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AN APPLICATION OF FAILURE FLOW ANALYSIS TO A GSFC SPACECRAFT PROJECT

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GODDARD SPACE FLIGHT CENTER
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SUMMARY

This report discusses the use of failure flow analysis to evaluate the test program of the Interplanetary Monitoring Platform I (IMP-I) spacecraft. The flow of defects from point of origin to point of detection is mapped. The effectiveness of the various screen systems is calculated, and the reasons for escape from the screens is presented. The distribution of causes of defects is examined, and the criticality of the defects is determined. The flight results are compared to the test performance.

The bench test screen and subsystem test screen are both only about 50% effective, while the system test is 92% effective. Design is a major cause of defects, but the number of parts defects - in test and in space - is significant. About half of the defects detected in test would have resulted in a much degraded subsystem performance if they occurred in space, but few defects would have affected the entire mission. The flight results seem to show the ability of a protoflight test program to detect fabrication caused defects.

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AN APPLICATION OF FAILURE FLOW ANALYSIS TO A GSFC SPACECRAFT PROJECT

INTRODUCTION

Failure flow analysis was developed by the General Electric Company and was applied to the RAE-A system test program in 1969 through a contract monitored by the Past Experience and Performance Program of the Test and Evaluation Division (ref. 1). This method of analyzing a test program showed promise for analyzing other GSFC test programs so a decision was made to do a failure flow analysis as an in-house effort.

Description of Failure Flow Analysis

Failure flow analysis depends on an accurate malfunction reporting system as its major source of data. The data is analyzed to provide information on such things as the criticality of defects, where the defect originated, what the cause of the defect was, why the defect escaped certain test screens, and others. In this way the defect can be tracked through a program from source to detection and diversion, and hence, the analogy with defects flowing through a system of screens.

There are two major facets to failure flow analysis. First, it critically examines a test program and indicates which areas need improving. Second, it points out the sources of defects, which could lead to the elimination of some sources and the diminution of others.

The Use of IMP-I for This Study

IMP-I was chosen as the program for the application of failure flow analysis. Although this study was undertaken primarily to evaluate the practicability of using failure flow analysis on a large scale basis, the IMP-I test program provided an opportunity to collect some data that would be useful regardless of failure flow analysis. More detailed reasons why IMP-I was used are provided in the next three paragraphs.

1. IMP-I was an in-house program. This meant that most of the testing was done at GSFC, and individual tests could be observed if desired. Also, many of the designers and fabricators of the hardware were available when questions arose on the nature or consequences of a particular malfunction.

2. IMP-I had an extensive and well documented subsystem test program. Past examinations of system test programs have been hampered by a lack of information on performance prior to system testing.

3. IMP-I was a protoflight spacecraft. Since the protoflight concept is becoming popular, and IMP-I was the most complicated protoflight spacecraft ever built at GSFC, then the IMP-I test program could provide valuable information on the strengths and weaknesses of the protoflight concept.

Definition of Terms

There are a number of terms that are used in failure flow analysis that need to be defined here.

1. Definition of Defect - the term defect encompasses the standard connotation of manufacturing flaws, but also includes any imperfection in the specifications, drawings, software, or hardware in a spacecraft program. In this report, two types of defects - systematic and non-systematic - are considered. Defects which can occur with regularity on all production units are described as "systematic." Defects which occur only by chance on isolated production units are described as "non-systematic."

2. Definition of Malfunction - defects are visible only when they manifest themselves through the occurrence of an anomalous condition in the program. Such anomalous conditions are normally termed "malfunction." Such terms as failure, anomaly, and problem are all included in "malfunction."

3. Definition of Protection - as used in failure flow analysis, protection is any hardware or procedure that is used to overcome the effects of a malfunction. For example, redundancy is a common type of hardware protection, and the ability to override an automatic operation with a ground command is a type of procedural protection.

4. Definition of Criticality - the "criticality" of a defect is determined from the effect a malfunction would have on the operation of the subsystem, and also the effect of the malfunctioning subsystem on the mission objectives. This report considers four levels of criticality - catastrophic, major degrading, minor degrading, and negligible. When the effects of protection, such as redundancy, are included, there are four ways of looking at the criticality of each defect: (1) subsystem before protection; (2) subsystem after protection; (3) mission before protection; and (4) mission after protection.

5. Definition of Screen - a screen is any activity whose purpose is the detection and diversion of defects. Detection is the acknowledgement that a defect exists and the identification of the defect. Diversion is the removal of the defect from the system. Defects may escape a screen, and thus remain in the program (or in the flow), by either escaping detection or by escaping diversion.

6. Definition of Card - a card is the smallest assembly of a subsystem or experiment. It is usually a trapezoidally shaped metal box that contains numerous piece parts, has its own connectors, and is potted as a unit. Some experiments contained only one card, while others used three or more. During bench test and subsystem test each card in an experiment or subsystem was often tested separately, rather than the whole subsystem or experiment.

7. Definition of Ineligible - a defect is ineligible for detection by a screen when the defect is of such a nature that the screen would not normally be expected to detect the defect (e.g., a defect that could only be found in thermal-vacuum would not be eligible for the vibration test screen). Ineligibility also applied to defects that were not in the flow yet, were not presented to the screen, were time dependent failure processes, were due to some variability in the hardware, or were not presented to the screen at a high enough level of assembly. (An example of a time dependent defect would be a void that requires a month to outgas to the point where the pressure is in the critical region for voltage breakdown. This would be ineligible for the thermal-vacuum test screen, since the test only lasts two weeks.)

8. Definition of Inadequate - a screen is inadequate if it does not detect a defect that it should detect.

Structure of Failure Flow Analysis

Failure flow analysis divides the test program into a series of screens. The defects are represented as "flowing" through the screen system with each screen acting like a sieve for particular kinds of defects. In the analysis each screen is considered separately, and then groups of screens are considered as an aggregate.

The screen system for IMP-I is presented in Figure 1. This screen system is shown divided into four separate groups - bench test, subsystem test, system test, and orbit. Individual screens in each group were examined, and then each group was considered as an aggregate. The next section of this report will deal with the bench test screen, and succeeding sections will be concerned with subsystem test screens, system test screens, space performance, and conclusions.

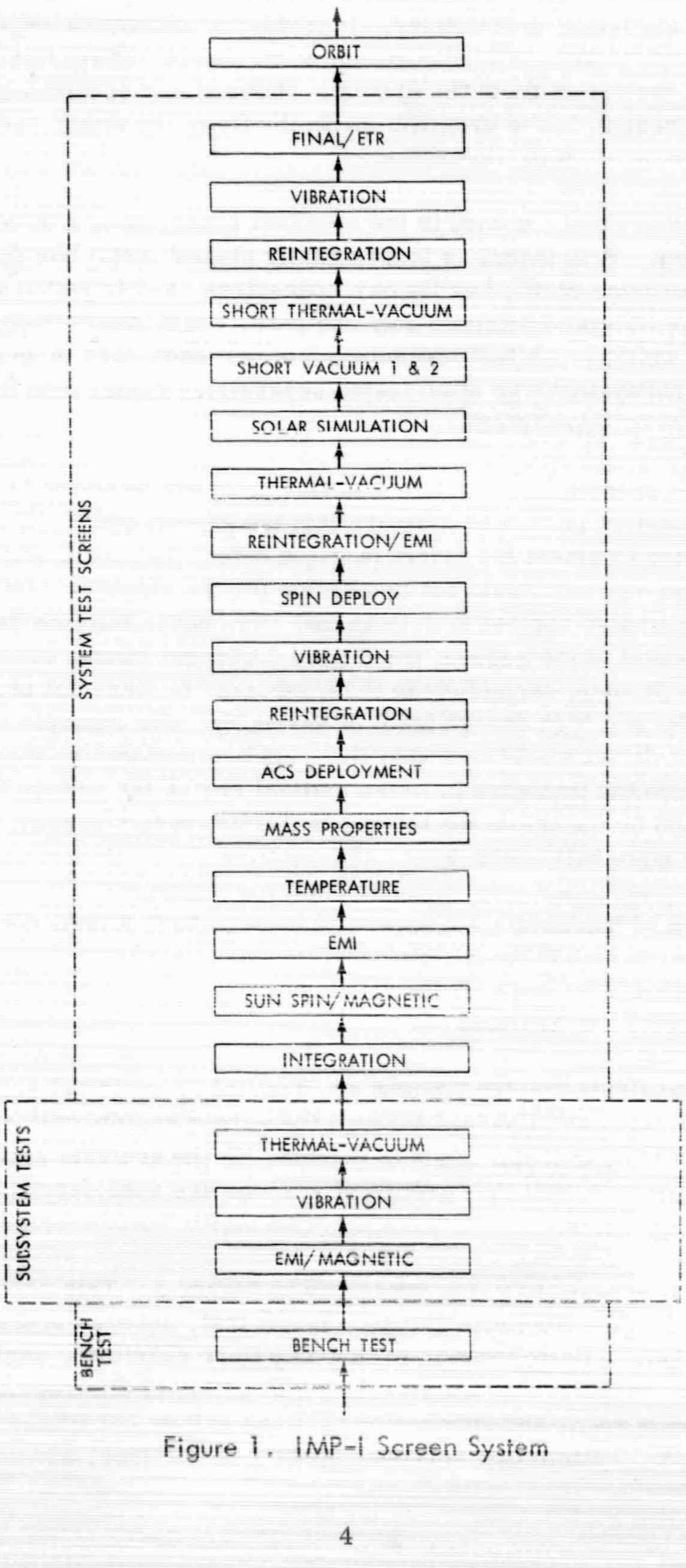

Figure 1. IMP-I Screen System

BENCH TEST SCREEN

Description of the Bench Test Screen

The bench test screen is shown in Figure 2. Any testing that is done subsequent to fabrication but prior to formal environmental test is included in this screen. This is the screen where the initial problems are worked out of the hardware. It could include anything from ambient testing to testing in a designer's own temperature or thermal-vacuum chamber. These tests can be thought of as developmental tests. For this reason, many defects found at this stage are not reported as malfunctions, although a few are reported, so that the extent of activity during the bench test screen is only partially known. The amount of testing done during this screen depends on the practice of each individual designer. The significance of the numbers is given below under Performance. . .

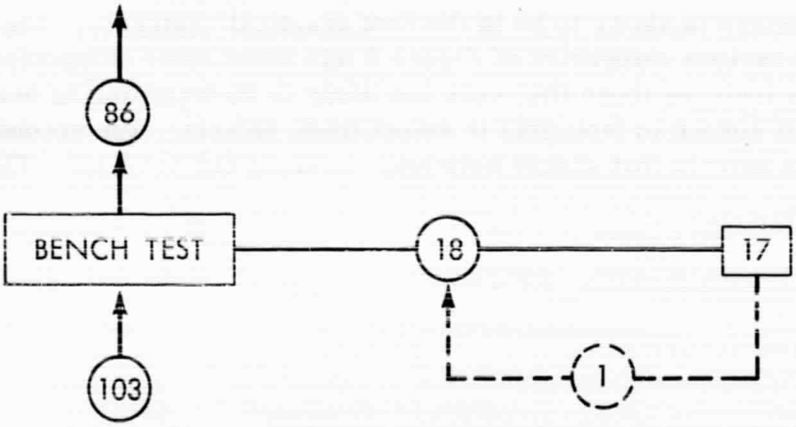

Figure 2. Bench Test Screen

One reason for considering the bench test as a screen is that a number of defects that are detected by a screen further downstream in the test program could have been found by the bench test screen. In failure flow terminology, bench test is the most eligible screen for a number of defects found later in the test program. If the reasons for escape from the bench test screen can be determined, then the bench test screen could possibly be made more effective, and the loading on the screens further downstream could be reduced.

