Space Power Workshop 2009

Power Subsystem Failures:
Stories of Arcs and Sparks

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Outline

- Battery Failures
- Main Power Bus Failures
- Pyro Related Problems
- Power Electronics Problems
- Power Converter Troubles
- G-Switch Issues
- Corona Induced Failures
- Failure Survey (Arrays, Batteries, Other)
- Bibliography

Ranger Battery Venting during Test

- Incident
  - 1800WH Ag-Zn battery experienced cell short due to dendrite growth during system thermo-vac testing, forcing emergency venting procedure
- Causes
  - Intrinsic properties of Ag-Zn battery chemistry
  - Solubility of reactants lead to separator penetration by dendritic short circuits
- Resolution
  - Battery technician dons rain coat and goggle, arms himself with a electric drill, goes into chamber, pulls battery, carries out back behind building and creates a vent in the battery case, releasing plume of hot, concentrated potassium hydroxide gas and liquids.
- Lesson
  - Whenever possible, avoid Ag-Zn batteries

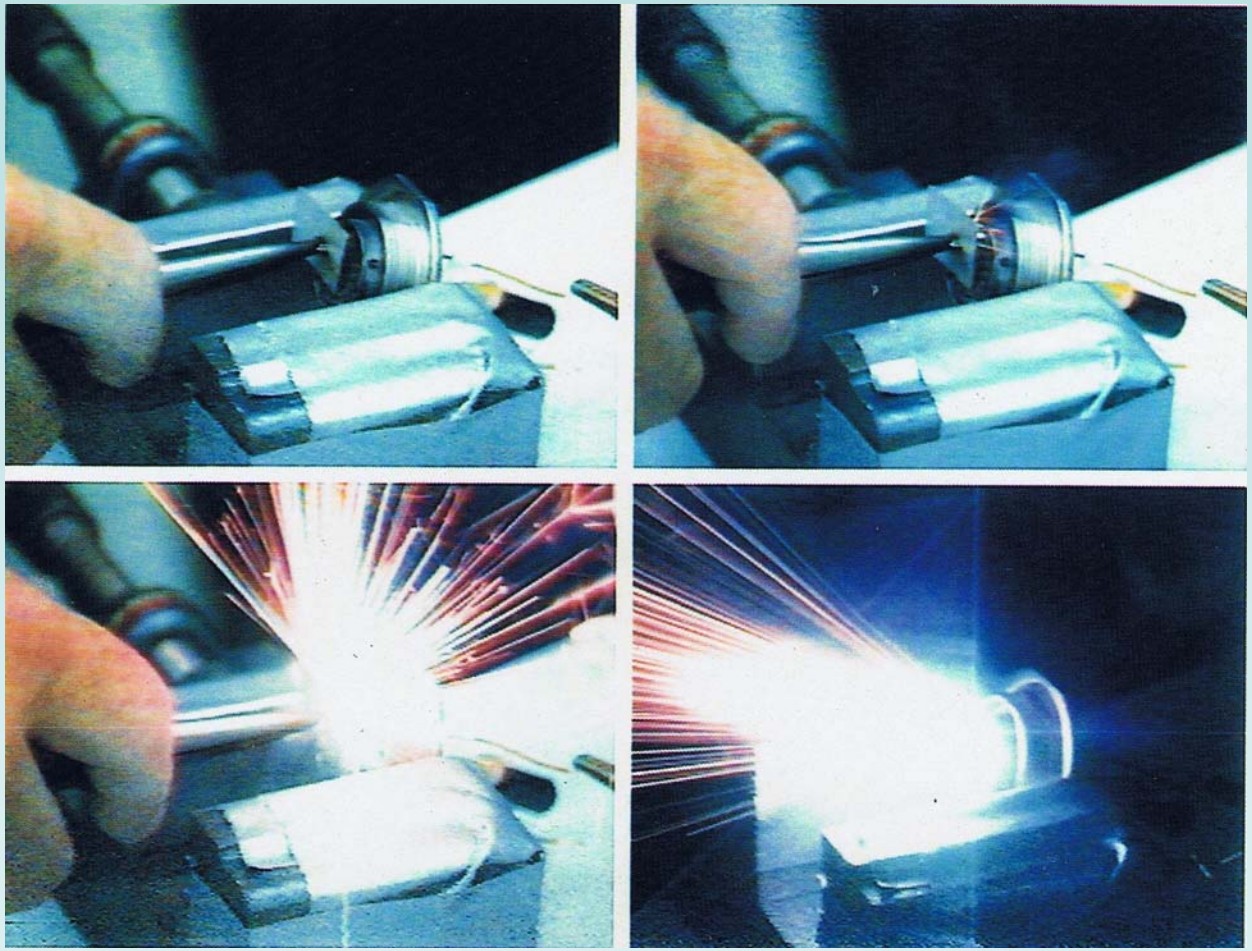
Ranger Venting During Flight

- Incident
  - In 1971, Mariner Mars experienced an unexpected battery venting causing a brief critical pressure region around the high voltage Canopus star tracker, resulting in a corona discharge. The arc caused a ground-loop current spike that resulted in the permanent loss of 22 telemetry channels in the Flight Data Subsystem (FDS).
- Cause
  - Use of Silver Zinc batteries
  - Primitive state of battery charger electronics
- Lesson
  - Don’t fly Silver-Zinc Batteries

