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A STUDY OF FIRST-DAY SPACE MALFUNCTIONS

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16. Abstract

A previous study had indicated that the number of first-day failures in space was higher than expected, and that elimination of "infant mortality" failures had not been achieved. The present study of 57 Goddard Space Flight Center spacecraft examines the first-day performances in summary and in detail. A total of 69 malfunctions, of which 45 were classified as failures, have been summarized by year of occurrence, by major subsystem of a spacecraft, by type of defect, and by severity. Despite the 45 first-day failures, the overall performance has been excellent. Of the 57 spacecraft, 27 had no first-day failures, and only five of the first-day failures resulted in unsuccessful missions. Redundancy eliminated the effect of 20 percent of the failures, and design reduced the impact of many other failures. A detailed study of each failure was made to determine the effect of the launch environment and to identify other factors, to judge the effectiveness of the test program, and to distill from the experiences lessons for the improvement of future space programs.

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INTRODUCTION

The performance of a spacecraft during launch and flight is influenced by many tangible and intangible factors. Good performance creates a feeling that the entire cycle—planning, design, production, quality assurance, test and evaluation, and management—is functioning as desired. A single catastrophic spacecraft loss, on the other hand, raises questions about every facet of the program. In fact, a committee investigating a catastrophic loss can usually find weaknesses in each facet of a program. The recommendations of such a committee not only improve follow-on spacecraft in the same program, but stimulate improvement in other programs. Another source of improvement for all programs may be from the composite experience gained from many spacecraft. Some reports, such as References 1 and 2, have depicted the number of failures versus time from launch. In each of these references, the number of failures per spacecraft were abnormally high for the first 30 days in space. The number of first-day failures departed even more from the longer term trend. These data raise the following fundamental questions:

1. Are the failures related to the launch environment?

2. Could a longer duration test in a simulated space environment reduce these early failures?

3. Can this experience be used to improve the performance of future spacecraft?

The present study is directed to the fundamental questions listed and to the development of any data which can be helpful in improving the performance of unmanned spacecraft. There are two primary handicaps in this kind of study:

1. The unavailability of the failed item for unambiguous failure analysis.

2. The incompleteness or lack of documented information.

The second handicap has been minimized by including only spacecraft which have been the responsibility of Goddard Space Flight Center. Documented information has been available in many cases, and in some cases, the experts on the failed item have been available for interview. The first handicap is the more difficult. The failure diagnosis usually indicates several possible causes. The selection of the most likely cause was made by the investigators after weighing the available evidence. Despite the limitations, an analysis of early space failures on Goddard Space Flight Center spacecraft will be valuable and useful to personnel concerned with the design, development, test, and performance of unmanned spacecraft.

DATA BASE

Daily Malfunction Frequency

Fifty-seven unmanned spacecraft developed under the management of Goddard Space Flight Center are the basis for this study. The experiments and subsystems for these spacecraft have been provided by various organizations, including Goddard Space Flight Center, other government agencies, universities, and aerospace companies. Eighteen of the spacecraft received a full system test at Goddard Space Flight Center, and 39 received a full system test in a contractor's facility. Figure 1 depicts the daily number of malfunctions and failures for the first month in space of the 57 spacecraft. This study will be restricted to the first-day performance, that is, 69 malfunctions, of which 45 are classified as failures. The following definitions will be applicable throughout the report:

1. A *malfunction* is any performance outside the specified limits, either a failure or a problem.

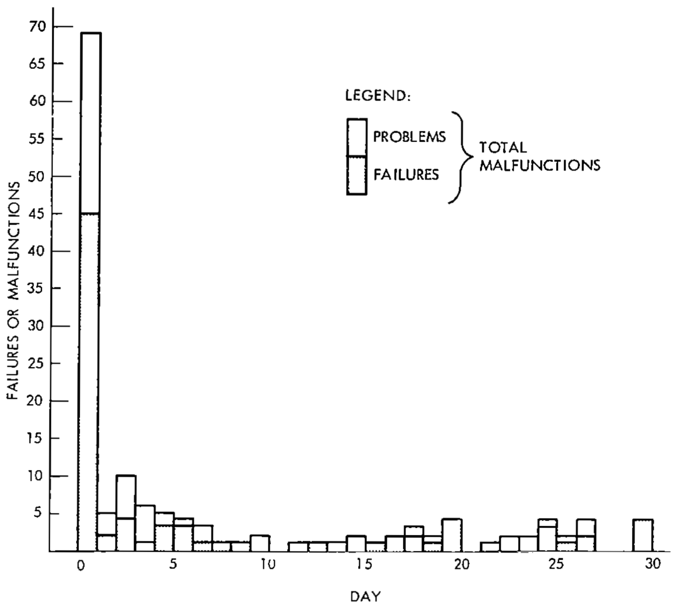

Figure 1—First-month space performance for 57 unmanned spacecraft.

2. A *failure* is the loss of operation of any function, part, component, or subsystem whether or not redundancy permitted recovery of operation.

3. A *problem* is any substandard performance or partial loss of function.

Table 1 lists the first-day failures and malfunctions for the time period from 1960 to 1970. For each year, the number of spacecraft together with the associated first-day performance is given. Table 2 categorizes the 45 failures and 69 malfunctions as mechanical, electrical, electromechanical, pyrotechnic, and miscellaneous groups. Table 3 classifies the malfunctions (and failures) by spacecraft function, that is, power, attitude control, command and data handling, structure, and experiments.

Table 1—First-day malfunctions of 57 unmanned spacecraft.

Launch Year	Number of Spacecraft	Number of Failures	Number of Malfunctions	Number of Spacecraft Without Failures	Number of Spacecraft Without Malfunctions
1960	2	1	1	1	1
1961	2	1	2	1	0
1962	8	4	8	4	3
1963	6	5	6	2	2
1964	8	6	7	6	5
1965	7	9	11	4	4
1966	6	5	9	2	2
1967	6	3	3	3	3
1968	4	4	7	2	1
1969	7	6	11	2	1
1970	1	1	4	0	0
Total	57	45	69	27	22

Table 2—Classification of first-day space malfunctions by type of device.

Type of Malfunction	Failures		Total Malfunctions	
	Number	Percent	Number	Percent
Electrical	25	55	39	57
Mechanical	8	18	11	16
Electromechanical	5	11	12	17
Pyrotechnic	4	9	4	6
Miscellaneous	3	7	3	4
Total	45	100	69	100

Annual First-Day Malfunction Frequency

The data on the number of first-day malfunctions per spacecraft each year, presented in Figure 2, indicate that first-day space failures, in broad terms, have not changed significantly over a 10-year time period. The total malfunctions appear slightly higher after 1964, and this coincides with the time when larger, more complex, spacecraft started to be launched. The bar graphs are averages per year and include the spacecraft which had no failures the first day. Of the sample of 57 spacecraft, 27 had

Table 3—Classification of first-day malfunctions by spacecraft function.

Spacecraft Function	Failures		Total Malfunctions	
	Number	Percent	Number	Percent
Experiment	25	55	33	48
Structure	4	9	9	13
Stabilization and control	5	11	7	10
Power	4	9	6	9
Command and data handling	4	9	11	16
Other	3	7	3	4
Total	45	100	69	100

no first-day failures. A look at these 27 by year (Table 1) also showed no strong trend and further indicated that the 57 spacecraft could be treated as one sample.

CRITICALITY OF MALFUNCTIONS

The 69 first-day malfunctions covered by this study include from relatively minor to catastrophic events. In some cases the consequences of a failure have been reduced because protection (e.g., redundancy) has been provided. Two terms are now defined that will help in the evaluation of the impact of the 69 malfunctions.

1. *Mission Criticality*—a measure of the effect of a malfunction on the achievement of the mission objectives. The loss is given as a percentage of the mission objectives.

