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Design Considerations for Space Flight Hardware

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SUMMARY

This paper presents a review of the environmental and design constraints along with some insight into the established design and quality assurance practices that apply to Low Earth Orbit (LEO) space flight hardware. It is intended as an introduction for people unfamiliar with space flight considerations. Some basic data and a bibliography are included. Figures from the literature are provided as examples of information that is available.

INTRODUCTION

This paper presents the basic design constraints that pertain to space flight hardware. It includes guidelines applicable to the development of payloads for expendable launch vehicles (ELVs) and the space shuttle payloads. This information is familiar to all space engineers, but the need exists for a primer for those new to the field. The reader is cautioned that much of this paper reflects the author's convictions. The prospective space engineer is encouraged to become more familiar with the literature to form his own opinions on the subject.

There are many aspects of the established design procedure for space flight hardware that at first glance appear unduly Byzantine; however, this approach has developed over the years to meet the challenges of space flight and has proved to be very successful. (See fig. 1.) Designing hardware for space use has unique problems that must be carefully addressed, and common design practices have evolved to ensure success. Recently, many small shuttle payload engineers have relearned the lessons of space flight hardware design from hard experience. (See Ridenoure, 1987.) The obstacles listed in this paper may be avoided by the discerning and prepared space engineer.

The most obvious difference between other hardware designs and space flight hardware designs is the effect of the space environment (vacuum, low gravity, radiation, etc.) on hardware. A second class of equally difficult challenges is presented by the limitations imposed by the launch vehicle. It currently costs thousands of dollars per pound to put a payload in orbit, so designing for minimum weight is critical. Other constraints, such as volume and power, arise directly and indirectly from the launch vehicle. The third general constraint, which is responsible for much of the intricacies of the space flight design process, is reliability. There is little or no opportunity for servicing space hardware in the event of a failure. This means the hardware must be designed and tested so that it either will not fail or will tolerate likely failures. The costs of reliability coupled with the cost of launch are what make space flight hardware so expensive. An automobile can be used as an example of the importance of reliability. If one bought a new car and then had to discard it at the first failure, such as a clogged filter, fouled spark plug, or flat tire, the economics of car ownership would not be very attractive (especially if coupled with gasoline costs of $100 per gallon). In space, the luxury of readily available and affordable servicing does not currently exist.

ENVIRONMENTAL CONSTRAINTS

Environmental effects are usually grouped into the following categories: (1) ground and prelaunch, (2) launch and ascent, and (3) space. For returning spacecraft, a fourth category of reentry must also be considered, but this last category will not be addressed in this paper.

Ground and Prelaunch Environments

Before jumping to the difficulties of the space environment, it is important to remember the more mundane environments that the hardware will see before launch. These include ground handling and storage environments, transportation environments, and launch site environments. Some specific considerations include the following: (1) electrostatic discharge due to handling; (2) shock (e.g., impact due to dropping), vibration, temperature range, atmospheric pressure drop, and humidity due to transportation; and (3) effects of the launch environment such as salt spray, moisture, temperature, sand and dust, fungus and mold growth, and lightning. If the effects of these environments are ignored, the design may never have the opportunity to prove itself in space.

The above conditions are most likely experienced by nonoperating hardware. Operating conditions on the ground must also be considered. For example, if the hardware has the potential for operating in an explosive atmosphere (e.g., due to a leak in a tank in a nearby system), safety considerations may require that the design be explosion proof. Verifying an explosion proof design can add significant expense to development costs.

Electrostatic discharge (ESD) refers to the possibility of damage to electronic devices due to a discharge of static electricity. This effect is not limited to space flight designs, as ESD susceptible parts (such as Complementary Metal Oxide Semiconductor technology, or CMOS, which is attractive for its low power consumption) are now commonly used in industry. (See table I.) All low level or signal level parts should be handled with care and the possibility of hidden damage should not be overlooked.

Launch and Ascent Environment

The launch environment varies with the launch vehicle. All launch vehicles impose acceleration on payloads (on the order of 5 or 6 g for an unmanned launch vehicle and about 3.5 g for the space shuttle). Considerable vibration is also present. For design, analysis, and testing purposes this vibration is typically split into the following three components for design, analysis, and testing purposes: (1) quasi-static or sine, (2) random, and (3) acoustic. Vibration environments are typically specified by spectral density. (See fig. 2.) The vibration that a piece of hardware will experience depends on where and how the hardware is mounted. Acoustic environments translate into vibration as sound pressure variations excite the structure. Acoustic vibrations vary depending on the shape of the hardware and material used. Shock due to pyrotechnic devices (such as for spacecraft separation) is also a consideration.

On ascent there is some temperature rise due to aerodynamic heating and, of course, a pressure drop. The pressure profile is important for vented enclosures and especially for operating electronics. The Paschen Law relates sparking potential to pressure. The possibility for arcing in electronics of even moderately high voltage occurs at low pressures encountered at some point on the ascent pressure profile. This is only one of the reasons for encapsulating electronics with an insulating material (known as conformal coating). Sealed enclosures are possible, but they become pressure vessels in vacuum, and maintaining the integrity of the seal is a challenge. A leaking sealed enclosure will eventually evacuate and could implode if returned to a pressurized environment.

Space Environment

The vacuum of space turns out to be a substantial factor in space hardware design. Although vestiges of the atmosphere cause significant aerodynamic drag over time in LEO, the vacuum in LEO is better than in vacuum chambers on Earth. The principal impacts on design are in heat transfer, material migration, and materials degradation.

The thermal environment in space presents a challenge to the thermal engineer, but to the individual hardware component manifests itself as a radiation and conduction problem with a fairly wide temperature range. (See fig. 3.) It is interesting to note that a spherically shaped gray body in orbit will have an average temperature of around 20 to 40 °C. However, temperatures reached by sun-facing or deep-space-facing surfaces will differ by a large amount and wide variations can take place as components move in and out of sunlight. Many thermal cycles will be experienced as most spacecraft go into eclipse once every orbit. Components on the fringe of the spacecraft (e.g., solar arrays) can experience extremely large temperature fluctuations. Low power dissipation electronic components are preferred because heat rejection capability is limited by the radiator size. A significant degree of thermal control can be achieved by the proper selection of surface coatings. (See table II.)