Performance of the Bench Test Screen

Every defect, with the exception of those generated during the test program, had to pass through the bench test screen. Of the 125 malfunctions reported in malfunction reports throughout the program, 17 were detected and diverted during bench test. As was mentioned earlier, however, not all malfunctions occurring during bench test are reported. The difference between the 125 malfunction reports and the 103 defects entering bench test is that 22 defects did not go through the bench test screen.

Reasons for Escape from Bench Test Screen

The reasons for escape from the bench test screen are given in Figure 3. The largest percentage is shown to be in the "not practical" category. Figure 4 combines the various categories of Figure 3 into three basic categories. The first category includes those that were not likely to be found during bench test. The bench test screen is ineligible to detect these defects. The second category includes those defects that should have been detected but were not. These are

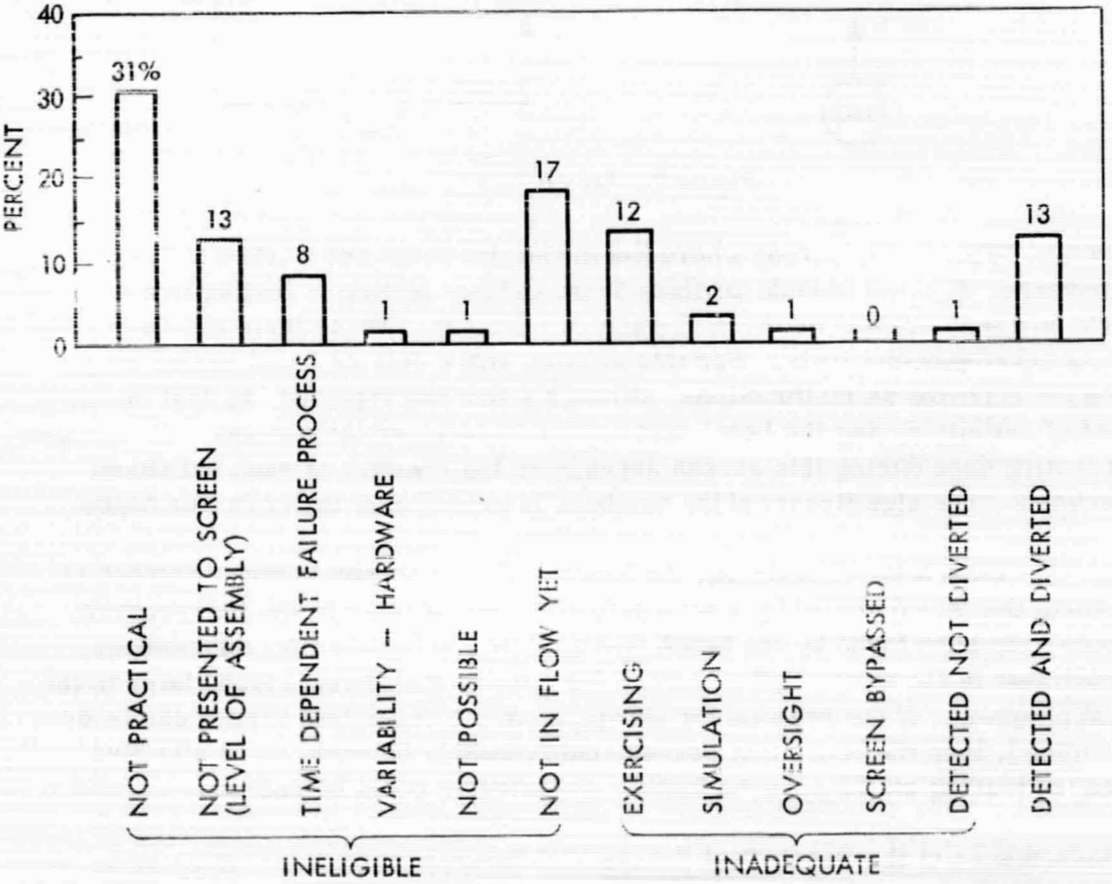

Figure 3. Reasons for Escape from Bench Test Screen

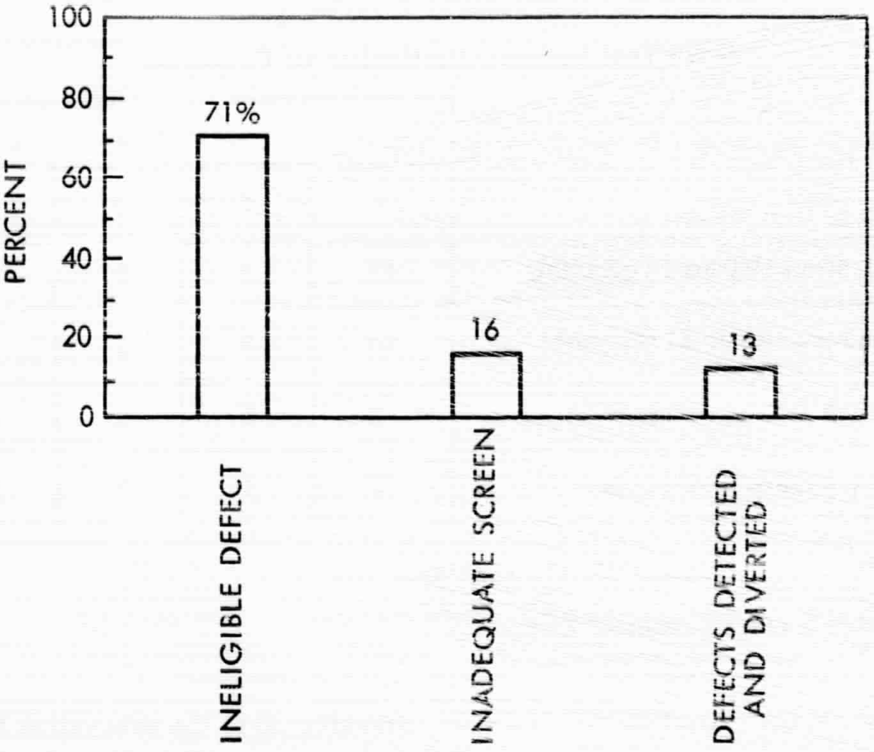

Figure 4. Diversions and General Reasons for Escape from Bench Test Screen

the true escapes, and generally speaking the screen was inadequate to detect them. The third category includes the defects that were detected and diverted. Figure 4 shows the bench test screen to be less than 50% effective. A screen effectiveness is calculated by dividing the number of defects eligible for detection in a screen into the number of defects that actually were detected. Because of the number of malfunctions that were unreported, not much confidence can be placed in the calculated effectiveness of the bench test screen.

Criticality of Defects Found in Bench Test Screen

As mentioned previously, there are four criticality categories. Category 1, catastrophic, is a 90 percent to 100 percent loss of operation. Category 2, major degrading, is a 50 percent to 90 percent loss of operation. Category 3, minor degrading, is a 10 percent to 50 percent loss of operation. Category 4, negligible, is a less than 10 percent loss of operation. Table 1 shows the subsystem and mission criticalities before and after protection of the defects detected in the bench test screen. The numbers in the table are numbers of defects.

Table 1

Bench Test Screen: Criticality vs Protection

	Criticality			
	1	2	3	4
Subsystem Before Protection	12	3	1	1
Subsystem After Protection	10	3	1	3
Mission Before Protection	2	2	1	12
Mission After Protection	2	1	1	13

Note 1: Criticality

1 90% - 100% loss
2 50% - 90% loss
3 10% - 50% loss
4 0% - 10% loss

Note 2: Numbers in table are number of defects.

Twelve of the seventeen defects were catastrophic to the subsystem before protection, and protection does very little to reduce the criticality. On the other hand only about one-eighth of the defects are catastrophic to the mission, but, again, there is practically no protection. If these patterns were to persist throughout the screen system, then a space malfunction would probably lead to the loss of a subsystem. If a malfunction occurred in a mission critical item, the probability would be that the mission would be lost. Consideration of the major degrading (criticality 2) defects does not improve this picture.

Criticality versus Probability of Space Malfunction

When the causes of the defects are considered, some of the defects will be shown to have been caused by some faulty test or checkout activity. These defects are classified as generated defects. There is also the possibility in any test program that some malfunctions will occur in test that would not necessarily occur in space. Because of these situations, each defect has been examined for its probability of causing a malfunction in space. Figure 5 presents the results of this examination. As can be seen, 71 percent of all the defects found in the bench test screen had a high probability of causing a malfunction in space. This information alone is not enough to describe the situation, however. Another important piece of information is how the most critical defects are distributed with respect to the probability of causing a space malfunction. If the catastrophic defects had a low probability of causing a space malfunction, then the alarm

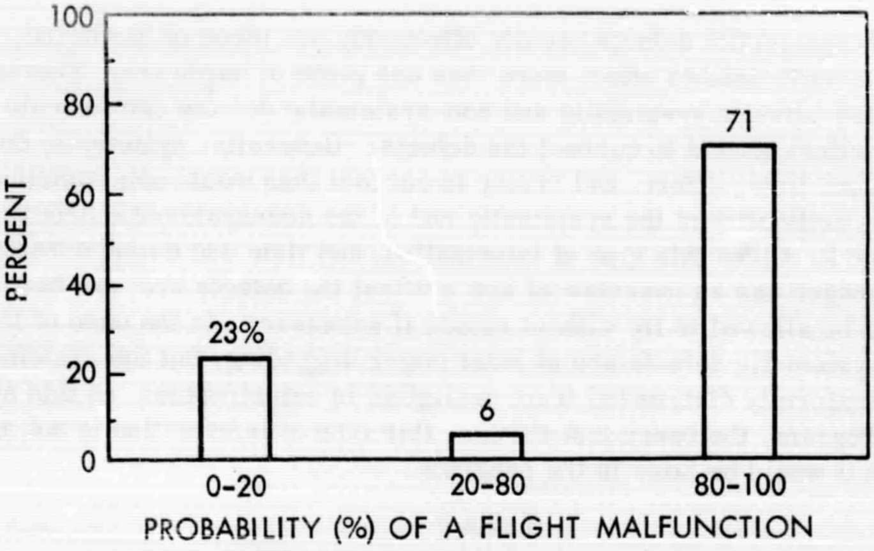

Figure 5. Probability that Defects Found in Bench Test Screen Would Have Caused a Malfunction in Space

caused by having a large percentage of catastrophic defects can be relieved. Table 2 shows, though, that this is not the case, since 85 percent of the catastrophic and major degrading defects (to subsystems before protection) had a high probability of causing a space malfunction.

