Necessity of Testing for Affordable Survivable Spacecraft

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Integrity ★ Service ★ Excellence

Abstract

- **All spacecraft charging standards require testing before solar arrays and spacecraft can be qualified**
- **Many programs still allow “qualification by similarity” or “qualification by analysis”**
- **This is contrary to the age-old reliability mantra, “Test like you are going to fly and fly what you have tested.”**
- **Lack of pre-flight testing leads to arcing from spacecraft charging and is to be avoided.**
- **Examples are given of spacecraft designs that led to expensive failures for lack of pre-flight testing**
- **Flow chart for affordable, survivable spacecraft development**
- **Proper method of technology transfer**
- **Guidelines for when design or production-process changes require retesting**
- **It is more cost-effective to test than to fly without testing**
- **Fly reliable spacecraft by performing pre-flight testing with flight-like hardware!**

Standards

- Spacecraft Design and Testing Standards that call out the necessity of testing for spacecraft charging and arcing before systems can be qualified for use in the space environment include:
    1. ECSS-E-ST-20-06C
    2. NASA-HDBK-4002A
    3. NASA-HDBK-4006
    4. NASA-STD-4005
    5. NASA TP-2361
    6. ANSI/AIAA Standard S-115
    7. JAXA JERG-2-211A
    8. ISO 11221

- Despite this, many programs still allow “qualification by similarity” or “qualification by analysis
- These practices are contrary to the age-old reliability mantra, “Test like you are going to fly and fly what you have tested.”

Example 1

- 1997, Company A launched two communications satellites into GEO orbit
- The first encountered unexplained power loss after a few weeks in orbit
- Power lost on one or two solar array strings at a time, with no recovery
- Decision made to launch the next satellite with modified solar array diodes, without testing. It too started to fail in similar ways to the first
- Ground testing at NASA Glenn Research Center proved that sustained arcing was to blame
- The changes made that should have been tested before flight –
  - solar cell spacing was tightened and
  - solar array string voltage was increased from 28 V to 100 V
- Corrective actions on newer spacecraft –
  - revised string layout,
  - grouting of solar arrays,
  - extra diodes emplaced to prevent interstring communication during an arc
- Total power lost 30-50%
- Amount of insured loss (including launch costs) estimated by authors at $460 M

Example 2

- In 1999, Company B placed a new series of communications satellites into service
- While a new concentrating design was supposed to increase power by a factor of two, cumulative power loss began immediately and continued rapidly
- The design had been extensively modelled and shown to have little or no spacecraft charging, but had not been tested under flight-like conditions
- The culprit this time was outgassing from the heated solar arrays contaminating the flexible concentrator mirrors
- While not a spacecraft arcing issue, flight-like testing was bypassed
- Corrective actions on newer spacecraft –
  - ditching the concentrators, and
  - accepting a 50% power loss
- Amount of insured loss (including launch costs) estimated by authors at $500 M

Example 4

- **Company C had advertised that its satellites were immune to space environment issues because all sensitive electronics were enclosed in a Faraday cage**
- **After four years on-orbit, one of its satellites stopped accepting commands, but did not turn off its attitude control or retransmit capability**
- **It was free to wander around the GEO belt, possibly interfering with transmissions from other satellites**
- **After 8 months adrift, its momentum wheels saturated, and the loss of attitude control brought its power down to system reboot levels, whereupon it recovered full operation far from its intended orbital allocation**
- **Ground tests and analysis showed that a metallic grommet intended to ground a thermal blanket was not properly contacting the multi-layer insulation conductors, and the resulting surface arc during a geomagnetic substorm was propagated into the Faraday cage, causing a bit flip that turned command and control off**
- **Upset happened ½ hour after leaving eclipse, under the highest electron temperatures ever recorded**
- **In this case, the testing that was omitted was testing of the grounds of all grommets (acceptance testing) before flight**
- **False command happened in a part not tested under arc-like transients**
- **Corrective actions taken in future spacecraft were –**
  - **replacement of the sensitive part, and**
  - **institution of a rigorous acceptance testing procedure**
- **Amount of revenue loss estimated by authors at $230 M**

Example 5

- Three years later, Company C began again having problems on some of its spacecraft
- This time it was housekeeping and payload telemetry multiplexers that were failing, with no recovery
- Initial failure led to a modification on the earth-sensor harness, but gave no prevention of further failures
- Three different mitigation strategies were used singly and in combination for subsequent spacecraft, including using redundant multiplexers, but failures did not stop
- A correlation between the 72 hour fluence of 2 MeV electrons and times of the failures highly implicated deep-dielectric discharges, and inspection of the spacecraft design showed that many highly sensitive electronics (although inside the “Faraday” cage) were essentially unshielded from penetrating electrons
- The design flaw was insufficient shielding
- The testing error was not using parts that had passed deep dielectric charging tests done for the community by NASA
- Tests that had been performed by Company C injected charge onto conductors, an unrealistic test for deep-dielectric charging
- The amount of insured loss cannot be estimated, as the failures continue
- Company C is lucky that a loss of commercial transmission or of command and control has not yet occurred