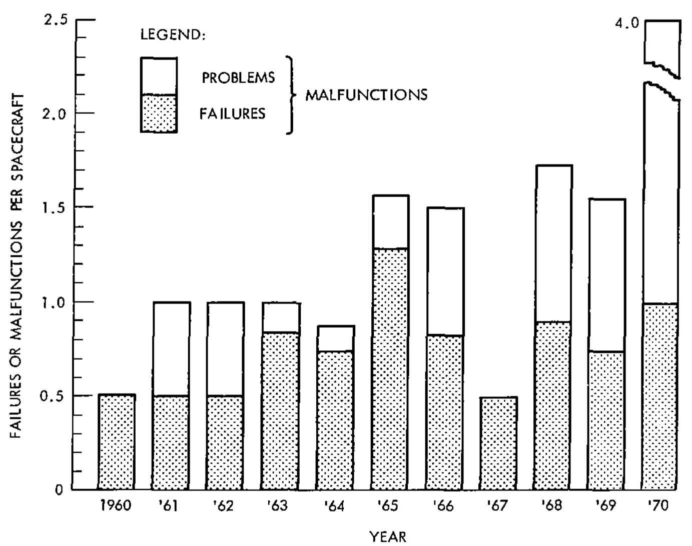

Figure 2—First-day space performance for 57 unmanned spacecraft.

2. *Component Criticality*—a measure of the effect of a malfunction on the operation of a component. The loss is given as a percentage of component operation.

Mission Criticality and component criticality can each be considered with and without the effects of protection. For example, a hypothetical malfunction could be that a photomultiplier tube fails. If the tube is a basic sensor in an experiment, then before protection, the loss of the tube is highly critical to the experiment (component). If there is a redundant tube that can be turned on, then the loss of the tube is not critical to the experiment. If the failure of the experiment (component) did not detract significantly from the mission objectives, as could be the case for spacecraft with several experiments, the mission criticality would be low with or without the redundant photomultiplier tube. Now suppose that the failure mode was a high voltage breakdown that damaged the spacecraft power supply. In this case the mission criticality would be high. If the spacecraft power supply were protected such that a high voltage breakdown of the tube would not damage the supply, then the mission criticality is again low. The preceding example illustrates how a single malfunction can be examined in terms of component criticality, before and after protection, and mission criticality before and after protection. There are two reasons for considering criticality before and after protection. First, there is something to be learned from a malfunction in terms of future efforts even if the criticality of the malfunction has been reduced by protection. Second, the effect of protection can be evaluated.

Figure 3 shows the mission criticality distribution. The catastrophic and major degrading malfunctions (categories 1 and 2) make up 13 percent of the total number of malfunctions before protection is considered. After protection these malfunctions are reduced to 8 percent of the total. The reason for this small decrease is that there was no protection for most of these malfunctions. This result emphasizes the importance of giving a great deal of attention to unprotected mission-critical items. (One fact that should be mentioned here is that there is a good deal of block redundancy at the piece-part level, so that the failure of a piece part may never show up as a malfunction, and thus the effect of redundancy at this level cannot be evaluated.)

Figure 4 shows the component criticality distribution of malfunctions. The catastrophic and major degrading (to the component) malfunctions make up 54 percent of the total before protection is considered. Protection reduces these malfunctions to 36 percent of the total. (The effectiveness of redundancy is higher when category 1, 2, and 3 malfunctions are used as the basis of comparison.)

Now consider the data of Figures 3 and 4 together. 54 percent of the malfunctions were catastrophic or major degrading to the components involved if redundancy had not been provided. Redundancy reduced the 54 percent to 36 percent. However, only 8 percent of the malfunctions were catastrophic or major degrading to the mission. The reduction from 36 percent to 8 percent is attributed to effective isolation of damage by design. For instance, catastrophic experiment failures have not resulted in catastrophic mission failures.

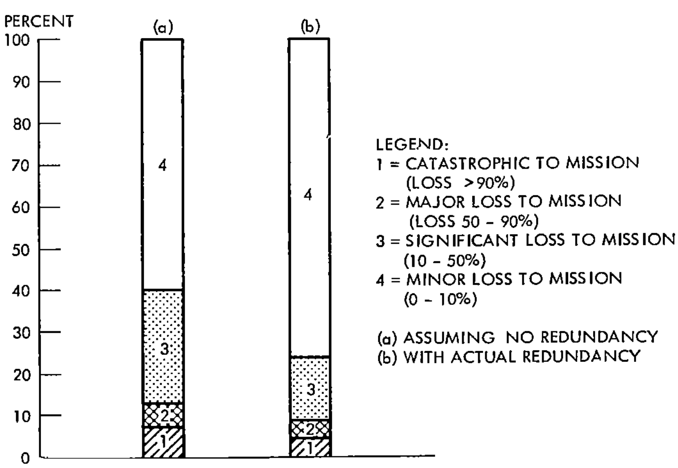

Figure 3—Mission criticality of first-day malfunctions of 57 unmanned spacecraft.

