Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO) Spacecraft

Independent Technical Assessment

Performed by

The NASA Engineering and Safety Center (NESC)

March 7, 2005

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Report of the ITA Findings to the NESC

1 Identification

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Short Title: CALIPSO Spacecraft Proteus Propulsion System Assessment	
Description: Personnel hazards associated with Proteus Hydrazine propulsion bus once loaded (launch-36 days)	
Date Received: 10-22-03	**Date ITA/I Initiated:** 11-06-03
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2 Executive Summary

The CALIPSO spacecraft is scheduled for launch on a Boeing Delta II rocket from Space Launch Complex-2 (SLC-2) at Vandenberg Air Force Base (VAFB) in 2005. CALIPSO uses an "off the shelf" hydrazine-fueled Proteus propulsion bus manufactured by Alcatel Space Industries. Refer to Addendum 3 to this report for Alcatel site visit notes. The bus is provided by the Centre National d'Etudes Spatiales (CNES) as part of its in-kind contribution to the joint mission. While an identical bus was flown in 2001 on the Jason-1 spacecraft, concerns have been raised by GSFC safety and engineering that the Proteus bus does not meet NASA fault tolerance design guidelines[1] or all of the Air Force Eastern and Western Range (EWR) requirements[2], thus posing an unacceptable hazard to processing personnel. The Air Force EWR, Kennedy Space Center (KSC) Expendable Launch Vehicle Office, and Langley Research Center (LaRC) are all in agreement that the spacecraft is safe to process and launch given the planned spacecraft integrity testing and operational controls in place. GSFC believes the risks from these potential events have been incorrectly classified and has recommended additional measures to mitigate personnel hazards assuming the undesired events will occur.

The scope of this effort was a review of the Proteus propulsion bus design and an assessment of the potential for personnel exposure to hydrazine propellant. Loss of mission, spacecraft or launch

facilities is obviously an undesired outcome, but was purposely placed outside the scope of this assessment. The duration of this assessment was two months. Specifically reviewed were the potential for leakage from the five (5) mechanical fittings on the Proteus bus, potential leakage through the thruster valves and the potential for an inadvertent firing of the thrusters. These personnel hazards exist only during the period when the system is filled and pressurized until launch (approximately 36 days). Material from a variety of sources was reviewed and a site visit was made to VAFB to review the payload processing facilities and Delta II pad where CALIPSO will be processed and launched. It should be noted that key CNES information requested for this assessment through the GSFC program office was not provided (ref. Appendix A). This fact limited the review team's ability to draw conclusions based on objective evidence and formed the basis for many of the requirements.

The NESC acknowledges that welded joints are superior to mechanical fittings in preventing leakage but attention to workmanship and proper verification of the joint integrity is required for both. Mechanical fittings do afford a greater degree of flexibility in the assembly and repair of tubing systems. However, a thorough risk assessment must be conducted early in the design process to arrive at a configuration that presents the overall minimum risk to personnel, the mission and the environment. During the course of the review it was noted that the hydrazine system does not have a tank isolation valve. The NESC team acknowledges that the omission of a tank isolation valve in the propulsion feed system is less safe during ground operations than a system that has the capability to isolate leaks; but while one may be safer, both can be made safe through proper hardware development and launch site processes. Again, a thorough risk assessment must be performed when designing the spacecraft to make these configuration decisions.

The Program adequately addressed all eleven (11) NESC requirements stated in this report and, therefore, the NESC concluded personnel risk is acceptable. Eight addendums to the original report have been added to this revision (Version 2.0) that provides the details substantiating the NESC position. The addendums describe a combination of tests, site inspections, analysis, and a summary briefing.

3 Detailed Description of the Problem

CALIPSO is a joint science mission between the CNES, LaRC and GSFC. It was selected as an Earth System Science Pathfinder satellite mission in December 1998 to address the role of clouds and aerosols in the Earth's radiation budget. The spacecraft includes a NASA light detecting and ranging (LIDAR) instrument, a NASA wide-field camera and a CNES imaging infrared radiometer.

The issues addressed in this assessment involve the Proteus spacecraft bus provided to CNES via subcontract with Alcatel Space Industries. This bus is identical to that flown on the Jason-1 mission launched in December 2001 on a Delta II from VAFB. NASA's Jet Propulsion Lab managed the Jason-1 mission. Issues on CALIPSO are associated with the Proteus hydrazine propulsion system used for orbit corrections depicted in Figure 1. The system has five (5) mechanical MS-33656 37° Army/Navy (A/N) fittings, one located at each of the four (4) 0.225 pound-force thrusters (Astrium model CHT 1N) and one at the outlet of the ten (10) gallon hydrazine tank manufactured by Rafael. All other connections in the hydrazine system are welded.

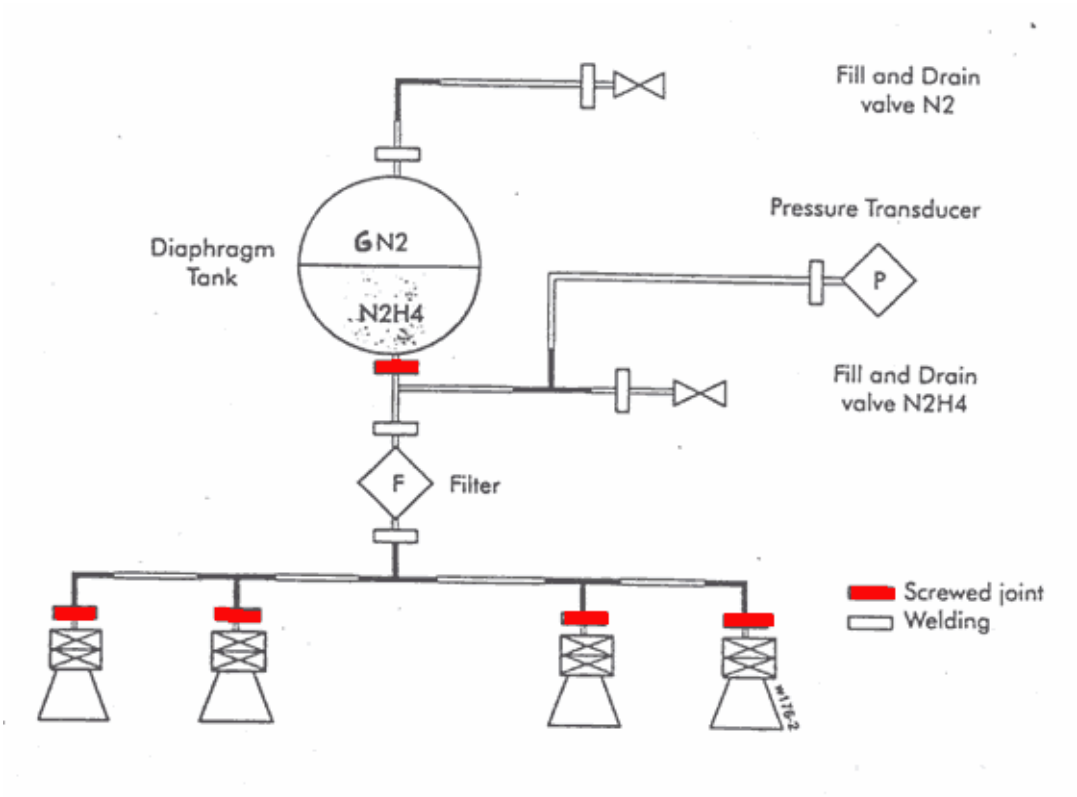

Figure 1. Schematic of CALIPSO Propulsion System

Three key issues have been highlighted: (1) use of mechanical fittings instead of welded joints for propulsion system fluid connections, (2) the potential for hydrazine leakage through thrusters, and (3) the potential for inadvertent thruster firing. Personnel risks associated with these issues are:

- Toxic exposure to hydrazine leakage from the mechanical fittings.
- Toxic exposure to un-reacted hydrazine in the thruster exhaust via leakage through the thruster valves or inadvertent thruster firing.
- Fire potential from hydrazine leakage and subsequent contact with incompatible spacecraft materials.
- Fire potential from thruster hot gas exhaust igniting combustible spacecraft materials.

4 Causal Factors

NESC focused on the three key issues as stated above. A detailed assessment of the causal factors that could potentially lead to a catastrophic event can be found in the NESC-developed fault tree (ref. Appendix B). A more general discussion follows.

Leakage through the mechanical fitting can be influenced by a number of design, environmental, assembly and processing factors. The design of the fitting must provide a consistent clamping force sufficient to provide sealing integrity in the environment to which it will be exposed. Key design factors include adequacy of structural/mechanical design margins and compatibility of material selections of the various A/N fitting components. Environmental factors that could influence leakage include temperature, pressure, vibration and shock. The environmental factors must consider the flight mission as well as those induced during spacecraft transportation and during ground processing. Assembly and processing factors that must be considered include proper torque application, potential for the introduction of contamination in the assembly and potential damage induced during assembly. A comprehensive qualification and acceptance test program can both certify the design for these conditions and verify the adequacy of the assembly process.

Leakage through the thruster can also be influenced by a number of design, environmental, assembly and processing factors. Flow control valves located upstream of each thruster physically control propellant flow to the thruster catalyst bed. Key design factors for the valve include adequacy of structural/mechanical design margins and compatibility of material selected for the valve components. A number of environmental factors can influence the performance of the valve and its propensity for leakage. They include temperature, pressure, vibration and shock, and must be considered for both the flight mission as well as those induced during spacecraft transportation and ground processing. Risk of leakage through the flow control valves can be significantly reduced with a comprehensive qualification and acceptance test program by certifying the design and verifying the adequacy of the assembly process.

An inadvertent thruster firing could be initiated by unintentionally applying power to the actuation circuit, the drivers or the valve solenoids. The power source could be from the Ground Support Equipment (GSE) or an internal short in the spacecraft electronics. One additional influencing factor could be an inadvertent ON command by the spacecraft or GSE software. Typical safeguards used to minimize the potential for inadvertent thruster firing includes redundancy in the design which would require multiple failures to apply power and designs having multiple inhibits to prevent inadvertent application of power.

5 NESC Risk Assessment

5.1 Overview

Anhydrous hydrazine (N_2H_4) is a colorless, oily, flammable liquid that is miscible with water. It has a penetrating odor resembling that of ammonia with an odor threshold of 3.7 parts per million (ppm). The National Institute of Occupational Safety and Health's immediately dangerous to life or health (NIOSH IDLH) limit is set at 50 ppm[3]. This is the recommended exposure limit to ensure that a worker can escape from an exposure condition that is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from the environment. The Occupational Safety and Health Administration permissible exposure limit (OSHA PEL) for hydrazine is 1 ppm[4]. This is expressed as a time-weighted average and is the concentration of a substance to which most workers can be exposed without adverse effect averaged over a normal 8-hour workday or a 40-hour work week. The American Conference of Governmental and Industrial Hygienists' threshold limit value (ACGIH TLV) is 0.01 ppm[5] and is expressed as a time-weighted average; the concentration of a substance to which most workers can be exposed without adverse effects. It should be noted that OSHA numbers are regulatory, whereas NIOSH and ACGIH numbers are advisory. NASA and the Air Force use the more stringent time-weighted TLV of 0.01 ppm as the limit for worker exposure[6].

Hydrazine liquid is extremely reactive and contact with incompatible materials can spur spontaneous combustion resulting in a fire. The explosive range of hydrazine in air is between 4.7 and 99 percent. Although hydrazine is detonable above concentrations of 4.7 percent in air, its low vapor pressure of 0.27 pounds per square inch absolute makes it more difficult to build up sufficient concentrations in a well-ventilated area[7].

The fact a hazardous event is unlikely to occur does not mean it *cannot* occur. For the three fault tree events considered in Appendix B (leakage of the mechanical fittings, leakage through the thruster valves and inadvertent firing of the thruster) a wide range of probabilities were derived by the GSFC and LaRC Safety Offices along with differing opinions on severity. There is subjectivity in

determining an event probability as evidenced by the wide spread between the two safety offices. It was not feasible for the NESC to better quantify the probabilities through specific testing or analysis in the timeframe given. Hydrazine is a hazardous commodity and in the NESC assessment team's judgment, the possibility of leakage does exist and the event severity is catastrophic to personnel. Given this premise, the focus of this assessment was to minimize the probability that the current design could initiate these undesired events and ensure operational controls are in place to maximize personnel safety.

5.2 Fault Tree Analysis and Mitigation

The CALIPSO fault tree (Appendix B) and mitigation table (Appendix C) were developed to identify all possible initiators leading to the three events and provide mitigation rationale for these events. The methods of verification specified by NASA system safety standards are inspection, test, analysis, demonstration and similarity. However, for this assessment, demonstration ("We flew it before") and similarity ("It worked on Jason-1") were not used as a means of closing fault tree events. Specifically, closeout of fault tree events could not be made due to the lack of availability of assembly level procedures and specifications. Events that could not be closed were incorporated into the NESC requirements.

6 Overview of the Initial ITA Plan

NESC reviewed the Proteus propulsion system design to assess the potential for personnel exposure to hydrazine from mechanical fittings or thrusters as well as the potential for inadvertent thruster firing. This assessment focused only on hazards present from the time the propulsion system is filled with hydrazine and pressurized to final closeout for launch, a period of about 36 days. Suitability of the system for flight and the potential for damage to flight hardware or launch facilities during ground processing were considered program risks and were not addressed. Likewise, this assessment did not address workmanship issues. It was assumed that stamp warranties, training, and process controls were properly implemented, hardware was built to print and work tasks were complete as documented.

Fault trees for each of the potential failures under assessment were developed as presented in Appendix B. Credible failure modes were identified and the controls the CALIPSO program has placed on those failures assessed. For failures the program has not already assessed or for which controls were deemed inadequate, independent testing was conducted to validate the program's approach or additional controls were recommended.

7 Modifications to the ITA Plan

While decisions to incorporate or eliminate certain tests were made as the assessment matured, the basic ITA approach outlined above remained unchanged. Initially, NESC planned to build a flight fidelity mockup of the hydrazine tank, tubing and thruster setup to perform leak and vibration testing. After NESC requests for accurate configuration drawings were denied to the program by CNES, the value of the vibration testing was deemed questionable and dropped. A separate issue arose when conflicting data on the compatibility of hydrazine with the nickel seal in the A/N fitting was discovered. Compatibility tests, consultation with material compatibility experts and a literature search were added. Information from NASA's White Sands Test Facility (WSTF) surfaced during final report preparation that resulted in the addition of a 36 day room temperature nickel seal soak test. These results are provided in Addendum 4 to this report (see Section 9.1.2 for details).

8 ITA Team

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9 ITA Identified Alternative Courses of Action

9.1.0 – Mechanical Fitting Leakage

Properly welded fluid connections are inherently more reliable than mechanical fittings and should be incorporated in fluid propulsion system designs when possible. There are some circumstances, however, under which mechanical fittings offer an appropriate design solution. Ready interface to off-the-shelf parts, ease of maintenance, or potential for damage to soft goods during welding all may dictate use of threaded joints. MS-33656 type 37° A/N-fittings have been employed successfully in aerospace applications for many years and are acceptable for limited use providing they are (1) properly assembled, (2) validated by leak check as an assembly before use, (3) exposed only to temperature, pressure, vibration and shock environments for which they are certified, and (4) incorporate a secondary locking feature. The Proteus bus uses five such fittings; one at the hydrazine tank outlet and one at each of the thruster inlets (see Figures 2 and 3 for details). While lock-wire is used as a secondary locking feature, it is suitable only for preventing significant rotation of the B-nut and full disengagement of the fitting. Lock-wire alone will not prevent loss of joint preload[8] with subsequent reduction of clamping force at the sealing surfaces, and thus cannot be counted upon to prevent a fitting from leaking.

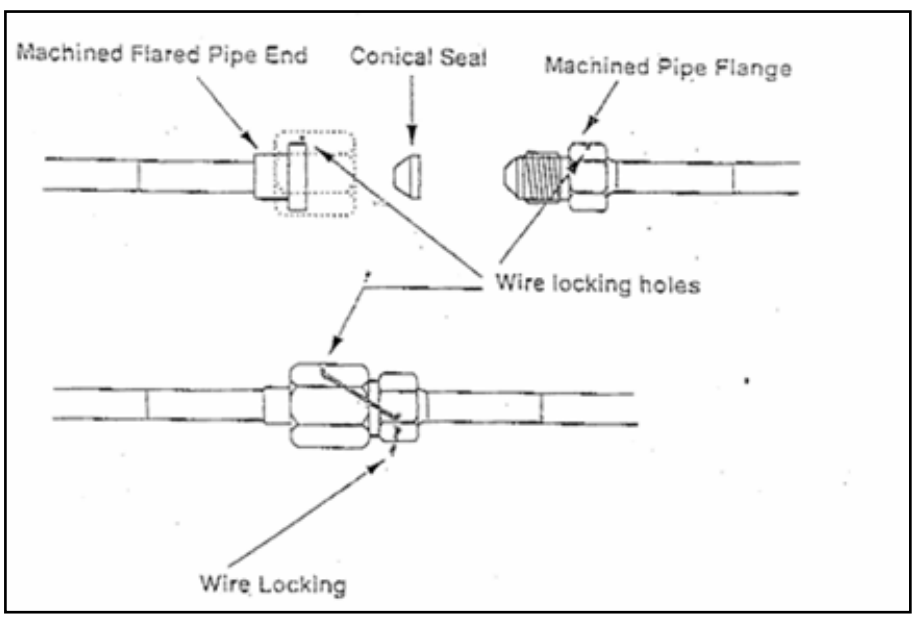

Figure 2. MS 33656 A/N fitting installation detail

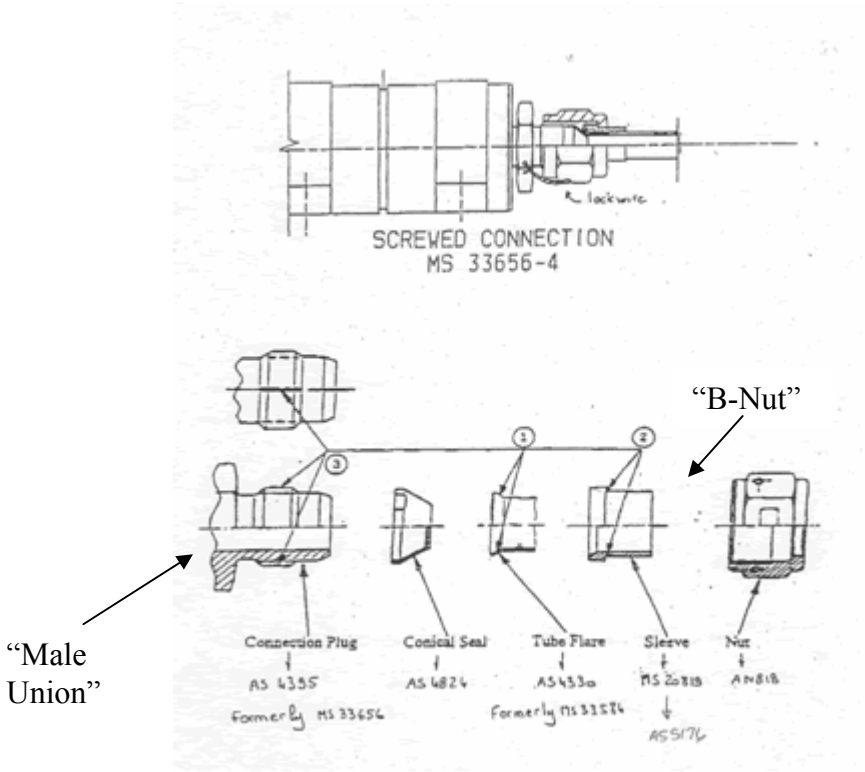

Figure 3. Exploded View of MS-33656-4 Fitting

While the NESC was not provided specific qualification and acceptance test data for the CALIPSO Proteus bus, the NESC reviewed relevant test data from other propulsion system and component tests. In general these tests addressed qualification, acceptance and sensitivity of the MS-33656 type 37° A/N fittings for exposure to the environmental conditions of temperature, pressure, vibration, shock and assembly cycles. The following sections of this report summarize three test series conducted on the MS-33656 threaded fitting and the mitigating actions required to assure integrity of the CALIPSO Proteus bus fittings.

9.1.0.0 – Review Voi-Shan Results of Evaluation Tests Conducted on Voi-Shan Conical Seals[9]

The objective of this test program was to demonstrate that the Voi-Shan conical seal would consistently seal a flared A/N fitting tube connection under varying applications. The test conditions were established in order to simulate very stringent requirements that could be encountered in actual usage. The environmental exposure conditions used in this test series are similar to the requirements for the CALIPSO spacecraft and in many cases bound them.

The test series used various sizes of the A/N 815 (fitting end, superseded by MS 33656, currently AS 4395), A/N 818 and A/N 819 (sleeve, superseded by MS 20819, currently AS5176), fittings and conical seals made in accordance with Voi-Shan standard VSF 1015 manufactured from aluminum, copper, tin and nickel. Test conditions included:

1. Pressure at room temperature of 1500–4500 pounds per square inch gage (psig) induced with helium, air and nitrogen and 6000 psig induced with hydraulic fluid.
2. Pressure at elevated temperature: 500°F at 3000 psig-air.
3. Pressure testing during repeated disassembly/assembly: 1500 psig for 20 cycles and 300 psig for 30 cycles.
4. Sine sweep vibration testing with 3000 psig pressure.
5. Torque relaxation combined with time (6 to 360 hours), pressure cycling and vibration.
6. Shock testing: 20g's shock at 3000 psig helium, and 100 g's shock at 3000 psig water.
7. Thermal Shock at 200ºF and 1500 psig-helium.
8. Pressure Impulse testing from 0-4500 psig at 35 cycles per minute for 100 cycles.

Several measurement techniques were used to measure leak rate depending on the tests being conducted. They included submersion in water or benzene, using a helium sensitive mass spectrometer, a visual inspection if liquids were being used as the pressure medium and pressure decay over time. Torque relaxation was measured by applying torque in the tightening direction and measuring the angle required to achieve to the original torque value.

The published results show a robust design for all of the configurations tested within the conditions specified. Test results indicated that all of the joints remained sealed with no leakage measured. The torque relaxation tests did show some relaxation over time and after exposure to pressure cycles. In the pressure cycle testing the largest change in torque was 27% and this occurred after the first pressure cycle. Torque relaxation reduced to no relaxation after the third cycle and only showed 13% relaxation after the second cycle worst case. Results of vibration tests showed no torque loss after exposure to vibration. The assembly, checkout and acceptance testing processes conducted on the CALIPSO Proteus bus can mitigate the two conditions (time and exposure to pressure) that did show some torque loss sensitivity.

9.1.0.1 – Review of European Retrievable Carrier (EURECA) Spacecraft Qualification Test Report for the ENN 51200 – Size 4 Joint for High Pressure Application[10]

The objective of this test program was to qualify the design of ENN 51200 E joint (MS-33656 flared tube connection) for the use in EURECA program for high-pressure applications. Qualification environments that the high-pressure joint was required to withstand include loads induced from the vibration environment, thermal environment, operational pressure and pressure cycling, mounting (assembly torque) activities, proof pressure and burst pressure. The environmental exposure conditions used in this test series are similar to the requirements for the CALIPSO spacecraft. Three configurations of tubing length combined with the MS-33656 fittings were included in the test series to represent different load influencing factors. These include an angle length configuration to induce torsion and bending on the fitting, a torsion lever configuration to induce torsion on the fitting, and a straight tube length to induce axial loads on the fitting during the thermal testing. Leak checks were performed pre and post exposure to the loading conditions. The setup for leak testing included a vacuum test chamber, the test article, a helium leak detector, a vacuum pump and a helium pressure supply. The external leak rate criteria indicated failure if it exceeded $1x10^{-6}$ standard cubic centimeters per second (scc/sec).

The published results of the test series indicated that there were no leak rate failures experienced for any of the three test configurations subjected to all of the loading conditions. The test report also emphasized that the loads induced by vibration in particular did not result in developing an external leak.

9.1.0.2 – Review of Experiments on the Robustness of Separable Fittings[11]

The objective of this test program was to investigate the effect of off nominal or stressing conditions on various mechanical fittings to assess the likelihood of leakage. Stressing conditions used in the test series included vibration (30 g's root mean square for 300 sec), thermal stress (exposure to cryogenic temperature), misalignment (2 degree offset), under-torque (50 % of nominal), and assembly in the presence of foreign debris (scoring of the sealing surface). The ½-inch size A/N fitting was one of four types being evaluated in the test series. Other types include a Dynatube fitting (beam seal tubing connector), a KC fitting (a modified A/N fitting with Teflon gasket), and a Swagelok fitting. Two test series were performed; one test series subjecting each fitting to various combinations of the stressing conditions and a second test series based on an eight row Taguchi matrix of conditions with the four fitting used in the first series plus one additional fitting called the GE fitting (A/N modified with a radiused or ball nose). Conditions for the second test series had also been modified based on results of the first test showing insensitivity to some of the stressing

conditions. The second test series has not been reported at this time so the following discussion is based on significant findings from the first test series.

Preliminary results of the first series of tests showed a wide variability of the various fitting responses to off-nominal conditions and identified some insensitivities that are relevant to the CALIPSO assessment. Even though these tests cannot explicitly quantify the integrity of the ¼-inch A/N fitting in the CALIPSO Proteus bus, data from these tests does show insensitivity or an inherent robustness of the A/N type fitting to some of the relevant causal factors associated with the hydrazine leak potential. It was determined that vibration and misalignment were not significant factors in the probability of leaks in the separable fittings as results showed negligible effect on the sealing qualities of the fittings. Surprisingly, the test series showed that vibration tended, if anything, to reduce leak rates more often than it increased them. In no case did a previously non-leaking fitting start to leak as a result of vibration and in 13 cases having the under-torque condition with a measurable leak rate, 10 cases had reduced leak rates after vibration. The two under-torqued A/N fittings with the largest pre-vibration leak rate had an increase in leak rate post vibration. With regard to misalignment, it was reported that the fittings appear to be sufficiently robust to withstand two degrees of misalignment prior to assembly. It was also reported that fittings that performed the most poorly were most sensitive to under-torque and contamination (scoring of the surface). Both the A/N and Swagelok fittings appeared to be sensitive to under-torque and surface scratches. However, appropriate inspection and assembly procedures and post-assembly acceptance testing can mitigate both of these sensitivities.

9.1.0.3 – Summary of Historical Data Review

MS-33656 threaded couplings show an inherent robustness if properly assembled, acceptance tested, leak checked and other appropriate checkouts are performed. Even though these test series do not constitute a qualification of these threaded fittings, they certainly demonstrate that the MS-33656 threaded coupling design provides adequate sealing integrity for the types of environments that the CALIPSO Proteus bus could be exposed to during its processing and flight mission.

9.1.1 – CALIPSO Proteus Bus Fitting Assembly

The torque level indicated by a gauge or wrench during fitting assembly does not represent actual clamping force at the sealing surface. In some cases, clamping force may not be sufficient to effectively seal a fitting, even though the B-nut is torqued to the specified level. Thread binding or physical interference with the wrench head can result in such a “false torque” condition. Mechanical fittings must be lubricated slightly to prevent galling and minimize the possibility of false torque. Quantity and location of lubricant must be controlled to ensure not only that it is applied but also that

it is applied only to moving parts and not to a sealing surface. Lube on a sealing surface may fill a scratch or other discrepancy allowing a fitting to pass leak check, only to be washed away or dissolved in the presence of liquid propellant creating a void that leads to a leak. CNES has indicated that lubricants were used in the assembly of the Proteus bus, but NESC was not provided copies of assembly procedures or specific data to indicate where, or in what quantities the lubricants were applied.

As an overarching statement, any procedure review or procedure development performed in response to the following eleven (11) NESC requirements ('R') should consider not only engineering content, but also the clarity or "workability" of the procedure from a human factors perspective. That is, care should be taken to ensure the procedures clearly convey the author's intent without ambiguity that could confuse the operator and lead to an unintended outcome.

NESC-R-001 – Program shall demonstrate that Alcatel training and/or assembly documentation provided for proper lubrication of fluid fittings during assembly. Assembly procedures shall clearly delineate the type, quantity and location where lubricant was applied and ensure sealing surfaces were kept dry and free of any contaminant.

Fittings must be visually inspected before assembly to ensure no discrepant condition exists that might lead to leakage. Damaged threads, burrs or machining marks may cause galling and subsequent false torque. A contaminant on a sealing surface may not be detected during leak checks, but be washed away or dissolved in the presence of liquid propellant creating a void that leads to a leak. NESC was not provided copies of assembly procedures documenting Proteus bus pre-assembly inspections.

NESC-R-002 – Program shall demonstrate that Alcatel training and/or assembly documentation provided for a visual inspection of fluid fittings prior to assembly. Assembly procedures shall ensure components had no visible defects and sealing surfaces were clean and dry.

9.1.2 – Material Compatibility

Fault tree assessment highlighted the potential for component failure as a result of material incompatibility. There was some conflict among the various sources consulted concerning the compatibility of nickel used in the MS-33656 fitting conical seals and hydrazine[12,13,14,15]. Materials experts at WSTF were consulted who indicated that decomposition of hydrazine when exposed to nickel is accelerated at temperatures above 212° F[16], but the small amount of surface area exposed in this application was insignificant to make decomposition a concern. The possibility of corrosion exists in the long-term, but it should not lead to leakage resulting in personnel exposure in the 36-day period under assessment. The fact Voi-Shan seals are not plated is also favorable in this regard.

However, since there were some lingering questions regarding compatibility and no evidence Alcatel conducted any definitive testing before incorporating nickel seals in the design, NESC elected to run a series of independent tests to ensure the seals and propellants were compatible. Aerojet was commissioned to conduct an accelerated aging test of the Voi-Shan nickel seals at elevated temperature and pressure, along with a room temperature "beaker soak test". The accelerated test will yield quick results, while the room temperature test will serve as a control to verify any positive evidence of decomposition is not due only to a temperature/pressure environment unlikely to be experienced by the spacecraft. Complete details of the Aerojet testing are included in Appendix E, and results are provided in Addendum 1 to this report.

9.1.3 – Post-Assembly Leak Checks

Leak checks provide confidence fluid fittings have been properly assembled and validate the overall integrity of the joints. They must be conducted at flight pressure, using media no more viscous than the propellants themselves and instrumentation suitable for detecting leaks at the smallest allowable level. Given the relatively low internal volume of the CALIPSO spacecraft and Delta-II launch vehicle fairing, hydrazine leakage at a detectible level may result in an accumulation that violates the OSHA PEL of 1 ppm during the 36-day period between propellant servicing and launch. The industry-standard approach to such situations is to conduct leak checks at flight pressure with helium using a mass spectrometer as a detector. Helium leak checks provide significant margin (approximately three orders of magnitude) over liquid hydrazine leakage. Therefore, a system verified leak tight with helium ($<10^{-6}$ scc/sec) will be leak tight for hydrazine unless a sufficient upsetting event occurs to change the status of the fitting[7].

CNES has indicated helium leak checks of the Proteus bus were conducted on a fitting-by-fitting basis after initial assembly. Total system leakage will be measured with an encapsulated helium mass spec before integration of the propulsion bus and again after environmental testing of the spacecraft. Specified limit for these tests is 8.4×10^{-5} scc/sec[17]. A final 12-hour decay test will be performed at the launch site before propellant servicing. NESC was not provided any other details regarding the leak test methods, specifications (including derivation of the 8.4×10^{-5} scc/sec limit), or detection equipment to be used for these tests. Bagging and long duration mass spectrometer measurements at both high and low pressure would provide maximum confidence that fittings do not have small but growing defects that could eventually leak hydrazine[7].

NESC-R-003 – Program shall demonstrate that the Proteus bus mechanical fittings are rigorously tested using techniques adequate to validate system integrity. Leak check procedures shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

While CNES indicated spacecraft environmental tests would simulate qualification-level vibration and thermal loads, NESC was not provided specific data describing the test series. If the acceptance test loads envelope shipping, transport and handling loads expected from propellant servicing through launch, the post-environment test leak check will serve not only to certify the assembly for the expected flight environment, but also as an effective screen for any fitting that may have passed initial leak checks at low (false) torque. During the site visit, VAFB relayed that the highest shock loading recorded during transport of a spacecraft was 0.6 g's. By comparison, the low frequency Delta II launch environment is 40 g's with high frequency response up to 2,500 g's[18]. Acceptance testing to these or higher levels would certainly envelope the expected ground processing loads.

NESC-R-004 – Program shall demonstrate that thermal and vibration loads applied to the spacecraft during environmental tests envelope conditions it will experience from servicing through launch.

9.1.4 – Handling Environment

Fluid fittings could be loosened if subjected to significant internal pressure or thermal transients. The period of highest vulnerability is during dynamic testing, especially propellant servicing, when pressures are cycled and the potential for flow-induced vibration exists. There is no indication that CALIPSO Proteus bus fittings will be subjected to cyclic thermal or transient pressures significant enough to cause leakage, and the induced vibration potential is minimal given the short line lengths and low flow rates involved. However, since the CALIPSO servicing procedures were not available for review, NESC was unable to assess controls placed on temperature, pressure and flow transients during hydrazine loading.

NESC-R-005 – Program shall demonstrate that servicing procedures adequately control temperature, pressure and flow rates to minimize the potential for leakage.

Even with all controls in place, the possibility of leakage still exists. Consequently, the program must take all reasonable precautions to ensure the spacecraft is monitored and personnel can be safely evacuated in the event of a leak. Industry-standard measures include a mix of fixed and portable

vapor detectors capable of monitoring in the appropriate range, area-warning systems and fixed control areas limiting the number of personnel with access to the spacecraft.

A site visit to VAFB was performed on December 17, 2003, to review the two potential payload processing facilities that will be used for CALIPSO and the Delta II launch pad "white room." A map of VAFB locating the various facilities is included as Appendix D. While the Astrotech facility was toured, the Spaceport Systems International (SSI) facility was under a security lockdown and was inaccessible. Hydrazine detectors used in the Astrotech facility can resolve leaks down to 0.001 ppm and typically are calibrated and set to sense at 0.005 ppm or one half of the ACGIH TLV. The Astrotech fixed detectors are Zellweger Analytics SPM line powered units with 0.005/0.010 ppm gas calibration keys while the portable units are SPM Z purge monitors with 0.005/0.010 ppm gas calibration keys. Both audible and visual alarms are tripped at 0.005 ppm and the automated response system commands roof louvers open and air exhaust fans to maximum capacity. Portable detectors are used at the beginning of every work shift to sweep the area for leaks before personnel are allowed to enter. A drain trench completely encompasses the area where CALIPSO will be fueled and serviced, and can easily capture the 30 kilograms (approximately 8 gallons) of hydrazine in the Proteus system. Similar detection schemes with alarms are used at the pad white room[6].

The Astrotech payload processing facility fire protection system incorporates dry- and wet-pipe deluge systems designed to meet code requirements while protecting hardware from damage caused by inadvertent activation[19]. The facilities are equipped with UV and IR detectors for continuous monitoring of high-hazard areas as well as ceiling-mounted smoke/heat detectors. Hydrazine sensors have fire alarm set points at one quarter the lower explosive limit (i.e., ¼ x 4.7 or 1.175 percent hydrazine in air). These alarms communicate with the base emergency response units. If SSI is selected to process CALIPSO, the project should verify the SSI detectors and alarms meet or exceed the capabilities stated above for the Astrotech facility.

Post-servicing operations in the vicinity of the CALIPSO spacecraft will be tightly controlled. "Amber light" operations will be in effect in the payload processing facility and at the SLC-2 launch pad white room. Per memo from the Air Force 30th Space Wing[20], "A flashing amber light indicates a hazardous operation is in progress in the controlled area. Non-essential personnel shall be cleared from the controlled area. Personnel shall not enter without permission from the safety official or in the absence of the safety official the entry control authority. Only mission essential personnel will be allowed near the spacecraft, all preventive measures will be instituted, facilities will be verified acceptable to handle a maximum credible spill and emergency response will be available and on call".

In the judgment of the NESC assessment team, the mix of hydrazine vapor detectors, fire detection and suppression equipment and personnel controls are adequate for conducting safe operations in vicinity of the CALIPSO spacecraft.

NESC-R-006 – Program shall verify that the controls at the processing facility and launch pad identified above are in place to monitor for leakage from the time hydrazine is loaded until final closeout for launch. Additionally, the program shall verify that spacecraft operations are minimized after hydrazine loading, and that provisions are made for area securing and the rapid evacuation of personnel should a leak develop. Further, the program shall coordinate with all other payload/Delta II processing personnel to ensure the program's approach for minimizing personnel exposure to potential hazards is properly integrated.

9.2.0 – Thruster Leakage

Thrusters selected for the Proteus bus are designed with normally closed series-redundant solenoid-actuated flow control valves manufactured by Moog. The thrusters are of a mature design. A schematic of the valve is depicted in Figure 4.

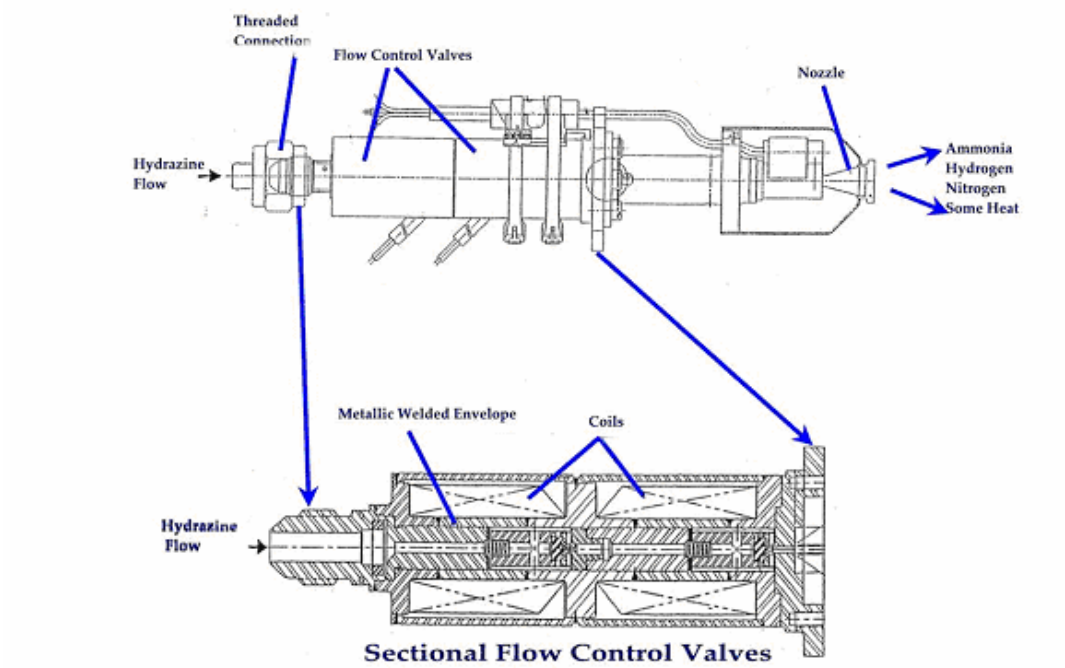

Figure 4. Moog Dual Seat Dual Servo Thruster Valve

NESC concludes the potential for external leakage from the thrusters either internally (across the control valves) or externally (thruster casing or seal) poses acceptable risk to personnel providing the program conducts an adequate pre-servicing leak check of each valve. While the program did indicate such testing was planned, NESC was not provided a specific description of the test or its pass/fail criteria.

NESC-R-007 – Program shall demonstrate that pre-servicing thruster leak checks will be adequate to validate system integrity. Leak check procedures shall test each valve independently and shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

During a site visit to Aerojet Space Propulsion, an issue with Moog thruster valves similar or identical to the Proteus valves came to light. A manufacturing process change by Moog resulted in a recall investigation on suspect serial number valves[21]. The program was notified of this and was working to clear the CALIPSO Proteus bus valve set.

NESC-R-008 Program shall verify that the Proteus Moog valves on CALIPSO do not have defective plunger assemblies.

9.3.0 – Thruster Inadvertent Firing

The Proteus thruster firing circuit incorporates a number of controls to ensure valves are not inadvertently opened causing a thruster to fire. NESC concurs the controls are adequate, but recommends further steps be taken to positively preclude the possibility of an inadvertent command during periods of dynamic testing, especially power-up. A schematic of the thruster wiring circuit is shown in Figure 5. It is worth noting that the Astrium specification sheet for the thruster lists nominal flow rate at 0.44 grams per second. Even with all four (4) thrusters firing at nominal flow rate, it would take 4.7 hours to drain the 30 kilograms of hydrazine in the propellant tank.