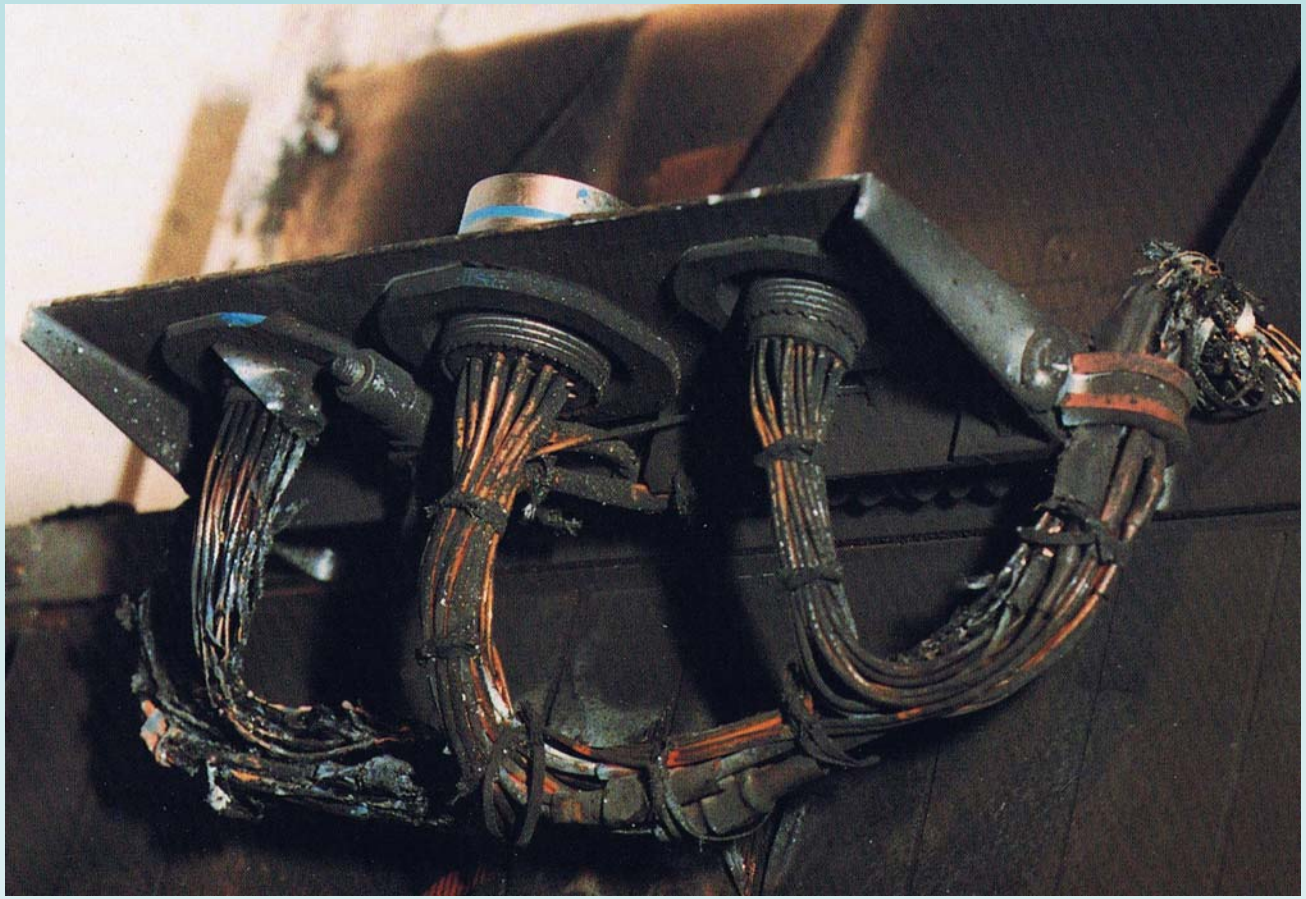
Magellan Battery Fire

- Incident:
  - Technician hooked up cables improperly during post power subsystem rework at Cape Canaveral, destroying battery and damaging the harness
- Causes
  - Technician not following instructions during rework
  - Lack of scoop-proof connector on “signal” connectors
  - Late change: add memory keep alive power lines to signal connector
  - Blind mating of connectors forced by mass/GC related battery change
  - Kapton pyrolyzes to carbon in presence of electrical fire
- Resolution
  - Crash development to add isolation to signal connectors
  - Crash program to do analysis of harness for damage
  - Launched successfully with flight spare battery