CLASSIFICATION OF MALFUNCTIONS

Malfunctions Related to Type of Device

A classification of the first-day space malfunctions by type of device is given in Table 2. It shows that the electrical type accounts for over 50 percent of total malfunctions, and also 50 percent of the failures. The percentage ranking is not emphasized, as

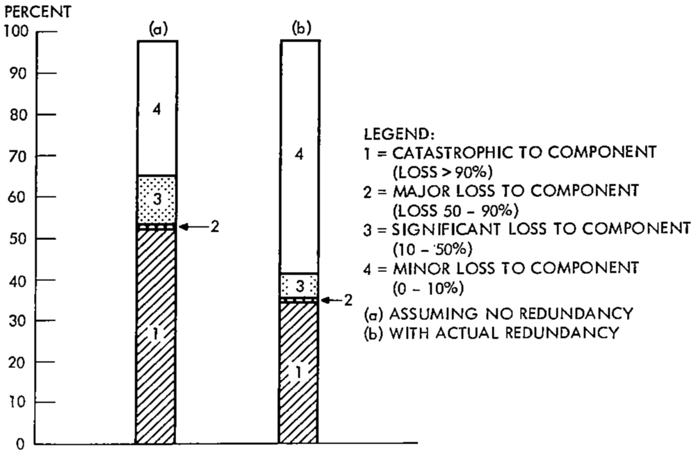

Figure 4—Component criticality of first-day malfunctions of 57 unmanned spacecraft.

it would probably be reordered if normalized by piece-part or black-box count. The results do indicate the type of device which has contributed the largest number of malfunctions and failures.

Another classification, by spacecraft function, is provided in Table 3. Over 50 percent of the failures have been on experiments. While this indicates a fruitful area for improving early space performance, two additional points need to be noted. Many experiments fly state-of-the-art hardware with the attendant risk. Also, a project manager can take a higher risk on an experiment knowing its failure will be isolated from other spacecraft functions. Overall, the performance of experiments has been good; at the same time, to improve our early space performance, the number of experiment failures needs to be reduced. The term "structure" as used in Table 3 includes such items as appendages and booms. In no case was there a failure of the basic spacecraft structure.

Malfunctions not Related to the Launch Environments

Since this paper deals with malfunctions that have occurred on the first operational day in space, the launch environments are a possible cause. The launch environment has many facets. The most obvious aspect is the vibration/acoustic environment. However, such things as changing pressure, outgassing of materials, and thermal effects during the first day are all possible causes of malfunctions. Many of the malfunctions fit into these categories, but there were a significant number that did not. Those malfunctions that were known or judged to be unrelated to an environment were removed from the sample of malfunctions. This diminished base of malfunctions—total minus those unrelated to environment—was then used to compute the test effectiveness, with respect to first-day malfunctions. A test effectiveness can be calculated for vibration, simulated space test, or total test program. For this purpose, the total number of vibration defects, for example, were those found in test plus those which occurred the first day in space. The vibration test effectiveness is then defined as the percentage found in test of the total number of defects.

A question might be asked as to how it was determined that some of the malfunctions were not related to the launch environments. In some cases, this was very simple, whereas in others it was a matter of judgment. For instance, two particular malfunctions were explained by a wiring error. The error in the drawing was not found until it was necessary to investigate the space malfunction, but these malfunctions certainly were not caused by the launch environments. In other cases, information available on the nature of the failures revealed that they were not caused by the launch environments. For example, one spacecraft spun up about the wrong axis because of the overpowering of the active nutation control system by an energy sink that was not fully anticipated. Again, this is not a launch environment problem. Many of these problems unrelated to the launch environments could possibly have been found during the environmental test sequence, but their detection would not have been due to the environment. Therefore, in assessing the effectiveness of environmental tests, the first-day failures not caused by the environment have been deleted. In the vibration-related study, 34 percent of the failures were judged to be unrelated to vibration, while in the thermal-vacuum study, 56 percent were judged to be unrelated to this environment.

