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COMET NUCLEUS TOUR
CONTOUR

MISHAP INVESTIGATION BOARD REPORT

MAY 31, 2003

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National Aeronautics and Space Administration

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EXECUTIVE SUMMARY

The Comet Nucleus Tour, CONTOUR, is part of the NASA Discovery series of solar system exploration satellites. NASA sponsored CONTOUR with Dr. Joseph Veverka of Cornell University as the principal investigator; it was designed, built, and operated by Johns Hopkins University's Applied Physics Laboratory with specialized support by NASA.

Launched on July 3, 2002, CONTOUR was intended to encounter at least two comets and perform a variety of investigations and analyses of the comet material. It remained in an eccentric Earth orbit until August 15, 2002, when an integral STAR™ 30BP solid rocket motor was fired to leave orbit and begin the transit to the comet Encke.

The mission design did not provide for telemetry coverage during the solid rocket motor burn and no provision was made to observe the burn optically. CONTOUR was programmed to re-establish telemetry contact with the ground following the burn. However, no signal was received. Active attempts to contact CONTOUR were unsuccessful. On August 16, 2002, limited ground observations identified what appeared to be three separate objects on slightly divergent trajectories near but behind CONTOUR's expected position. Further attempts to contact CONTOUR were made through December 20, 2002, when NASA and Johns Hopkins University's Applied Physics Laboratory concluded that the spacecraft had been lost.

On August 22, 2002, NASA established a Type A Mishap Investigation Board as defined by NASA Policy Guideline 8621.1, NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping, to review the circumstances and potential lessons from the apparent loss of CONTOUR. Because of the lack of telemetry and observational data during the solid rocket motor burn, the Board concentrated on a review of available design, manufacture, testing, and operations documentation. In addition, the Board commissioned several additional analyses in areas where the Board considered the Applied Physics Laboratory analyses to be incomplete.

The Board was unable to determine with certainty the proximate cause of the failure due to the lack of data during the solid rocket motor burn phase of the mission. The Board was able to narrow an initial extensive list of possible causes to a few possible proximate causes. Although it could not unequivocally determine the proximate cause of the failure, the Board identified a number of possible root causes and significant observations that could result in mission failures and has documented these findings along with recommendations to prevent recurrences. These recommendations address ineffectiveness in communicating NASA's lessons learned, a lack of rigor in engineering process and documentation, and inadequate level of detail in technical reviews.

The probable proximate cause, alternate proximate causes, possible root causes, and significant observations are:

Probable Proximate Cause

- Overheating of the CONTOUR spacecraft by the solid rocket motor exhaust plume

Alternate Proximate Causes

- Catastrophic failure of the solid rocket motor
- Collision with space debris or meteoroids
- Loss of dynamic control of the spacecraft

Root Causes (Apply to one or more of the possible proximate causes.)

- CONTOUR Project reliance on analysis by similarity
- Inadequate systems engineering process
- Inadequate review function

Significant Observations

- Lack of telemetry during critical event
- Significant reliance on subcontractors without adequate oversight, insight and review
- Inadequate communication between APL and ATK
- ATK analytic models were not specific to CONTOUR
- Limited understanding of solid rocket motor plume heating environments in space
- Lack of orbital debris conjunction plan
- Limited understanding of CONTOUR solid rocket motor operating conditions

1. CONTOUR PROJECT DESCRIPTION

Project Management

The Comet Nucleus Tour, or CONTOUR, mission was proposed by Cornell University for the Discovery Program as a principal investigator (PI)-led mission in response to NASA's Announcement of Opportunity AO-96-055-02. NASA selected CONTOUR as the sixth mission within the Discovery Program in August 1997.

Program authority for the Discovery Program is delegated from the Associate Administrator for the Office of Space Science (AA/OSS) through the director of the NASA Management Office (NMO) to the Discovery Program Manager (DPM) within NMO. The CONTOUR PI at Cornell University is responsible for the overall success of the mission, and accountable to the Associate Administrator for Space Science for scientific success and to the DPM for programmatic success.

The implementing organization for CONTOUR was The Johns Hopkins University/Applied Physics Laboratory (APL). The project manager at APL oversaw the technical implementation of the project and was responsible for the design, development, test, and mission operations, and coordinated the work of all CONTOUR partners and contractors.

The APL Space Department Management Advisory Committee, augmented with management personnel from Cornell University, was the governing Program Management Council (PMC) for the CONTOUR Project and was chaired by the APL Space Department head. The DPM was an ad hoc member of these review boards.

An Independent Assessment Team (IAT) of experts from various disciplines was chartered by the DPM to assess the project status, evaluate project risks, and make recommendations to ensure mission success. The IAT[1] was selected prior to the Confirmation Review in February 2000, and participated in all major project reviews through launch in July 2002.

The APL director was responsible for certifying the CONTOUR mission readiness to the AA for Space Science through the Discovery Program Office.

Mission Technical Description

CONTOUR was designed to be a flexible, low-cost mission to study the nature and diversity of cometary nuclei by performing a baseline mission consisting of flybys of the comets Encke and Schwassmann-Wachmann-3 (SW3), with the possibility of an extended mission to encounter the comet d'Arrest.

CONTOUR's four-instrument payload suite consisted of dual imagers (CONTOUR Forward Imager (CFI), a wide-angle imager, and CONTOUR Remote Imager and Spectrograph (CRISP), a tracking high-resolution imager and spectral mapper), a mapping spectrometer (Neutral Gas and Ion Mass Spectrometer (NGIMS)), and a dust analyzer (Comet Dust Analyzer (CIDA)). CIDA was built and calibrated by vonHoerner and Sulger of Germany. NGIMS was provided by NASA Goddard Space Flight Center (GSFC), while CRISP and CFI were built by APL.

The spacecraft body (Fig. 1) was an aluminum octagon with solar cells mounted on the sides and back. The spacecraft had multilayer dust protection to survive the expected impact environments at the comet targets. The dust shield, built of multiple layers of Nextel® with a Kevlar® backstop, protected the forward end of the spacecraft, except where the solid rocket motor (SRM) nozzle protruded through the dust shield.

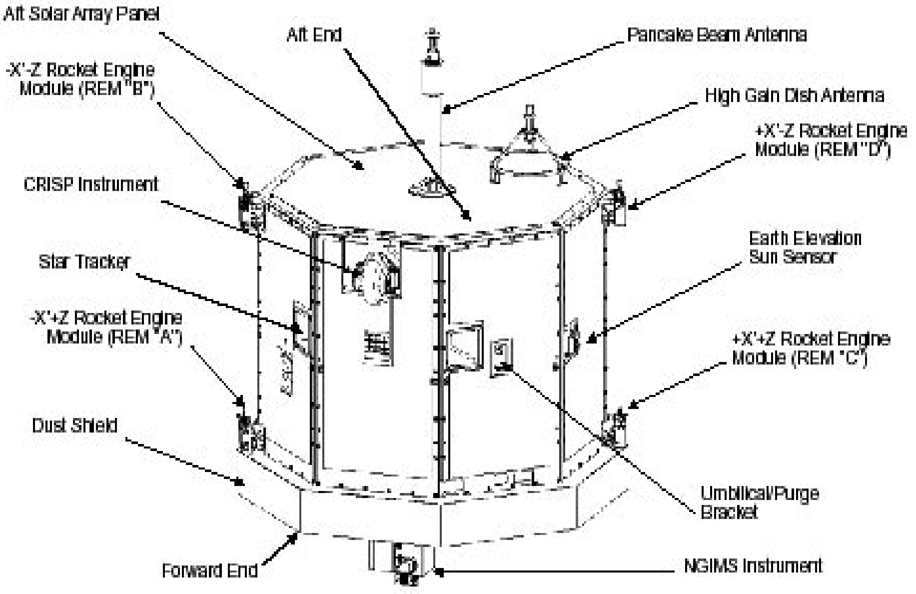

Figure 1.
The CONTOUR spacecraft.

During comet encounters, CONTOUR was to be three-axis stabilized. Otherwise it would have been kept in one of two spin-stabilized modes, including a hibernation mode during which there would be no ground contact. The Jet Propulsion Laboratory (JPL), Pasadena, CA. provided Deep Space Network (DSN) tracking and navigation support.

The maneuvering propulsion system used hydrazine. Attitude thrusters placed at the corners of the spacecraft provided redundant roll, pitch, and yaw control, without interference to the instruments from thruster plumes. Three of the instruments, CIDA, NGIMS, and CFI, were mounted on the front of the spacecraft and observed through apertures in the dust shield. CRISP was mounted on the side of the spacecraft, where it was protected from dust impacts. The high-gain antenna, mounted on the back of the spacecraft, provided downlink at X-band. Two low-gain antennas at opposite sides of the spacecraft and a multidirectional pancake-beam antenna on the back of the spacecraft provided uplink and downlink coverage over the entire mission. With the exception of CRISP, all the instrument and antenna pointing was controlled by moving the spacecraft. CONTOUR was designed to use two-way non-coherent Doppler technique instead of deep space transponders.

Following launch into a phasing orbit using a Delta-7425 vehicle in July 2002, the spacecraft remained orbiting the Earth in highly elliptic phasing orbits (Fig. 2) with a period of 1.75 days until it was to be injected into an interplanetary trajectory on August 15, 2002. The injection maneuver was designed to be performed at a perigee altitude of approximately 225 km with a STAR™ 30BP SRM, which was embedded into and permanently attached to the spacecraft.

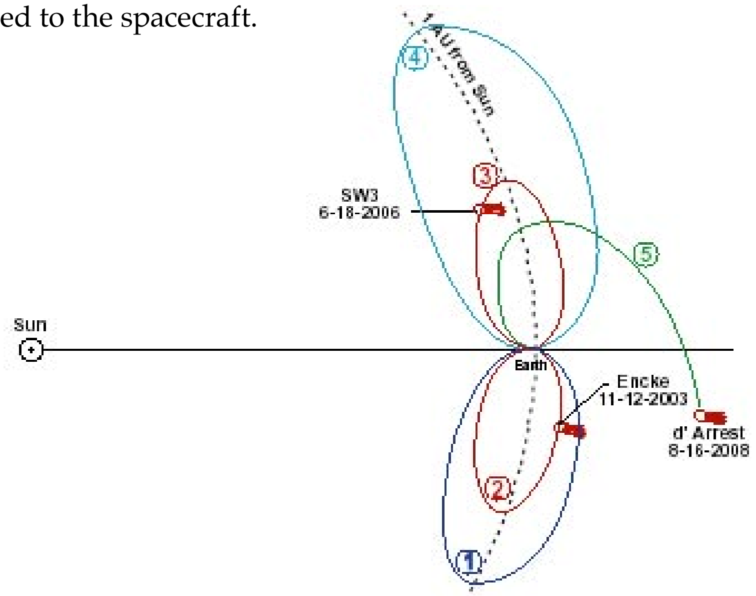

Figure 2.
CONTOUR trajectory.

After the spacecraft had been injected into its final trajectory on August 15, CONTOUR would have been on a 1-year Earth-return loop that would have positioned it for an encounter with comet Encke in November 2003. Three Earth-gravity assist maneuvers would then have been used to retarget the spacecraft for an encounter with comet SW3 in June 2006. Two more Earth-gravity assists would have enabled it to reach comet d'Arrest in a possible extended mission.

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2. CONTOUR MISHAP DESCRIPTION

The CONTOUR spacecraft, designed to image and measure the chemical makeup of comet nuclei and its surrounding gases, was launched into Earth orbit July 3, 2002 from the Kennedy Space Center on a Delta II launch vehicle. APL reported that all spacecraft subsystems had been performing nominally during a 43-day phasing orbit period, when 23 hydrazine-fueled propulsive maneuvers were performed to establish the orbital geometry and phasing necessary to prepare for an Earth escape trajectory to the comet Encke.

At 4:49 a.m. Eastern Daylight Time (EDT) on August 15, 2002, the CONTOUR spacecraft initiated a 50-second STAR™ 30BP SRM burn to accelerate the spacecraft and place it onto a path toward comet Encke. APL concluded that orbital geometry and spacecraft attitude during the burn did not permit spacecraft communication with the APL flight operations team via the NASA DSN or similar communications channels. The APL operations team expected to regain contact with CONTOUR at approximately 5:35 a.m. EDT via DSN. No signal from the spacecraft was received at the expected time.

The CONTOUR onboard redundancy management system included a command sequence programmed into the spacecraft flight computer that was designed to establish alternate methods of communication with Earth if contact were lost. The 60-hour sequence was programmed to start 96 hours after CONTOUR received its last command from ground operators. The sequence would initiate with the first of CONTOUR's two transmitters cycling 10 hours each through the low-gain and multidirectional (pancake) beam antennas on CONTOUR's aft side (opposite the dust shield) and the forward-side low-gain antenna. The second transmitter would then repeat the pattern. By August 22, the APL flight operations team predicted that the spacecraft would have completed the first cycle of having each of its transmitters attempt to send a signal through each antenna. APL attempts to communicate with CONTOUR during this period were unsuccessful.

