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NASA Unmanned Flight Anomaly Report:

PRODUCT ASSURANCE MEASURES APPLICABLE TO PREVENTION OF JPL IN-FLIGHT ANOMALIES

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National Aeronautics and
Space Administration

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David Oberhettinger

S. Cornford
Manager, Reliability Technology Group

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

FOREWORD

This document was prepared by the Reliability Engineering Section of the Jet Propulsion Laboratory's Office of Engineering and Mission Assurance (OEMA) to describe recent results and progress of a Flight Anomaly Characterization (FAC) research task. It represents one of a series of analyses of in-flight hardware anomalies which have occurred on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. Funded by NASA Code QT under Research Technology Operation Plan (RTOP) 623-63-03, entitled *Flight Anomaly Characterization*, their objective is to search for meaningful characterizations of in-flight anomaly data relating to trends, patterns, or similarities that can be exploited to improve product assurance programs. Such improvements may ultimately lead to reduced numbers of anomalies on future unmanned flight programs.

For further information on the content of this report, contact Steve Cornford at (818) 354-1701.

ABSTRACT

This NASA Unmanned Flight Anomaly Report correlates in-flight anomalies during the Viking, Voyager, Magellan, Galileo, TOPEX, and Mars Observer missions with those product assurance measures which should be considered to prevent a reoccurrence under similar circumstances. Only those in-flight anomalies which were documented in Problem/Failure Reports (PFRs) were reviewed.

The objective of this analysis was to identify specific product assurance program recommendations which should be considered for implementation in current and future flight projects. Table 1 relates these recommendations to the corresponding in-flight "hard" failures. In response to an in-flight problem with release of an RTG boom, for example, Table 1 recommends:

> *"Consider the post-firing condition of pyro squibs in FMECAs. After firing, look for sneak paths created by conductive debris across the squib terminals."*

I. INTRODUCTION

The data in this report correlates in-flight anomalies during the Viking, Voyager, Magellan, Galileo, TOPEX, and Mars Observer missions with those product assurance measures which should be considered to prevent a reoccurrence under similar circumstances. Only those in-flight anomalies which were documented in Problem/Failure Reports (PFRs) were reviewed. The results are directed toward recommending product assurance process improvements which would lead to a reduced level of risk for future unmanned space missions.

Reference (1) provided the procedure that was used in obtaining these correlations, which were documented in several reports produced by the Flight Anomaly Characterization (FAC) RTOP task. JPL used a two-step methodology to group and analyze sets of in-flight spacecraft anomalies with common characteristics, allowing identification of product assurance implications for future flight projects. In reference (1), a flow diagram was prepared showing pertinent data from each JPL in-flight anomaly report. After the anomalies were arranged by spacecraft and subassembly, those that appeared related were designated as a group for further analysis. Analysis of these groups ("uplink/downlink anomalies," "mechanical anomalies," etc.) was documented in the FAC reports. This new report captures the results of the individual group analyses in a table format.

II. DATA ANALYSIS & RECOMMENDATIONS

The correlation of product assurance program activities with in-flight incidents is provided in the following table. Table 1 focuses on only those in-flight incidents which represented hard failures, or soft failures which threatened the primary mission. It provides specific product assurance program recommendations which should be considered for implementation. These conclusions are supported by data derived from the results of the FAC task, which conducted extensive reviews of anomaly documentation, identified failure trends, and contacted project personnel to verify conclusions.

Although the anomalies in Table 1 include some rated as representing a "minor" mission impact, these incidents could have posed major problems in the absence of redundancy or with greater spacecraft autonomy.

III. REFERENCE

(1) *Development of a Method for Flight Anomaly Characterization*, JPL document D-11382, dated January 1994.

IV. BIBLIOGRAPHY

The information in Table 1 was drawn from the following reports produced by the FAC RTOP task:

Oberhettinger, D.: Investigation of Thermal Sensor Failures Aboard Unmanned Spacecraft, Jet Propulsion Laboratory Document D-11377, April 1994.