Vibration-Related Malfunctions

The first method used to analyze space malfunctions was to decide whether the malfunctions were probably or even possibly related to the launch vibration. In most cases, the launch vibration environment could not definitely be established as the cause of the problem. A number of reports did mention vibration as a possible cause, though, and when this was the case, the malfunction was considered vibration related. There were other malfunctions that were judged to be possibly vibration related, although reports did not attempt to assess the cause.

The second way in which the data were analyzed was to determine whether the malfunction was unrelated to vibration; that is, if vibration could not be ruled out, then it might possibly have been the cause. A few additional malfunctions fell into this unknown category. These two methods will be used to put bounds on the vibration test effectiveness.

Vibration Test Effectiveness

The vibration ground test and flight data were examined to try to answer two basic questions:

1. How well does the vibration ground test detect malfunctions that are vibration related?

2. Is there any relation between the number of malfunctions a spacecraft has during test and whether it has any in space?

The answer to the first question can be thought of as the test effectiveness. According to the definition of test effectiveness given previously, the vibration ground test was found to be between 80 percent and 90 percent effective. The data were also used to calculate the vibration test effectiveness for several different types of spacecraft equipment: electrical, mechanical, electromechanical, and pyrotechnic. The results are summarized in Figure 5. The mechanical device test effectiveness indicates that vibration testing eliminates almost all vibration caused mechanical device malfunctions. The electrical device test effectiveness is nearly as good as the mechanical. The electromechanical device test effectiveness drops off significantly, and the pyrotechnic device test effectiveness is poor. The upper bound on the test effectiveness was calculated from the defects that were possibly vibration related. The lower bound was calculated from the possibles plus the unknowns. The sample for electromechanical and pyrotechnic devices is small, and this tends to diminish the confidence in the calculated test effectiveness of these devices.

In order to answer the second question about the relationship of the number of test malfunctions and the number of space malfunctions, the spacecraft were categorized according to the number of malfunctions they had experienced during vibration test. These data are presented in Figure 6. The abscissa is the number of malfunctions a spacecraft had during test, and the ordinate is the number of spacecraft with that given number of malfunctions. The space performance was then examined to determine how many spacecraft in each category later had a space failure. For example, of the eight spacecraft that had zero test malfunctions, only one (12 percent) suffered a space failure. Of the four spacecraft that had four test malfunctions, two (50 percent) had space failures. The percent in each category is shown in Figure 7.

Malfunctions With Unknown Cause

In a strict sense, all of the malfunctions could be classified as due to an unknown cause. In no case was the hardware recovered. Hence, the various classifications have been made on the basis of circumstantial evidence and judgment. This leads to an apparent contradiction, which is explainable. With respect to the thermal-vacuum environment, some 30 percent of the malfunctions were classified as unknown, but with respect to the vibration environment, only 22 percent were classified as unknown (see Figure 8). An example will make the contradiction understandable.

An experiment which had a sealed cover did not function in space. The evidence indicated that the ordnance used to eject the cover did not fire. A no-fire condition could result either from a broken bridge wire in the ordnance, or from an open circuit, and there were several connectors in the firing line. Thus, for the purpose of classification, this failure was possibly related to vibration, but unknown for its relationship to the thermal-vacuum environment.