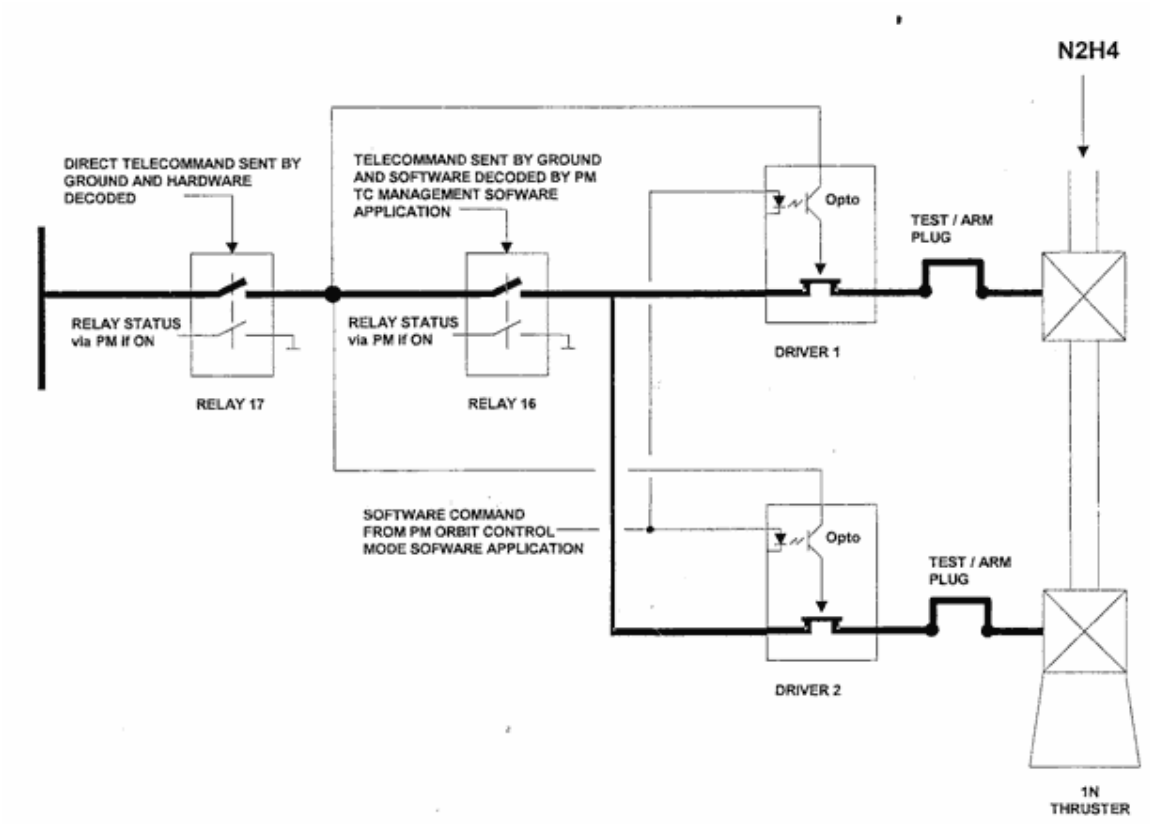

Figure 5. Thruster Circuit Schematic with New Test/Arm Plugs (PM refers to spacecraft processor module)

NESC-R-009 – Program shall demonstrate that test procedures verify relays 16 and 17 are open before power is applied to the spacecraft. Since the design incorporates latching relays, verification of the last stable state by data retrieval or written record is acceptable.

NESC-R-010 – Steps for inserting and removing test/arm plugs shall be explicitly called out in the ground processing timeline. Final installation for flight shall occur as late as possible; until that time, plugs shall only be installed as required for thruster valve testing.

NESC-R-011 – Program shall verify that all thruster firing circuit inhibits function as designed.

10 Conclusion

It should again be noted that key CNES information requested for this assessment through the GSFC Program Office was not provided (ref. Appendix A). This fact limited the review team's ability to draw conclusions based on objective evidence and formed the basis for many of the requirements. At this time, the NESC cannot objectively conclude that the Proteus bus as designed poses either acceptable or unacceptable risk to personnel. The Program must adequately address all eleven (11) requirements stated in this report before the NESC can conclude personnel risk is acceptable. These requirements call for review of CNES assembly and acceptance test procedures and verification that the planned acceptance testing and integrity checks are performed by CNES before hydrazine is loaded into the system. Further, verification of the planned operational controls (e.g., leak detection, alarms, installation of thruster arm plugs, personnel controls and minimizing spacecraft operations once loaded) are required to mitigate the risks to an acceptable level. Aerojet conducted a series of tests on the compatibility of hydrazine with the Voi-Shan nickel conical seals. These test results are documented in Addendum 1 to this report.

The expected response from the CALIPSO program to the NESC will be an action plan indicating how the program will implement the eleven (11) NESC requirements using their in-line engineering, operation and safety organizations. NESC will approve the action plan and determine the adequacy of the Program's responses. (Refer to Addendum 8). As originator of the actions, NESC will provide status (open or closed) on each requirement at the appropriate CALIPSO milestone review prior to hydrazine loading. The Program should use Appendix C as a guide to address the NESC's requirements.

11 Minority Report

The NESC assessment team observed that there is no isolation valve downstream of the CALIPSO propellant tank. The GRC members were of the opinion that the program needed to address this issue in response to a specific NESC recommendation and offered the following:

> "The lack of an isolation valve in the Proteus bus design maximizes the potential for loss if any one of the three hazardous events were to occur, since there would then be no expedient means to stop the flow of hydrazine from the propellant tank. As a result, the worst-case failure effect is that most of the hydrazine in the propulsion system would be released, possibly causing a catastrophic event (personnel injury or fire). There is no evidence that a formal risk assessment was performed to address these three hazardous events related to the design decision to omit an isolation valve".

"Minority Opinion Recommendation – Program should perform or make available a formal risk assessment to address the three hazardous events related to the design decision to omit an isolation valve. As part of including an isolation valve in the design, this assessment should consider the replacement of the mechanical fitting closest to the tank with a welded joint."

Two NESC Review Board (NRB) members concurred with including this recommendation in the final report. The remainder did not, however, so by Board consensus it was rejected. While a thorough risk assessment early in the design process might have led to a different design solution, an assessment performed today would not reduce the potential for leakage from the fittings or thrusters and thus would not help mitigate the risks associated with the current design. Instead of incorporating the suggested recommendation, the Board ensured the lessons learned from this study and documented in Section 12 highlighted sound design solutions and underscored the need for thorough risk assessments early in the planning of any project.

12 Lessons Learned

Project managers should strive to ensure issues are surfaced and resolved, through independent assessment if necessary, early in the design process so technical changes can be effected with fewer cost and schedule implications. Thorough risk assessments must be performed to arrive at a configuration that presents the overall minimum risk to personnel, the mission and the environment. Such assessments should be well documented, approved through a formal process, and made available for reference should questions arise as a project proceeds.

When NASA is involved in missions with outside partners, the level of NASA insight and influence on non-NASA hardware design, verification and acceptance testing should be documented, clearly communicated, and carried as a project risk to be tracked. There was clearly confusion over certain safety requirements among the organizations involved in CALIPSO. The roles of various in-line and independent safety organizations should be clearly defined and their expectations documented as project requirements. Projects should then act to meet these requirements or, when warranted, process waivers with rigorous, documented, technical rationale.

Properly welded fluid connections are inherently more reliable than mechanical fittings and should be incorporated in fluid propulsion designs employing hazardous commodities whenever possible. This requirement should be reflected in appropriate Agency-level design standards and variance accepted only when accompanied by appropriate risk trades and supporting technical rationale.

Since lock wire does not prevent torque relaxation, it cannot be relied upon as a secondary locking device to prevent fluid fitting leakage. NASA or industry should spearhead development of a redundantly-sealed fluid fitting with an integral locking feature that, once engaged, will positively preclude loss of clamping force at the sealing surfaces. Ramped, inter-locking teeth between the inside rear of the B-nut and back of the tube end might serve this purpose if the ramp angle and teeth were sized to prevent nut rotation and loss of axial load with the fitting at full torque (ref. Nord-Lock Bolt Securing System, Nord-Lock AB, Mattmar, Sweden, www.nord-lock.com).

13 References

(1) NASA Procedural Requirement NPR-8715.3, "NASA Safety Manual", Change 1, June 19, 2003.

(2) CALIPSO-Tailored Eastern and Western Range 127-1 Safety Regulations, Doc. TP2.LB.0.AQ.1836 ASC, dated October 21-22, 2002.

(3) National Institute for Occupational Safety and Health (NIOSH), "Pocket Guide to Chemical Hazards". U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention. Cincinnati, OH. 1997.

(4) Occupational Safety and Health Administration (OSHA), "Occupational Safety and Health Standards, Toxic and Hazardous Substances". *Code of Federal Regulations.* 29 CFR 1910.1000. 1998.

(5) American Conference of Governmental Industrial Hygienists (ACGIH), "1999 TLVs and BEIs. Threshold Limit Values for Chemical Substances and Physical Agents, Biological Exposure Indices". Cincinnati, OH. 1999.

(6) Email from Thomas Palo, KSC Launch Services Program Safety and Mission Assurance Office, dated 1-9-04 with attachment – "CALIPSO Propulsion System Safety Assessment", dated December 2003.

(7) K. Coste, "Summary Comments on NESC CALIPSO Review", Aerospace Corporation TOR#2004(2181)-1, January 14, 2004.

(8) John H. Bickford, "An Introduction to the Design and Behavior of Bolted Joints", Third Edition, p. 553. Marcel Dekker, Inc. 270 Madison Avenue, New York, NY, 10016. 1995.

(9) Results of Evaluation Tests Conducted on Voi-Shan Conical Seals, Voi-Shan Engineering Report No. 249-64, March 6, 1964.

(10) EURECA – 31654-RP-EA-103, ISS.1, "Qualification Test Report for the ENN 51200-Size 4 European Retrievable Carrier", June 28, 1989.

(11) S. Georgian et al, "Experiments on the Robustness of Separable Fittings", AIAA#96-3116, 32nd Joint Propulsion Conference, July 1-3, 1996, Lake Buena Vista, FL.

(12) MSFC-HDBK-527, rev. F, "Material Selection List for Space Hardware Systems," September 30, 1988.

(13) B. Quill, "Spill Prevention Guidance Document", Appendix E – Chemical Compatibility Matrix, Users Guide UG-2033-ENV, Naval Facilities Engineering Research Center, October 1998.

(14) E. Cadwallader and L. Piper, "Hydrazine Compatibility Survey", CPIA Publication 236, June 1973.

(15) L. Toth et al, "Propellant/Material Compatibility Program and Results", NASA Technical Memorandum 33-779, August 15, 1976.

(16) M.D. Pedley et al, "Explosion, Compatibility and Safety Hazards of Hydrazine". RD-WSTF-002, NASA Johnson Space Center White Sands Test Facility, February 20, 1990.

(17) NESC–CALIPSO Propulsion Brief-6 by Don Porter, LaRC Mission Assurance Office, "Design for Minimum Risk Information", p. DJP-23, November 5, 2003.

(18) Boeing Delta II Interface Control Document for CALIPSO, MCD 01H0074 New, March 31, 2003.

(19) Astrotech VAFB Facility Safety Manual, SHI-ASO-M0011, Revision B, February 7, 2002.

(20) Memo dated November 17, 2003, from Air Force 30th Space Wing Chief of System Safety, Micheal McCombs.

(21) Lockheed Martin Space Systems Mission Success Bulletin #03-32, "Moog Dual Seat Propellant Valve with a Defective Plunger Assembly", December 12, 2003.

14 List of Acronyms

ACGIH TLV	American Conference of Governmental and Industrial Hygienists' threshold limit value
A/N	Army/Navy
CALIPSO	Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observations
CNES	Centre National d'Etudes Spatiales
EURECA	European Retrievable Carrier
EWR	Eastern and Western Range
GRC	Glenn Research Center
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
ITA/I	Independent Technical Assessment/Inspection
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LIDAR	Light detecting and ranging
N_2H_4	Anhydrous Hydrazine
NCE	NESC Chief Engineer
NESC	NASA Engineering and Safety Center
NIOSH IDLH	National Institute of Occupational Safety and Health immediately dangerous to life or health limit
OSHA PEL	Occupational Safety and Health Administration permissible exposure limit
PM	Processor Module
ppm	parts per million
psig	pounds per square inch gage
scc/sec	Standard cubic centimeters per second
SLC	Space Launch Complex
SSI	Spaceport Systems International
VAFB	Vandenberg Air Force Base
WSTF	White Sands Test Facility

Approval and Document Revision History

Approved:	Original signature on file NESC Director	5-7-04 Date
Approved:	Original signature on file NESC Director	1-27-05 Date
N/A	Approval Signature Not Required	4-12-05

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	CALIPSO Independent Technical Assessment/Inspection (ITA/I) Report	Richard J. Gilbrech	1-27-04
2.0	Inserted 8 Addendums	Richard. J. Gilbrech	1-27-05
2.0	1. Update Addendum page 2-1 2. Delete Addendum page 4-2 3. Repaginate document	Richard J. Gilbrech	4-12-05

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Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
1	CLOSED	Provide a briefing summarizing project background and issues	3-Nov-03	· Action assigned	Calipso Project
			6-Nov-03	· Complete	
2	CLOSED	Provide a briefing summarizing safety issues with Calipso design	12-Nov-03	· Action assigned	Goddard Safety
			13-Nov-03	· Complete	
3	CLOSED	Provide detailed mechanical fitting configuration data including part numbers, materials, torque specifications	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Should be able to answer this with information available in various documents, visits to Alcatel, etc. Data to be provided by Nov 28.	
			25-Nov-03	MSPSP contains some data	
			1-Dec-03	CNES provided more details	
			15-Dec-03	CNES provided material and wall thickness of tubing	
4	CLOSED in part	Provide mechanical fitting qualification and acceptance test data.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· SOHO qual test data is identical to that used for Calipso. SOHO data provided. Need Calipso acceptance test data.	
5	CLOSED in part	Provide detailed mechanical fitting installation procedure including alignment verification, thread lubrication, and torque.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Jim Free provided some details	
			1-Dec-03	CNES provided some details but no procedures for review	
			22-Dec-03	Requested grease application (how much and were) on 12-4-03 - no response provided	

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
6	CLOSED in part	Provide detailed fluid system configuration drawing showing component locations (tank, lines, fittings, brackets, thrusters), line routing, and line lengths	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Alcatel will not provide this detail	
			16-Dec-03	CNES provided one drawing with thruster locations - no tubing or clamp layout dimensions.	
7	CLOSED	Provide detailed summary of mechanical fitting leak check procedures, specifications, and test results	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Jim Free email provided some detail	
			1-Dec-03	CNES provided some details	
			15-Dec-03	CNES provided detailed summary of procedures, no pass/fail criteria or test results from subassembly checks to date.	
			12-May-04	Details provided by Alcatel during site visit.	
8	CLOSED	Provide summary of environments to which propulsion system will be exposed following hyper servicing, to include vibration, pressure, and thermal.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Once fueled, the only environmental change is vibration from the move to the pad. Process timeline to be provided by Nov 28.	
			25-Nov-03	Jim Free provided schedule with limited details and information on processing facility environment	

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
9	CLOSED	Provide mass properties of key propulsion system components, esp. tank, lines, and thrusters.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	MSPSP provides some details	
			5-Dec-03	Don Porter provided thruster mass and dimensions	
			16-Dec-03	CNES provided estimated mass of tank, lines and thrusters	
10	1-Dec-03	Determine whether mechanical fitting qual tests are adequate to address expected environment.	6-Nov-03	· Action assigned - due Dec 1	NESC Team
			22-Dec-03	Waiting on CNES data package	
11	CLOSED	Identify additional testing required to assess suitability of mechanical fittings for use on Calipso spacecraft.	6-Nov-03	· Action assigned - due Dec 1	NESC Team
			17-Dec-03	Insufficient configuration data to make vibe/leak tests traceable to flight	
12	CLOSED in part	Provide thruster qualification and acceptance test data.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24. Data presently available to be provided by Nov 28.	
			15-Dec-03	CNES assembling data package for mail delivery	
			12-May-04	Thruster leak & thermal/vibe details provided during Alcatel site visit.	
13	1-Dec-03	Determine whether thruster qual tests are adequate to address expected environment.	6-Nov-03	· Action assigned - due Dec 1	NESC Team
			22-Dec-03	Waiting on CNES data package	
14	1-Dec-03	Identify additional testing required to assess suitability of thrusters for use on Calipso spacecraft.	6-Nov-03	· Action assigned - due Dec 1	NESC Team

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
15	CANCELLED	Review Calipso propulsion system with respect to EWR 127-1 requirements.	6-Nov-03	· Action assigned - Due Dec 5	Aerojet
			22-Dec-03	Non-Disclosure Agreement delays - cancelled action	
16	CLOSED	Provide a copy of the tailored EWR 127-1 requirements	13-Nov-03	· Action assigned	Goddard Safety
			17-Nov-03	· Closed. Data provided.	
17	CLOSED	Provide contacts at SSI and Astrotech	13-Nov-03	· Action assigned	Goddard Safety
			17-Nov-03	· Closed. Contact info provided.	
18	CLOSED	Provide questions for Alcatel site visit.	13-Nov-03	· Action assigned	NESC Team
			14-Nov-03	· Closed. Questions forwarded to Calipso Project.	
19	CLOSED in part	Provide electrical drawings detailing operation of test and arm plugs.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Drawing provided w/o operations details	
			22-Dec-03	Julie Schneringer (KSC resident office at VAFB) provided detailed ground processing timeline for Jason 1. Still need point where arm plugs are installed (added after Jason)	
			12-May-04	Details provided during Alcatel site visit. Test & arm plugs installed for last time before shipment to VAFB.	
20	CLOSED	Provide a copy of the Jason-1 servicing (ML 902, 908, 920, 934 & 950) and emergency offload (ML 925 & 926) procedures. Note: Calipso procedures available no earlier than 6 months before launch (June 2004).	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
21	CLOSED	Provide a copy of the Project MSPSP.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Copy available in LiveLink at LaRC. Passwords to be provided by Nov 28.	
			25-Nov-03	Jim Free provided electronic copy	
22	CLOSED	Provide a ground operations timeline detailing tasks performed and personnel access from spacecraft servicing through launch.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data to be provided by Nov 28.	
			25-Nov-03	Jim Free provided schedule with limited details	
			17-Dec-03	Julie Schneringer (KSC resident office at VAFB) provided detailed ground processing timeline for Jason 1.	
23	CLOSED	Provide data indicating how spacecraft is accessed for propellant servicing.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data to be provided in coordination with KSC. Available data to be provided by Nov 28.	
			25-Nov-03	Jim Free email with pictures and details	
24	CLOSED	Provide data, including photographs if available, detailing accessibility of mechanical fittings and thrusters after installation in the spacecraft.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Available photos will be provided by Nov 28. New pictures taken during Alcatel site visit in November will also be provided.	
			25-Nov-03	Photos provided by Jim Free	
25	24-Nov-03	Provide safe life, stress, and fracture mechanics data for propellant tank. In particular, since the tank presumably captures the elastomeric bladder in a hemispherical weld joint, the fracture mechanics analysis must include an assessment of the residual stresses at this location.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Update 02-03-05

No	ECD	Description	Status / Comments		Actionee
26	CLOSED	Prepare an interim summary of NESC assessment for presentation to Calipso Project.	17-Nov-03	· Action assigned - due Dec 8	NESC Team
			5-Dec-03	Provided status briefing to GSFC Deputy Center Director	
27	CLOSED	Prepare fault trees for use as assessment tools: fitting leak, thruster leak, thruster inadvertent firing.	19-Nov-03	· Action assigned - due Nov 28	Robinson - GRC
			24-Nov-03	· Preliminary fault trees have been prepared and will be forwarded for comment.	
			25-Nov-03	Preliminary fault trees forwarded for comment.	
			18-Dec-03	Updated drafts of fault trees and mitigation provided	
			22-Dec-03	Draft hazard analysis provided for comment	
			23-Dec-03	Final fault tree, mitigation and report text provided	
28	CLOSED	Determine how quickly Aerojet could set up a vibration test.	21-Nov-03	· Action assigned - due Nov 25	Aerojet
			25-Nov-03	· Vibration lab has some openings, and testing could be performed in the month of December. Need specific requirements before schedule can be finalized.	
29	CLOSED	Provide a ROM cost for compatibility and vibration tests.	21-Nov-03	· Action assigned - due Nov 25	Aerojet
			25-Nov-03	ROM Cost Delivered	

Appendix B. CALIPSO Fault Tree Analysis

Final Fault Trees for Independent Assessment of CALIPSO
By: Ed Zampino and Bill Schoren at NASA Glenn Research Center
January 8, 2004.

Three Fault Trees were developed for the Independent Assessment of CALIPSO.
The three Undesired Top Level Events were:

1. Leakage of Mechanical Fittings
2. Inadvertent opening of thruster valves L-36 days to Launch
3. Leakage of Thruster Control Valve

References

Presentation Slides from NESC Briefing dated November 5, 2003.

Presentation Titled: "Inadvertent Actuation of Valves," Slides NESC-CALIPSO PROPULSION, DJP-7 and DJP-9. Also, "Design Sketches & Satellite Exploded Views," Slides NESC-CALIPSO PROPULSION, DJP-2 and DJP-3.

PIC-LB-O-AN-0060-ASPI, Issue 01, from ALCATEL SPACE, Chapter 6.1.1 – Page 3, 4, and 5.

PIC-LB-O-AN-0060-ASPI, Issue 01, from ALCATEL SPACE, Page 43.

SOHO PROJECT, - JCWG #4 – PROPULSION SYSTEM ISSUES, SCREW JOINT QUALIFICATION STATUS-REPORTS- GSE SPECIFICATIONS. Memorandum 92323ESTO392, R. Brandt. 1992.

AIAA 96-3116, "Experiments on the Robustness of Separable Fittings" S. M. Georgian et al, July 1996.

Report- "REQUESTED INFORMATION REGARDING THE PROTEUS BUS PROPULSION SYSTEM," December 2003.

CALIPSO MS Fitting Leak Test Summary Report, Prepared by D. Asato, Propulsion Branch 597, NASA Goddard Space Flight Center

Moog Space Products Division Monopropellant Thruster Valve Specification Sheet for Model 51-184.

This analysis is based on the following assumptions:

1. Leakage of Mechanical Fittings

   a. The fittings will not go through coupling/uncoupling/re-coupling cycles during the ground test and pre-launch checkout phases. This type of wear will not be significant.
   b. The coupling of the fittings, if done improperly, can cause damage that may lead to leaks.
   c. If the couplings possess structural defects such cracks, major internal flaws, or they are produced out of a material that was not specified in the design, this may result in external leakage.
   d. Excessive Temperature from some source may cause the fittings to expand and be under strain. This could cause fittings to crack (or fail) allowing leakage of N2H4. Although this condition is highly unlikely it has been included in the fault tree.

e. The fittings have to be designed to take the stress (forces) exerted from within by internal fuel line pressure (pressure of the N2H4).

f. The fittings must be designed to withstand forces from launch vibration. There are other events that can expose the fittings to shock such as equipment collision.

2. Inadvertent opening of thruster valves L-36 days

a. During ground testing, input power to the enabling circuits will be provided by Ground Support Equipment (GSE). During the ground testing/processing, GSE will provide power only when it is necessary to check out required system functions. Otherwise, power will not be provided.

b. The only way that power can be provided to the spacecraft (and the thruster actuation circuits) is through input ports that only connect to the GSE.

c. When input voltage is provided to the actuation circuit, a signal (tele-command) is sent to the first relay that energizes the relay.

d. When a second tele-command is sent to the second relay, the relay is energized.

e. A software command from the Processor Module (PM) orbit control mode software application is required to provide power to the Drivers 1 and 2. This action enables power to reach the solenoid valve coils in both thruster valves. (Ref. Slide DJP-4)

f. When the Arm plugs are removed from the circuit leading to the thruster valve solenoid coils, this action cuts off the physical path (breaks the circuit) by which power can be provided to the solenoid coils.

g. Even if the top (first) thruster valve coils are energized and the valve opens, this does not constitute an inadvertent firing of the 1N Thruster. Both valves must open for a thruster firing to occur.

3. Leakage of Thruster Flow valve.

a. The thruster valves are not disassembled following their initial fabrication, QC Testing, and shipping from Moog Corporation. However, the assembly and testing of the thruster valves, if done improperly, can result in an undetected defective seal leading to external leaks.

b. There is a leak test performed by the valve manufacturer (Moog) and a leak check performed at the thruster level of system assembly in Germany.

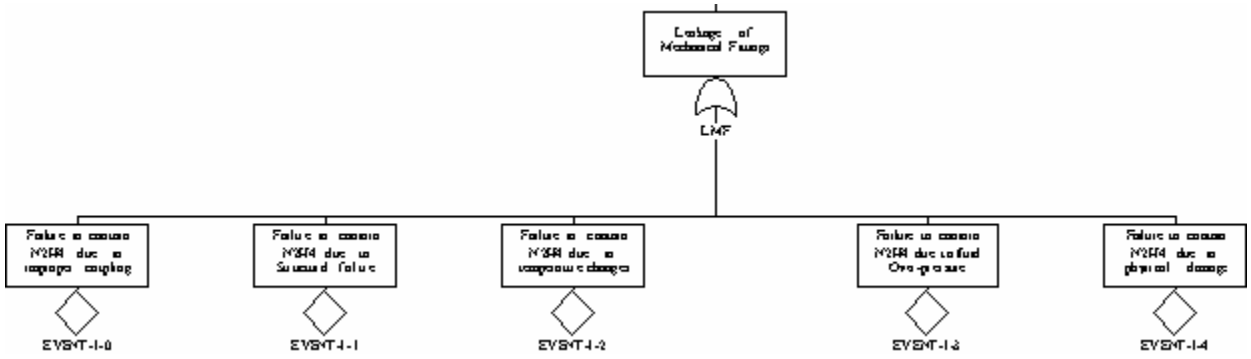
   If these leak checks are not performed correctly and are ineffective, a defective valve could go undetected and be included as a part of CALIPSO.

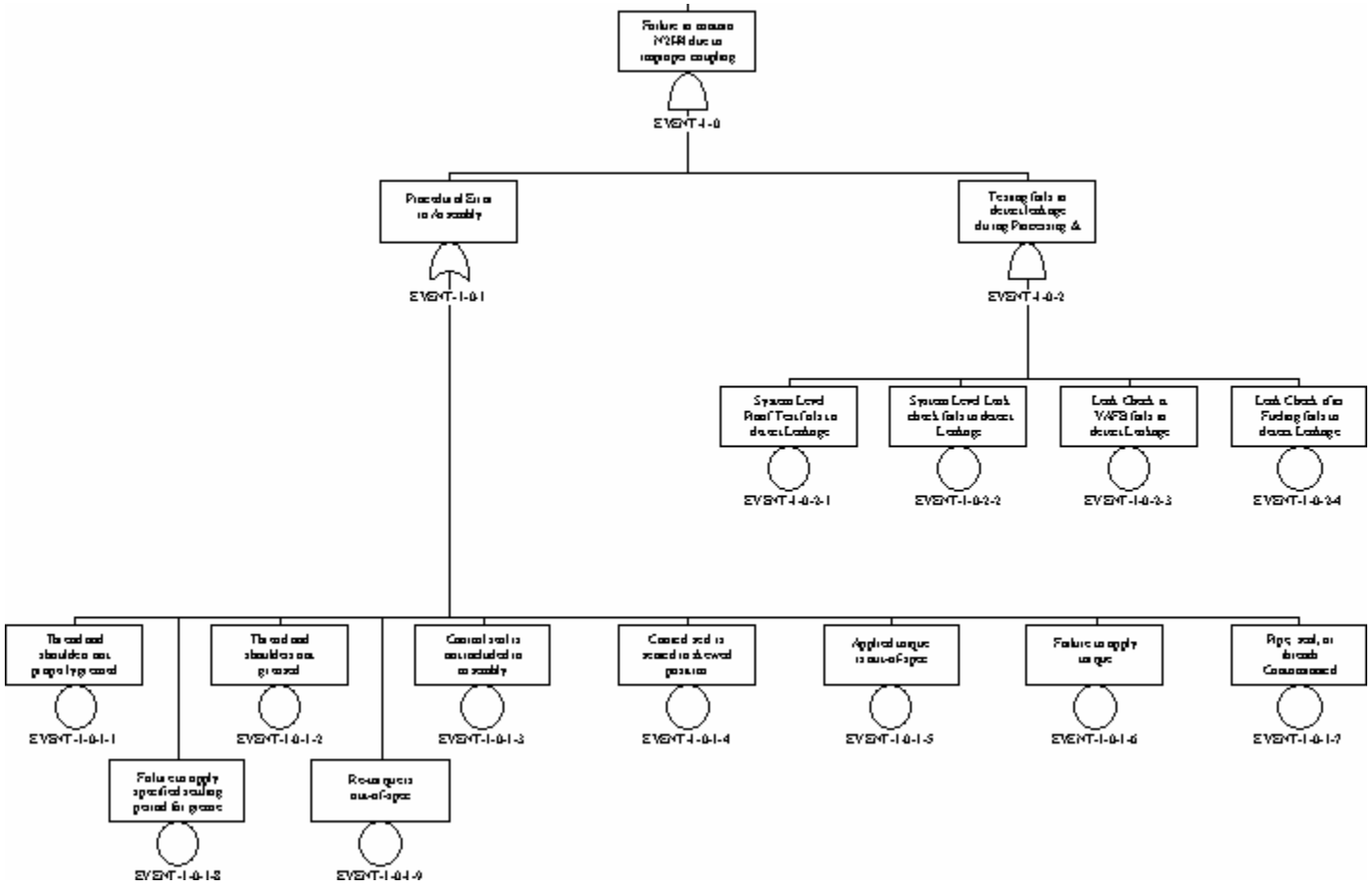
c. If the welds, seams, metallic envelope, and outer casing possess structural defects such cracks, major internal flaws, or they are produced out of a material that was not specified in the design, this may result in failure: external leakage failure mode. Defective valve assembly could also lead to internal leakage. Failure of the valve to close properly (the armature/poppet assembly does not close against the valve seat) could be caused by a defective valve spring, contamination lodged between the poppet and seat, or a defective valve seat.

d. Excessive Temperature from some source may cause the seams or joints in the valve to expand and be under strain. This could cause parts to crack (or fail) allowing leakage of N2H4. Although this condition is highly unlikely it has been included in the fault tree.

e. The thruster valves have to be designed to take the stress (forces) exerted from within by internal fuel line pressure (pressure of the N2H4).

f. The thruster valves must be designed to withstand forces from launch vibration. There are other events that can expose the valves to shock such as equipment collision.


Leakage of Mechanical Fasteners
LMF
Failure to cause MSFR due to improper coupling
Failure to cause MSFR due to Structural Failure
Failure to cause MSFR due to improper clamping
Failure to cause MSFR due to fatigue Over-pressure
Failure to cause MSFR due to physical damage
EVENT-1-0
EVENT-1-1
EVENT-1-2
EVENT-1-3
EVENT-1-4


EVENT-1-0
EVENT-1-0-1
EVENT-1-0-2
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EVENT-1-0-2-2
EVENT-1-0-2-3
EVENT-1-0-2-4
EVENT-1-0-1-1
EVENT-1-0-1-2
EVENT-1-0-1-3
EVENT-1-0-1-4
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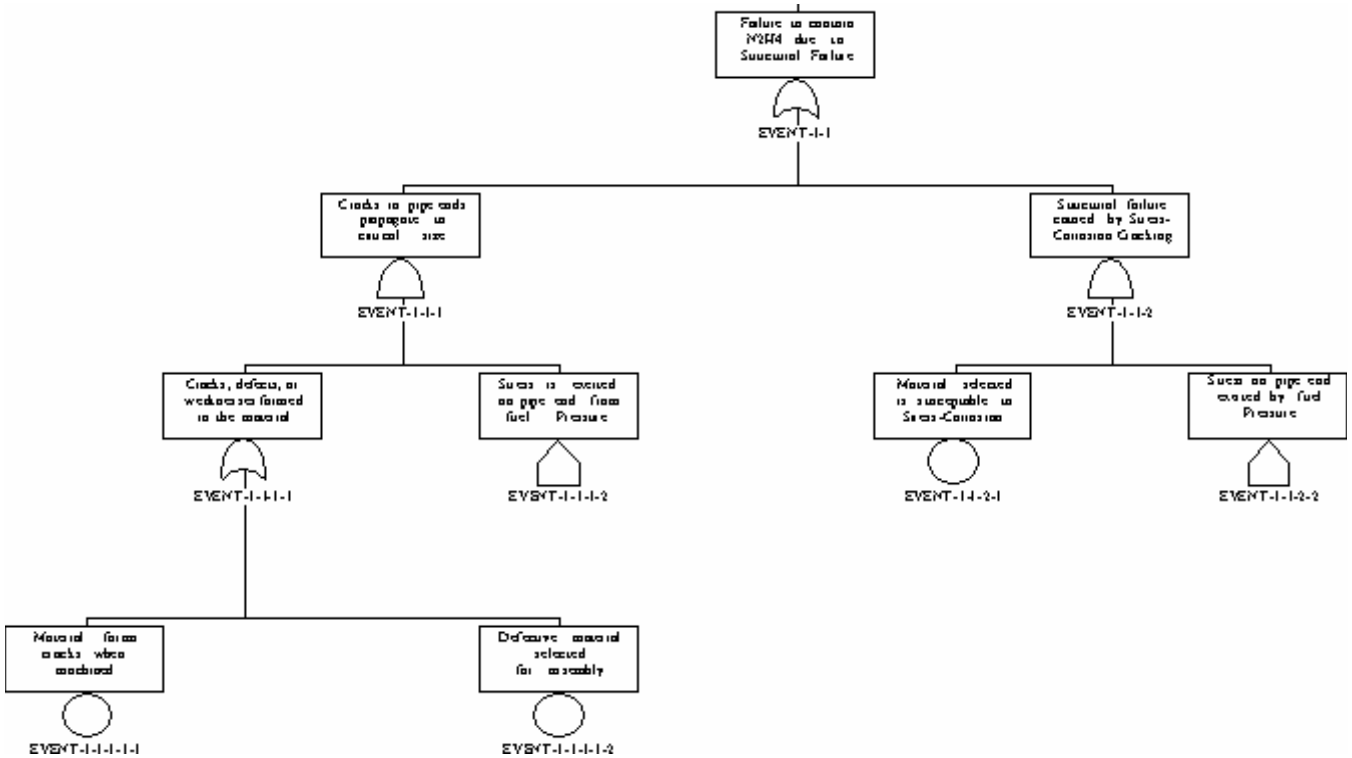
EVENT-1-0-1-8
EVENT-1-0-1-9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EVENT-1-1-2
EVENT-1-1-1-1
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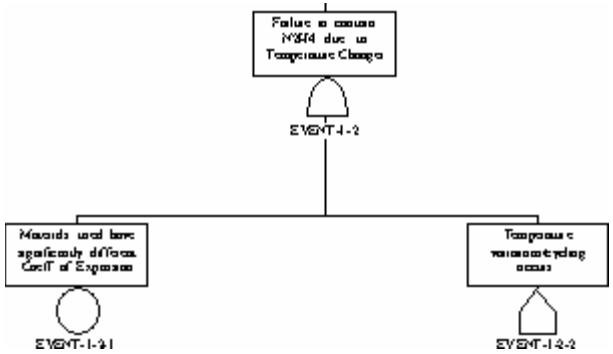
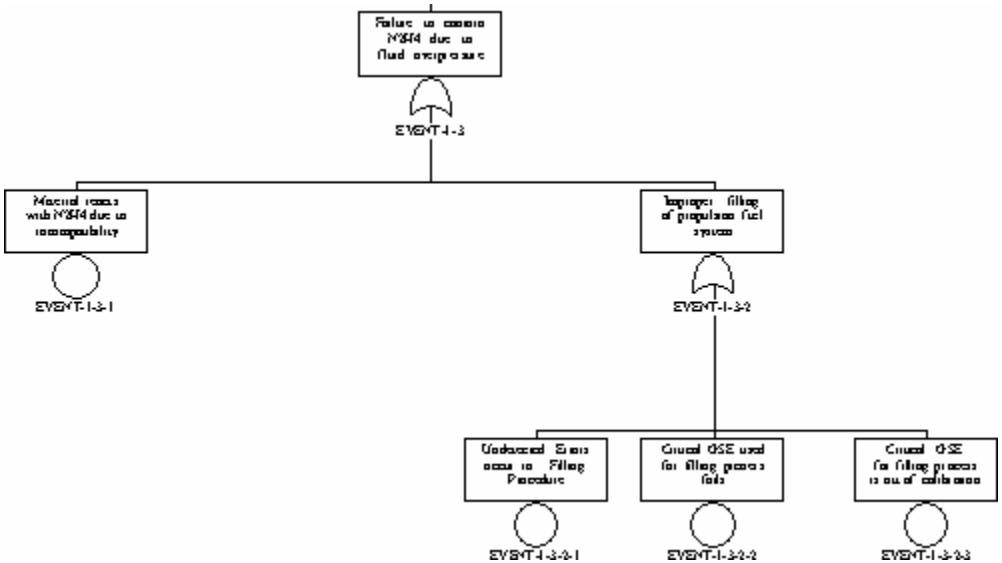
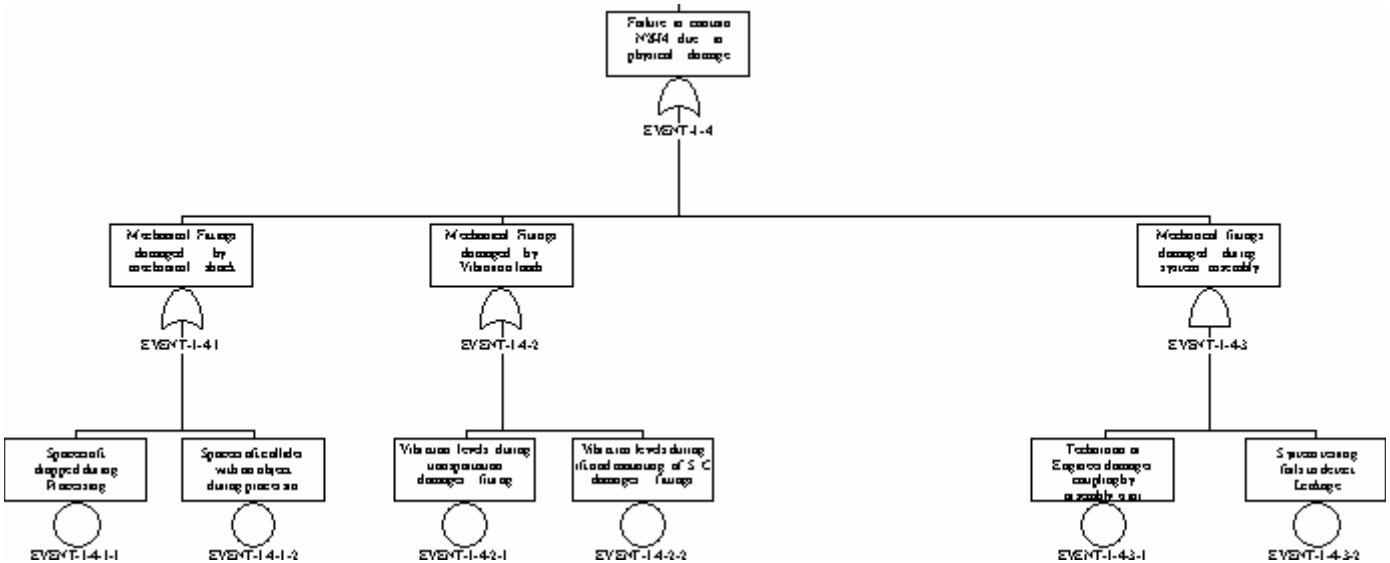
EVENT-1-1-1-1-2


Failure to cause
NSR4 due to
Temperature Change
EVENT-1-2
Materials used have
significantly different
Coeff of Expansion
EVENT-1-2-1
Temperature
variation cycling
occurs
EVENT-1-2-2