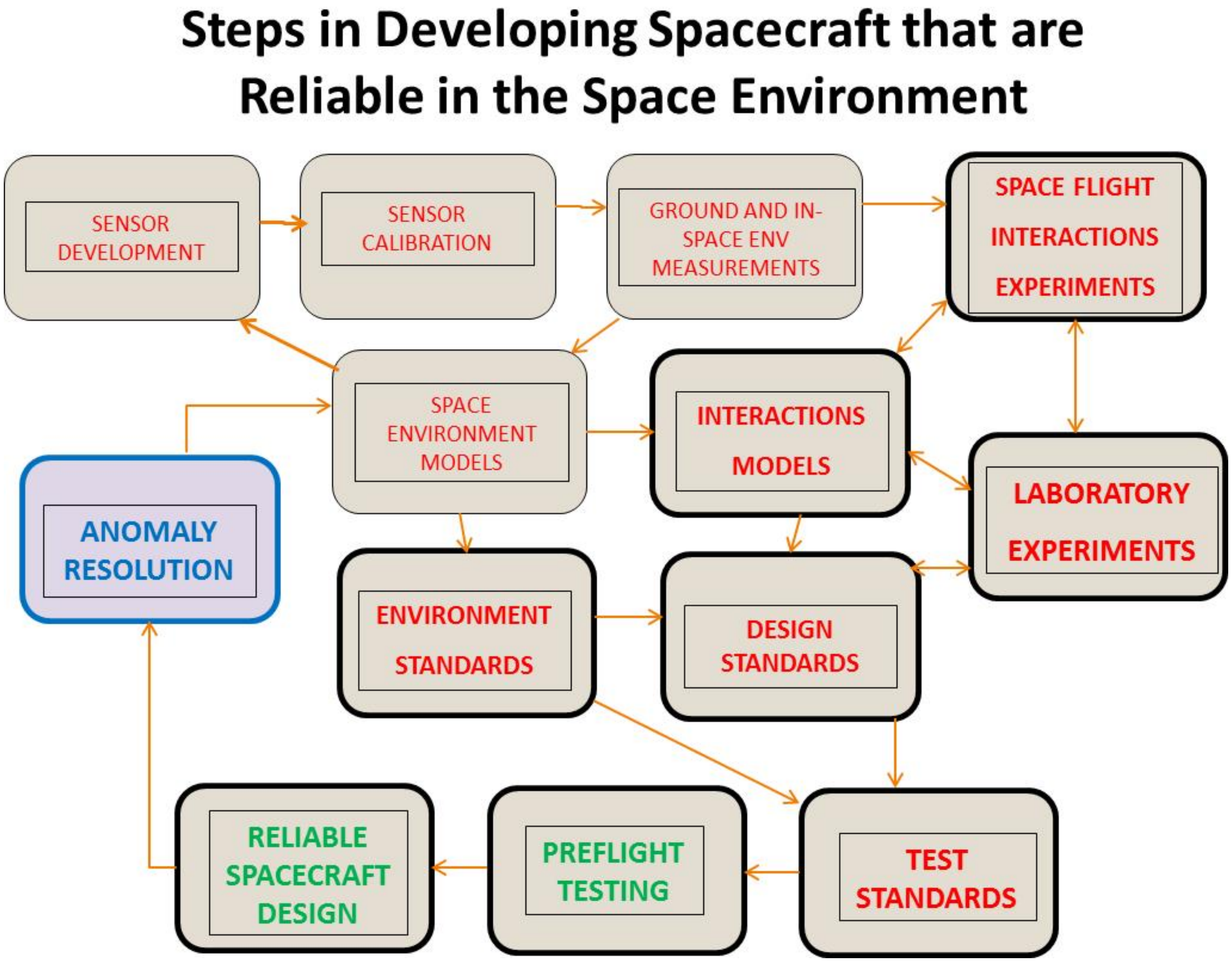
Example 6

- Government Agency D had built an interplanetary spacecraft with 400 V arrays
- Although the design of the solar arrays themselves had been analysed and approved by a spacecraft arcing expert, bare wiring was used on the power harness, with a 400 V difference between adjacent traces only a few mm apart
- Similar configurations had been previously tested in another government lab and shown to undergo sustained arcing under simulated space conditions, but these warnings went unheeded
- Finally, after the sustained arcing failure of Company A above, the power harness design was shown to several spacecraft arcing experts, who unanimously recommended that the power harnesses be modified to prevent sustained arcing
- One of the 2 arrays was already installed on the spacecraft, but it was removed shortly before launch, the power traces on the arrays were covered with Kapton tape, and they were reinstalled
- Launch and mission went off without a hitch
- Here, corrective action based on previous tests saved the day

