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ENVIRONMENTAL TEST CONTRIBUTION TO SPACECRAFT RELIABILITY

by Kenneth R. Mercy

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Greenbelt, Md.

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ABSTRACT

Typical problems that have a major impact on some space programs are discussed. These problems include those that involve the interdependence of equipment in a system complex.

The experiences obtained in producing reliable spacecraft for several programs (Relay, Syncom, Tiros, etc.) are analyzed. The techniques used to control and appraise space programs differ and are influenced by the spacecraft design, target dates, and budget restrictions. The validity of these techniques is indicated by the results of the test programs. Problem occurrences are analyzed relative to program phase. The results of this study are discussed with regard to optimizing techniques of quality and reliability planning for space hardware.

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ENVIRONMENTAL TEST CONTRIBUTION TO SPACECRAFT RELIABILITY*

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INTRODUCTION

Equipment used for initial space exploration must be reliable if it is to meet the intended objectives within a reasonable time and cost. Many ways of obtaining reliability, commonly used in the engineering and manufacturing fields, were found lacking in the perfection needed for producing remote-controlled, unmanned spacecraft. Logistics also were an obstacle to reliability. Small quantities of materials, parts, and assemblies were obtained from widely-scattered sources around the world. Some of these items had to be developed for the special applications within the research laboratories. Traceability of material and the control of all items were not possible within the program plan. It was necessary to modify old techniques and introduce new ones. To achieve reliability, greater emphasis was placed on environmental testing. To meet this requirement, it was necessary to develop new and more sophisticated environmental facilities, which in turn demanded test procedures, involving new engineering approaches. The rapid growth of this effort embodied many people with specialized talents. Some of their far-removed and distant-related accomplishments were not known in the true perspective to the overall space program. A review of Goddard Space Flight Center's spacecraft history, including space programs such as Relay, Syncom and Tiros, is presented to show the contribution made by the environmental sciences.

SPACECRAFT STRUCTURAL STRESSES

A much discussed and often troublesome phase of environmental testing is the vibration test. This test is intended to add some level of confidence that the spacecraft can survive handling and launch stresses without damage or degradation. From the stress-analyst viewpoint, vibration contributes some, but not all of the flight stress loads. The launch-vehicle thrust load plus loads due to wind conditions must be included. Thus, vibration testing of spacecraft involves a trade-off in the concept of launch simulation. In addition, the vibration tests are conducted separately in three orthogonal directions, as compared with a combined effect applied in flight. Knowing the initial concepts, one must look deeper to understand fully the purpose, limitations, and intent of conducting this test.

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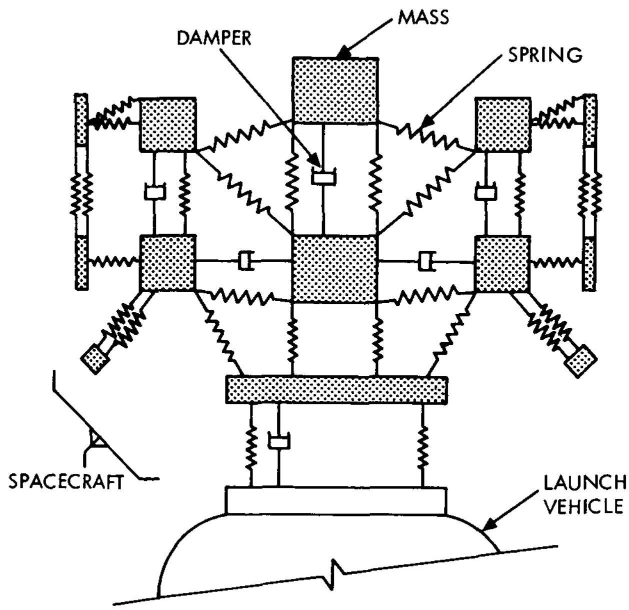


Figure 1—Spacecraft as a lumped mass vibration system.

A typical spacecraft design, when analyzed by a vibration engineer, appears as an assembly of large and small masses, springs, and dampers. Figure 1 can be considered a schematic of a spacecraft as a lumped-mass vibratory system attached to a launch vehicle. The spacecraft is attached to the vehicle with massless springs and dampers. The vehicle itself is made up of masses, springs, and dampers. Similarly, the spacecraft appendages, subsystems, and components are shown. Thus, any part of the spacecraft (whether it be a box, a panel, a tank, or the internal parts of a transistor) can be idealized as a vibrating system.

A vibration system will respond to steady-state and random vibration; it will also be excited into resonance by shock excitation. The frequency response of each element or combination of elements will depend on the mass and its elastic members, in accordance with the basic vibration formula for resonant frequency:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}},$$

where

f = resonant frequency,

k = spring constant, and

m = mass.

Not only will a vibrating system be excited at the fundamental frequency, but additional resonant frequencies are possible for the higher modes of vibration. The higher structural modes and their resonant frequency can be illustrated by a free-free beam (Figure 2). As the frequency of excitation is increased beyond the fundamental resonance, another vibrating pattern or mode with its own resonant frequency appears. Increasing the frequency still further will create other resonances. Thus, a spacecraft with thousands of parts will have many thousand possible resonant frequencies within the launch-vehicle excitation range.