Table 2

Probability of Flight Malfunction vs Criticality of the Malfunctions Found in Bench Test Screen (Numbers in table are numbers of defects)

Criticality	0-20	20-80	80-100
1	2	1	7
2	0	0	3
3	2	0	0
4	0	0	2

Probability (%) of a Flight Malfunction

Criticality in percent loss of function:

1 - 90% - 100%

2 - 50% - 90%

3 - 10% - 50%

4 - 0% - 10%

Criticality versus the Systematic Nature of Defects

In a program where several "identical" pieces of hardware are going to be made, the determination of the systematic nature of the defects can be of some benefit. Non-systematic defects usually affect only one piece of hardware, whereas systematic defects affect more than one piece of hardware. Therefore, the distribution between systematic and non-systematic defects can indicate the extent of the effort needed to correct the defects. Generally, systematic defects would take more time, effort, and money to correct than would non-systematic defects. The criticality of the systematic and of the non-systematic defects is given in Table 3. Given this type of information, and time and dollar constraints, a project manager has an overview of how critical the defects are, and how many defects could be allowed to fly without repair if necessary. In the case of IMP-I, all the non-systematic defects are at least major degrading, but the systematic defects are uniformly distributed from negligible to catastrophic. At this stage of the test program, the bench test screen, this type of information is not as important as it would be later in the program.

Table 3

Systematic Nature of Defects vs Criticality of Defects
Found in Bench Test Screen

	Systematic	Non-Systematic
1	2	8
2	1	2
3	2	0
4	2	0

Criticality in percent loss of function

1 - 90% - 100%
2 - 50% - 90%
3 - 10% - 50%
4 - 0% - 10%

Causes of Defects

The causes of the defects detected in the bench test screen are shown in Table 4. The causes are presented in five general categories: design, fabrication/assembly, parts/materials, operator error/GSE/handling, and miscellaneous. During the analysis, each of these categories has a number of sub-categories. For example, design has a packaging and mounting sub-category. Thus, if any one sub-category begins to accumulate a large number of defects then this particular cause could be flagged as a matter for attention. The large percentage of design defects shown in Table 4 is not surprising for the bench test screen since this screen is used to debug the hardware. What is somewhat surprising is the 12 percent due to parts/materials. This seems to be a high percentage, but there are no data from other spacecraft at this level of test which would indicate the "normal" number of parts/materials defects.

Table 4

Causes of Defects Found in Bench Test Screen

Design	41%
Fabrication/Assembly	29%
Parts/Materials	12%
Operator/GSE/Handling	12%
Miscellaneous	6%

SUBSYSTEM TEST SCREENS

This section of the report will failure flow analyze each of the subsystem test screens individually and also analyze the aggregate of the three screens as an overall subsystem test screen.

Description of Subsystem Test Screens

The subsystem test screens are shown in Figure 6. These are seen to be three individual screens: magnetic/EMI, vibration, and thermal-vacuum.

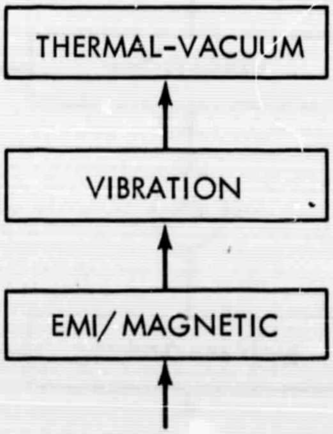

Figure 6. Subsystem Test Screens

1. The magnetic/EMI test screen is a combination of two tests — magnetic and electromagnetic interference. These are different from the other

environmental screens in that the subsystem must meet certain magnetic and radiation specifications rather than survive a particular environmental stress. These tests were run according to the IMP-I test specification for subsystems (ref. 2).

2. Cards were subjected to vibration according to the IMP-I specification for subsystems (ref. 2).
3. Cards were subjected to thermal-vacuum according to the IMP-I specification for subsystems (ref. 2).

Performance of the Subsystem Test Screen

Figure 7 presents the performance of each subsystem test screen in failure flow format. The bubble below each screen shows the number of defects in the

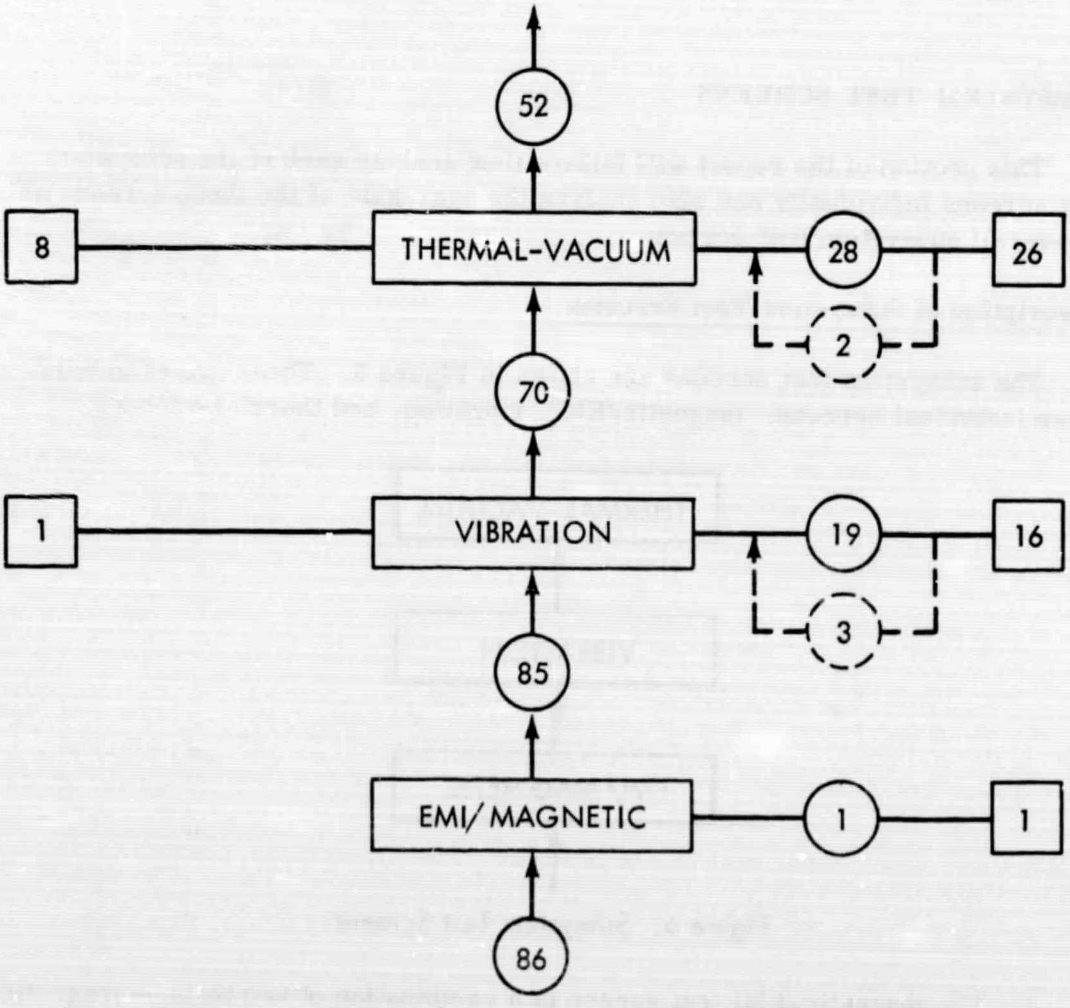

Figure 7. Performance of Subsystem Test Screens in Failure Flow Format

flow entering that screen. A bubble to the left of a screen gives the number of defects, not previously in the flow, that enter the flow at that screen. Thus, the total number of defects presented to a screen is the sum of the lower bubble and the left bubble.

The bubble to the right of a screen indicates the number of detections in that screen, while the dotted bubble indicates the number of additional times defects were detected at the screen before they were diverted. The rectangle to the right of each screen shows the number of diversions made at the screen.

As can be seen in Figure 7, 86 defects were in the flow from the bench test screen, nine defects entered the flow during subsystem test, 43 defects were diverted, so 52 defects remained in the flow to the system test screen.

Some special attention should be given to the Magnetic/EMI screen which shows only one detection and diversion. As stated earlier, magnetic and EMI tests are used to determine if the magnetic and radiative properties are within specified limits. Consequently, there are almost never any functional failures during these tests, and therefore, no malfunction reports. The fact that there were no malfunction reports does not mean that there were no problems or out of specification tests. Figure 8 gives the results of the magnetic and EMI tests.

	Number of Tests	Number Unsatisfactory	Percent Unsatisfactory
Magnetic	114	17	15%
EMI	94	32	33%

Figure 8. Results of Subsystem EMI and Magnetic Tests

Compared with IMP-F, which was also a protoflight spacecraft, IMP-I had about 6 percent fewer unsatisfactory magnetic tests. This difference does not seem to be significant, so that with respect to magnetic tests IMP-I is about normal. There is no significant amount of data with which to compare the EMI test results.

Reasons for Escape from Subsystem Test Screens

The reasons for escape from each subsystem test screen are given in Figures 9, 10, and 11. Figure 9 concerns only the magnetic/EMI screen, Figure 10 only the vibration screen, and Figure 11 only the thermal-vacuum screen.

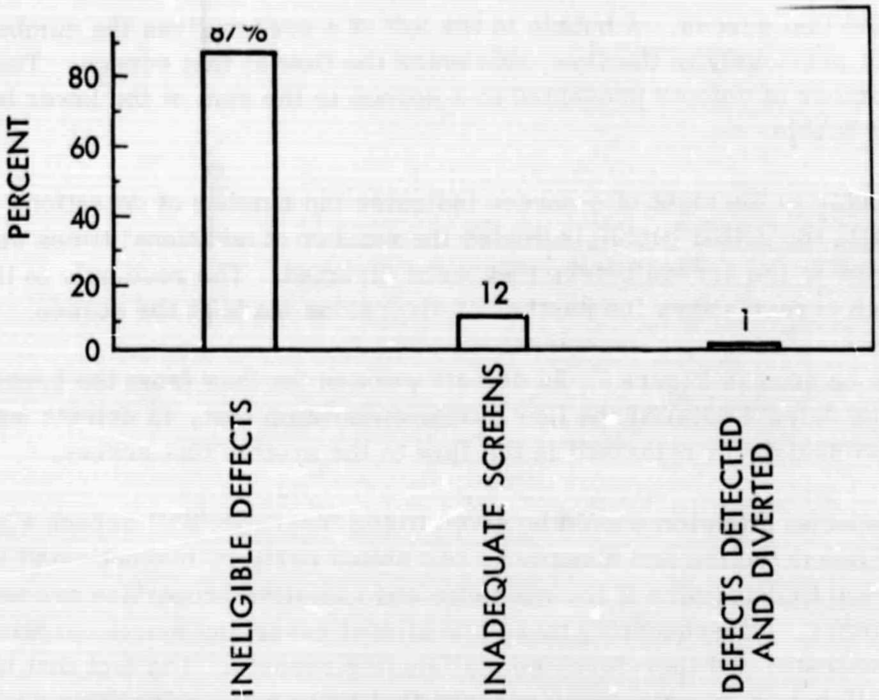

Figure 9. Diversions and Reasons for Escape from EMI/ Magnetic Subsystem Test Screen

The vast majority, 87 percent, of the escapes from the magnetic/EMI subsystem test screen are shown to be in the ineligible category. *

Figure 10 shows that ineligibility is the primary reason for escape from the vibration test screen. This figure indirectly shows that the subsystem vibration test effectiveness is 47 percent, which is not much different from the bench test effectiveness of 50 percent.