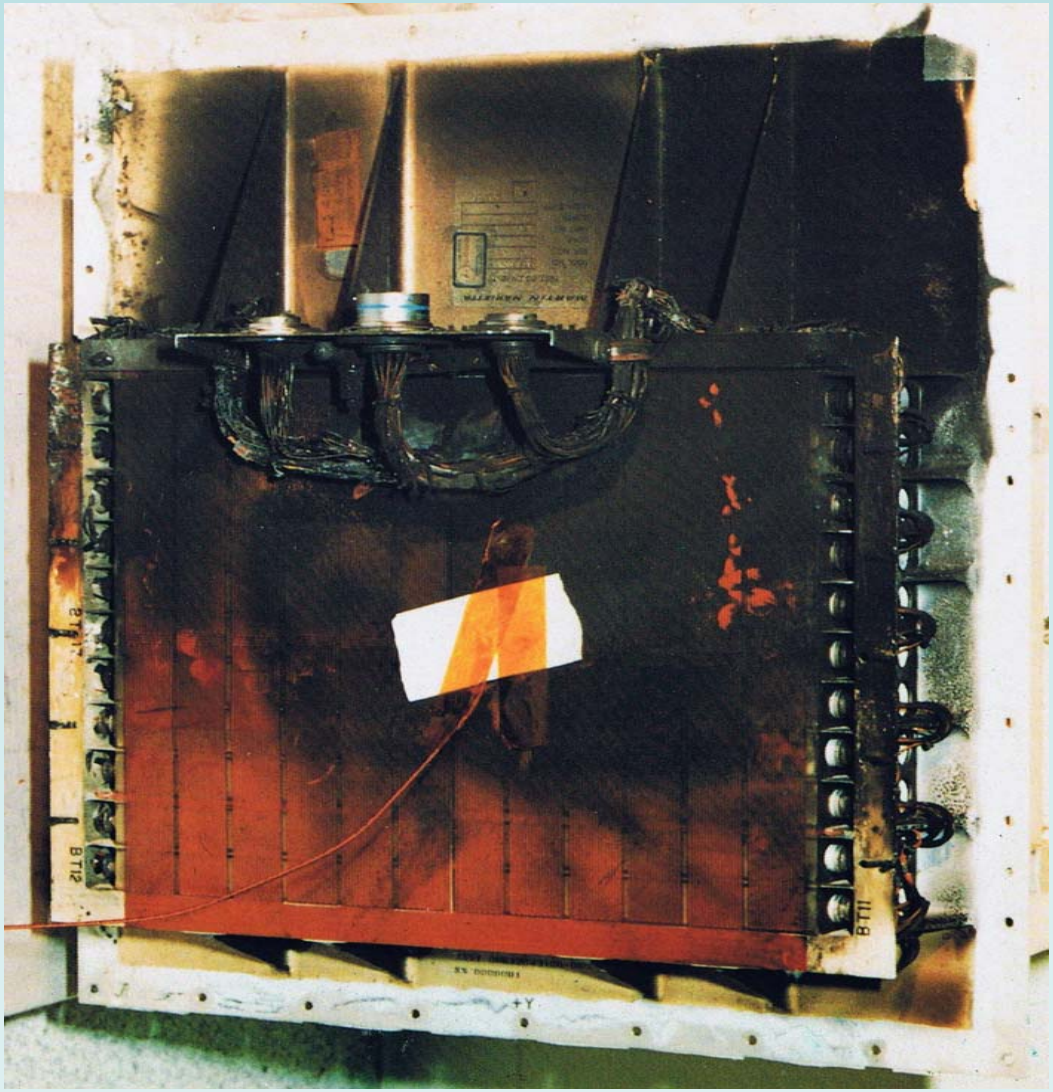
Demonstration of Electrical Arc



Damage to Battery Harness

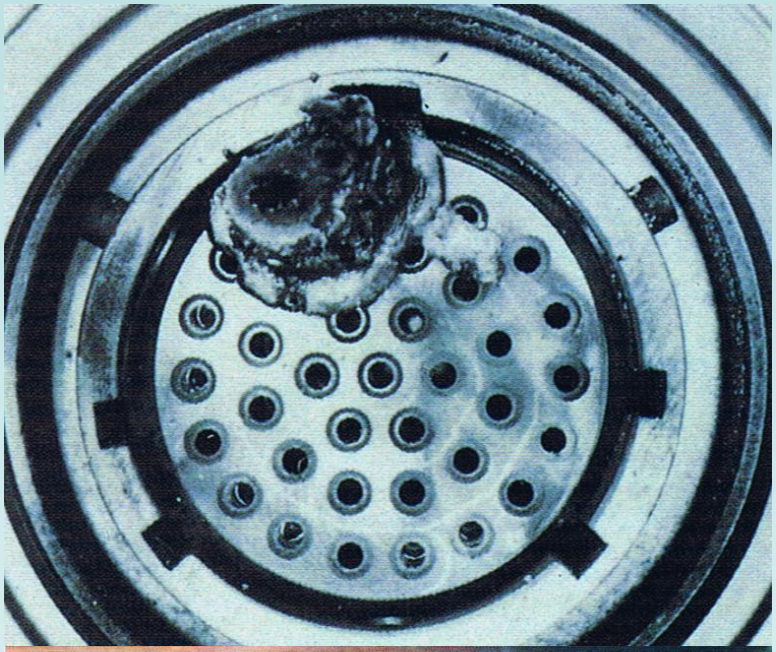


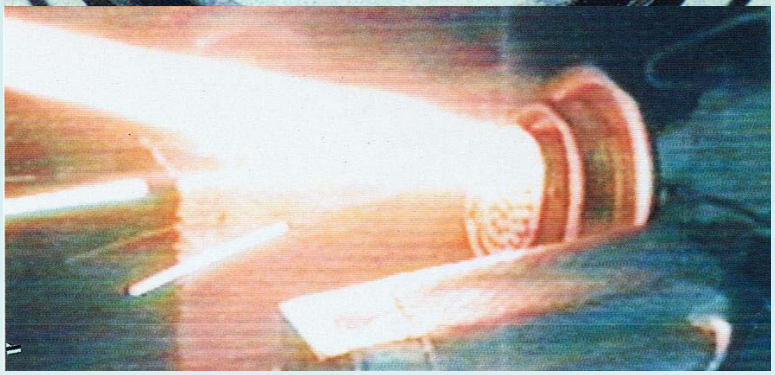
Battery, Post Mishap



Blind Mating Demonstration

Female Connector Damage





Fault Propagation

- Possible blind mate issue identified at CDR
- Incorrect Male/Female Alignment in ATLO
- High side to return short through Memory Keep Alive via splice in harness
- Plasma arc initiated by non-isolated female sense connector of battery
- Arc propagates through connector and back into battery harness
- Battery harness insulation is pyrolyzed
- Battery internal short circuits propagate