From August 16 through August 21, ground-based telescope images from the University of Arizona's Lunar and Planetary Laboratory Spacewatch Project at Kitt Peak, AZ revealed three objects at locations on trajectories similar to that expected for CONTOUR. These images strongly suggested that the spacecraft had broken apart. NASA consulted the Department of Defense for assistance in confirming the apparent breakup. Data from Department of Defense assets supported this conclusion.

Efforts to communicate with the spacecraft were scaled back to once a week through early December 2002, when the spacecraft was expected to enter a more favorable viewing geometry. NASA officially declared the CONTOUR mission a loss after the December 2002 communication attempts failed.

3. CONTOUR MISHAP METHOD OF INVESTIGATION

On August 22, 2002, the Associate Administrator for Space Science established the NASA CONTOUR Mishap Investigation Board (MIB) with Theron Bradley, Jr., NASA Chief Engineer, as chair. The purpose of this Board was to examine the processes, data, and actions surrounding the events of August 15 to search for proximate and root causes and develop recommendations that may be applicable to future missions. The letter establishing the CONTOUR Mishap Investigation Board is in Appendix A.

The initial organizational meetings of the Board were held at NASA Headquarters (HQ) beginning on August 23, 2002. An overview briefing of the CONTOUR mission was held at APL on September 5, 2002. The briefing included material on the CONTOUR spacecraft, subsystems, development, test, launch processing, initial operations, navigation, and spacecraft health status up to the SRM burn. An overview briefing of the STAR™ 30BP SRM design, manufacture, test, and verification activities, was held at Alliant Techsystems Tactical Systems Company LLC (ATK, formerly Thiokol) on September 6, 2002.

Following the initial information gathering meetings, the Board used Fault Tree Analysis to identify and analyze a broad range of possible failure scenarios, and to provide a systematic process to track possible causes to closure. Leads and sub-teams were assigned to the various fault tree branches/items based on areas of expertise. The leads documented and tracked the analysis and information gathering necessary to disposition each identified fault tree event. The CONTOUR MIB Fault Tree diagram is provided in Appendix B, the Fault Tree narrative is in Appendix C, and Fault Tree Closeout Records are in Appendix D.

The Board held twice-weekly meetings and teleconferences to track the status of sub-team activities and discuss special areas of interest. Throughout the investigation there were regular requests made of both APL and ATK for information and data in support of the Board. Both APL and ATK provided full and open communication in response to all Board requests and provided specialized technical expertise when requested. There were also several special topic meetings held at APL, ATK, GSFC, and NASA HQ in which all or part of the Board participated. The minutes from each of these meetings are provided in Appendix E.

During investigation of specific potential failure modes, the Board concluded that additional technical reviews of various design, manufacture, and operational aspects of CONTOUR, beyond those performed in support of the initial product design, were required to determine or confirm actual spacecraft performance. These included special independent analysis tasks initiated and directed by the Board such as plume analyses, heat transfer analyses, dynamics and stability analyses, propellant aging and performance studies. These reviews were generally performed by experts selected by the Board using independent data or data provided as appropriate by APL and ATK. The results of these reviews are included in Appendix F.

In addition to the NASA Mishap Board activities, APL and ATK performed their own independent mishap investigations in parallel. The Board considered the APL and ATK findings, data, and analyses in reaching its independent conclusions. Additionally, the NASA Board reviewed its data, concerns, and approaches with cognizant APL and ATK experts on multiple occasions during the investigation to ensure the information being considered by the Board was complete. Copies of the APL Internal Failure Review Board Presentation and ATK Internal Failure Review Board Presentation are included in Appendices G and H, respectively.

The Board held Fault Tree Closure Reviews on December 10 - 11, 2002 and March 13, 2003 where the Team reviewed and reached consensus on each fault tree closure. Following completion of the Board fault tree reviews, the Board assembled a prioritized list of plausible causes for the loss of CONTOUR, including a description of the basis for determining plausibility, and an explanation of potential causes considered but determined to be implausible. The Board assembled observations concerning the CONTOUR design, fabrication, and operations processes, along with specific technical concerns generated during review of plausible causes, and developed a set of recommendations. The final prioritized list of plausible causes and recommendations was then reviewed by the broader group of Board advisors. Report results were then briefed to APL and ATK personnel prior to release of the final report.

A list of contractors supporting the CONTOUR MIB is provided in Appendix I. Appendix J contains additional bibliographical information to supplement the references. The nomenclature and units list is provided in Appendix K.

4. CONTOUR MISHAP PROBABLE AND ALTERNATE PROXIMATE CAUSES

Specific policy was used to conduct the investigation and to provide key definitions to guide the investigation. NASA Procedures and Guidelines (NPG) 8621.1, NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping, provided these key definitions for NASA mishap investigations. The NPG as modified by the NASA Office of Safety and Mission Assurance[2] defines proximate cause as: "The event(s) and condition(s) that occurred immediately before the undesired outcome, directly caused its occurrence and, if eliminated, or modified, would have prevented the undesirable outcome."

CONTOUR Mishap Probable Proximate Cause

The CONTOUR Board concludes that the probable proximate cause for loss of the CONTOUR spacecraft was overheating of the forward-end of the spacecraft due to base heating from the SRM exhaust plume. The CONTOUR SRM nozzle was embedded within the spacecraft to a greater degree than is typical (Fig. 3), and the resultant near-field effect of exhaust plume heating was not adequately accounted for in the design. Overheating may have caused substantial material weakening and structural degradation, which could have led to catastrophic dynamic instability. The deficiencies in the design process are discussed further in sections 5 and 6 of this report.

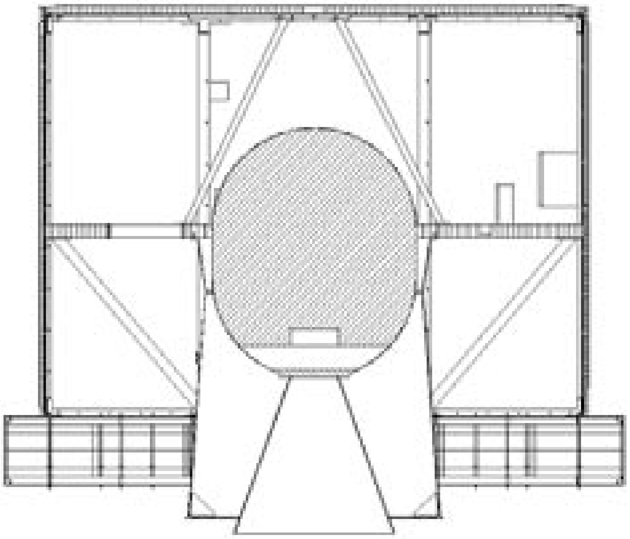

Figure 3. CONTOUR SRM configuration.

The APL CONTOUR plume heating analysis[3] assumed a worst-case combined radiative-convective plume heating environment of 50 suns (1 sun = 1358 W/m^2). The MIB commissioned multiple independent plume analysis efforts[4,5,6,7] which indicated the heating was higher than APL had predicted. APL did not consider possible degradation in material surface properties[8] due to plume contamination. This compounded the under-prediction of heating during the design phase. Changes in the surface absorptivity and emissivity because of plume impingement can significantly increase the effective radiative heat transfer from the plume in a given area.

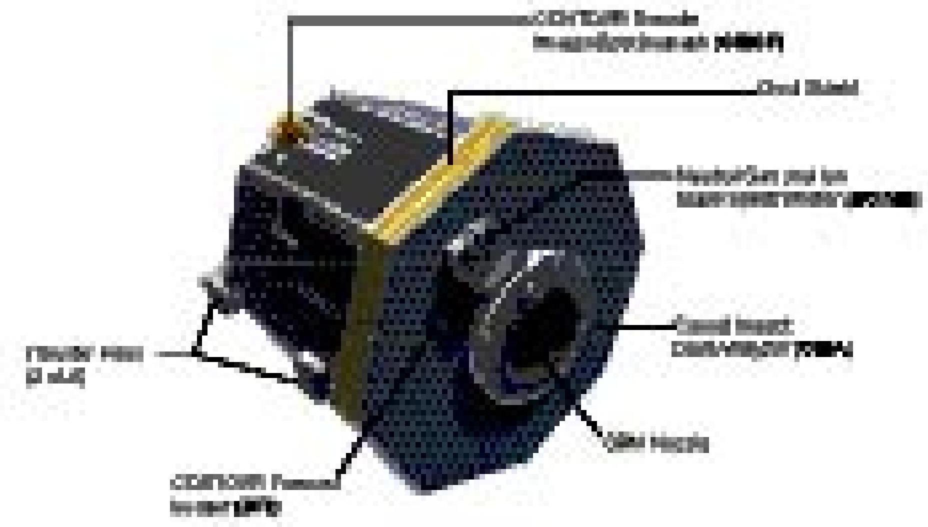

Figure 4. Forward end of the CONTOUR spacecraft.

It is beyond the scope of the MIB to analyze all the possible failure scenarios that could result from high localized heating of the forward end of the CONTOUR spacecraft. The MIB commissioned sufficient thermal analyses[9] to conclude that some components such as the forward low-gain antenna are likely to have experienced temperatures high enough to melt the components.

Alternate Proximate Causes

The Board could not rule out several other possible failure modes for this spacecraft because of the lack of telemetry and paucity of observational data during the SRM firing, uncertainties in the analyses used for original design and reconstruction of the failure, and minimal evidentiary debris from the failure. Such failure modes include:

- Catastrophic failure of the SRM
- Collision with space debris or meteoroids
- Loss of dynamic control of the spacecraft

These alternate failure modes were considered in detail and are reported in the Appendix C fault tree narrative. In addition, other potential failure modes are mentioned in the APL and ATK failure analyses (reference Appendices G and H).

5. CONTOUR MISHAP ROOT CAUSES AND RECOMMENDATIONS

NPG 8621.1 as modified by the NASA Office of Safety and Mission Assurance[10] defines root cause as: "One of multiple organizational factors that contributed to or created the proximate cause and subsequent undesirable outcome and, if eliminated or modified would have prevented the undesirable outcome." The following CONTOUR mishap root causes apply to one or more of the identified CONTOUR mishap possible proximate causes.

CONTOUR Mishap Root Cause No. 1: CONTOUR Project Reliance on Analysis by Similarity

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Recommendations:

- Do not rely heavily on previous analysis unless it has been shown to be applicable and appropriate. The CONTOUR Project's unfamiliarity with SRM applications led to an over-reliance on previous analysis or "heritage" that was not sufficient for the CONTOUR spacecraft.
- NASA and its contractors should work together to recognize and acknowledge the limits of expertise on a project so that the necessary resources can be identified and applied.
- Conduct inheritance review early in the project life cycle. The inheritance review objective is to properly evaluate an inherited element's capability and prior use versus a project's specific requirements. Heritage not only entails selecting a component with previous flight experience, but also ensuring that the application is consistent and within the bounds of its previous qualification.

CONTOUR Mishap Root Cause No. 2: Inadequate Systems Engineering Process

Based on the Board's observation of relevant APL processes and procedures, APL's approach to establishing requirements and specifications with subcontractors and consultants, as well as execution of routine peer reviews of internally conducted technical work, often appeared to be less rigorous and less complete compared to other similar NASA work. For example, APL did not appear to have a thorough understanding of STAR™ 30BP in-flight thermal environments/requirements, which could have been resolved with a more formal requirement specification/agreement with ATK. This general observation includes other elements of the design process as well, which appeared to lack detailed design memoranda and similar documentation. As a result, the Board concludes that candid, critical, and constructive peer and independent reviews, as well as similar systems engineering work, were impeded by this approach, and that this situation enhanced the risk of potential design errors going undetected.

The Board observes that a less formal approach to documenting engineering design work at APL is compensated for by a robust test program followed by any necessary redesign and retest. In this case, the impracticality of testing the assembled SRM with the spacecraft did not allow the traditional APL approach of design and test cycles to be accomplished. The basic weakness in the general reduced rigor of engineering documentation, and the specific inapplicability of the usual design-and-test cycle method in the case of the CONTOUR SRM did not appear to be recognized, or accepted and accommodated within the APL systems engineering strategy for CONTOUR.

Recommendations:

APL should:

- Establish and apply clear standards for conducting and documenting engineering work and associated peer and independent reviews.

NASA should:

- Establish clear standards for conducting and documenting engineering work and associated peer and independent reviews.
- Develop appropriate requirements for NASA's use or equivalent standards to conduct APL engineering work.