Brown, A.: Analysis of Uplink/Downlink Anomalies on Six JPL Spacecraft, Jet Propulsion Laboratory Document D-11383, September 1994.

Oberhettinger, D.: Investigation of Mechanical Anomalies Affecting Interplanetary Spacecraft, Jet Propulsion Laboratory Document D-11951, September 1994.

Oberhettinger, D.: Investigation of Environmentally Induced Anomalies Aboard JPL Spacecraft, Jet Propulsion Laboratory Document D-12546, June 1995.

Gonzales, C.: Correlation of the Magellan Flight PFR History with Ground Test Results (Draft), July 1995.

V. GLOSSARY

The acronyms in the above document and in Table 1 are defined as follows:

AACS	Attitude and Articulation Control System
BOL	Beginning-Of-Life
CCS	Command and Control Subsystem
CST	Canopus Star Tracker
DC	Direct Current
EOL	End-Of-Life
EMI	Electromagnetic Interference
ER	Electron Reflectometer Instrument
ESD	Electrostatic Discharge
FAC	Flight Anomaly Characterization
FDS	Flight Data Subsystem
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
GSFC	Goddard Space Flight Center
HET	High-Energy Telescope
IRU	Inertial Reference Unit
IRIS	Infrared Interferometer Spectrometer
IRTM	Infrared Thermal Mapper
JPL	Jet Propulsion Laboratory

LECP	Low Energy Charged Particle Experiment
MAG	Magnetometer
NIMS	Near Infrared Mapping Spectrometer
NSI	NASA Standard Initiator
OEMA	JPL Office of Engineering and Mission Assurance
OSR	Optical Solar Reflector
PA	Product Assurance
PFR	Problem/Failure Report
QA	Quality Assurance
RAM	Random Access Memory
REM	Rocket Engine Module
RIU	Remote Interface Unit
RPE	Runaway Program Execution Error
RTG	Radioisotope Thermal Electric Generator
RTOP	Research Technology Operation Plan
S/C	Spacecraft
SEU	Single Event Upset
TWTA	Traveling Wave Tube Amplifier

Table 1

Recommendations for Prevention of Major JPL Failure Modes*

DESCRIPTION OF HARD FAILURE[1]	TOTAL FAILURES SUPPORTING RECOMM'NS #/%[2]	PFR NUMBER	MISSION IMPACT[3]	PROGRAM	RECOMMENDATIONS
PA Program Measures: Design-Related Failures					
High electronics bay temperatures due to darkening of the OSR surface from outgassing of adhesive onto OSR tiles.	3 (4%)	52228 52240	PM PM	MGN MGN	Provide adequate thermal margins to reduce mission risk resulting from diminished thermal control.
High REM temperature in a tail-towards-sun orientation.		52226	PM	MGN	
A voltage transient, possibly from NSI firing, caused the loss of an AACS memory board.	2 (3%)	52235	Minor	MGN	Review the electrical grounding of flight hardware toward development of a grounding standard.
An ungrounded shielding box conducted ESD to an amplifier; its failure degraded performance of the Canopus Star Tracker.		41009	PM	VOY1	
A voltage transient, possibly from NSI firing, caused the loss of an AACS memory board.	6 (8%)	52235	Minor	MGN	Review the potential for noise or transient-induced state changes. Realistic, instrumented, power-on system tests of NSI firing could be performed to test the sensitivity of spacecraft electronics to the pyro current surge and investigate the potential for noise-induced failures. Hardware redundancy (with physical separation of units) has benefit in assuring spacecraft survival in noise environments.
AACS lost heartbeat due to an RPE error, and it went into a heartbeat loss response execution. Caused by either s/w timing or pyro firing.		52236	PM	MGN	
The AACS attempted to write to protected memory. Pyro firing related runaway program execution (RPE) error.		52238	PM	MGN	
AACS lost heartbeat due to an RPE error thought to be a software problem, but it may have been induced by pyro firing currents.		52241	PM	MGN	
Power transient caused a switch to stick, damaging a resistor and increasing current in the LECP instrument.		41014	PM	VOY1	
IRU lost power 26 seconds after Viking Lander separation. EMI from pyro firing may have shorted a diode or output transistor.		35409	LRS	VIK2	

*The footnotes to Table 1 are listed on page 8.