Without gravity there is no buoyancy-driven convection (although there may be surface-tension-driven convection), so heat transfer must be by radiation or conduction (even in sealed containers). Fans are a possible solution to provide convection in sealed containers, but they require power, represent a failure mode, and do not help if the container leaks.

With the absence of convection, most practical heat removal from a hardware component is via conduction and radiation. For electronic piece parts, conduction is the primary mode of heat removal. Design for conduction heat transfer usually entails good thermal conductivity and contact throughout the system (e.g., using large mounting areas with many bolts and even the use of thermally conductive fillers or adhesives). The area of conduction via bolted joints in vacuum could benefit from more application-oriented research. Although heat pipes or active thermal control systems are possible, reliability and integration considerations do not encourage their use.

Low-g material migration is a problem of floating and wandering bits of contamination with electrically conductive material being especially troublesome (another reason for conformal coating of electronics). Extensive cleanliness and contamination control efforts are required. Material migration in vacuum includes the problems associated with outgassing, low vapor pressure metals, contamination, and lubrication. Outgassing is the release of material such as the evaporation of volatile components or the disabsorption of entrained materials. This outgassing can cause problems if the outgassed material is deposited on optical or thermal control devices that rely on surface optical properties to work. Outgassing in a confined area could result in a pressure rise that exceeds the critical Paschen Law pressure which would result in arcing. High vapor pressure metals, such as cadmium, grow whiskers in vacuum which can cause electrical shorts (e.g., between connector pins). Choosing a lubricant requires special care in vacuum because many common lubricants become ineffective or migrate away from where they are needed and become contaminants, while the surfaces to be lubricated will then gall or cold weld.

Materials degradation arises from exposure to radiation and to atomic oxygen in LEO. The main types of radiation that can damage materials are ionizing radiation, protons, and ultraviolet radiation. Radiation effects are not as much a concern on the ground because the Earth's atmosphere provides attenuation. The Earth's trapped radiation belts are a source of proton problems especially around the South Atlantic Anomaly, which is the name of a dip in the inner-radiation belt over South America. Electronics are susceptible to a total dose of radiation that will cause total failure and are also susceptible to temporary failures called single event upsets (SEU) or "bi flips" caused by an ionizing particle passing through a particular location or a chip (like a memory cell). Unpredictable radiation bursts can come from solar flares. Atomic oxygen in low orbits will attack susceptible external surfaces and can cause thermal system degradation, so proper materials must be selected for exposed surfaces.

Spacecraft charging is an interesting effect that arises from space plas electrons charging dielectric surfaces. (Voltage differences of 10 000 V are possible in eclipse.) Subsequent discharges from these potentials can cause electronic system upsets. The harmful effects of charging can be avoided if proper design practices are followed (e.g., ensure proper grounding and bondi and provide conductive external surfaces).

One aspect of the LEO environment that is steadily getting worse and wil present severe problems in the future is the presence of orbital debris. Meteoroids and micrometeoroids are of some concern; however, with the advent of space flight, manmade debris from launch vehicles and spacecraft is becoming a major hazard. The major design impact is the need for shielding, which adds costly weight. The required shield weight depends on the acceptab probability of penetration of debris, which in turn depends on the distributi of debris particles. At present, the debris environment is not accurately characterized except that it is growing worse. There are many shielding desi equations in the literature and they differ considerably.

DESIGN CONSTRAINTS

The principal design constraint for flight hardware is weight. (Although this is properly referred to as mass, engineers tend to talk about weight and it is less confusing to stick with the argot.) There is a limit on the amount of payload weight that a launch vehicle can place in orbit. There is also a center of gravity (c.g., more properly center of mass) limitation on the payload due to launch vehicle bending moments.

These severe weight restrictions necessitate extreme measures to reduce weight. Mass properties are watched closely throughout the stages of system design and development with the maintenance of a weight budget. The weight margin, governed by the project manager, is whittled down over the course of the project's development as subsystems fail to meet their weight allocations due to underestimates or unforseen problems. This happens despite using elegant and sophisticated design practices (e.g., by using lightweight materials or chemically milling components to minimum allowable thicknesses). Factors of safety are typically pushed to their lower limits because of weight constraints. The solutions to many design problems also tend to add weight. Weight is an underlying consideration in nearly all aspects of space design.

Electrical power is a commodity that is also closely watched by project management. A power budget similar to the weight budget is kept. The limitation on power is directly connected to weight. The power subsystem tends to be very heavy due to items like batteries, and power requirements are controlled carefully to keep the power subsystem weight down. Most spacecraft obtain electrical power from solar cell arrays, which are limited in output by weight and size constraints. They only produce power in sunlight and so must be augmented by batteries to provide power in eclipse. Thermal dissipation is also a consideration in power constraints.

Volume is limited by the launch vehicle shroud. (See fig. 4.) Items such as antennas and solar arrays are launched folded-up and deployed on orbit. In the stowed configuration they are latched to prevent damage due to acceleration and vibration. Mechanisms for latch release and boom extension are major in-line reliability items for the entire spacecraft and are therefore carefully designed. Pyrotechnic devices are typically used in areas where high reliability is needed, such as separation from the launch vehicle.

A consumables budget is kept for such items as propellants. Spacecraft life is usually limited by the amount of propellant carried and ranges typically from 1 to 10 years. Even at 250 n mi altitude, there is significant atmospheric drag which causes orbit decay which shortens the life of the spacecraft or increases the need for propellants to provide thrust for drag compensation. The longer the life, the more challenging the reliability goal because of the greater time available for a failure to occur.