CONTOUR Mishap Root Cause No. 3: Inadequate Review Function

The Board is concerned that the non-typical aspects of the CONTOUR SRM implementation (refer to CONTOUR Mishap Significant Observation No. 2) and Project use of heritage SRM analysis did not receive more scrutiny during the CONTOUR review process. The NASA Discovery Program practice of using independent review teams made up of experienced space system developers to perform review functions at major milestone reviews is a valuable resource and should be continued. However, these types of reviews are often high-level and based on viewgraph presentations, and cannot provide the same depth of discernment that can be achieved through a thorough independent technical peer review process and day-to-day oversight by a dedicated NASA Center project management function. It is not clear that APL and NASA reviewed CONTOUR sufficiently to understand the risk incurred with the implementation approach.

Recommendations:

APL should:

- Reassess its internal peer and independent review processes.

NASA should:

- Reevaluate NASA oversight and review requirements, particularly for PI-led projects.

6. CONTOUR Mishap Significant Observations and Recommendations

NPG 8621.1 defines a significant observation as: "A factor, event, or circumstance identified during the investigation that did not contribute to the mishap or close call, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur." Based on this definition, the Board determined that there were seven significant observations for the CONTOUR mishap.

CONTOUR Mishap Significant Observation No. 1: Lack of Telemetry During Critical Events

CONTOUR SRM operations were performed without telemetry coverage. Performing operations without telemetry does not increase the likelihood of failure, but makes any potential post-failure analysis more difficult if not impossible. The inability to determine a failure mechanism in such a situation can impact multiple future missions that possess any commonality with the failed mission. The Board is unanimous in the opinion that performing mission-critical maneuvers without telemetry coverage is unacceptable unless proven to be absolutely unavoidable. Lack of engineering telemetry during critical events has been a recurring observation from several recent mission failure investigations; specifically Mars Observer, Mars Polar Lander, and now CONTOUR. The following paraphrased quote is from the Mars Polar Lander failure investigation, "The decision not to have critical event telemetry was a defensible project decision, but an indefensible programmatic one." Some NASA projects have continued to neglect this lesson; however, engineering telemetry during critical events is a must. One of the few possible exceptions to this requirement might be when planetary bodies obscure the spacecraft's view of Earth.

The Board remains unconvinced that the CONTOUR Project lacked viable options for telemetry coverage during the SRM burn. It was apparent that the CONTOUR Project did not consider the use of airborne P-3 assets, United States Air Force facilities in the region (Diego Garcia), or other possible assets.

Recommendations:

NASA should:

- Establish a policy that clearly defines mission-critical events that must be monitored. Waiver of such policy should not be given without due consideration of all possible options, including application of national assets. Introduction of such waivers should be prior to Mission Confirmation Review to allow adequate time for consideration of alternatives.

NASA and APL should:

- Establish a process to ensure that applicable lessons learned information is considered and implemented as appropriate on NASA/APL projects.

CONTOUR Mishap Significant Observation No. 2: Significant Reliance on Subcontractors without Adequate Oversight, Insight, and Review

The CONTOUR Project acquired the STAR™ 30BP serial number (S/N) 074 from Hughes Satellite Systems (now Boeing Satellite Systems) in an arrangement brokered by ATK. The Project's rationale was that Hughes and ATK had already deemed this motor flight worthy, and both organizations had significantly more SRM expertise than APL. Hughes had already dispositioned all of the S/N 074 non-conformances as acceptable, and the Project reviewed these non-conformances with the confidence that Hughes found them permissible. The Board did not fault this approach; however, it provided an indication to the Board that the Project lacked SRM expertise and was heavily reliant on its subcontractor. During the course of the CONTOUR mishap investigation, the Board became aware that APL possessed in-house SRM expertise assigned to projects other than CONTOUR. It was noted that APL drew upon these resources for the internal APL CONTOUR failure investigation.

The CONTOUR Project also relinquished responsibility of spacecraft dynamic analysis for SRM firing to a consultant, and relied heavily on the consultant's findings and conclusions to verify the sufficiency of the spacecraft design. The lack of in-depth Project oversight resulted in several deficiencies in analysis for the SRM firing event that concerned both performance and stability, although neither are believed to have contributed to the mishap. The consultant assumed that under acceleration, the spinning spacecraft with fuel slosh effects was a stable system, and no analysis was performed. The Board also found no evidence that the issue of stability with fuel slosh was raised within the Project. To rule out fuel slosh as a contributor to the mishap, the Board produced an internal fuel slosh analysis[11] and had it reviewed by Boeing experts.

The APL consultant's performance analysis also assumed a straight-line fit of the mass properties parameters during the SRM burn. There was no request from APL to ATK for the SRM mass properties variation over the burn. Board inquiries revealed that spacecraft inertias dropped rapidly near the end of burn, and that the spacecraft center-of-mass (CM) migrated initially away from, and then toward the SRM nozzle. The APL dynamics consultant revisited the original performance analysis with the new mass property profile and found a slight, yet within specifications, drop in performance. APL did not verify the spacecraft attitude performance during the SRM firing due to the limitations of their dynamic simulator, and was thus entirely reliant on the consultant's results.

The concern is not whether the subcontractors were competent, but whether the CONTOUR Project was sufficiently involved to ensure that the subcontractors were provided all the information needed to perform their tasks, and to question and penetrate the subcontractor analyses and conclusions for appropriate application to CONTOUR.

Recommendations:

- NASA and its prime contractors should retain sufficient oversight of subcontracted work to ensure that design, manufacture, and testing meet the intended use and expected reliability.

In addition, NASA should ensure that contractors:
- Compare the required personnel capabilities to the core capabilities of the project.
- Augment any shortcomings with outside support.
- Show sufficient overlap to guarantee a solid review process and to identify knowledge risks.

CONTOUR Mishap Significant Observation No. 3: Inadequate Communication between APL and ATK

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Information acquired during the investigation suggested that ATK typically deals with customers significantly more experienced with SRM applications than the CONTOUR Project. As a result, ATK does not normally have an active role in the spacecraft design.

Recommendation:

- Involve major subcontractors early in the spacecraft design process so they understand and "buy in" to how their product integrates into the overall design.

CONTOUR Mishap Significant Observation No. 4: ATK Analytical Models Were Not Specific to CONTOUR

Throughout this post-failure investigation, CONTOUR SRM data and configuration reconstruction was complicated by the fact that several of the ATK reports were not specific to the CONTOUR SRM but rather to a general STAR™ 30 motor configuration that was scaled where appropriate. This was apparent in the propellant grain structural and ballistic analyses. More worrisome was the difficulty in reconstructing the CONTOUR SRM as-built propellant grain configuration. This required repeated reviews of the STAR™ 30 blueprints and CONTOUR Manufacturing and Inspection Report (M&IR) by ATK. Although radiographs eventually confirmed the as-built configuration, the true configuration was not available until after most of the analytical work for this investigation was completed (including ATK's thermal analysis). Fortunately, the impact to all the results was minimal, and as a consequence this observation did not contribute to the failure.

Recommendation:

- The SRM vendor and customer must understand and communicate the fidelity and applicability of the models to be used in the project.

CONTOUR Mishap Significant Observation No. 5: Limited Understanding of SRM Plume Heating Environments in Space

The Board expended significant effort in attempting to locate authoritative information resources in the area of SRM convective and radiative heating from exhaust plumes in a space environment. It appears that many spacecraft/SRM configurations have relied on analysis and qualification by similarity to previously successful configurations. Since there have been no reports of mission failures resulting from convective and radiative plume heating, NASA has not expended the resources to thoroughly characterize the phenomena and correlate them to flight data. As a result, these analyses are based on best estimates of crucial variables and extrapolations from other configurations.

Recommendation:

NASA should:

- Develop spacecraft thermal design guidelines for vehicles using SRM's. These guidelines should summarize the key aspects of the design problem, capture the salient design issues, describe the available analytical and empirical resources, and capture the lessons learned.

CONTOUR Mishap Significant Observation No. 6: Lack of Orbital Debris Conjunction Plan

Although the CONTOUR Project made arrangements to have orbital debris conjunction analysis performed by USSPACECOM, there was no formal plan in place for reporting conjunctions to APL, and no threshold was established for the minimum allowable closest approach or maximum allowable probability of impact. In addition, there was no plan for action to be taken if an unacceptable conjunction were to occur.

Recommendation:

NASA and APL should:

- Require action thresholds and general action plans when an operational analysis, such as conjunction analysis, is performed. This will allow for a proper response by the project.

CONTOUR Mishap Significant Observation No.7: Limited Understanding of the CONTOUR SRM Operating Conditions

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Recommendation:

- Devote stringent attention when determining applicability of standard motor requirements toward special missions operations. Vendors and customers alike must bear this responsibility.

7. REFERENCES

[1] Schallenmuler, A., CONTOUR Independent Assessment Team Report, Findings and Recommendations, Dec. 15, 2000.

[2] NASA OSMA, Definitions of Root Cause Analysis and Related Terms, 2003.

[3] NASA Mission Investigation Team Site Visit to APL Regarding Failure of CONTOUR during SRM Firing Activity, APL, Sept. 5, 2002.

[4] Smith, S. and P. Anderson, CONTOUR Spacecraft Base Heating Assessment, MSFC Group, Report No. MG-03-173, Mar. 20, 2003.

[5] Woronowicz, M., STAR30BP Convective Influences on SPAF Closeout Ring, Dec. 10, 2002.

[6] Giacobbe, F., Analysis of Thermal Effects of Exhaust Plume.
Dec. 10, 2002.

[7] Rattenni, L., CONTOUR SRM Plume Convective Heating Analysis, Final Report, LR-RPT-070, May 15, 2003.

[8] TIROS-N Anomaly 8 - N2H4 System did not Cool Down as Fast as Expected, Feb. 28, 1979.

[9] Colbert, B., J. Maroney and S. Sutherlin, CONTOUR Spacecraft Base Heating Thermal Analysis Report, Report No. MG-03-446, July 18, 2003.

[10] NASA OSMA, Definitions of Root Cause Analysis and Related Terms, 2003.

[11] Starin, S., CONTOUR MIB: Fuel Slosh Analysis, Apr. 2003.

APPENDIX A

Letter Establishing the CONTOUR Mishap Investigation Board

SS August 28, 2002

TO: Distribution

FROM: S/Associate Administrator for Space Science

SUBJECT: Appointment of Mishap Investigation Board for the Comet Nucleus Tour (CONTOUR) Mission

1. INTRODUCTION/BACKGROUND

The CONTOUR spacecraft, designed to image and measure the chemical makeup of comet nuclei and its surrounding gases, was launched into Earth orbit July 3, 2002 from the Kennedy Space Center on a Delta II launch vehicle. At 4:49 am EDT on August 15, 2002, the spacecraft initiated a solid-fuel rocket motor burn to accelerate the spacecraft and place it onto a path towards the comet Encke. Spacecraft attitude during the burn did not permit communications with the flight control team. At completion of the burn, the spacecraft was programmed to maneuver to an Earth-point attitude and re-establish communications with ground operators. Acquisition of signal did not occur. Although attempts to contact the CONTOUR spacecraft are continuing, it appears that there is a significant likelihood of mission failure. A CONTOUR Mishap Investigation Board has therefore been assembled.

2. ESTABLISHMENT

a. The CONTOUR Mishap Investigation Board (hereinafter referred to as the Board) is hereby established in the public interest to gather information, conduct necessary analyses, and determine the facts of the CONTOUR mishap. The Board will determine the cause(s) of the CONTOUR mishap in terms of (1) dominant root cause(s), (2) contributing cause(s), and (3) significant observations.

b. The Board will recommend preventive measures and other appropriate actions to preclude recurrence of a similar mishap.

c. The Chairperson of the Board will report to the NASA Office of Space Science (OSS) Associate Administrator (AA), who serves as the appointing official.

3. AUTHORITIES AND RESPONSIBILITIES

a. The Board will:

  1. Obtain and analyze whatever evidence, facts, and opinions it considers relevant. The Board will use reports of studies, findings, recommendations, and other actions by NASA officials and contractors. The Board may conduct inquiries, hearings, tests, and other actions it deems appropriate. The Board may take testimony and receive statements from witnesses.
  2. Impound property, equipment, and records as necessary.
  3. Determine the actual cause(s), or if unable, determine probable cause(s) of the CONTOUR mishap, and document and prioritize their findings in terms of (a) the dominant root cause(s) of the mishap, (b) contributing cause(s), and (c) significant observations.

4. Develop recommendations for preventive and other appropriate actions. A finding may warrant one or more recommendations, or may stand-alone.
5. Provide a final written report to the Appointing Official by October 21, 2002 in the format specified in NPG 8621.1.
6. Provide a proposed lessons learned summary and a proposed corrective action implementation plan.
7. Perform any other duties that may be requested by the Appointing Official or designee.

b. The Chairperson will:
   1. Conduct Board activities in accordance with the provisions of this letter, NPD 8621.1G and NPG 8621.1, and any other instructions that the Appointing Official or designee may issue or invoke.
   2. Establish and document, as necessary, rules and procedures for the organization and operation of the Board, including any subgroups.
   3. Establish and document the format and content of verbal and written reports to and by the Board.
   4. Designate any representatives, consultants, experts, liaison officers, or other individuals who may be required to support the activities of the Board and define the duties and responsibilities of those persons.
   5. Establish and announce a target date for submitting a final report and keep all concerned NASA officials informed of the Board's plans, progress, and findings.
   6. Designate another member of the Board to act as Chairperson in his/her absence.

