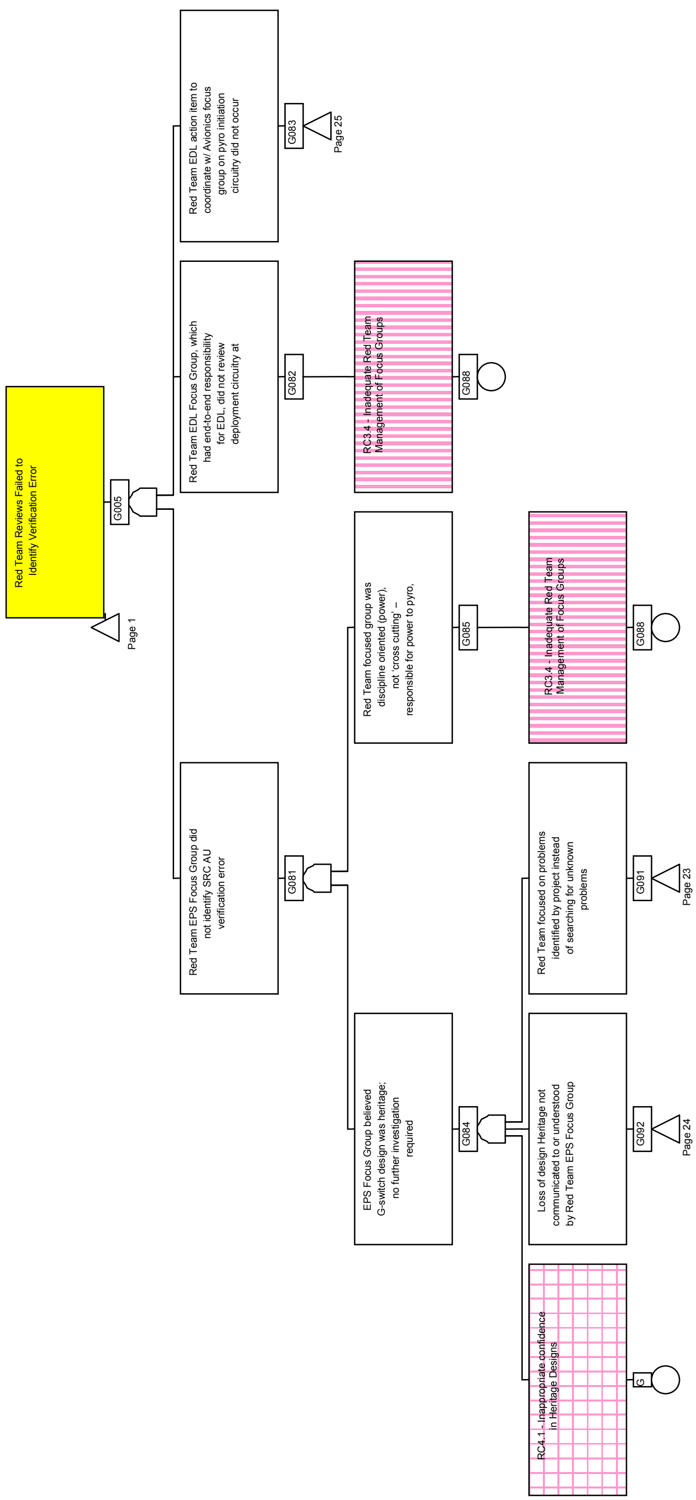
I


Red Team Reviews Failed to Identify Verification Error
Page 1
G005
Red Team EPS Focus Group did not identify SRC AU verification error
G081
Red Team EDL Focus Group, which had end-to-end responsibility for EDL, did not review deployment circuitry at
G082
Red Team EDL action item to coordinate w/ Avionics focus group on pyro initiation circuitry did not occur
G083
Page 25
RC3.4 - Inadequate Red Team Management of Focus Groups
G088
Red Team focused group was discipline oriented (power), not 'cross cutting' – responsible for power to pyro,
G085
RC3.4 - Inadequate Red Team Management of Focus Groups
G088
EPS Focus Group believed G-switch design was heritage; no further investigation required
G084
Red Team focused on problems identified by project instead of searching for unknown problems
G091
Page 23
Loss of design Heritage not communicated to or understood by Red Team EPS Focus Group
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RC4.1 - Inappropriate confidence in Heritage Designs
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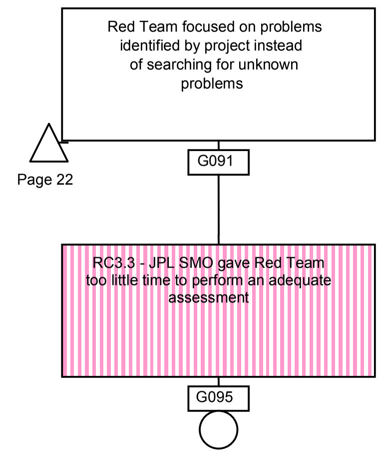
Red Team focused on problems identified by project instead of searching for unknown problems
G091
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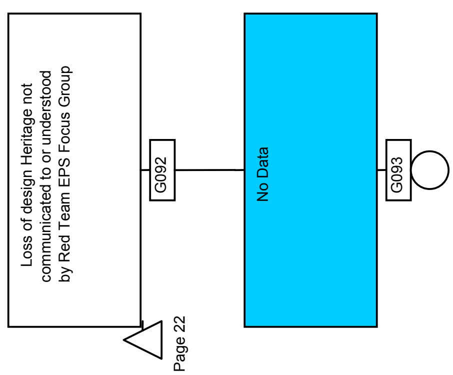
RC3.3 - JPL SMO gave Red Team too little time to perform an adequate assessment
G095


Loss of design Heritage not communicated to or understood by Red Team EPS Focus Group