Figure 11 shows that more defects are eligible for the thermal-vacuum subsystem test screen than for any other subsystem test screen. One reason for this is that the thermal-vauum test provides time for a detailed functional check, whereas magnetic/EMI and vibration are usually followed by cursory functional tests. Since more defects are eligible for this screen, more defects are detected and diverted in the thermal-vacuum screen than the others, but the test effectiveness is 52 percent.

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*If the test effectiveness for this screen is based on the defects reported in the malfunction reports, then the effectiveness is only seven percent. However, an examination of the reported defects reveals that each was an electromagnetic interference type of defect. With this information the data presented in Figure 8 can be used to calculate an effectiveness of 77 percent. This 77 percent effectiveness is probably more representative of the magnetic/EMI screen than the seven percent.

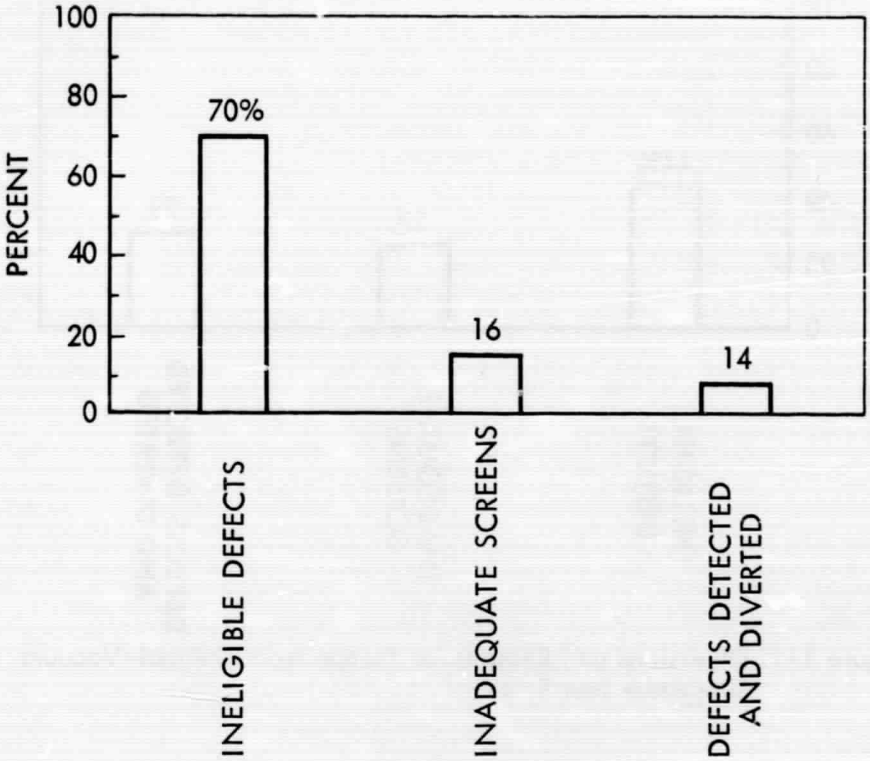

Figure 10. Diversions and Reasons for Escape from Vibration Subsystem Test Screen

The fact that the bench test screen, the vibration test screen and the thermal-vacuum test screen each have a test effectiveness around 50 percent suggests that a 50 percent test effectiveness may be a characteristic test effectiveness for subsystem tests. Since this result is based on IMP-I data only, subsystem test results from other protoflight programs are needed to substantiate the conclusion. The test effectiveness for the magnetic/EMI screen has been ignored while reaching this result because of the different way it is calculated.

Considering the aggregate of the subsystem test screens, the reasons for escape are presented in Figure 12. As would be expected, the dominant reason is ineligibility. The overall subsystem test screen effectiveness is 46 percent.

A more detailed examination of those defects that were ineligible for detection at the subystem level yields some interesting information. Sixty percent of the defects ineligible for detection at the subsystem level were ineligible because they required a higher level of assembly for detection. Put another way, 40 percent of all the defects that escaped detection during subsystem test escaped because the system level of assembly was necessary to detect them.

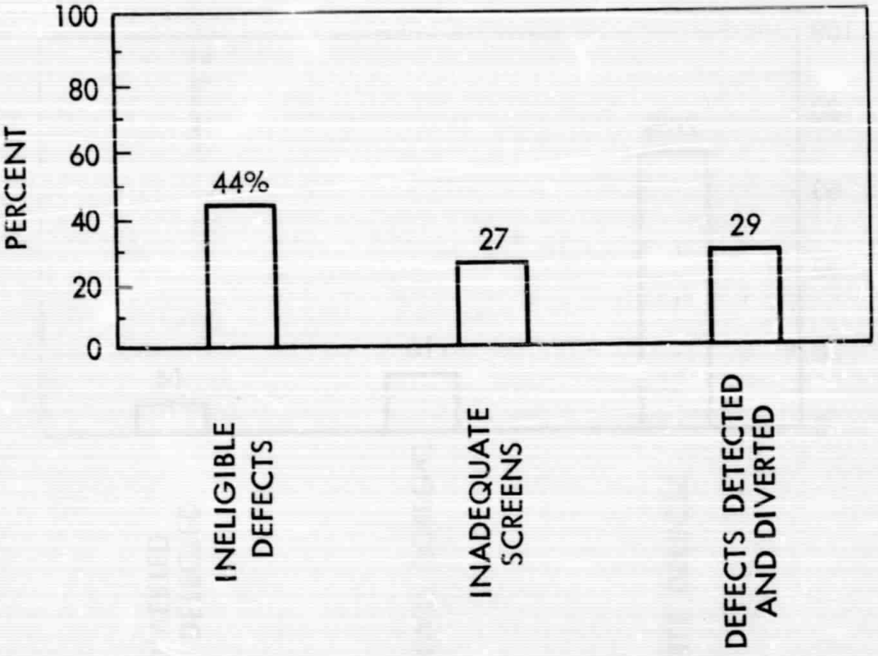

Figure 11. Diversions and Reasons for Escape from Thermal-Vacuum Subsystem Test Screen.

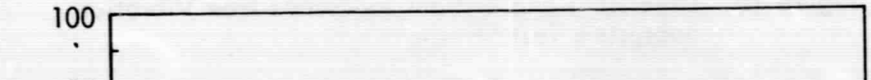

Figure 12. Diversions and Reasons for Escape from Subsystem Test Screens.

Criticality of Defects Detected in Subsystem Test Screens

The one defect detected in the magnetic/EMI screen was catastrophic to the subsystem before and after protection, but had a negligible effect on the mission before and after protection.

The criticality of defects found in the subsystem vibration test is presented in Table 5. There are more defects in the negligible and minor degrading to subsystem categories than in the major degrading and catastrophic categories. The defects detected in vibration would have had negligible effect on the mission. Protection had no effect on the defects detected in vibration.

Table 5

Vibration Test Screen: Criticality vs Protection
(Numbers in table are number of defects)

Criticality	1	2	3	4
Subsystem Before Protection	3	2	3	8
Subsystem After Protection	3	2	3	8
Mission Before Protection	0	0	2	14
Mission After Protection	0	0	2	14

The criticality of the defects detected in the subsystem thermal-vacuum test is shown in Table 6. Again there are a few more defects in the minor

Table 6

Thermal-Vacuum Screen: Criticality vs Protection
(Numbers in table are number of defects)

Criticality	1	2	3	4
Subsystem Before Protection	8	3	5	10
Subsystem After Protection	6	3	5	12
Mission Before Protection	0	0	0	26
Mission After Protection	0	0	0	26

criticality to subsystem categories than in the major criticality categories. Every defect was in the negligible to mission category. Protection reduces the criticality to subsystem for only two of the eight catastrophic defects, and has no effect on any other defects.

Table 7 presents the criticality analysis for the overall subsystem test screen. The same comments can be made about the aggregate as were made about the individual screens. An interesting observation is the comparison between the criticality of the defects found in the bench test screen and the criticality of the defects found in the subsystem test screen. Most of the defects found in the bench test were in the catastrophic to subsystem category, but for the subsystem screen there were more defects in the minor criticality categories than the major.

Table 7

Subsystem Test Screen: Criticality vs Protection
(Numbers in table are number of defects)

Criticality	1	2	3	4
Subsystem Before Protection	12	5	8	18
Subsystem After Protection	10	5	8	20
Mission Before Protection	0	0	2	41
Mission After Protection	0	0	2	41

In both the bench test screen and the subsystem test screen the criticality of defects is affected very little by protection.

Criticality versus Probability of Space Malfunction

Table 8 presents the distribution of defects detected in the subsystem tests according to their probability of causing a space malfunction. As can be seen, most of the defects would have resulted in a flight malfunction if they had not been diverted during the test program.

The distribution of defects according to criticality and probability of causing a space malfunction is shown in Table 9. Note that all of the catastrophic and major degrading defects had a high probability of causing a problem in space.

Table 8

Probability that Defects Found in Subsystem Test Screens Would Have Caused a Malfunction in Space

(Numbers in table are number of defects)

	0-20	20-80	80-100
Vibration	1	4	11
Thermal-Vacuum	8	4	14
Total Subsystem	9	8	26

Probability (%) of a Flight Malfunction

Table 9

Probability of Flight Malfunction vs Criticality of the Malfunctions Found in Vibration Subsystem Test Screen

(Numbers in table are numbers of defects)

Criticality	0-20	20-80	80-100
1	0	0	3
2	0	1	1
3	1	0	2
4	0	3	5

Probability (%) of a Flight Malfunction

Table 10 gives the same data for the subsystem thermal-vacuum test. Although most of the catastrophic and major degrading defects were likely to have caused a space malfunction, there were a few that were detected during test that had a low probability of causing a space malfunction.

The data for the overall subsystem test screen is shown in Table 11. These data all indicate that the defects detected during subsystem test were "real" defects that would have caused malfunctions later, and did not result from the amount or severity of testing.