EVENT-1-3
EVENT-1-3-1
EVENT-1-3-2
EVENT-1-3-2-1
EVENT-1-3-2-2
EVENT-1-3-2-3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EVENT-I-4-1
EVENT-I-4-2
EVENT-I-4-3
EVENT-I-4-1-1
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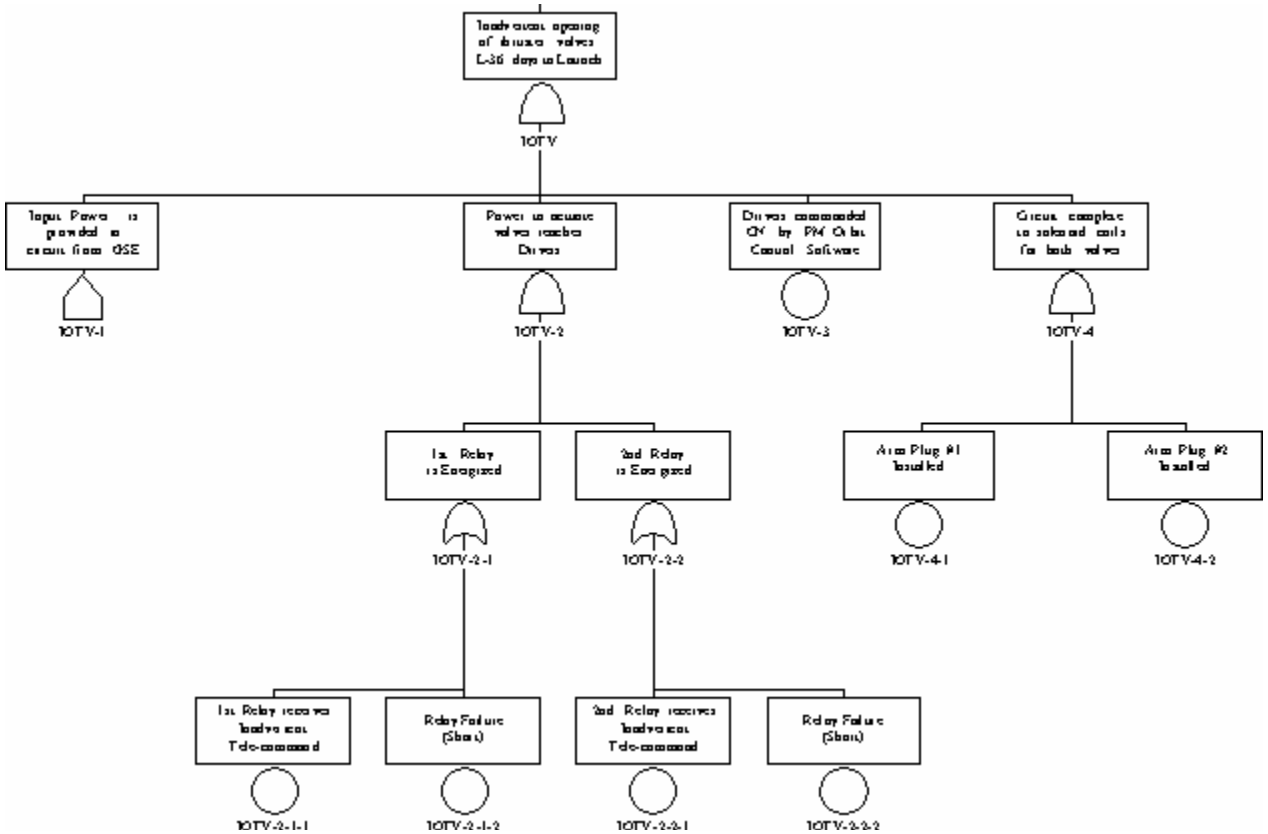
EVENT-I-4-2-2
EVENT-I-4-3-1
EVENT-I-4-3-2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10TV-2
10TV-3
10TV-4
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10TV-2-2
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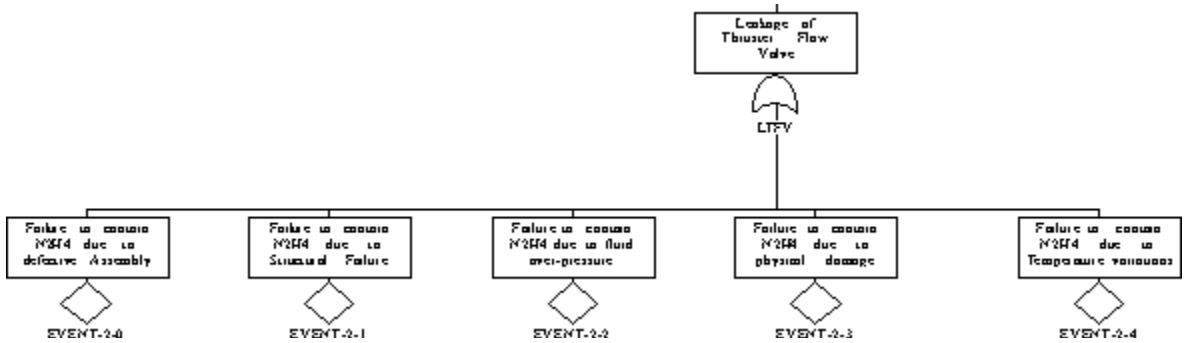
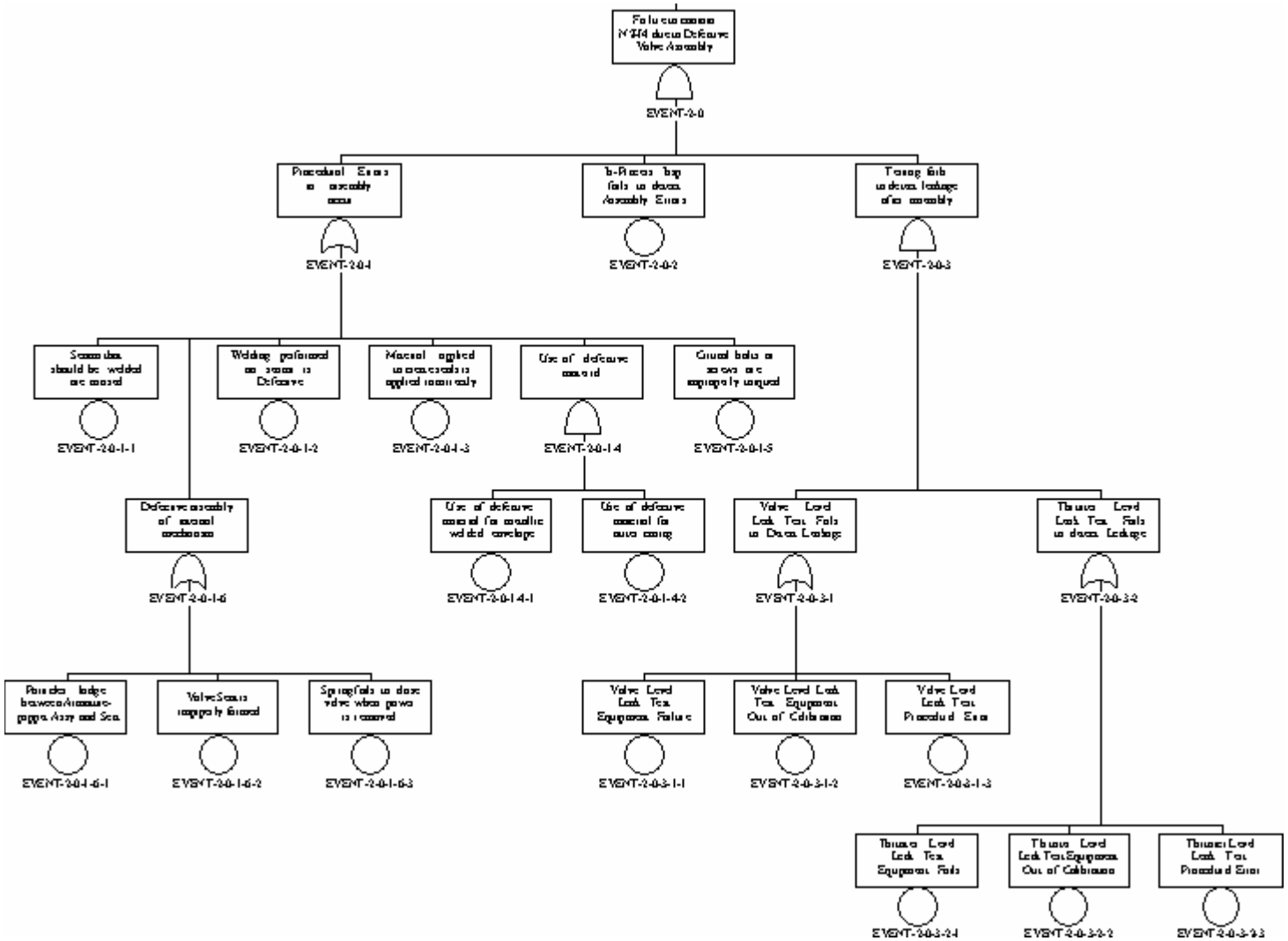
10TV-2-2-1
10TV-2-2-2


Leakage of Thruster Flow Valve
LTFV
Failure to cease N2H4 due to defective Assembly
Failure to cease N2H4 due to Structural Failure
Failure to cease N2H4 due to fluid over-pressure
Failure to cease N2H4 due to physical damage
Failure to cease N2H4 due to Temperature variances
EVENT-2-0
EVENT-2-1
EVENT-2-2
EVENT-2-3
EVENT-2-4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EVENT-2-0-1-6-2
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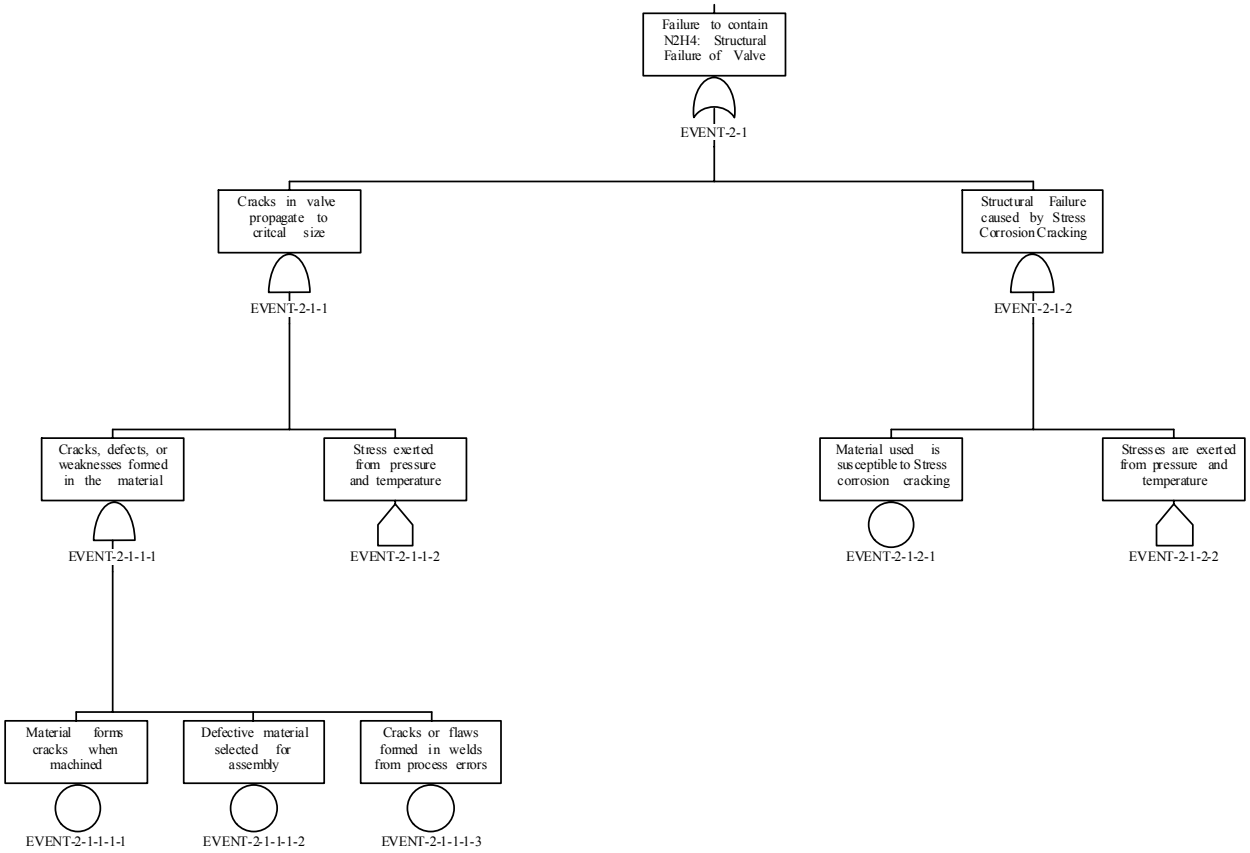
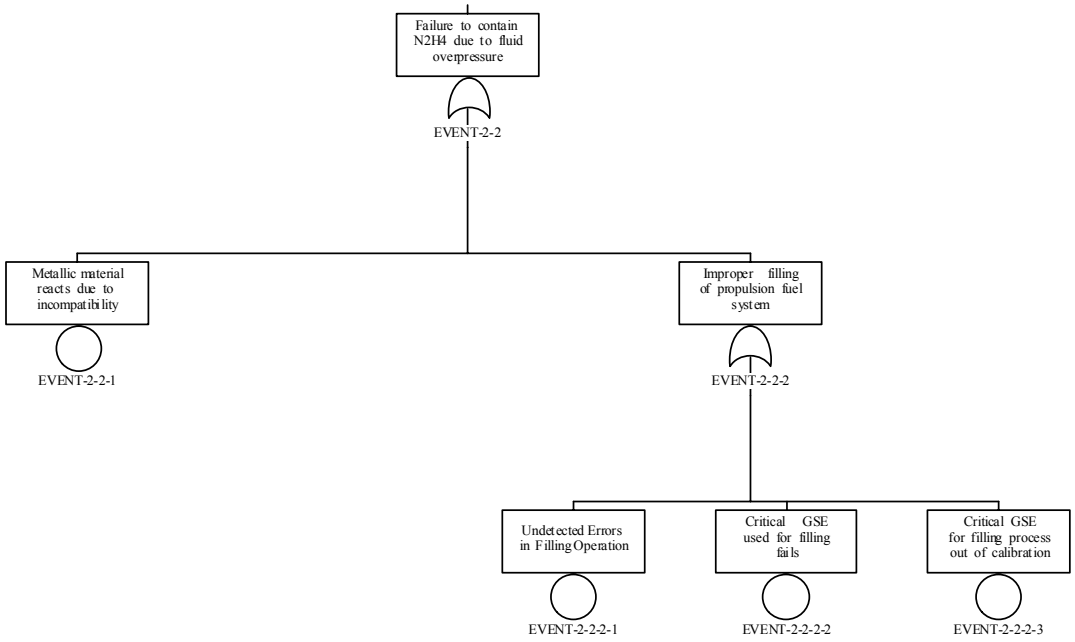
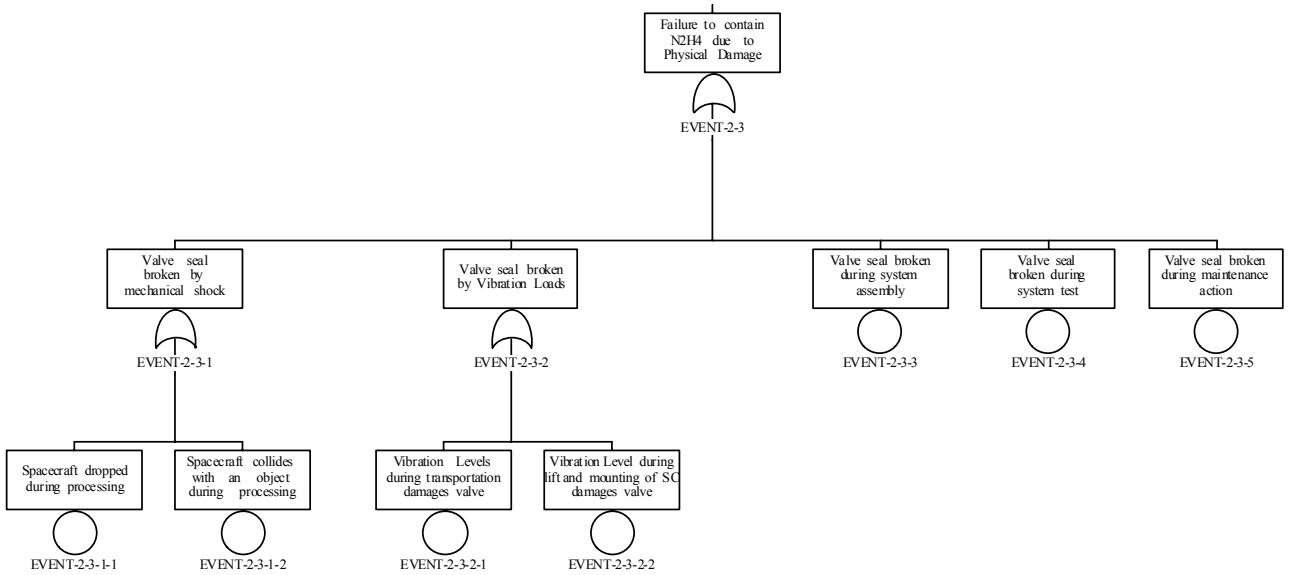
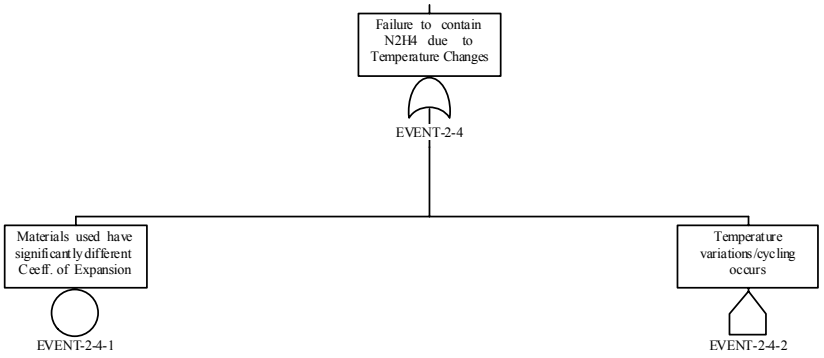
EVENT-2-0-3-2-3


Failure to contain N2H4: Structural Failure of Valve
EVENT-2-1
Cracks in valve propagate to critcal size
EVENT-2-1-1
Structural Failure caused by Stress Corrosion Cracking
EVENT-2-1-2
Cracks, defects, or weaknesses formed in the material
EVENT-2-1-1-1
Stress exerted from pressure and temperature
EVENT-2-1-1-2
Material used is susceptible to Stress corrosion cracking
EVENT-2-1-2-1
Stresses are exerted from pressure and temperature
EVENT-2-1-2-2
Material forms cracks when machined
EVENT-2-1-1-1-1
Defective material selected for assembly
EVENT-2-1-1-1-2
Cracks or flaws formed in welds from process errors
EVENT-2-1-1-1-3


Failure to contain N2H4 due to fluid overpressure
EVENT-2-2
Metallic material reacts due to incompatibility
EVENT-2-2-1
Improper filling of propulsion fuel system
EVENT-2-2-2
Undetected Errors in Filling Operation
EVENT-2-2-2-1
Critical GSE used for filling fails
EVENT-2-2-2-2
Critical GSE for filling process out of calibration
EVENT-2-2-2-3


Failure to contain N2H4 due to Physical Damage
EVENT-2-3
Valve seal broken by mechanical shock
EVENT-2-3-1
Valve seal broken by Vibration Loads
EVENT-2-3-2
Valve seal broken during system assembly
EVENT-2-3-3
Valve seal broken during system test
EVENT-2-3-4
Valve seal broken during maintenance action
EVENT-2-3-5
Spacecraft dropped during processing
EVENT-2-3-1-1
Spacecraft collides with an object during processing
EVENT-2-3-1-2
Vibration Levels during transportation damages valve
EVENT-2-3-2-1
Vibration Level during lift and mounting of SC damages valve
EVENT-2-3-2-2


Failure to contain N2H4 due to Temperature Changes
EVENT-2-4
Materials used have significantly different Coeff. of Expansion
EVENT-2-4-1
Temperature variations/cycling occurs
EVENT-2-4-2

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
1-0	**Failure to contain N2H4 due to improper coupling**		
1-0-1	**Procedural Error in Assembly**		Refer to NESC-R-001 and NESC-R-002.
1-0-1-1	Thread and shoulders not proper greased		
1-0-1-2	Thread and shoulders not greased		
1-0-1-3	Conical seal is not included in assembly		
1-0-1-4	Conical seal is seated in skewed position		
1-0-1-5	Applied torque is out-of-spec		
1-0-1-6	Failure to apply torque		
1-0-1-7	Pipe, seal, or threads contaminated		
1-0-1-8	Failure to apply specified settling period for grease		
1-0-1-9	Re-torque is out-of-spec		
1-0-2	**Testing fails to detect leakage during processing & integration**		Refer to NESC-R-003.
1-0-2-1	System Level Proof Test fails to detect leakage		
1-0-2-2	System Level Leak Test fails to detect leakage		
1-0-2-3	Leak Check at VAFB fails to detect leakage		
1-0-2-4	Leak Check after fueling fails to detect leakage		
1-1	**Failure to contain N2H4 due to Structural Failure**		
1-1-1	**Cracks in pipe ends propagate to critical size**		Refer to NESC-R-002 and NESC-R-003.
1-1-1-1	Cracks, defects, or weaknesses formed in the material		
1-1-1-1-1	Material forms cracks when machined		
1-1-1-1-2	Defective material selected for assembly		
1-1-1-2	**Stress is exerted on pipe end from fuel pressure***		
1-1-2	**Structural failure caused by stress-corrosion cracking**	Analysis	Materials assessment performed to preclude use of stress corrosion susceptible materials. Closed - Reference PIC-LB-0-

*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
			AN-0060-ASPI Chapter 6.1.1.
1-1-2-1	Material selected is susceptible to Stress-Corrosion		
1-1-2-2	**Stress is exerted on pipe end from fuel pressure***		
1-2	**Failure to contain N2H4 due to Temperature Changes**	Analysis/ Inspection	Spacecraft temperature controlled to small variations during ground processing. Closed - Reference Launch Vehicle ICD MDC-01H0074.
1-2-1	Materials used have significantly different Coefficient of thermal Expansion		
1-2-2	**Temperature variations/cycling occurs***		
1-3	**Failure to contain N2H4 due to Fluid Over-pressure**		
1-3-1	Material reacts with N2H4 due to incompatibility	Analysis	Material assessment performed to preclude use of materials incompatible with N2H4. Closed pending results of Aerojet compatibility tests. Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1. Materials used are compatible with N2H4 according to MSFC-HDBK-527 rev. F.
1-3-2	**Improper filling of propulsion fuel system**		Refer to NESC-R-005.
1-3-2-1	Undetected Errors occur in Filling Procedure		
1-3-2-2	Critical GSE used for filling process fails		
1-3-2-3	Critical GSE for filling process is out of calibration		
1-4	**Failure to contain N2H4 due to physical damage**		
1-4-1	**Mechanical Fittings damaged by mechanical shock**		Refer to NESC-R-004.
1-4-1-1	Spacecraft dropped during processing		
1-4-1-2	Spacecraft collides with an object during processing		

*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
1-4-2	**Mechanical Fittings damaged by vibration loads**		Refer to NESC-R-004.
1-4-2-1	Vibration levels during transportation damages fittings		
1-4-2-2	Vibration levels during lifting and mounting of Spacecraft damages fittings		
1-4-3	**Mechanical Fittings damaged during system assembly**		Refer to NESC-R-001, NESC-R-002, and NESC-R-003.
1-4-3-1	Technician or Engineer damages coupling by assembly error		
1-4-3-2	System testing fails to detect Leakage		

*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Inadvertent Opening of Thruster Valves

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
IOTV-1	**Input power is provided to circuit from GSE***		
IOTV-2	**Power to actuate valves reaches drivers**		
IOTV-2-1	1st relay is Energized		Refer to NESC-009.
IOTV-2-1-1	1st Relay receives Inadvertent Tele-command		
IOTV-2-1-2	Relay Failure (Short)		
IOTV-2-2	2nd relay is Energized		Refer to NESC-009.
IOTV-2-2-1	2nd Relay receives Inadvertent Tele-command		
IOTV-2-2-2	Relay Failure (Short)		
IOTV-2-3	Opt-couplers commanded ON by PM orbit Control Software		Refer to NESC-009.
IOTV-3	**Power provided to solenoid coils for both valves**		
IOTV-3-1	Arm Plug #1 Installed too early before fairing installation		Refer to NESC-R-010.
IOTV-3-2	Arm Plug #2 Installed too early before fairing installation		Refer to NESC-R-010.

Note - After propulsion system filling operations (including Launch Pad operations), inadvertent opening of a pair of thruster valves requires three commands. (Three inhibits) These commands are needed to enable the power to reach the solenoid valve coils. (See page 5 Chapter 6.1.2 Annex 2 to HR-1 of PIC-LB-0-AN-0060-ASPI). In addition, the arm plugs for both thruster valves would have to be installed to provide a path for power. Moreover, during filling operations, the spacecraft cannot be powered because the spacecraft battery and the Ground Support Equipment are not electrically connected to the spacecraft power bus.

*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Inadvertent Opening of Thruster Valves

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
2-0	**Failure to contain N2H4 due to Defective Valve Assembly**		
2-0-1	**Procedural Errors in assembly occur**		Refer to NESC-R-007 and NESC-R-008.
2-0-1-1	Seams that should be welded are missed		
2-0-1-2	Welding performed on seams is defective		
2-01-3	Material applied to create seals is applied incorrectly		
2-0-1-4	**Use of defective material**		
2-0-1-4-1	Use of defective material for metallic welded envelope		
2-0-1-4-2	Use of defective material for outer casing		
2-0-1-5	Critical bolts or screws are improperly torqued		
2-0-1-6	**Defective assembly of internal mechanism**		
2-0-1-6-1	Particles lodge between Armature-poppet Assembly & Seat		
2-0-1-6-2	Valve Seal is improperly formed		
2-0-1-6-3	Spring fails to close valve when power is removed		
2-0-2	**In-process Inspection Fails to Detect Assembly Errors**		Refer to NESC-R-007 and NESC-R-008.
2-0-3	**Testing Fails to Detect Leakage after Assembly**		Refer to NESC-R-003 and NESC-R-007.
2-0-3-1	**Valve Level Leak Test Fails to Detect Leakage**		
2-0-3-1-1	Valve Level Leak Test Equipment Fails		
2-0-3-1-2	Valve Level Leak Test Equipment Out of Calibration		
2-0-3-1-3	Valve Level Leak Test Procedural Error		
2-0-3-2	**Thruster Level Leak Test Fails to Detect Leakage**		
2-0-3-2-1	Thruster Level Leak Test Equipment Fails		
2-0-3-2-2	Thruster Level Leak Test Equipment Out of Calibration		
2-0-3-2-3	Thruster Level Leak Test Procedural Error		

*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Leakage of Thruster Flow Valve

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
2-1	**Failure to contain N2H4: Structural Failure of Valve**		
2-1-1	**Cracks in valve propagate to critical size**		Refer to NESC-R-003 and NESC-R-007.
2-1-1-1	**Cracks, defects, or weaknesses formed in the material**		
2-1-1-1-1	Material forms cracks when machined		
2-1-1-1-2	Defective material selected for assembly		
2-1-1-1-3	Cracks or flaws formed in welds from process errors		
2-1-1-2	**Stress exerted from pressure and temperature***		
2-1-2	**Structural Failure caused by Stress Corrosion Cracking**	Analysis	Materials assessment performed to preclude use of stress corrosion susceptible materials. Closed - Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1.
2-1-2-1	Material used is susceptible to Stress-Corrosion		
2-1-2-2	**Stress exerted from pressure and temperature***		
2-2	**Failure to contain N2H4 due to Fluid Over-pressure**		
2-2-1	Material reacts with N2H4 due to incompatibility	Analysis	Material assessment performed to preclude use of materials incompatible with N2H4. Closed pending Aerojet compatibility test result. Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1. Materials used are compatible with N2H4 according to MSFC-HDBK-527 rev. F.
2-2-2	**Improper filling of propulsion fuel system**		Refer to NESC-R-005.
2-2-2-1	Undetected Errors occur in Filling Procedure		
2-2-2-2	Critical GSE used for filling process fails		
2-2-2-3	Critical GSE for filling process is out of calibration		
2-3	**Failure to contain N2H4 due to physical**		

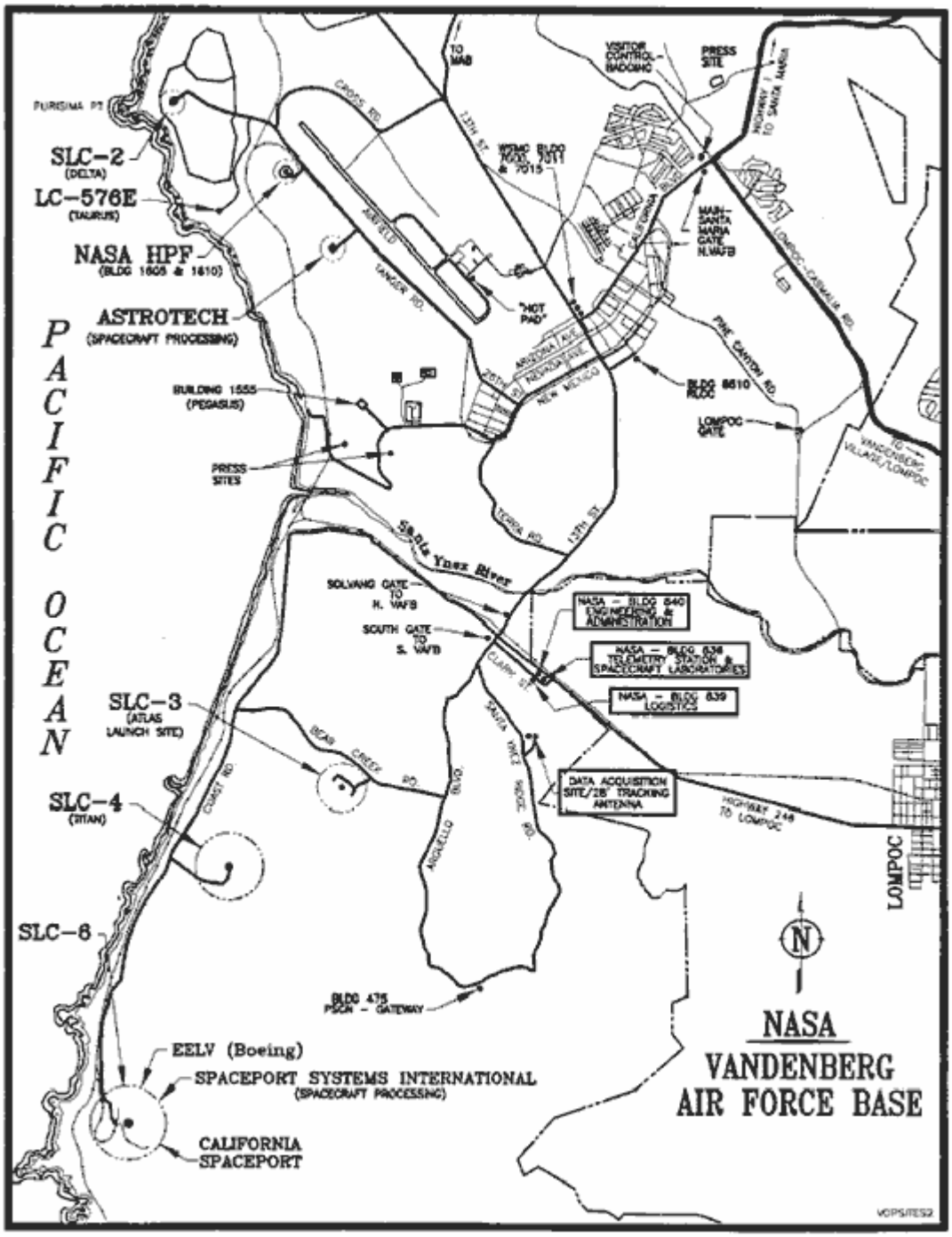
*** - Expected conditions**

Appendix C. CALIPSO Fault Tree Mitigation Matrix
Leakage of Thruster Flow Valve

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
	damage		
2-3-1	**Valve seal broken by mechanical shock**		Refer to NESC-R-004.
2-3-1-1	Spacecraft dropped during processing		
2-3-1-2	Spacecraft collides with an object during processing		
2-3-2	**Valve seal broken by vibration loads**		Refer to NESC-R-004.
2-3-2-1	Vibration levels during transportation damages valve		
2-3-2-2	Vibration levels during lift and mounting of Spacecraft damages valve		
2-3-3	Valve seal broken during system assembly		Refer to NESC-R-007.
2-3-4	Valve seal broken during system test		
2-3-5	Valve seal broken during maintenance action		
2-4	**Failure to contain N2H4 due to Temperature Changes**	Analysis/ Inspection	Spacecraft temperature controlled to small variations during ground processing. Closed - Reference Launch Vehicle ICD MDC-01H0074.
2-4-1	Materials used have significantly different Coefficients of Thermal Expansion		
2-4-2	**Temperature variations/cycling occurs***		

*** - Expected conditions**

Appendix D. VAFB Site Map



Aerojet CALIPSO Test Plan

A02026.11

January 9, 2004

Aerojet Evaluation Team

- Dr. Scott Miller, Manager - Systems and Bipropellant Technology
- Jack DeBoer, Staff Engineer
- Patrick Cabral, Development Engineer

Aerojet Test Plan Summary

- **Mechanical Fitting Evaluation Objectives**
  - **Simulate both valve (CRES male inlet fitting to titanium flared tube) and tank (titanium male inlet fitting to titanium flared tube) fitting configurations to the best fidelity possible given available CALIPSO information**
  - **Perform hydrazine soak test simulating pre-launch loaded system duration to assess effect of hydrazine on nickel seal material**

Aerojet Test Plan Summary (Cont'd)

- **Hot Soak Test of Nickel Seals**
  - **Place qty 16 nickel seals in hydrazine for parallel exposure test on nickel material only. Volume of hydrazine and seal quantity is outlined below.**

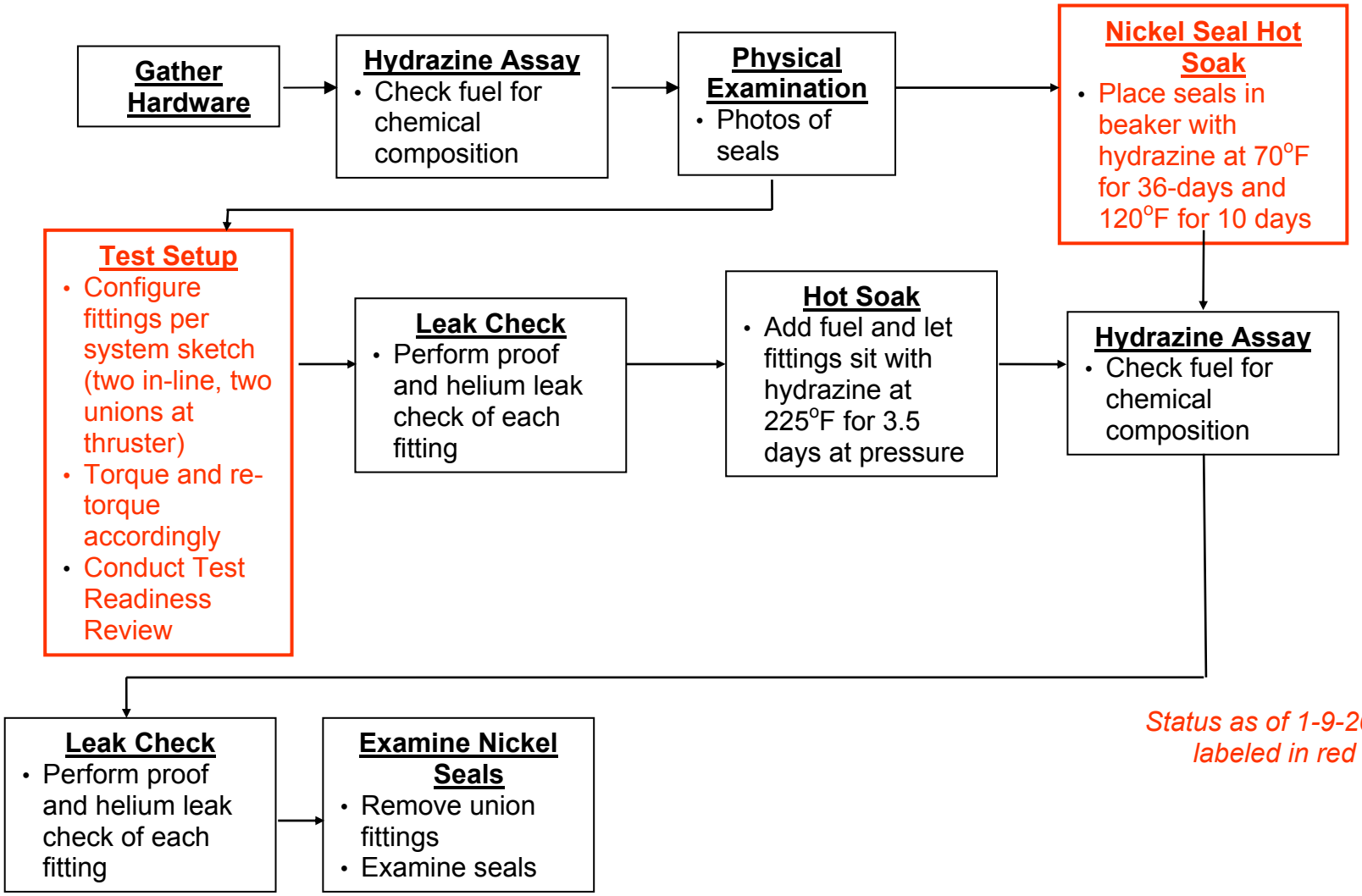
Sample Description	Volume of Hydrazine	QTY of Seals	Test Duration	Temperature
Control	50 mL	0	36-days	Ambient
Fitting Exposure	50 mL	5	36-days	Ambient
Fitting Exposure at Elevated Temperature	50 mL	5	10-days	120°F
One Seal Exposure	50 mL	1	36-days	Ambient
Fitting Exposure with Weekly Check	100 mL	5	36-days	Ambient

  - **Perform hydrazine assays before and after testing on all samples; Weekly tests performed on 100 mL for duration of test**
  - **Success criteria for post-test assays (nickel ppm and gas evolution rate) to be discussed by team when results are available**

Aerojet Test Plan Summary (Cont'd)

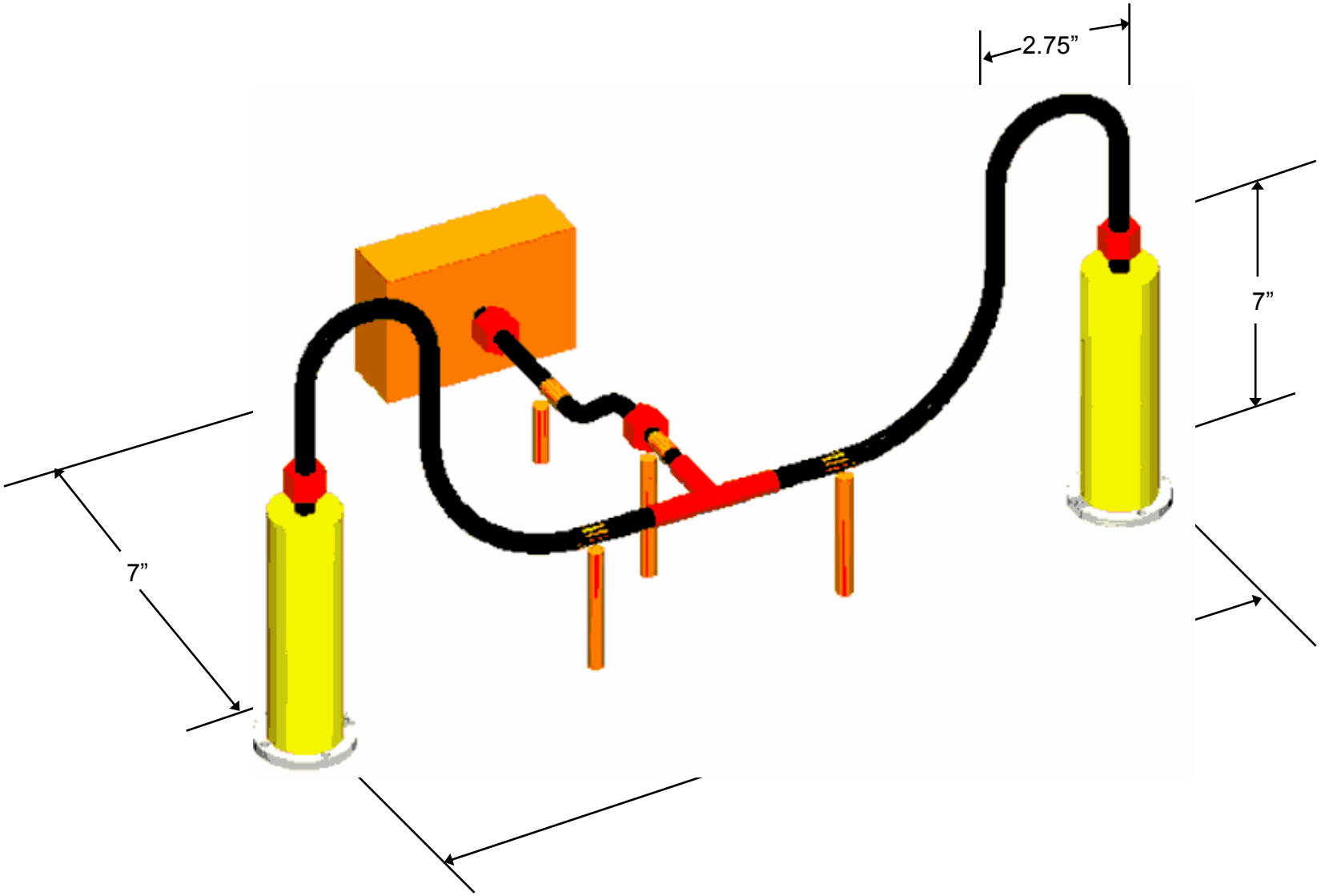
- **Hot Soak Test of Test Hardware**
  - **Obtain flight-like mechanical fittings (MS33656-4). CRES and titanium fittings are available.**
  - **Prepare test hardware approximating portion of CALIPSO system (fittings + tubing) using representative tubing material and lengths, and assembled according to CALIPSO procedures**
  - **Torque fittings to 100% flight torque (including re-tightening schedule), apply torque stripe**
  - **Proof test at 480 psig (1.5 x MEOP)**
  - **GHe leak test at 320 psig (MEOP)**
  - **Load test hardware with N2H4, perform accelerated exposure test representative of 36 days duration in Aerojet sea level test chamber (225F for 3.5 days)**
  - **Obtain pre- and post-exposure N2H4 samples, perform assays**
  - **Decontaminate, repeat proof and GHe leak tests**
  - **Check torque strength of unions at thruster location by ensuring it is greater than or equal to original torque value**
  - **Undo thruster fitting and examine nickel seals**
  - **Examine seals to determine surface effects of nickel and hydrazine interaction. Distribute results of seals to team for evaluation and further direction. Success criteria for post-test assays (nickel ppm and gas evolution rate) to be discussed by team.**

Aerojet Test Plan Summary (Cont'd)