G092
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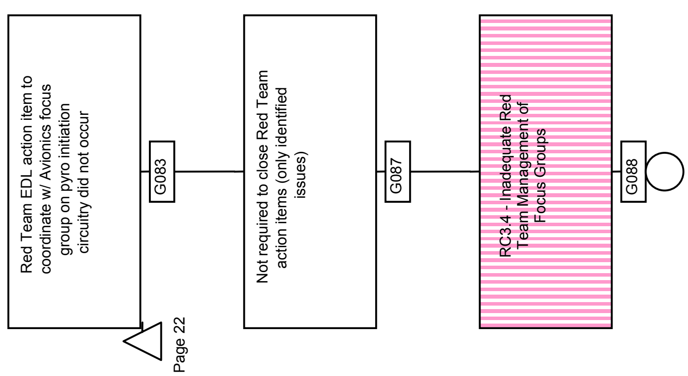
No Data
G093


Red Team EDL action item to coordinate w/ Avionics focus group on pyro initiation circuitry did not occur
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Not required to close Red Team action items (only identified issues)
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RC3.4 - Inadequate Red Team Management of Focus Groups
G088

Appendix F Contents

F-1 Genesis Project Environment

The JPL Failure Review Board report was not complete at the time of publication. Please request this information from Dr. John Klein at: John.W.Klein@jpl.nasa.gov

Appendix G

Contractors Supporting the Genesis MIB

Lockheed Martin Personnel who provided significant support to the MIB:

Douglas W. Banning
Richard P. Bland
Gerald W. Byers
Edward K. Clint
Robert A. Corwin
Calvin L. Craig, Jr
Jack A. Dekker
Robin D. Diloreti
Randy R. Doggett
Peter G. Doukas
C. Thomas Edquist
Rick A. Emerie
Steven J. Glenn
Jeffery J. Greteman
Richard A. Kriegbaum
Kelli L. Kubala
Donald C. Larson
Shelby L. Logan
Charles R. Love
Gary D. Mahonchak
Alfred D. McKinney
Lloyd P. Oldham
Brian W. Overman
David E. Perkins
Charles E. Rasbach
Owen G. Short
Nicholas G. Smith
Jarvis T. Songer
Kenny R. Starnes
Patricia A. Stroh
Joseph M. Vellinga
William H. Willcockson
Randall S. Wilson
Alison E. Zehnle

Appendix H

Meeting Minutes

Proprietary and/or Export Control Sensitive text removed.