Because there are typically many electronic boxes in close proximity and with shared power buses, electromagnetic compatibility (EMC) is an important issue. Electromagnetic interference (EMI) is hard to design out other than using commonly accepted packaging, grounding, bonding, and shielding practices. Electrical and electronic boxes are usually tested for EMC individually to some interference limits, but frequently compatibility problems are not apparent until the whole system is tested together. EMI is usually divided into two major categories: whether the box is susceptible to EMI and whether the box causes interference. In both cases, there is a further subdivision as to whether the interference is radiated (electromagnetic waves) or conducted (e.g., noise on the power bus).

The amount of data that can be downlinked to the ground is limited, sometimes by spacecraft systems (e.g., antenna size or amplifier power) or by relay systems. As an example, the multiple access data rate of the NASA Tracking and Data Relay Satellite System can be up to 50 kilobits per second. Not all of the data capacity is necessarily available for the science payload as some of the data allocation will probably be devoted to housekeeping data. Housekeeping data is used to determine the status and health of the various subsystems, to determine failure causes, and to provide for engineering and operational needs. Uplinked commands are similarly a limited commodity and are usually closely managed along with the data requirements.

Finally, and perhaps most importantly, are considerations of safety, reliability, and quality assurance (SR&QA). Costs to launch a payload are high, costs to design and build space hardware are excessive, and costs to repair hardware in space are currently unthinkable. One cannot afford to have a failure in orbit because there is no cheap, easy way to fix hardware in orbit. The design has to be reliable and fault tolerant, and faults should not propagate. Hardware or system redundancy is one method used, but the ever-present weight constraint must be considered. All failure causes and modes have to be analyzed and their effects determined during the design stage. For these reasons, reliability winds up being a major cost driver.

Safety has to be kept in mind throughout the design process. For unmanned spacecraft, safety is a primary concern during ground operations and launch. Hazardous materials should be avoided because of the possibility that a launch failure could introduce these materials into the environment. Range safety may require destruct devices on dangerous items such as propellant tanks. Servicing of hardware on the launch pad is to be avoided. High pressure systems pose a hazard and are not usually fully loaded until personnel are finished working in the area. Ground cable and plumbing connections, known as umbilicals, are available on the launch pad to handle safety functions and ground operations.

The formal safety review process is just that, a review. The safety committee will review the design to determine if everything possible has been done to ensure a safe design, but will not generally tell how to design the system to be safe. In manned space flight (shuttle) the safety constraints are rigid and overriding. Safety becomes a major driver in system design and forces many trades to be done in other areas in order to accommodate required redundancy or fault tolerance.

DESIGN AND QUALITY ASSURANCE PRACTICES

The basic approach used to develop flight hardware is to (1) design carefully, (2) analyze and verify the system on paper, (3) test thoroughly (perhaps by building and destructively testing a qualification item or system), and (4) rigidly control the flight hardware build and test process to conform to the paper design. An incredible amount of paperwork is generated by a flight project. There is a common saying that if all the paper on a flight project were stacked up, there would be no need for a launch vehicle to get to orbit.

Once a document is established, it is placed in configuration control. Because of the interrelationships of all the parts of a complex system, it is important to document, review, and control any and all changes to the design. The formal configuration control process holds the system together.

Simplicity should be the guiding light for the design engineer. The simpler design is usually more reliable. There are so many other complicating factors that arise from design constraints and system interfaces that it is important not to introduce unnecessary complications. Pyrotechnic actuators are an example of a simple, reliable device for one-shot applications that are commonly used on spacecraft.

Because of the way a "minor" change can ripple through the system design, detailed analysis is performed throughout the design process in order to get the paper as perfect as possible. Because weight constraints dictate low safety factors, detailed static and dynamic structural analysis and modeling is performed. Fracture control, stress corrosion, and fatigue must be accounted for. Thermal analysis and modeling, stress analysis, hazard analysis, and reliability analysis are performed in detail. Usually a "reliability number", related to the probability of success, is developed for parts and then for systems (e.g., per MIL-HDBK-217); it is important to keep in mind that this number is not absolute, but is only useful in making relative comparisons.

Interfaces (e.g., for power, data commands, fluids, etc.) between the spacecraft, carrier, launch vehicle, and ground services must be carefully defined. It is usually difficult to add or modify an interface after the negotiations between the various parties have been completed and the interfaces defined. Sometimes a spacecraft will make an allocation of power, commands, data, etc., which become a design constraint for the component in question.

As with most complex and expensive system designs, there is a detailed and formal design review process. First there is a concept review at the beginning of the design process to determine what the system is to accomplish and how to go about it. It is vital to determine and document the requirements for the system as a whole, as well as for the individual components, as early as possible. There are so many other constraints that it is prohibitively expensive to figure out each step as it is reached. This may seem to be a given, but it is rare that a project starts out with adequately defined requirements.

Because of the myriad design considerations, a trade study approach is taken. The various considerations (weight, reliability, power, thermal, component availability, etc.) have to be traded off against each other. This is done with an eye to minimizing the loss or "hit" to each while optimizing the total system. Trade studies crop up continually as one or another budget gets into trouble or the solution to a problem necessitates increased weight and/or power consumption.

A Preliminary Design Review (PDR) is held to review preliminary versions of drawings, specifications, plans, analysis, design criteria, and supporting documents. The PDR provides a check that the design is going in the proper direction before starting the involved process of filling in and documenting all the details of the design. Typically the PDR includes an overall system specification, subsystem specifications (which cover large subsets of the system), and individual component specifications.

A Critical Design Review (CDR) is held to review the finished design in detail. This includes final versions of drawings, specification changes, detailed procedures for testing and operation, detailed analysis and modeling, and a truckload of supporting documentation. Everything is done on paper first. The emphasis is on getting the paper design right, testing and verifying it, and then carefully controlling the hardware throughout its life according to the design documentation.

The paper mill does not stop with the design. As the flight hardware is built and tested, documentation is generated recording every aspect of the hardware's life. All parts and materials used have a paper trail back to their origins so that bad lots can be found and excised. The trail follows them throughout their life to ensure they have been properly stored and tested and that they are not stressed. Parts and materials of unknown origin are not even allowed in the vicinity of flight hardware. All occurrences, tests, material exposures, environmental exposures, and any other relevant information about the history of a piece of hardware is recorded in a log so that any future failure can be properly analyzed and its cause determined.