Table 10

Probability of Flight Malfunction vs Criticality of the Malfunctions Found in Thermal-Vacuum Subsystem Test Screen
(Numbers in table are number of defects)

Criticality	0-20	20-80	80-100
1	2	2	4
2	1	0	2
3	1	1	3
4	4	1	5

Probability (%) of a Flight Malfunction

Table 11

Probability of Flight Malfunction vs Criticality of the Malfunctions Found in the Subsystem Test Screens
(Numbers in table are number of defects)

Criticality	0-20	20-80	80-100
1	2	2	8
2	1	1	3
3	2	1	5
4	4	4	10

Probability (%) of a Flight Malfunction

Criticality versus the Systematic Nature of Defects

The systematic nature of defects detected in the subsystem test screens is presented in Figure 13. As was the case for the bench test screen, there are more non-systematic than systematic defects. The distribution between systematic and non-systematic defects is shown to be approximately the same for both

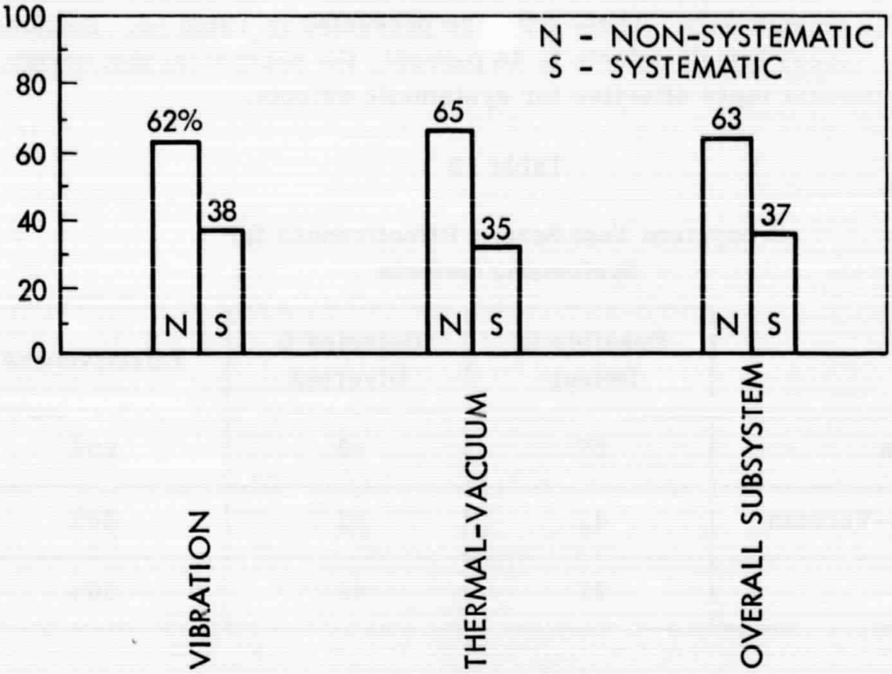

Figure 13. Breakdown of Systematic and Non-Systematic Defects Found in the Subsystem Test Screens

the vibration test and the thermal-vacuum test. Table 12 gives the distribution of systematic and non-systematic defects detected during subsystem test according

Table 12

Systematic Nature of Defects vs Criticality of Defects Found in Subsystem Test Screen (Numbers in table are number of defects)

Criticality	Systematic	Non-Systematic
1	5	7
2	1	4
3	3	5
4	7	11

to criticality. The systematic defects are distributed according to criticality in about the same way as the systematic defects detected in the bench test screen. There were proportionally fewer major criticality non-systematic defects during sysbystem test than during bench test.

An interesting sidelight here is the determination of the screen effectiveness for systematic defects only. These data are presented in Table 13. Because the screen effectiveness for all defects is 46 percent, the subsystem test screens are 10 to 15 percent more effective for systematic defects.

Table 13

Subsystem Test Screen Effectiveness for Systematic Defects

	Possible to Detect	Detected & Diverted	Effectiveness
Vibration	27	16	60%
Thermal-Vacuum	43	26	60%
Overall	77	43	56%

Causes of Defects

The causes of the defects found in the subsystem vibration test screen are presented in Figure 14. There are two significant differences between the causes of the defects detected in vibration and those detected in bench test. First, the relative percentages for design and for fabrication are switched from the bench test results. This is not surprising, as the vibration test is usually a good screen for workmanship type defects. Second, the percentage of parts/materials defects has doubled. There does not seem to be an immediate explanation for this.

Figure 15 presents the same type of data for the thermal-vacuum test screen. Again, there are more fabrication caused defects than design defects, but the number of part/materials defects is the same as in bench test.

Figure 16 gives the cause data for the aggregate subsystem test screen. There is a higher percentage of fabrication defects than design defects, which is different from bench test, and the percentage of parts/materials problems is slightly higher than for bench test.

Environmental Sensitivity of Defects

Figure 17 depicts the percent of the defects detected in each environment that were determined to have been sensitive to that environment. Nearly all of the defects detected in vibration and EMI tests were sensitive to

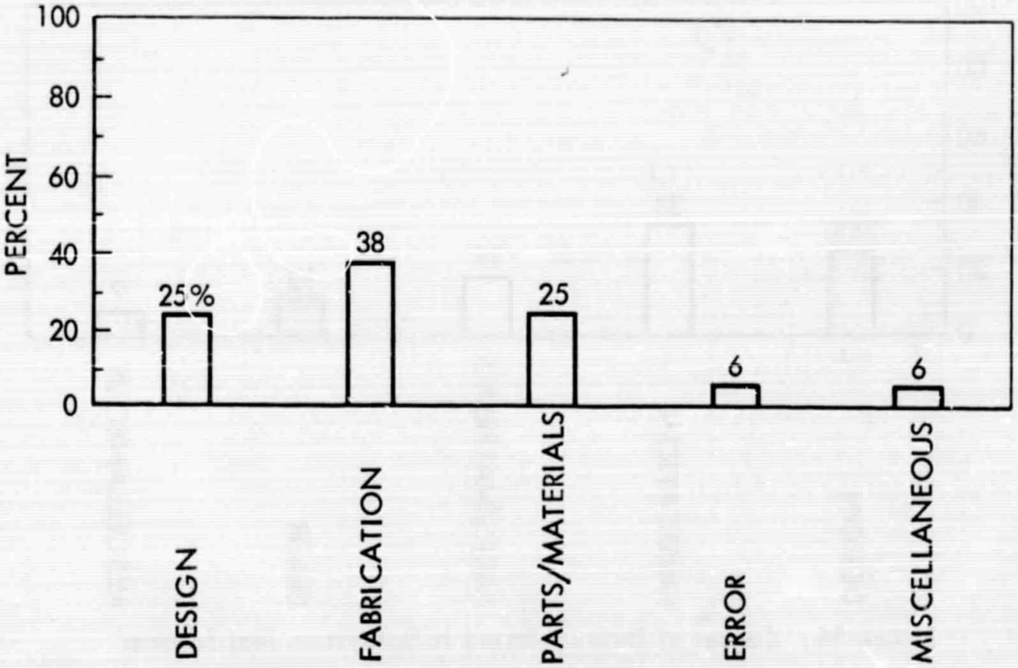

Figure 14. Causes of Defects Found in Vibration Subsystem Test Screen

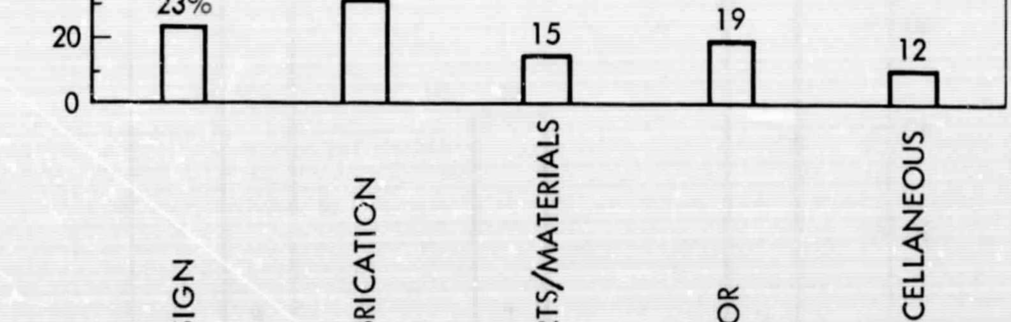

Figure 15. Causes of Defects Found in Thermal-Vacuum Subsystem Test Screen

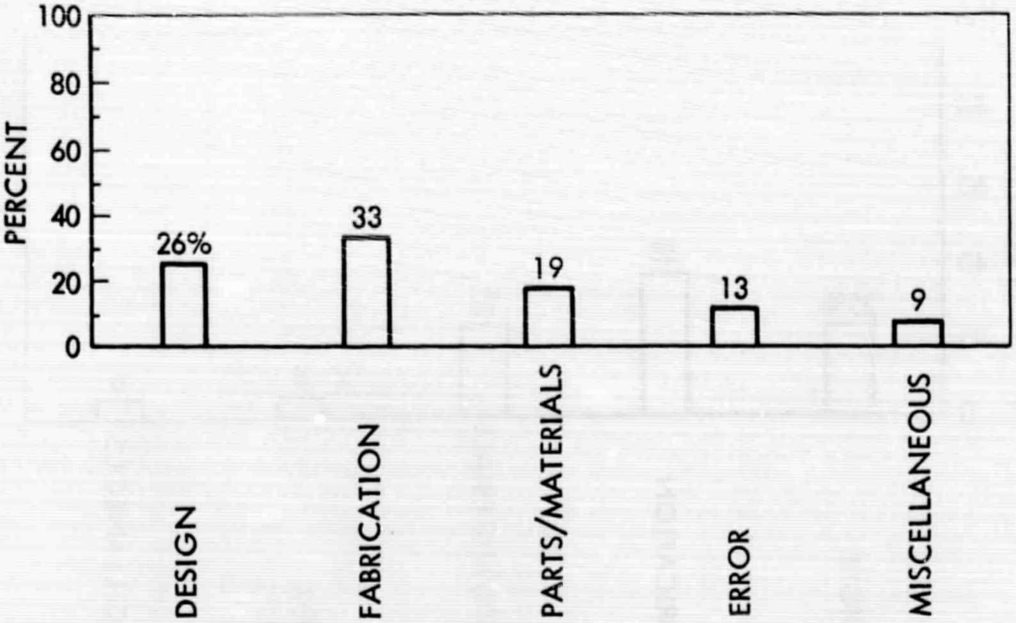

Figure 16. Causes of Defects Found in Subsystem Test Screens

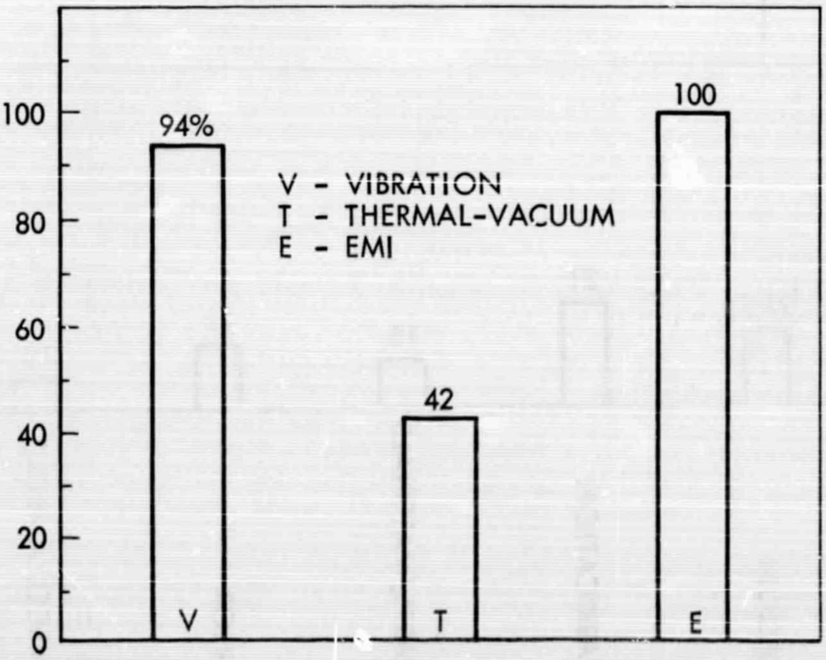

Figure 17. Environmental Sensitivity of Defects Found in Each Subsystem Test Screen

the particular environment, but less than half of the defects found in thermal-vacuum were sensitive to that environment. There are two possible explanations for this. First, the malfunction may have been caused by vibration, but not detected until thermal-vacuum. This is a possibility because of the lack of a comprehensive functional check between vibration test and thermal-vacuum. Second, the defects could have been eligible for, and escaped the bench test.