The most important aspect of the vibration problem is the resultant stresses at these resonant frequencies. At resonance, the amplitude of the elastic member exceeds the amplitude of the adjacent structure by a factor which is limited by the damping of the material or the applied damping.

The basic stress level is directly related to the vibration amplitudes. The stress vs frequency will be similar to that in Figure 3, which shows light and heavy damping.

If the damping for each vibrating system does not keep dynamic stresses within the fatigue limitations of the material, failure will occur. The fatigue life of some materials used in spacecraft construction is shown in Figure 4.

The acceptable stress level will depend on the number of stress cycles and the amplitude experienced during the life of the spacecraft or its component parts. Some part or segment of the structure with low resonant frequencies may experience only a few hundred cycles, in comparison to over a million cycles for those with higher resonant frequencies. In some cases, fatigue life can be an important factor. For example, if solder is used as a stress element, a fatigue failure may occur. Compared with steel, for instance, solder has a low fatigue limit; it will not survive many cycles at low stresses. (See Figure 4.)

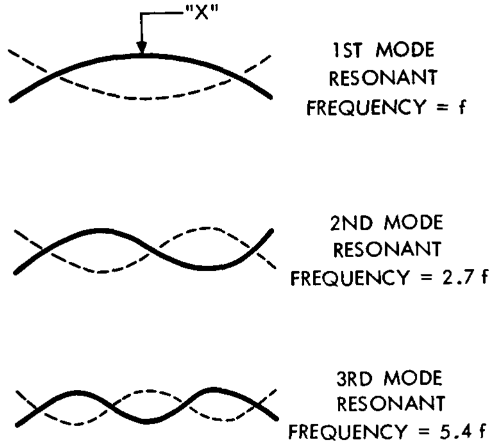


Figure 2—Vibration modes of a free—free beam.

The ultimate strength of the materials will be different if vibratory loads are applied by themselves, or in combination with steady-state loads. One of the tools that the designer uses to equate these differences is the Goodman-type diagram. (See Figure 5.) This diagram indicates that the ultimate strength of the material for a vibratory stress alone is only one-third (σ_u). This level would represent lateral dynamic loads on a spacecraft during flight without shear wind loads. It would also be applicable to the spacecraft during test in any direction.

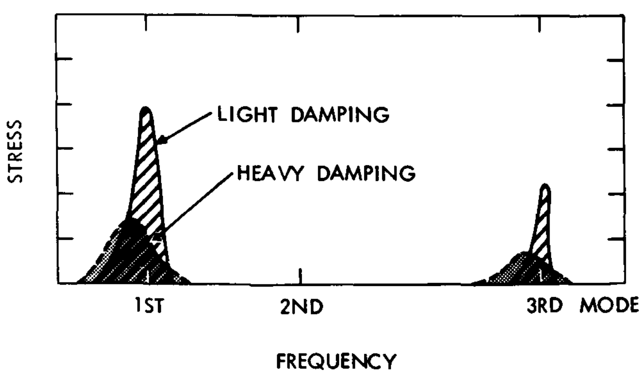


Figure 3—Stress vs frequency.

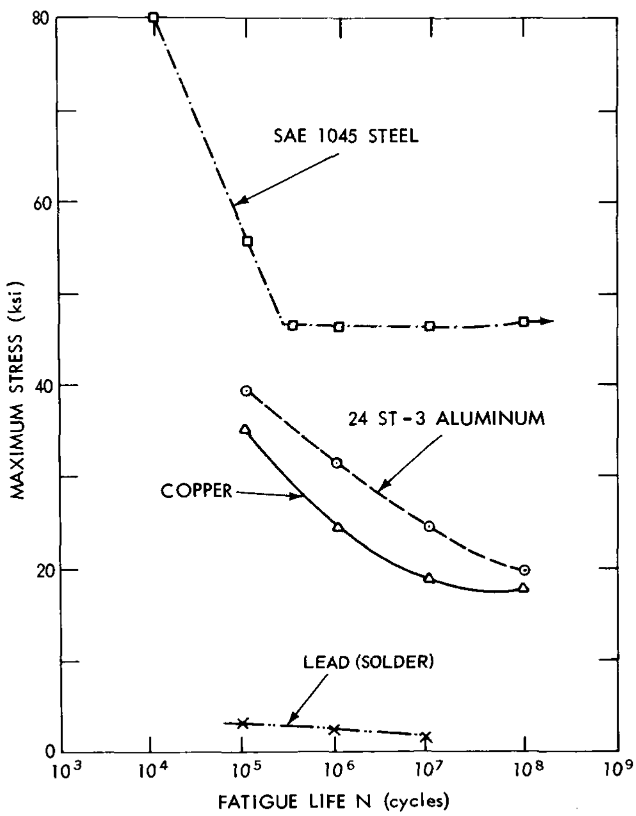


Figure 4—Fatigue life of materials.