Lessons Learned, MGN Battery Fire

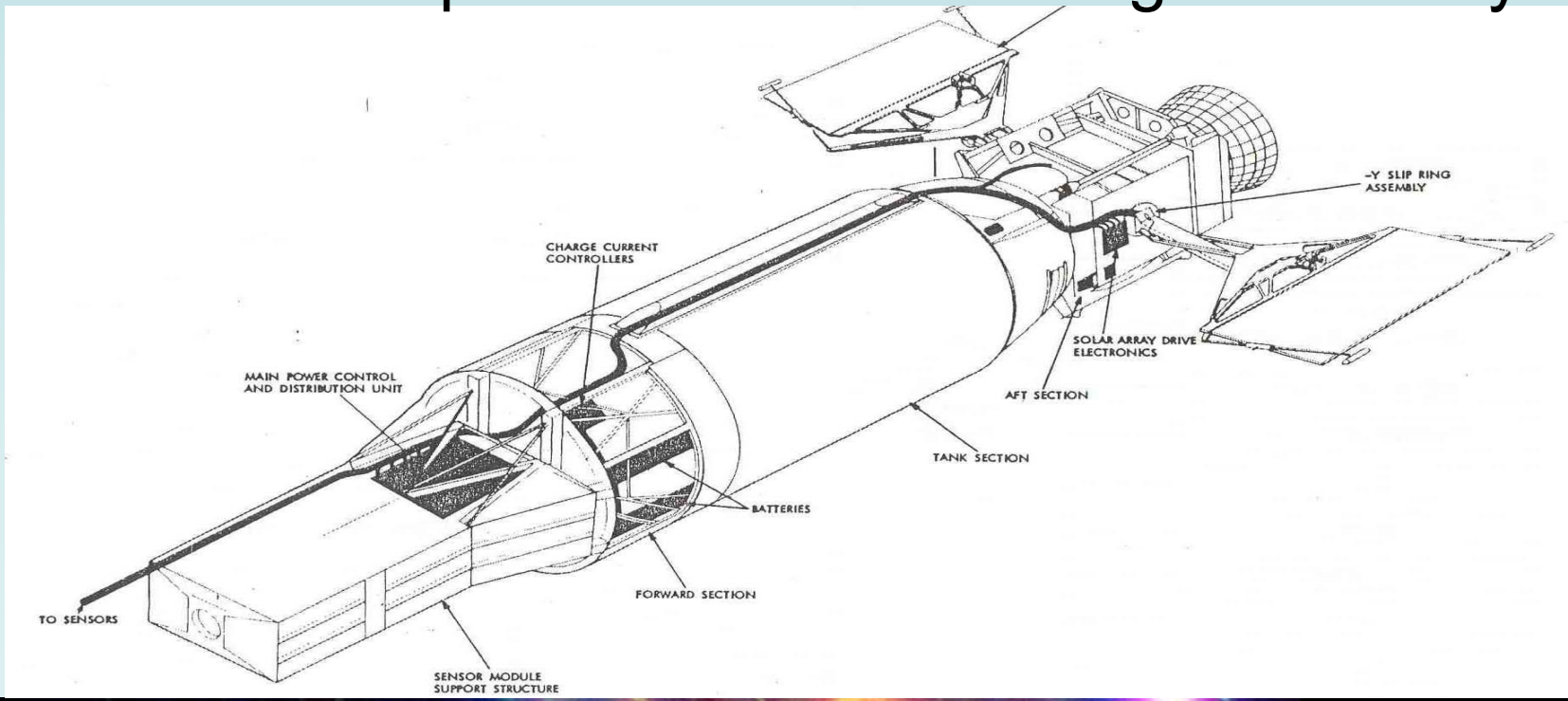
- Fire increased awareness of plasma-arc phenomenon – Kapton video widely available
- Avoid the use of Teflon coated Kapton wiring
- Avoid building-in blind mating of connectors in design process (or redesign)
- Insure connections to battery are all scoop-proof, uniquely keyed, including “non-power” sense connectors
- Insure all battery sense lines are properly isolated with resistors or diodes

MER In-flight Depassivation

- Incident
  - During flight testbed simulation of critical EDL sequence, MER flight computer experienced multiple reboots when exposed to low voltages supplied by Li-SO_2 batteries
- Cause
  - MER failed to incorporate battery depassivation circuits into design to prepare for EDL
- Resolution
  - Depassivation was done into constant potential bus by manipulating charge levels in the week before EDL
- Lesson
  - In the future, all spacecraft using liquid-cathode, lithium primary batteries shall include resistive depassivation circuits

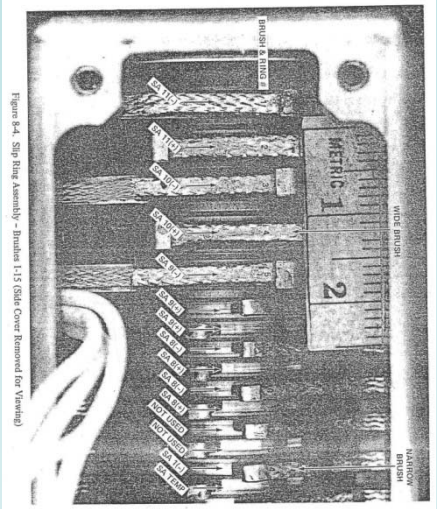
SEASAT Failure (1 of 3)

- Incident
  - After 11 months, a massive, progressive short occurred in one of the slip ring assemblies used to transfer power from the rotating solar arrays



SEASAT (2 of 3)

- Cause
  - Arc between two adjacent slip rings of opposite electrical polarity
  - Requirement to alternate positive/negative brushes to “reduce magnetic moments” that did not exist
  - Spacecraft bus was purchased as fixed cost item through NASA Low Cost Systems Office
  - The slip ring assembly had no applicable flight experience
  - The solar array drive electronics had undergone extensive redesign