SYSTEM TEST SCREENS

Description of System Test Screens

The system test screens are shown in Figure 18. System tests include all tests performed on the integrated or partially integrated spacecraft, including the environomental tests according to the IMP-I specifications, (ref. 3 and ref. 4). There are 17 system test screens: (1) integration; (2) sun spin/magnetic; (3) EMI; (4) temperature; (5) mass properties; (6) ACS deployment; (7) reintegration; (8) vibration/shock; (9) spin deployment; (10) reintegration/EMI; (11) thermal-vacuum; (12) solar simulation setup/SES failure/solar simulation; (13) short vacuum tests one and two; (14) short thermal-vacuum; (15) reintegration; (16) vibration; (17) final and ETR checkout.

1. The integration screen includes all the integration and test activities of spacecraft up to May 25, 1970. This is the period when the spacecraft was put together for the first time, and a functional checkout of the entire spacecraft system could be accomplished.

2. The sun spin/magnetic screen is a combination of two tests. The sun spin test checked out the optical aspect system. The magnetic test determined the magnetic properties of the spacecraft. This screen covers the period from May 25, 1970 to May 26, 1970.

3. This screen is the EMI test of the entire spacecraft. It covers the period from June 4, 1970 to June 11, 1970.

4. The temperature test screen is the week long temperature only test of the spacecraft. It covers the period from June 12, 1970 to June 19, 1970.

5. The mass properties screen is not really a test screen, but is included as a screen because the measurement of the mass properties occurred during the test program. Such properties as weight, center of gravity, and balance are measured, and these measurements are the reference measurements until launch. This screen covers the period from July 28, 1970 to August 5, 1970.

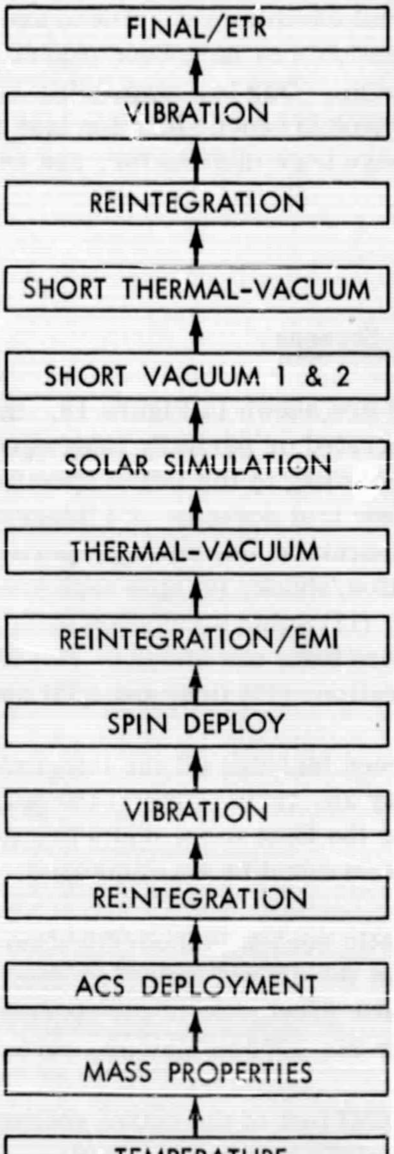

Figure 18. System Test Screens

6. The attitude control system (ACS) deployment test was done between August 6, 1970 and August 18, 1970. This test checked the deployment of the ACS booms.

7. Between August 19, 1970 and September 24, 1970 the spacecraft was partially disassembled and then reassembled. This period of activity is the reintegration test screen.

8. The vibration and shock tests were run between September 25, 1970 and September 30, 1970. The spacecraft received three axis sine and random vibration at protoflight levels according to the IMP-I specification, and a pyrotechnic shock test.

9. A series of spin deployment tests were run between October 2, 1970 and October 20, 1970. This screen was to test the various boom deployment mechanisms under conditions of underspin and overspin as well as normal spin. The tests were performed in the dynamic test chamber (DTC).

10. The period from October 21, 1970 to October 31, 1970 was another reintegration period. An EMI test was performed, and the spacecraft was setup for the thermal-vacuum test.

11. The thermal-vacuum test was performed between November 2, 1970 and November 14, 1970. Protoflight levels were used according to the IMP-I test specification.

12. The period of November 14, 1970 to December 20, 1970 has three parts that make up this screen. The first part is the preparation of the spacecraft and the test facility for the solar simulation test. The second part is the failure of the spacecraft positioner in the space environment simulator. While the positioner was being repaired, there was some disassembly and reassembly of the spacecraft and some functional checkout. The third part is the solar simulation test.

13. Due to a problem in the encoder that was thought to be vacuum caused, two short vacuum tests were run between December 21, 1970 and January 8, 1971.

14. A short thermal-vacuum test was performed at protoflight levels between January 11, 1970 and January 14, 1970.

15. This screen is another reintegration period between January 18, 1971 and January 27, 1971. Another mass properties measurement was also done during this time.

16. A vibration test was run between January 28, 1971 and February 1, 1971.

17. This screen includes the final magnetic measurements, sun spin test, shipment to ETR, and checkout at ETR. It covers the period from February 3, 1971 to February 15, 1971.

Performance of the System Test Screens

Figure 19 presents the performance of each system test screen in failure flow format. As can be seen in Figure 19, a number of screens did not detect any defects. The reason for this is that most of the defects were not eligible for these screens. The screens with no detections have been included to preserve continuity of the test program. They have not been combined with other screens so that they would not confuse the screening activity of the other screens.

The remaining paragraphs of this section will not analyse every screen, as was done in the subsystem test screen section, but will concentrate on the more important screens.

Reasons for Escape from System Test Screens

The reasons for escape from eleven system test screens are presented in Table 14. The escapes attributed to some inadequacy range from seven percent in system thermal-vacuum test to 35 percent in system temperature. With the exception of the thermal-vacuum test, those screens that entail a thorough functional test such as the reintegration screens, have the largest percentages in the inadequate category. These same screens, including thermal-vacuum, also have the highest detection percentages.

The comparison of similar screens at the system level and the subsystem level is of some interest. The system EMI test had 25 percent of its escapes due to inadequacy, and the subystems EMI test had only 12 percent. The system vibration test had 17 percent escapes due to inadequacy, and the subsystem test had 16 percent. There were seven percent inadequate escapes for the system thermal-vacuum test, but 27 percent for the subsystem thermal-vacuum test.

There does not seem to be any correlation between reasons for escape from these particular system screens and the corresponding subsystem screens. However, Figure 20 presents the summary of the reasons for escape from the system test screens. Comparing this with Figure 12, the reasons for escape from subsystem screens and from the system screens, when all the screens are