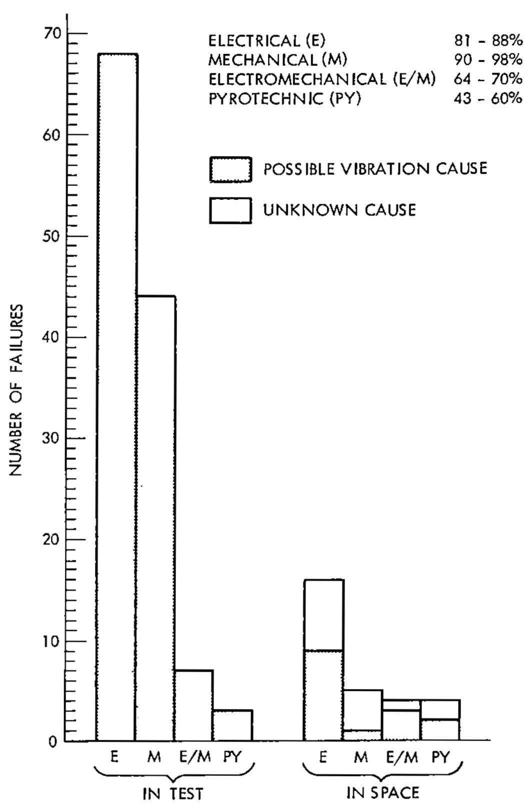

Figure 5—Vibration test effectiveness.

Thermal-Vacuum Related Malfunctions

About 9 percent of the malfunctions were judged to be caused by the thermal-vacuum environment. In each case except one, the evidence indicated a corona problem. In one case, the corona was catastrophic to the mission, and in the others, it was catastrophic to an experiment. Another 29 percent were classified as due to unknown causes and could possibly have been related to the thermal-vacuum environment.

The number of malfunctions related to the thermal-vacuum environment is small compared to the number related to the vibration environment (9 percent versus 44 percent). This is due to the fact that this study considers only the first-day malfunctions. A study of malfunctions that occurred after the first day could be expected to change the ratio.

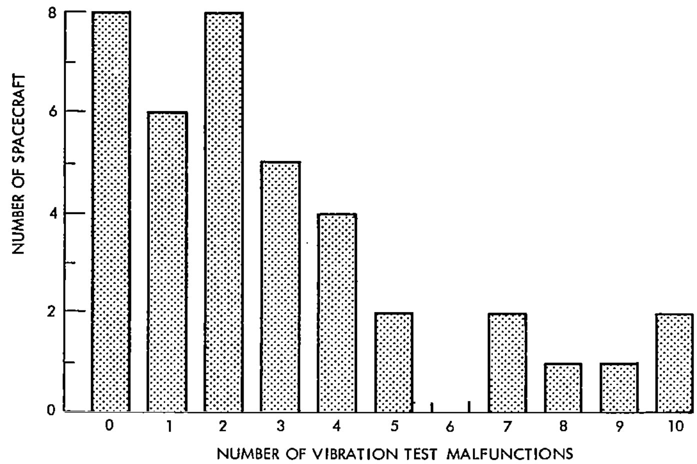

Figure 6—Vibration test performance.

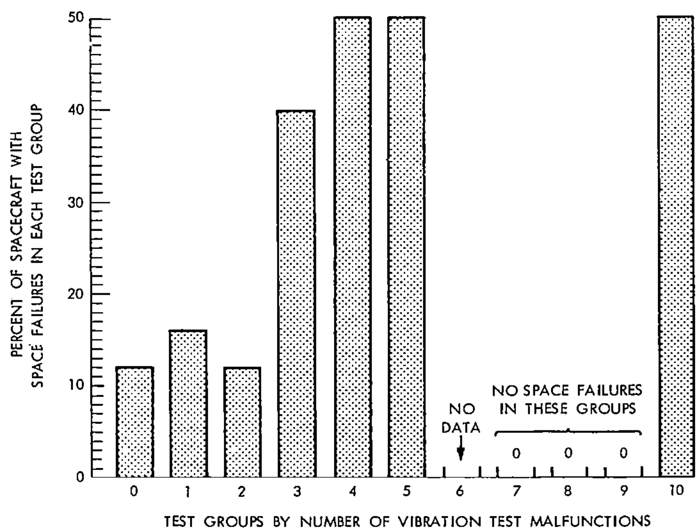

Figure 7—Relationship of first-day space failures to the launch environment.

Thermal-Vacuum Test Effectiveness

An estimate of the effectiveness of the thermal-vacuum ground test with respect to first-day space failures was derived from detailed data on 43 of the 57 spacecraft. (The use of 43 spacecraft for this part of the study was dictated by the lack of test data for some programs.) The test effectiveness is the total number of failures found in the thermal-vacuum test of the flight spacecraft divided by that same number plus the number of first-day space failures related to the thermal-vacuum environment.