WIDE BRUSH
NARROW BRUSH
METRIC
1
2
BRUSH & RING 1
BRUSH
BRUSH
BRUSH

SEASAT (3 of 3)

- Programmatic Lessons
  - To stay within tight fiscal constraints, fundamental decisions made early on that resulted in fatal design/implementation shortfalls
  - Continuing schedule and funding pressure – reduced insight, testing, documentation
  - Over reliance on “Standard Flight Proven Bus” resulted in belief that past history justifies elimination of sound engineering practices
  - Lack of penetration into hardware developments precluded knowledge gaining communication
  - Alternate views/opinions stifled – contractor/government team attempts to convey magnitude of concerns resulting from overly constrained resources ignored by management
  - Lack of vigor in chain of command review/approval of documentation, testing modifications, performance waivers and training set stage for failure

SEASAT: Lessons Learned . . .And Not Learned:
Rick Obenschain - Acting Director of Flight Programs and Projects, NASA Goddard Space Flight Center

Report of the Seasat Failure Review Board

DECEMBER 21, 1978

Magellan Pyro Problem

- Incident
  - In 1989 Magellan commanded pyros to separate the solid rocket motor used for Venus Orbit Insertion, losing a significant amount of spacecraft memory in the process
- Cause
  - The pyros resulted in a plasma arc, creating a ground current loop, and damage to electronics
- Resolution
  - Magellan was able to operate with the remaining memory
- Lessons
  - FMEAs of pyro induced ground loops are necessary
  - Isolation of pyros onto a separate “critical bus” with dedicated ground tree is highly recommended
  - Grounding must be studied with respect to pyro firing
  - FMEA must include possible ground currents created by pyros

MER Pyro Firing/Fuse problem

- Incident
  - During rework/destack, pyro firings blew chassis-to-return fuses due to chassis currents
- Cause
  - Project decision to stick with fuse protection
  - Use of fuses in chassis-to-return location
  - Propensity for NISIs (squibs) to produce plasma current into the chassis
- Resolution
  - Crash program of spacecraft testing and analysis
  - Launched Spirit with blown fuses, Opportunity with fuses intact
  - Opportunity and Spirit both landed, with blown fuses
- Lessons
  - Avoid fuses in the future if possible
  - Look carefully at grounding scheme and pyros
  - Design systems tolerant to ground bounce induced by pyros

Magellan Current Shunt

- Problem
  - Voltage drop anomaly noted during system thermovac test
  - Darkening of Soluthane near current shunt observed
- Cause
  - Mechanical connection to current shunt used
  - Thermal cycling resulted in reduced compression of nut and lugged terminal and higher impedance
- Resolution
  - Rework of flight hardware required
  - Resulted in decabling MGN Battery At KSC & Battery Fire
- Lessons
  - Avoid using mechanical fasteners as power connections
  - Avoid subsystems designs that cannot be reworked

Cassini SSPS Toggles

- Incident
  - Solid-State Power Switches change state autonomously during mission
- Cause
  - Single Event Effects (SEE) due to heavy particles striking voltage comparators in SSPS
- Resolution
  - Not a problem in flight due to fault protection software and presence of status info on every SSPS state
  - Use robust designs for circuits using voltage comparators, e.g. Majority voted, triple redundant
  - Perform analysis for SEE effects on circuits where sensitive parts are used, especially non-robust designs
  - Component level testing of critical components

TOPEX Opto-couplers

- Incident
  - TOPEX spacecraft was left without attitude control after a long and fruitful mission
- Cause
  - Isolated prop drive circuits used opto-couplers thought to be rad-hard, used in many other circuits too, such as reaction wheels, etc.
  - Radiation effects: displacement damage from protons reduced current transfer ratio of opto-couplers
- Resolution
  - Jason-1 and Jason-II taking over operational duties
- Lessons
  - Robust circuit design taking into account displacement damage
  - Use hardened opto-couplers

COTS DC-DC Converter Issues

- Mars Pathfinder – quality and delivery schedule
- Jason - test failures, delays, scrap, rework
- DS1
  - Performance issues, replacements prelaunch
  - Star-tracker failure in flight (non-space part)
- SIRTF & Genesis
  - Using non space-rated supplies.
  - Converter life test failure due to poor quality capacitor
  - Combination of rework and replacement
- MER Rovers
  - Rebuild of every converter performed at great cost
- Other programs with reliability issues
  - MLS, Quickscat/Seawinds, SRTM, Stardust, MVACS

GRACE DC-DC Converter

- Incident
  - COTS DC-DC converter failure in instrument
- Causes
  - Instrument designer wanted ultra-stable voltages
  - Used two DC-DC converters in series
  - Did not meet stability criteria:
  - Mismatch in output / input impedance
    - Note that DC-DC converters have negative input impedance
  - Oscillation of converters resulted in failure of second unit
- Resolution
  - 50% of GRACE instrument disabled
- Also see HST Lessons Relearned