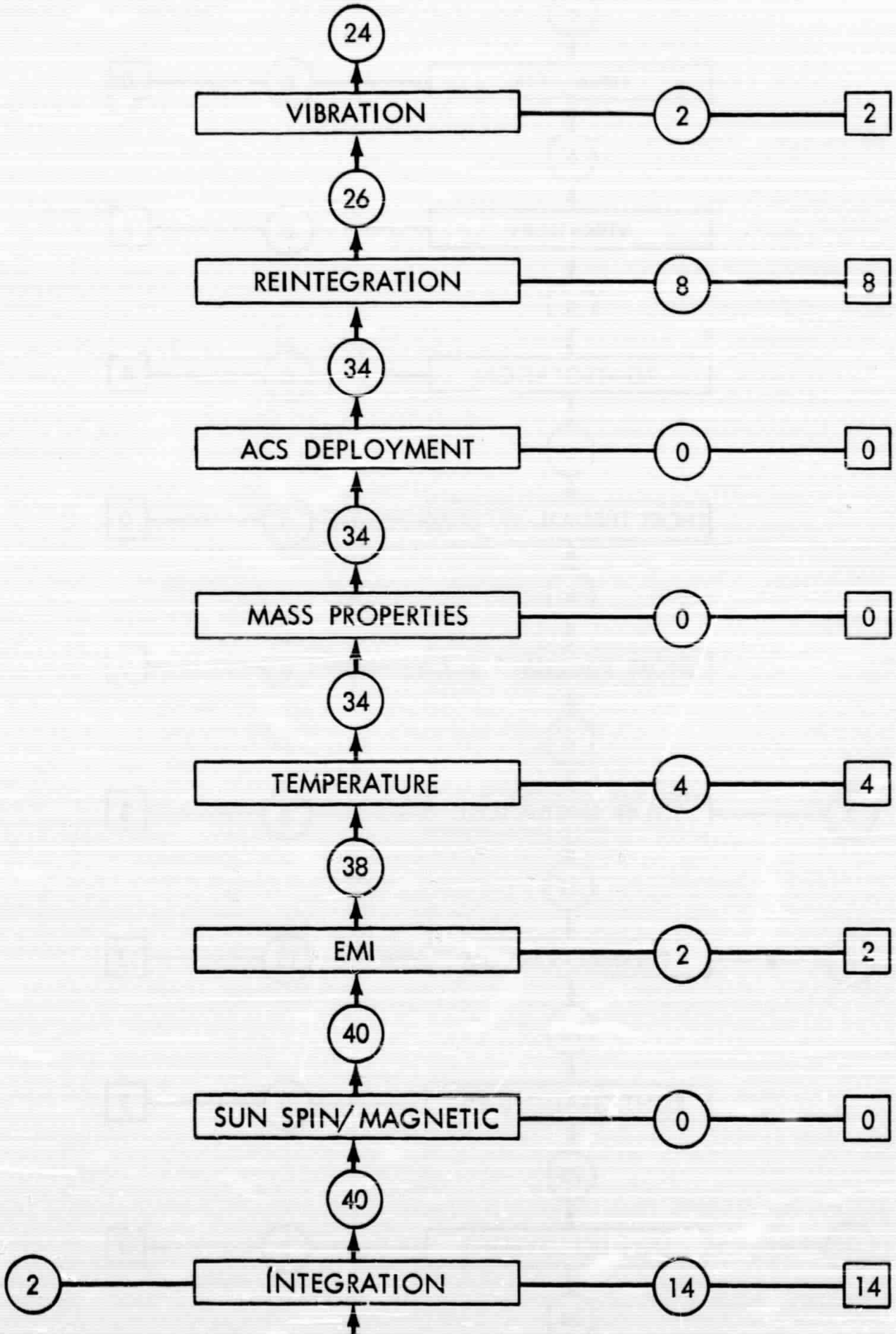

Figure 19. Performance of System Test Screens in Failure Flow Format

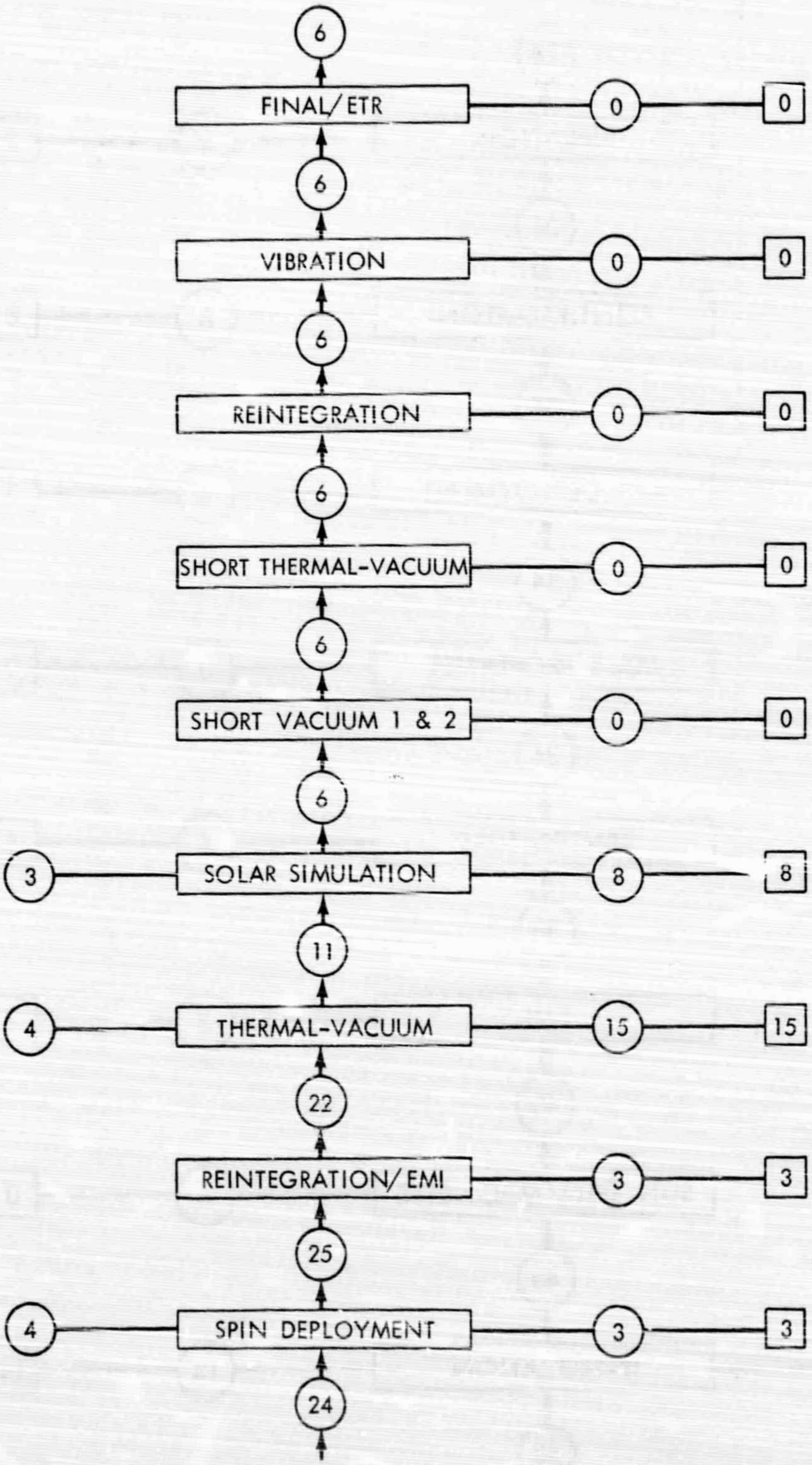

Figure 19. Performance of System Test Screens in Failure Flow Format (Continued)

Table 14

Reasons for Escape from Eleven System Test Screens

	Ineligible	Inadequate	Diverted
Integration	50%	29%	21%
EMI	71	25	4
Temperature	55	35	10
Reintegration	60	22	18
Vibration	78	17	5
Spin Deployment	77	14	9
Reintegration/EMI	66	25	9
Thermal-Vacuum	41	7	52
Solar Simulation	36	7	57
Final Vibration	83	17	0
Final ETR	83	17	0

considered, are distributed almost identically. An important note here is that 49% of all the defects detected in the system test screens required the system level for detection.

Table 15 gives the screen effectiveness for the screens in Table 14. The effectiveness stays between 13 percent and 44 percent until the thermal-vacuum screen is reached, where the effectiveness jumps to 88 percent. Despite the low effectiveness for some of the screens, the overall system test screen effectiveness is 92 percent. This is considerably higher than the 50 percent subsystem screen effectiveness.

Criticality of Defects Detected in System Test Screens

The criticality to the subsystem, before protection, of the defects found in the system test is presented in Table 16. Some 42 percent of the defects are in

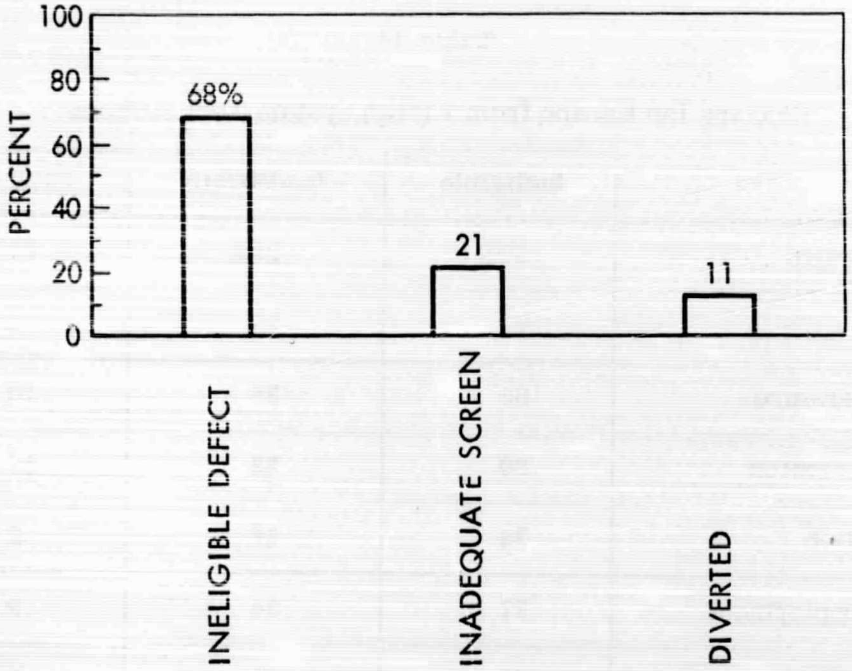

Figure 20. Summary of Diversions and Reasons for Escape from System Test Screens

the major degrading or catastrophic categories. Forty percent of the defects detected by the subsystem screens were in these categories, so that the criticality of defects found in the system test screens is almost the same as the criticality of the defects detected during subsystem test. One fact that needs to be noticed here is the large number of catastrophic and major degrading defects that have escaped as far downstream as the thermal-vacuum test.

Table 17 shows the mission criticality of defects detected during system test. There are relatively few mission catastrophic or major degrading defects, and these are caught early in the system test screens.

The effects of protection on subsystem criticality are illustrated by the matrix in Table 18. The rows give the criticality before protection and the columns give the criticality after protection. The numbers along the diagonal indicate those defects that were not affected by protection; the numbers above the diagonal indicate the defects whose criticality was reduced by protection; and the numbers below the diagonal indicate the defects whose criticality was increased by protection. An example of how criticality would be increased by protection would be an experiment that generates enough noise to affect several other experiments, but does not affect itself. The protection for the other experiments is to turn the noisy experiment off, which makes the defect catastrophic! As has been the case with the bench test screen and the subsystem test

Table 15

Screen Effectiveness for Eleven System Test Screens

Integration	42%
EMI	13
Temperature	18
Reintegration	44
Vibration	25
Spin Deployment	37
Reintegration/EMI	27
Thermal-Vacuum	88
Solar Simulation	89
Final Vibration[1]	—
Final/ETR[1]	—

[1] NOTE: No defects eligible for these two screens, therefore effectiveness is undefined.

screens, there is very little protection for the defects found in the system test screens. Table 19 is a similar treatment of the effects of protection on mission criticality. As usual, there is little effect of protection.

The last factor to be considered in this section is the proneness of the defects detected in system test to cause a space malfunction if they were not detected. The data for this consideration are presented in Table 20. As can be seen, most of the more critical defects could have caused a space malfunction if they had not been detected in test.

Criticality Versus the Systematic Nature of Defects

The distribution between systematic and non-systematic defects is shown in Figure 21. There are nearly equal numbers of each, which is different from the subsystem screens where there were more non-systematic defects. The bench test screen results were midway between the subsystem and system results.

Table 16

Subsystem Criticality (Before Protection) of Defects Found in System Test Screens (Numbers in table are numbers of defects)

Integration	6	2	2	4
EMI	0	1	0	1
Temperature	2	0	1	1
Reintegration	0	3	0	5
Vibration	0	1	1	0
Spin Deployment	1	0	0	2
Reintegration/EMI	1	1	1	0
Thermal-Vacuum	3	3	2	7
Solar Simulation	0	1	3	4
	1	2	3	4

Criticality

Table 17

Mission Criticality (Before Protection) of Defects Found in System Test Screens (Numbers in table are number of defects)

Integration	3	1		10
EMI				2
Temperature	1			3
Reintegration				8
Vibration				2
Spin Deployment	1			2
Reintegration/EMI				3
Thermal-Vacuum				15
Solar Simulation				8
	1	2	3	4

Criticality

Table 18

Effects of Protection on Subsystem Criticality
(Numbers in table are numbers of defects)

	AFTER			
BEFORE	1	2	3	4
1	11			2
2		9	2	1
3			9	
4	2			22

Table 19

Effects of Protection on Mission Criticality
(Numbers in table are numbers of defects)

	AFTER			
BEFORE	1	2	3	4
1	4			1
2			1	
3				
4				53

The systematic defects detected in system test screens were equally divided between major degrading and minor degrading criticality. The subsystem test screens had almost twice as many systematic defects of minor degrading criticality as major degrading criticality. The bench test screen was the same as the system test screen in that the systematic defects were uniformly distributed over criticality.