DESCRIPTION OF HARD FAILURE[1]	TOTAL FAILURES SUPPORTING RECOMM'NS #/%[2]	PFR NUMBER	MISSION IMPACT[3]	PROGRAM	RECOMMENDATIONS
For unknown reasons, one redundant pyro channel did not fire at RTG boom release. Also, VOY2 PFRs 41001A and 41001B "erroneous indications" may indicate possible sneak paths.	1 (1%)	41002	Minor	VOY2	Consider the post-firing condition of pyros in FMECAs. After firing, look for sneak paths created by conductive debris across the squib terminals.
ESD into an FDS logic circuit caused excessive offset between the CCS and FDS clocks and a loss of key science data.	1 (1%)	41035	PM	VOY1	Consider use of transient suppressors on sensitive module interconnections. Since this incident, mitigation of ESD charging on spacecraft structures has been studied.
Radiation degraded the Delrin insulation on transistor leads, and current leakage disabled the CST position command function.	4 (5%)	41009	PM	VOY1	Review materials for radiation sensitivity. Select radiation hardened parts or employ spot shielding (TOPEX).
Degraded IRIS instrument accuracy due to radiation sensitivity of silicone rubber motor damper and mounts.		41026	PM	VOY2	
Possible latch-up of star tracker from numerous SEUs.		59031	Minor	TOPEX	
RIU telemetry failed due to radiation induced failure of multiplexer.		59033	PM	TOPEX	
Five TWTA shut-offs, with later recovery.	7 (9%)	52231	Minor	MGN	Maintain redundancy for critical systems.
Receiver local oscillator dropped out, then recovered during second deployment phase		52617	Minor	GLL	
High gain antenna deployment failure.		58331	MLD	GLL	
Total failure of X-band subcarriers on Transmitter A. The cause was undetermined.		52621	SLD	MGN	
Oscillator failed; X-Band downlink lost after 15 years due to possible random part failure. Switched to alternate transmitter.		58257	PM	VOY1	
Lost spacecraft data when "B" Memory failed due to CD 4049 inverter failure. The "A" memory was used for the rest of the mission.		41017	LRS	VOY1	
Science data was anomalous due to a bad CD 4061 RAM chip in Memory "B".		41012	PM	VOY2	
IRTM scan platform misaligned, affecting telescope function.	3 (4%)	35407	PM	VIK2	Conduct thorough modeling of spacecraft in all orientations. Model and evaluate all variations from the physical configuration baseline. Utilize JPL's integrated modeling environment for successive design iterations on complex systems.
Inadequate structural analysis resulted in Voyager I and II thruster plume impingement, causing propellant losses.		41003a 41003b	PM PM	VOY1 VOY2	