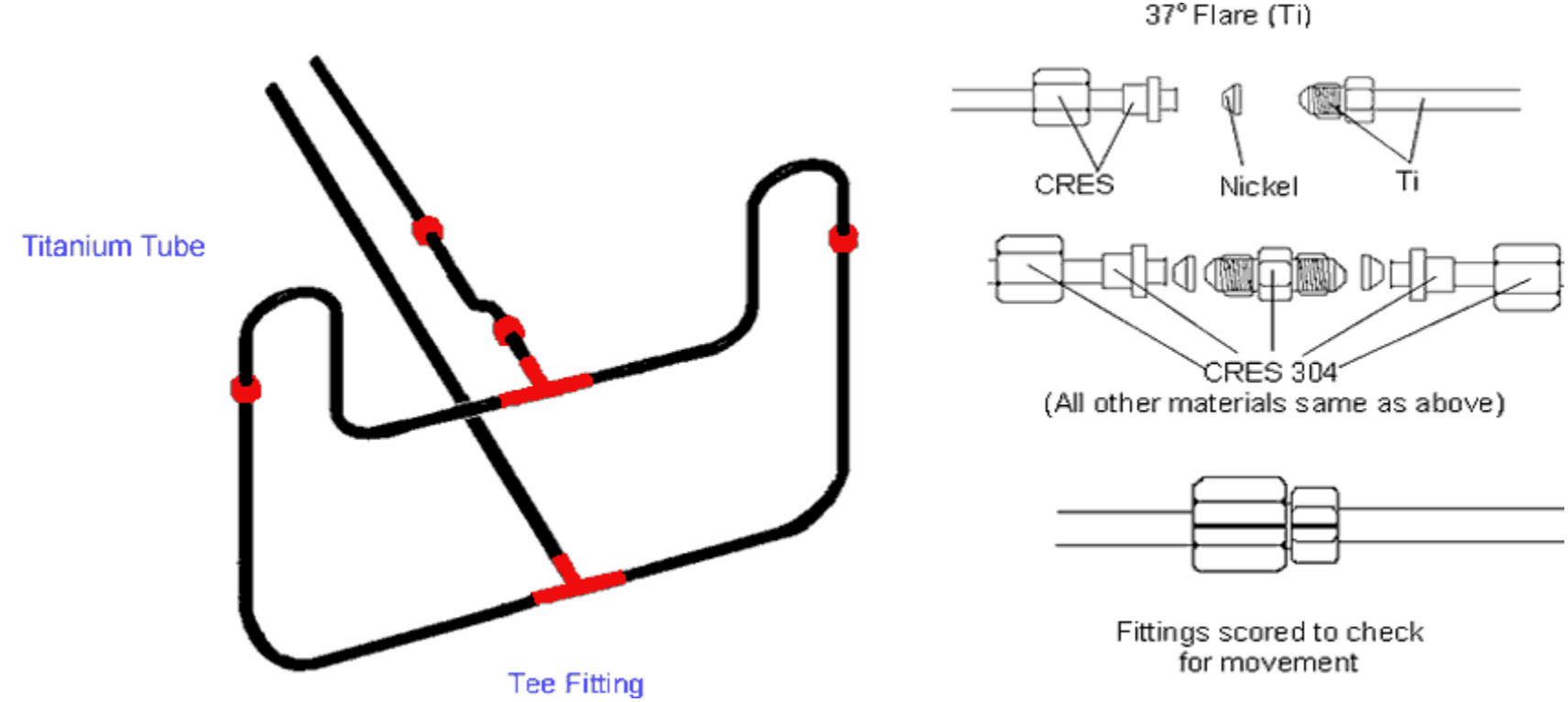
Status as of 1-9-2004 labeled in red

Propulsion System Schematic for Test

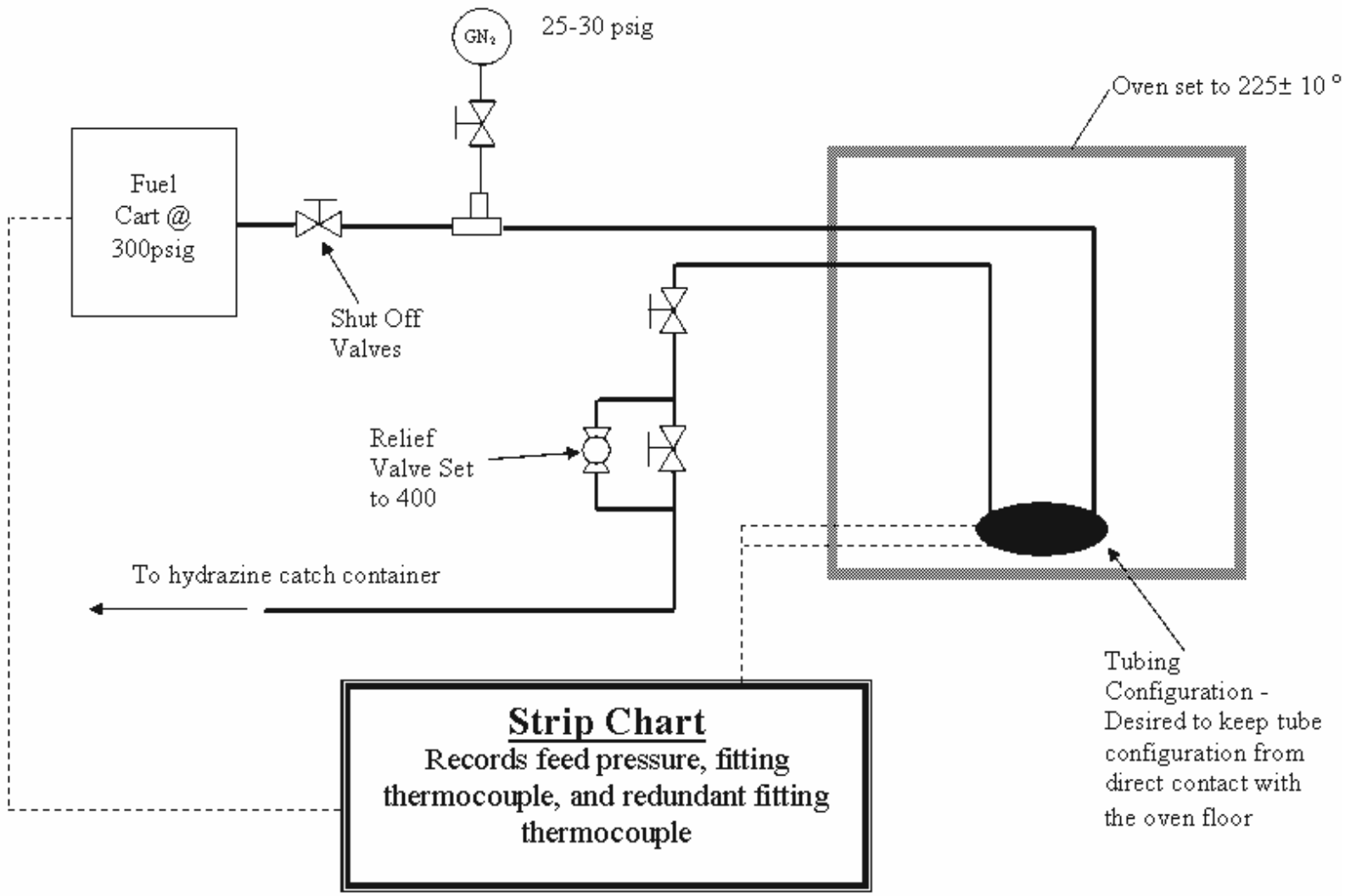


Hot Soak Test Setup

- **Four fittings to be tested: Two in titanium line, and two CRES at thruster location**
  - **Thruster fittings simulated for hot soak test due to the uncertainty of the valves acquired. Valves need to function properly when exposed to hydrazine for decontamination purposes.**
- **Lines filled with hydrazine and stored in oven**
  - **Temp at 225°F; Line pressure at 320 psig; Duration of 3.5 days**



Hot Soak Test Facility



Aerojet Test Plan Summary (Cont'd)

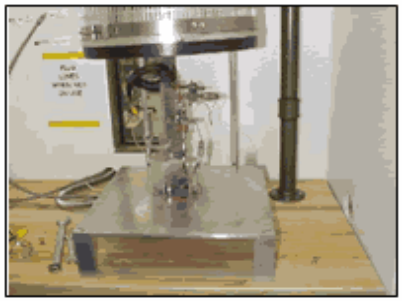
Hydrazine Compatibility Test

- **Sample of hydrazine before and after hot soak, and for ambient test in chemistry lab**
  - **Trace metals test**
    - **Inductively Coupled Plasma (ICP) technique used**
      - **Nickel levels to 1 ppm**
      - **All other metals down to ppb**

Aerojet Test Plan Summary (Cont'd)

Pressure consoles

Helium leak detector



Test Stand/Vacuum chamber

Proof/Leak Testing

- **Proof test at 1.5 X 320 psig**
  - **Test hardware will be capped on one end and pressurized with GN2. Fitting will be snooped to check for leaks**
  - **GP-TE-016 High Pressure Console to control pressure input**
- **Helium Leak Check**
  - **Fittings tested for leaks at 320 psig with GHe via "bag" isolation and mass spectrometer**
  - **GP-TE-002 Test Stand Bay to control pressure input**
  - **Mass Spectrometer (Varian Turbo Auto-Test 947)**
    - **Integrity >= $1X10^{-8}$ scc/sec. ($1x10^{-6}$ scc/sec. typical max allowable for acceptance of rocket engines)**

Aerojet Test Plan Summary (Cont'd)

- **Mechanical Fitting Evaluation - Schedule and Status**
  - Obtain all required information or proceed based on assumptions: Complete
  - Gather materials: Complete
  - Prepare and review test plan: Complete
  - Conduct Test Readiness Review: Complete
  - Prepare hot soak test setup: Complete
  - Hydrazine exposure (Hot Soak Test): Complete
  - Hydrazine exposure (Ambient Test Nickel Seals Only): Complete
  - Hydrazine exposure (120°F Test Nickel Seals Only): Complete
  - Final examination and analysis (Hot Soak Test): Complete
  - Final examination and analysis (Ambient Test Nickel Seals Only): Complete
  - Final examination and analysis (120°F Test Nickel Seals Only): Complete

Aerojet Test Plan Summary (Cont'd)

- **Mechanical Fitting Evaluation - Schedule and Status**
  - Obtain all required information or proceed based on assumptions: Complete
  - Gather materials: Complete
  - Prepare and review test plan: Complete
  - Conduct Test Readiness Review: Complete
  - Prepare hot soak test setup: Complete
  - Hydrazine exposure (Hot Soak Test): Complete
  - Hydrazine exposure (Ambient Test Nickel Seals Only): Complete
  - Hydrazine exposure (120°F Test Nickel Seals Only): Complete
  - Final examination and analysis (Hot Soak Test): Complete
  - Final examination and analysis (Ambient Test Nickel Seals Only): Complete
  - Final examination and analysis (120°F Test Nickel Seals Only): Complete

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Addendum 1. **Aerojet A/N Fitting Hydrazine Exposure Tests**

Addendum 2. **Aerospace Evaluation Report**

Addendum 3. **Notes from Alcatel Site Visit May 12 & 13, 2004**

Addendum 4. **WSTF Proteus Propulsion Bus Hydrazine Material Compatibility Report**

Addendum 5. **KSC Modeling Analysis of Hydrazine Leak Detection Systems for the CALIPSO Spacecraft**

Addendum 6. **Zellweger Analytics Model CM4 Evaluation Hydrazine Vapor Detector Analysis for CALIPSO Alarm Times, Concentrations, and Fallback Times at Various Sample Tubing Lengths**

Addendum 7. **CALIPSO Fire Protection Assessment**

Addendum 8. **PowerPoint Presentation, Update of NESC Requirements/Actions to Integrated Program Management Council, February 2, 2005**

Addendum 1

Aerojet A/N Fitting Hydrazine Exposure Tests

Nickel - Hydrazine Compatibility Test Report

REPORT NUMBER

2004-R-2517

Prepared by

Aerojet

Redmond, WA

Prepared For

NASA Engineering and Safety Center (NESC)
Langley Research Center

AEROJET

Redmond Operations

Redmond, WA

Nickel - Hydrazine Compatibility Test Report

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1.0 INTRODUCTION

The CALIPSO spacecraft scheduled for a 2005 launch at Vandenberg Air Force Base uses a French Proteus bus. The bus propulsion system utilizes a series of mechanical AN type fittings instead of welded joints at the propellant tank, thruster and other system interfaces. The NASA Engineering and Safety Center (NESC) has performed an investigation of this propulsion system to ensure that personnel at Vandenberg will not be in danger while the spacecraft is being prepared for launch. Of major concern is the risk of having a mechanical fitting leak, thereby exposing personnel to the hydrazine propellant. The spacecraft will be filled with hydrazine for 36 days prior to launch and a leak of any kind could result in a catastrophic failure.

One action item of the NESC was to independently investigate compatibility of the mechanical fittings with hydrazine for the 36-day exposure period. The metals included in the fittings are titanium, steel (CRES 304), and nickel. There have been several investigations with titanium and steel to show that they are compatible with hydrazine. A similar literature search of nickel compatibility produces contradictory results.

Outlined in USAF Propellant Handbook AFRPL-TR-69-149[1] are data relative to the compatibility of metals with hydrazine. A class level "A" is given to a metal classified as having no limitations for its use in hydrazine. Conversely, a class level "D" is given to a metal that is completely unsuitable for use with hydrazine. Studies reported in this handout independently rank nickel compatibility in hydrazine as a class A, or D for a range of testing parameters. However, for this application, no finite conclusions could be made whether or not the nickel used in this configuration was acceptable or not. The NESC therefore requested that Aerojet perform a series of compatibility tests between nickel and hydrazine to investigate this issue.

2.0 SCOPE

A sketch of the mechanical fittings used in this propulsion system can be seen in Figure 1 below.

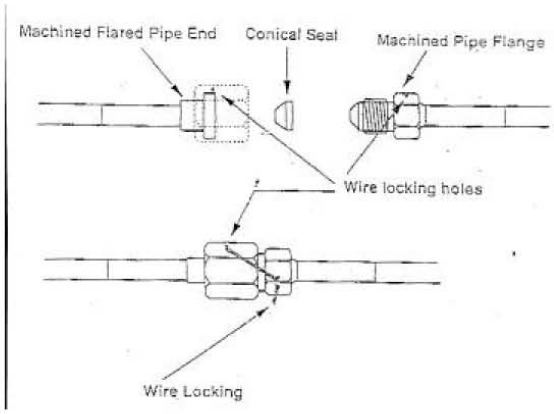


Figure 1 – Schematic of Mechanical Fittings

The propulsion system uses titanium tubing welded to titanium threads. The adjacent tube is flared to a 37° angle with a CRES 304 B-Nut and tube sleeve. A nickel conical seal is secured in between the tube ends to ensure a leak tight seal.

A concern of the NESC was the 36-day exposure period the fitting would experience before launch. To test the compatibility of nickel in hydrazine, a series of tests were performed. The first test involved making a propulsion system mock up, exposing it to hydrazine and checking for traces of nickel after 36 days. Arrhenius equations show that for a 36-day exposure at room temperature, an accelerated test can be set up for 3.5 days with the system at 225°F. The second set of tests involved placing nickel conical seals in hydrazine with no other metals present. The hydrazine samples were placed at room temperature for 75 days to add margin to the 36-day exposure time, while a parallel test at 120°F was set up to accelerate the test to 10 days. Again, the accelerated test temperature and duration were set up to simulate 36 days of exposure.

At the conclusion of each test, the test samples were visually inspected for surface changes, and the hydrazine was assayed to determine levels of iron, nickel, and other constituents vs. pre-test and control samples.

3.0 TEST SETUP

The two separate parallel tests included in this investigation were a hot soak test of a representative portion of the propulsion system, and a nickel soak test.

3.1 Hot Soak Test

The hot soak test configuration is modeled after the bus propulsion system. Figure 2 below shows a rough schematic of half of the CALIPSO propulsion system.

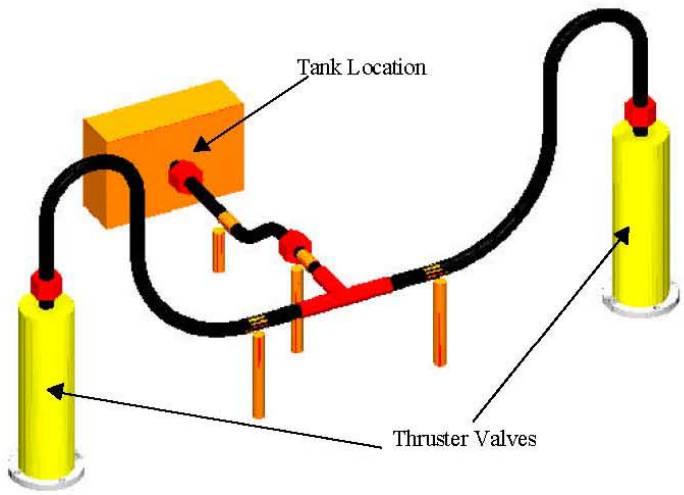


Figure 2 – Rough Schematic of Half of the CALIPSO Propulsion System

To test this configuration, two thruster valves similar to those used in the CALIPSO propulsion system were acquired from Moog. However, the valves were development units with minimal quality documentation. Due to the risks involved with operating a system with hydrazine at elevated pressure and temperature, it was decided that the thruster valves would not be used in the hot soak test configuration. A standard CRES 304 male to male tube union was used in their place since the valves have a stainless steel body with male threads. The final test configuration can be seen in Figure 3 along with the label and corresponding sketch of each fitting.

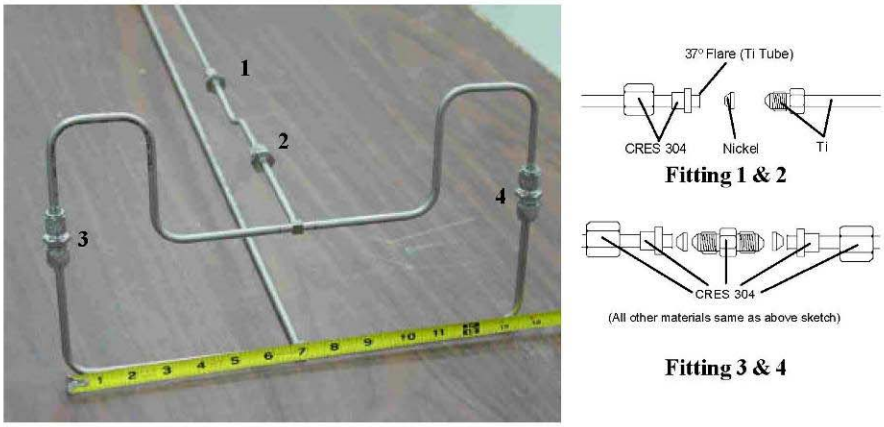


Figure 3 – Test Configuration for the Hot Soak at 225°F With Sketch of Fitting Location

The assembled test section was then subjected to a proof and helium leak check to ensure the fittings were assembled properly. After the leak check, the section was sent to the test lab to be placed in a temperature controlled oven. The hot soak test section was set up so that no fittings were in direct contact with the oven walls. The tube section was elevated to ensure the fittings were also placed roughly in the middle of the oven. Figure 4 shows the test section in the oven and Figure 5 is a rough sketch of the test facility.

Figure 4 – Test Section in Oven Prior to Beginning Hot Soak Test

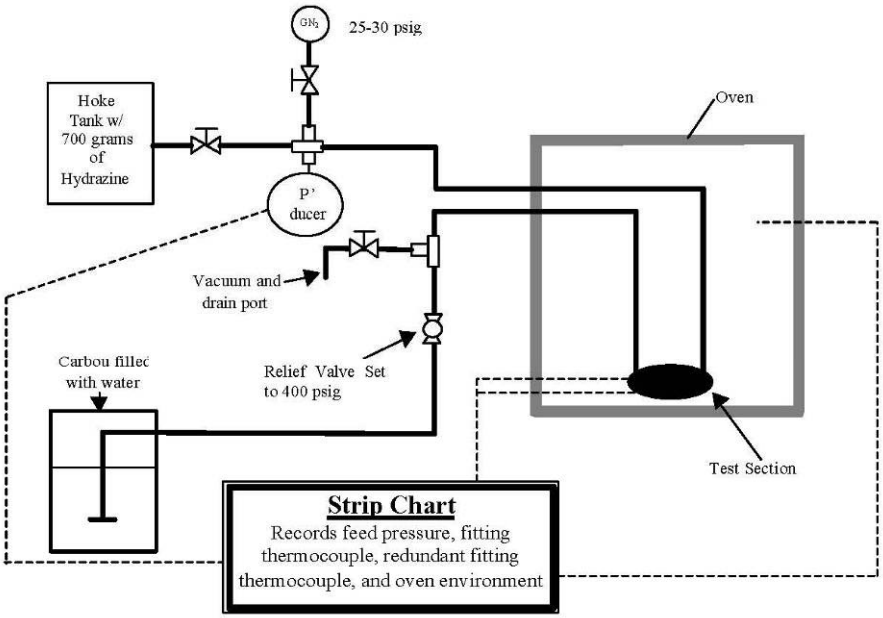


Figure 5 – Sketch of the Test Facility Used for the Hot Soak Test

Hydrazine was then introduced and the line pressure was regulated to 320 ± 10 psig and the oven temperature was controlled to 225 +0/-10 °F. The temperature and line pressure were monitored with a strip chart recording the line pressure, and the temperatures of fittings 1 and 2, and the oven. Periodically, the hydrazine within the test section was locked into place by shutting the valve from the supply hydrazine to ensure there were no leaks within the test section throughout the test period of 3.5 days. This test of line pressure was performed twice daily.

The hydrazine used in this test was collected before and after the soak for an analysis to determine the level of metal introduced from the fittings. A comparison of these analyses can be found in section 4.0.

3.1.1 Torque Schedule

All fittings in the test section were assembled with 177 in-lbs. of torque. Each fitting also followed the same torque schedule as the CALIPSO program with several re-torques. Table 1 outlines the torque schedule used for each fitting.

Table 1 – Torque Schedule Used for the Assembly of the Hot Soak Test Configuration

Fitting Number (Refer to Figure 3)	Number of Re-torques	Time Delay for Re-tightening
1	3	1) 1 min after first tightening 2) 2 min after first tightening 3) 24 hrs. after first tightening
2	2	1) 1 min after first tightening 2) 12 hrs. after first tightening
3	2	1) 1 min after first tightening 2) 12 hrs. after first tightening
4	2	1) 1 min after first tightening 2) 12 hrs. after first tightening

3.2 Nickel Seal Soak Tests

The nickel seal soak tests were developed to measure the compatibility of the seals and hydrazine without any other components present. The (previously described) hot soak test was performed with several metals that contain nickel. Any results of nickel interaction could be from the CRES 304 fittings, or the system used for testing. The nickel soak tests only contained hydrazine and the nickel seals. Any metals found in the hydrazine after any length of time would come directly from the seals themselves. The nickel seal soak tests were divided into two groups. The first group began in parallel with the hot soak test with unused seals. The second group of soak tests began after the hot soak test was completed using the seals removed from the flight configuration. These seals had different surface characteristics due to their use in a fitting.

3.2.1 New Seals

To ensure the amount of nickel seal exposure in the hydrazine was similar to the propulsion system, the nickel seal surface area in contact with hydrazine for any fitting was assumed. The nickel surface area to hydrazine volume ratio was then calculated for the length of one fitting. (Volume based on a 0.218" diameter and a 1.25" length). This ratio was then used to determine the amount of hydrazine required to achieve this same ratio for exposure of an entire nickel seal. The result was 10 mL of hydrazine for every nickel seal used in a soak test.

With the calculated ratio of hydrazine and nickel surface area determined, the test was set up to provide a variety of results. The test was divided up into two separate environments. There were several samples left at room temperature for 75 days, and one sample monitored at 120°F for 10 days. The room temperature test included three hydrazine samples of 50 mL, and one hydrazine sample of 100 mL. One 50 mL sample was a control, which contained no nickel seals and acted as a baseline for comparison of nickel levels. A second 50 mL sample contained five nickel seals, and the last 50 mL sample contained one nickel seal. The one nickel seal sample was used to determine if the amount of nickel interaction could be scaled down linearly for different area to volume ratios when compared to the 5 seal sample. The 100 mL sample contained 5 nickel seals set up for weekly analysis over a 36-day period. The analysis technique used requires 10 mL of

hydrazine per run, which would leave this sample with 50 mL remaining at the end of 36 –days, leaving all samples with the same volume of hydrazine. The last sample at 120°F contained 50 mL of hydrazine with five nickel seals. The results of this test were compared to the 36day exposure sample to validate the use of an accelerated test. Table 2 shows a breakdown of the new seal soak tests performed, and Figures 6 and 7 show the hydrazine samples in their respective test configurations.

Table 2 – New Seal Soak Test Breakdown

Sample Description	Volume of Hydrazine	Seals QTY	Test Duration	Temperature	Scheduled Analysis [days]
Control	50 mL	0	75-days	Ambient	0, 36, 75
Fitting Exposure	50 mL	5	75-days	Ambient	36, 75
Fitting Exposure at Elevated Temperature	50 mL	5	10-days	120°F	10
One Seal Exposure	50 mL	1	75-days	Ambient	36, 75
Fitting Exposure with Weekly Check	100 mL	5	75-days	Ambient	7, 14, 21, 28, 36, 75

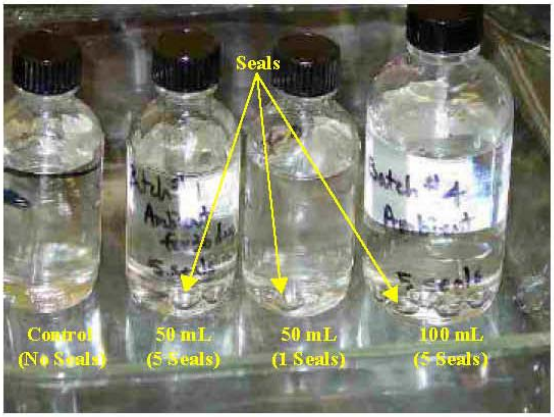


Figure 6 – New Seal Soak Ambient Test Setup

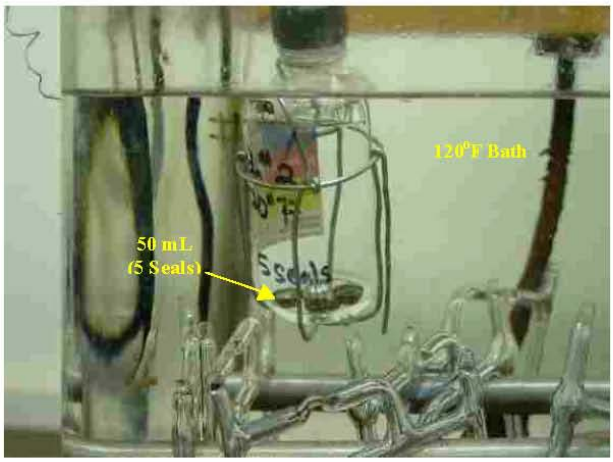


Figure 7 - 120°F Accelerated New Seal Soak Test Setup

3.2.2 Used Seals

The seals used in the soak test outlined in 3.2.1 were placed in hydrazine as delivered from the manufacturer. To compare the effects of surface characteristics, the seals used in the hot soak test were removed from the flight-like configuration and placed in hydrazine for an extended soak time of 36 days. Table 3 outlines the test setup for the used seals removed from the hot soak test configuration. The seals were labeled according to their fitting designation outlined in Figure 3. Fittings 3 and 4 have upstream and downstream designations due to the use of a union used in place of a thruster. (Upstream refers to the union location where the thruster is attached in the flight configuration.)

Table 3 – Used Seal Soak Test Breakdown

Sample Description	Volume of Hydrazine	Seals QTY	Test Duration	Temperature	Scheduled Analysis [days]
Control	30 mL	0	38-days	Ambient	0, 38
Fitting #1	30 mL	1	38-days	Ambient	14, 21, 38
Fitting #2	30 mL	1	38-days	Ambient	14, 21, 38
Fitting #3 (Upstream)	30 mL	1	38-days	Ambient	14, 21, 38
Fitting #3 (Downstream)	30 mL	1	38-days	Ambient	14, 21, 38
Fitting #4 (Upstream)	30 mL	1	38-days	Ambient	14, 21, 38
Fitting #4 (Downstream)	30 mL	1	38-days	Ambient	14, 21, 38

3.3 Materials Used

Table f4 outlines the materials used in the construction of the test setup used in the hot soak test, and the nickel seal soak tests.

Table 4 – Fitting and Tubing Material Used for the Hot Soak and Nickel Soak Tests

Part #	Description
AN815-4J	0.25" OD CRES 304 Flared Union
AN815-4T	0.25" OD Titanium Flared Union
AN818-4J	0.25" OD CRES 304 "B-Nut"
AS5176-J-04	0.25" OD CRES 304 Flared Sleeve
A54824N04	0.25" OD Nickel Conical Seal
Ti 3AL-2.5V	0.254/0.25" OD x 0.0172/0.0148" Wall Titanium Tubing

Along with the materials listed above, a Krytox Grade 240 AC lubricant was applied to each fitting before assembly. The same lubricant is used in the assembly of the fittings for the CALIPSO spacecraft.

3.3.1 Nickel Seals

Table 4 shows the part number of the nickel seals used throughout these tests. The information shown in table 5 outlines the elements that make up the seals and the percentage of each present in one seal. This information was provided by the supplier at the time of delivery.

Table 5 – Elemental Breakdown of the Nickel Seals

Element	%
Carbon (C)	0.015
Manganese (Mn)	0.245
Sulfur (S)	0.0005
Silicon (Si)	0.007
Nickel (Ni)	99.39
Copper (Cu)	0.004
Cobalt (Co)	0.005
Iron (Fe)	0.14

Visually, the seals have a shiny appearance with well defined edges. Figure 8 shows images of a seal taken under a microscope prior to installation in the hot soak test configuration. All seals used in these tests had a similar appearance.

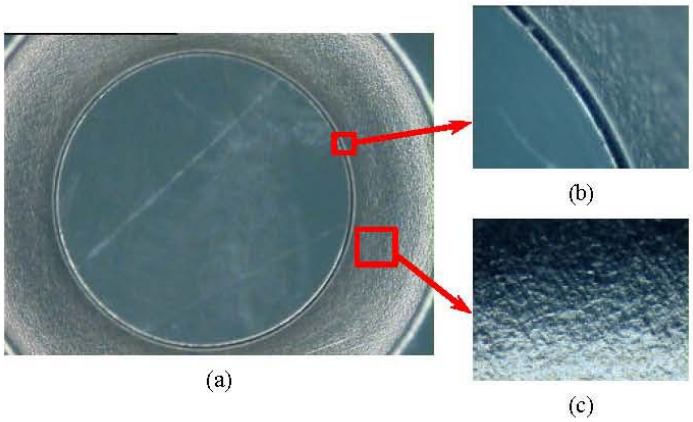


Figure 8 – Magnified Images of the Nickel Seals. (a) Image looking down into cone of seal. [37x] (b) Close-up of rim edge. [202x] (c) Close-up of seal wall. [100x]

4.0 RESULTS & DISCUSSION

4.1 Hot Soak Test

The hot soak test began on Wednesday, January 14, 2004 at 8:30am and continued until Sunday, January 18, 2004 at 9:10 am. The test duration was 4 days and 40 minutes, surpassing the expected test duration of 3.5 days. The average fitting temperature throughout the time period was 222°F, with an average line pressure monitored to 320 psig.

4.1.1 Hydrazine Assay Comparison

Table six shows the comparison of nickel levels in the hydrazine samples taken before and after the soak test. An Inductively Coupled Plasma (ICP) technique was used to measure trace metals in the hydrazine samples. The ICP machine can be used to trace metals in a solution with an accuracy of around ± 20 parts-per-billion (ppb). The values listed below were obtained with a 10 mL volume of sample placed in the measuring device.

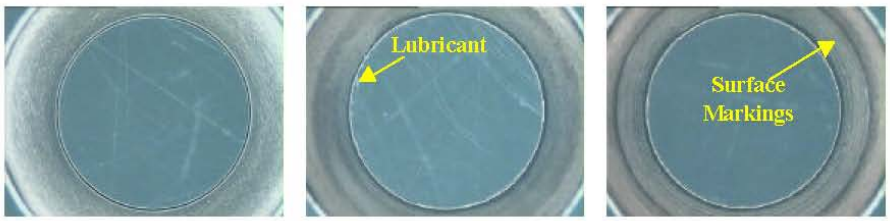
Table 6 – Nickel Levels in Hydrazine Before and After Hot Soak

Hydrazine Sample	Nickel Levels [ppb]
Pre-Hot Soak	48
Post-Hot Soak	37

The results are presented in parts-per-billion (ppb) by weight, which can be interpreted as 48 grams of nickel per every billion grams of hydrazine. Levels of nickel are present in the hydrazine, however, did not increase when exposed to the fittings for the 3.5-days. This shows the nickel seals have little interaction with the hydrazine.

4.1.2 Visual Observation

The nickel seals all had surface-scratch markings from the location where the flared tube and male threads sandwiched the seal together. Some seals had traces of residual lubricant, however no seal appeared to have pitting or evidence of corrosion. Figure 9 shows a comparison of a pre-soak seal and two seals after soak testing.



(a) (b) (c)

Figure 9 – Comparison of nickel seal appearance before and after hot soak test: (a) Sample seal before test, (b) fitting 1 seal after soak test, (c) fitting 3 seal after soak test. [All images x 37]

4.1.3 Torque Requirements

At the completion of the hot soak and before disassembly, the original torque strength applied to each fitting was checked. The original torque strength of each fitting per the torque schedule outlined in Table 1 was 177 in-lbs. All but one fitting B-Nut failed this test. Table 7 below outlines the torque strength of the fittings after the hot soak test, where upstream and downstream refer to the respective sides of the union used in place of the thrusters. Upstream is the B-Nut that simulates the thruster connection in the propulsion system.

Table 7 – Fitting Torque Strength Post-Hot Soak Test

Fitting #	Torque Strength [in-lbs]
1	145
2	145
3 (Upstream)	> 177
3 (Downstream)	160
4 (Upstream)	150
4 (Downstream)	175

Results show that the torque strength decreased for all but one fitting during the hot soak test. Evidence of whether or not this was an artifact of the hydrazine exposure, the elevated temperature, or a combination of both is not clear. The re-torque schedule shown in section 3.1.1 was followed and all fittings began the test with 177 in-lbs of torque. (The torque schedule was compromised for fitting 1. Section 4.1.4.2 explains why this fitting did not follow the torque schedule. However, it does not appear to be the cause of the decreased torque strength.) Even with a maximum difference in torque strength of 32 in-lbs, no fitting leaked throughout, and after, the hot soak test.

4.1.4 Test Operation

4.1.4.1 Oven Performance

The oven used in the hot soak test performed well throughout the test period with a few instances of instability. The initial occurrence with the oven happened the first night the oven was left unattended. Shortly after personnel had completed a leak check of the test section, the oven door became slightly un-latched and allowed the temperature inside of the oven to drop. A thermocouple was placed near the bottom of the oven to monitor the environment temperature, and its reading dropped from 222°F to an average of about 215°F for a 13 hour period until the work shift began the next day. The reading on the strip chart showed that in this time, the oven control system tried to regulate temperatures with a large fluctuation of this thermocouple reading. However, the fitting temperatures dropped only 2°F, staying within 5°F of the 225°F target. It was determined that the test section temperatures did not drop significantly enough to re-start the test and that the test would be extended for 13 hours to compensate for this occurrence. The oven door was secured with wire and the door remained closed for the completion of the test.

A second complication with the oven was a delayed relay in the oven control scheme. At times, the oven temperature would instantly begin to rise from 222°F to around 230°F, then the controller would regulate temperatures. This happened approximately 6 times throughout the test period with no repeatability. In the late morning hours of the second day of the test, the oven reached its over temperature limit of 235°F and shut all power to the oven. A test technician heard the oven alarm and reset the oven after 10 minutes of shut down. The fitting temperatures remained at 222°F during this down time and the test resumed. The line pressure was stabilized and it was determined that this shut down would not affect the results of the test. This was the only time that the oven shut down by itself.

4.1.4.2 Fitting Integrity

As mentioned in section 3.1, the assembled test section followed a torque schedule similar to the procedures of the CALIPSO program. After all re-torques were completed, the section was put through a proof pressure and helium leak check to ensure fidelity of the test configuration. During the pre-hot soak proof pressure test using snoop on each fitting, it was discovered that there was a leak in fitting #1. This fitting was subjected to 3 re-torques at 177 in-lbs. and failed the proof pressure test at 480 psig (1.5 x MEOP). The fitting was disassembled and examined. It was discovered that there was a small notch in the rim of the titanium threads that did not allow the fitting to form a leak tight seal. The fitting was polished using fine sandpaper (level 600) and re-assembled with a new nickel seal. The threads were also cleaned and Krytox 240 AC was applied once again. Since the torque schedule defined the last re-torque to take place 24 hours after the original tightening, it was determined to only perform 2 re-torques due to time constraints in the test lab. After the second re-torque the system was put through a second proof pressure check. The fitting did not leak during this second leak check the test began prior to performing the last re-torque of fitting 1.

4.1.4.3 Line Pressure

Throughout the test, the line pressure of the test section was controlled by a pressure regulator. To ensure that there were no leaks throughout the test section, the valve from the pressure regulator was shut off and the trapped pressure was monitored. It was observed that the line

pressure was highly sensitive to the temperature of the lab. Part of the test section was secured outside of the oven, and as room temperatures decreased, so did the recorded line pressure. This was confirmed with a technician covering the test section outside of the oven with insulation. As soon as the tube was covered, there was an instant increase in line pressure. This pressure fluctuation was observed throughout the test period. At no time did pressure drop due to a leak in the system.

4.2 Nickel Soak Tests

The test plan outlined in section 3.2 shows two sets of soak tests with a range of assays to be completed throughout the test period. The motivation behind this plan was to track changes in nickel levels over the test duration. However, the reported data is limited due to an anomaly with the analysis equipment used for the hydrazine assays.

4.2.1 Assay Equipment Anomaly

The hydrazine assays were analyzed using a Perkin Elmer Optima 3000 Axial ICP-OES instrument used for tracking metals in solutions. Hydrazine assays were to be performed on a weekly basis throughout the duration of both soak tests beginning on January 9. When the third week sample of the new seal test was analyzed (Week of January 26), the results showed inconsistencies and errors when compared to previous samples. This resulted in a detailed investigation of the ICP instrument with two maintenance visits and a completed repair on March 9. Therefore, the results presented in the next two sections are limited to assays preformed prior to January 26, and after March 9.

4.2.2 New Seals

The new seals were placed in hydrazine on January 9 and completed testing on March 22. Hydrazine samples were analyzed for the first two weekly assays, and at the end of the 75-day test duration. Tables 8 shows the nickel levels measured with the ICP instrument. Data is shown as the raw nickel level in parts per billion (ppb), the change in nickel levels between the control and the sample of interest (Δ), and the change in nickel per seal in the sample (Δ / seal). Figure 10 represents this data as a function of time.

Table 8 – Nickel Levels in New Seal Samples after the Specified Days of Exposure and Temperature

Sample Description	Seals QTY	Day from Start of Soak [days]	Temp.	Nickel Levels [ppb]	Δ [ppb]	Δ / seal [ppb]
Control	0	75	Ambient	31	0	--
Fitting Exposure	5	75	Ambient	221	190	38
Fitting Exposure at Elevated Temperature	5	10	120°F	86	55	11
One Seal Exposure	1	75	Ambient	72	41	41
Fitting Exposure with Weekly Check	5	7	Ambient	50	19	3.8
		13	Ambient	91	60	12
		75	Ambient	181	150	30

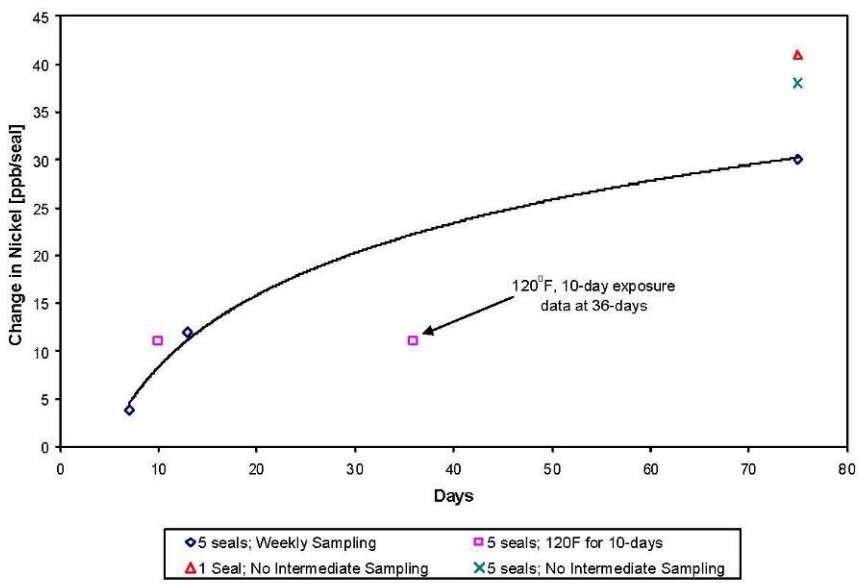


Figure 10 – Change in Nickel Levels per Seal Present in Hydrazine Sample

The data presented graphically shows the general trend of nickel levels over an extended amount of time. The trend line shown is based on the weekly sampling data and is a rough estimate due to the lack of data in the middle of the soak test. However, the trend is expected with this type of

compatibility test. The rate of metal leeching is greatest at the beginning of exposure and then begins to level off with time.