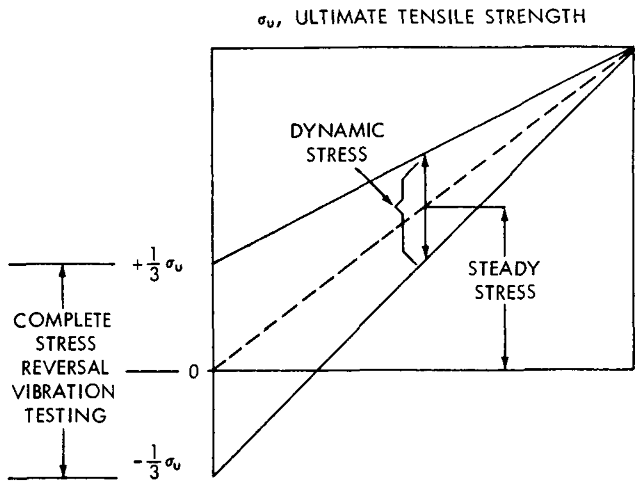


Figure 5—Goodman diagram to determine acceptable material stresses for combined steady and dynamic stresses.

For a spacecraft in flight, the static loads in the thrust direction would normally be represented on the Goodman chart at some level where there would be fluctuating stresses, but no stress reversal. Thus, higher stresses could be tolerated before failure occurs. Obviously our present-day vibration testing techniques cannot give exact simulation of the material stresses. A typical flight-acceleration record for a Thor-Agena launch (Figure 6) shows the type of static and dynamic loads that exists on some launches. These records were taken at the Agena interface with the spacecraft adapter for a 1000-pound spacecraft. The peak amplitudes or resultant stresses exist for a very few seconds The steady-state vehicle acceleration can be noted in the thrust-axis record; it can equal or exceed the dynamic component. The vibration wave is complex at the beginning with major dynamic loads occurring at frequencies of 15, 40, and 79 Hz during lift-off, followed by frequencies in the range of 0 to 25 Hz at trans-sonic speed. Just before

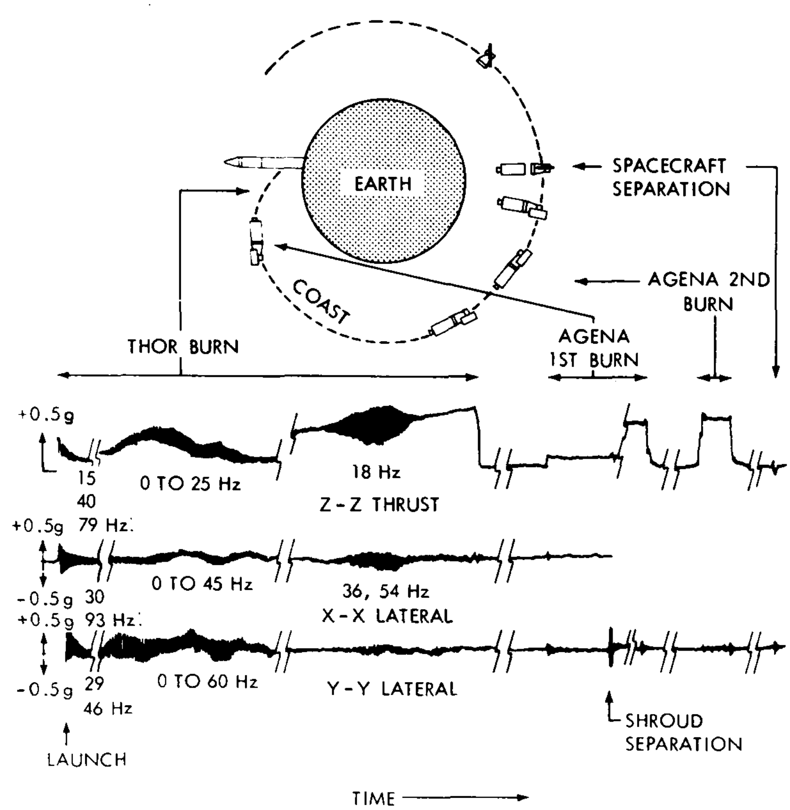


Figure 6—Spacecraft acceleration and vibration during flight.

burnout of the first stage, there is a strong 18-Hz resonant frequency. Other frequencies range from 17 Hz at vernier-engine cutoff to 152 Hz at Agena cutoff. Higher frequencies are present, but are not shown on this instrumentation record. The peak loads occur for less than a minute, and at the lower frequencies. The resultant stresses throughout the spacecraft are usually not known because of unknown damping coefficients and the phase relationship between the structural elements, except where studies and measurements are made for a specific condition.

Thus, those knowledgeable of the many indeterminate factors involved sometimes wonder whether the testing is beneficial or harmful. Because of the complexity of the unmanned spacecraft, the emphasis has been on vibration testing of the complete spacecraft. In each program, a prototype spacecraft is subjected to test levels 50 percent higher than those for the flight model, to ensure a margin of safety in the design. New programs also have the advantage of studying the response of a simulated loaded spacecraft structure (an engineering model) to the prototype levels. Structural problems or potential high-stress areas are usually uncovered with this model and corrected before the prototype and flight-model tests. Figure 7 shows the number of significant problems encountered in some typical programs during vibration tests of the flight model spacecrafts; the figure shows the number of significant launch-related problems encountered in flight for the same spacecrafts.