Example 7

- International Space Station (ISS)
- Based on analyses and tests performed before flight, it was expected to charge due to its high voltage (160 V) solar arrays to about 140 V negative of the surrounding plasma
- ISS anodized aluminium structure could not stand off this voltage, and the astronauts' space suits could not stand off even 70 V
  - Controlling ISS potentials would not only preserve the thermal properties of the structure, but
  - Might even save an astronaut's life
- A crash program was put in place to equip ISS with a plasma contactor (PCU) to control its potentials and a plasma measuring device (FPP) to measure its charging and monitor its environment. These were put in place on ISS when the first solar array panel was launched
- It later turned out that the Russian segment had much more ion collecting area than was in the plan (and test results and designs had not been shared), so ISS has never charged up to the expected potentials
- However, it still charges up to -90 V maximum, and the plasma contactor is still being used (to our knowledge) when extravehicular activity is in progress
- Here, the problem was not in a lack of testing, but in communication of the designs and test results

Flowchart for Reliable Designs



Steps in Developing Spacecraft that are Reliable in the Space Environment

Guidelines for When Testing is Necessary

- Major factors in spacecraft differential surface charging and arcing are:
  - geometry near triple points (the junction of the space plasma, a conductor and an insulator),
  - solar array string voltage and string layout,
  - separation between adjacent cells that are at > 50 V with respect to one another,
  - coverglass material and coatings,
  - grounding schemes,
  - uncoated insulators, and
  - arc mitigation strategies
- Major factors in deep-dielectric charging and arcing are:
  - use of Teflon and fiberglass (always bad actors),
  - total areal mass of shielding,
  - interior temperature range (insulators are better at storing charge at low temperatures),
  - areas of ungrounded conductors, etc.
- When any of these factors are changed, requalification testing is necessary
- Don't forget acceptance testing (sometimes called workmanship testing). No design can prevent failures if the workmanship is lacking
- Finally, if any new design feature is not in compliance with established spacecraft charging standards, testing should be mandatory!

A Success Story

- A further example is in order here
- Company E was worried because the design of their main antennas could not comply with NASA TP-2361
- A proprietary meeting of many government experts was called to discuss what strategy should be used going forward
- The expert consensus was that the design could be used if proper spacecraft charging qualification testing was performed before use
- No problems were found in testing, and the design was implemented without failures on-orbit

THE TRADEOFF – COST OF TESTING VS RISK OF FAILURE

- Commercial and government laboratories can test materials and components for spacecraft manufacturers
- Assuming $30 k per week of testing, one month of qualification testing should be about $120 k, and would be sufficient for many design changes
- Taking the satellite and launch costs to be worth about $350 M, the probability of failure would have to be less than one in 3000 to justify not doing the testing
- Even the most optimistic manufacturer would not take those odds
- Yet, insufficient testing leads to several spacecraft anomalies per year leading to permanent degradation of performance or loss of some mission capability
- A word about testing:
  - Test facilities experts are equipped to guide the spacecraft or component manufacturer step by step through the testing necessary to achieve his/her goals
  - Many times, consultation with the experts is free, and companies and governments can protect proprietary designs and procedures through non-disclosure agreements (NDAs)
  - There is no excuse for ignoring the necessary testing!

THE NEED FOR TESTING FLIGHTLIKE HARDWARE

- Hardware to be tested should always be as flightlike as possible
- If Kapton wiring is used in the flight article, it should be used in the test article
- Solar array test articles should have sufficient cells that all geometrical configurations between cells are represented, and tests should be performed with the same string voltages and grounding schemes as the real flight article
- If the flight substrate is Kapton, it should also be for the test article
- The most severe expected environments should be simulated
- Ground testing of flight hardware is not science, where general principles are tested
  - The object is to see if a specific design and construction will survive in the space environment
- A good example for ground testing is the program at JPL, where spacecraft testing is rigorous
  - A famous JPL scientist once proudly proclaimed, “Our spacecraft do not arc!”
  - While that sentiment is optimistic, a good track record (the result of testing) is not only something to be proud of, but an advertising edge in the competitive space market

Conclusions

- **“Qualification by similarity” and/or “qualification by analysis” are not qualification!**
- **Nature does not care how similar you think your design is to previous designs or how much you trust your analysis**
- **If you want to know how something will work in the space environment, test it in a realistic space environment**
- **You will save money (and perhaps your reputation) by doing so**

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