The test effectiveness was 98 percent when the only space failures included were those considered to be related to the thermal-vacuum environment. When the space failures also included those categorized as due to unknown cause, the indicated test effectiveness was 91 percent.

An estimate of the overall test program effectiveness with respect to first-day failures gave 93 percent. This was calculated using all failures detected in the test program and all first-day space failures from the 43 spacecraft.

DISCUSSION

Criticality

The data on criticality of malfunctions has some important reliability implications. Of nine catastrophic and major degrading mission-critical failures, five did not have redundancy. Of the four which had redundancy, one failure caused such widespread damage that the redundancy was of no value. Also, in no case was a catastrophic mission failure attributed to an electronic piece-part failure, although one possible open circuit could have been a relay failure. Although the conclusion is obvious, the data emphasize the need for special attention to non-redundant items.

Of the total 69 component malfunctions, 45 were classified as failures. About 40 percent of these were eliminated by redundancy. Of the remainder, about 40 percent were restricted in effect to the component or experiment, and did not result in a significant mission loss. In other words,

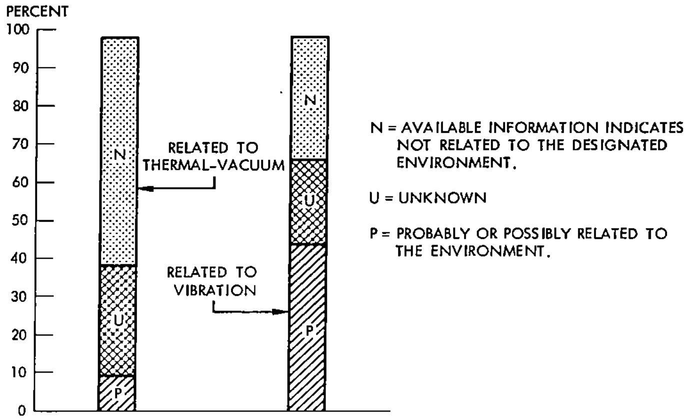

Figure 8—Relationship of first-day space failures to the launch environment.

design, either redundancy or isolation of damage, reduced to 16 the number of failures which had a significant effect on attaining mission objectives.

Overall, the mission criticality of component failures has been reduced effectively either by redundancy or by isolation of failure damage by design. On the other hand, these data indicate that catastrophic and significantly degrading mission failures can be expected in the future. The cause will probably not be a failure of an electronic piece part, but rather a design, a function, or an item that cannot be effectively demonstrated in test. It should be noted that there is no way of knowing how many mission-critical failures were saved by redundancy of electronic piece parts.

Catastrophic Failures

Catastrophic and major degrading mission failures have usually been the result of a design problem which was not or could not be tested adequately. Table 4 attempts to summarize the category 1 and 2 mission-critical failures. The summary is a gross oversimplification, for each failure was the subject of intensive study and investigation. In most cases, a comprehensive report gives much more information than can be documented here. However, some important lessons learned from the catastrophic mission failures are summarized below:

1. Special attention and analysis is required for non-redundant, mission-critical items, especially if they cannot be functionally tested in the system configuration.

2. Although electronic piece parts can cause loss of missions, the experience reported does not show this to be a prominent cause.

3. Deployment mechanisms should be designed with large margins of safety. If feasible, redundancy in force producing elements should be considered.

4. Deployment tests should be performed after vibration tests, and should include temperature simulation when applicable.

5. High voltage subsystems should be tested in a launch-pressure profile environment if possible. If this is not possible, then turn-on in space must be delayed until the subsystem is known to be out of the critical-pressure region. That is, the turn-on time used in orbit should be no sooner than that used in the simulated space test of the spacecraft.

6. The design capacity of an attitude control system must be sufficient to handle all sources of energy dissipation, including the energy dissipation from the fluid in any heat pipes.

Table 4—Summary of category 1 and 2 mission failures.