4. MEMBERSHIP

The Chairperson, members of the Board, ex-officio representative, and supporting staff as designated in the Attachment.

5. MEETINGS

The Chairperson will arrange for meetings and for necessary records and/or minutes of meetings.

6. ADMINISTRATIVE AND OTHER SUPPORT

a. NASA Headquarters will arrange for office space and other facilities and services that may be requested by the Chairperson or designee.
b. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and service that may be required.

7. DURATION

The Appointing Official will dismiss the Board when it has fulfilled its responsibilities.

8. CANCELLATION

The appointment letter is automatically cancelled 1 year from its date of issue, unless otherwise extended by the establishing authority.

Edward J. Weiler

Distribution:
S/Mr. C. Scolese
S/Mr. K. Ledbetter
SE/Dr. C. Hartman
SS/Dr. R. Fisher
SZ/Dr. A. Kinney
SP/Mr. R. Maizel
APL/Mr. T. Krimigis
CONTOUR MIB Board Members, Advisors, and Observers

ATTACHMENT

Comet Nucleus Tour (CONTOUR) Mishap Investigation Board (MIB)

Members

Mr. Theron Bradley, Jr.	Chairperson NASA Headquarters Chief Engineer
Mr. Charles Gay	Executive Secretary NASA Headquarters Office of Space Science
Mr. Patrick Martin	NASA Headquarters Office of Safety and Mission Assurance
Mr. David Stephenson	Marshall Space Flight Center
Mr. Craig Tooley	Goddard Space Flight Center

Advisors

Admiral J. Paul Reason	United States Navy, Retired
Admiral Joe Lopez	United States Navy, Retired
Mr. David Mangus	Goddard Space Flight Center
Mr. Jeffrey Umland	Jet Propulsion Laboratory
Mr. Michael Leeds	Jet Propulsion Laboratory, Retired
Mr. Mike Adams	Aerospace Corporation
Mr. Dan Perez	Aerospace Corporation
Mr. Don Savage	NASA Headquarters Public Affairs
Mr. Steven Schmidt	NASA Headquarters Special Assistant to the Administrator

Observers

Mr. Anthony Carro	NASA Headquarters

APPENDIX B

CONTOUR Mishap Investigation Board Fault Tree Diagram

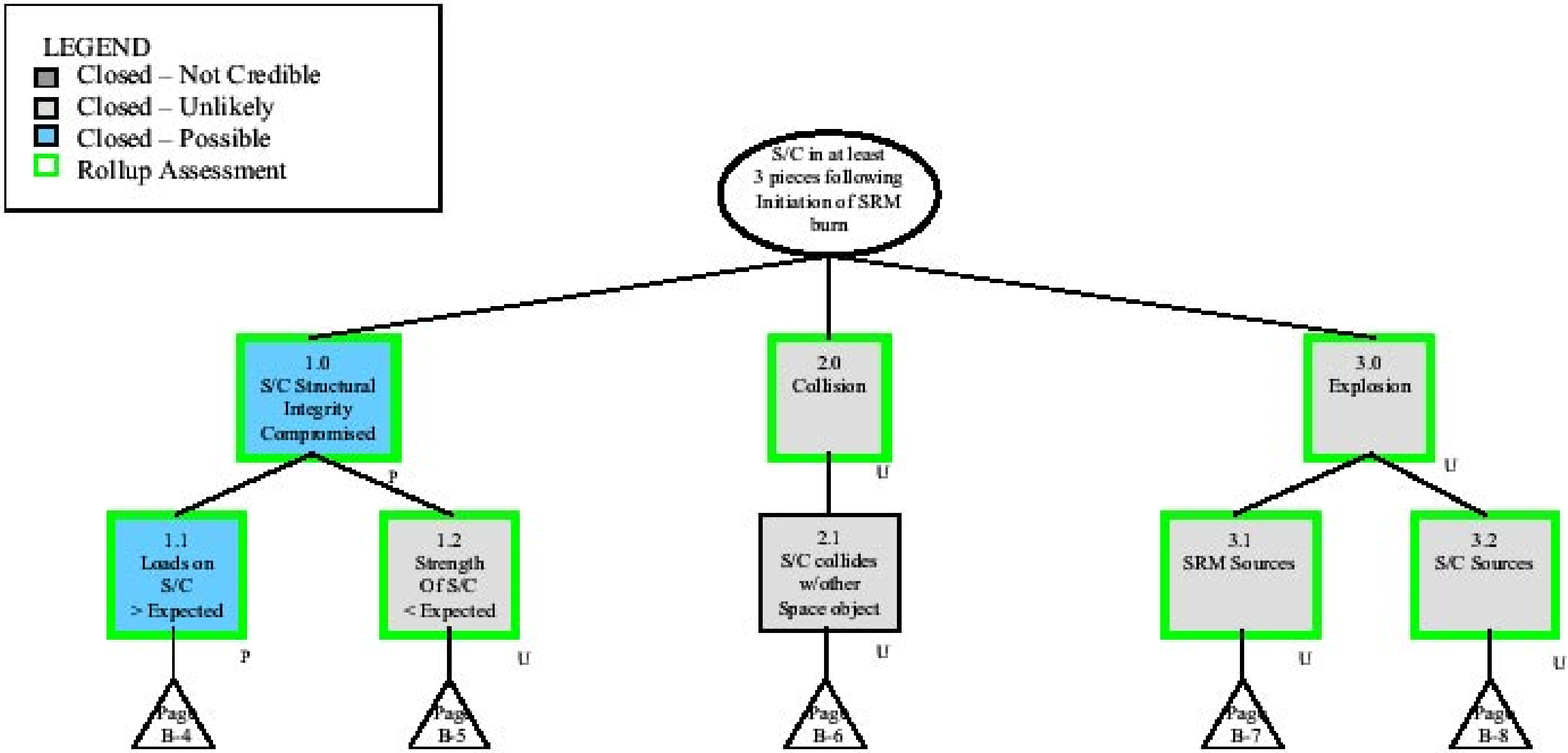

Figure B-1. CONTOUR fault tree diagram.

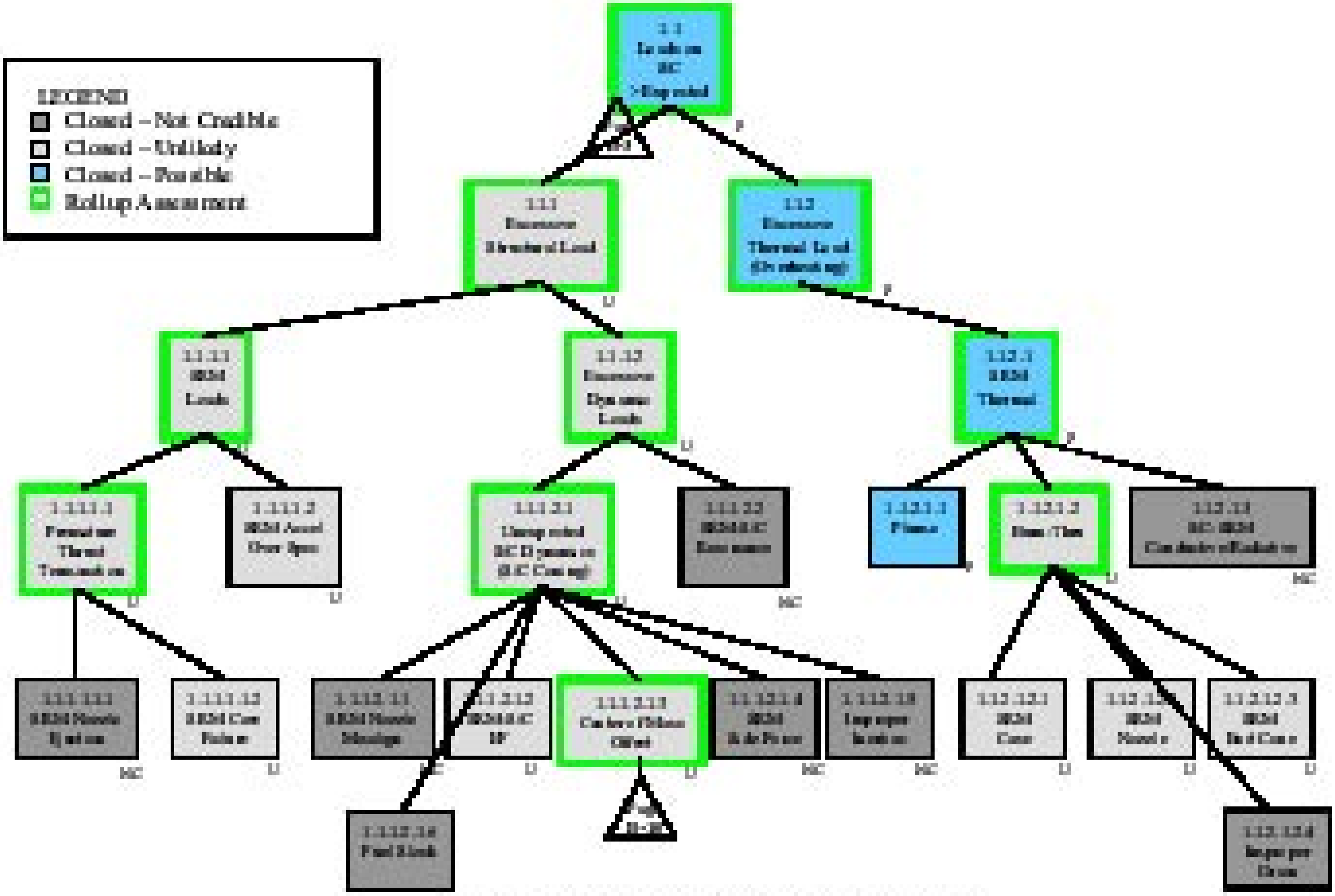

Figure B-1. CONTOUR fault tree diagram, continued.

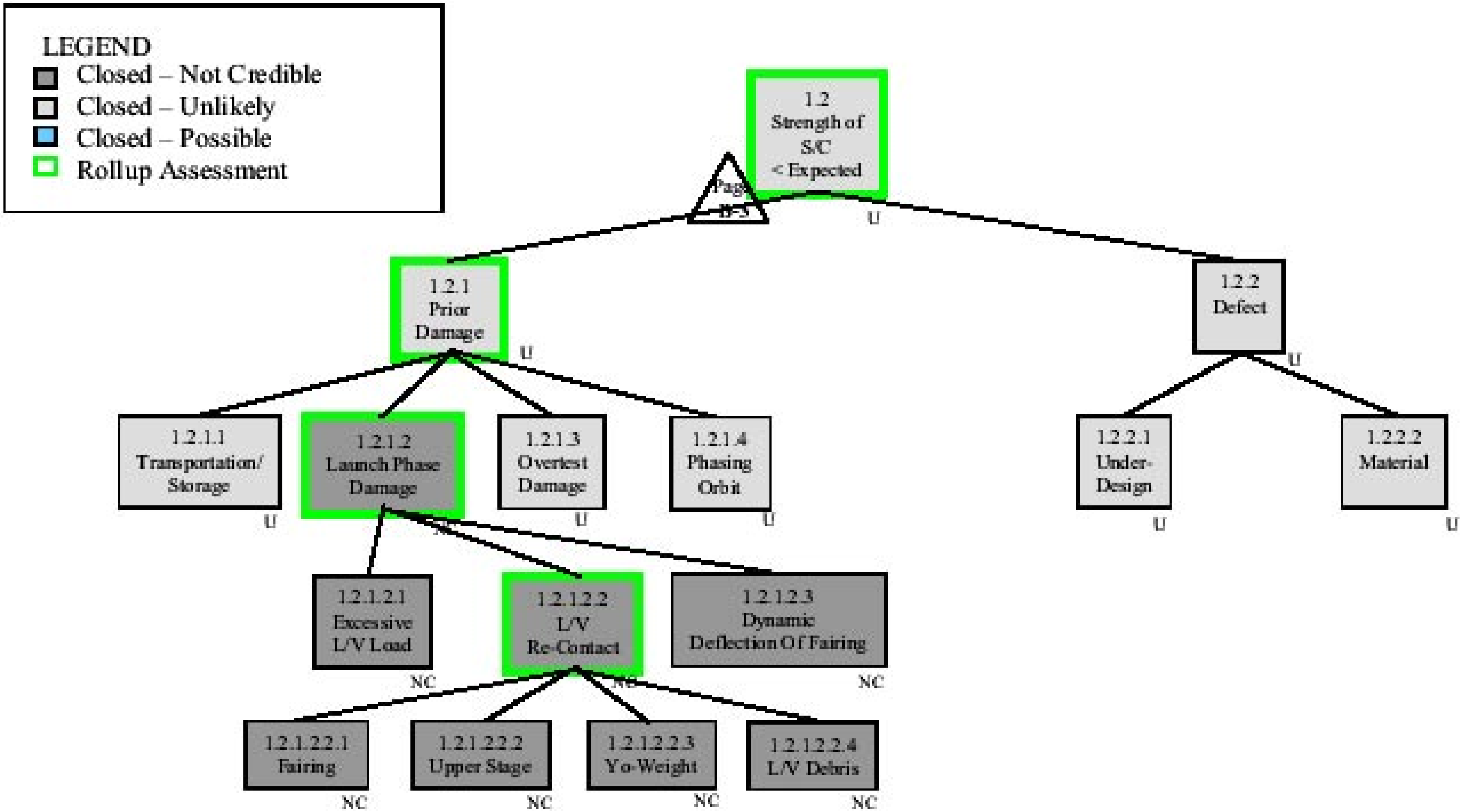

Figure B-1. CONTOUR fault tree diagram, continued.