MRO HEPS Failure

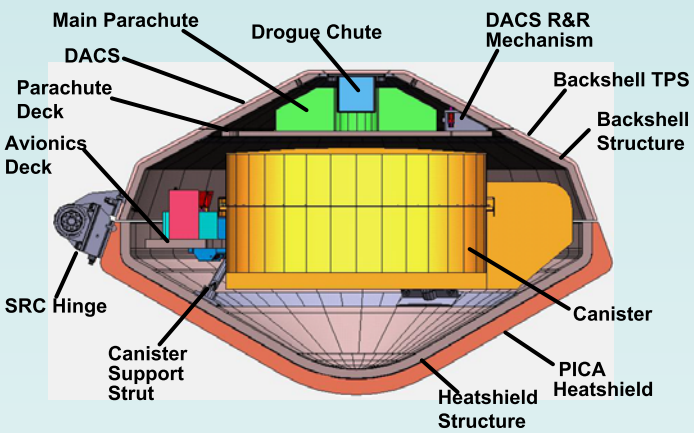
- Incident
  - High efficiency Power Supply failed
  - HEPS is a custom power supply for +5 volts / +12 volts
  - Loss of power to portion of hi-res camera pixel array
- Causes
  - Old design, unit on shelf, selected for cost containment
  - Design review found issue with radiation tolerance of parts
  - Opportunity to redesign out failures declined during development
  - Single-point-failure found in failure investigation
    - Heat sinking of A and B side FETs on single plate
    - Single-event Gate Rupture (SEGR) would take out both sides
    - SEGR induced short of A causes over-temp of B side FET
- Resolution
  - Faster, Better, Cheaper, Isn't
  - Always question statement, "This hardware is wonderful!"
  - Poor custom designs not more reliable than COTS designs

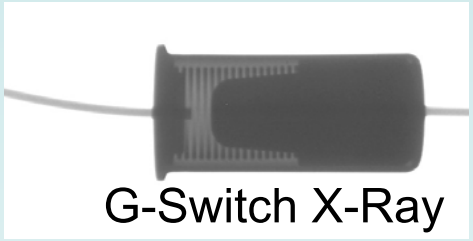
Viking Lightning Strike

- Incident
  - While on the launch pad, a Viking Spacecraft experienced an anomalous power turn-on while the spacecraft was unattended.
  - This resulted in totally discharging the spacecraft batteries.
- Cause
  - The most probable cause from local lightning
  - Spacecraft powered "ON“ via motorized switch which connects the spacecraft batteries to the bus
  - The induced lightning current caused a relay in the support equipment to connect and initiate the spacecraft power turn-on.
- Resolution
  - The Viking Spacecraft batteries had to be replaced at great expense
- Lessons
  - FMEAs of GSE are required to prevent damage to flight hardware
  - Lightning suppression of all umbilical lines must be included for each spacecraft to provide protection from direct strikes

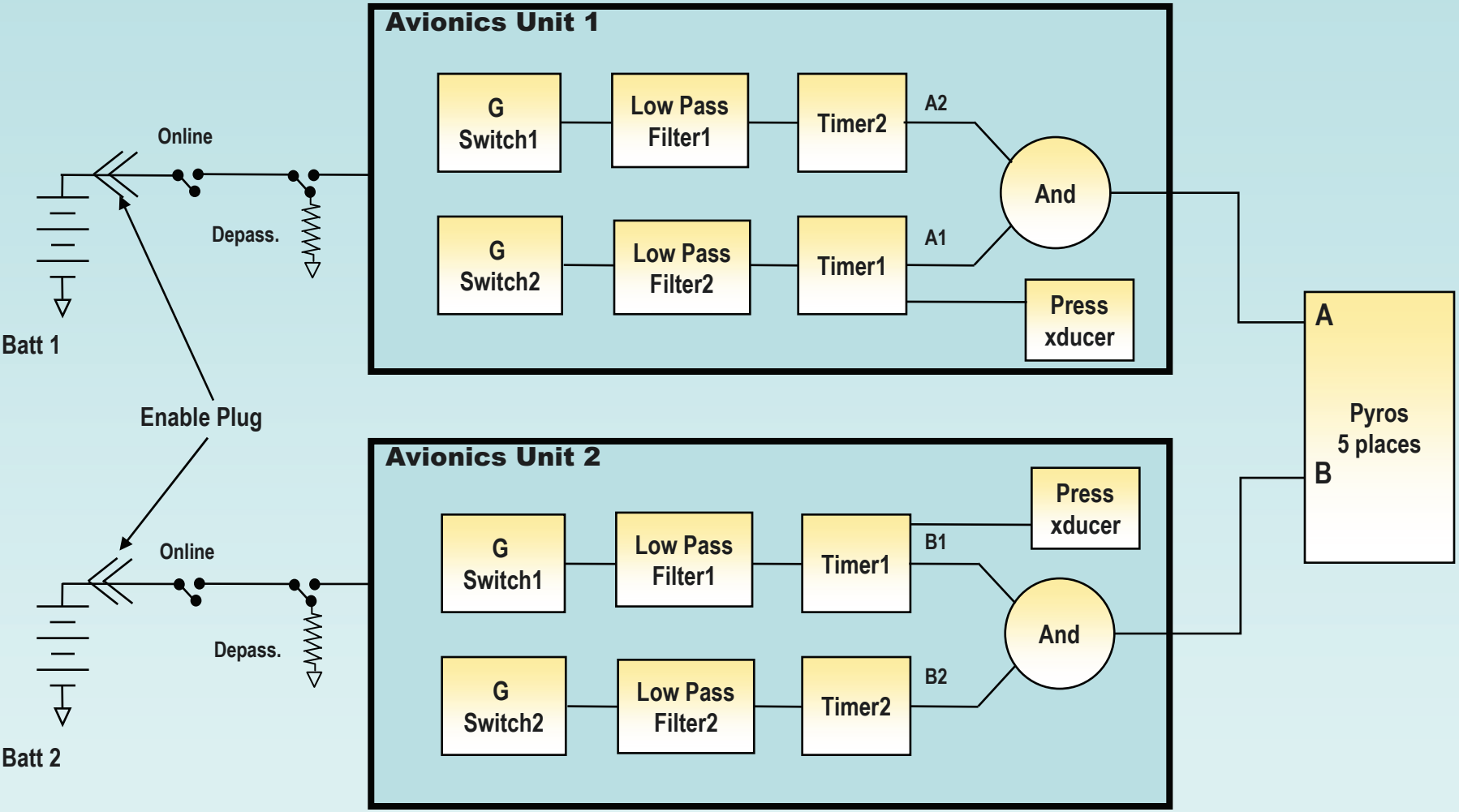
Genesis G-Switch

- Genesis return capsule failed to fire drogue chute pyro during earth return and augured in ballistically at Utah test range