Item	Redundant	Design Problem	Tested Adequately	Description
1	No	Yes	No	Could not maintain earth lock because the horizon scanners locked on extraneous thermal gradients in the earth's infrared image. Gas supply in the attitude control system was depleted in about 9 days. Corrected subsequently by reduction of bandwidth for horizon scanners.
2	No	Yes	No	Two of eleven booms deployed only partially and one made a false horizon for the horizon scanner. A single cause was not determined, but marginal torque of the springs in the boom hinges was a prominent factor.
3	Yes	Yes	No	Solar panel failed to deploy completely. Spinup completed deployment.
4	Yes	No	No	Vidicon camera degraded because of contamination from third stage rocket.
5	Yes	No	No	Arcing of star tracker caused electrical transients and noise which caused widespread damage. Many functions including telemetry were affected.
6	No	Yes	Yes	Controller failed to properly control the charge current to the batteries and temperature became excessive. One possible cause was an open circuit from a relay failure.
7	?	?	?	Sharp cut-off of telemetry signal 20 seconds after ignition of apogee motor. Many failure modes possible. Pressurized titanium tanks were notch sensitive, which made them suspect, but postmortem tests did not verify this conclusively.
8	Yes	No	Yes	A squib failure precluded spin-up of spacecraft/booster. Redundant squib satisfactory.
9	No	Yes	No	Rapid and excessive nutation overpowered the automatic nutation control system and the spacecraft went into a flat spin. A principal cause was the lack of definitive data on the damping characteristics of the heat pipes. Several experiments still provided good data.

Experiment Failures

The data have shown that over 50 percent of the first-day failures were on experiments, and this is the most fruitful area for improving the first-day space performance. The information available on each failure was reviewed for clues on ways to improve the first-day space performance of experiments. There is no single weakness evident, as indicated by the tabulation in Table 5.

Table 5—Classification of first-day space failures of experiments.

Classification	Percent of Failures
Fragile and sensitive items	24
Wiring, connectors, shorts	16
High voltage	12
Electronic piece part	8
Contamination	8
Unknown	20
Miscellaneous	12

The surprise is the comparatively low percentage of failures attributed to fragile and sensitive items. These items have been and will continue to be a source of concern, but the record to date has been very good. Continued vigilance on high voltage susceptibility, wiring errors and routing, and interrupted circuits from marginal connectors is necessary; and especially, it should be demonstrated that vibration does not cause changes in these items. Quality assurance, screening tests, preferred parts burn-in tests, redundancy, etc. have apparently been quite successful in limiting failures from electronic piece parts. The item in the table on contamination shows only 8 percent but this factor probably will be more important in the future. With the trend toward more cryogenic-type detectors, the outgassing of materials will be more critical. A heater capability on a cryogenic detector could possibly have saved one experiment. Future cryogenic detectors are planned to have a heater capability to offset possible contamination problems.

These data show that improvement of experiment performance in early space life will not be achieved by the elimination of a single primary cause. Improvement will be achieved only by continued or increased diligence and vigilance in all the known trouble areas.

CONCLUSIONS

This study has dealt only with first-day space malfunctions and failures. Consequently, it may give a distorted picture of the performance of GSFC spacecraft for the ten years covered by the study. On the success side of the picture, 56 of the 57 spacecraft obtained useful scientific data. A listing of the scientific accomplishments would be most impressive, but would be too extensive for this study. It will suffice to say that there has been a quantum jump in our knowledge of the earth, lunar, and cislunar atmospheres, of the sun, and of the stars. In addition, the advances in communications, television transmissions between continents, and weather forecasting are already accepted as everyday happenings. Truly the successes are outstanding, and the present study is not intended to detract from them. Our purpose will be achieved if the experience documented in this study is helpful in reducing the number of first-day space malfunctions in the next decade.

The following conclusions are drawn from the study of first-day malfunctions:

1. The incidence of first-day malfunctions has been higher than desired.

2. The ratio of catastrophic mission malfunctions to the total first-day malfunctions is small.

3. Electronic piece-part failures have not been a cause of the catastrophic mission failures.

4. Catastrophic or major degrading first-day mission failures were usually identified with items that could not be (or were not) given an adequate system level test.

5. Corona failures, although not prominent in number, can be catastrophic in damage.

6. The vibration/acoustic launch environment is estimated to account for 30 to 60 percent of the first-day space failures reviewed in this study.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, May 17, 1971
697-12-06-01-51

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