The number of problems occurring at the system level of test reaffirms the difficulty of fully understanding the dynamic environment. The adequacy of the tests is indicated by the good performance of the spacecraft after launch. Whether or not the vibration tests are forcing the designer to ruggedize his design beyond a reasonable safety limit will always be debatable.

The types of test problem encountered after vibration tests on the prototype and flight model spacecraft are listed in Table 1. The majority of these items would have severely degraded the performance of the spacecraft. The problems occur at any level of assembly and in any part of the spacecraft. The failure mode appears to be the result of localized resonant condition with very little damping present. Thus, the problems may be classed as subtle vibration design problems that can easily be influenced by variations in fabrication and assembly procedures.

It is apparent that the vibration-related problems indicated are not easily detected before testing. Designing a spacecraft to cope with the potential problems has been good, otherwise many more problems would be noted. In one spacecraft, an overhanging delicate box assembly was noted to have transmissibilities of the order of 12X. By careful study and the design of a coulomb damper strut, this vibration environment was reduced 50 percent.

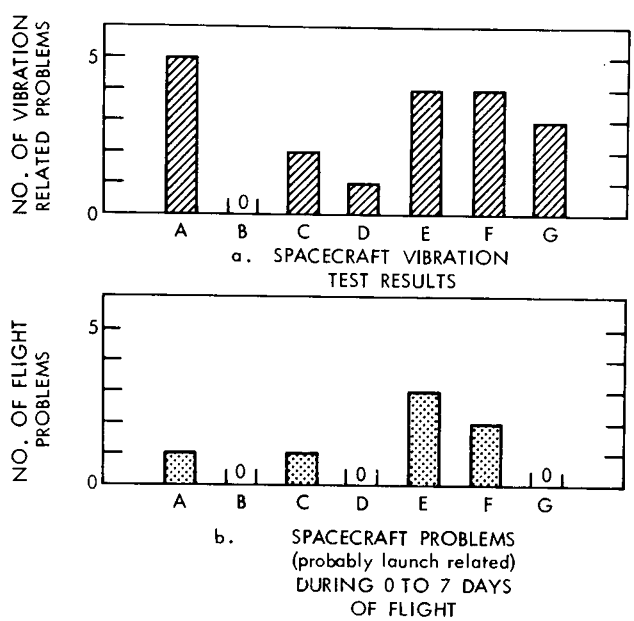


Figure 7—Vibration acceptance test results vs flight experience.

Table 1

Vibration Design Problems Noted after Spacecraft Vibration Tests.

Defective component or subsystem	Problems	
	Prototype model	Flight model
Command receiver	Reduced sensitivity caused by a damaged zener diode	
Experiment package	Mounting flange fractured	
Power supply	Cracked terminal seal in transformer caused oil leak	Broken solder joint because of taut wire
Battery cell	Internal connection failed	(1) Internal connection failed (2) Cell became shorted
Telemetry transmitter		(1) Cracked coil reduced power output by 50 percent (2) Degraded vacuum tube caused output to vary
Beacon transmitter		(1) Reduced output (2) Failure of transmitter; vibration transmissibility was excessive (about 16X)
Charge controller		Broken wire
Clock circuit		Leaky transistor
Camera		(1) Lens rotated in mounting (2) Shutter moved out of place
Recorder		Magnetic tape came off capstan and jammed recorder
Despin mechanism		Weight dropped off

Large solar paddles are always potential trouble areas. Studies for one spacecraft showed vibration modes of panels in conflict with the spacecraft structure. Attachment stresses were high enough to cause failure. Decoupling techniques were successfully applied before final system tests and flight.

THERMAL FACTORS

Unmanned spacecraft have varied considerably in the methods employed to establish a thermal base for the subsystems and instrument packages. In a vacuum, the heat flow from hot bodies to cold bodies must be by radiation and conduction without convection. The restricted heat flow can cause localized high temperatures that can damage thermally sensitive components. Also, components can be damaged by the extreme cold encountered in the earth's shadow. Thermal control of major zones of a spacecraft has been made possible by either a passive or active design. Passive controls are simple and use the physical characteristics, absorptivity, and emissivity of the surface coatings. Active controls are devices that alter the rate of heat flow from the surfaces, to other parts of the spacecraft or to outer space. The complexity of the thermal design can best be understood by enumerating the basic factors involved. These are as follows:

Solar

Intensity
Spectrum

Spacecraft

Sun aspect angle
Spin-stabilized
Attitude controls

Spacecraft Thermal Control

Active
Passive
Absorptivity
Emissivity
Angle of incidence
Heat sinks

Orbit

Percent sun
Earth's shadow
Period
Earth albedo
Earth shine

Spacecraft Materials

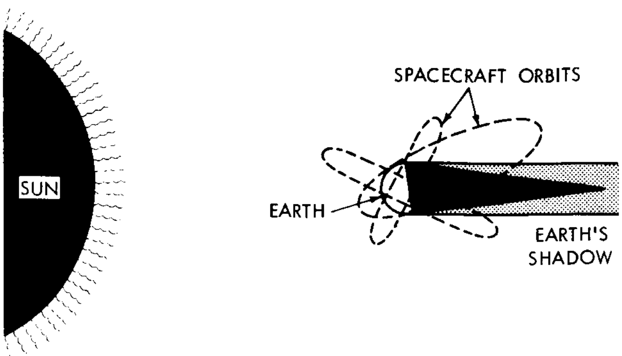
Thermal conductance of material
Thermal conductance of joints
Pressurized components of spacecraft
Degradation of materials in space

Spacecraft Operation

Internal heat generators
Operation cycle

The thermal design must be considered as part of a system, since it involves many factors interrelated with other disciplines. Some of the thermal approaches conflict with the overall spacecraft design. For example, the best thermal conductance joint design would not dampen the spacecraft structure enough to reduce the vibratory stress loads. In cases where surfaces are electrically insulated, the thermal conductance properties are poor.

