NECESSITY OF TESTING FOR AFFORDABLE SURVIVABLE SPACECRAFT

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ABSTRACT

Despite the fact that all national and international spacecraft charging standards require testing before solar arrays and spacecraft can be qualified in the space environment, 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."

Lack of pre-flight testing is shown here to lead to spacecraft failures due to arcing from spacecraft charging and is to be avoided. Numerous examples are given of spacecraft designs that were deficient and led to expensive failures because pre-flight testing was not done. A flow chart for affordable, survivable spacecraft development is given, and a proper method of technology transfer is emphasized. Guidelines are presented to allow determination of when design or production-process changes may be sufficient to require retesting. It is shown that it is more cost-effective to test than to fly without testing. Finally, we appeal to spacecraft developers and manufacturers to fly reliable spacecraft by performing pre-flight testing with flight-like hardware.

1. 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 ECSS-E-ST-20-06C [1], NASA-HDBK-4002A [2], NASA-HDBK-4006 [3], NASA-STD-4005 [4], NASA TP-2361 [5], JAXA JERG-2-211A [6], ISO 11221 [7], and ANSI/AAA S-115. 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." [9]

Reasons for ignoring this mantra are many: schedule deadlines, overreliance on computer modelling, complacency, costs of testing, similarity of new systems to older flight-qualified systems, etc. Such attitudes are recipes for disaster. Project managers have even been heard to say, "I can't test this. It might fail, and then I'd never meet my schedule." What is more important, the schedule, or mission success? Lack of testing makes your satellite into a test on orbit, from which you cannot recover.

2. EXAMPLES

In order to prevent embarrassment, the company names will be disguised. All dollar losses are estimates by the authors.

In 1997, Company A launched two communications satellites into GEO orbit. The first encountered unexplained power loss after only a few weeks in orbit. Power seemed to be lost on one or two solar array strings at a time, with no recovery. A decision was 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 the NASA Glenn Research Center proved conclusively that sustained arcing was the culprit. The changes made that should have been tested before flight – solar cell spacing was tightened and the 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 at $460 M.

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 at $500 M.

Company C had advertised that its satellites were immune to space environment issues because all sensitive electronics were enclosed in a Faraday cage. However, after four years on-orbit, one of its satellites stopped accepting commands, but did not turn off its attitude control or retransmit capability. This meant 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. The 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. Also, the false command happened in a part that had not been tested under arc-like transients. Corrective actions taken were replacement of the sensitive part and institution of a rigorous acceptance testing procedure. Amount of revenue loss is estimated at $230 M.

Three years later, Company C began having problems on some of its spacecraft once again. This time it was housekeeping and payload telemetry multiplexers that were failing, with no recovery. An initial failure led to a modification on the earth-sensor harness, with however no prevention of further failures. Some 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. The 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.

Government Agency D had built an interplanetary spacecraft with high voltage (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 arrays was already installed on the spacecraft, but it was removed shortly before launch, and the power traces on the two arrays were covered with Kapton tape, and they were reinstalled. The launch and mission went off without a hitch. Here, corrective action based on previous tests saved the day.

Finally, we cannot close this section without mentioning the International Space Station (ISS). Based on analyses and tests performed before flight [9], it was expected to charge due to its high voltage (160 V) solar arrays to about 140 V negative of the surrounding plasma. Since the ISS anodized aluminium structure could not stand off this type of voltage, and the astronauts' space suits could not stand off even a fraction of this, 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. In fact, these were put in place on ISS when the first solar array panel was launched. As it later turned out, because the Russian segment had much more ion collecting area than was in the plan (and test results and designs had not been shared), ISS has never charged up to the expected potentials [10]. However, it still charges up to potentials dangerous to the astronauts (estimated 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. Incidentally, there is good evidence that the high voltage arrays have undergone sustained arcing due to micrometeoroid impact, but power loss has not been extensive.

3. A FLOWCHART FOR AFFORDABLE, SURVIVABLE SPACECRAFT

Figure 1 shows a flowchart for making sure your spacecraft survives the natural environment. Technology transfer should be assured by not accepting a contract without specifying compliance with all relevant standards. Standards are written from hard-won experience and to ignore them is to fly at your own peril. Every engineer must know all aspects of the space environment through which his spacecraft will fly and mitigation techniques to prevent failures. No single aspect of the standards or the space environment can be safely ignored. Even if it appears that your satellite survived launch and is working, cumulative effects and worst-case environments are still in store.