To verify the design, qualification units are built exactly corresponding to the design documentation and are identical to flight units except that their purpose is to qualify the design for the environments to be experienced by the flight units. These units are tested to their limits and are even destroyed by the testing. In cases where the safety factor has been kept large enough, a protoflight approach can be used where the qualification unit is not overstressed in testing and is used for flight.

Testing includes vibration, shock, thermal-vacuum (fig. 5), EMI, operating life, proof or burst pressure, and tests for all environments and requirements in the specification. Thermal-vacuum tests subject the hardware to thermal cycles in vacuum between the specified extremes and check for outgassing; they may include a pump-down test to simulate ascent. Test results are documented in detail and analyzed. Acceptance tests to verify workmanship are performed to levels generally less than the qualification tests to avoid overstressing the units and using up their useful life, but are nearly as extensive.

A preship review is held after the hardware is built and tested to review test results, failures and problems, and changes and to determine if the hardware is ready to be shipped to the launch site. Of course, procedures for ground operations at the launch site are well documented.

PARTS, MATERIALS, AND PROCESSES

Parts, materials, and process design considerations require significant engineering effort to avoid system failures. The Government-Industry Data Exchange Program (GIDEP) provides data on failures from many projects. Publications such as GIDEP Alerts are a good source for application experience and potential problem information. Goddard Space Flight Center's "Materials TIPS" is an excellent source of information for spacecraft applications.

Some typical materials problems include the following: incompatible materials, attack by solvents and cleaning agents, change in properties due to age or environments (e.g., radiation damage and atomic oxygen attack), expansion and shrinkage, defects, delamination, poor adhesion, inadequate plating or coating, embrittlement, mercury contamination, stress corrosion, fatigue, etc.

Incorrectly designed or implemented processes can cause failures. Soldering of electrical connections is a good example of a process that can seriously affect reliability. Good soldering, according to NHB 5300-4 (3A-1), requires the following: good workmanship (certification is usually required), proper environmental conditions, facility cleanliness, proper tools and equipment, properly selected materials (solder, flux, solvents), proper preparation of conductors, proper part mounting, application of the proper amount of solder, removal of residue, and inspection. Stress relief and materials compatibility are important. Detailed logs are kept to document exact soldering conditions for each assembly, and the amount of the paper involved in assuring quality soldering is enormous.

Electrical, Electronic, and Electromechanical (EEE) parts pose a special challenge to the space engineer. There is a NASA Standard EEE Parts List, MIL-STD-975, but the list is very limited and tends to lag behind the state of the art by many years. (See table III.) This is because the standard parts are usually those with a flight history (i.e., they have flown in space). In the space business, once something has flown, it becomes imbued with a magical aura of success. This is understandable as flight is the ultimate test. However, in the case of parts, this aura is dangerous as performance depends on the application of the part and also on the degree to which the part manufacturing process remains the same. A standard part may not be right for a particular application and may not meet certain requirements. For example, the standard parts list had not yet addressed radiation susceptibility in its recent Revision G.

Military specifications and standards are frequently used in space flight projects in all design disciplines. NASA "Grade 1" parts correspond to "S level" military parts and are acceptable for flight use. "Grade 2" parts correspond to military "B level" parts. The Joint Army Navy (JAN) specifications cover high reliability military EEE parts. There are military specifications and qualified parts lists (QPLs) covering various types of parts (e.g., MIL-M-38510 for microcircuits, MIL-S-19500 for transistors and diodes). Not only the part, but the manufacturer must be certified to get on a QPL. "Slash Sheets" are issued for individually approved parts that are appended to the specification. The test methods specified by the QPLs are given in MIL-STD-883. MIL-STD-883C not only specifies test methods, but also lists requirements that a part must meet in order to use the term MIL-STD-883 in advertising. Thus, a MIL-STD-883 part is "better" than a commercial part, but is still a nonstandard part. Military specifications and standards are frequently used in space flight projects in all design disciplines. Testing and screening of non-QPL parts can help build confidence in their use to some degree, but use of a nonstandard part usually entails a lot of paperwork.

Table IV shows the current relationship between NASA standard parts and military specifications. In the near future, Application Specific Integrated Circuits (ASICs) will cause a rethinking of parts qualification. It may be desirable to qualify a programmable logic device in the exact configuration in which it will fly rather than allowing a generic qualification. MIL-I-38535 specifies Qualified Manufacturer's Line (QML) requirements, which essentially qualify a process independent of the types of parts being built. Although QMLs were conceived to support ASICs, they may wind up being used to make near-Level B parts.

CMOS electronic parts are desirable because of their inherent low power consumption, but they are susceptible to ESD and radiation effects. In some CMOS parts, a parasitic SCR (silicon controlled rectifier) can be activated by a power glitch or cosmic ray causing potentially destructive "latch-up." Anomalous "bit-flips" (SEU) can occur due to charged particle radiation passing through the device. NMOS (n-channel Metal Oxide Semiconductor) devices are generally more susceptible to total dose radiation damage, some failing after exposure to doses less than 1000 rad (si).

Parts are derated to avoid stressing. (See table V.) Appendix A of MIL-STD-975 gives a general guide to derating, but each particular application of a part has to be examined to determine the proper derating. (For example, capacitive load versus inductive load could make a difference as to the amount of derating necessary for a relay.) Worst case analysis is performed on the circuit to determine if any parts could be overstressed in each particular application. A thermal analysis identifies hot spots and calculates junction temperatures for individual parts. Wire and fuse selection and sizing have to be carefully considered for use in the unusual thermal environment of space.