Many spacecraft have thermal characteristics that can cause catastrophic failure if uncontrolled. Thermal analyses without supporting tests would not provide the accuracy needed in these critical areas. A system test of the complete spacecraft is essential to give confidence before launch. But there are many ways of conducting these tests. Some may distort the thermal gradients and prevent a thorough evaluation. Solar-simulation vacuum tests offer the best approach; but their complexity, high cost, and other factors often prohibit them. Thermal-soak type tests, which are less costly, must be carefully controlled to prevent damage to some components. In one major program, an off-the-shelf battery cell not designed to be operated at the spacecraft temperature level encountered in a thermal-soak test was used over very limited temperature range. Due to higher spacecraft test temperatures expected, a trade-off in test procedures was necessary which reduced somewhat the advantages of full system tests.



SPACECRAFT FLIGHT DATA
THERMAL RANGE °C

Spacecraft	Stabilization	Thermal control	Internal structure	Batteries	Solar panel
1	Spin	Active	-3 to 27	-3 to 26	-42 to 12
2	Spin	Passive	-7 to 26		
3	Spin	Passive	2 to 26	5 to 35	2 to 82
4	Spin	Passive	-88* to 45	-44* to 44	-- to 14

*Extrapolated

Figure 8—Flight thermal data.

The test temperatures are based on the extremes expected during flight, with prototype spacecraft subjected to an additional 10 to 15°C margin. Spacecraft thermal data from telemeti records have shown low and high temperature extremes of -88°C and +82°C, respectively (see Figure 8). The extreme cold conditions have been experienced for spacecraft which, at some seasonal time, spend considerable percentage of their orbit period in the earth's shadow. In general, the basic instrument package in a nominal orbit is kept at habitable temperatures.

Since the spacecraft are considered ready for flight when they reach the system environmental tests, good performance without failures is expected. Experience has shown that this level of perfection is uncommon, and many problems are uncovered at this time. Table 2 shows a compilation of thermally related problems noted during environmental tests on the

Table 2

Thermal-Vacuum Related Problems Noted During Spacecraft Environmental Tests.

Defective component or subsystem	Problems	
	Prototype model	Flight model
Wideband subsystem	(1) Transponder malfunctioned during cold phase, requiring replacement of a 2N1405 transistor (2) TWT experienced helix current runaway during cold phase requiring replacement of the tube	
Clock oscillator	Low output during 50°C thermal-vacuum, requiring change of design and addition of thermal insulation	
Solar cells		Physical degradation during solar vacuum of bond between cell and cover

Table 2 (Continued)

Defective component or subsystem	Problems	
	Prototype model	Flight model
Camera electronics		(1) Picture lost synchronization during cold phase (2) Unwanted pulse triggered shutter circuit
Low-frequency beacon		Lost 40db in output level during 50°C hot phase, recovered at 27°C
No. 1 recorder		Magnetic tape disengaged during cold phase
No. 2 recorder		Magnetic tape disengaged during hot phase
Beacon subcarrier oscillator		Would not function at 0°C
Power converter		Experienced thermal runaway at 50°C

prototype and flight model spacecraft. These problems can be considered typical for the unmanned spacecraft. There is a wide variety of problem types which involve materials and their sensitivity to small or extreme changes in temperature. Variation in electrical characteristics in a system complex is difficult to anticipate, especially when some items have no past history. No one technique or control can prevent these malfunctions, but a balanced program approach backed up by environmental tests is necessary.

A comparison of thermal test results with flight history is presented in Figure 9. The results of flight operations for the first 30 days showed 4 of 7 spacecraft experiencing possible thermal problems. The many problems noted both in test and flight emphasize the need for a good thermal-vacuum system test.

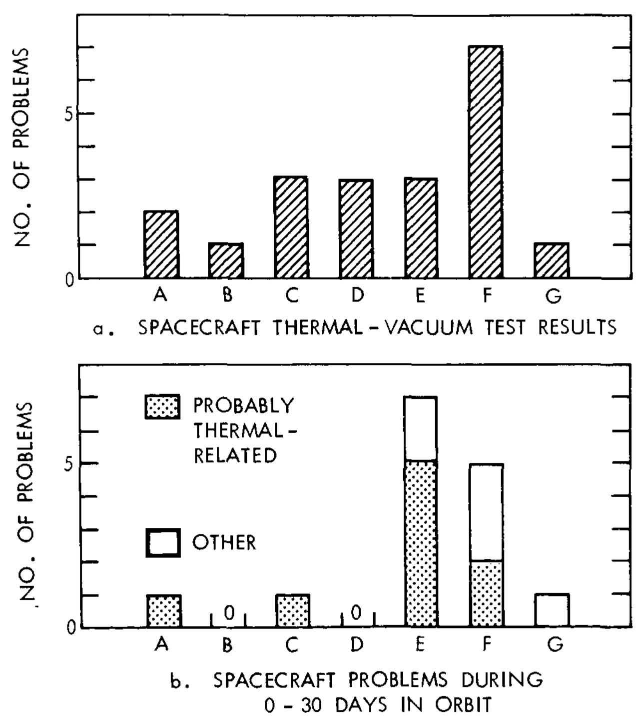


Figure 9—Thermal—vacuum test results vs flight experience.