DESCRIPTION OF HARD FAILURE[1]	TOTAL FAILURES SUPPORTING RECOMM'NS #/%[2]	PFR NUMBER	MISSION IMPACT[3]	PROGRAM	RECOMMENDATIONS
OSR contamination resulted in twice the anticipated EOL absorptance.	2 (3%)	52228 52240	PM PM	MGN MGN	Address contamination concerns early in the hardware build cycle.
Part failure: 5 thermal sensors (on 1 PFR) failed open. Part failure: 8 Magellan and Galileo thermal sensors demonstrated vulnerability to high temperature and to temperature cycling, in addition to possibly other environmental stresses. PFR 58333 may be a random failure. The failure mode for the other Galileo sensors appears to be differential rates of thermal expansion of the sensor body versus the sensor wire.	9 (12%)	52244 52604 52605 52606 52611 52613 52618 58333 58334	Minor Minor Minor Minor Minor Minor Minor Minor Minor	MGN GLL GLL GLL GLL GLL GLL GLL GLL	Develop a flight qualified mounting configuration for thermal sensors which provides strain relief adequate to accommodate thermal cycling. Review established engineering specifications and procedures on the use of bonding and potting compounds. Provide the proper environmental requirements for part selection.
PA Program Measures: Analysis-Related Failures					
High electronics bay temperatures due to outgassing of adhesive on OSR tiles, causing darkening of the OSR surface.	2 (3%)	52228 52240	PM PM	MGN MGN	Consider outgassing products when determining surface optical properties, and consider vacuum bake-out of all organic adhesives. Update the optical properties database to include the Magellan experience, and supply BOL/EOL thermal property data for NASA-wide use.
A voltage transient, possibly from NSI firing, caused the loss of an AACS memory board. Receiver 1 failed 20 minutes after powering due to short circuits to the chassis from the 30V return.	2 (3%)	52235 41029	Minor LRS	MGN VOY2	Upgrade standard circuit analysis methods, which do not consider vulnerabilities which are not represented on schematic diagrams, such as circuit board proximity to the ground plane. Upgrade PA scrutiny of electronics packaging.
Insolation of the interior of the rocket nozzle could not be simulated with the existing test fixture.	1 (1%)	52226	PM	MGN	Consider use of improved automated tools for integrating thermal analysis with three-dimensional modeling of spacecraft structures.
Radiation degraded the Delrin insulation on transistor leads, and current leakage disabled the CST position command function. Degraded IRIS instrument accuracy due to radiation sensitivity of silicone rubber motor damper and mounts.	2 (3%)	41009 41026	PM PM	VOY1 VOY2	Incorporate radiation-induced behavior into worst case, failure mode and effects and fault tree analyses.
D.C. bus imbalance changed values in numerous incidents due to conductive debris causing "short" circuits across adjacent slip rings between the spun and despun sections of the spacecraft. Organic materials such as Solithane serve as a "getter" for conductive debris.	1 (1%)	52607	PM	GLL	Perform an FMECA of potential path-to-path short circuits for slip rings at the spacecraft spun/despun interface. Determine margin between expected currents and damage thresholds. Consider that organic materials can act as a "getter" for debris.

DESCRIPTION OF HARD FAILURE[1]	TOTAL FAILURES SUPPORTING RECOMM'NS #/%[2]	PFR NUMBER	MISSION IMPACT[3]	PROGRAM	RECOMMENDATIONS
Scan platform actuator gears stuck due to dissimilar metals. Data lost. Deployment mechanism failed to fully deploy solar panels per design. High gain antenna deployment failure. Telemetry indicated Mag Boom not deployed. Thermal shrinkage of the lanyard rotated microswitch in mount. Uncompensated stator-to-platform misalignment caused s/c turn errors.	5 (6%)	41015 52230 58331 58332 52612	PM Minor MLD Minor PM	VOY2 MGN GLL GLL GLL	Mechanical failure mode analysis and design margin assessment are beneficial in the design and review of complex mechanisms which lack backup. Use of failure mechanisms analysis would improve fault trees by highlighting the underlying "physics of failure" issues that cause the failure modes in the fault tree or FMEA. Design of actuators and "one-shot " mechanisms require intensive review.
Five TWTA shut-offs, with later recovery. (Had occurred four times during ground test.) Receiver local oscillator dropped out. This failure mode was seen during ground vibration tests. Unable to establish an uplink. Caused by a known problem with shorting polycarbonate capacitors.	3 (4%)	52252 52617 41033	Minor Minor PM	MGN GLL VOY2	Ensure that the underlying "physics of failure" are understood for all ground test failures, and are considered in launch decisions.
PA Program Measures: Process-Related Failures					
REM thermal modeling was delegated to a vendor, and a vendor fix was not tested.	1 (1%)	52226	PM	MGN	**Avoid delegating responsibility for thermal control design; it should be retained by the spacecraft prime contractor.**
NIMS cover would not jettison due to thermal expansion caused by energizing of the shield heater-- a flight rule violation.	1 (1%)	52603	MLD	GLL	"Fly it like you test it:" JPL now requires a deployment review prior to every commanded deployment.
Gyro bearing contamination or lack of lubrication.	1 (1%)	52223	PM	MGN	Update program for contamination control in fabrication and handling to reflect bearing failure modes.
A propellant heater line short resulted in a soft ground violation and anomalous radar pre-regulator current. A cable clamp had caused a similar short prior to launch. Degraded performance of the Electron Reflector instrument due to ER case shorting to the S/C chassis ground thru cable or connector.	2 (3%)	52245 59014	Minor Minor	MGN MO	Review fabrication processes for cables and improve QA inspection. Conduct cable design reviews.