The results presented after 75 days of exposure are all within 11 ppb, showing the same amount of nickel leeching per seal in the hydrazine. The linear relationship between one seal in sample, and 5 seals is confirmed with this data. All of this data is presented without taking into account the ratio of nickel seal surface area and the volume of hydrazine. However, the one seal sample, and the five seal sample with no intermediate sampling were exposed to the same volume of hydrazine and their change in nickel per seal was within 3 ppb.

The final data point of the sample tested at 120°F was plotted twice at 10 days, and at 36 days. The 36-day plot is shown since the elevated temperature test was supposed to simulate 36 days of exposure after 10 days. The data clearly falls in family of the weekly exposure data at room temperature after 10 days, and out of family for 36 days. The accelerated test did not appear to simulate the 36 days of exposure.

4.2.3 Used Seals

Once the hot soak test was completed, the seals were removed, cleaned of lubricant, and placed in hydrazine. Each individual seal was placed in the same amount of hydrazine in separate containers on February 2 for 38 days at ambient conditions. Table 9 and Figure 11 show the amount of nickel found in the hydrazine samples. (All references to fitting numbers can be found in Figure 3.)

Table 9 – Nickel Levels in Used Seal Samples after 38 - Days of Exposure at Ambient Conditions

Sample Description	Seals QTY	Day from Start of Soak [days]	Temp.	Nickel Levels [ppb]	Δ [ppb]
Control	0	38	Ambient	45	0
Fitting #1	1	38	Ambient	88	43
Fitting #2	1	38	Ambient	63	18
Fitting #3 (Upstream)	1	38	Ambient	95	50
Fitting #3 (Downstream)	1	38	Ambient	160	115
Fitting #4 (Upstream)	1	38	Ambient	90	45
Fitting #4 (Downstream)	1	38	Ambient	199	154

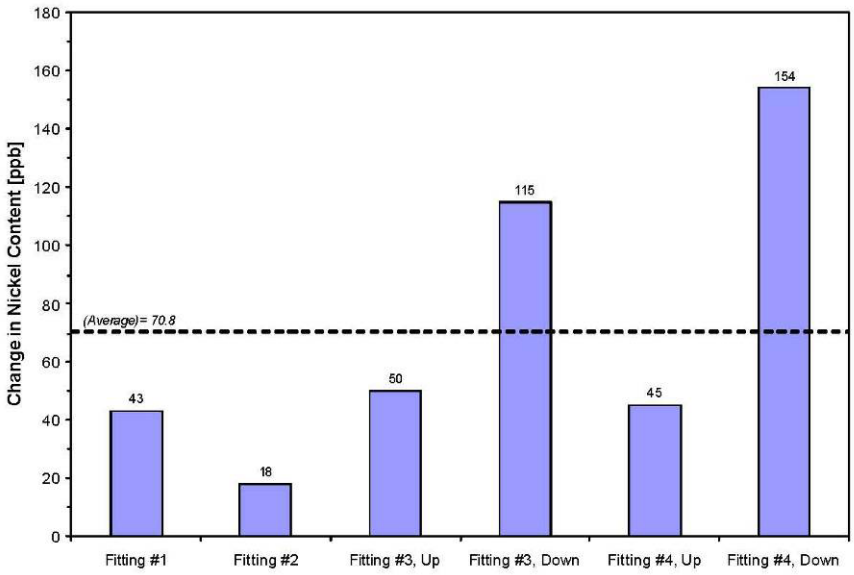


Figure 11 – Change in Nickel Levels per Used Seal

The data presented shows a wide spread of nickel levels for used seals. A maximum change was measured to be 154 ppb, while the minimum change was only 18 ppb. This spread shows the sensitivity of nickel leeching to the surface properties of the seals. All samples were tested in the same volume of hydrazine under the same temperature conditions, and were torqued to the same value for the hot soak of 3.5-days at 225°F.

4.2.4 Comparison of New and Used Seal Data

The major difference from the two sets of soak tests was the surface condition of the used seals. The spread of nickel leeching for the used seals after 38 days was 136 ppb, while the new seals had a spread of 11 ppb after 75 days. This data was observed with a varying amount of hydrazine at the time a sample was removed for analysis. A seal that has a change in its surface properties will react differently in the hydrazine than a new seal.

4.3 General Observations

The data collected shows that the nickel from these seals does leech into the hydrazine, but in small amounts. Of all the testing completed, the largest nickel level recorded in any hydrazine sample was 221 ppb. As a comparison to hydrazine purity standards, the levels of iron acceptably for hydrazine used on a spacecraft is between 2 and 4 ppm. The measured value of 0.2 ppm will not affect the hydrazine any more than leeching of other metals from the propulsion system tank and fuel lines.

The most realistic test performed in this investigation was the hot soak test with a propulsion system mock-up exposed to hydrazine at elevated temperatures. The amount of nickel exposed to the hydrazine is representative of the flight system, whereas the soak tests had a much higher nickel seal surface area to hydrazine volume ratio. The results of this test showed no noticeable increase in nickel levels after exposure was completed as shown in Table 6. In fact, with the CRES fittings and titanium tubing, the change in iron found in the post-hot soak hydrazine sample was on the order of 1000 ppb. Clearly, leeching of metals is occurring in the propulsion system at normal rates. However, the seals do not add a concern of nickel levels in hydrazine.

5.0 CONCLUSIONS

The hot soak test and the series of nickel seal soak tests with both used and new seals showed the effects of nickel leeching into hydrazine. The results showed that the nickel leeching into the hydrazine occurred in small amounts relative the other metals found in the propulsion system. The seals did not appear to corrode in the hydrazine after various lengths of time and different volumes of hydrazine exposure. Based on the compatibility ranking used in AFRPL-TR-69-149, the nickel seals used in this propulsion system can by classified as a class "A" application. The seals do not appear to compromise the integrity of the fittings used in this propulsion system.

6.0 REFERENCES

1. Marsh, W. R., and Knox, B. P., "USAF Propellant Handbook, Hydrazine Fuels, Volume I," AFRPL-TR-69-149, March 1970.

Addendum 2

NOTE

This study is not provided as part of the CALIPSO Report. For more information on Aerospace's review summary, please contact the NASA Engineering and Safety Center (NESC) at NESC@nasa.gov.

Title:	Summary Comments on NESC CALIPSO Review
Aerospace Report Number:	TOR-2004(218)-1
Date:	14 January 2004

Addendum 3

Notes from Alcatel Site Visit May 12 & 13, 2004

Rick Gilbrech (06-04-04)

The purpose of this site visit was to gather information from Alcatel and CNES concerning NESC and IPMC actions regarding the CALIPSO Proteus propulsion bus. The meeting included attendees from Alcatel, CNES, NASA GSFC, NASA GRC, and the NESC. The meeting began with an overview of response information by Alcatel and a tour of the 100,000 class spacecraft assembly/welding/x-ray/cleaning room used to assemble the CALIPSO Proteus bus. The facility was clean, well organized, and comparable to clean room assembly facilities in America. The team that performs all of Alcatel propulsion assembly consists of three operating technicians each with at least three years experience assembling Alcatel propulsion systems and a quality control inspector with 7 years experience at Alcatel. This team assembles 100 A/N fittings per year and can be traced by name to the specific inspections, lubrications and assembly of the 5 CALIPSO Proteus A/N fittings. The leak detection lead that performs the testing at Alcatel also travels to VAFB with the same equipment to perform the fill and drain valve and thruster valve leak tests. An attendance list and summary of actions was completed at the close of the two-day meeting (ref. Minutes of Meeting CNES document # CAL-P0-CR-682-CNES, filename "MOM-safety_NESC & IPMC Propu-Audit 13-5-04.doc").

NESC-R-001

Project shall demonstrate that Alcatel training and/or assembly documentation provided for proper lubrication of fluid fittings during assembly. Assembly procedures shall clearly delineate the type, quantity, and location where lubricant was applied and ensure sealing surfaces are kept dry and free of any contaminant.

Site Visit Notes:

Torque Wrench: During the tour of the assembly clean room it was noted that the torque wrench used to tighten the B-nuts for CALIPSO is calibrated annually. The 5 CALIPSO A/N assembly procedures were performed in Dec 03 and the calibration occurred two months earlier in Oct 03. The wrench has a ±1.0 N-m tolerance.

Hydrazine tank fitting: The hydrazine tank comes certified clean from Raphael with the outlet tube and male end of the tank A/N fitting attached. The tank is bolted to a non-flight assembly plate and the plate is mounted to a rotating assembly cart. The jig on the assembly cart has a locking rotational wheel that allows 360º plate rotation about the Y-axis (i.e., flip the tank upside down) for easy access to the top and bottom of the tank during assembly. With the tank upside down (bottom facing upward) the fitting is oriented horizontally where a handheld magnifier was

used to perform a 4X visual inspection of this sealing surface. No flaws were noted in any of the visual inspections, but if they were, the part would be examined under 40X magnification. This and all fitting surface inspections are done by the quality control (QC) inspector's eyes only. The female fitting with a short (6 inch) pre-formed ¼" diameter tube (certified clean) is supplied by Raphael and received a similar successful 4X visual inspection under a binocular microscope. Note that this female tube end is flared on a flaring machine at Raphael whereas the four thruster female fittings use machined tube ends fabricated at Alcatel. The nickel conical seal was given a 4X visual (both sides) with a binocular microscope.

The fittings were then lubricated with 6 drops of Opanol lubricant applied as follows: 2 drops 180 degrees apart on the middle portion of the male threads. The tech then changes to a new set of gloves and applies 2 drops to the backside of the 37º flare tube end that contacts the sleeve, changes gloves once more and applies 2 drops to the outside of the sleeve that contacts the female nut. The lube procedure is witnessed and stamped by QC.

The torque sequence was then performed with each torque step recorded and stamped by QC. The actual CALIPSO torqueing procedure was presented showing that the torque wrench ID and valid calibration dates were recorded. Note the fitting is horizontal for assembly and accessed through cutouts in the bottom of the non-flight assembly plate. Neither break away nor running torque on subsequent torques was recorded, just a verification that 20 N-m was achieved. The final step was installing the lock wire which was also witnessed and stamped by the QC inspector. All of these procedures were successfully completed for the CALIPSO Proteus tank fitting with no anomalies noted.

Thruster Fittings: The tubes with machined flare ends are fabricated and cleaned at Alcatel. A 4X visual inspection was performed but unlike the tank fitting, they follow a slightly different assembly process. Once inspected, they are lubricated and temporary caps are installed to protect the sealing surfaces. The upper and lower tube assemblies are pre-positioned and welded as described below. Both assemblies are installed on the –X propulsion panel where the final weld is performed joining upper and lower assemblies. The protective caps are removed, the female fittings are cleaned and then given another 4X visual inspection. The thruster male fittings and both sides of the nickel seals are given a 4X visual inspection and then the fittings are lubricated as described for the tank fitting. The fittings are then assembled, torqued and lock wired with similar witness/stamp by QC.

Tubing Assembly Sequence: The N2 and N2H4 fill and drain valves along with their weld-prepped tube lines are pre-positioned on the upper (+X) side of the non-flight assembly plate. The N2H4 fill and drain valve line mates to the assembled tank fitting/pre-formed ¼" diameter tube stub described above. The lower line assemblies are pre-positioned next and then upper and lower tube assemblies are welded in a maintain-clean weld process (orbital arc welder using parent material with inert gas purge). These are then detached from the non-flight assembly plate (still as two separate assemblies) and installed on the –X propulsion panel. The final weld attaching the upper fill/drain line to the lower thruster feed manifold is performed. With the –X propulsion panel in flight orientation the thruster female fittings are pointing towards the ground. The technician indicated the nickel seal is placed on the male fitting integral to the thruster and

the thruster is brought vertically up to mate with its corresponding female half. This is considered the ideal orientation to assemble an A/N fitting with the least likelihood of the seal shifting as the two halves are brought together.

NESC-R-002

Project shall demonstrate Alcatel training and/or assembly documentation provided for a visual inspection of fluid fittings prior to assembly. Assembly procedures shall ensure components had no visible defects and sealing surfaces were clean and dry.

Site Visit Notes:

Technician training referenced a torque training manual (#15) and on the job peer training. All other issues were addressed above in NESC-R-001 notes.

NESC R-003

Project shall demonstrate that the PROTEUS mechanical fittings are rigorously tested using techniques adequate to validate system integrity. Leak check procedures shall specify test method, equipment to be used, media, test pressure, and allowable leak rate.

Site Visit Notes:

Acceptance Tests at Alcatel

Proof Test/Fitting Sniff Test: Once the tubing assembly is completed, the acceptance testing begins. The first step is a pressure proof test with GHe to 33 bar gage for 5 minutes. The pressurization rate and the temperature rate are both controlled (temperature not to exceed 35°C and pressurization rate not to exceed 0.5 bar/min). The pressure is lowered to 22 bar and the 5 A/N fittings are sniffed with a mass spectrometer with pass criteria of leakage $<10^{-6}$ standard cubic centimeters per second (scc/sec) of GHe. This portable mass spectrometer has a sensitivity of 10^{-9} scc/sec level. According to the leak detect lead, Jean Rodriguez, the mass spectrometer is calibrated before any leak test with a calibrated GHe leak (during the tour, the calibration bottle shown indicated 10^{-7} scc/sec). Each of the five fittings registered in the 10^{-9} scc/sec range in the as run CALIPSO procedure.

Overall leak test: The next test is the overall leak test to quantify leakage from the 5 A/N fittings. The entire –X propulsion panel with tank, tubing, valves and thrusters is installed in a transport container. The system is pressurized to 22 bar with GHe and the fill and drain valves are torqued close to less than flight torque and capped. The fill and drain valve seats are designed to permanently deform when torqued to flight torque to ensure maximum sealing. Therefore the only time these valves are torqued to flight level is when the tank is filled and pressurized and the valves will not be opened again. To prevent leakage through the thrusters from contributing to the overall leak rate, special sealing fixtures are attached to each of the four thruster nozzles to extract any leakage through the thruster seats. The sealing fixtures have tubes running to a separate vacuum pump to isolate their leakage. A blower is installed and switched

on inside the container to circulate flow. The container is then flushed with GN2 for one hour and sealed at ambient pressure. The mass spectrometer is calibrated and leakage is measured for 12 hours. Data acquisition is stopped and the mass spectrometer is recalibrated. A calibrated GHe leak (6.5×10^{-5} scc/sec) is then introduced into the container for the next 12 hours and recorded. Data acquisition is again stopped and the mass spectrometer is calibrated. Data is again recorded for 5 minutes to confirm no drift or anomaly with the mass spectrometer then the test is concluded. A formula is then used comparing the leak rate slopes before and after the introduction of the calibrated leak to derive the overall leak rate. The derived overall leak rate for CALIPSO was 2.39×10^{-6} scc/sec. The success criterion is 8.4×10^{-5} scc/sec.

Thruster leak tests: The system is pressurized to 22 bar with GHe and the thruster sealing fixture is attached to a thruster and connected to the mass spectrometer. Leakage is then measured and the procedure repeated for the other three thrusters. All passed the success criteria of leakage $< 10^{-5}$ scc/sec.

Fill and drain valve leak test: With the system pressurized to 22 bar with GHe, the GN2 fill and drain valve is connected to the mass spectrometer via its A/N connector and leakage recorded. This is repeated for the N2H4 fill and drain valve. Both passed the success criteria of leakage < 2.8x10-4 scc/sec.

After these leak tests the system is pressurized to 13 bar and a gas sample is drawn through the fill and drain valves to verify cleanliness and moisture requirements are met.

<u>Post Environmental Test Leak Checks at Alcatel</u>

The Proteus bus is then integrated with the instrument and put through thermal and vibration testing with the system pressurized at 3 bar. After this the following leak tests are repeated:

Overall leak test: The entire spacecraft is put in a transport container and the above procedure is repeated.

Thruster leak tests: The above procedure is repeated although this time the test/arm plug is used to check the individual valve seats (downstream first, then upstream) to the same leak criteria. Once these tests are completed the test/arm plugs remains installed for the remainder of the launch campaign.

Fill and drain valve leak tests**:** The leak test is repeated as described above.

After these leak tests the hydrazine pressure transducer is calibrated at 22 bar and then a mass flow test is performed on each individual thruster with the system at 2.5 bar to 7.5 scc/sec. This test verifies that the software and wiring are controlling correctly. Although all four thrusters are normally fired simultaneously, this verification is needed in case of a thruster failure where the software can deselect the thruster opposite the failed thruster and the remaining two can still be used without loss of mission (one fault tolerance).

Leak testing at VAFB

After transport and receipt at VAFC, the system is pressurized to 22 bar with GHe and a 12 hour pressure decay test is performed by monitoring the onboard temperature and pressure via telemetry. A pressure polynomial equation accounting for temperature variation is used to determine the pressure. The temperature measurement range is -40 to 60 °C with 12 bits (1 sign + 11 data) corresponding to 0 VDC low (-40 °C) and 5.1 VDC high (60 °C) yielding a temperature resolution of 0.0488 °C. Similarly, the pressure measurement range is 0 to 22 bar with 11 bit resolution or 0.0107 bar. Adding in the 0.2% FS error of the pressure transducer (0.044 bar), the quoted resolution of the end to end pressure measurement is 0.054 bar. The success criterion of the 12 hour leak test is that the pressure drops no more than the resolution of the measurement system (e.g., 22.0 – 0.054 = 21.946 bar final pressure). With the system still at 22 bar, the thruster and fill and drain valve leak tests are performed as described above. As mentioned, the test/arm plugs are installed so this thruster leak test measures leakage across both seats.

NESC-R-004

Project shall demonstrate thermal and vibration loads applied to the spacecraft during environmental tests envelope conditions it will experience from servicing through launch.

Site Visit Notes:

Environmental test conditions

The vibration level inputs at the shaker table are on the order of 1.5 to 2 g's resulting in predicted first mode levels at the center of the –X propulsion panel of 9 g's and 20 g's at the thrusters. The thermal environments during test at Alcatel and at VAFB are summarized in the following table.

	Alcatel Average Test Temp ºC	Alcatel Thermal Cycling Temp ºC	VAFB Temp ºC (PPF/White Room)
Max	30	45	25 / 20.6
Min	15	0	19 /15

Temperature during spacecraft transport from the Payload Processing Facility to the pad is not quoted, but the handling can is double bagged and purged with dry gaseous nitrogen during this period.

Qualification tested hardware

Alcatel does not have access to the EUREKA A/N fitting qualification data as was implied. Qualification for Proteus was performed through a propulsion qualification model put through a mechanical and thermal environment that enveloped the Delta II interface control document levels. Alcatel stated the vibration levels were 1.5 x Delta II grms levels and a final performance

test was conducted. Alcatel has an action to provide the report detailing these test levels. Alcatel also referenced qualification data from Raphael that was performed for an Israeli satellite and another program from EADS on the GLOBALSTAR program. Bryant Cramer has the action to provide these two test reports.

NESC-R-005

Project shall demonstrate that servicing procedures adequately control temperature, pressure, and flow rates to minimize the potential for leakage.

Site Visit Notes:

Alcatel provided the procedure used to fill and pressurize JASON-1 that will be used for CALIPSO. This procedure detailed adequate control of temperature and pressurization rates during filling and pressurization to preclude significant internal pressure or thermal transients. Hydrazine fill flow rate is limited to < 8.3 cm^3/sec for the first 5 liters and then kept at < 33 cm^3/sec for the remaining fuel load (28 kg total for JASON-1). Nitrogen pressurization is constrained to $T_{max} < 35$ ºC and $\Delta P/\Delta t < 0.5$ bar/min. Pressurization to 10 bar is incrementally achieved over 20 minutes with a 3 minute hold at 5 bar. From 10 to 15 bar the constraint applied is $T_{max} < 35$ ºC and $\Delta P/\Delta t < 0.2$ bar/min. Once at 15 bar, there is a planned 30 minute hold then the final target pressure of 19.22 bar is achieved following a pressure/temperature table in the procedure.

NESC-R-006

Project shall verify that the controls at the processing facility and launch pad identified in the Final Report are in place to monitor for leakage from the time hydrazine is loaded until final closeout for launch. Additionally, the Project shall verify that spacecraft operations are minimized after hydrazine loading and that provisions are made for area securing and the rapid evacuation of personnel should a leak develop. Further, the Project shall coordinate with other payload/Delta II processing personnel to ensure the Project's approach for minimizing personnel exposure to potential hazards is properly integrated.

Site Visit Notes:

Jose Caraballo presented the capabilities of the VAFB payload processing facility and SLC-2 white room detection/alarm systems that will be in place. Once the PPF site selection is made, these controls will be reviewed and verified. Bryant Cramer took an action to scrub the spacecraft processing 36-day timeline to ensure the fueling operation cannot be pushed any closer to launch. Cramer will also coordinate with other payload/Delta II processing personnel to ensure the Project's approach for minimizing personnel exposure to potential hazards is properly integrated.

NESC-R-007

Project shall demonstrate pre-servicing thruster leak checks will be adequate to validate system integrity. Leak check procedures should test each valve independently and shall specify the test method, equipment to be used, media, test pressure, and allowable leak rate.

Site Visit Notes:

The thruster leak check details were covered above in NESC-R-003 notes.

NESC-R-008

Project shall verify that the PROTEUS Moog valves on CALIPSO do not have defective plunger assemblies.

Site Visit Notes:

Alcatel provided the thruster valve part and serial numbers. The CALIPSO Proteus thruster valves were supplied by Wright Components Co. (also known as EG&G Perkin Elmer) with part number 18207-14, serial numbers 029, 030, 033 and 034. The suspect valves with defective plunger assemblies were manufactured by MOOG after it purchased Wright Components in 2001 and moved manufacturing from Phelps, NY, to East Aurora, NY. The CALIPSO thruster valve part number and serial numbers used by Alcatel are exempt from the MOOG defective plunger issue.

NESC-R-009

The Project shall demonstrate that test procedures verify relays 16 and 17 are open before power is applied to the spacecraft. Since the design incorporates latching relays, verification of the last stable state by data retrieval or written record is acceptable.

Site Visit Notes:

After the test/arm plugs are installed the final time at Alcatel before shipment to VAFB, the ability of the ground operator to close relays 16 and 17 is inhibited by removing the telecommand "close relays 16 and 17" from the electrical ground support equipment Main Control and Data Test (MCDT) database. Two MCDT's perform health and safety telemetry monitoring, telecommand sending and control, and specific checkout equipment control and monitoring (ref. CALIPSO Missile System Pre-launch Safety Package, p. 134). The software routine that powers off the spacecraft has a step to telecommand open relays 16 and 17. The independent relay position feedback circuit is checked and if the open indication is not received, an error message is displayed on the operators screen. Alcatel agreed to add a warning screen instead of an error message on the operator's monitor and also add a safety warning in the procedure in case of this error/warning message dealing with relays 16 and 17. The forbidden

command management procedure (removal and verification) will be reviewed at the Pre-Shipping Review before the spacecraft leaves Alcatel.

NESC-R-010

Steps for inserting and removing test/arm plugs shall be explicitly called out in the ground processing timeline. Final installation for flight shall occur as late as possible; until that time, plugs should only be installed as required for thruster valve testing.

Site Visit Notes:

Alcatel stated that the test/arm plugs will only be used to perform the individual thruster valve seat leak tests outline in NESC-R-003. There eight plugs, two for each thruster circuit allowing each thruster to be fired individually. Once these tests are completed the plugs will remain in the spacecraft from that point on. Alcatel's rationale is based on reliability concerns that once the spacecraft is fueled, there is no way to verify the test/arm plug function without hot firing the thrusters.

NESC-R-011

The Project shall verify that all thruster firing circuit inhibits function as designed.

Site Visit Notes:

Alcatel indicated the individual thruster mass flow test is considered the verification of the thruster wiring/inhibit circuitry. The test is designed to ensure that the polarity within the attitude control system is correct and to ensure that no significant blockage exists. No other evidence of manufacturing quality inspections or electrical continuity/resistance/functional checkouts was provided. The planned individual thruster mass flow test only exercises four of the possible eight combinations of the three commands (relay 17, 16 and spacecraft software opto-driver commands). Considering each command as a binary switch will result in 8 possible combinations or binary states. At power up all three are off (state 000 in binary terms), then relay 17 is commanded on (say 100 in binary terms), next relay 16 is commanded on (state 110) and finally the spacecraft software opto-driver command is sent resulting in thruster firing (state 111). This means states 001, 010, 011 and 101 are never exercised.

Bob Kichak (originator of this requirement) agreed that the planned mass flow checkout is an approach comparable to NASA programs (i.e., to confirm functionality), but wanted to recommend that the additional four states be exercised during the test if this could be reasonably accommodated. This would guarantee the inhibits function as intended.

IPMC Action 1 (assigned 1-22-04)

NESC to examine the magnitude of a fire hazard associated with hydrazine leakage onto adjacent materials and recommend suitable mitigation activities.

Site Visit Notes:

Alcatel provide a listing of materials in the vicinity of the A/N fittings. Jim Free will provide a photo with labels identifying where these materials are located. Alcatel will provide chemical composition and estimated mass of these materials. The project provided material information on the barrier diaphragm between CALIPSO and CloudSAT and KSC provided material compatibility test reports on the diaphragm "skrim" cloth. NESC to have WSTF evaluate the hydrazine compatibility of these materials.

IPMC Action 2 (assigned 1-22-04)

NESC to work with VAFB to assess the adequacy of range capabilities to handle hydrazine leak rates ranging from catastrophic to plausible.

Site Visit Notes:

Alcatel will investigate the option of placing one to two ¼" Teflon leak detect tubes through the Multi Layer Insulation (MLI) blanket into the cavity between the –X closeout panel and the –X propulsion panel where the thrusters' fittings are located. These will stay installed until just before Dual Payload Attach Fitting (DPAF) installation in the PPF. There are 13 calendar days between fueling and DPAF mate on the current timeline. Once mated to the DPAF, the project will assume responsibility to install leak detection into the DPAF for the remainder of time in the PPF and at the SLC-2 white room.

IPMC Action 3 (assigned 1-22-04)

Project to explore adding an accelerometer package on the satellite to capture accidental impacts due to lifting, transport, or accidents that might promote a hydrazine leak once the spacecraft is fueled.

Site Visit Notes:

The project is to define the accelerometer package requirements (g threshold considered hazardous, accelerometer specs (# axes, range, electronic vs. visually read trip gage), etc.). Alcatel to assess the feasibility of NASA's proposed plan.

IPMC Action 4 (assigned 1-22-04)

OSMA (Code Q) to consider the need for a waiver to either NPR 8715.3 or EWR-127.

Site Visit Notes: Cramer to continue working waiver to NPR 8715.3 with Code Q.

IPMC Action 5 (assigned 1-22-04)

Project to implement all NESC requirements by traveling to France with a small team of civil servants to examine Alcatel procedures in a proprietary sensitive environment. Team to include the Chair of the Safety Working Group and a NESC Representative.

Site Visit Notes: Meeting accomplished.

IPMC Action 6 (assigned 1-22-04)

Project to identify a highly experienced KSC lead person to be solely and fully responsible for personnel safety throughout the Launch Campaign, consistent with the IPMC course of action.

Site Visit Notes:

Jose Caraballo proposed Tom Palo (KSC ELV Safety Officer) and Gary Hendricks (KSC CALIPSO/CloudSAT Mission Assurance Manager) as co-leads with NASA VAFB Resident Office personnel serving as backups. This role would be active from hydrazine fueling until launch and will be accomplished by transferring the "Ops Safety Control Authority" from the project (normally Jose Caraballo) to this person for the remainder of the launch campaign. It was not clear exactly how this role would be defined and enforced in the ground ops process as the Launch Site Support Plan that establishes the ground processing authorities and procedures will not be modified to reflect this change. Concern is that the level of authority and in-line involvement of this person may not be clear to everyone. For example, it was not clear whether this person be a required signature on procedure redlines or other deviations from normal planned procedure. Perhaps a letter from the Program office clearly delineating this would avoid confusion.

IPMC Action 7 (assigned 1-22-04)

NESC to provide a risk assessment (NASA 5 x 5 matrix) of the propulsion issue once all of the propulsion actions are completed.

Site Visit Notes:

NESC to review all available information gained at Alcatel site visit and then assign the before and after risk levels on a 5 x 5 matrix.

IPMC Action 8 (AETD request of January 29, 2004)

Verify that the mechanical design of the spacecraft, DPAF, GSE, and the way they are used during mating precludes unplanned contact between the two spacecraft, the various parts of

the DPAF, and/or the GSE required in the vicinity during the several mating operations. Fixturing should provide sufficient guidance (e.g. guide pins) during the mating to preclude inadvertent lateral motion of the pieces while mechanical stops should preclude inadvertent vertical motion until initial positioning and stabilization had been achieved. This verification should include not only the DPAF to CALIPSO but also any parts of CloudSat that come near CALIPSO during the mating process. Consider whether it would be advantageous from a safety perspective to mate CALIPSO to the upper DPAF cone before it is removed from the loading facility.

Site Visit Notes:

During inspection of the CALIPSO spacecraft it was observed that thruster nozzles will protrude about 2" below the –X closeout panel. Access to the underside of the spacecraft in its upright position on the handling fixture once fueled will be very limited (only from beneath with no side access).

IPMC Action 9 (AETD request of January 29, 2004)

For the time period prior to DPAF mate, conduct a fire safety analysis to show that all materials in CALIPSO, the DPAF, CloudSat, and required GSE are appropriate for use in the presence of leaking liquid hydrazine, that the worst-case fire scenario is manageable, and that personnel can be protected. In this scenario, it should be assumed that the entire contents of the propellant tank would be emptied within 1 hour. See Addendum 7 to this report.

Site Visit Notes:

See IPMC-1.

IPMC Action 10 (AETD request of January 29, 2004)

For the period prior to DPAF mate, verify that the hydrazine leak detection capabilities and contingency plans for use during this time frame are sufficient to keep personnel safe under the assumption that the entire contents of the propellant tank would be emptied within 1 hour.

Site Visit Notes:

Jose Caraballo presented PPF precautions prior to DPAF mate. These include toxic vapor leak detect systems and alarms as standard measures. Additional measures will include personnel dosimeter badges and a Zellweger Analytics CM4 continuous gas monitor with four point leak ports. See Caraballo briefing presented on 5-12-04 for additional details.

IPMC Action 11 (AETD request of January 29, 2004)

For the time period after DPAF mate, conduct a fire safety analysis to show that all materials in CALIPSO, the DPAF, CloudSat, and required GSE are appropriate for use in the presence of leaking liquid hydrazine, that the worst-case fire scenario is manageable and that personnel can be protected. In this scenario, it should be assumed that the leak rate is at least 1 gram per hour and as much as 10 grams/hour and that liquid will be present.

Site Visit Notes:

See IPMC-1.

IPMC Action 12 (AETD request of January 29, 2004)

During the planned in-plant assessment of the propulsion system and bus pursuant to NESC Recommendations 1, 2, and 3, it should be verified that:

a) The assembly procedures are sufficient to ensure that the desired pre-load can be consistently developed in the propulsion system threaded fittings;

b) <u>Every</u> threaded fitting was inspected, assembled and <u>independently verified</u> to have been assembled per the procedure (e.g. QA witnessing of lubrication and torqueing of every fitting and individually noted). Recall that the EURECA qualification test article leaked due to a single improperly lubricated fitting;

c) The fittings are of the AN type with class 3 precision threads, and

d) The qualified design and processes developed for EURECA have been transferred to the CALIPSO spacecraft team with fidelity and rigor or that they have executed an equivalent qualification process.

Site Visit Notes:

Alcatel stated that the A/N fittings have Class 3A precision threads. See NESC-R-001, 002 and 004 for details on the other issues.

IPMC Action 13 (AETD request of March 1, 2004)

The Project will conduct a Peer Review all of the lifting and handling procedures as well as the DPAF attachment procedures as they represent the highest risk activities once the spacecraft is fueled.

Site Visit Notes:

Jose Caraballo proposed the normal peer review process be augmented with 2 independent operational type personnel (Cramer suggests Jim Free and Steve Scott) to participate in the lifting procedure review for those involving the fueled spacecraft. These independent reviewers will report their results to AETD.

Addendum 4

WSTF Proteus Propulsion Bus Hydrazine Material Compatibility Report

Calipso Materials Assessment for Contact with Hydrazine (N_2H_4)

INTRODUCTION

White Sands Test Facility (WSTF) was requested by the NESC to perform a quick material compatibility assessment of the Calipso spacecraft materials in contact with hydrazine. The analysis was performed with limited information on the materials and only a cursory understanding of the physical system. As such, the results presented are general in nature, except where specific material samples were received and tested.

This assessment addresses the issue of incidental contact of hydrazine (liquid or vapor) with a list of materials from the Calipso craft provided by NESC personnel. The incidental contact scenario was specified by NESC personnel and would result from a leaking AN fitting. Note: No materials specification or certification sheets were provided for the initial assessment. Scrim fabric was added to the list after the preliminary results were delivered. A certification sheet was provided for it. It is understood these materials are not intended for long-term contact and are not used as materials of construction to contain hydrazine.

The primary hazard from incidental contact is considered to be hydrazine decomposition as a result of material contact. This could be from catalytic decomposition or oxidation on material surfaces. Both mechanisms are exothermic and could result in fire and/or explosion hazards. Secondary hazards may result from material degradation but those are not assessed here as WSTF does not have sufficient information on the system.

Toxicity hazards are not addressed as NESC personnel have indicated the system is instrumented with adequate monitoring protection to warn personnel of a release.

BACKGROUND

To determine the potential for fire hazard, it is necessary to assess the conditions that would create a fire. The familiar NFPA fire triangle is applicable in this situation. The fuel is the leaked hydrazine. The oxidizer is the oxygen in ambient air. The materials in question will be considered possible ignition sources for this assessment; however, thermal and electrical sources are also possible ignition sources.

The lower flammability limit for hydrazine in air is 4.7% (v/v). At ambient conditions, hydrazine vapor in air is not flammable. The flash and fire points for hydrazine are both 124 ºF. The flash point is defined as the lowest temperature at which the liquid gives off enough vapor to form an ignitable mixture at or near the surface (Sax 1984). A sustained fire may not occur at the flash point but will at the fire point. The fire point is defined as the lowest temperature at which fire continuously burns, in still air, over a liquid surface upon exposure to an ignition source (Scott, Burns, Lewis, 1949). At ambient conditions hydrazine does not have a high enough vapor pressure to form a flammable mixture in

air. Thus, a potential ignition source will have to heat the hydrazine first and then still have sufficient energy to ignite a mixture.

MATERIAL LIST

The following is the list of material information provided to WSTF by NESC personnel. Below each name is a brief description of how and where the material is used in the spacecraft and the approximate mass or geometry.

Metals

- Aluminum:

	Alloy:
thruster bracket (200g*4)	7075 T7351
mounting web (20g*6)	7075 T7351
panel (1m², thickness 0.6mm)	6061 T6
half thruster thermal bracket (25g *4)	7075 T7351
lower frame (10kg)	7010 T7451

- Titanium:
  TA3V tubing
  TA6V: tubing bracket (15g), pressure transducer (200g), filter housing (130g), screw

- Copper:
  thruster thermal conductor (140g)

- Stainless steel
  onduflex washer

Non-Metals

- POM GF25 (polyoxymetylen):
  harness support (1g/supports)

- Epoxy base adhesive paste:
  insert bonding (2g/insert), CTA bounding

- polyester (velcro)+fixing ribbon:
  MLI fixing (1g/support)

- ETFE:
  climping ring (blue): (2g)

- Paint: Aeroglaze Z306:

primer epoxy base / paint polyurethane (0.7m², thickness 35 to 90 microns, 150g/m²)

- chotherm:
  conductive silicone elastomer fiber glass reinforced foil (thickness 0.38mm, 616g/m²)

- kapton (black & orange):
  4.5g/m for 50mm width

- chofoil aluminum +acrylic:
  10g/m²

- MLI:
  external face: aluminized kapton (quasi all surface are covered with-see velcros-)

- CTA:
  thermistance & heater (80*30mm each, 0.075g/cm²)

- Scrim fabric

ASSESSMENT

Where noted, WSTF personnel researched a material name to better identify it for the evaluation.

Aluminum:	Alloy:
thruster bracket (200g*4)	7075 T7351
mounting web (20g*6)	7075 T7351
panel (1m², thickness 0.6mm)	6061 T6
half thruster thermal bracket (25g *4)	7075 T7351
lower frame (10kg)	7010 T7451

Aluminum is compatible with hydrazine. As Figure 1 (below) shows, aluminum results in a lower hydrazine decomposition rate than titanium. All alloys listed above are acceptable for incidental contact. Per Schmidt (pg 691), aluminum alloys are "acceptable for brief general service based on 7 to 90 day immersion tests." In general, aluminum alloys should not represent a hazard from incidental contact with hydrazine.

- Titanium:
  TA3V tubing
  TA6V: tubing bracket (15g), pressure transducer (200g), filter housing (130g), screw

WSTF does not have data for these alloys as specified. TA3V and TA6V are assumed to stand for Ti-Al-3V and Ti-Al-6V respectively. In general, titanium-aluminum-vanadium alloys are considered to be compatible with hydrazine.

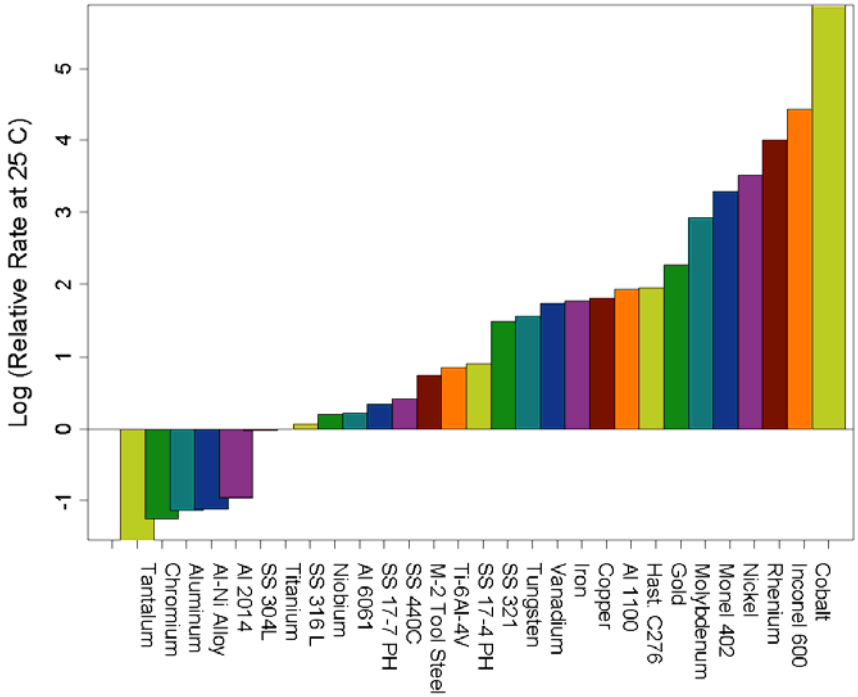


Figure 1. Relative Decomposition Rates of Hydrazine in Contact with Metals
(Relative to Titanium. Data from AIAA-SP-084-1999 and/or WSTF test data.)

- Copper:
  thruster thermal conductor (140g)

Highly oxidized blue-green (patina) copper is considered incompatible with hydrazine. A demonstration performed at WSTF has shown that highly oxidized copper is a potential ignition source for hydrazine combustion. The copper oxide used in the demonstration had a high surface area. When the hydrazine liquid contacted the copper oxide, the hydrazine began to oxidize and release heat. The heat vaporized some of the hydrazine and created a flammable mixture in the air space. The hydrazine continued to react with the copper oxide to the point that the oxide was glowing and became hot enough to be an

ignition source for the flammable hydrazine/air mixture. The hydrazine vapor ignited in air and burned until the hydrazine was depleted.

From a photograph provided to WSTF, the copper in the Calipso craft appears to be in the form of a braid. This presents a high surface area for incidental contact; however the surface does not appear to be highly oxidized. Additional information from the NESC indicated the copper had a tin coating.

Without the tin coating, could the copper braid react with hydrazine vapor and act as an ignition source? Copper is a very good heat conductor so the base metal under the corrosion is going to be flowing heat away from the hydrazine reaction site. A thick oxide layer (patina) might be insulated enough for a localized hot spot to form. The copper does not appear to be highly oxidized and therefore, would not seem to be a credible ignition source. If as indicated by NESC personnel, hydrazine vapor contact is the only possible type of exposure given the braid location, then it is even less likely that a hot spot could form on the copper.

No information was found for hydrazine reactivity with tin.

- Stainless steel
  onduflex washer

The washer material was described by NESC personnel as "decontaminated stainless steel Z6CN 18-09 (HV-350)." Z6CN 18-09 (HV-350) is listed as a 303 designation stainless steel and is comparable to SS 304 on the chart. It is considered acceptable for incidental contact. 300 series stainless steels are generally considered compatible with hydrazine.

<u>Non-Metals</u>

- POM GF25 (polyoxymetylen):
  harness support (1g/supports)

From an internet search, it was discovered that polyoxymetylen is the Swedish name for acetal, also known as Delrin®. It is not considered compatible, but not considered an ignition source either. It may degrade in hydrazine.

- Epoxy base adhesive paste:
  insert bonding (2g/insert), CTA bounding

In general, epoxies are not considered compatible, however, they not considered ignition sources either. Epoxy is a generic term and there are so many different formulations and fillers it is not possible to assess without testing. Very few epoxies have been tested because they are not considered compatible and do not warrant the expense.