The same conservatism that makes flight-proven parts acceptable applies to flight hardware in general and, at the electronic box level, makes more sense because the application situation may not vary as much. This has led to several efforts in the past to develop standardized hardware that could be used on many different spacecraft. To make something that is all things to all people is to make it so expensive that no one can afford to use it. It is also hard to make trades when working around standard hardware with fixed weight and power specs. If the hardware is not exactly right for an application, the design engineer may have to make some modifications that can wind up being as expensive as designing a new item. Conservatism will lead to the standard item being older, proven technology with its higher weight and power limitations. The adage "if it works, don't touch it" points out the difficulties of modernizing. On the face of it, standardization appears to offer savings in development costs, design time, and the possibility of quantity buys. Unfortunately, it has not worked out that way. Each spacecraft has its own unique problems and solutions. This is not to say that one must start from scratch on each design; it is helpful to use as much existing design as possible from other projects. For example, 28 V dc power systems are frequently encountered, so it is best to stick with that voltage to allow the use of existing electrical/electronic boxes.

CONCLUDING REMARKS

This paper lists some of the major problem areas and provides a bibliography for a starting point for those unfamiliar with space hardware design. The design of hardware for space flight use is really a rather straightforward job once all the unusual design constraints have been recognized. At this time, space engineering depends on experienced people who have learned their lessons the hard way; the design criteria is just now starting to become well documented in the literature. Hopefully, in the future it will not be as difficult to dig up the little tidbits of information that are needed to stay out of trouble in even the simplest design situations.

BIBLIOGRAPHY

Revisions and dates of government specifications and documents are not given to avoid confusion. Some documents are revised annually. Comments reflect the author's opinion of the listed document.

Overview

Corliss, W.R.: Scientific Satellites. NASA SP-133, 1967.

Still the most useful and readable introduction to spacecraft design, although dated and written to be of interest to a general audience.

Records of Achievement, NASA Special Publications. NASA SP-470, 1983.

A list of NASA Special Publications (SPs), Conference Publications (CPs), and Reference Publications (RPs) from 1961 to 1983. Some of these publications are too dated or general to be of interest, but there are quite a few gems buried in this list.

NASA SP-8000 series, for example: Lyle, R.; Stabekis, P.; and Stroud, R: Spacecraft Thermal Control. NASA SP-8105, 1973.

The SP-8000 series of monographs was an attempt to develop "uniform design criteria for space vehicles." While not completely successful (some of the monographs are out of date and do not contain recent developments or are too narrowly focused), it represents an admirable attempt to record the knowledge of the first generation of spacecraft engineers. SP-8105 is a typical survey monographs which may serve as an overview of the area, but does not contain much detail.

Get-Away Special (GAS) Small Self-Contained Payloads Experimenter's Handbook, NASA Goddard Space Flight Center, Special Payloads Division.

An overview of the GAS concept in vugraph format with facing page text. Contains some basic tips and interesting shuttle environment data.

JSC-07700, Vol. XIV, Space Shuttle Systems Payload Accommodations, 1986.

This document purports to tell you everything you always wanted to know about the Shuttle. It contains descriptions of accommodations for and requirements on payloads (see especially Attachment 1, ICD 2-19001, the generic interface control document). Must reading for Shuttle payload engineers.

SLP/2104, Spacelab Payload Accommodations Handbook

A kind of Vol. XIV for Spacelab, this document contains some useful tidbits for general use, such as the guidelines for wire sizing.

High Energy Astronomy Observatory, Mission C, Phase A. NASA TM X-64652, vols. 1 - 3, 1972

A fairly complete documentation of the Phase A design of the HEAO-C spacecraft. Contains a helpful amount of detail on the design of the various subsystems even though it is a conceptual design document because it builds on the two previous HEAO designs.

Space Environment

Jursa, A.S., ed.: Handbook of Geophysics and the Space Environment. Fourth ed. Air Force Geophysics Laboratory, 1985.

A general overview of the space environment.

Lehmann, J.; Tanner, S.G.; and Wilkesson, T., eds.: The Shuttle Environment Workshop. (Rept. 24-5087 Systematics General Corp.; NASA Contract NAS5-27362.) NASA CR-170496, 1983.

Contains data on shuttle environments from the early flights.

Leger, L.J.; Visentine, J.T.; and Kuminecz, J.E.: Low Earth orbit Atomic Oxygen Effects on Surfaces. AIAA TP-84-0548, Jan. 1984.

Contains additional data on atomic oxygen effects from STS-5 and STS-8 flights.

Cour-Palais, B.G.: Hypervelocity Impact Investigations and Meteoroid Shielding Experience Related to Apollo and Skylab. Orbital Debris, NASA CP-2360, 1985, pp. 247-275.

There is a dearth of hard data in this area. This paper presents some useful information.

Watts, J.W., Jr.; and Wright, J.J.: Charged Particle Radiation Environment for the Spacelab and Other Missions in Low Earth Orbit - Rev. A. NASA TM X-73358, 1976.

Estimates of the radiation environment in LEO.

Purvis, C.K. et al.: Design Guidelines for Assessing and Controlling Spacecraft Charging Effects. NASA TP-2361, 1984.

A general overview of design criteria for spacecraft charging with an extensive bibliography.

Parts, Materials, and Processes

Material Branch, NASA GSFC: Materials TIPs for Spacecraft Applications. NASA Goddard Space Flight Center.

A compendium of miscellaneous information that makes for fascinating reading.

Tirado, J.S.; and Hi-rel ICs: A Class of Difference. Electronic Engineering Times, no. 15, July 11, 1988, pp. T24-T48.

A good introduction to the world of military parts.

McNulty, P.J.: Radiation Effects of Electronic Systems, Proceedings of the Air Force Geophysics Laboratory Workshop on the Earth's Radiation Belts, Jan. 26-27, 1981, R.C. Sagalyn, W.N. Spjeldvik, and W.J. Burke, eds., Air Force Geophysics Laboratory, Hanscom, MA, 1981, pp. 99-124.

A good introduction to radiation effects on electronic parts. Although the paper is dated, standard electronic parts are also dated.

MIL-STD-975G, NASA Standard Electrical, Electronics, and Electromechanical (EEE)
Parts List.