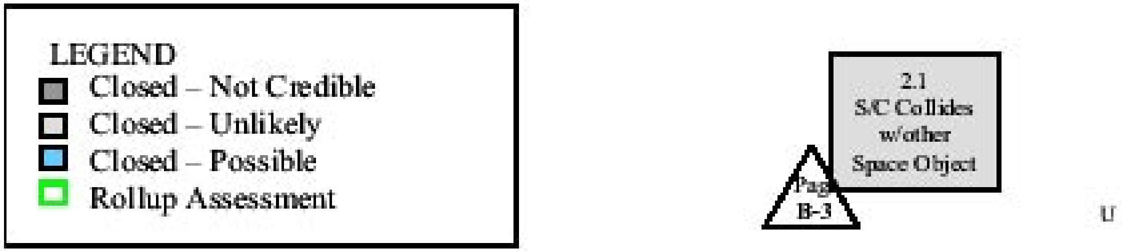

Figure B-1. CONTOUR fault tree diagram, continued.

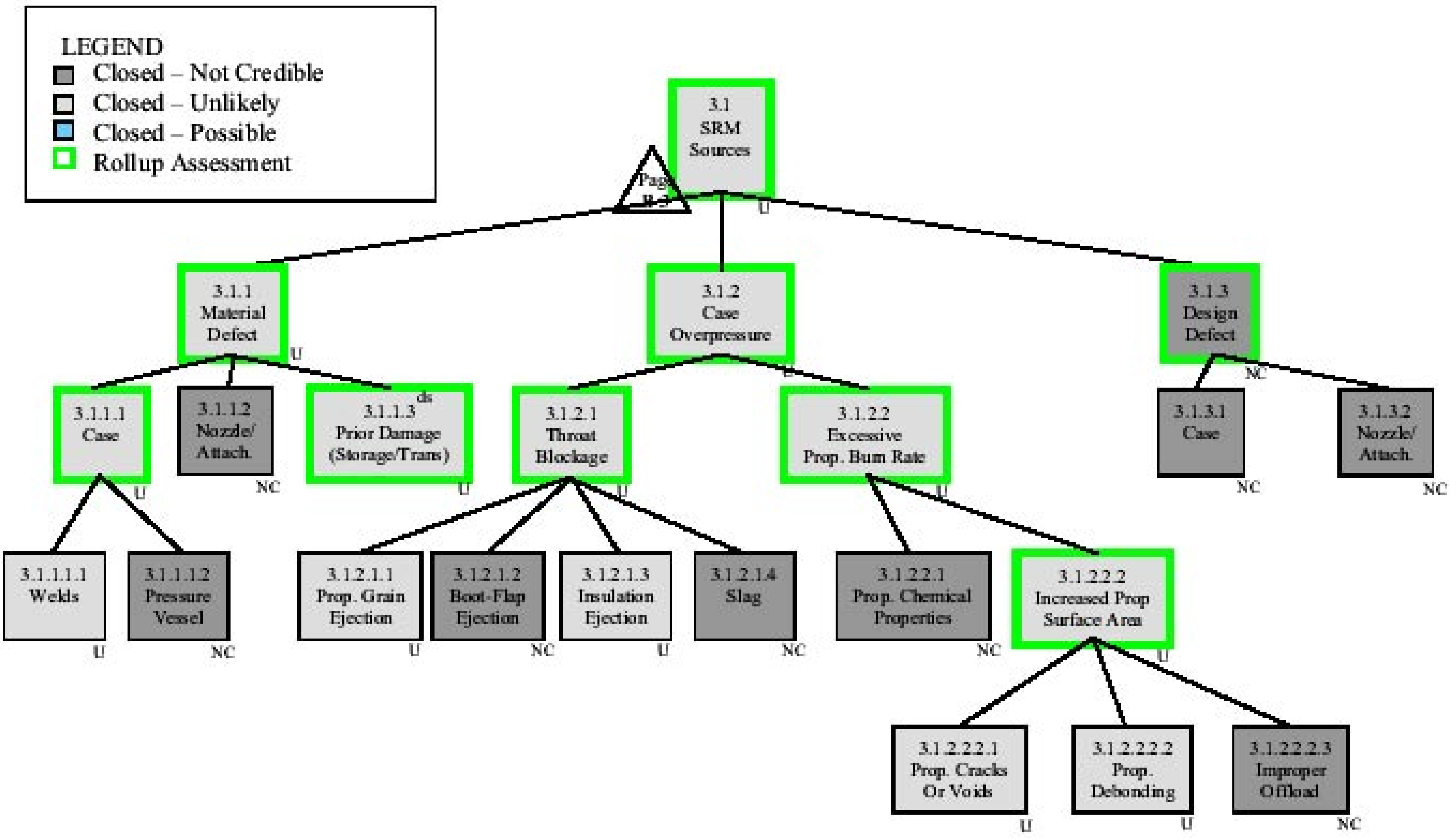

Figure B-1. CONTOUR fault tree diagram, continued.

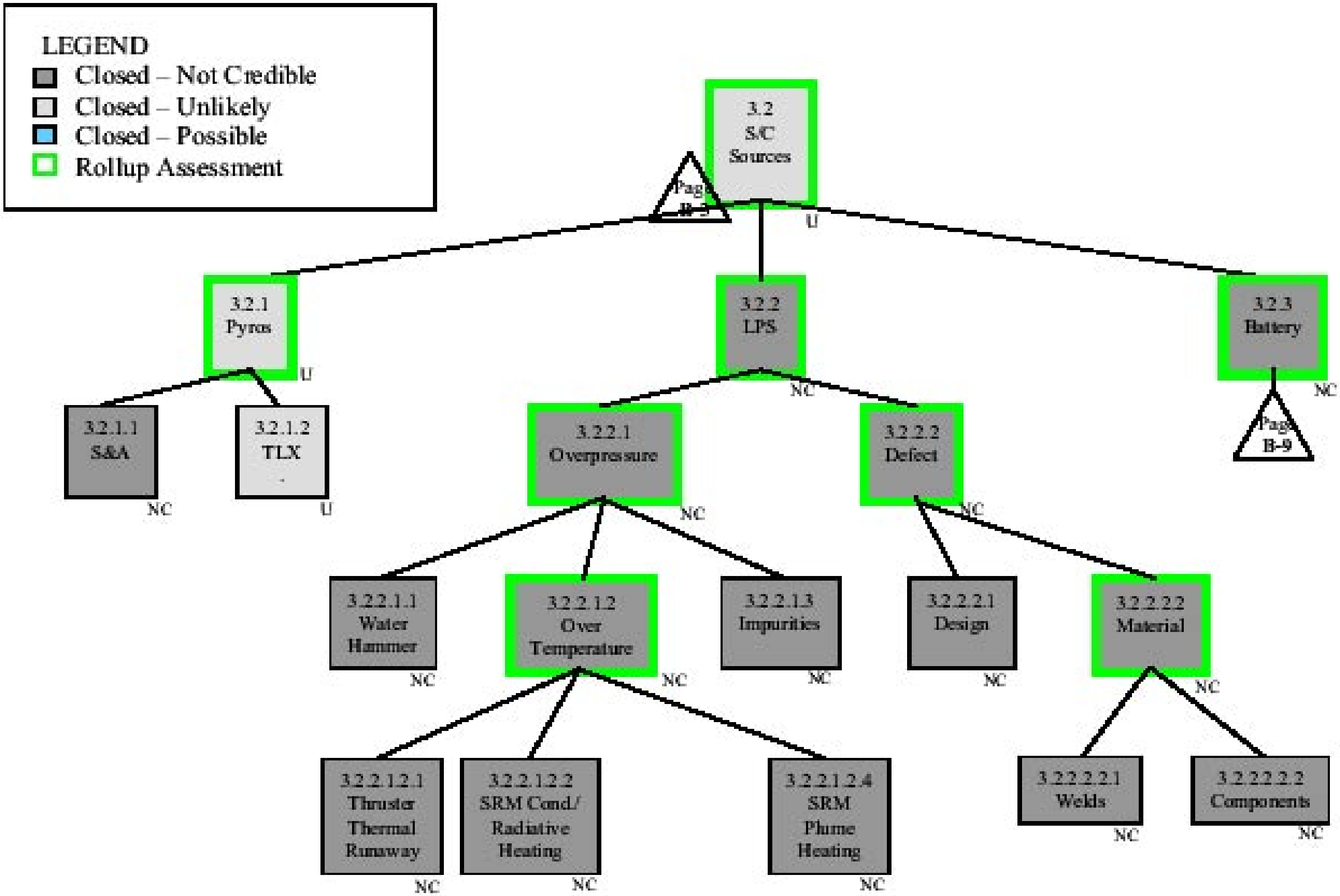

Figure B-1. CONTOUR fault tree diagram, continued.

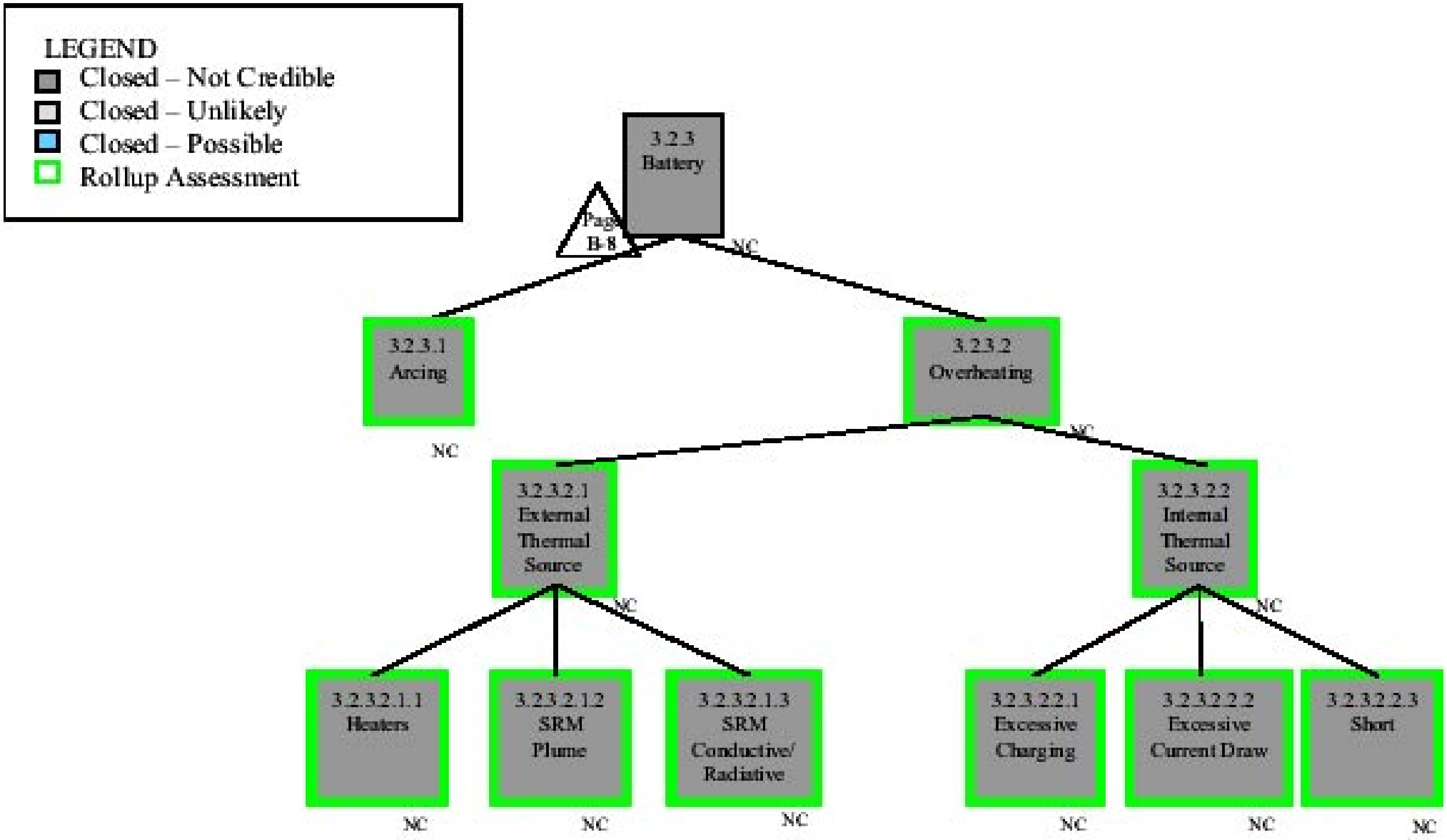

Figure B-1. CONTOUR fault tree diagram, continued.