ENVIRONMENTAL AND SYSTEM INTERACTIONS

A spacecraft problem can involve not only one environmental parameter but many professional disciplines. Designs and assemblies of individual items good by themselves can give unexpected trouble when taken together. Electrical, chemical, materials, thermal, vacuum, vibration, fabrication, and procurement factors can interact in one troublesome area.

Electrical-Thermal-Chemical-Pressure

The space programs were accelerated by using as many off-the-shelf items as possible. The procurement of rechargeable NiCd batteries was one of the important items of this category. The relatively small orders for spacecraft made it necessary to accept the manufacturer's time scale for his normal production runs. Thus, the long-lead time and lengthy spacecraft schedules introduced shelf life as an important environmental factor. Battery cell leakage was encountered. This deficiency alone resulted in a chain reaction of problems. A leaky cell causes a battery pack to be electrically unbalanced, followed by excessive charge rates per cell, gas generation, pressure buildup, case distortion, and fracture of thermal-conducting path in spacecraft.

When batteries were subjected to vibration, sometimes the internal electrical connections were broken. Investigation revealed that the internal electrical connection in the battery cell was accomplished by a blind weld. Quality-control of this operation to determine if a satisfactory weld was made for vibratory stresses was difficult and almost impossible.

Batteries had limited temperature range, especially when cellulose acetate separators were used. Batteries created their own thermal loads and required a good spacecraft system thermal design to dissipate the heat loads in a vacuum environment. Thermal-vacuum testing of a complete operating spacecraft was found to overstress the batteries at the prescribed hot-soak temperatures. Test program trade-offs were found necessary to circumvent the problem. The manufacturer indicated that the battery cell separators disintegrated above 35°C, while spacecraft tests were required at 50°C. Attempts to increase battery temperature limits with polypropylene separators early in the space program created other problems. Development time is not always predictable in many phases of the space programs.

Other thermal interfaces required the spacecraft designer to develop electrical-insulating/heat-transfer cements to conduct heat from battery casings to the spacecraft structure without electrically grounding the battery case. Solar simulation and thermal-gradient type test were necessary to help resolve this localized thermal problem. Vibration tests also were necessary, as indicated by failures of the spacecraft thermal joints.

Battery operation generates heat which must be removed to prevent excessive temperatures. A shorted battery cell or an overcharged condition amplifies this condition. Cell temperature use leads to gas generation and catastrophic internal pressures. To prevent spacecraft damage, electrical and pressure-protective devices are incorporated in the spacecraft system design. The real solution of this problem is the coordination of the efforts of many people (the battery supplier, the spacecraft designer, the thermal engineer, the vibration engineer, the test operations, etc.) to resolve the technical interfaces early in the program.

Electrical-Material-Corona-Vacuum-Thermal-Vibration

The battery problem is not unique, but is representative of many spacecraft problem areas. Another significant interface item is the traveling-wave tube (TWT) used in a communications spacecraft. This high-power tube (10 watts) was in the final stages of development at the time that it was needed for the spacecraft. With only a few specimens available, it was necessary to resolve the critical vibration and thermal interfaces. The delicate construction of the tube forced the spacecraft designer to incorporate a vibration-isolator type mounting. This mounting, in turn, obstructed the thermal-conduction path for the high-heat load (50 watts). The tube design required that the collector temperature be maintained below 180°C. A separate heat sink was found necessary; in order to conserve weight, the final design used a remote part of the spacecraft structure for this purpose. A braided copper thermal conductor satisfied this unusual requirement. The heat load was also related to the spacecraft operating cycle. Operation was required during the period of mutual visibility between ground stations on two continents; thus, a cooling-off period during part of the orbit was possible. The environmental systems tests were important in proving that the communications subsystem could meet its space objectives. The large thermal gradients emphasized the need for the more realistic solar simulation-vacuum tests.

Before the system test, a thermal-vacuum subsystem test of the TWT revealed a serious deficiency in the tube construction. Investigation uncovered an arcover condition in the highly precise, small feed-through fitting of the tube. Material, fabrication procedures, and seal design had to be reworked. Although recovery operation was time-consuming and costly, the detection of this deficiency at the subsystem level prevented more costly delays at the system level.