The EEE parts that many space hardware designs are required to use.

Parts, Materials and Processes Experience Summary, vol. 2, NASA SP-6507, 1973.

A compendium of information from the Government-Industry Data Exchange Program (GIDEP). A handy reference, but the GIDEP ALERT reports are more entertaining and timely.

MIL-HDBK-5, Metallic Materials and Elements for Aerospace Vehicle Structures, Rev. D, 1983.

MIL-HDBK-17, Plastics for Aerospace Vehicles, Rev. A, 1971.

Data on structural properties of materials.

Zerlaut, G.A.; Carroll, W.F.; and Gates. D.W.: Spacecraft Temperature-Control Coatings: Selection, Utilization, and Problems Related to the Space Environment Spacecraft Systems. Proceedings of the 16th IAF Congress, vol. 1, M. Lunc and D. Cautheir-Villard, eds., Gordon and Beach, New York, 1966, pp. 259-313.

An introduction to thermal control. Although dated, it appears to be the source of the ubiquitous figure showing the availability of materials to provide various combinations of optical properties.

Safety, Reliability, and Quality Assurance

Ridenoure, R.W.: A Systems-Level Performance History of Get Away Specials After 25 Space Shuttle Missions. The 1986 Get Away Special Experimenter's Symposium, L.R. Thomas and F.L. Mosier, eds., NASA CP-2438, 1987, pp. 79-86.

A fascinating summary of GAS payload performance with a list of failure causes. It appears that GAS payload designers relearned a good deal of space engineering the hard way.

KHB 1700.7, Space Transportation System Payload Ground Safety Handbook.

Presents the detailed safety requirements a payload and ground support equipment (GSE) must meet during ground operations.

NHB 1700.7, NASA Headquarters, Safety Policy and Requirements for Payloads Using the Space Transportation System. NASA TM-80469, 1979.

Presents the safety policy for the STS.

MIL-STD-1540B, Test Requirements for Space Vehicles.

Describes the kind of testing that could be required for a space-flight program.

Bloomquist, et al.: On-Orbit Spacecraft Reliability. PRC R-1863, Planning Research Corporation, 1978.

Contains failure rate estimates based on historical spacecraft reliability data.

Electromagnetic Compatibility, ESD, and Bonding

MIL-STD-461B, Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference.

Presents basic box level EMC requirements. Class A2 covers spacecraft.

MIL-STD-462, Electromagnetic Interference Characteristics, Measurement of.

Descriptions of the tests to be performed to determine if a unit meets the requirements of MIL-STD-461.

DOD-STD-1686, Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices).

Includes an overview of ESD.

MIL-B-5087B, Bonding, Electrical, and Lightning Protection, for Aerospace Systems.

Spacecraft requirements are usually for Class R bonding.

Hawkins, K.: Space Vehicle and Associated Subsystem Weight Growth. Presented to 47th Annual Conference of the Society of Allied Weight Engineers Inc., Detroit, Michigan, May 23-25, 1988.

Contains some historical data on weight growth of spacecraft from concept to launch.

Military documents may be available from:

Naval Publications and Forms Distribution Center
5801 Tabor Avenue
Philadelphia, PA 19120-5099

TABLE I. - PART CONSTITUENTS SUSCEPTIBLE TO ESD

[From DOD-HDBK-263.]

Part Constituent	Part Type	Failure Mechanism	Failure Indicator
MOS Structures	MOS FET (Discretes) MOS ICs Semiconductors with metal-ization cross-overs Digital ICs (Bipolar and MOS) Linear ICs (Bipolar and MOS) MOS Capacitors Hybrids Linear ICs	Dielectric breakdown from excess voltage and subsequent high current	Short (high leakage)
Semiconductor Junctions	Diodes (PN, PIN, Schottky) Transistors, Bipolar Junction Field Effect Transistors Thyristors Bipolar ICs, Digital and Linear Input Protection Circuits on: Discrete MOS FETs MOS ICs	Microdiffusion from micro-plasma-secondary breakdown from excess energy or heat Current filament growth by silicon and aluminum dif-fusion (electromigration)	
Film Resistors	Hybrid ICs: Thick Film Resistors Thin Film Resistors Monolithic IC-Thin Film Resistors Encapsulated Film Re-sistors	Dielectric breakdown, voltage dependent-crea-tion of new current paths Joule heating-energy de-pendent-destruction of minute current paths	Resistance shift
Metallization Strips	Hybrid ICs Monolithic ICs Multiple Finger Overlay Transistors	Joule heating-energy de-pendent metallization burnout	Open
Field Effect Structures and Nonconductive Lids	LSI and Memory ICs employ-ing nonconductive quartz or ceramic package lids especially ultraviolet EPROMS	Surface inversion or gate threshhold voltages shifts from ions deposit-ed on surface from ESD	Operational degradation
Piezoelectric Crystals	Crystal Oscillators Surface Acoustic Wave Devices	Crystal fracture from mechanical forces when excessive voltage is applied	Operational degradation
Closely Spaced Electrodes	Surface Acoustic Wave Devices Thin metal unpassivated, unprotected semiconductors and microcircuits	Arc discharge melting and fusing of electrode metal	Operational degradation

DOD-HDBK-263
2 May 1980

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TABLE II. - PARAMETERS FOR SELECTED SPACECRAFT SURFACE MATERIALS

[From NASA SP-8027, spacecraft radiation torques, Oct. 1969.]