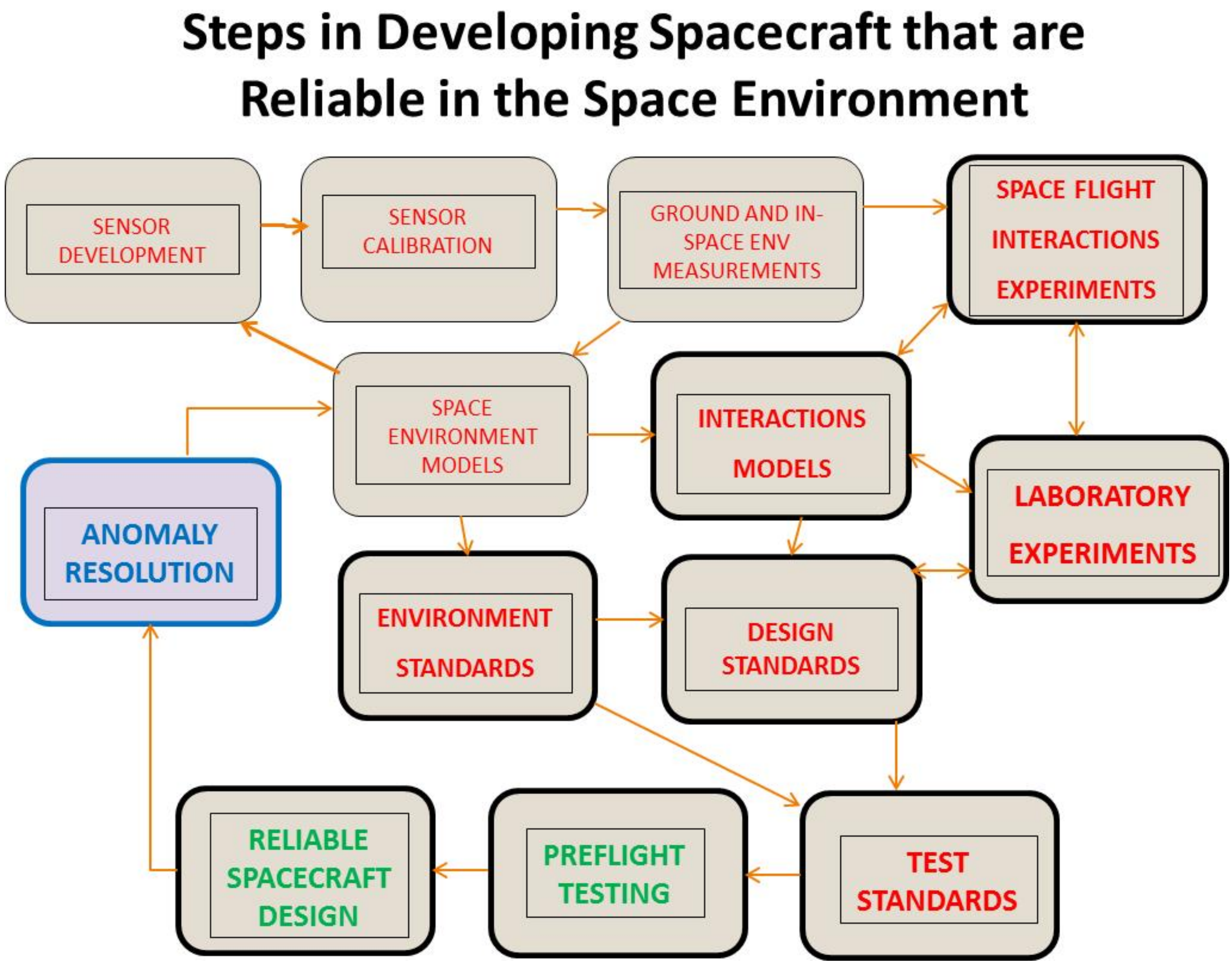

Fig. 1. A flowchart for building and flying reliable, affordable spacecraft.

4. GUIDELINES

Major factors in spacecraft differential surface charging and arcing are: the geometry near triple points (the junction of the space plasma, a conductor and an insulator), the solar array string voltage and string layout, the separation between adjacent cells that are at > 50 V with respect to one another, the coverglass material and coatings, grounding schemes, uncoated insulators, and any arc mitigation strategies. Major factors in deep-dielectric charging and arcing are: the use of Teflon and fiberglass (always bad actors), the total areal mass of shielding, the interior temperature range (insulators are better at storing charge at low temperatures), areas of ungrounded conductors, etc. Whenever any of these factors are changed, requalification testing is in order. And, don't forget acceptance testing (sometimes called workmanship testing). It goes without saying that 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 further example is in order here. Company E was worried because the design of their main antennas could not comply with NASA TP-2361 [5]. 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.

5. THE TRADEOFF – COST OF TESTING VS RISK OF FAILURE

Commercial and government laboratories exist that 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.

6. 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 perhaps somewhat 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.

7. CONCLUSION

'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.

8. REFERENCES

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