Corona or high-voltage arcover of electrical circuits as indicated in the TWT tests is a common spacecraft condition, but is difficult to diagnose and prevent. Since most of the spacecraft high voltage elements are not observable during test and some elements are deeply buried in potted materials, corona can only be detected by noting the spacecraft electrical performance. Other electrical problems or simplified test procedures can make these observations difficult. In some cases, catastrophic failures have occurred. Vacuum testing is one of the important tools in detecting to detect corona. High voltage at gas pressures of 10 to 10^{-2} torr will accentuate this condition. Insulation materials, outgassing of materials, material changes with temperature, sharp edges, and the vibration environment can also help produce corona. The vagueness that surrounds this problem emphasizes the importance of environmental tests.

Electrical Materials, Thermal Vacuum

Another spacecraft problem resulted in a catastrophic power failure that could be attributed to materials, heat, vacuum, and the passage of time. A high-power 2N665 transistor in the charge-controller circuit was mounted on a Berlox pad to provide electrical insulation. A thin sheet of indium improved the thermal-conducting path between the Berlox and the spacecraft mounting. After 56 hours of exposure to maximum flight temperatures during a solar-vacuum test, the indium had flowed enough to cause a short-circuit between the spacecraft and the transistor terminal. This apparently minor defect in design would have had serious effects in orbit.

ELECTRICAL AND ELECTROMAGNETIC INTERFERENCE

The spacecraft designs (which are a collection of many different types of electrical, electronic, and electro-mechanical devices) have been plagued with interference problems. Some have originated internally, and some have been rf of the space environment. The internal problems have been either power line surges, due to various component operations, or rf generated—which affects other sensitive circuits. Typical examples of flight experiences are as follows:

1. Command subsystem has operated by internal or external rf signal from an unknown source.
2. Camera shutters have operated at the improper spacecraft attitude.
3. Camera shutters have generated electrical signals on impacting stops as noted on video output.
4. Circuit noise levels have reduced signal level to marginal operating conditions.

Environmental test techniques for detecting the causes of interference have been improving over the years, but the more complex spacecraft makes it difficult to perform all the possible combinations of operating modes for changes of environment. Environmental facilities like thermal-vacuum chambers are not conducive to rf studies. Thus, careful test planning using other techniques is essential to ensure that the interference problem has been adequately covered.

MAGNETIC ENVIRONMENT

The magnetic fields generated within a spacecraft and interaction with the earth's magnetic field are important test considerations. In order that scientific measurements can be made with magnetometers, the ambient magnetic field of the spacecraft must be controlled to prevent interference similar to the electromagnetic interference previously discussed. The choice of spacecraft materials, shielding, and electrical fields are studied in magnetic fields that neutralize the earth and man-made fields.

The influence of the earth's field on the orbiting spacecraft can create a magnetic moment which changes the attitude of the spacecraft. This condition must also be studied so that the magnetic moments can be neutralized. In some cases, spacecraft have incorporated a controlled magnetic moment to obtain attitude corrections. Thus, the magnetic environmental test plays an important part in the unmanned spacecraft program.

PROBLEM ANALYSES

The environmental test program for GSFC unmanned spacecraft has uncovered a variety of problems. If perfect technique could be employed from design, selection of materials, fabrication, and assembly, no malfunctions would occur at the systems test level. Unfortunately, the small quantities of parts and materials required for a program and the experimental nature of some of the assemblies used have not permitted the usual production controls and quality assurance to be fully employed. To compensate for this program deficiency, considerable effort has been expended in providing engineering reviews of design, fabrication, and test. The effectiveness of this approach is shown by a problem analysis of a typical program.

The number of significant problems encountered in different environments by the prototype and flight model spacecraft is shown in Figure 10. Of the 52 prototype-model problems, 30 were uncovered by environmental test, with vibration accounting for the majority. The flight model encountered 17 problems, 10 of which were related to environment.

A further study of the type of problems encountered during the environmental test is shown in Figure 11. As expected, the design qualification tests of the prototype model uncovered 18 design problems, nine of which would have been catastrophic in flight. The flight model had two design problems—both of which would have been catastrophic. This confirms the philosophy that testing the flight model as a complete system is important.

Quality control problems were significant for both the prototype and flight models. A large percentage of these were catastrophic, but it must be noted that the elimination of quality control problems by themselves would not be sufficient to assure a successful program.

The history of the flight model spacecraft in orbit indicates that the program was successful. A serious deficiency was noted in the power supply after launch, but fortunately this circuit was redundant. The deficiency was a temperature-related transistor malfunction which was previously noted during prototype model environmental testing. It was diagnosed as a defective part. A more precise analysis would have revealed a design-fabrication factor interacting with a cold thermal environment.

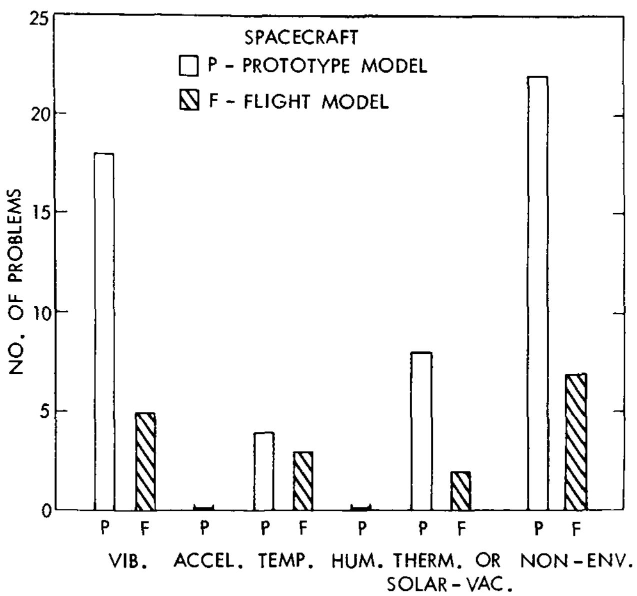


Figure 10—Spacecraft environmental related problems.