Material	Reflectance, 0.6 to 2.0 microns	Emittance at room temperature, 1 micron	Solar absorptance
White paints		0.79 to 0.93	0.33
White paints exposed to Sun		.82 to .92	.59
Black paints		.88 to .91	.94
Black paints exposed to Sun		.84 to .87	.98
White paints after nuclear radiation			.35
Inorganic paint			.10
Inorganic paint after nuclear radiation			.23
Aluminum film		.01	.07
Silver film		.01	.05
Gold film		.01	.19
Copper film		.01	.17
Platinum film		.03	.24
Sandblasted aluminum	0.4 to 0.7	.2	.42
Sandblasted stainless steel		.85	.75
Aluminum foil		.04	.12
Inconel foil		.1	.38
Inconel X foil		.15	.66
Chemically polished beryllium	.4 to .9	.10	.50
Alumina	.8 to .98[c]		
Zirconium oxide	.8 to .98[c]	.03	
Magnesium oxide	.82 to .96	.04	
Thorium oxide	.8 to .94[c]	.06	
Steel with various finishes	.15 to .8[c]		
Oxidized stainless steel at 600° C		.2	
Oxidized stainless steel at 1000° C		.4	
Bare n-on-p solar cell	.32 to .31 (.4 to 1.0 micron)	.3 at 149° C	
SiO-coated solar cell	.01 to .16 (.6 to 1.0 micron)		

[a]Adapted from refs. 21 and 26.

[b]Values are approximate, intended to be indicative and not for design use.

[c]Below 0.6 micron, a sharp decrease in reflectance occurs.

TABLE III. - EXAMPLE OF STANDARD PARTS LISTED IN MIL-STD-975G

[Note the "slash sheet" numbers and the lack of Grade 1 parts. Parts policies must account for the unavailability of high reliability parts.]

MIL-M-38510, MICROCIRCUITS
Microprocessors

Commercial Part No. 1/	Word Size (Bits)	Fixed Instruction	Technology	Case Size	Clock Frequency (Max)	JAN Part Number 2/		
						M38510/	Grade 1	Grade 2
Z80A	8	Yes	NMOS	40-pin DIP	4 MHz	48001		B*X
Z8002	16	Yes	NMOS	40-pin DIP	4 MHz	52002		B*X
Z8002A	16	Yes	NMOS	40-pin DIP	6 MHz	52004		B*X
8086	16	Yes	NMOS	40-pin-DIP	5 MHz	53001		B*X

1/ Use the JANM38510 part number for ordering.
2/ The * is for choice of package style. The X is for choice of lead finish. Refer to the QPL for specific choices.

TABLE IV. - EEE PARTS CORRESPONDENCE

MILITARY QPL (See Note at Bottom)

NASA STANDARD	ICs	DIODES & TRANSISTORS	CAPACITORS	RESISTORS
Grade 1 MIL-S-38510 Level S	MIL-S-19500 JANS	Established Reliability (ER) Level S (or R)	Established Reliability (ER) Level S (or R)	Established Reliability (ER) Level S (or R)
Grade 2	Level B	JANTXV	Level P	Level P
Non-standard	Std. Military Drawings MIL-STD-883C MIL-I-38535 QML Source Control Drawing (SCD) Commercial Parts	JANTX JAN	Level M Level L	Level M MIL-R-11

JAN - Joint Army Navy
QML - Qualified Manufacturer's List

Note: The NASA Standard EEE Parts are a subset of the military QPL parts; that is, not all military Level B parts are acceptable NASA Standard Grade 2 parts.

TABLE V. - EXAMPLE OF A DERATING GUIDE FROM

MIL-STD-975G, APPENDIX A-1[a]

Wire Size (AWG)	Derate to - Amperes Maximum		Remarks
	Bundle or Cable	Single	
30	0.7	1.3	
28	1.0	1.8	
26	1.4	2.5	
24	2.0	3.3	1. Current ratings for bundles or cables are based on bundles of 15 or more wires at +70°C in a hard vacuum. For smaller bundles, the allowable current may be proportionally increased as the bundle approaches a single wire.
22	2.5	4.5	
20	3.7	6.5	
18	5.0	9.2	
16	6.5	13.0	
14	8.5	19.0	2. Deratings listed are for Teflon insulated wire (TYPE TFE) rated for +200°C.
12	11.5	25.0	
10	16.5	33.0	
8	23.0	44.0	a. For 150°C wire, use 80% of value shown in table.
6	30.0	60.0	
4	40.0	81.0	b. For 135°C wire, use 70% of value shown in table.
2	50.0	108.0	
0	75.0	147.0	c. For 105°C wire, use 50% of value shown in table.
00	87.5	169.0	

[a]These guidelines should be used as minimum derating criteria and should be evaluated for applicability on a case-by-case basis.

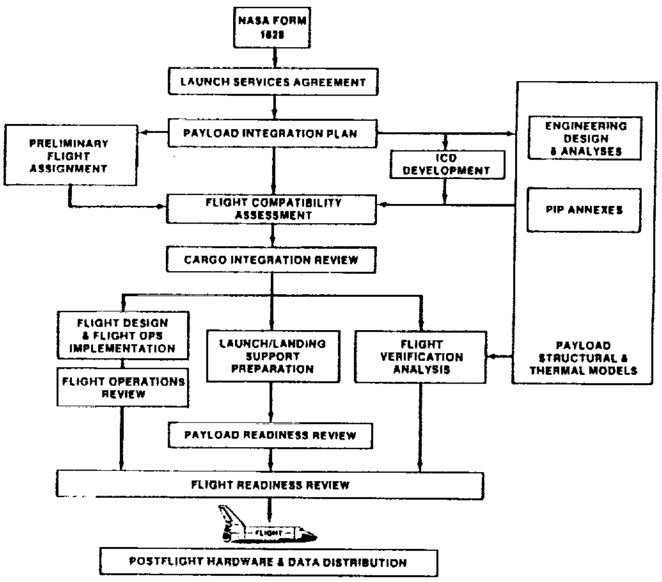


FIGURE 1. - SHUTTLE PAYLOAD INTEGRATION PROCESS. (FROM REF. 5.)