Appendix I

Press Releases

Contents

Donald Savage
Headquarters, Washington
(Phone: 202/358-1727)

Sept. 10, 2004

RELEASE : 04-295

NASA Appoints Genesis Mishap Investigation Board Leader

NASA's Associate Administrator for Science Al Diaz announced today, Dr. Michael Ryschkewitsch, Director of the Applied Engineering and Technology Directorate at NASA's Goddard Space Flight Center (GSFC), Greenbelt, Md., would lead the Genesis Mishap Investigation Board (MIB).

The MIB will gather information; analyze the facts; identify the proximate cause(s), root cause(s) and contributing factors relating to the Genesis mission; and recommend appropriate actions to prevent a future similar mishap. The Genesis sample return capsule failed to deploy its parachutes, as it descended through Earth's atmosphere September 8.

The MIB will include experts from NASA, other government agencies and external consultants. The Board's investigation report is due to NASA Headquarters in mid-November. NASA will release the names of additional MIB members as soon as available. The Board's initial meeting is next week.

Prior to his current assignment, Ryschkewitsch was Deputy Director of the GSFC Applied Engineering and Technology Directorate. He also served as the center's Deputy Director of the Systems, Technology and Advanced Concepts Directorate.

He has a bachelor's degree and Ph.D. in physics from Duke University, Durham, N.C. Prior to joining NASA, he served as a postdoctoral fellow and Visiting Assistant Professor of Physics at the University of Delaware. He joined GSFC in 1982 as a cryogenics engineer. He served as Head of the Cryogenic Systems Development Section and Assistant Branch Head for the Electromechanical Systems Branch. He was selected as Associate Chief of the Space Technology Division in 1990.

He led the GSFC team that worked with Ball Aerospace to develop the concept for the Corrective Optics Space Telescope Axial Replacement (COSTAR), used in the repair of the Hubble Space Telescope. In 1992, he was selected to form, then became Chief, of the Engineering Directorate Systems Engineering Office.

He is a past recipient of the Robert Baumann Award for Mission Success. In 2004 he received the NASA Engineering and Safety Center Leadership Award.

NASA's Jet Propulsion Laboratory (JPL) in Pasadena, Calif., manages the Genesis mission for NASA's Science Mission Directorate, Washington. Lockheed Martin Space Systems, Denver, developed and operated the spacecraft. JPL is a division of the California Institute of Technology, Pasadena. News and information about Genesis is available on the Internet at:

http://www.nasa.gov/genesis

For background information about Genesis, visit:

http://genesismission.jpl.nasa.gov

For information about NASA on the Internet, visit:

http://www.nasa.gov

- end

Donald Savage
Headquarters, Washington
(Phone: 202/358-1727)

Sept. 20, 2004

RELEASE : 04-306

Genesis Mishap Investigation Board Status Report #1

The NASA Genesis Mishap Investigation Board (MIB) arrived at Dugway Proving Ground (DPG), Utah, September 10, to take charge of the investigation. The Genesis Sample Return Capsule (SRC) impacted the ground after its drogue and parafoil systems failed to deploy during re-entry September 8. Dr. Michael Ryschkewitsch is the leader of the MIB.

Thanks to excellent work by the Genesis Project Team, functioning as an initial response team, the wreckage of the SRC and its contents of scientific samples were recovered from the dry lakebed. The science team continues work securing and curating the recovered sample materials, working independently from the activities of the MIB.

Since the initial recovery of the hardware, an inventory was made of the impact crater, both by visual examination and metal detector, to ensure no significant wreckage remains. The recovery team finished its work and turned the impact crater site back over to DPG.

The team finalized plans for preparing and transporting the SRC wreckage to Lockheed Martin Space Systems' facilities in Denver, where the spacecraft was built and tested.