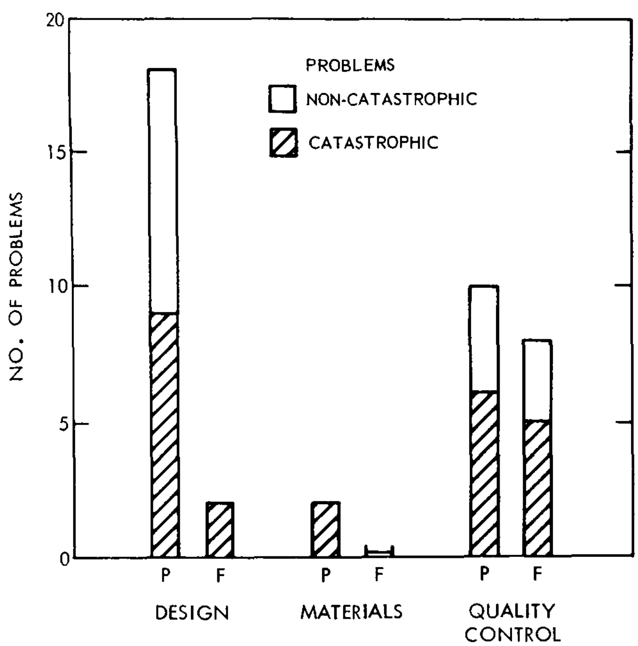


Figure 11—Environmental related problems categorized.

Another flight problem involved the command subsystem. Rf interference caused a sporadic change of spacecraft operating state. Although troublesome, it did not affect the overall program. This condition was not detected during testing; the rf orbit environments were not known. The need for greater emphasis on interference testing was indicated by the experience in this program.

The spacecraft encountered a problem with its one-year cutoff timer. This electrochemical device failed to operate at the one-year time limit or anytime thereafter. A device of this type needs more test history before its reliability can be established.

SPACE PROGRAM RESULTS

The test philosophy and techniques followed in the Goddard programs differ in some respects; but, in general, a major emphasis is placed on full-scale systems testing of the prototype and the flight spacecraft. The results are indicated by the data obtained from 49 launches during the years 1960 through 1966. A total of 251 experiments were flown (see Figure 12). Sixty-three percent met the mission objectives as planned; an additional 30 percent obtained useful data, although abnormal conditions were present. A total of 93-percent success for this ever-changing space technology is a fine achievement.

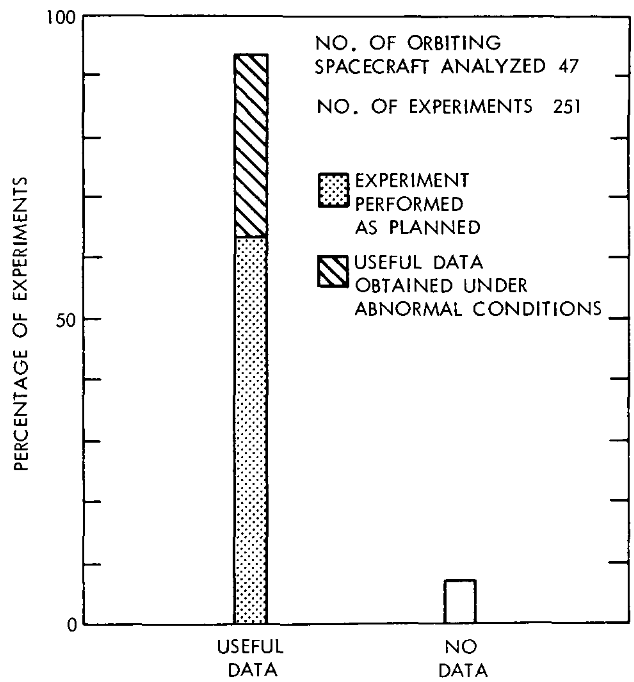


Figure 12—Flight experience of GSFC spacecraft from 1960 to 1966.

CONCLUSIONS

The unmanned spacecraft programs have used material and parts from many widely scattered sources that have not been amenable to the engineering control necessary to assure high reliability. In addition, the complexity of the design and the unknowns relative to dynamic, thermal, and other environments have prevented precise engineering analyses to be performed within the scope of the programs. Program objectives, in view of these obstacles, have been reached by placing greater emphasis on simulated environmental testing of the completed spacecraft. The tests have uncovered many hidden problem areas that could have caused loss of scientific data.

Test and flight results have shown that the many facets of producing a spacecraft interact in such a manner that it is difficult to attribute reliability to any one factor. Optimizing techniques for space programs, based on past experience, are needed if reliability is to be achieved within the restrictions of time and cost.

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