DESCRIPTION OF HARD FAILURE[1]	TOTAL FAILURES SUPPORTING RECOMM'NS #/%[2]	PFR NUMBER	MISSION IMPACT[3]	PROGRAM	RECOMMENDATIONS
Degradation of the X-Band transmitter due to a failed chip capacitor in the transponder, likely damaged during assembly.	1 (1%)	52243	PM	MGN	Implement QA inspection measures which will reliably detect damage during assembly.
PA Program Measures: Test-Related Failures					
High electronics bay temperatures due to outgassing of adhesive on OSR tiles, causing darkening of the OSR surface.	2 (3%)	52228 52240	PM PM	MGN MGN	Include a "hot margin" phase in system thermal-vacuum test to demonstrate spacecraft operation at temperatures greater than worst case design predictions. Consider requiring vacuum bakeout of all organic adhesives, especially structural.
REM thermal modeling was delegated to a vendor, and a fix was not tested. REM nozzle entrapment could not be simulated, and a low emittance nozzle coating impeded heat transfer.	1 (1%)	52226	PM	MGN	Perform solar thermal-vacuum test at the subsystem level; or if subsystem testing is not performed, system solar thermal-vacuum test should simulate several attitudes for the subsystem. Verify thermal control design changes by test.
Low output of the high gain antenna due to M.C. 3005 transistor failure in the solid state amplifier, aggravated by a poor solder connection to the heat sink.	2 (3%)	41031 41032	PM PM	VOY2 VOY1	Provide adequate burn-in for power transistors. Consider use of a thermal scan test for subassemblies to identify "hot spots" caused by poor thermal connection of devices.
Part failure: 5 thermal sensors (on 1 PFR) failed open. Part failure: 8 Magellan and Galileo thermal sensors demonstrated vulnerability to high temperature and to temperature cycling, in addition to possibly other environmental stresses. PFR 58333 may be a random failure. The failure mode for the other Galileo sensors appears to be differential rates of thermal expansion of the sensor body versus the sensor wire.	9 (12%)	52244 52604 52605 52606 52611 52613 52618 58333 58334	Minor Minor Minor Minor Minor Minor Minor Minor Minor	MGN GLL GLL GLL GLL GLL GLL GLL GLL	Perform mock-up tests of the flight configuration (or of a standardized mount) in high temperature and thermal cycle environments. Based on the test data, flight qualify the piece part and assembly procedure, and determine environmental margins based on test-to-failure. Study of GSFC and Air Force records shows that this problem extends beyond JPL.
A bad memory cell led to a parity error and spacecraft safing. A known gate oxide deficiency caused charge leakage, changing the bit value of the memory cell.	1 (1%)	52224	Minor	MGN	Perform parts qualification test.
PA Program Measures: Unknown-Related Failures					
Instrument analyzer wheel stuck. Data was lost; cause unknown. No counts in Channels 12,13,14, and 15 of the HET telescope due to a random transistor failure.	2 (3%)	41019 41048	SLD Minor	VOY2 VOY1	Problem/failure analysis did not disclose a corrective action to prevent reoccurrences.

Legend:

[1] **Table 1 includes the following in-flight hardware failures: (1) hard failures and (2) those soft failures (i.e., glitches and out of adjustment conditions) which threatened the primary mission (including loss of the data which was expected from an instrument).**

[2] **Parenthesis indicate the percentage of the 77 PFRs listed in Table 1. (The 77 include 52 distinct PFR numbers, some of which appear more than once in the table.)**

[3] **PM = Potential for Major Impact MLD = Major Loss or Mission Degradation**
SLD = Significant Loss or Mission Degradation LRS = Loss of Redundant Subsystem