- polyester (velcro)+fixing ribbon:
  MLI fixing (1g/support)

Polyester materials should be susceptible to ammonolysis, which in this case should make them incompatible with all the hydrazines as well as ammonia. Schmidt discusses the hydrazinolysis of esters on page 425 and 426 and again on 710. The Cole Parmer chemical resistance chart shows a severe effect not recommended (D rating) for ammonia with Hytrel (a polyester) and a moderate effect (C rating) for hydrazine. The interaction between polyester and hydrazine is not considered to be an ignition source though the material will be degraded.

- ETFE:
  climping ring (blue): (2g)

One source on the internet (www.meyersplastics.com) indicated that Rulon® was a brand name for ETFE. KSC's approved material list (KTI-5211) lists Rulon A as an 'A' rating, meaning it is acceptable for use within the described conditions (750 psig or less and 160 °F or less).

AIAA-084-1999, Table 15 lists Roulon J Film (misspelled?) as not compatible with hydrazine. A second entry for the same name indicates a significant weight loss and color change. This material is degraded by hydrazine but is not an ignition source.

- Paint: Aeroglaze Z306:
  primer epoxy base / paint polyurethane (0.7m², thickness 35 to 90 microns, 150g/m²)

Schmidt discusses some polycyanurate resins and their lack of compatibility with hydrazine on page 711. Based on the reactivity of polyesters and polyamides with the hydrazines and ammonia there is no reason to expect a polyurethane linkage to do any better.

AIAA-084-1999, Table 15 lists a polyurethane topcoat that changed from a rigid coating to softened, flexible and wrinkled after 48 hrs exposure to hydrazine at 160 °F.

This material is not compatible but probably not an ignition source.

- chotherm:
  conductive silicone elastomer fiber glass reinforced foil (thickness 0.38mm, 616g/m²)

Cured silicone is fine for incidental contact. Initially it was believed there was an additive to make it electrically conductive. Here conductive refers to thermally conductive so there is apparently no additive to make it electrically conductive. The silicone foil is conductive due to its suppleness that allows good thermal contact conductivity between a

unit and its supporting structural panel. With fiberglass reinforcement it is considered acceptable for incidental contact.

Fiber glass entrained in a polymer is typically considered compatible with hydrazine. Fiber glass by itself represents a high surface area for air oxidation of hydrazine and can be an ignition source.

- kapton (black & orange):
  4.5g/m for 50mm width

Kapton is a polyimide and will dissolve in hydrazine. It is not an ignition source; however, loss of insulation on a wire could lead to an electrical ignition hazard or other electrical problems.

- chofoil aluminium +acrylic:
  $10g/m^2$

See comments on aluminum above.

Acrylic has been subjected to a 2-hr screening test in hydrazine at ambient temperature (ref. LWO-680333, 09/13/95). The material had no effect on the hydrazine.

- MLI:
  external face: aluminized kapton (quasi all surface are covered with-see velcros-)

Assumed to stand for Multiple Layer Insulation. The MLI is composed of 7 layers and 6 spacers as shown below:

	Number	thickness	material	External face coating	Internal face coating
External layer	1	25 μm	kapton	none	Aluminized
Spacers	6	-	billon	-	-
Other layers	5	6 μm	Mylar	Aluminized	Aluminized
Internal layer	1	25 μm	kapton	Aluminized	none

See comments on aluminum above.

See comments on kapton above.

Billon - *Pronunciation:* (bil'*u*n), [key] —*n.*
1. an alloy used in coinage, consisting of gold or silver with a larger amount of base metal.
2. an alloy of silver with copper or the like, used for coins of small denomination.
3. any coin struck from such an alloy.

The composition of 'billon' spacer material could not be identified, therefore, a sample of the MLI was submitted for compatibility testing. The report from this test is WSTF# 04-38718. This report is attached as Appendix A. In summary, a small section containing most of the components attached to the MLI was exposed to a small quantity (~10 ml) of hydrazine. Several of the components dissolved or deformed upon exposure but did not ignite. Pre- and post-test photographs are included in the report. The hydrazine liquid changed color to yellow immediately upon exposure.

- CTA:
  thermistance & heater (80*30mm each, 0.075g/cm²)

CTA is a French acronym for "Controle Thermique Actif" (Active Thermal Control). The materials of construction were not provided. Most thermocouples have a stainless steel sheath. Heaters can be a variety of configurations and materials of construction. Depending on materials and previous heat cycling, the surface may be oxidized and represent a possible ignition source.

- Scrim fabric

The material specification sheet for the scrim fabric identifies the material as metallized polyester/nylon. A note at the bottom says the material "has a silver reflective side." It is unknown whether the metallized portion of the material really is silver or if it just looks that way. Two calls to the manufacturer on 09/08/04 to resolve the issue went unanswered. Assuming the metallized portion is silver (though it does not seem likely), the silver is a potential ignition source especially if the surface is oxidized. As with the copper, a high level of oxidation would be required to be a credible ignition source.

Nylon is listed as 'Not Compatible' in SP-084-1999, Table 15, Effects of Hydrazine on Nonmetals (pg 68). Schmidt mentions Nylon specifically on page 710 as dissolving.

See comments on polyester above.

SUMMARY

The tin coating on the copper braid material has not been precisely identified. No reactivity data for tin and hydrazine was found in the literature. A test for incidental contact exposure is recommended to verify this material will not pose a reactivity hazard.

Within the constraints of the limited information received on the materials in question and the cursory understanding of the physical system, it is believed that there is little risk of fire resulting from an incidental contact of system materials with hydrazine.

REFERENCES

Scott, F. E., J. J. Burns, and B. Lewis. *Explosive Properties of Hydrazine*. BM-RI-4460, Bureau of Mines, Pittsburgh, PA, 1949.

Sax, I. N. *Dangerous Properties of Industrial Materials*. New York: Van Nostrand, 1984.

Schmidt, Eckart W. *Hydrazine and its Derivatives: Preparation, Properties, Applications*. Second Edition. New York: Wiley-Interscience, 2001.

Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Hydrazine. American Institute of Aeronautics and Astronautics Special Project Report, AIAA SP-084-1999.

Material Selection List for Reactive Fluid Service, Kennedy Space Center publication KTI-5211.

Appendix A

WSTF Report 04-38718

NASA WSTF TEST REQUEST Note to test facility: A copy of this request should be returned with test report.		OFFICE USE ONLY TEST FACILITY I.D. NUMBER **04-38718**
NAME **Richard Gilbrech**	ORGANIZATION **NESC**	COORDINATOR **rs**
ADDRESS **NASA/Langley Research Center** **Hampton, VA 23681-0001**		REQUEST NO. **WSTF** TEST FACILITY **WSTF**
DATE **08/10/04**	PHONE **(757) 864-3303**	CODE

1. MANUFACTURER'S IDENTIFICATION (Item Description)	2. MANFACTURER'S NAME
Proteus Propulsion Bus Multiple-Layer Insulation	**Alcatel Space Industries** **54, rue La Boetie** **75008, Paris, France**

3. SPECIFICATION	4.CHEMICAL CLASS	5. GENERIC USE
	Assembly	**MLI**

6. TEST DOCUMENT NASA-STD-6001	7. TEST REQUIRED NASA STD-6001
	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ 11 ☐ 12 ☐ 13 ☐ 14 ☒ 15 ☐ 16 ☐ 17 ☐ 18 ☐ VCM ☐ CTVS ☐ SPEC ☐ VAC BAKE

8. VEHICLE	9. PART NO. & SERIAL NO.	10. PROJECT	11. USE TEMPERATURE
		G4S	

12. USE ATMOSPHERE/FLUID	13. IGNITER TYPE	14. USE PRESSURE	15. USE THICKNESS
Hydrazine		**Ambient**	**As Received**

16. INTENDED APPLICATION	17. QUANTITY INHABITABLE AREA/HAZARDOUS FLUID/VACUUM

18. CURE TIME	19. CURE TEMPERATURE	20. CURE PRESSURE

21. TEST ARTICLE WEIGHT	22. TEST ARTICLE AREA	23. NUMBER OF ITEMS TESTED	24. NUMBER OF ITEMS TO BE FLOWN

25. TEST CHAMBER VOLUME	26. TEST CHAMBER ATMOSPHERE	27. TEST CHAMBER PRESSURE	28. TEST CHAMBER TEMPERATURE

29. TEST CHAMBER DURATION	30. CLEANING SPEC	31. MATERIAL CODE	32. PHOTOGRAPHIC COVERAGE
			☐ VIDEO ☐ STILLS ☒ NONE

33. SPECIAL INSTRUCTIONS

Perform a Screening test (Beaker) in Hydrazine on a representative sample of the MLI assembly.

WSTF Form 514 (Formerly JSC Form 2035)

NASA STD 6001
TEST 15: REACTIVITY OF MATERIALS IN AEROSPACE FLUIDS
SCREENING TEST
NON-STANDARD TEST *

ASSEMBLED ARTICLE

Proteus Propulsion Bus Multiple-Layer Insulation

TEST ARTICLE DESCRIPTION

Preparation Information

The test sample was cut to contain all the layers of the insulation and most of the other components attached to the Proteus Propulsion Bus Multiple-Layer Insulation.

Pretest Photograph(s): NASA-WSTF 0804e6471 0804e6477

TEST CONDITIONS

Test Environment: Liquid phase of hydrazine (N_2H_4)

Test Temperature: Ambient

Test Duration: 2 Hr

TEST RESULTS, OBSERVATIONS, AND COMMENTS

Pretest Weight: 0.738 g *

Posttest Weight: 0.503 g

TABLE 1. MATERIAL CHARACTERISTICS

Component	Pretest Observations	Posttest Changes
Proteus Propulsion Bus Multiple-Layer	metallic, shiny, smooth, flexible, assembly	see below
Velcro	white, flexible, rectangular, solid	wrinkled
Wire	silver, flexible, wire	unchanged
Thread	white, flexible, thread	unchanged
Reddish Spacer (under thread)	translucent, red, smooth, nontacky, truncated circle, solid	dissolved
Tape (on edge of sample)	translucent, orange, smooth, nontacky, adherent, solid	dissolved
Multiple Insulation Layers	opaque, orange and white sheets, flexible, smooth, nontacky, solid	mottled, soft, wrinkled, partially dissolved

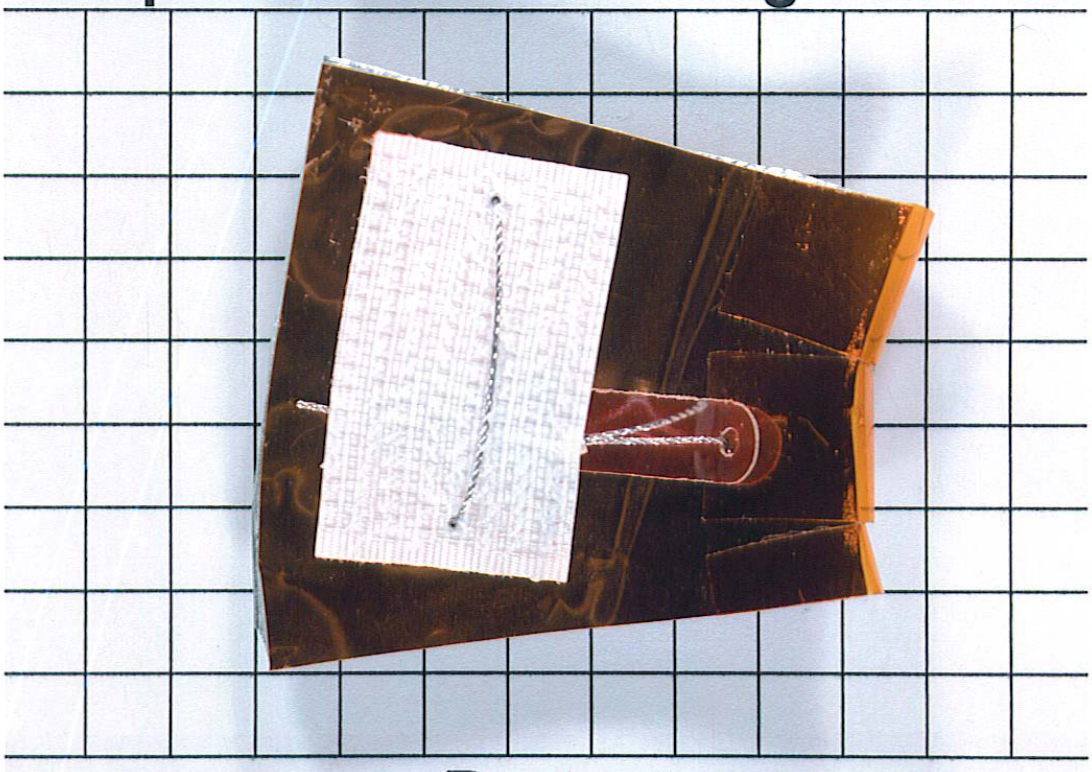
Note(s): The test sample discolored and partially dissolved in the test fluid. The test fluid became yellow in color and contained particulate.

Posttest Photograph(s): NASA-WSTF 0804e6478

4
WSTF NO. 04-38718
Protons Propulsion Bus
Multiple-Layer Insulation

5

WSTF No. 04-38718
Proteus Propulsion Bus
Multi-Layer Insulation
Liquid N_2H_4 Screening Test 15



Pretest
1 Grid Length = 0.5 cm

6

WSTF No. 04-38718
Proteus Propulsion Bus
Multi-Layer Insulation
Liquid N_2H_4 Screening Test 15

Posttest

1 Grid Length = 0.5 cm

Addendum 5

KSC Modeling Analysis of Hydrazine Leak Detection Systems for the CALIPSO Spacecraft

Analysis and Report written by Rebecca Young (retired)

Modified and Edited by Dale Lueck/YA-C3/321-867-8764 on January 10, 2005

Introduction

The CALIPSO spacecraft (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) Proteus propulsion system contains four ¼" A/N threaded fittings. This led to a concern about leakage of hydrazine (Hz) when the spacecraft is fueled 36 days before launch. For this reason, the NASA Engineering Safety Center (NESC) CALIPSO Independent Technical Assessment (ITA) requested that KSC perform a safety hazards analyses for the Hz leak detection system that will be used to monitor the CALIPSO spacecraft at the Vandenberg Air Force Base. The system consists of a Zellweger Model Single Point Monitor (SPM) and Sentry 5000 Hazardous Vapor Detection System (HVDS) for monitoring the Payload Processing Facility (PPF) ASO West High Bay. The SPM and the HVDS will be supplemented with an additional SPM or a Zellweger CM4, which is a 4-channel continuous monitor that will be located 4 feet from the spacecraft. The requested analysis includes two parts: (1) the effect of using various lengths of sample intake tubing on response time and concentration reading, using a Zellweger Model CM4 sensor, and (2) the time required for the vapor from a leak source to reach a significant concentration that would threaten personnel in the area. The goal for the analysis is to ensure that the personnel can be safely evacuated, if a leak should occur.

Instrument Analysis

The best way to characterize the performance of any instrument is to test several of them using a set up similar to its application. In this case, no instrument was tested. However, KSC was able to obtain test data for a CM4 instrument that was calibrated to measure monomethyl hydrazine (MMH) vapors. The data was taken in the Wiltech Toxic Vapor Detection Laboratory for the purpose of using it in the Hypergolic Maintenance Facility at KSC. The MMH vapor concentrations used for the test were 15, 50, and 97 ppb. The intake tubing lengths were 1, 50, 100, 150, 200, 250, 300, 350 and 400 ft. The intake tubing material was Teflon FEP, ¼-inch O.D and 3/16-inch I.D.

It needs to be pointed out that the data was obtained using MMH not Hz. Therefore, it may not be accurate for the CALIPSO application. However, it can provide information on instrument performance and indicate the general trend of responses.

It is also important to note that the data obtained is from only one CM4 instrument. Testing of several CM4 instruments would provide data with a higher confidence level.

Results for the concentration response of the CM4 versus tubing length are plotted in Figures 1, 2, and 3.

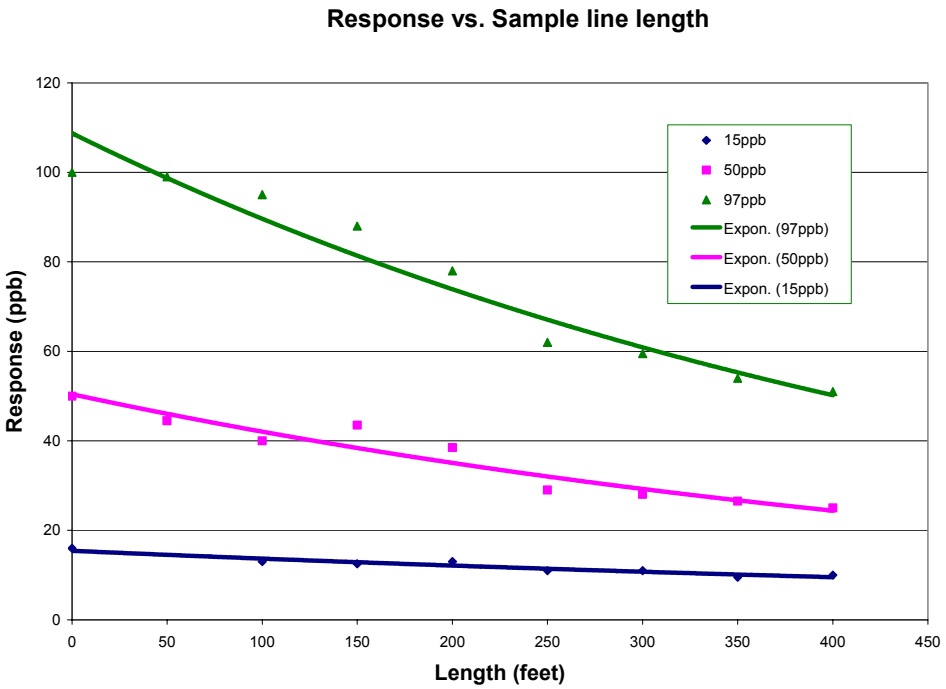


Figure 1. Concentration Response vs. Intake Tubing Length

Figure 1 shows a decreasing concentration when longer tubing is used. In this figure, each data point plotted is an average of several data points. Relative to the values at 1 foot, the 400 foot tubing length responses are down by 41%, 50% and 52% for the 15, 50, and 97 ppb vapors respectively, with smaller decreases at shorter tubing lengths.

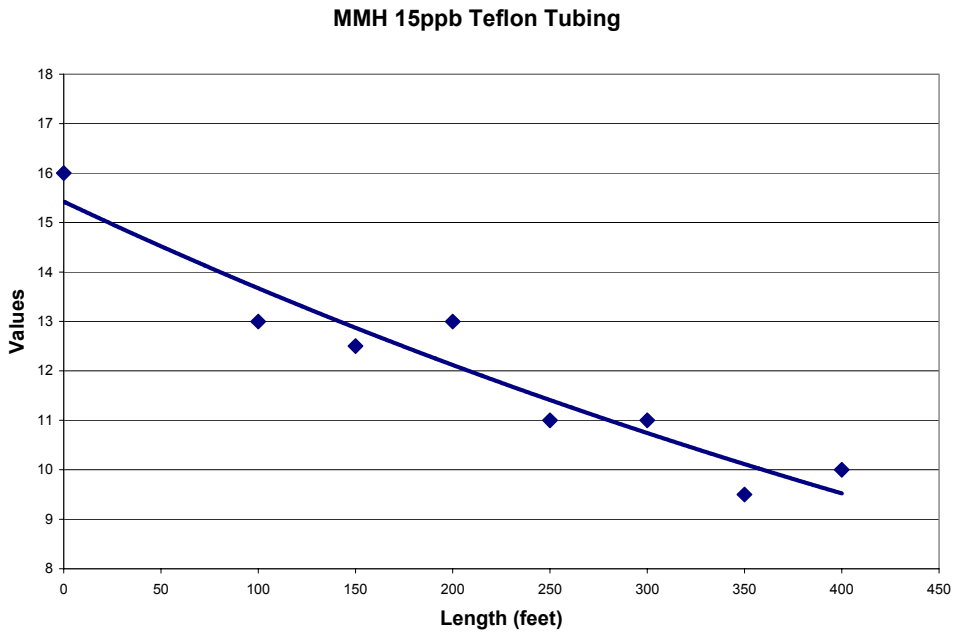


Figure 2. Response of a 15 ppb MMH Vapor vs. Intake Tubing Length

Figure 2 is an expansion of Figure 1, at 15 ppb vapor concentration, for better viewing.

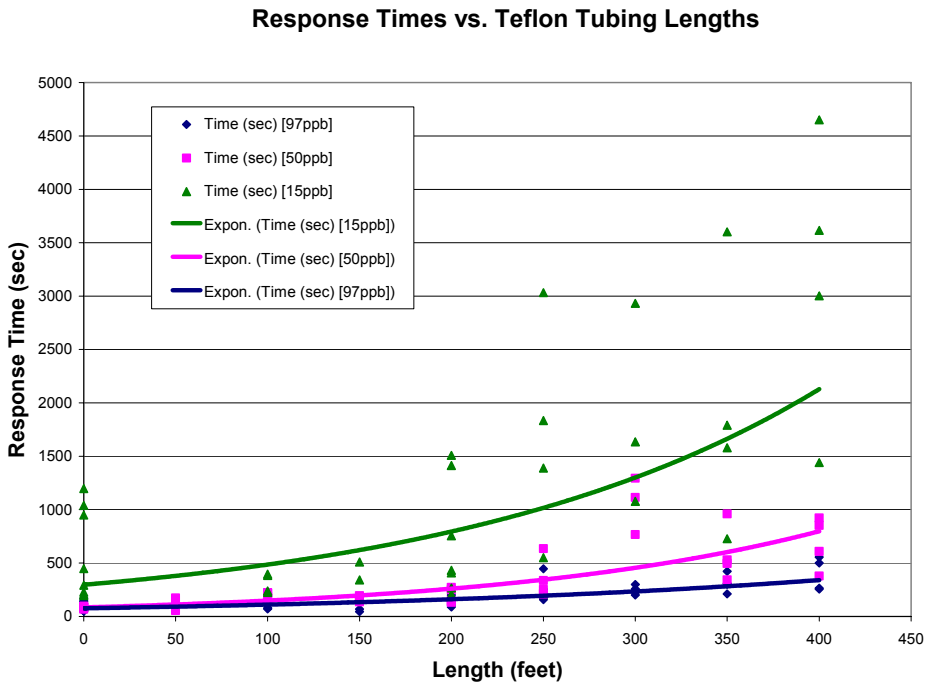


Figure 3. Response Time vs. Tubing Length

Figure 3 shows the response time, defined as the first response above baseline reported by the instrument (~10 ppb), for the three MMH concentrations using various lengths of tubing. Due to

the scattering of the data, all data points are plotted for better understanding of the instrument. The plot shows the longer the tubing, the longer the overall response time and the larger the scatter of data. Note that the scatter for the 15 ppb vapor is particularly large.

Analysis of Time Required for a Leak to Achieve 10 PPB and LEL Concentrations

KSC was provided with the following parameters for the analysis:

For the PPF, the worst-case leak rate is 1 kg/hour, volume of the PPF Cell (ASO West High Bay) is 105,600 ft^3 (2990 M^3),-- the flow through air exchange rate is 4 changes per hour, the temperature is $72^0F \pm 3^0F$, and the relative humidity is $45 \pm 10\%$.

For the SLC-2 white room, the worst-case leak rate is 10 g/hour, the volume of the white room is 18300 ft^3 (518 M^3) with level 6 raised to the highest point, the flow through air exchange rate is 30 changes per hour, the temperature is $62^0F \pm 5^0F$, and the relative humidity is $50 \pm 10\%$.

Time needed for a facility to reach a specific concentration can be calculated from the following Equation[1]. This equation assumes all leaked liquid is vaporized and the vapor is perfectly mixed with the facility air.

$$C = \frac{q}{nV}(1-e^{-nt}) + (C_1-C_2)\, e^{-nt} + C_2 \qquad \text{(Equation 1)}$$

where:

C = concentration in the space when completely mixed (m^3/m^3)
q = amount of pollutant added to the space (m^3/hr)
n = number of volume changes per hour
V = volume of the space (m^3)
t = time (hours)
C_1 = concentration in the space at start (m^3/m^3)
C_2 = concentration in the supply air (m^3/m^3)

The amount (q) of Hz added to the space can be calculated form the ideal gas law. For the PPF, assuming 1 kg/hour of liquid Hz is evaporated completely at 72^0F, the volume of Hz vapor from the leak can be calculated from Equation 2.

$$q = nRT/P \qquad \text{(Equation 2)}$$

where:

q = volume (liter)
n = number of moles of Hz = 1000g/32g per mole
R = universal gas constant = 0.082
T = temperature (K^0) = 295.4 K^0
P = atmosphere pressure (atm) = 1 atm

[1] http://www.engineeringtoolbox.com/37_120.html

q = (1000 / 32) x 0.082 x 295.4 /1 = 756.96 liter /hr = 0.757 m^3/hr

For the PPF, the plots for concentration vs. time, from Equation 1, are shown in Figures 4, 5, and 6.

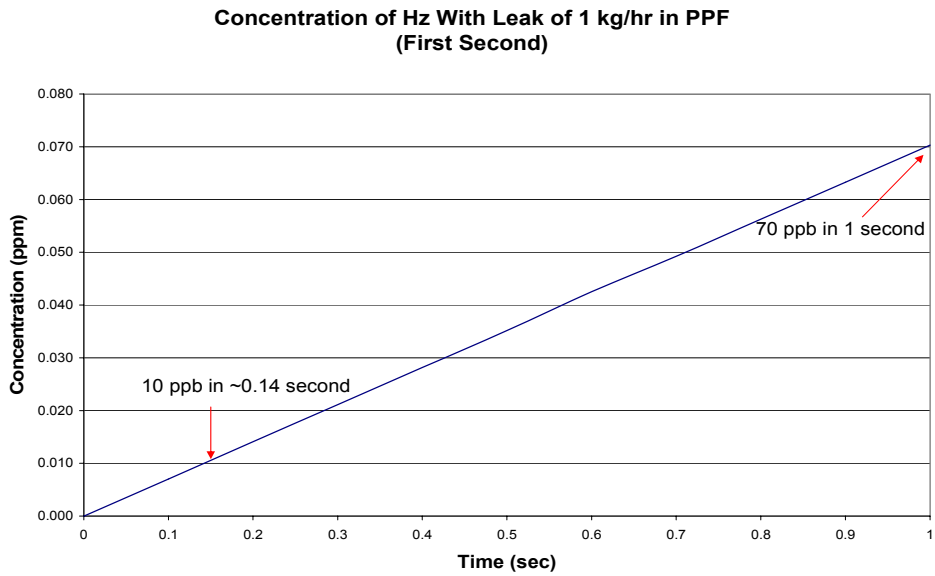


Figure 4. Concentrations of Hz in PPF during First Second of Leak

Figure 4 shows if there is a leak, the PPF will have a concentration of 10 ppb in 0.14 seconds and 70 ppb in 1 second. The number of drops of Hz to yield 10 ppb and 70 ppb can be calculated as follows:

Leak rate per hour = 1000g
Leak rate per second = 1000 / 3600 = 0.2778g/sec
Take 20 drops are in 1 cc
Take 1cc liquid Hz equals 1 g (specific gravity of Hz is 1.004
Drop for 70 ppb = 0.2778 x 20 = 5.56 (at the end of 1 second)
Drop for 10 ppb = 5.56 / 7 = 0.79 (at the end of 0.14 second)

The calculation indicates the vapor from a few drops of liquid Hz could achieve a concentration well above the ACGIH TWA value of 10 ppb within 1 second. If the detector is placed close by the leak source and the alarm is set at 10 ppb, the time to alarm will be largely determined by the instrument response time. Therefore, it is paramount to ascertain the response time of the instrument, including any delays due to tubing length.

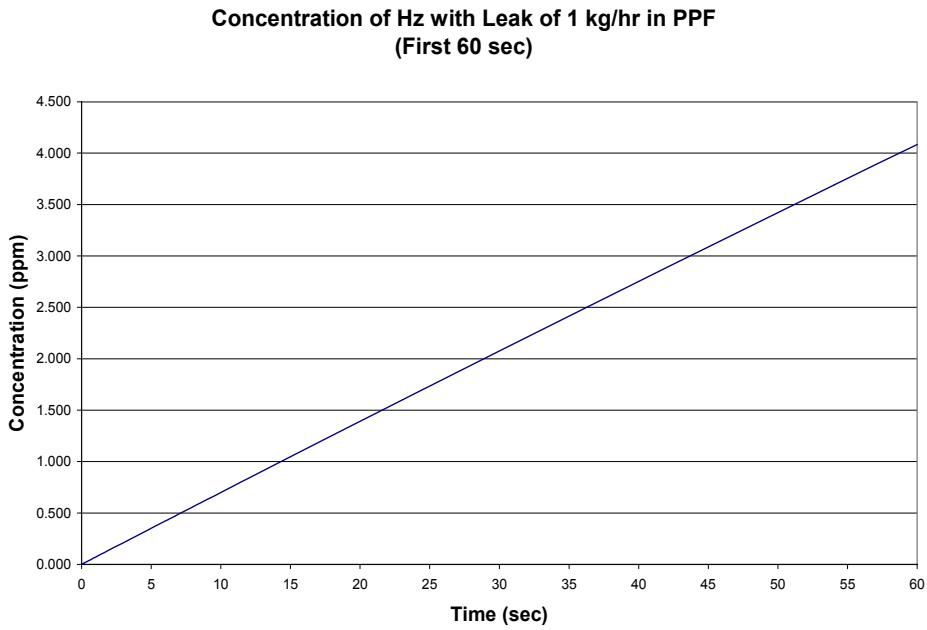


Figure 5. Concentrations of Hz in PPF during First 60 seconds of Leak

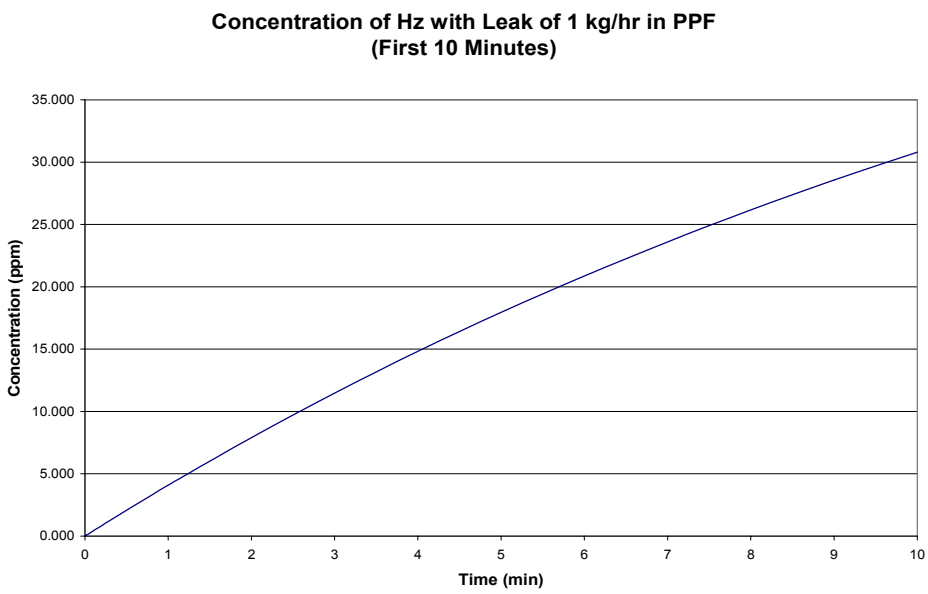


Figure 6. Concentrations of Hz in PPF during first 10 Minutes of Leak

For the white room, the plots for concentration vs. time from Equation 1, are shown in Figures 7, 8, and 9.

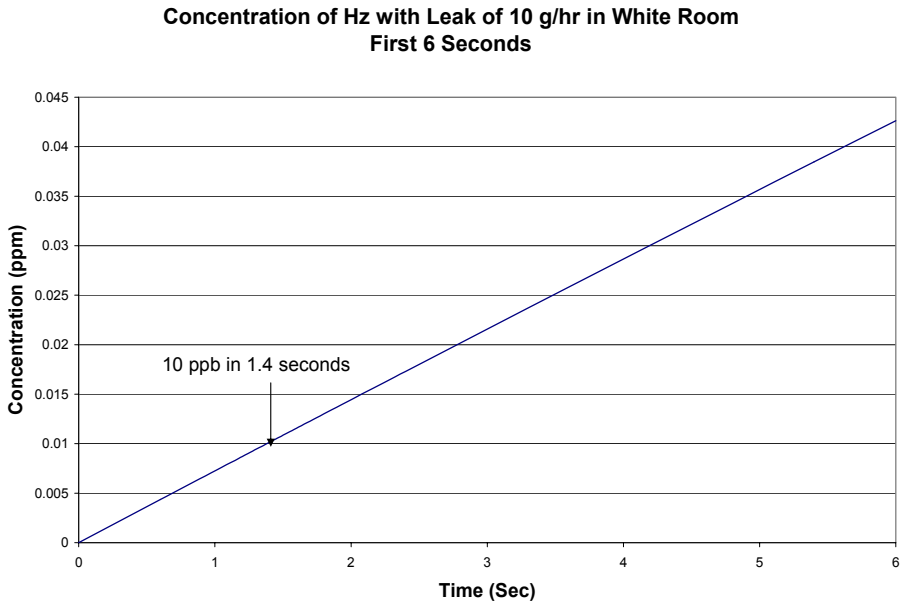


Figure 7. Concentrations of Hz in White Room During First 6 Seconds of Leak

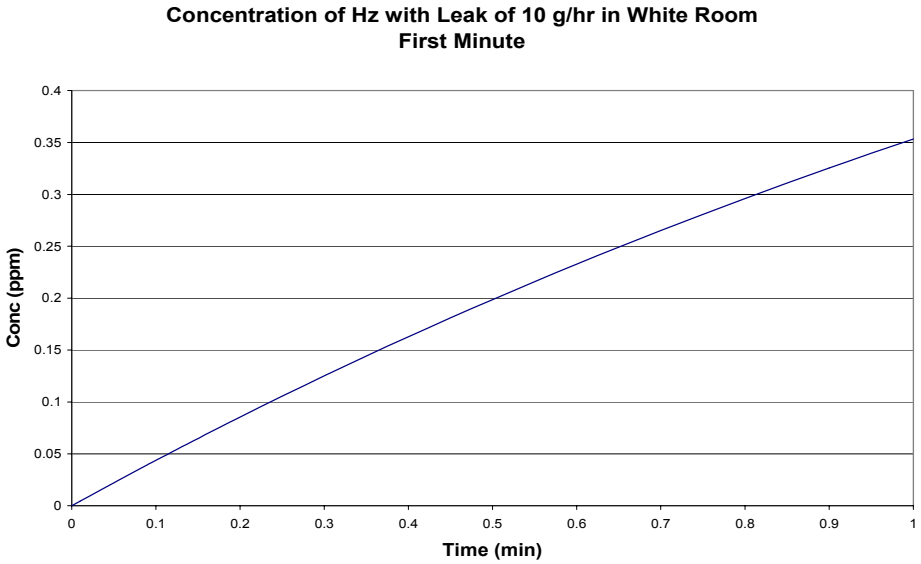


Figure 8. Concentrations of Hz in White Room During First Minute of Leak

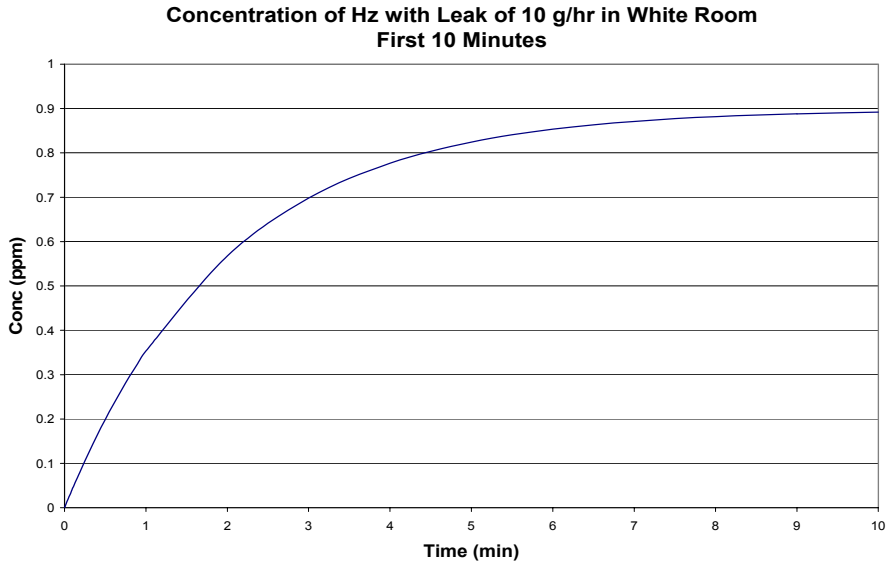


Figure 9. Concentrations of Hz in White Room During First 10 Minutes of Leak

As for the PPF, the calculation for the white room also shows that a leak can produce concentrations that exceed the 10 ppb TWA. It takes vaporization of only a fraction of a drop of Hz to yield this concentration.

In general, the calculation shows that even a small leak can produce Hz vapor concentration above the TWA within a few seconds. The time for the instrument to alarm will depend on the response time of the instrument, plus any delays caused by long sample lines.

The Microsoft Excel© spread sheet for the calculations is provided in Appendix A of this Addendum.

Analysis for Potential Explosion

In the case there is a leak on the AN fitting and assume all liquid accumulated in the canister, the Hz vapor pressure can be calculated from Equation 3[2] relating the hydrazine equilibrium vapor pressure to the temperature of the liquid:

$$\text{Log } p(\text{mmHg}) = -6.50603 - \frac{653.880}{T} + 0.047914\,T - 4.9886 \times 10^{-5} T^2 \qquad \text{(Equation 3)}$$

T in K^0

From Equation 3, the calculated vapor pressure of Hz at 295.37^0K is 12 mmHg.

[2] Schmidt, Eckart, *Hydrazine and Its Derivatives*, 2nd ed. John Wiley& Son, New York, 2001, p.189

The concentration in the closed canister can be calculated from the partial vapor pressure of Hz:

$$12 \text{ mmHg} / 760 \text{ mm Hg} \times 10^6 = 15{,}789 \text{ ppm or } \sim 1.6\%$$

The above concentration is the maximum concentration that can be produced at 72^0F, when the spacecraft is at PPF. As the temperature in the white room is very close to that of the PPF (62^0F vs. 72^0F), the maximum concentration that can be generated in the white room can also be considered ~ 1.6%. This concentration is below the Lower Explosive Limit of 4.7%[3]. Therefore, the possibility of explosion is low, if the only source of heating is from the room and no reactive materials are in contact with the hydrazine vapors or liquid. However, any external source of heat, or heat produced from reaction of the hydrazine, could quickly escalate the vapor concentration or produce a positive feedback leading to explosive concentrations.

Conclusion and Recommendation

The analysis of the CM4 data using MMH vapor showed concentration readings decreased as the sample intake tubing length increased. Therefore, one needs to consider the possibility that exposure to vapor concentrations of 10 ppb through long sample tubes may not trigger an alarm set at 10 ppb. The analysis also showed the instrument response time increases as the length of sample intake tubing increases. In addition to longer response time, the scatter of the data is greater for low concentration and long tubing. The scatter lowers the confidence in the performance of the instrument. To gain confidence in the instrument, it is recommended that we test the CM4 with Hz vapors using a set up similar to its intended use. Hz vapor of concentrations slightly above 10 ppb (12-15 ppb), 100 ppb, 1 ppm, and 50 ppm are recommended, along with sample tubing length of 1, 50 100, and 150 feet.

The model used here to calculate vapor concentrations does not address the rate of vaporization of any leaked hydrazine liquid. The approach used assumes all liquid is vaporized and immediately is spread evenly throughout the enclosed volume of the room. A more sophisticated model would require detailed knowledge of many parameters to calculate the heat transfer into any spilled liquid and calculate the resulting evaporation rate, followed by an analysis of the air currents, convective transport, and diffusion of the resulting vapors. Such a study is well beyond the scope of the present work and would be subject to many assumptions that would significantly affect the outcome. What the current calculations do show is that a few drops of spilled hydrazine can produce concentrations exceeding the allowable TWA value of 10 ppb, even if the entire room volume is diluting the hydrazine vapor. Such an even distribution is rarely achieved, and it is wise to assume that both lower and higher concentrations would exist in the room, and would move in ways that could pose a hazard to unprotected personnel. Similarly, the equilibrium vapor pressure only shows that some source of external heating would be necessary to achieve the LEL for hydrazine, but even a small reaction site or a warm surface could drastically change the outcome to a far more dangerous situation.

In summary, if an instrument such as the CM4, SPM, or Sentry 5000 is calibrated with Hz and is tested in a setup similar to its application, and can perform as expected, it would provide the best

[3] http://msds.ksc.nasa.gov/msds/07770/

assurance for personnel safety. Setting the alarm to 10 ppb and monitoring within the spacecraft, close to the likely leak site, should provide an early alarm with sufficient time for personnel to safely evacuate the area.