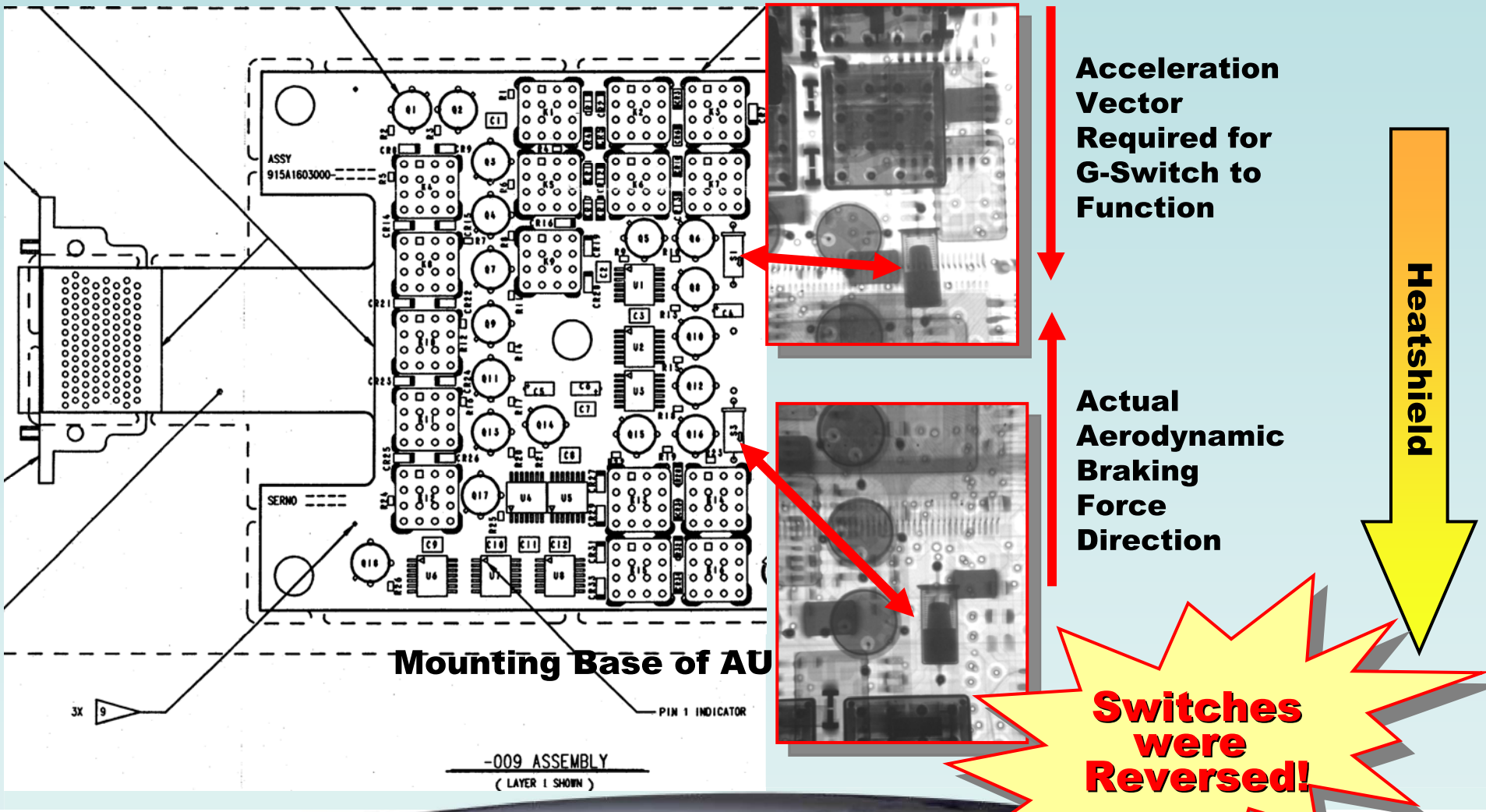




G-Switch Functional Block Diagram



G-Switch Orientation



Genesis Chain of Events

- Schematic copied from Stardust
- Box CDR lacked technical content
- Verification requirements not clear
  - Centrifuge test expected (in CDR package), but not required. Verification matrix had test, but no detail
  - Systems Engineering did not have to sign off on Subsystem plans
- Designer verified **function** (open/close) of switches
- Systems Engineering believed **orientation** of switches were verified
- Electrical designer incorrectly performed orientation verification via Mechanical drawing inspection
- Red Team review assumed design was correct because it was a "heritage" design
- Systems Engineering did not close the loop with the designer
- Systems Engineering not required to review test result

Breakdown

- Heritage
- Design Review Weakness
- Systems Engineering Breakdown; Heritage
- Systems Engineering Breakdown
- Systems Engineering Breakdown; Heritage
- Design Review Weakness; Heritage
- Systems Engineering Breakdown

Genesis

- Lessons learned
  - Strengthen execution of systems engineering team
  - Improve the design review process
  - Treat heritage hardware like a new design
  - Redundant systems do not insure reliability

Genesis Mishap Investigation and Stardust Entry,
by Dr. Mike “Riskyswitch”
Ryschkewitsch and Pete Spidaliere,
GSFC NASA
http://klabs.org/reports.htm#genesis

JPL Corona Events in Space

- Ranger 6:
  - During launch the camera was inadvertently powered. In addition a nearby enclosure was insufficiently vented for boost pressure decay. As the spacecraft passed the critical pressure region, a corona discharge occurred, disabling the camera system. The result was a complete loss of imaging data.
- Viking 2
  - Lander's downlink failed while on the surface of Mars. This suggested that the high voltage power converter developed a corona discharge while in the critical CO_2 pressure region present near the surface of Mars.