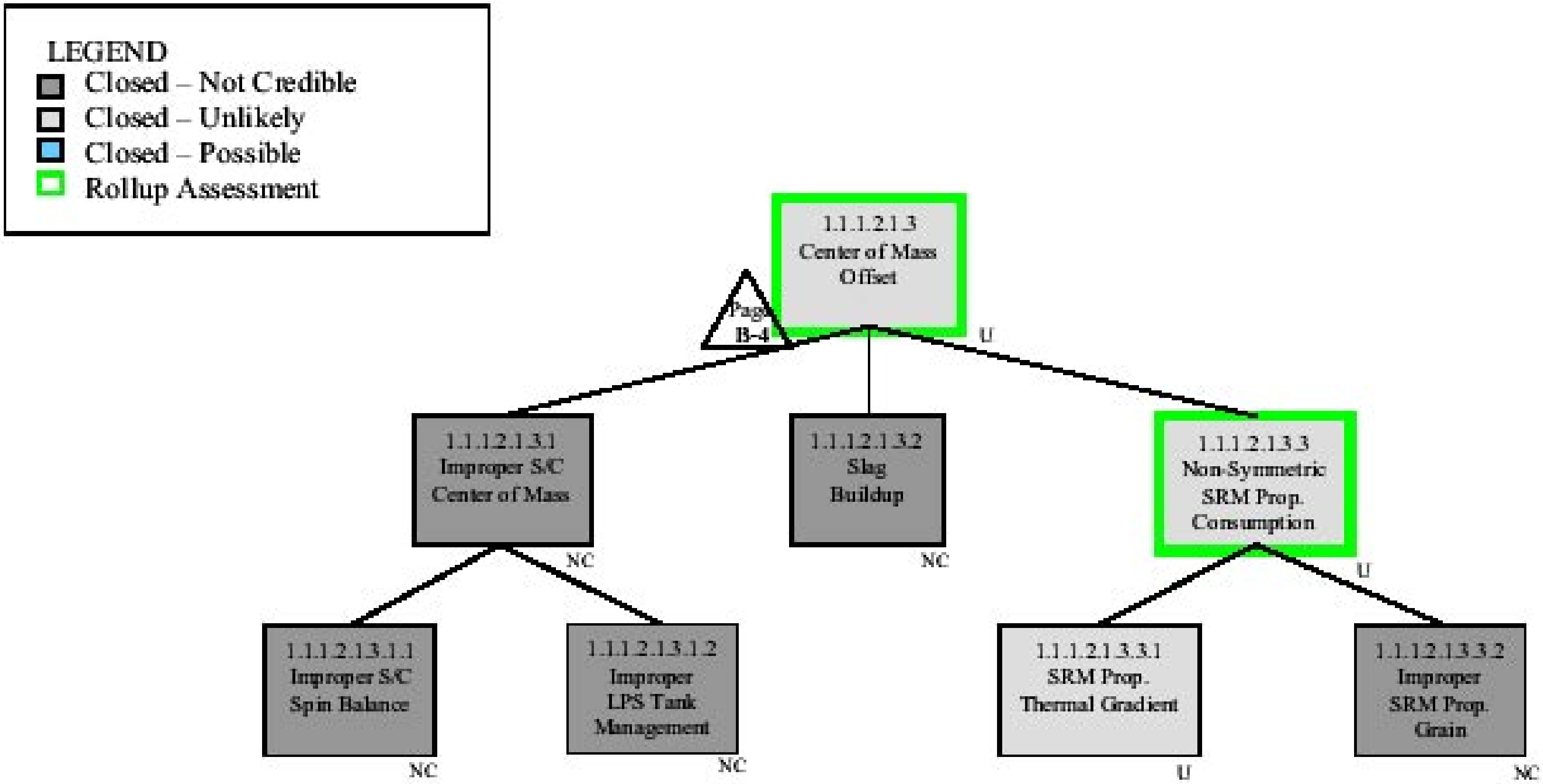

Figure B-1. CONTOUR fault tree diagram, concluded.

APPENDIX C

CONTOUR MISHAP INVESTIGATION BOARD FAULT TREE NARRATIVE

Proprietary and/or Export Controlled,
Not for Public Release

APPENDIX D

CONTOUR Mishap Investigation Board Fault Tree Closeout Records

**Proprietary and/or Export Controlled,
Not for Public Release**

APPENDIX E

CONTOUR Mishap Investigation Board Meeting Minutes

**Proprietary and/or Export Controlled,
Not for Public Release**

APPENDIX F

Analyses Commissioned by the CONTOUR Mishap Investigation Board

**Proprietary and/or Export Controlled,
Not for Public Release**

APPENDIX G

APL Internal Failure Review Board Presentation

**Proprietary and/or Export Controlled,
Not for Public Release**

APPENDIX H

ATK Internal Failure Review Board Presentation

**Proprietary and/or Export Controlled,
Not for Public Release**

APPENDIX I
Contractors Supporting the CONTOUR MIB

Contractors Supporting the CONTOUR MIB

Name	Affiliation
Dr. Michael Woronowicz	Swales Aerospace, Beltsville, MD
Mr. Frank Giacobbe	Swales Aerospace, Beltsville, MD
Mr. Louis Rattenni	Consultant, Harpers Ferry, WV
Mr. Sheldon D. Smith	Plumetech, Huntsville, AL
Mr. Bob Colbert	Jacobs Sverdrup Engineering, Huntsville, AL
Mr. Steven Sutherlin	Jacobs Sverdrup Engineering, Huntsville, AL

APPENDIX J

Bibliography

Document #	Title/Description	Author	Issue Date
APL0001	Program Status/Propulsion Subsystem CDR, CONTOUR	Stratton et al	
APL0002	SRM flight temp and heater telemetry, CONTOUR		
APL0003	Reports, CONTOUR Problem Failure		
APL0004	Mechanical Drawings 7379-0000 to –0756, CONTOUR		
APL0005	Presentation, NASA Discovery Program, CONTOUR	Farquhar	9/05/02
APL0006	Presentation, APL Fault Tree, CONTOUR	APL	9/05/02
APL0007	Presentation, Briefing to CONTOUR MIB	APL	9/05/02
APL0008	Monthly Status Reports, various, CONTOUR	APL	Various
APL0009	CONTOUR Mishap Investigation - submittal of requested information	General Dynamics	9/20/02
APL0010	CONTOUR end item data package - propulsion	General Dynamics	4/24/01
APL0011	Procedure, CONTOUR spacecraft spin balance/mass properties	APL	
APL0012	Report, CONTOUR mass property test	Mantech	2/02
APL0013	E-mail, spin balance of fueled CONTOUR spacecraft	McGinley	6/13/02
APL0014	Responses, post-APL/ATK review questions and requests for information	APL	9/24/02
APL0015	Event timeline, CONTOUR		
APL0016	Initial estimates for SRM convective influences on NGIMS	Woronowicz/ Swales	3/16/01
APL0017	Final report, INDOSTAR Program	Rattenni/ Consultant	11/01/96
APL0018	CONTOUR humidity data @ KSC		
APL0019	Critical events monitoring rationale, CONTOUR		6/21/02
APL0020	CONTOUR method of transferring mass property information		
APL0021	Minutes, CONTOUR PDR	APL	1/19/02
APL0022	Report, CONTOUR Independent Review	Aerospace Corp	1/13/00
APL0023	Minutes, CONTOUR CDR	APL	12/26/00
APL0024	Report, CONTOUR Independent Assessment Team (IAT)	Schallenmuller	12/15/00
APL0025	Spectrochemical Analysis - payload adapter ring	Jorgensen Forge	10/06/00
APL0026	Engineering notes, CONTOUR propulsion/nav/GN&C	APL	
APL0027	Report, CONTOUR spinning mode: stability during SRM burn	van der Ha	2/22/00
APL0028	Top level requirements, CONTOUR ADCS subsystem:	van der Ha	9/20/99
APL0030	Presentation, CONTOUR guidance and control subsystem: spinning mode	van der Ha	1/19/00
APL0031	Presentation, CONTOUR guidance and control subsystem: spinning mode, monthly progress meeting	van der Ha	12/07/99
APL0032	Report, CONTOUR spinning mode: maneuver analysis	van der Ha	6/28/99
APL0033	Report, CONTOUR spinning mode: phases and activities	van der Ha	5/24/99
APL0034	Report, CONTOUR spinning mode: attitude determination concept	van der Ha	12/17/99
APL0035	Contract, CONTOUR spacecraft		7/03/00
APL0036	Photographs/transparencies, CONTOUR SRM installation	APL	5/21/02 - 5/23/02

APL0037	Package, CONTOUR Critical Design Review	APL	12/12/00
APL0038	Contingency plan, CONTOUR	NASA HQ	4/02
APL0039	Nutation damping under jet damping effects	van der Ha	11/21/02
APL0040	Notes, CONTOUR spin rate fluctuations wrt/temperature	Dellinger	11/21/02
APL0041	Procedure, CONTOUR spacecraft shipping and handling - Rev A	APL	3/06/02
APL0042	Procedure, CONTOUR spacecraft shipping and handling - Rev B	APL	3/18/02
APL0043	Notes, CONTOUR spacecraft shipping and handling	APL	
ATK0001	Report, Orbit Insertion Motor for the HS-376 Satellite, Qualification Test	Stratton et al	6/10/85
ATK0002	Side force data, STAR 30		
ATK0003	Reserved		
ATK0004	STAR 30BP motor CG and MOI migration through burn		
ATK0005	Tabulated ballistic data, CONTOUR motor		
ATK0006	Propellant flight history, STAR 30 motors		
ATK0007	Motor Log Book S/N 074		
ATK0008	Correspondence, ATK - Various		
ATK0009	Presentation, CONTOUR motor throat assembly thermo-structural analysis	Feltman	9/06/02
ATK0010	RFI's, ATK	ATK	9/05/02
ATK0011	Investigation Review #2, CONTOUR flight anomaly	ATK	9/06/02
ATK0012	Responses to 9/13 questions to ATK	ATK	9/24/02
ATK0013	Report, DMSP flight (STAR37A) anomaly investigation	ATK	5/10/91
ATK0014	Manufacturing and Inspection Record - Hydrostatic Proof Testing	ATK	11/18/82
ATK0015	Manufacturing and Inspection Record - S/N 074 (4 volumes)	ATK	
ATK0016	Drawing package, solid rocket motor	ATK	
ATK0017	Report, STAR 30 case structural	ATK	8/07/78
ATK0018	Model Specification, TE-M-700 STAR 30 series rocket motor	ATK	10/13/00
ATK0019	Specification, titanium alloy (6A1-4V)	ATK	11/19/97
ATK0020	Specification, heat treatment, titanium alloy (6A1-4V)	ATK	5/21/93
ATK0021	Specification, welding, inert gas, tungsten arc, with acid etch cleaning	ATK	6/21/99
ATK0022	Configuration Record, STAR 30BP rocket motor, S/N 074, Rev A	ATK	
ATK0023	Report, inert STAR 37FM motor post-test evaluation	ATK	7/07/98
ATK0024	Viewgraphs, CONTOUR thermal model generator thermal analysis	ATK	10/01/02
ATK0025	Attendees list, 9/6/02 meeting at ATK, Elkton Operations	ATK	9/06/02
ATK0026	Stress analysis, TE-M-700-5 propellant grain	ATK	6/05/78
ATK0027	Report, ATK CONTOUR Investigation Report to NASA MIB	ATK	10/31/02
ATK0028	Report, CONTOUR STAR 30BP Mishap Investigation, Appendix A	ATK	10/31/02
ATK0029	Report, CONTOUR STAR 30BP Mishap Investigation, Appendix B	ATK	10/31/02
ATK0030	Report, CONTOUR STAR 30BP Mishap Investigation, Appendix C	ATK	10/31/02
ATK0031	Animation, CONTOUR STAR 30BP Mishap Investigation, spacecraft	ATK	10/31/02
BOE0001	Nutation time constant model parameters, CONTOUR spacecraft	SwRI	4/01/02
BOE0002	Flight data, STAR 30	Boeing	9/04/02
BOE0003	Post-flight analysis, Delta II CONTOUR launch vehicle	Boeing	8/01/02
BOE0004	Specification, Delta II CONTOUR mission	Boeing	5/02