The MIB determined all the science-specific hardware is not relevant to the Board's work in determining the causes of the mishap. That hardware was released to the Project's Science and Curation Team for continued processing. At the request of the Board, NASA's Jet Propulsion Laboratory, Pasadena, Calif., and Lockheed Martin have begun the process of sorting and assembling the Genesis records and data.

News and information about Genesis is available on the Internet at: http://www.nasa.gov/genesis & http://genesismission.jpl.nasa.gov

- end -

DC Agle (818) 393-9011
Jet Propulsion Laboratory, Pasadena, Calif.

Donald Savage (202) 358-1547
NASA Headquarters, Washington, D.C.

Bill Jeffs (281) 483-5035
Johnson Space Center, Houston

NEWS RELEASE: 2004-236 September 23, 2004

GENESIS MISSION STATUS REPORT

The Genesis team has shipped its first scientific sample from the mission's specially constructed cleanroom at the U.S. Army Proving Ground in Dugway, Utah. The sample, containing what are known as "lid foils," was attached to the interior lid of the Genesis sample return capsule.

"This is the first batch in what we are growing more confident will be many more scientifically valuable samples," said Genesis Project Manager Don Sweetnam of NASA's Jet Propulsion Laboratory, Pasadena, Calif. "It appears that we have recovered about 75 to 80 percent of these lid foils. A great deal of credit has to go to the dedicated men and women of Genesis who continue to do very precise, detailed work out there in the Utah desert."

After the sample was shipped from Utah, it was received by Genesis co-investigator Nishizumi Kunihiko from the University of California, Berkeley, Space Sciences Laboratory.

In addition to the lid foils, there was optimistic news about the collector array. Team members from JPL arrived in Utah on Monday with a special fixture to aid in handling the science canister's stack of four collector arrays. The stack was successfully removed as one piece. With the stack on the fixture, the team has begun the process of disassembling the arrays. Several large pieces of individual collector materials, including one completely intact hexagon, were recovered from the top array.

The Genesis cleanroom activities are focused on getting the materials ready for shipping. A date has not yet been selected for transporting the Genesis science canister and recovered collector materials from Dugway to NASA's Johnson Space Center in Houston. The team continues its meticulous work and believes that a significant repository of solar wind materials has survived that will keep the science community busy working on their science objectives.

News and information about Genesis is available online at http://www.nasa.gov/genesis . For background information about Genesis, visit http://genesismission.jpl.nasa.gov . For information about NASA visit http://www.nasa.gov .

-end

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NASA Headquarters, Washington, D.C.

Bill Jeffs (281) 483-5035
Johnson Space Center, Houston

NEWS RELEASE: 2004-245 September 30, 2004

GENESIS MISSION STATUS REPORT

The Genesis team is preparing to ship its samples of the Sun from the mission's temporary cleanroom at the U.S. Army Proving Ground, Dugway, Utah, to NASA's Johnson Space Center, Houston.

"We have essentially completed the recovery and documentation process and now are in the business of preparing everything for transport," said Eileen Stansbery, Johnson Space Center assistant director of astromaterials research and exploration science. "We still have a way to go before we can quantify our recovery of the solar sample. I can tell you we have come a long way from September 8, and things are looking very, very good."

A major milestone in the process was the recovery of the Genesis mission's four separate segments of the concentrator target. Designed to measure the isotopic ratios of oxygen and nitrogen, the segments contain within their structure the samples that are the mission's most important science goal.

"Retrieving the concentrator target was our number one priority," Stansbery said. "When I first saw three of the four target segments were intact, and the fourth was mostly intact, my heart leapt. Inside those segments are three years of the solar samples, which to the scientific community, means eons worth of history of the birth of our solar system. I saw those, and I knew we had just overcome a major hurdle."

Other milestones in the recovery process included the discovery that the gold foil collector was undamaged and in excellent condition. The gold foil, which is expected to contain almost a million billion atoms of solar wind, was considered the number two priority for science recovery. The polished aluminum collector was misshapen by the impact. However, it is intact and expected to also yield secrets about the Sun. Another occurred when the cleanroom team disassembled the collector arrays. They revealed, among large amounts of useable array material, some almost whole sapphire and coated sapphire collectors and a metallic glass collector.