References

[1] http://www.engineeringtoolbox.com/37_120.html

[2] Schmidt, Eckart, *Hydrazine and Its Derivatives*, 2nd ed. John Wiley& Son, New York, 2001, p.189

[3] http://msds.ksc.nasa.gov/msds/07770/

Addendum 6

Zellweger Analytics Model CM4 Evaluation Hydrazine Vapor Detector Analysis for CALIPSO Alarm Times, Concentrations, and Fallback Times at Various Sample Tubing Lengths

USTDC Task Order 3CCI00254

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Purpose:

The KSC Applied Chemistry Laboratory conducted testing of the Zellweger Analytics model CM4 hydrazine vapor detector in support of an on-going assessment of personnel safety hazards associated with the CALIPSO spacecraft. Tests were designed to ascertain instrument accuracy and alarm response time upon exposure as well as the recovery time upon removal of hydrazine vapors at varying concentrations. The addendum contains additional testing requested to clarify response times at 1 ppm, delays caused by tape advance cycles, and some quick qualitative testing for some common interferences. Some of the conclusions in the main body are re-analyzed in the addendum as new incites into the testing protocol arose when comparing the data sets

Introduction:

The Zellweger Analytics model CM4 Toxic Gas Monitor is designed to continuously monitor toxic gases at four different points up to 300 feet away using chemcassette technology. The chemcassette consists of a paper tape reel dosed with a chemical indicator specific to the toxic gas in question. An internal pump draws vapors at a designated flow rate through four separate sampling tubes to react with the paper tape. Four stationary optic sensors are located at the reaction sites of respective sampling points on the paper tape. Each sensor has integrated audio and visual alarms that may be set manually for upper and lower concentration levels. The lowest alarm concentration level is the TLV (Threshold Limit Value) for the vapor in question (10 ppb for hydrazine).

Sampling cycle times are dictated internally by the concentration of toxic vapor detected. A sampling cycle involves advancing the chemcassette to present unexposed substrate tape to the four sampling points. The tape may be advanced automatically as dictated by the instrument or may be forced manually. One fresh chemcassette provides approximately one month of unattended continuous monitoring without the occurrence of a major gas event. If a gas release does occur, the instrument reports an alarm and advances the tape to expose virgin substrate tape and continues monitoring. Thus, the sampling cycle time decreases and the tape advances more quickly. Therefore, in the event of a hydrazine leak, the tape is consumed more rapidly and necessitates earlier replacement.

The CM4 is "gas tested" for proper response by Zellweger Analytics. An optics verification card is provided for the user to confirm that the optics are functional. The user is otherwise unable to calibrate the instrument.

Testing was conducted to determine the accuracy of the instrument's concentration measurements, the alarm response time upon exposure to hydrazine vapors, and the instrument's recovery time upon removal of said hydrazine vapors. Tests were conducted with an alarm setting of 10 ppb for four different tubing lengths (5, 50, 100, and 150 ft.) at four different hydrazine concentrations (12, 150, 1000, and 50,000 ppb).

Experimental Methods:

All testing was conducted in Hood 1 of the Applied Chemistry Laboratory (ACL) in the O&C building at Kennedy Space Center. The Zellweger Analytics CM4 detector was provided to the ACL by the United Space Alliance (USA).

Hydrazine vapors were generated using Kin-Tek vapor standard generators. Miller-Nelson Flow Controllers provided humid air for mixing with the hydrazine vapors to the designated concentrations. Hydrazine vapors were transported via Teflon tubing to a mixing tube where they were allowed to equilibrate with the humid, dilution air. After equilibration, the sample tubes were inserted directly into the mixing tube. The actual concentrations of the hydrazine vapors were verified before and after dilution using the ACL Standard Laboratory Procedure 4.2, "Determination of Concentrations of N_2H_4 vapor in Nitrogen or Air by the Coulometric Titration Method".

The 1/4" OD x 3/16" ID FEP sampling tubing obtained from Zeus Industrial Products was prepared upon receipt by initial rinsing with deionized H_2O followed by an isopropyl alcohol rinse. Finally, gaseous N_2 was flushed through the tubing. After cleaning, the tubing was cut to the desired lengths: four 5 ft, four 50 ft, four 100 ft, and four 150 ft. pieces.

The concentrations (12, 150, and 1000 ppb) and tubing lengths (5, 50, 100, and 150 ft.) were analyzed at least four times each for repeatability. The 50,000 ppb tests were necessary as 50,000 ppb (50 ppm) is the OSHA Immediate Danger to Life and Health (IDLH) threshold for hydrazine. However, they were performed only once and for shorter exposure times for each tubing length for several reasons. One reason was to avoid endangering the experimenter. Another reason was that the upper detection limit of the CM4 for hydrazine is 1000 ppb. Considering the "sticky" nature of hydrazine vapors, repeated extended exposure of the instrument to these high-level hydrazine concentrations could contaminate the instrument optics rendering the CM4 inoperable and preventing completion of the testing. Moreover, it was noted upon initial testing of the 50,000 ppb vapors that the alarm response was almost instantaneous upon exposure. In fact, the brief delay reported in the response time results was due to the manual tape advancement. Introduction of this experimental error was necessary in order to insert the tubing and capture the alarm response. Consequently, the four points obtained from each single 50,000 ppb trial were deemed sufficient for repeatability in this study.

Each time the CM4 was powered ON, the "quick start procedure" was performed and the lower alarm levels for each sampling point were set to 10 ppb. The "optics verification" was executed daily. The flows through each sampling tube were adjusted to 180 cc/min prior to each test run as considerable drift in the flow rates was noted over time. The aforementioned procedures were conducted as directed in the CM4 Operator's Manual.

After allowing the hydrazine vapors to equilibrate to the designated concentration in the mixing tube, the flows for each sampling point are adjusted to 180cc/min. Next, the CM4 is set to monitor mode with the sampling tubing exposed to fresh air for ten minutes to establish a stable zero baseline. Once a baseline is established, the sampling tubing is inserted directly into the mixing tube while simultaneously advancing the chemcassette tape manually and initiating the data collection software.

The sampling tubing is exposed to the hydrazine vapors within the mixing tube, the exposure time is recorded and the sampling tubing is withdrawn from the mixing tube. Then the tubing is exposed to fresh air while simultaneously advancing the chemcassette tape manually. The CM4 remains in monitor mode until a 0 ppb concentration reading is recorded for all four points. A typical plot of the instrument response will suddenly drop to zero because the CM4 is programmed to auto-zero when the concentration falls below 8 ppb. This also prevents any meaningful measurement of the instrument baseline noise.

Results:

Figure 1 is a graphical representation of the CM4 alarm times versus the sampling tubing length at each concentration. The alarm level was set at the hydrazine TLV of 10 ppb. One clearly observable trend is the decrease in alarm response time with increasing exposure concentrations. A second noticeable trend is an increase in alarm time with increasing tubing length. This trend is dramatic at low concentrations and nearly indistinguishable at concentrations of 1000 ppb or more.

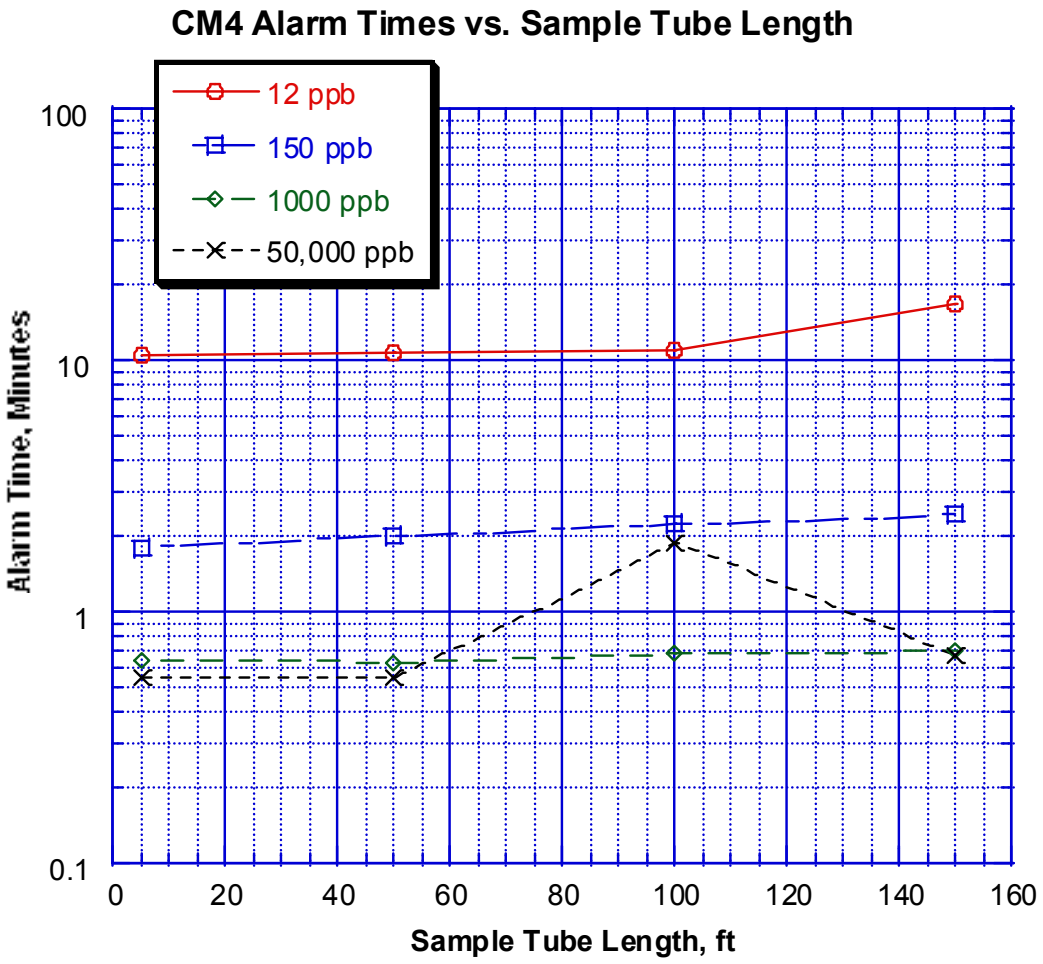


Figure 1. CM4 Alarm Time vs. Tubing Length at Various Hydrazine Concentrations

Fallback time is defined as the time required for the CM4 to return to a zero ppb baseline following exposure to hydrazine vapor. Trends in the fallback time are less clearly defined than those of alarm times. Figure 2 is a plot of fallback time versus tubing length at each concentration. At lower concentrations, the tubing length appears to have little effect on the fallback time. Also, we observed a tendency for the fallback times to increase with increasing hydrazine concentration exposure. Fallback time behavior is erratic at hydrazine concentrations of 1000 ppb and especially at the higher 50,000 ppb concentration. It is important to note while studying Figure 2 that the duration of exposure of the 50,000 ppb hydrazine vapors through the 5 ft. tubing was for 5 minutes while the 50,000 ppb exposures through the 50, 100, and 150 ft. tubing were for 1.5 minute durations. This modification was made with time constraints following the observation that it may take up to 128 minutes following a 50,000 ppb exposure to fallback to 0 ppb. This was the maximum fallback time observed in the 5 ft tubing trial.

The unpredictable fallback times at higher concentrations are likely due to the aforementioned "sticky" nature of hydrazine vapors. Residual hydrazine may adsorb within the sampling tubing or on the detector optics during exposure and require more time to be flushed from the system. Several experiments were conducted to elucidate a correlation between exposure time and fallback time. It was determined that duration of exposure has little effect on fallback time at low hydrazine concentrations ($\leq$ 150 ppb). In contrast, fallback time does increase with increasing exposure duration at hydrazine concentrations of 1000 ppb or higher. This was demonstrated by the extended fallback time of the 5 minute 50,000 ppb exposure through the 5ft. tubing versus the 1.5 minute exposures of the same concentration through the 50, 100, and 150 ft tubing. Additional experiments were conducted to determine if hydrazine residue accumulating in the sampling tubing from previous tests affected the fallback times of later test runs. No decrease in the fallback or alarm times was observed when fresh tubing was used.

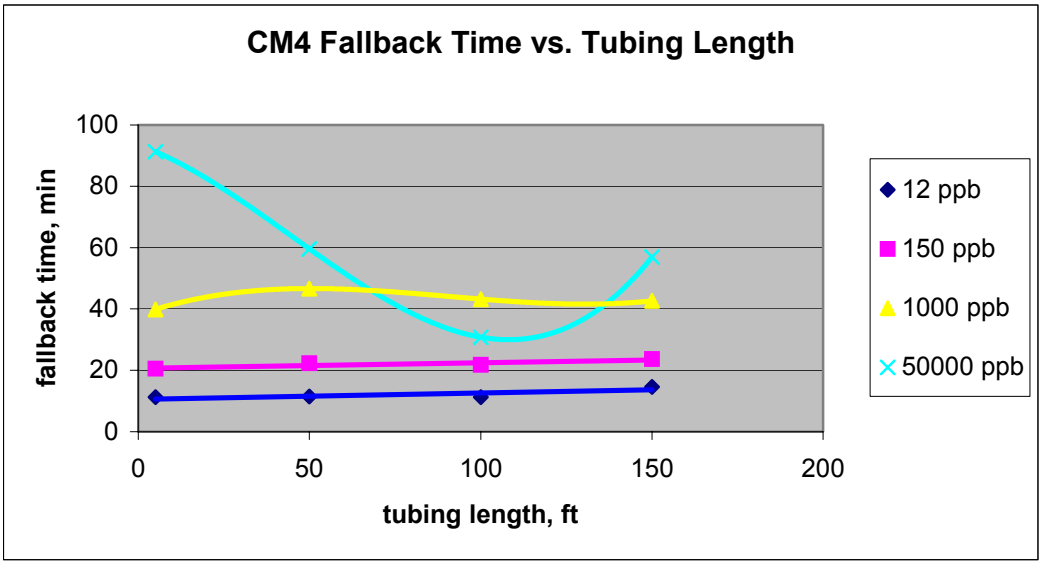


Figure 2. CM4 Fallback Time vs. Tubing Lengths at Various Hydrazine Concentrations

The average CM4 alarm response and fallback times are presented in Tables 1 and 2 respectively.

Table 1. Average CM4 Alarm Times for Various Hydrazine Concentrations and Sampling Tubing Lengths

	Average alarm time, min			
Tubing length, ft	**12 ppb**	**150 ppb**	**1,000 ppb**	**50,000 ppb**
5	10.53	1.78	0.64	0.55
50	10.65	1.99	0.63	0.55
100	11.01	2.26	0.69	1.87
150	16.90	2.44	0.70	0.67

Table 2. Average CM4 Fallback Times for Various Hydrazine Concentrations and Sampling Tubing Lengths

	Average fallback time, min			
Tubing length, ft	**12 ppb**	**150 ppb**	**1,000 ppb**	**50,000 ppb**
5	11.23	20.57	39.88	91.26
50	11.45	22.29	46.66	59.59
100	11.30	21.78	43.22	30.80
150	14.57	23.67	42.62	56.89

Concentration response for hydrazine vapors of 1000 ppb or greater are beyond the capabilities of the CM4. The average CM4 concentration response for 12 and 150 ppb hydrazine vapors are presented for each tubing length along with the respective percent errors in Table 3. Most notable is that all reported concentrations are above the known concentration standard used in the testing. This seems to be a systematic error in the instrument calibration, which can not be adjusted by the operator. However, from the standpoint of industrial hygiene and worker protection, the error is on the side of safety. The instrument will alarm earlier and report higher concentrations than the actual instrument exposure. The concentration response clearly decreases with increasing tube length. However, the percent error is not consistent for any given tube length for hydrazine concentrations of 12 and 150 ppb. Also, the percent error increases significantly with increasing concentration at a given tubing length with a 69.3% error at 150 ppb through 5-ft. tubing as compared to a 35.8% error at 12 ppb through the 5-ft. tubing.

Table 3. Average CM4 Concentration Responses at Various Tubing Lengths and their Associated Percent Error

Tubing length, ft	12 ppb		150 ppb	
	Avg. CM4 response, ppb	% Error	Avg. CM4 response, ppb	% Error
5	16.3	35.8	254	69.3
50	17.2	43.3	230	53.3
100	14.1	17.5	224	49.3
150	12.8	6.67	220	46.7

Figure 3 illustrates a decrease in the CM4 concentration response with increasing tube length when exposed to 12 and 150 ppb hydrazine vapors. Concentration response for hydrazine vapors of 1000 ppb or greater are beyond the capabilities of the CM4. The response for these hydrazine vapor concentrations lying within the range of the CM4 suggest that the additional surface area presented by the longer tubing is responsible for the decreased concentration response. The longer tubing would provide additional adsorption sites for the hydrazine vapor, thus decreasing the concentration of the vapors reaching the detector and resulting in a lower concentration response. If this were the case, one would expect to see a more pronounced effect at the lower concentrations. The data seems to support this theory, as we see a larger change in the 12 ppb response with increased tubing length than we do with the 150 ppb samples.

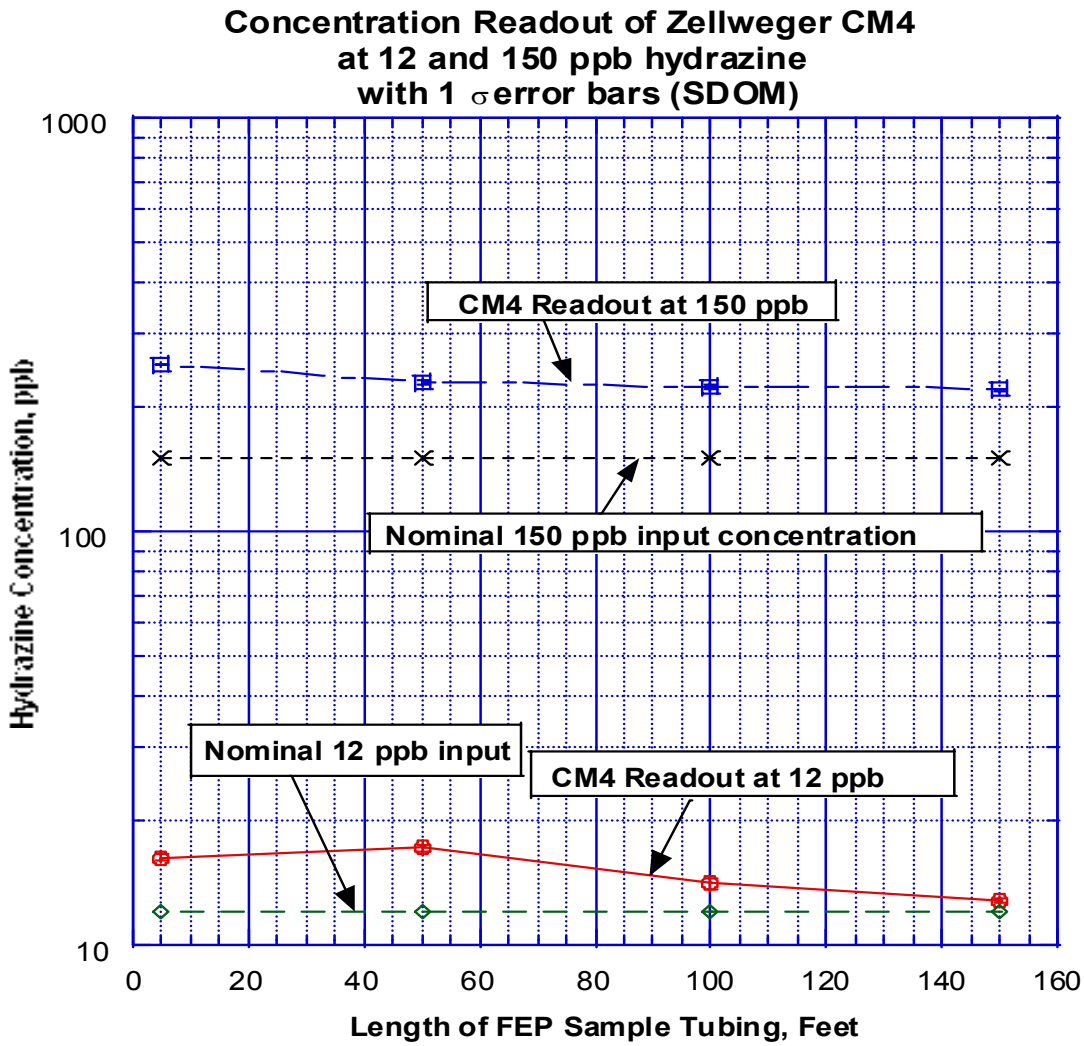


Figure 3. CM4 Concentration Response vs. Tubing Length with Hydrazine Exposure

In addition, hydrazine vapor has the ability to permeate through Teflon tubing. In fact, this property is utilized at high temperatures by the Kin-Tek vapor standard generators that furnish the hydrazine vapors for these experiments. Therefore, a second possibility is that the additional area provided by the longer tubing provides more area for permeation of the hydrazine vapors. This too would result in the observed decreased concentration response. Further testing would be required to determine the actual source of the varying concentration response.

Since the instrument is calibrated by the manufacturer, it is possible that the actual concentration of the vapors used for calibration were lower than the reported values. This could have been caused by either tubing absorption (caused by dirty or incompatible tubing) or reaction of the vapors with the sample tubing or other materials used in the manufacturer's vapor generation system (such as metallic materials which oxidize hydrazine vapors in the presence of

oxygen). In either case, the result would be low response at the manufacturers calibration, and a higher reported concentration when properly analyzed vapor streams are presented by others. This seems to be the case in our lab results, as all the reported concentrations are above our known, analyzed vapor concentrations.

Conclusions:

The CM4 Toxic Gas Monitor is capable of detecting a hydrazine release of 10 ppb or higher. A hydrazine release of 12 ppb may be detected in as little as 11 minutes or as long as 26 minutes. Vapors of 1000 ppb concentration or higher alarmed much more quickly, and in < 40 seconds for most samples. Inspection of the raw data presents an apparent discrepancy between the analysts observation that < 5 second alarm times seemed to occur for high concentration samples. Because of the protocol adopted for the low concentration (necessitated by variable sampling cycle times occurring with automatic tape advancement), we forced the tape to advance manually to eliminate the initial variable time period. This gave good results on the low concentrations where the ~40 seconds delay imposed by the manual advance had little effect on the 10-20 minute response times at 12 ppb. However, the same protocol at high concentrations (1000 and 50,000 ppb) introduced these same delays into a very fast instrument response. We also observed that the sample tubes would pick up diluted hydrazine vapors as soon as the sample tube approached the hood face (with 50 ppm samples), well before insertion into the hydrazine vapor flow. Attempts to do rapid connections and simultaneous data triggering gave highly variable results due to the aforementioned pre-insertion alarms and delays in connecting some of the tube fittings.

NOTE: **Further testing on the alarm times at higher concentrations was done in the Addendum at the end of this report. Please refer to those results for further discussions.**

The CM4 should be considered a qualitative rather than quantitative vapor detection instrument, due to the consistently high readings obtained at all on-scale concentrations. . The concentration response of the CM4 decreases with increasing sample tubing length. This decrease is observed with clean tubing in a laboratory environment. Larger decreases would be expected if the tubing is not cleaned regularly or becomes contaminated with dust of other hydrazine absorbents. Consequently, the shortest possible length of tubing is preferable. Considerations to minimize the sample tubing length should be made when placing this instrument for use in monitoring hydrazine vapor releases.

The CM4 may take as long as 128 minutes to return to a zero baseline following detection of high concentration hydrazine vapor release. This limitation may present significant delay in confirming that a faulty seal has been repaired properly, although cleanup and decontamination from any spills would also be lengthy procedures. If delays in cleanup confirmation are an issue, a second instrument could be used after cleanup and portable instruments used to confirm that hydrazine is no longer present. Separate cleaning and drying of the sample tubing might perform the same function (see tubing cleaning procedure on page 6-3, Experimental Methods, paragraph 3).

Also, it is not known whether extended exposure to highly concentrated hydrazine vapors will damage the instrument beyond repair as exposure to these vapors during testing was limited

to brief periods as previously discussed. In the event of a major gas release it would again be advisable to have a second instrument on hand.

Addendum:

Further testing of the CM4 was requested for potential interferences (cigarette smoke, isopropyl alcohol, and perfume) that might cause False Positives and to confirm our less-than-5-Second Response Time observations for high concentrations. Since the manual tape advance times were observed to be long compared with the alarm response times suggested in the report, the tape advance times for both manual advance and automatic advance were timed to clarify their impact on instrument alarm times as well. Due to the occurrence of some alarms from the instrument when sampling at the face of the fume hood while generating 50 ppm concentrations, it was deemed sufficient to test only at the 1 ppm levels to avoid possible lab worker exposures.

Tape Advance Times:

Alarm times in the main body of the report were measured after a manual tape advance to eliminate large variations in alarm times observed in preliminary testing at low concentrations. These variations were largely associated with the random tape advance cycle at low concentrations that would occur, causing a new cycle to begin every 10 minutes, even if we were approaching an alarm signal from an applied 12 ppb sample. This technique allowed the analyst to attach the four sample tubes, and start the data acquisition system to do the data recording from which the alarm times were extracted. This worked well for the 12 ppb samples where the added 35-40 second manual tape advance cycles were small compared with the 10-20 minute alarm times being measured. However, at the higher concentrations, the manual tape advance cycle could cause problems in measuring these much shorter alarm times.

The tape advance times for both manual tape advance and automatic (machine initiated) tape advance times were measured with a stop watch.

Test:	Tape Advance	Time in Seconds *
1.	Automatic Advance	5
2.	Manual Advance	35
3.	Automatic Advance	4
4.	Manual Advance	37
		*Measured with stopwatch

The measured tape delay times confirm that a significantly longer delay occurs with a manual tape advance over an automatic tape advance. The 5 second or less automatic advance is a minor delay for high concentrations, but should be considered as potentially adding to the observed alarm times in this report, as we always started alarm time measurements after a tape advance.

Interferences:

Other types of hydrazine analyzers have been observed to produce false alarms under some circumstances. Cigarette smoke produces a color change on hydrazine dosimeter badges mounted in the breathing zone of smokers, as it should, since cigarette smoke contains hydrazine, as well as several other carcinogens. For CALIPSO, we are mainly concerned with smoke residue, since smoking will not be allowed near the spacecraft. Isopropyl alcohol (IPA) causes false alarms in electrochemical hydrazine analyzers where some impurity in IPA is likely the cause. Some contaminant in IPA can apparently be oxidized by electrochemical cells at the TLV level for IPA (400 ppm). On a 10 ppb HZ analyzer, the contaminating compound is about equal to 20 ppb HZ for a 400 ppm IPA concentration. Even higher concentrations of IPA occur in hypergol operations, where IPA is used to rinse out HZ residues in fuel manifolds and tanks following testing of these systems. Concerns about perfume have not been documented in laboratory experiments, but are supplied here to alleviate potential concerns with the CM4. These tests were performed by placing the candidate interference on an absorbent wipe inside a polyethylene Ziploc bag, and then inserting the sample tube into the bag to draw off a saturated vapor sample. The cigarette smoke sample was done by enclosing a lab coat purposely infused with smoke into a similar bag as a worst-case scenario. The absorbent wipe alone was done as a control sample in case any alarms occurred to eliminate the wipe as a cause.

Test:	Potential Interference		Analysis Time (minutes)	Results
5.	Absorbent Wipe in 3 Gallon Plastic Bag	Sample Background	22	No signal
6.	91 % Isopropyl Alcohol (IPA) on Absorbent Wipe in 3-L. Plastic Bag	Less Pure Grade	60	No signal
7.	2-Propanol (IPA), ACS Grade 99.5+%, Absorbent Wipe in 3-L. Plastic Bag	Higher Purity	20	No signal
8.	Lab Coat in 3-L. Plastic Bag	Sample Background	12	No signal
9.	Cigarette Smoke on Lab Coat in 3-L. Plastic Bag	2 Brands puffed into plastic bag with lab coat	22	No signal
10.	Perfume Spayed on Absorbent Wipe in 3 L. Plastic Bag	Endless Fun for Women: Euro Collection	20	No signal

None of the potential interferences tested produced a signal for hydrazine in these tests.

Confirmation of Alarm Times at 1 PPM Concentrations

Due to the delays in the manual tape advance when measuring the alarm times for the 1 ppm and 50 ppm concentrations, we reported that the actual alarm times appeared to be much shorter than the times recorded by the data acquisition system. In fact, on the 50 ppm samples, alarms were occasionally observed while the analyst attempted to hook up the tubing inside the hood, but had not yet made a connection. Christy felt that these high concentrations would alarm in less than 5 seconds in many cases. Here we attempt to confirm this observation with a modified timing procedure which eliminates the tape advance delays so dominant at short alarm times.

The modified procedure is as follows:

1) Wait for the automatic tape advance on the preceding zero baseline to occur.

2) With stop watch in hand, rapidly insert two sample tubes into the open HZ source tube and start the stop watch simultaneously.

3) Manually time the delay to the first audible alarm from either tube.

This procedure should produce timing accuracies of about ±1 second, we judged. The results are shown below.

Tests 11-13 were done on January 27, 2005. Tests 14 – 22 were done on January 28.

Test:	Response To 1 ppm HZ with 150' Tubing	Alarm Time (minutes)	Previous Work
	1-27-05 Automatic tape advance		
11.	Time to alarm: Automatic tape advance	1.50 min. to alarm	0.62 - 0.87 min.
12.	Time to alarm: Automatic tape advance	0.72 min. (43 sec.) to alarm	0.62 - 0.87 min.
13.	Time to alarm: Automatic tape advance	0.72 min. (43 sec.) to alarm	0.62 - 0.87 min.
	1-28-05, after all night purge of tubing with room air via CM4 pump operation		
14.	Time to alarm: Automatic tape advance	1.58 min. (96 sec.) to alarm	0.62 - 0.87 min.
15.	Time to alarm: Automatic tape advance	1.45 min. (87 sec.) to alarm	0.62 - 0.87 min.
16.	Time to alarm: Automatic tape advance	0.66 min. (39 sec.) to alarm	0.62 - 0.87 min.

Test:	Response To 1 ppm HZ with 50' Tubing	Analysis Time (minutes)	Previous Work
17.	Time to alarm: Automatic tape advance	0.33 min. (20 sec.) to alarm	0.51 - 0.84 min.
18.	Time to alarm: Automatic tape advance	0.175 min. (10.5 sec.) alarm	0.51 - 0.84 min.
19.	Time to alarm: Automatic tape advance	0.38 min. (23 sec.) to alarm	0.51 - 0.84 min.
	Manual tape advance		
20.	Time to alarm: Manual tape advance	0.875 min. (52.5 sec.) to alarm	0.51 - 0.84 min.
21.	Time to alarm: Manual tape advance	0.85 min. (51sec.) to alarm	0.51 - 0.84 min.
22.	Time to alarm: Manual tape advance	0.88 min. (53sec.) to alarm	0.51 - 0.84 min.

Points 1 & 2 activated
Set MATLAB to draw at 1 second
11-13 Suggest that optics may need to have one exposure to 'condition' the sensor with successive responses taking less time.
(?) Past testing showed that this first 'slow' response is independent of tubing

The surprisingly long and variable alarm times caused the analyst to repeat the Manual tape advance protocol to ensure nothing had changed. The manual advance times show results at the top end of previous results, and a quite tight total variation in times.

Discussion and Conclusions:

The data on the tape advance delay show a substantial increase in time for the manual advance. Typical manual advance times were over 35 seconds, with automatic advance

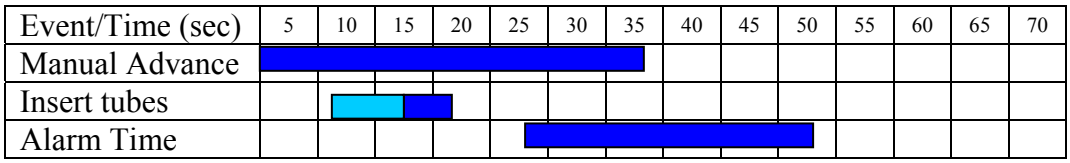
occurring in < 5 sec. The crude interference testing shows no detectable interference for isopropyl alcohol (IPA) either in low purity or high purity versions. Likewise, no interferences were found for cigarette smoke on a lab coat or a variety of perfumes.

The data taken to confirm a <5 sec response time at 1 ppm did not show times below 10 seconds. When done with automatic advance with exposure beginning just after a tape advance, the delay times averaged 66 sec. with a standard deviation of 27 sec. (range of 39 to 96 sec.) for the 150-foot sample tube. The 50-foot sample tube averaged 18 sec., with a standard deviation of 7 sec. Using a modified manual advance procedure on the 50 foot length (timing and tape advance were started after tubing insertion), the times were much more consistent (average: 52 sec., standard deviation 1 sec.). The difference in average times at 50 feet between automatic and manual tape advance seems to reflect the difference in tape advance times discussed above, and this would be expected since the alarm is inhibited during the 35 second manual tape advance cycle.

In view of these results, it appears we will withdraw our conclusion that alarm response times below 5 seconds will occur with 1 ppm vapor concentrations. Explaining the variations in alarm times requires some more detailed analysis of the experimental procedures and hidden causes for delays or other effects.

Why were shorter alarm times seen with the slower manual advance?

The manual advance procedure, as used in the initial data, has a more complex and variable sequence of events:



Note that the tubing is attached and drawing sample before the timing has been started. This allows the tubing to be conditioned by the entering hydrazine vapor before we actually start the timing. Some tubing will have a head start if it was inserted into the vapor earlier in the insertion window, or hydrazine exposure occurs before the actual insertion (area represented by light blue bar). These effects will shorten the apparent time to alarm. We believe these effects explain why shorter times were observed for manual tape advance sequences in the pre-Jan 27 data.

Why were the alarm times for automatic tape advance so variable?

Upon closer examination, the longer alarm times at 150-foot length (in addendum) always occurred at the beginning of a test sequence. This would be in keeping with the tubing requiring more time to alarm when the surface has not been pre-conditioned by earlier HZ exposure. Run # 11 was the first hydrazine exposure in several days. Runs 14 and 15 followed an all-night purge by room air when the instrument was left running over night with the tubing attached. Here we would not only remove any hydrazine residuals occupying active adsorption

sites on the tubing, but also introduce a potential dust residue to further adsorb hydrazine vapors.

Re-cleaning of the sample tubing might have prevented a second long alarm time. Follow on measurements were within times for the earlier testing. These results should warn potential designers and users that alarm times on a system that has not seen any hydrazine recently, or is dirty with dust and particulates, will take much longer to alarm than fresh, clean tubing that had some hydrazine exposure earlier in the day. Alarm times up around 90 seconds appear to be the norm for 150-foot tubing without recent conditioning by hydrazine vapors.

The following Appendix contains Tabulated data summary for all exposure runs.

Addendum 6
Appendix: Tabulated Data Summary for All Exposure Runs

This spreadsheet contains data from testing a Zellweger CM4 analyzer on hydrazine for response time
with various FEP tubing lengths and HZ concentrations of 12 & 150 ppb, 1 and 50 ppm.
All data done for Calipso spacecraft paid for by NESC, Nov-Dec 2004

Run #	.jpg #	HZ Conc	Tube Length	Exposure time	Alarm time Ch.1	Alarm time Ch.2	Alarm time Ch.3	Alarm time Ch.4	Avg. Alarm Time	Fall time Ch.1	Fall time Ch.2	Fall time Ch.3	Fall time Ch.4	Avg. Fall Time	Conc readout before vapor OFF Ch.1	Ch.2	Ch.3	Ch.4	AVG Equil CM4 Conc	Comments
		ppb	ft	min	min	min	min	min	min	min	min	min	min	min	ppb	ppb	ppb	ppb	ppb	
hz12test23	12ppb5ft-1.jpg	12	5	20	10.75	10.75	10.41	10.75	10.67	10.73	10.56	10.73	10.73	10.69	18	16	18	17	17.25	
hz12test25	12ppb5ft-2.jpg	12	5	20	10.76	10.76	10.6	10.76	10.72	11.11	11.11	11.11	11.11	11.11	16	15	15	15	15.25	
hz12test26	12ppb5ft-3.jpg	12	5	20	10.38	10.38	10.04	10.38	10.30	11.09	11.09	11.09	11.09	11.09	16	15	17	17	16.25	
hz12test27	12ppb5ft-4.jpg	12	5	20	10.82	10.82	10.82	10.82	10.82	11.69	11.69	11.69	11.69	11.69	16	14	16	15	15.25	
hz12test28	12ppb5ft-5.jpg	12	5	20	10.2	10.2	9.91	10.34	10.16	11.57	11.57	11.57	11.57	11.57	17	17	17	18	17.25	
hz12test29	12ppb50ft-1.jpg	12	50	30	10.33	10.33	10.33	10.33	10.33	11.22	11.22	11.22	11.22	11.22	17	15	17	16	16.25	2 step rise
hz12test30	12ppb50ft-2.jpg	12	50	25	10.98	10.98	10.98	10.98	10.98	11.48	11.48	11.48	11.48	11.48	20	18	20	19	19.25	2 step rise
hz12test31	12ppb50ft-3.jpg	12	50	20	10.7	10.7	10.85	10.85	10.78	11.34	11.17	11.34	11.34	11.30	17	15	16	16	16.00	
hz12test33	12ppb50ft-4.jpg	12	50	20	10.49	10.64	10.64	10.64	10.60	11.42	11.25	11.25	11.25	11.29	18	15	17	17	16.75	Ch1 very high
hz12test34	12ppb50ft-5.jpg	12	50	20	10.74	10.74	10	10.74	10.56	11.97	11.97	11.97	11.97	11.97	17	17	19	18	17.75	
hz12test35	12ppb100ft-1.jpg	12	100	20	11.04	12.7	10.87	12.54	11.79	11.22	11.05	11.22	11.05	11.14	13	11	14	10	12.00	
hz12test36	12ppb100ft-2.jpg	12	100	20	10.76	10.76	10.76	10.76	10.76	11.56	11.39	11.56	11.39	11.48	14	13	14	13	13.50	
hz12test37	12ppb100ft-3.jpg	12	100	20	10.75	10.75	10.75	10.75	10.75	11.24	11.24	11.24	11.24	11.24	16	14	16	15	15.25	
hz12test38	12ppb100ft-4.jpg	12	100	20	10.74	10.74	10.74	10.74	10.74	11.35	11.35	11.35	11.35	11.35	15	15	18	15	15.75	
hz12test39	12ppb150ft-1.jpg	12	150	40	26.08	26.08	26.08	26.08	26.08	26.07	26.07	26.07	26.07	26.07	13	12	13	12	12.50	2 step fall, alarm slow
hz12test40	12ppb150ft-2.jpg	12	150	40	26	26	26	26	26.00	11.47	11.3	11.47	11.47	11.43	13	13	14	13	13.25	alarm slow
hz12test41	12ppb150ft-3.jpg	12	150	20	11.09	11.09	11.09	11.09	11.09	11.33	11.16	11.33	11.33	11.29	12	11	13	13	12.25	
hz12test42	12ppb150ft-4.jpg	12	150	22	10.64	10.64	10.64	10.64	10.64	12.71	12.71	12.87	12.71	12.75	12	12	13	12	12.25	
hz12test43	12ppb150ft-5.jpg	12	150	20	10.71	10.71	10.71	10.71	10.71	11.36	11.19	11.36	11.36	11.32	14	13	14	14	13.75	
hz12test44	150ppb5ft-1.jpg	150	5	10	1.7	1.86	1.7	1.86	1.78	12.15	14.79	12.31	15.29	13.64	259	251	264	263	259.25	
hz12test45	150ppb5ft-2.jpg	150	5	20	1.53	1.71	1.36	1.71	1.58	21.78	21.95	21.78	21.95	21.87	273	267	281	276	274.25	
hz50test03	150ppb5ft-3.jpg	150	5	10	2.02	2.36	1.85	2.53	2.19	14.28	26.19	13.94	26.19	20.15	229	228	238	219	228.50	
hz50test04	150ppb5ft-4.jpg	150	5	10	1.88	2.05	1.71	2.05	1.92	21.89	22.06	21.89	22.06	21.98	247	250	249	245	247.75	
hz50test05	150ppb5ft-5.jpg	150	5	10	0.96	1.25	0.96	1.25	1.11	20.6	20.77	20.6	20.77	20.69	247	248	257	258	252.50	
hz50test06	150ppb5ft-6.jpg	150	5	10	1.7	2.04	1.7	2.04	1.87	20.88	21.05	20.88	21.05	20.97	252	252	253	251	252.00	
hz50test07	150ppb5ft-7.jpg	150	5	20	1.66	1.99	1.66	1.82	1.78	19.09	19.26	19.09	21.98	19.86	257	245	247	252	250.25	
hz50test08	150ppb5ft-8.jpg	150	5	20	1.65	1.98	1.65	1.82	1.78	26.86	26.86	26.86	27.01	26.90	275	251	253	265	261.00	
hz150test09	150ppb5ft-9.jpg	150	5	20	2.22	2.22	1.88	2.22	2.14	21.43	21.43	21.43	21.43	21.43	247	251	264	263	256.25	
hz150test10	150ppb5ft-10.jpg	150	5	20	1.71	1.88	1.54	1.88	1.75	19.39	19.55	19.55	19.55	19.51	258	264	269	277	267.00	
hz150test11	150ppb5ft-11.jpg	150	5	10	1.65	1.81	1.65	1.81	1.73	19.19	19.36	19.19	19.36	19.28	246	241	255	254	249.00	
hz150test12	150ppb50ft-1.jpg	150	50	10	2.05	2.39	2.05	2.39	2.22	24.15	24.32	24.15	24.32	24.24	238	223	239	231	232.75	
hz150test13	150ppb50ft-2.jpg	150	50	10	1.48	1.81	1.48	1.64	1.60	25.32	25.49	25.32	25.49	25.41	241	230	247	244	240.50	
hz150test14	150ppb50ft-3.jpg	150	50	10	2.05	2.39	1.88	2.39	2.18	23.94	24.11	23.94	24.11	24.03	216	212	231	219	219.50	
hz150test15	150ppb50ft-4.jpg	150	50	10	1.85	2.19	1.68	2.19	1.98	18.08	18.08	17.91	17.91	18.00	230	215	229	227	225.25	
hz150test16	150ppb50ft-5.jpg	150	50	10	1.87	2.2	1.7	2.2	1.99	19.63	19.8	19.63	20.14	19.80	234	216	239	230	229.75	
hz150test18	150ppb100ft-1.jpg	150	100	10	2.31	2.77	2.62	2.77	2.62	25.07	25.07	25.07	25.07	25.07	202	209	211	205	206.75	
hz150test19	150ppb100ft-2.jpg	150	100	10	1.82	2.1	1.82	1.96	1.93	21.32	21.49	21.49	21.49	21.45	226	226	228	237	229.25	
hz150test20	150ppb100ft-3.jpg	150	100	10	2.51	2.84	2.51	2.84	2.68	18.61	18.61	18.61	18.61	18.61	218	209	209	203	209.75	
hz150test21	150ppb100ft-4.jpg	150	100	10	1.88	2.22	1.88	2.05	2.01	22.78	22.78	22.78	22.78	22.78	232	227	241	236	234.00	
hz150test22	150ppb100ft-5.jpg	150	100	10	2.21	2.52	2.05	2.36	2.29	21.95	21.95	21.95	21.95	21.95	225	223	230	224	225.50	
hz150test23	150ppb100ft-6.jpg	150	100	10	1.83	2.33	1.83	2.17	2.04	20.88	20.84	20.84	20.84	20.80	236	233	250	229	237.00	
hz150test24	150ppb150ft-1.jpg	150	150	10	2.43	3.08	2.75	3.08	2.84	23.7	23.7	23.7	23.7	23.70	212	212	219	215	214.50	
hz150test25	150ppb150ft-2.jpg	150	150	10	2.22	2.39	2.05	2.56	2.31	21.24	21.24	21.24	21.73	21.36	227	220	221	228	224.00	
hz150test26	150ppb150ft-3.jpg	150	150	10	2.39	2.73	2.22	2.73	2.52	31.77	31.77	31.77	31.77	31.77	217	206	220	214	214.25	
hz150test27	150ppb150ft-4.jpg	150	150	11.5	1.94	2.26	1.94	2.26	2.10	17.8	17.94	17.8	17.8	17.84	239	215	230	227	227.75	
hz1000test4	1000ppb5ft-1.jpg	1000	5	5.5	0.52	0.6	0.52	0.6	0.56	38.01	38.01	38.1	38.1	38.06	1000	1000	1000	1000	1000.00	
hz1000test5	1000ppb5ft-2.jpg	1000	5	5	0.61	0.7	0.7	0.7	0.68	39.53	39.53	39.53	39.53	39.53	1000	1000	1000	1000	1000.00	
hz1000test6	1000ppb5ft-3.jpg	1000	5	6.5	0.61	0.7	0.61	0.7	0.66	43.4	43.4	43.49	43.4	43.42	1000	1000	1000	1000	1000.00	
hz1000test7	1000ppb5ft-4.jpg	1000	5	5	0.61	0.7	0.61	0.7	0.66	38.43	38.43	38.76	38.43	38.51	1000	1000	1000	1000	1000.00	
hz1000test9	1000ppb50ft-1.jpg	1000	50	5	0.67	0.75	0.67	0.84	0.73	37.99	37.99	37.99	37.9	37.97	1000	1000	1000	1000	1000.00	
hz1000test10	1000ppb50ft-2.jpg	1000	50	5	0.52	0.61	0.52	0.61	0.57	44.33	74.63	44.33	44.33	51.91	1000	1000	1000	1000	1000.00	
hz1000test11	1000ppb50ft-3.jpg	1000	50	5	0.6	0.6	0.51	0.6	0.58	38.75	53.9	53.9	53.9	50.11	1000	1000	1000	1000	1000.00	
															1000	1000	1000	1000	1000.00	
hz1000test12	1000ppb100ft-1.jpg	1000	100	5	0.59	0.59	0.51	0.59	0.57	47.22	47.13	47.13	47.13	47.15	1000	1000	1000	1000	1000.00	
hz1000test13	1000ppb100ft-2.jpg	1000	100	5	0.7	0.79	0.7	0.79	0.75	40.97	41.06	40.97	40.97	40.99	1000	1000	1000	1000	1000.00	
hz1000test14	1000ppb100ft-3.jpg	1000	100	5	0.68	0.76	0.68	0.76	0.72	36.66	36.66	36.66	36.66	36.66	1000	1000	1000	1000	1000.00	
hz1000test15	1000ppb100ft-4.jpg	1000	100	5	0.67	0.75	0.67	0.75	0.71	48.08	48	48.08	48.08	48.06	1000	1000	1000	1000	1000.00	
hz1000test16	1000ppb150ft-1.jpg	1000	150	5	0.7	0.78	0.7	0.87	0.76	38.75	38.75	38.75	38.68	38.73	1000	1000	1000	1000	1000.00	
hz1000test17	1000ppb150ft-2.jpg	1000	150	5	0.62	0.69	0.62	0.69	0.66	46.22	46.3	46.22	46.22	46.24	1000	1000	1000	1000	1000.00	
hz1000test18	1000ppb150ft-3.jpg	1000	150	5	0.7	0.78	0.7	0.78	0.74	38.94	38.94	39.46	38.94	39.07	1000	1000	1000	1000	1000.00	
hz1000test19	1000ppb150ft-4.jpg	1000	150	5	0.62	0.7	0.62	0.7	0.66	46.4	46.49	46.49	46.4	46.45	1000	1000	1000	1000	1000.00	
hz50ppmtest1	50ppm5ft-1.jpg	50000	5	5	0.59	0.51	0.59	0.51	0.55	59.18	96.61	81.53	127.7	91.26	1000	1000	1000	1000	1000	
hz50ppmtest7	50ppm50ft-2.jpg	50000	50	1.5	0.61	0.53	0.53	0.53	0.55	38.07	66.87	51.55	81.87	59.59	1000	1000	1000	1000	1000	
hz50ppmtest6	50ppm100ft-2.jpg	50000	100	1.5	1.7	2.04	1.7	2.04	1.87	30.71	30.88	30.71	30.88	30.80	1000	1000	1000	1000	1000	
hz50ppmtest5	50ppm150ft-1.jpg	50000	150	1.5	0.69	0.61	0.61	0.78	0.67	35.53	78.41	78.41	35.19	56.89	1000	1000	1000	1000	1000	