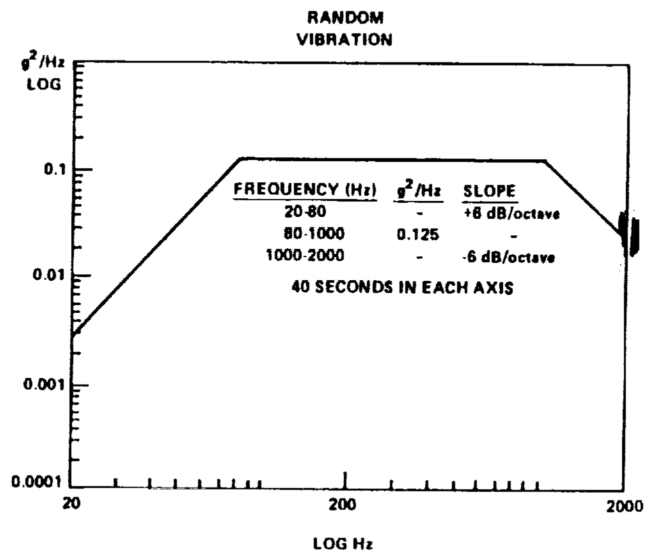


FIGURE 2. - VIBRATION ENVIRONMENT FOR SHUTTLE PAYLOADS. (FROM REF. 4.)

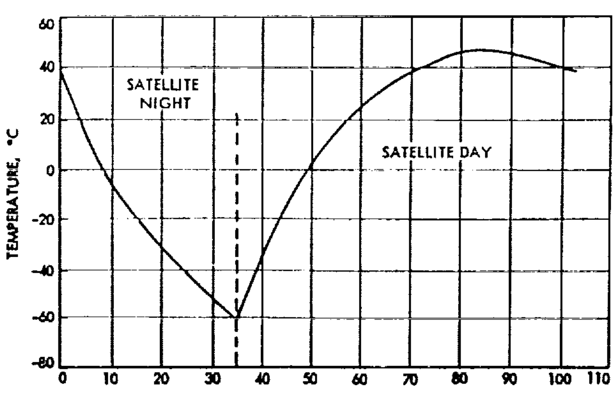


FIGURE 3. - AN EXTREME EXAMPLE OF THERMAL CYCLING EXPERIENCED ON ORBIT IS GIVEN BY THIS PLOT OF THE TEMPERATURE OF THE NIMBUS 2 SOLAR ARRAYS. THE BODY OF THE SPACECRAFT HAS MORE MASS AND CAN BE INSULATED TO MODERATE THE SWINGS IN TEMPERATURE. (FROM NASA SP-8074, SPACECRAFT SOLAR CELL ARRAYS, MAY 1971.)

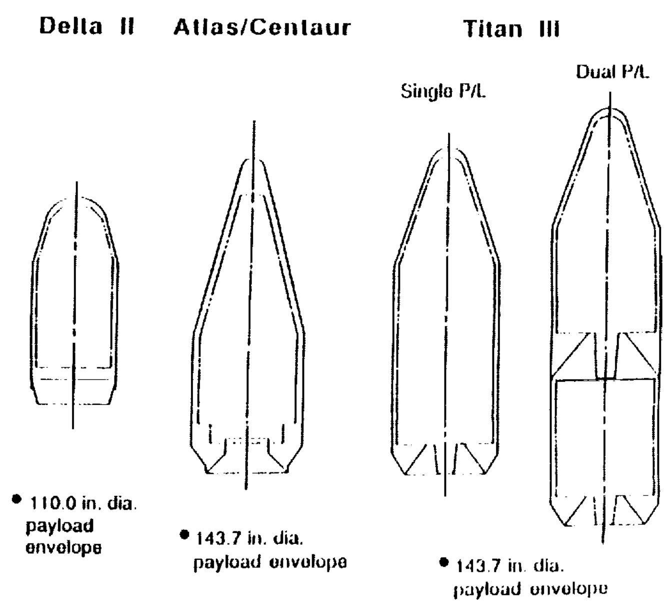
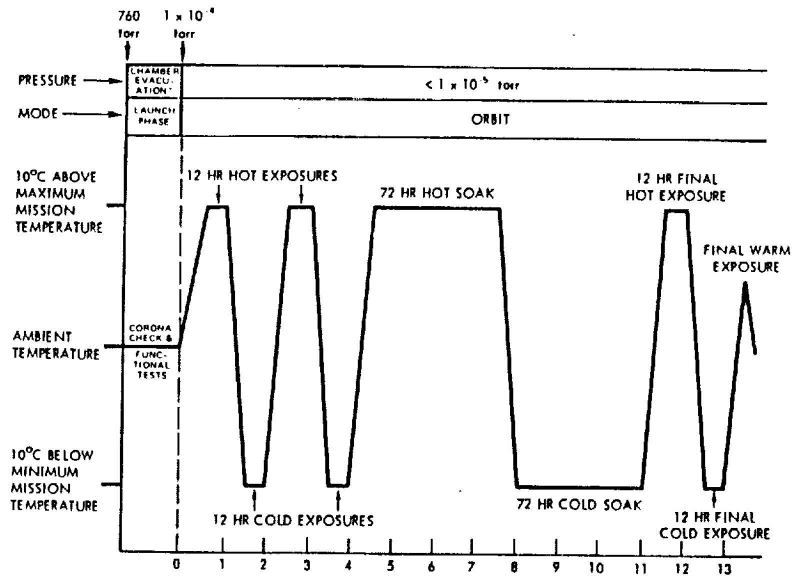


FIGURE 4. - TYPICAL PAYLOAD ENVELOPES.



*Chamber evacuation takes about 2 hours so time scale is disproportionate here.

**The plot shows 12 hours for each temperature transition; actually, the transition periods vary widely with spacecraft, mission, and test equipment.

FIGURE 5. - TYPICAL THERMAL-VACUUM TEST CYCLE FOR PROTOTYPE SPACECRAFT. (FROM NASA SP-8105, SPACECRAFT THERMAL CONTROL, MAY 1973.)

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15. Supplementary Notes

16. Abstract

This paper presents a review of the environmental and design constraints along with some insight into the established design and quality assurance practices that apply to Low Earth Orbit (LEO) space flight hardware. It is intended as an introduction for people unfamiliar with space flight considerations. Some basic data and a bibliography are included.

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