Packing solar samples for transport is a little different than packing a house-worth of belongings for a cross-country move. After the meticulous process of inspection and documentation, each segment of collector gets its own ID number, photograph and carrying case. The samples and shipping containers fill the space of about two full size refrigerators. The Genesis material will probably move to the Johnson Space Center within the next week.

"If you had told me September 8 that we would be ready to move Genesis samples to Houston within the month I would have replied, 'no way,'" said Genesis Project Manager Don Sweetnam of NASA's Jet Propulsion Laboratory, Pasadena, Calif. "But here we are, with an opportunity to fulfill our major science objectives. It is a great day for Genesis, and I expect many more to come."

For more information about the Genesis mission on the Internet, visit http://www.nasa.gov/genesis . For background information about Genesis on the Internet, visit http://genesismission.jpl.nasa.gov .

-end

Donald Savage Oct. 14, 2004
Headquarters, Washington
(Phone: 202/358-1727)

RELEASE: 04-345

NASA's Genesis Mishap Board & Researchers Both Report Progress

As scientists begin to unpack more than 3,000 containers of samples of the sun brought to Earth by NASA's Genesis mission, the Mishap Investigation Board (MIB) has identified a likely direct cause of the failure of Genesis' parachute system to open.

The parachute system failed to deploy when Genesis returned to Earth September 8, 2004. The MIB, analyzing the Genesis capsule at a facility near Denver, said the likely cause was a design error that involves the orientation of gravity-switch devices. The switches sense the braking caused by the high-speed entry into the atmosphere, and then initiate the timing sequence leading to deployment of the craft's drogue parachute and parafoil.

"This single cause has not yet been fully confirmed, nor has it been determined whether it is the only problem within the Genesis system," said Dr. Michael G. Ryschkewitsch, the MIB chair. "The Board is working to confirm this proximate cause, to determine why this error happened, why it was not caught by the test program and an extensive set of in-process and after-the-fact reviews of the Genesis system."

Meanwhile, scientists unpacking samples at NASA's Johnson Space Center (JSC), Houston, curation facility remain upbeat in their assessment of the prospects for obtaining useful science from the recovered samples.

The facility counted more than 3,000 tracking numbers for the containers that hold pieces of wafers from the five collector panels. The panels secured samples of atoms and ions from the solar wind that were collected during Genesis' nearly three-year mission in deep space. Some of the containers hold as many as 96 pieces of the wafers. The team has been preparing the samples for study since the science payload and recovered samples arrived at JSC October 4.

Planning is under way for preliminary examination of the samples to prepare for allocation to the science community. The samples eventually will be moved to the JSC Genesis clean room where they will be cleaned, examined and then distributed to scientists, promising researchers years of study into the origins and evolution of the solar system.

"We cheered the news from the science team about the recovery of a significant amount of the precious

samples of the sun," said Dr. Ghassem Asrar, deputy associate administrator for the Science Mission Directorate at NASA Headquarters, Washington. "Despite the hard landing, Genesis was able to deliver. However, we await the final report of the Mishap Board to understand what caused the malfunction, and to hear the Board's recommendations for how we can avoid such a problem in the future," he added.

The recovered remains of the Sample Return Capsule (SRC) are undergoing engineering inspections and tests at the Waterton, Colo., facility of Lockheed Martin Astronautics (LMA). The Genesis spacecraft and SRC were built at Waterton. Lockheed Martin is supporting the MIB both to examine the recovered hardware and in assembling documentation relevant to the development of the space system.

"Both Lockheed Martin and JPL have been providing every possible support to our investigation. All of the people from both organizations who were involved in the Genesis project have been extremely professional and cooperative in helping the Board do its work," said Dr. Ryschkewitsch.

The safety critical pyrotechnic devices and the damaged lithium sulfur dioxide battery have been secured to allow safe operations. The battery has been transported to the Jet Propulsion Laboratory in Pasadena (JPL), Calif., to begin detailed evaluation.