KSC0001-1	Operations & Maintenance Instruction E50R: Dynamic Balancing Operations, Rev C		10/02/98
KSC0001-2	Operations & Maintenance Instruction E50R: Dynamic Balancing Operations, Rev D		5/23/02
KSC0002	Test Record, E2529: Dynamic Balancing Operation		Various
KSC0003	Test Record, E2064: Fuel System Preps for P/L Servicing - SAEF-II/PHSF/VPF		6/03/02
KSC0004	Problem Report, PC-3-01538-000 Unable to Verify Pressure on LPG1		6/06/02
KSC0005	Operations & Maintenance Instruction E2064: Fuel System Preparations for Payload Servicing, Rev B		2/17/99
KSC0006	Operations & Maintenance Instruction E5534: Preps for Spacecraft Fuel Loading, Rev B		9/20/01
KSC0007	Test Records, E5534: Preps for Spacecraft Fuel Loading		Various
KSC0008	Operations & Maintenance Instruction E5502: Spacecraft Fuel Loading, Rev B		9/20/01
KSC0009	Test Records, E5502: Preps for Spacecraft Fuel Loading		Various
KSC0010	Operations & Maintenance Instruction E6067: Fuel System Maintenance and Servicing - PHSF, SAEF-2, VPF, Rev B		1/12/00
KSC0011	Test Record, E6067:Fuel System Maintenance and Servicing		1/12/00
KSC0012	Operations & Maintenance Instruction E6518: Spin Machine Maintenance and Certification, Rev A		10/11/95
KSC0013	Test Record, E6518: Spin Machine Maintenance and Certification		10/11/95
KSC0014	CONTOUR WADs in TDC Impound		
KSC0015	Package, CONTOUR Missile System Prelaunch Safety	APL	7/01
KSC0016	CD, PAF Accels 11/14/02 Delta II Dynamic Environment		11/14/02
MIS0001	Report, DMSP F-10 Mishap Investigation	Kaxangey/ Aerospace Corp	6/91
MIS0002	Documents/CD, Delta Star/Hydrazine	MDA	11/14/02
MIS0003	Preliminary: CONTOUR MIB Requests for Information/Conjunction analysis	Taylor/JPL	11/21/02
MIS0004	Report, STAR 30BP Convective Influences on SPAF Closeout Ring	Woronowicz/ Swales	12/10/02
MIS0005	Report, Analysis of Thermal Effects of Exhaust Plume	Giacobbe/ Swales	12/10/02
MIS0007	Report, Development of a Novel Free Molecule Rocket Plume Model	Woronowicz/ Swales	
MIS0008	Report, Further Studies Using a Novel Free Molecule Rocket Plume Model	Woronowicz/ Swales	
MIS0009	Report, AIAA 2000-3190, Solid Motor Plume Analysis for the STAR-1 Spacecraft	Rattenni	7/17/00
MIS0010	Report, AIAA 2002-3750, CTPB and HTPB Propellants for Extended Space Missions	Moore	7/07/02
MIS0011	Report, AAS 03-204, Navigating CONTOUR Using the Noncoherent Transceiver Technique	Carranza, et al	2/09/03
MIS0012	Slag and Thermal Environment of a Spinning Rocket Motor	Chang	5/01/91
MIS0013	Report, Estimation of Heat Transfer Coefficient and Absorbed Heat Flux by the SPAF or Other Surfaces in the Vicinity of the CONTOUR SPAF Closeout Blanket	Giacobbe	4/03/03

MIS0014	Report, CONTOUR Spacecraft Base Heating Assessment, MG-03-173	S. Smith, Anderson	3/20/03
IOT0001	Report, Transverse Torque Required to Generate 25g's	Mangus	11/26/02
IOT0002	Additional SPAF MS values	Sholar	11/06/02
IOT0003	Data, propellant ageing	Williams	10/10/02
IOT0004	Analysis, Ballistic Anomalies in Solid Rocket Motors	Heister/ Landsbaum	11/01/91
IOT0005	Analysis, Thermal Effects of Exhaust Plume	Giacobbe	12/10/02
IOT0006	Report, APL Internal MIB Final, 10/30/02	APL	10/30/02
IOT0007	Briefing, APL Failure Overview, 9/05/02	APL	9/05/02
IOT0008	Notes, APL Meeting, 9/27/02	Gay	9/27/02
IOT0009	Minutes, APL Review, 9/05/02	Gay	9/05/02
IOT0010	Minutes, APL Review, 10/30/02	Gay	10/30/02
IOT0011	Briefing, ATK failure overview, 9/6/02	ATK	9/06/02
IOT0012	Response document, ATK, RSF021015	Feltman	10/15/02
IOT0013	Response document, ATK, OTC0230ACEC-00204	Carr	10/07/02
IOT0014	Response document, ATK - CEC-002-05 residual thrust	Carr	10/15/02
IOT0015	Minutes, ATK review, 10/31/02	Gay	10/31/02
IOT0016	Contract agreement, ATK/APL	APL	6/13/00
IOT0017	Drawings, battery	Eagle-Picher	11/07/00
IOT0018	Procedure, battery acceptance test (ATP20009RevA)	Eagle-Picher	9/04/01
IOT0019	Schematics, battery electrical	APL	10/10/02
IOT0020	Plan, battery handling 7379-9180	APL	10/25/01
IOT0021	Specification, battery 7379-9054	APL	10/30/01
IOT0022	Battery temperature predictions	Panneton	8/03/01
IOT0023	Blanket mockup (solid model for closeout blanket strength testing)	APL	11/04/02
IOT0024	Board questions/requests responses	APL	9/04/02
IOT0025	Board questions/requests responses (questions 1-4)	APL	9/04/02
IOT0026	Board questions/requests on CONTOUR	Gay	8/27/02
IOT0027	Boeing fishbone of launch vehicle	Boeing	9/11/02
IOT0028	Diagram, BSAT launch vehicle interface, Orbital	OSC	3/28/03
IOT0029	BSS comments on 12/10/02 telecon with the CONTOUR Project personnel	Boeing	12/10/02
IOT0030	Critical Design Review, CONTOUR	APL	12/12/00
IOT0031	Critical Design Review, color VG3	APL	12/12/00
IOT0032	Analysis, COG offset	Rogers	8/29/02
IOT0033	Specification, component environmental, 7379-9010	APL	8/28/00
IOT0034	Actual grain dimension, CONTOUR	ATK	12/13/02
IOT0035	Report, CONTOUR base environment status, 2/11/03	B. Smith	2/11/03
IOT0036	Preliminary Report, CONTOUR base plume induced environments, 3/4/03	B. Smith	3/04/03
IOT0037	Test, CONTOUR button thermal	APL	1/30/03
IOT0038	Collision analysis by small particles, CONTOUR	Johnson	10/10/02
IOT0039	Drawing, CONTOUR cross section	APL	8/27/02
IOT0041	Overview, CONTOUR Flight Readiness Review spacecraft status	APL	6/26/02
IOT0042	Analysis, CONTOUR grain stress	Landsbaum, Sallam	2/04/03
IOT0043	Report, CONTOUR Independent Assessment Team, findings & recommendations	Schallenmuller	12/15/00
IOT0044	Report, CONTOUR MIB STAR 30BP SRM convective plume heating final segment (NGIMS heating)	Rattenni	4/22/03
IOT0045	Preliminary Findings, CONTOUR MIB STAR 30BP SRM convective plume heating	Rattenni	4/10/03

IOT0046	Report, CONTOUR MIB STAR 30BP SRM radiative plume heating	Rattenni	3/11/03
IOT0047	Plan, CONTOUR mission assurance	APL	12/01/99
IOT0048	Concept, CONTOUR mission operations	APL	9/01/00
IOT0049	Assessment, CONTOUR orbital debris	APL	7/25/00
IOT0050	Paper, "Navigating CONTOUR Using the Noncoherent Transceiver Technique"	Carranza, et al	2/09/03
IOT0051	Procedure, CONTOUR performance test	APL	3/01/02
IOT0052	Pin tip temperature, CONTOUR	ATK	12/06/02
IOT0053	Press kit, CONTOUR	NASA	7/02/03
IOT0054	Project plan, CONTOUR	APL	2/01/01
IOT0055	Project policy & procedures, CONTOUR, closure of action items from project review	Chiu	3/06/00
IOT0056	Thermal analysis, CONTOUR thermal model generator	ATK	10/01/02
IOT0057	Analysis, CONTOUR propellant tank	APL	1/23/03
IOT0058	Interim results, CONTOUR propellant temperature with APL Viewfactors	ATK	11/05/02
IOT0059	Procedure, CONTOUR SRM processing	APL	3/17/02
IOT0060	Procedure, CONTOUR spacecraft acoustic test, 7379-9251	APL	1/14/02
IOT0061	Assessment, CONTOUR spacecraft base heating, SD 05-010001 Revision: 00	B. Smith	3/20/03
IOT0062	Assessment, CONTOUR spacecraft base heating, SD 05-010001 Revision: 00	B. Smith	3/20/03
IOT0063	Report, CONTOUR spacecraft breakup options as related to predicted separation velocities	Mangus	3/01/03
IOT0064	Procedure, CONTOUR spacecraft functional test	APL	3/18/02
IOT0065	Procedure, CONTOUR spacecraft separation/shock test, 7379-9252	APL	1/14/02
IOT0066	Procedure, CONTOUR spacecraft shipping and handling, 7379-9420	APL	3/18/02
IOT0067	Procedure, CONTOUR spacecraft spin balance/mass properties, 7379-9253	APL	1/14/02
IOT0068	Procedure, CONTOUR spacecraft vibration test, 7379-9250	APL	1/14/02
IOT0069	Report, CONTOUR SRM analysis for variable offload configurations STAR 30BP, S/N 074	Bulthsinghala	2/19/03
IOT0070	Analysis, CONTOUR SRM ballistics, STAR 30BP, S/N 074	Bulthsinghala	1/22/03
IOT0071	File, CONTOUR SRM burn command	APL	10/09/02
IOT0072	Telemetry, CONTOUR SRM state v01 (last telemetry)	APL	12/09/02
IOT0073	Structure Peer Review & FFR, CONTOUR structural analysis: 08/07/00	Sholar	8/07/00
IOT0074	Structural FFR, CONTOUR, thermal design 04/07/00	APL	4/07/00
IOT0075	Questions from NASA HQ meeting, thermal	APL	10/10/02
IOT0076	Timeline, Delta V and G load	Mangus	3/28/03
IOT0077	Diagram, CONTOUR with instruments	APL	8/25/02
IOT0078	CONTOUR-FM1 (accel data during launch)	APL	11/26/02
IOT0079	Preliminary Report Summary, CONTOUR mishap investigation	Bradley	11/05/02
IOT0080	Conversation with Jim Stratton	Leeds	10/03/02
IOT0081	Diagrams, CONTOUR spacecraft layout	Willey	12/12/00
IOT0082	Detailed mission requirements, CONTOUR	APL	3/29/01
IOT0083	dipak J2000 sc p v 0802 0816 (CONTOUR Ephemeris)	JPL	10/09/02
IOT0084	Pre-Ship Review, CONTOUR, April 2002	Reynolds	4/01/02
IOT0085	Report, Effect of Temperature on Ultimate Tensile Strength of Aluminum Alloys	Perez	1/03/03
IOT0086	SRM burn performance - Delta V error budget	van der Ha	4/10/03
IOT0087	Database, APL failure scenario	APL	9/10/02
IOT0088	APL fabrication feasibility review action items	APL	8/09/00
IOT0089	Final CONTOUR navigation results, T. Taylor	Taylor	4/11/03
IOT0090	MIB final post review questions 09/13/02	MIB	9/13/02