Solar Array Failures (1 of 2)

Date	Spacecraft	Failure Description
9-Nov-08	NigComSat 1	Second solar array fails; total loss
1-Aug-08	various	SES announces solar array problems with LM-A2100 satellites
6/1/2007	EchoStar V	Eighth solar array strip lost
2/1/2007	Beidou 1D (2A)	Fails to deploy solar arrays, problem resolved in Apr 2007
11/7/2006	Sinosat 2	IOT: Solar array/antenna deployment fails, total loss
10/3/2006	Hotbird 3	Substantial damage to a solar array and partial power loss
1/1/2004	Telstar 14	Estrela do Sul IOT: North solar array deployed only partially
8/1/2002	Echostar VI	Three solar array strings lost since 2001
7/1/2002	Echostar V	Two solar array strings lost since 2001
12/7/2001	Arabsat 3A	Short circuit in solar array drive mechanism

Solar Arrays (2 of 2)

10/23/2001	Echostar VI	Loss of two solar array strings (of a total of 112) announced
9/3/2001	Thuraya	Boeing announces power degradation on 702 model solar arrays
9/2/2001	XM2	Boeing announces power degradation on 702 model solar arrays
9/1/2001	XM1	Boeing announces power degradation on 702 model solar arrays
3/1/2001	Sirius	'Minor problem' with solar arrays
9/1/1998	Sirius 2	Loss of some solar cells
5/19/1998	Echostar IV	One of two solar panels did not deploy
8/30/1997	PAS 6	Circuit failures in solar arrays, DC power loss
6/30/1997	Midori [I]	Total loss: breakdown of a soldered part at the base of panel
3/18/1997	Intelsat 801	IOT: Faulty ground command --> bent solar array
3/26/1996	Anik E1	South solar panel failed

Battery Failures

10/1/2007	Landsat 5	Diminished battery capacity after cell failure
11/2/2006	MGS	Battery failure caused by faulty data upload, total loss
1/25/2005	AO-40	Catastrophic failure of main battery pack
2/23/2002	BeppoSAX	Failure of four battery cells, mission had to be terminated
12/15/1998	HGS-1	Partial loss of ability to recharge batteries, battery cell failure
11/21/1998	Palapa C1	Partial loss of ability to recharge batteries, battery cell failure
6/1/1998	PAS-5	Partial loss of ability to recharge batteries
2/1/1998	Galaxy VIII-I	Battery cell failure, partial loss of eclipse protection
2/13/1996	Palapa C1	IOT: Battery charger partial failure

Other Power Failures (1 of 2)

7/11998	Echostar III	Overheated power converters; several transponders lost
14-Jul-08	EchoStar 2	Power system failure, total loss
29-Jun-08	Galaxy 26	Partial failure of power system, half of capacity lost
6/17/2008	Eutelsat W5	Reduced capacity after power system anomaly
28-Jan-08	Eutelsat W2M	IOT: Major anomaly of power subsystem, likely total loss
3/19/2007	New Horizons	Temporary safe mode after memory error, recovered
3/14/2007	Hotbird 2	Anomaly in power sub-system
3/6/2007	Universitetsky	Stops transmitting for unknown reason
10/1/2006	Thaicom 3	Put in graveyard orbit after power problems; total loss
5/29/2006	COMPASS 2	IOT: Low voltage, various malfunctions
12/1/2005	IMAGE	Power supply subsystems fail, total loss
10/27/2005	SSETI Express	Shutdown following undervoltage - design flaw
4/19/2005	Garuda 1	Power level restored to 95 percent
4/5/2005	Garuda 1	Almost complete loss of power, unknown reason

Other Power Failures (2 of 2)

1/14/2005	IS-804	Electrical anomaly, total loss
11/28/2004	IA-7	Power failure, considered total loss
4/1/2004	PAS-6	Another power anomaly, total loss
3/17/2004	PAS-6	Power anomaly, moved to storage orbit
10/24/2003	ADEOS II	Power supply problem, contact lost, total loss
9/19/2003	Telstar 4	Short circuit of its primary power bus, total loss
6/1/2003	Mars Express	Faulty connection decreases available power by 30 percent
2/20/2003	Nimiq 2	Malfunction affects available power, some transponders off
9/6/2001	PAS-7	Sudden loss of 25 percent of power, to be declared "Constructive Total Loss"
9/1/1998	Galaxy VIII-I	Partial loss of ability to recharge batteries
4/1/1998	Cakrawarta 1	Failure of power regulator, loss of 20% energy during eclipses
10/4/1997	Insat 2D	Short circuit, loss of power, total loss

Bibliography

1. http://www.sat-index.co.uk/failures/ **Satellite Failure Reports**
2. http://klabs.org/reports.htm **NASA Failure Investigation Rpts**
3. **NASA Lessons Learned Database - llis.nasa.gov**