The MIB is evaluating the recovered hardware, pertinent documentation, impact site recovery activities and interviewing people from development teams. The MIB is using a fault tree as its guide. A fault tree is a formal method for determining, organizing and evaluating possible direct causes for a mishap and to trace them to root causes.

The Board's charter is to examine every possible cause and to determine whether it was related to the mishap. The Board expects to complete its work by late November.

For information about NASA and agency programs on the Web, visit:

http://www.nasa.gov

- end

Appendix J

Bibliography

Document #	Title/Description	Author	Issue Date	DS page #
ABL0001	Packing Slip for PO 245594C; to Hi-Shear Technology Corp.	Ablestik Laboratories	4/4/96	45
ABL0002	Packing List; for PO 245594C; to Hi-Shear Technology Corp.	Ablestik Laboratories	2/29/96	47
ABL0003	Certificate of Conformance for PO 245594C; to Hi-Shear Technology Corp.	Ablestik Laboratories	2/29/96	48-49
AST0001	Packing Slip for PO 244942C; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/18/96	78
AST0002	Packing Slip for PO 244942C; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/18/96	85
AST0003	Certificate of Conformance for PO 244942C	"Astro Seal, Inc."	3/18/96	86
AST0004	Packing Slip for PO 244942C; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/12/96	100-101
AST0005	Packing Slip for PO 24942C; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/13/96	104
AST0006	Packing Slip for PO 244942C; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/12/96	105
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AST0009	Certificate of Conformance for PO 244942C	"Astro Seal, Inc."	3/5/96	119
AST0010	Packing Slip for 244948P1; to Hi-Shear Technology Corp.	"Astro Seal, Inc."	3/4/96	136
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AST0012	Certificate of Conformance for PO 244948P	"Astro Seal, Inc."	2/29/96	143
AST0013	Certificate of Conformance (#11134); for glass or ceramic insulators	"Astro Seal, Inc."	10/30/95	149
BMC0001	Certificate of Test	Brown Metals Company	5/16/94	26
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CAR0001	Certificate of Tests (No. 19816); for Fry Steel Company	Carpenter Technology Corporation	3/8/95	87-90
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CAR0003	Certificate of Tests (No. 19855); for Fry Steel Company	Carpenter Technology Corporation	9/22/95	145-147
CON0001	"Certification (No. 0211420) for PO 11030; Astro Seal, Inc."	"Continental Heat Treating, Inc."	3/1/95	91
CON0002	"Certification (No. 0210880) for PO 11030; Astro Seal, Inc."	"Continental Heat Treating, Inc."	2/23/96	124
COO0001	Manufacturing Order - Ordnance Group	Coors Ceramics	3/14/96	56
COO0002	Packing Slip; PO 244818C; to Hi-Shear Technology Corp.	Coors Ceramics	12/19/95	59
COO0003	Packing List; PO244818C; to Hi-Shear Technology Corp.	Coors Ceramics	12/14/95	62
COO0004	Certificate of Compliance for PO 244818C	Coors Ceramics	12/13/95	63
COO0005	Customer Deviation Request for PO 244818C	Coors Ceramics	12/1/95	64-65
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DUR0001	"Mechanical Properties Report for PO 11658; Astro Seal, Inc."	"Durkee Testing Laboratories, Inc."	3/21/96	92-99

Document #	Title/Description	Author	Issue Date	DS page#
DUR0002	"Mechanical Properties Report for PO 11474; Astro Seal, Inc."	"Durkee Testing Laboratories, Inc."	2/29/96	125-132
EBW0001	Packing Slip; PO 245132; Hi-Shear Technology Corp.	E.B. Welding	4/23/96	178
EBW0002	"Invoice, PO 245132; to Hi-Shear Technology Corp."	E.B. Welding	4/18/96	179
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EBW0012	Packing Slip; PO 245132; Hi-Shear Technology Corp.	E.B. Welding	5/4/95	189
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