IOT0091	APL fishbone for CONTOUR	APL	9/11/02
IOT0092	Report, Further Studies Using a Novel Free Molecule Rocket Plume Model	Woronowicz	12/13/02
IOT0093	Software, CONTOUR guidance and navigation flight and test bed	Heiligman	12/21/01
IOT0094	Heat transfer coef calculations for CONTOUR SPAF in closeout blanket	Giacobbe	4/03/03
IOT0095	Work Instruction Sheet, Hydrazine LPS, WI-34314-980	Primex	6/04/01
IOT0096	Non-conformance report, hydrazine tank porosity, RR 92144	ATK	3/26/01
IOT0097-01	White room humidity level, image 1		
IOT0097-02	White room humidity level, image 2		
IOT0097-03	White room humidity level, image 3		
IOT0098	Integrated Mission Assurance Review, CONTOUR	APL, KSC	6/11/02
IOT0099	Inertia database 2, CONTOUR	APL	11/12/02
IOT0100	Plan, CONTOUR integration and test, 7379-9030	APL	8/21/01
IOT0101	Policy, internal delivery review	Chiu	9/05/01
IOT0102	Report, Spinning Mode: Analysis of ‘Jet Damping’ Effects during SRM Burn	van der Ha	11/04/02
IOT0103	Requests for Information, CONTOUR MIB	Taylor	11/25/02
IOT0104	Procedure, CONTOUR spacecraft launch countdown, 7379-9394	APL	6/29/02
IOT0105	Procedure, CONTOUR launch pad hazardous closeout, 7379-9267	APL	6/17/02
IOT0106	Procedure, CONTOUR launch site mechanical handling, 7379-9241	APL	4/02/02
IOT0107	Test Plan, CONTOUR launch site operations, 7379-9240	APL	11/28/01
IOT0108	Report, Mass Properties During SRM Burn	APL	10/17/02
IOT0109	Report, Mass Properties Post KSC	Sholar	10/01/02
IOT0110	Mechanical properties, solid rocket fuel	Stratton	12/02/00
IOT0111	Report, CONTOUR Spacecraft Strength Margins @ Star 30BP Interface	Sholar	12/18/02
IOT0112	Mission success criteria, CONTOUR	APL	
IOT0113	Mission timeline, CONTOUR, v.20	APL	9/06/02
IOT0114	Report, CONTOUR Moment of Inertia Variation during SRM Firing	Mangus	5/09/03
IOT0115	Monthly telecon, status report of CONTOUR, 09/12/02	Reynolds	9/12/02
IOT0116	Manufacturing Readiness Review, CONTOUR	APL	5/15/02
IOT0117	Purchase specification, near 9 ampere hour advanced nickel cadmium battery cells near 7352-9054	APL	10/17/02
IOT0118	Notes, residence time for throat blockage	Perez	12/17/02
IOT0119	NASA Procedures and Guidelines, NPG 8621	NASA	6/02/00
IOT0120	Report, Nutation Damping Under Jet-Damping Effects during SRM Burn	van der Ha	11/21/02
IOT0121	OSC Pegasus Propellant Tank Assembly, P/N D20388	OSC	3/11/98
IOT0122	Action item responses, CONTOUR PDR, #10, 11,14, 17,28,35,38,39	Reynolds	4/04/00
IOT0123	Preliminary Design Review, CONTOUR	APL	1/18/00
IOT0124	Pre-Environmental Review, CONTOUR	APL	1/08/02
IOT0125	Plume analysis, Indostar		
IOT0126	Post review question/answer for 9/13/02, APL	APL	9/24/02
IOT0127	Pre-SRM burn state vectors	Dunham	10/09/02
IOT0128	Pre-ship Review, CONTOUR	APL	4/19/02
IOT0129	Qualification Test Report, Orbit Insertion Motor for HS-376 Satellite	ATK	6/10/85
IOT0130	Question 2 re: APL response, 9/13/02	APL	9/13/02
IOT0131	Question 4 re: mass properties history, APL response, 9/13/02	APL	9/13/02
IOT0132	Question 7 re: SRM vibration test, APL response, 9/13/02	APL	9/13/02

IOT0133	Question 16 re: SRM separation, APL response, 9/13/02	APL	9/13/02
IOT0134	Question 19 re: MOI ratio spin stable, APL answer, 9/13/02	APL	9/13/02
IOT0135	Data requests for ATK, Item 1, ballistic data	Carr	9/19/02
IOT0136	Response re: viewgraph presentation on thermostat cycling	Prins	1/13/03
IOT0137	Report, Revised CONTOUR Button and SPAF Thermal Analysis	Magee	5/09/03
IOT0138	Report, Revised CONTOUR Button and SPAF Thermal Analysis	Magee	1/21/03
IOT0139	Report, Rocket Thrust Perturbation from Discharge of an Inert Body	Murdock	3/01/86
IOT0140	Report, Slag Accumulation in TITAN SRMU	Murdock	6/27/94
IOT0141	Report, Slag Effects on Coning Instability for CONTOUR	Stampleman	12/05/02
IOT0142	Report, Slag Effects on Coning Instability for CONTOUR update	Stampleman	12/09/02
IOT0143	Software Development/Management Plan, 7379-9330	APL	1/01/00
IOT0144	Solid Rocket Motor Characteristics	Stratton	8/30/02
IOT0145	Report, AIAA 2000-3575, Solid Rocket Nozzle Anomalies	Patel	2000
IOT0146	Spacecraft debris field		9/04/02
IOT0147	Spacecraft debris, Hawaii		9/04/02
IOT0148	Procedure, spacecraft fuel loading, OMI#E5502	Boeing	9/20/01
IOT0149	Diagram, spacecraft orbital configuration	APL	11/08/02
IOT0150	Test, CONTOUR SPAF closeout blanket strength	APL	11/28/02
IOT0151	Thermal Analysis, SPAF buttons	APL	1/09/03
IOT0152	Thermal Analysis, SPAF buttons, rev. A	APL	1/13/03
IOT0153	Spin mode stability update	van der Ha	9/18/02
IOT0154	Spin rate versus temperature	van der Ha	11/21/02
IOT0155	Spinning mode stability	van der Ha	2/22/00
IOT0156	SRM burn control commands	APL	9/09/02
IOT0157	Procedure, SRM heater wiring checkout, 7379-9091	APL	3/08/02
IOT0158	Preliminary report, SRM mass properties	Stratton	8/29/01
IOT0159	SRM ballistic data	Carr	9/19/02
IOT0160	Overview, SRM	Willey	7/14/00
IOT0161	SRM propellant grain discoloration	Crock	1/24/03
IOT0162	Integration procedure, safe/arm switch assembly, 7379-9265	APL	3/08/02
IOT0163	SRM thermal analysis, MIB requested	APL	9/24/02
IOT0164	Case study, SRM throat blockage	Aerospace	12/17/02
IOT0165	Case study, SRM throat blockage, Rev 1	Aerospace	12/18/02
IOT0166	Stage 1 actions (Mehoke response to heating and thread items)	Mehoke	1/21/03
IOT0167	Report, STAR 30 BP Convective Influences on SPAF Closeout Ring	Woronowicz	12/10/02
IOT0168-01	STAR 30 grain (x-ray of various parts), ATK-1202529-01	ATK	
IOT0168-02	STAR 30 grain (x-ray of various parts), ATK-1202529-02	ATK	
IOT0168-03	STAR 30 grain (x-ray of various parts), ATK-1202529-03	ATK	
IOT0168-04	STAR 30 grain (x-ray of various parts), ATK-1202529-04	ATK	
IOT0168-05	STAR 30 grain (x-ray of various parts), ATK-1202529-05	ATK	
IOT0168-06	STAR 30 grain (x-ray of various parts), ATK-1202529-06	ATK	
IOT0169	Report, STAR 30B Exhaust Plume Searchlight Effect and Closeout Blanket Fastening Button Thermal Analysis for CONTOUR MIB	Giacobbe	6/12/03
IOT0170	Structural analysis, STAR 30 motor	Sallam	11/21/02
IOT0171	Structural analysis, STAR 30 motor, final	Sallam	1/17/03
IOT0172	Thermo-structural analysis, STAR 30 motor	Sallam	1/17/03
IOT0173	STAR 30 plume data, AEDC	AEDC	8/24/85
IOT0174	STAR 30 thermostat cycling and temperature profiles	Prins	12/19/02
IOT0175	STAR 30BP SRM thermal properties	Stratton	11/19/01

IOT0176	STAR 30C apogee motor firing temperature data summary	Iwai/Boeing	2/05/03
IOT0177	STAR30 key thermal properties, ATK	ATK	2/04/03
IOT0178	STAR30BP expected burn characteristics	Unknown	6/12/00
IOT0179	State of hydrazine tanks	Stratton	8/29/02
IOT0180	Structural analysis, Peer Review/FFR	Sholar	8/07/00
IOT0181	Report, Studies Using a Novel Free Molecule Rocket Plume Model	Woronowicz	12/13/02
IOT0182	Document, CONTOUR Mission System Requirements, 7379-9001	APL	11/21/00
IOT0183	Document, CONTOUR Test Interfaces and Requirements, 7379-9031	APL	1/04/02
IOT0184	Presentation, CONTOUR Thermal - Structural FFR	APL	8/07/00
IOT0185	Integrated ATK/APL analysis, Thermal Analysis of the CONTOUR STAR 30BP Motor During Cruise	ATK	2/04/03
IOT0186	Thermal design, CONTOUR Critical Design Review	Mehoke	12/12/00
IOT0187	Questions to ATK and response, Theron Bradley	ATK	12/11/02
IOT0188	Report, Thrust Force and Spacecraft Acceleration during SRM Burn	Mangus	4/24/03
IOT0189	Report, Results of Time-Varying Jet Damping Torque during SRM Burn	van der Ha	11/18/02
IOT0190	Report, TIROS-N Anomaly: Contamination of Thermal Surfaces during SRM Burn	Predmore/ NASA	2/28/79
IOT0191	Spreadsheet, CONTOUR environments comparison	Gay	6/09/03
IOT0192-01	CONTOUR Spacecraft Base Heating Assessment, SD 05-010001 Revision:01 Title Page	B. Smith	5/30/03
IOT0192-02	CONTOUR Spacecraft Base Heating Assessment, SD 05-010001 Revision:01	B. Smith	5/30/03
IOT0193	Final Report, CONTOUR SRM Plume Convective Heating Analysis, Rev A	Rattenni	5/15/03
IOT0194	Report, Cooperative Efforts on Plume Radiative Heat Transfer	Giacobbe	6/10/03
IOT0195	Report, CONTOUR Dynamic Performance due to NGIMS Loss	Mangus	5/30/03
IOT0196	Report, Further Analysis of Star 30 Convective Influences on SPAF Closeout Ring	Woronowicz	5/20/03

APPENDIX K

CONTOUR Mishap Investigation Board Nomenclature

ACRONYMS

ACM	Attitude Control Maneuver
ADCS	Attitude Determination and Control Subsystem
AEDC	Arnold Engineering Development Center, Arnold AFB, TN
AKM	Apogee Kick Motor
ATK	Alliant Techsystems Tactical Systems Company LLC, Elkton, MD
APL	Johns Hopkins University Applied Physics Laboratory, Laurel, MD
B-SAT	Broadcasting Satellite System Corporation of Tokyo
BSS	Boeing Satellite Systems
CA	Conjunction Analysis
CDR	Critical Design Review
CFI	CONTOUR Forward Imager
CIDA	Comet Dust Analyzer
COLA	Collision Avoidance
CONTOUR	Comet Nucleus Tour
CM	Center of Mass
CRISP	CONTOUR Remote Imager and Spectrograph
DMSP	Defense Meteorological Satellite Program
DPM	Discovery Program Manager
DSN	NASA Deep Space Network
EB weld	Electron Beam weld
ETA	Explosive Transfer Assembly
FFR	Fabrication Feasibility Review

FRR	Flight Readiness Review
GSFC	Goddard Space Flight Center, Greenbelt, MD
JHU/APL	The Johns Hopkins University/Applied Physics Laboratory, Laurel, MD
JSC	Johnson Space Center, Houston, TX
KSC	Kennedy Space Center, FL
LAT	Lot Acceptance Testing
LEO	Low Earth Orbit
LPS	Liquid Propulsion System
MECO	Main Engine Cutoff
MEOP	Maximum Expected Operating Pressure
M&IR	Manufacturing and Inspection Report
MIB	Mishap Investigation Board
MLI	Multi-Layer Insulation
MOI	Moment of Inertia
MRR	Manufacturing Readiness Review
MS	Margin of Safety
NCR	Non-Conformance Report
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NEAR	Near Earth Asteroid Rendezvous
NGIMS	Neutral Gas and Ion Mass Spectrometer
NMO	NASA Management Office, Pasadena, CA
NPG	NASA Procedures and Guidelines

OSC	Orbital Sciences Corporation, Dulles, VA
PAF	Payload Adaptor Fitting
PER	Pre-Environmental Review
PI	Principal Investigator
PMC	Program Management Council
PSD	Power Spectral Density
PSR	Pre-Ship Review
PT	Penetrant Testing
R_{gain}	SRM feed forward disturbance torque
RCS	Reaction Control System
RFI	Requests for Information
RT	Radiographic Testing
S&A	Safe and Arm device
S/C	Spacecraft
SCM	Spin Control Maneuver
S/N	Serial Number
SAEF	Spacecraft Assembly and Encapsulation Facility, KSC
SPAF	Spacecraft/Payload Attachment Fitting
SRM	Solid Rocket Motor
SRMU	Solid Rocket Motor Upgrade
SW3	Comet Schwassmann-Wachmann-3
TBI	Through-Bulkhead Initiators
TCS	Thermal Control System

TDC	Technical Document Center
TIMED	Termosphere, Ionosphere, Mesosphere, Energetics, and Dynamics spacecraft
TMG	Thermal Model Generator
UT	Ultrasonic Testing
WAD	Work Authorization Document

UNITS

AU	Astronomical Unit
cm	centimeter
g	acceleration of gravity
km	kilometer
lbf	pounds-force
lbm	pounds-mass
psig	pounds per square inch, gauge
sun	1358 Watts per square meter