Conc Readout Analysis		SDOM
statistics on 12 ppb, all ft		
Average	15.1	
Std Dev	2.2	0.25594952
statistics on 12 ppb, 5 ft		
Average	16.3	
Std Dev	1.2	0.260313576
statistics on 12 ppb, 50 ft		
Average	17.2	
Std Dev	1.5	0.3
statistics on 12 ppb, 100 ft		
Average	14.1	
Std Dev	1.9	0.481966458
statistics on 12 ppb, 150 ft		
Average	12.8	
Std Dev	0.8	0.186378223
statistics on 150 ppb, all ft		
Average	237.2	
Std Dev	19.0	1.860044046
statistics on 150 ppb, 5 ft		
Average	254	
Std Dev	13	0.291873039
statistics on 150 ppb, 50 ft		
Average	230	
Std Dev	10	2.2751229
statistics on 150 ppb, 100 ft		
Average	224	
Std Dev	13	2.633039219
statistics on 150 ppb, 150 ft		
Average	220	
Std Dev	8	2.085415626
statistics on1000 ppb, all ft		
Average	1000.0	
Std Dev	0.0	
statistics on 1000 ppb, 5 ft		
Average	1000	
Std Dev	0	
statistics on 1000 ppb, 50 ft		
Average	1000	
Std Dev	0	
statistics on 1000 ppb, 100 ft		
Average	1000	
Std Dev	0	
statistics on 1000 ppb, 150 ft		
Average	1000	
Std Dev	0	

Alarm Time Analysis		SDOM
12 ppb, 5 ft		
avg	10.53	
Std Dev	0.29	0.064997
12 ppb, 50 ft		
avg	10.65	
Std Dev	0.27	0.06076
12 ppb, 100 ft		
avg	11.01	
Std Dev	0.63	0.039626
12 ppb, 150 ft		
avg	16.90	
Std Dev	7.65	1.7117
150 ppb, 5 ft		
avg	1.78	
Std Dev	0.32	0.047724
150 ppb, 50 ft		
avg	1.99	
Std Dev	0.31	0.070295
150 ppb, 100 ft		
avg	2.26	
Std Dev	0.38	0.072839
150 ppb, 150 ft		
avg	2.44	
Std Dev	0.38	0.094337
1000 ppb, 5ft		
avg	0.636875	
Std. Dev	0.064054	0.016014
1000 ppb, 50 ft		
Average	0.625	
Std. Dev.	0.097	0.028002
1000 ppb, 100ft		
Average	0.68625	
Std. Dev	0.081803	0.029451
1000 ppb, 150 ft		
Average	0.704375	
Std. Dev	0.070045	0.017511

Fall Time Analysis		SDOM
12 ppb, 5 ft		
avg	11.23	
Std Dev	0.37	0.08
12 ppb, 50 ft		
avg	11.45	
Std Dev	0.28	0.08
12 ppb, 100 ft		
avg	11.30	
Std Dev	0.14	0.04
12 ppb, 150 ft		
avg	14.57	
Std Dev	5.93	1.33
150 ppb, 5 ft		
avg	20.57	
Std Dev	3.58	0.54
150 ppb, 50 ft		
avg	22.29	
Std Dev	2.95	0.66
150 ppb, 100 ft		
avg	21.78	
Std Dev	2.00	0.41
150 ppb, 150 ft		
avg	23.67	
Std Dev	5.29	1.32
1000 ppb, 5ft		
avg	39.88	
Std. Dev	2.184575	0.546145
1000 ppb, 50 ft		
Average	46.66167	
Std. Dev.	10.95724	3.163083
1000 ppb, 100ft		
Average	43.21625	
Std. Dev	4.813583	1.203396
1000 ppb, 150 ft		
Average	42.62188	
Std. Dev	3.84725	0.961813

Alarm times, Minutes — Std Dev of Mean

Sample Line Length, Ft	Hydrazine Concentration 12	150	1000	50000	Hydrazine Concentration 12	150	1000	50000
5	10.53	1.78	0.637	0.55	0.06	0.05	0.064	
50	10.65	1.99	0.625	0.55	0.06	0.07	0.097	
100	11.01	2.26	0.686	1.87	0.04	0.07	0.082	
150	16.90	2.44	0.704	0.67	1.71	0.09	0.070	

Concentration Response — Std. Dev. Of Mean

Sample Line Length, Ft	Hydrazine Concentration 12	150	1000	50000	Hydrazine Concentration 12	150	1000	50000
5	16.25	254.34			0.26	0.29		
50	17.20	229.55			0.34	2.28		
100	14.13	223.71			0.48	2.63		
150	12.80	220.13			0.19	2.09		

Sample Line Length, Ft	Hydrazine Conc 12	150	StdDev of Conc 12	150
5	16.3	254	0.26	0.3
50	17.2	230	0.34	2.3
100	14.1	224	0.48	2.6
150	12.8	220	0.19	2.1

Addendum 7

CALIPSO Fire Protection Assessment

Michael B.Stevens, P.E.
KSC Authority Having Jurisdiction
TA-G

This assessment will demonstrate that personnel can evacuate the CALIPSO processing facilities with negligible risk of injury from fire should a hydrazine leak occur.

Assumptions

1. Hydrazine leakage form a point source at a constant rate of 1 Kg/hour.
2. Surrounding air is static with no purge.
3. Equal dispersion of the hydrazine vapor.
4. Materials in the vicinity of the leak are hydrazine-compatible (data from WSTF materials analysis).
5. Hydrazine detection system is enabled and properly configured to detect leakage.
6. Detector alarm will sound within 40 seconds of sense tube exposure to a 1 ppm source (data from KSC Applied Chemistry lab test of Zellweger Analytics Model CM4 hydrazine detector with 50-foot maximum sense tube length).
7. Personnel evacuate at an average speed of 3 mph (leisurely walk).
8. Worst-case evacuation distance 120 feet (Astrotech facility data).

Given

1. Lower Explosive Limit (LEL) of hydrazine is 4.7% = 47,000 ppm
2. Hydrazine = N_2H_4
3. Molecular weight N_2H_4 = m_{N2H4} = 32
4. Molecular weight Air = m_{air} = 28.6
5. Mass density Air = p_{air} = 1.2

Time Required for Evacuation

120 Ft * 3600 sec / 3 miles * 1 mile / 5280 ft = **27.27 seconds, or assume**
28 seconds required for personnel to evacuate area.

Mass of Hydrazine (M_{N2H4}) Leaked During Detection/Evacuation Period

0.28 grams/sec * (time to detect + time to evacuate) =
0.28 grams/sec * (40 + 28) = **19.04 grams N_2H_4 or 0.019 Kg N_2H_4 released**
19.04 grams N_2H_4 * 1 cc/1.008 grams = **18.9 cc N_2H_4 or 0.639 oz N_2H_4 released**

Since the number of moles of gas per unit volume is given by

$$\frac{\rho}{m} = \frac{n}{V}.$$

where n is the number of moles of gas present, mass density ρ and molar mass m of the gas:

$M_{N2H2} = p_{N2H2} V_{N2H2}$
$M_{N2H2} = p_{air} (m_{N2H2} / m_{air}) V_{N2H2}$
$0.019 \text{ Kg} = 1.2 (32/28.6) V_{N2H2}$
$0.019 = 1.34 V_{N2H4}$
$V = 0.014$

0.014 / 0.047 = **0.30 m^3 Volume of N_2H_4 at LEL when evacuation is complete.**

Proceeding as above, but using only time to detect yields **0.17 m^3 volume of N_2H_4 at LEL when evacuation is initiated.**

<u>Conclusion</u>:

Hydrazine vapor at the lower explosive limit may occupy a volume of 0.32 cubic meters when the detector alarm sounds and expands to 0.64 cubic meters in the 28 seconds required to fully evacuate the facility. Personnel will be well outside the LEL-occupied volume at all times and thus exposed to negligible risk of injury due to fire. Since all materials in the immediate vicinity of the leak are hydrazine-compatible, no immediate ignition source is present and ignition of the vapor is unlikely before the facility can be evacuated. Consequently, the availability of fire detection and suppression equipment does not play a role in this assessment.

Note that the underlying assumptions are worst-case from the perspective of vapor detection and accumulation. KSC tests of the Zellweger CM4 vapor detector suggest that detection times of 10-20 seconds may be realized in the field with 50-feet of sample tubing and the detector configured for automatic tape advance, implying the LEL-occupied volumes may actually be smaller than calculated above. Purge gas, if provided, will tend to sweep away and dilute hydrazine vapor and reduce the potential for ignition. The calculations were completed for the Astrotech processing facility, but the results also hold true for the SLC-2 white room since the evacuation distance is considerably shorter (40 vs. 120 feet), and the assumed leak rate much lower (10 g/hr vs. 1 Kg/hr).

Addendum 8

PowerPoint Presentation, Update of NESC Requirements/Actions to Integrated Program Management Council

NASA Engineering and Safety Center (NESC)

CALIPSO Independent Technical Assessment/Inspection (ITA/I)

03-001-E

Update of NESC Requirements/Actions to Integrated Program Management Council

2-02-05

Rick J. Gilbrech

This briefing is for status only. See final report for engineering data analysis.

NESC Assessment Overview

- On 6-Nov-03, GSFC Deputy Director (Bill Townsend) requested NESC to review Proteus propulsion bus hydrazine issues related to personnel safety.
- NESC site visit of VAFB (Astrotech & SLC-2 pad) on 17-Dec-03.
- NESC delivered summary briefing to Integrated Program Management Council held at GSFC on 22-Jan-04 with follow up briefing at NASA Headquarters to Space Science and S&MA Associate Administrators.
- NESC ITA/I lead participated in Alcatel site visit week of 12-May-04.
- NESC supported Ground Ops Working Group meeting at VAFB on 8-Jul-04.
- Status of NESC requirement/actions delivered to IPMC 9-28-04.
- Final closure update presented today.

Problem Statement

- Review CALIPSO spacecraft design and assess potential for personnel exposure to hydrazine propellant. Loss of mission, spacecraft or launch facilities were placed outside the scope of this assessment.
- Assessment focused on three key areas for filled and pressurized hydrazine system (L-36 days to lift-off).
  - Leakage from fluid system mechanical fittings
  - Leakage from thrusters
  - Inadvertent firing of thrusters

Investigation Team

Team Members

Dr. Rick Gilbrech (LaRC) - NESC Principal Engineer
John McManamen (JSC) - NESC Mech. Sys. Discipline Engineer
Tim Wilson (KSC) - NESC Chief Engineer, KSC
Frank Robinson (GRC) – Safety and Mission Assurance
Bill Schoren (GRC) – Safety and Mission Assurance

Expert Consultants

Ed Zampino (GRC) – Safety and Mission Assurance
Chris Hansen (JSC) - Mechanical Systems
Jay Bennett (JSC) – Materials and Processes
Tom Draus (KSC) – Orbiter Hypergolic Systems
Dr. Scott Miller (Aerojet) – NESC Consultant
Jack DeBoer (Aerojet) - NESC Consultant
Keith Coste (Aerospace Corporation) – NESC Consultant

NESC Activities to Date

- Aerojet A/N fitting hydrazine exposure tests completed
- Aerospace evaluation report delivered
- Alcatel site visit complete
  - **Note: Alcatel was exceptionally open and cooperative**
- WSTF Proteus propulsion bus hydrazine material compatibility report delivered
- NESC requirements/actions closure update presented to IPMC 9-28-04
- KSC modeling/analysis of hydrazine leak detection systems at VAFB completed
- KSC testing of hydrazine leak detection system planned for VAFB completed
- KSC fire safety analysis completed
- NESC CALIPSO Final Report, *Revision 2*, approved and released 1-27-05
- NESC final closure status presented today

NESC-R-001 – Fitting Assembly

- **Requirement**
  - Program shall demonstrate that Alcatel training and/or assembly documentation provided for proper lubrication of fluid fittings during assembly. Assembly procedures shall clearly delineate the type, quantity and location where lubricant was applied and ensure sealing surfaces were kept dry and free of any contaminant.

- **Closure Rationale**
  - NESC Alcatel site visit revealed training, assembly documentation and procedures were clear and adequate to satisfy the requirement
    - Procedures used to assembly the 5 Proteus A/N fittings clearly called out the type and quantity along with the specific location of the lubricant. Training and experience of technicians performing the work was sufficient and comparable to US spacecraft industry. The work is performed in a 100,000 class clean room and technicians used appropriate gear (head, body and feet covers along with gloves) to keep surfaces dry and free of contaminant. Assembly sequence and jigs provide orientations and access conducive to a well-assembled fitting.

CLOSED

NESC-R-002 – Fitting Assembly

- **Requirement**
  - Program shall demonstrate that Alcatel training and/or assembly documentation provided for a visual inspection of fluid fittings prior to assembly. Assembly procedures shall ensure components had no visible defects and sealing surfaces were clean and dry.

- **Closure Rationale**
  - NESC Alcatel site visit revealed training, assembly documentation and procedures were clear and adequate to satisfy the requirement
    - All surfaces (threads, sleeves and both sides of the conical seals) received a 4X visual inspection by the quality inspector prior to assembly and all were verified clean and dry.

CLOSED

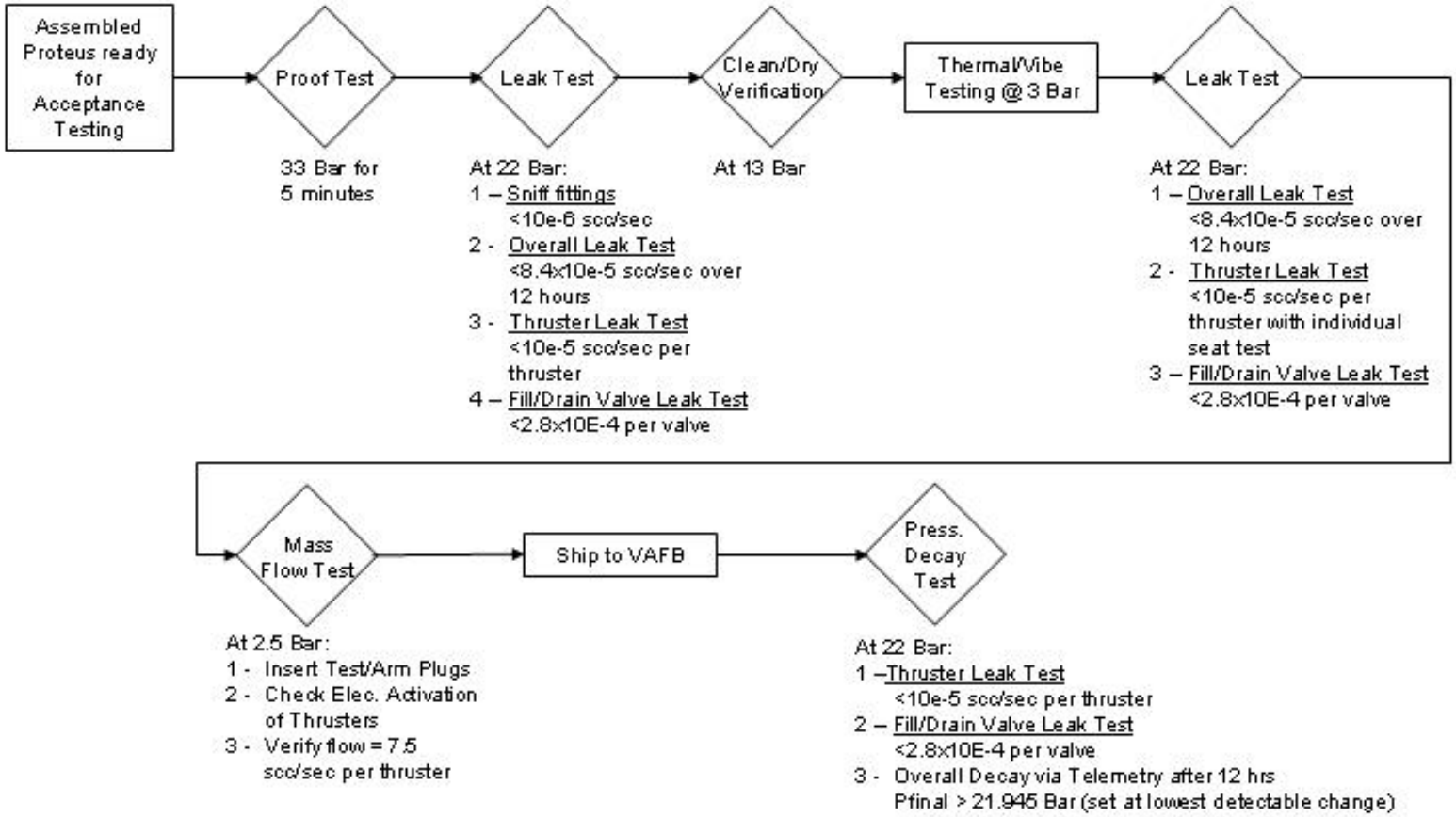
NESC-R-003 – Post Assembly Leak Checks

- **Requirement**
  - Program shall demonstrate that the Proteus bus mechanical fittings are rigorously tested using techniques adequate to validate system integrity. Leak check procedures shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

- **Closure Rationale**
  - NESC Alcatel site visit revealed leak test procedures and results adequate to validate system integrity
    - See following chart for leak test roadmap

CLOSED

Alcatel Helium Leak Test Summary



NESC-R-004 – Ground Handling Loads

- **Requirement**
  - Program shall demonstrate that thermal and vibration loads applied to the spacecraft during environmental tests envelope conditions it will experience from servicing through launch.

- **Open**
  - Alcatel reported vibration test levels of 2 g's at the tank fitting and 8 g's at the thruster fittings. These levels envelope the highest recorded ground handling loads at VAFB of 0.6 g's.

CLOSED

Note: Open item at 9-28-04 IPMC

NESC-R-005 – Handling Environment

- **Requirement**
  - Program shall demonstrate that servicing procedures adequately control temperature, pressure and flow rates to minimize the potential for leakage.

- **Closure Rationale**
  - NESC Alcatel site visit revealed training, assembly documentation and procedures were clear and adequate to satisfy the requirement
    - JASON-1 procedures presented will be used for CALIPSO and clearly delineate fill and pressurization rates adequate to preclude large temperature or pressure excursions

CLOSED

NESC-R-006 – Handling Environment

- **Requirement**
  - Program shall verify that the controls at the processing facility and launch pad identified in the final report are in place to monitor for leakage from the time hydrazine is loaded until final closeout for launch.
  - Additionally, the program shall verify that spacecraft operations are minimized after hydrazine loading, and that provisions are made for area securing and the rapid evacuation of personnel should a leak develop.
  - Further, the program shall coordinate with all other payload/Delta II processing personnel to ensure the program's approach for minimizing personnel exposure to potential hazards is properly integrated.

- **Closure Rationale**
  - Astrotech payload processing facility and SLC-2 white room capabilities presented by Caraballo along with procedures presented at Ground Operations Working Group Meeting at VAFB on July 7, 2004, are adequate to address facility controls and coordination with all other payload/processing personnel. Program indicated tanking can not be moved any closer to launch and reviewed the processing timeline to minimize operations after loading.

CLOSED

NESC-R-007 – Thruster Leakage

- **Requirement**
  - Program shall demonstrate that pre-servicing thruster leak checks will be adequate to validate system integrity. Leak check procedures shall test each valve independently and shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

- **Closure Rationale**
  - NESC Alcatel site visit revealed procedures were clear and adequate to satisfy the requirement (reference NESC-R-003 for details).

CLOSED

NESC-R-008 – Thruster Valve Defect Concern

- **Requirement**
  - Program shall verify that the Proteus Moog valves on CALIPSO do not have defective plunger assemblies.

- **Closure Rationale**
  - CALIPSO Proteus thruster valves were supplied by Wright Components Co. (also known as EG&G Perkin Elmer) with part number 18207-14, serial numbers 029, 030, 033, and 034. The suspect valves with defective plunger assemblies were manufactured by MOOG after it purchased Wright Components in 2001 and moved manufacturing from Phelps, NY, to East Aurora, NY. The CALIPSO thruster valve part number and serial numbers used by Alcatel are exempt from the MOOG defective plunger issue.

CLOSED

NESC-R-009 – Thruster Inadvertent Firing

- **Requirement**
  - Program shall demonstrate that test procedures verify relays 16 and 17 are open before power is applied to the spacecraft. Since the design incorporates latching relays, verification of the last stable state by data retrieval or written record is acceptable.

- **Closure Rationale**
  - Before shipment to VAFB, the ability of the ground operator to close relays 16 and 17 is inhibited by removing the telecommand "close relays 16 and 17" from the electrical ground support equipment Main Control and Data Test (MCDT) database. The software routine that powers off the spacecraft has a step to telecommand open relays 16 and 17. The independent relay position feedback circuit is checked and if the open indication is not received, an error message is displayed on the operators screen. Alcatel agreed to add a warning screen instead of an error message on the operator's monitor and also add a safety warning in the procedure in case of this error/warning message dealing with relays 16 and 17. The forbidden command management procedure (removal and verification) will be reviewed at the Pre-Shipping Review before the spacecraft leaves Alcatel.

CLOSED

NESC-R-010 – Thruster Inadvertent Firing

- **Requirement**
  - Steps for inserting and removing test/arm plugs shall be explicitly called out in the ground processing timeline. Final installation for flight shall occur as late as possible; until that time, plugs shall only be installed as required for thruster valve testing.
- **Closure Rationale**
  - Alcatel stated that the test/arm plugs will only be used to perform the individual thruster valve seat leak tests outline in NESC-R-003. Once these tests are completed the plugs will remain in the spacecraft from that point on. Alcatel's rationale is based on reliability concerns that once the spacecraft is fueled, there is no way to verify the test/arm plug function without hot firing the thrusters.

CLOSED

NESC-R-011 – Thruster Inadvertent Firing

- **Requirement**
  - Program shall verify that all thruster firing circuit inhibits function as designed.

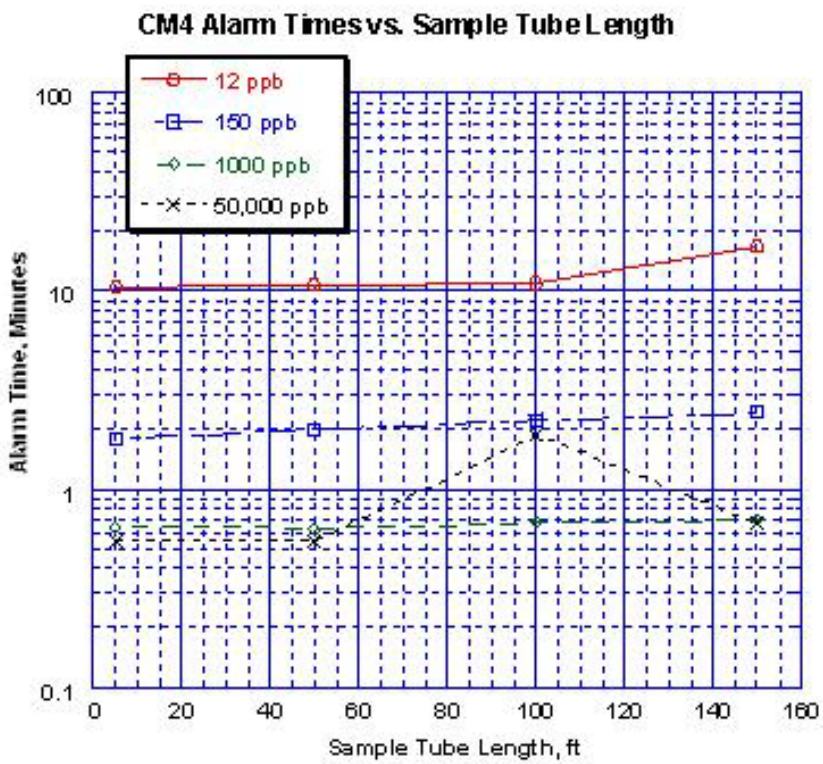
- **Closure Rationale**
  - Alcatel indicated that the individual thruster mass flow test is considered the verification of the thruster wiring/inhibit circuitry. No other evidence of manufacturing quality inspections or electrical continuity/resistance/functional checkouts was provided. The current Alcatel approach is comparable to NASA programs (i.e., to confirm functionality) and is sufficient to close the action.
    - NESC recommended Alcatel exercise all possible combinations of the three switches (relays 16, 17 and the opto-drivers) to guarantee the inhibits function as intended if it could be reasonably accommodated. Current testing will activate four of the eight possible combinations. This is under consideration by Alcatel but not required.

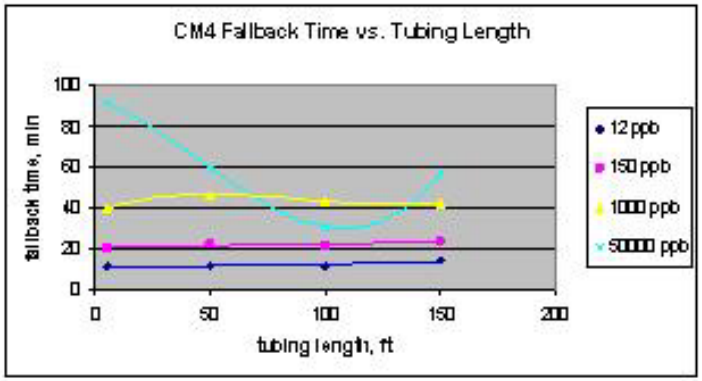
CLOSED

IPMC #1 – Fire Hazard Analysis

- **Requirement**
  - NESC to examine the magnitude of a fire hazard associated with hydrazine leakage onto adjacent materials and recommend suitable mitigation activities.
- **Closure Rationale**
  - Proteus propulsion bus hydrazine materials compatibility analysis/test by White Sands Test Facility indicated no credible ignition sources.
  - KSC analysis/test of VAFB hydrazine leak detection systems concluded Zellweger Analytics CM4 hydrazine detector consistently detected hydrazine in sufficient timeframe and resolution to be an effective safety alarm
    - Minimize CM4 tube lengths to minimize alarm delay
    - Recognize long fallback times (or time for instrument to clear and resume accurate detection) after alarms with high concentration (e.g., 40 minutes for 1 part per million)

IPMC #1 – Fire Hazard Analysis (cont.)
KSC Leak Detector Test Results





IPMC #1 – Fire Hazard Analysis (cont.)

- **Closure Rationale (cont.)**
  - KSC fire safety analysis concluded that a hydrazine leak, given the results above, presents very little risk to facility occupants at Astrotech and the SLC-2 white room (personnel egress times, toxicity hazard, fire potential and lower explosive limit considered).
  - NESC concurs with the supplemental safeguards planned by Program
    - Enhanced hydrazine monitoring – CM4, sniff checks, dosimeter badges, portable detector spot checks
    - Enhanced training & evacuation drills
    - Streamlined processing – essential personnel only, peer review of lifting ops
    - Single safety lead

CLOSED

Note: Open item at 9-28-04 IPMC

IPMC #2 – VAFB Capability

- **Requirement**
  - NESC to work with VAFB to assess the adequacy of range capabilities to handle hydrazine leak rates ranging from catastrophic to plausible.
- **Closure Rationale**
  - Results from IPMC #1 were discussed with Astrotech, Boeing SLC-2 pad personnel and VAFB Range on 1-25-05. They confirmed that they can handle the worst case scenario considered:

    30 kg (~8 gallons) of hydrazine at 22 bar (319 psi)

    Worst case leak rate at payload processing facility: 1 kg/hr

    Worst case leak rate at launch pad white room: 10 g/hr

CLOSED

Note: Open item at 9-28-04 IPMC

IPMC #7 – Before/After 5x5 Risk Matrix

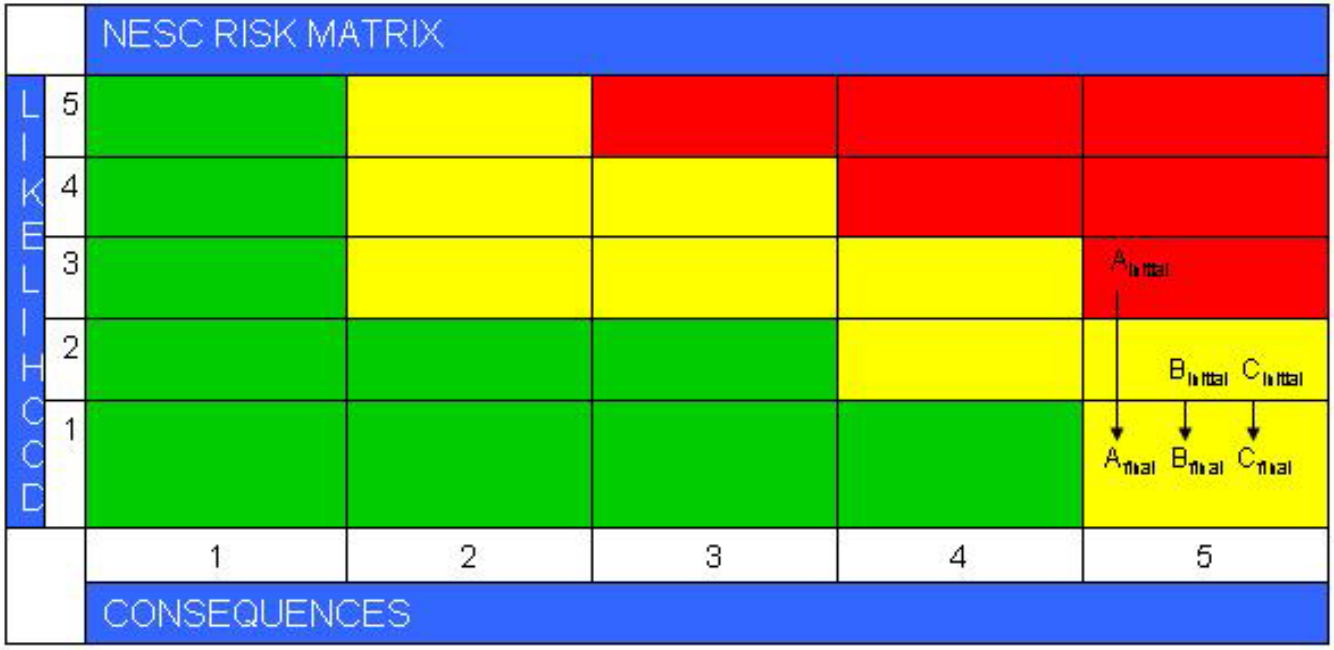
- **Requirement**
  - NESC to provide a risk assessment (NASA 5x5 matrix) of the potential for personnel exposure to hydrazine propellant once all of the propulsion actions are completed. Loss of mission, spacecraft or launch facilities were placed outside the scope of this assessment.

- **Closure Rationale**
  - Successful closure of all 11 NESC requirements and IPMC Actions #1 & #2.

CLOSED

Note: Open item at 9-28-04 IPMC

CALIPSO Personnel Hazard from Hydrazine Exposure



HAZARDOUS EVENTS

A – Personnel Injury from Hydrazine Leakage from Mechanical Fittings
B – Personnel Injury from Inadvertent Opening of Thruster Valves
C – Personnel Injury from Hydrazine Leakage from Thruster Valves

ASSESSMENTS

$_{initial}$ – Initial NESC Assessment
$_{final}$ – Final NESC Assessment

NESC RISK ASSESSMENT

RISK DEFINITIONS

Risk. Measure of the potential inability to achieve overall program objectives within defined constraints and has two components. (1) the probability/likelihood of failing to achieve a particular outcome, and (2) the consequences/impacts of failing to achieve that outcome

Consequences Impact (typically categorized as negative) to program/project (loss, injury, disadvantage)

Likelihood. Ordinal scale. Relative ranking of probability of occurrence. Numerical scale. estimated probability an event will occur combined with the uncertainty in the probability assessment

RISK MANAGEMENT. An organized, systematic decision making process that efficiently identifies risks, assesses or analyzes risks, and effectively reduces or eliminates risks to achieving program goals. (NESC Risk Management Plan)

NESC ASSESSMENT RISK MANAGEMENT APPLICATION (NAMA). The NESC database used to assess and prioritize concerns brought to the attention of the NESC. URL http://xx

What is the likelihood the situation or circumstance will happen?

LIKELIHOOD Level	Probability	... of ...	Example
5	Very Likely	Likely to occur often. Likelihood of occurrence is estimated to be greater than 0.10 (10-1) per operational opportunity	Lost work case per worker over a 20 year private industry career
4	High	Expected to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.01 and 0.10 (10-2 and 10-1) per operational opportunity	Failures per U.S. EV Launch (1980 - 2001)
3	Moderate	Likely to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.01 and 0.001 (10-2 and 10-3) per operational opportunity	Place holder
2	Low	Unlikely but possible to occur. Likelihood of occurrence is estimated to be between 0.001 and 0.000001 (10-3 and 10-6) per operational opportunity	Fatal crashes per automobile trip
1	Very Low	Likelihood of occurrence is estimated to be less than .000001 (<10-6) per operational opportunity	Fatal crashes per passenger airplane departure

NESC RISK MATRIX

LIKELIHOOD \ CONSEQUENCES	1	2	3	4	5
5					
4					
3					
2					
1					

LEGEND

- High – Accepted for NESC Board review. Probable NESC follow-on IA.
- Medium – Accepted for NESC Board review. NESC or other NASA IA action required.
- Low – Not Boarded by NESC. Direct referral to other NASA IA org.

RISK CONSEQUENCE SCORING TERMS

1	Safety, Health, Environment is defined as impact to life, health, working environment and natural environment
2	Mission Success definition includes impacts to Major Mission Objectives (MMOs) as well as hardware loss
3	National Significance is defined as the degree to which national prestige, visibility and public relations are impacted
4	Safety, Health, Environment, Mission Success and National Significance can exist concurrently and are not mutually exclusive
5	Risk scoring is accomplished by 'multiplying' Likelihood (L) X Consequence (C). Note numerical value is reflective of the ordered pair L, C. Care must be taken when using multiplied values as measure. When determining risk consequence among Cost, Schedule, and Technical, the highest score is represented in the NESC Risk Matrix as a single score value.

What is the Consequence (Safety, Health, Environment, Mission Success, National Significance) of this NESC Risk?

CONSEQUENCE Level	1	2	3	4	5
Safety, Health, Environment	Minimal/no safety or health plan violations / Minimal to no environ impacts	Could result in injury or illness not resulting in lost work day / Minimal environmt damage	Could result in injury or occupational illness resulting in one or more lost work day / Mk. environmt damage w/o law viol	Could result in permanent partial disability, injuries or occupational illness / Reversible environmt damage – violates law	Could result in death or perm. total disability / Irreversible severe environ damage that violates law or regulation
Mission Success	Hardware loss between $200K and $1 Million / Failure to any one MMO	Hardware loss between $1M and $10 Million / Failure to meet > 30% of supplemnt objectives	Hardware loss between $10M and $100 Million / Failure to meet any one MMO	Hardware loss between $100M and $250 Million / Failure to meet > 30% MMO's	Hardware loss exceeding $250 Million / Failure to meet all Major Mission Objectives (MMO's)
National Significance	Minimal or no identified National Prestige or Visibility	Low National Prestige and Visibility	Moderate National Prestige and Visibility	Significant National Prestige and Visibility	High National Prestige and Visibility

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This briefing is for status only. See final report for engineering data analysis.