Table 20

Probability of Flight Malfunction vs Criticality of the Malfunctions Found in the System Test Screens (Numbers in table are number of defects)

Criticality	Probability (%) of a Flight Malfunction		
	0-20	20-80	80-100
1	1	1	11
2	2	2	8
3	1	1	8
4	7	2	15

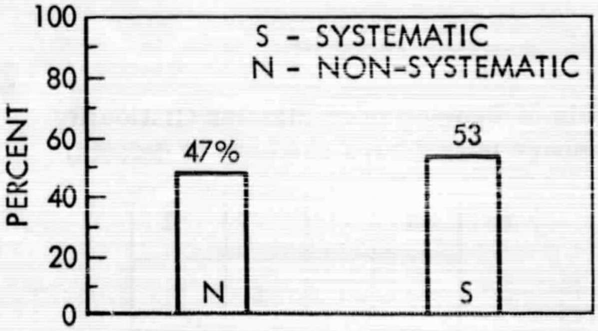

Figure 21. Distribution of Systematic and Non-Systematic Defects Found in the System Test Screens

The screen effectiveness for systematic defects for nine system screens is given in Table 21. Thermal-vacuum has a systematic defect effectiveness equal to the subsystem thermal-vacuum test, but system vibration test is not as effective as subsystem vibration. The overall system screen effectiveness for systematic defects is 89 percent, which is considerably better than the subsystem screen. Since the effectiveness of the system screens for any kind of defect is 92 percent, the screen effectiveness for systematic and non-systematic defects is about the same.

Causes of Defects

The causes of the defects found in the system screens are presented in Figure 22. Design is the major cause, with fabrication second, and

Table 21

System Test Screen Effectiveness for Systematic Defects

	Possible to Detect	Detected & Diverted	Effectiveness
Integration	19	8	42%
EMI	8	0	0%
Temperature	16	3	19%
Reintegration	13	5	38%
Vibration	6	2	33%
Spin Deployment	5	1	20%
Reintegration/EMI	7	2	29%
Thermal-Vacuum	8	5	63%
Solar Simulation	3	2	67%

parts/material third. These results are almost identical to the bench test screen results, but are quite different from the subsystem screen results (Figure 14). The large percentage of design defects could be a result of the protoflight concept.

Environmental Sensitivity of Defects

Figure 23 gives the percentage of the defects found in an environmental screen that were sensitive to that environment. Note that only 40 percent of the defects found in thermal-vacuum were precipitated by the thermal-vacuum environment. All of the defects found in the solar simulation screen were found before the test actually began, so none were susceptible to the environment.

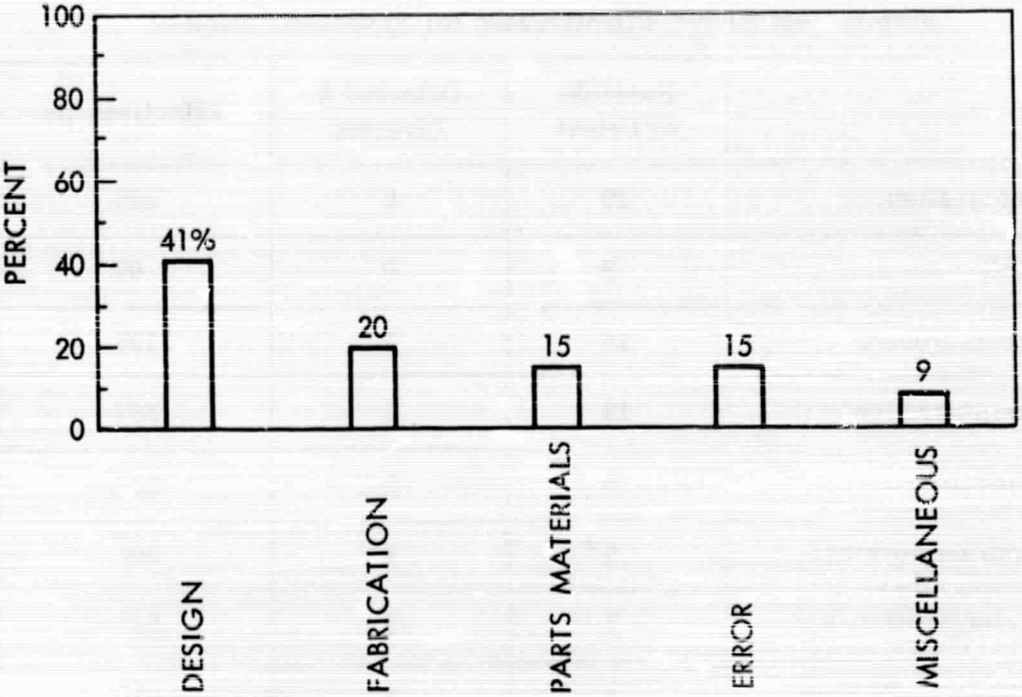

Figure 22. Causes of Defects Found in System Test Screens

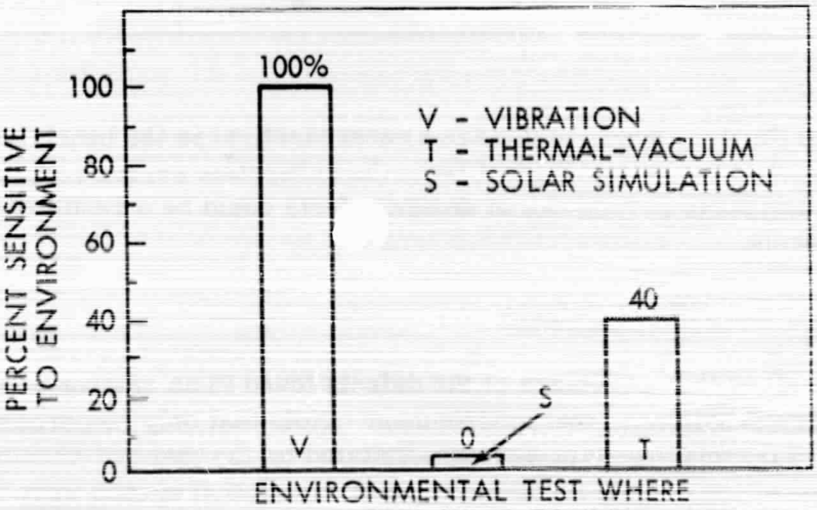

Figure 23. Environmental Sensitivity of Defects Found in Environmental Test Screens

SPACE PERFORMANCE

Description of Malfunctions in Space

There were seven malfunctions in space that were used for this failure flow analysis.

1. Following the boom deployment sequence, the -Y axis ACS boom was indicated as not being locked. Since the spacecraft was successfully despun, the micro-switch used to indicate lock is the prime suspect.

2. Eight days after turn-on, the main telescope of the University of Chicago experiment failed causing a major loss of data. An open circuit in a painted stripe connection to the detector is the prime suspect.

3. The spacecraft does not respond as planned to the attitude control system. Since the ACS is working properly, this is either a dynamics problem or a computational problem, rather than a failure.

4. The +X antenna motor failed after the antenna had been extended to 78 feet out of a planned 120 feet. These motors had been a problem during the entire program.

5. Dr. MacDonald's Very Low Energy Detector was damaged by radiation and was turned off.

6. Dr. Erikson's Impedance Probe failed after its objectives had been achieved. A stuck relay is suspected.

7. Dr. Ogilvie's experiment is inoperative. A high voltage problem due to outgassing of a void in potting is suspected.

In addition to these seven malfunctions there are four anomalies that have not been used because there is not enough information or because the anomaly is no real problem.

1. The on-board computer had some cases of "lapse of memory." It is a hardware problem, but it can be overcome with a software change. There was not enough information to do the failure flow analysis of this problem.

2. There were a few cases of the right command being sent, but the wrong action taking place. This has not been a recurring problem, and there is no explanation as to why it ever occurred.

3. Dr. Cline's experiment was planned to be turned off and on as the spacecraft entered and exited the radiation belt. During the twelfth orbit it failed to respond to an ON command, but about a month later it did respond. No cause is known, but the experiment will be left on to avoid the problem.

4. One of the solar panels was suspected to be inoperative, but this was later found to have been the result of a shadow.

Discussion of the Space Malfunctions

Of the seven malfunctions, one was a likely candidate for detection during test, one was a problem through the whole program, two can almost be classified as random failures, two could not have been detected in test and one probably could not have been detected in test.

1. The University of Chicago experiment that failed was not in the spacecraft for either thermal-vacuum or solar simulation. An identical experiment failed after solar simulation, for a different reason, and was replaced by the experiment that ultimately failed in space.

2. The antenna motors had problems throughout the whole program, some of which were similar to the space failure. These were usually wear problems, so the flight motors were exercised as little as possible during test.

3. The ACS boom micro-switch failure could have been a random failure, or it could have been damaged.

4. There are a number of relays used to step Dr. Erikson's experiment through a series of measurements. All of the relays up to the failed relay are still operative, so a random failure seems more likely than wear out.

5. The dynamics problem could not have been detected in test.

6. The damage to the Very Low Energy Detector could not have been detected in test, since it was an unusual environment that caused the failure.

7. The time to outgas the suspected void in Dr. Ogilvie's experiment was longer (800 hrs. vs. 312 hrs.) than any thermal-vacuum test and probably could not have been detected in test.

Eighty-six percent of the defects were catastrophic to subsystems before protection; 14 percent were negligible. Seventy-one percent were catastrophic after protection. Fourteen percent were major degrading to the mission before protection, but none were more than negligible after protection. (If the three problems for which there are no explanations are included, then 60 percent of the defects were catastrophic to subsystems before protection, and 50% were still catastrophic after protection.)

Forty-three percent of the defects that caused malfunctions in space were systematic defects. Design is the major cause of defects, with parts/materials a close second.

Twenty-nine percent of the defects appear to be sensitive to the space environment.

SUMMARY AND INTERPRETATION

This section consists of two parts. The first part summarizes the data gathered by using failure flow analysis. The second part interprets the data in a way that an evaluation of the test program is produced.

Summary of Data

The entire screen system from bench test to space is presented in failure flow format in Figure 24. This first part presents the significant data from each of the four data sections of the report - bench test screen, subsystem test screen, system test screens, and space performance.

1. Bench Test Screen

- Ineligibility for detection is the major reason for escape
- The screen was 50% effective, but this is somewhat uncertain
- Two-thirds of the defects detected were catastrophic to subsystems before protection
- One-eighth of the defects detected were at least major degrading to the mission before protection
- Protection did little to change criticality

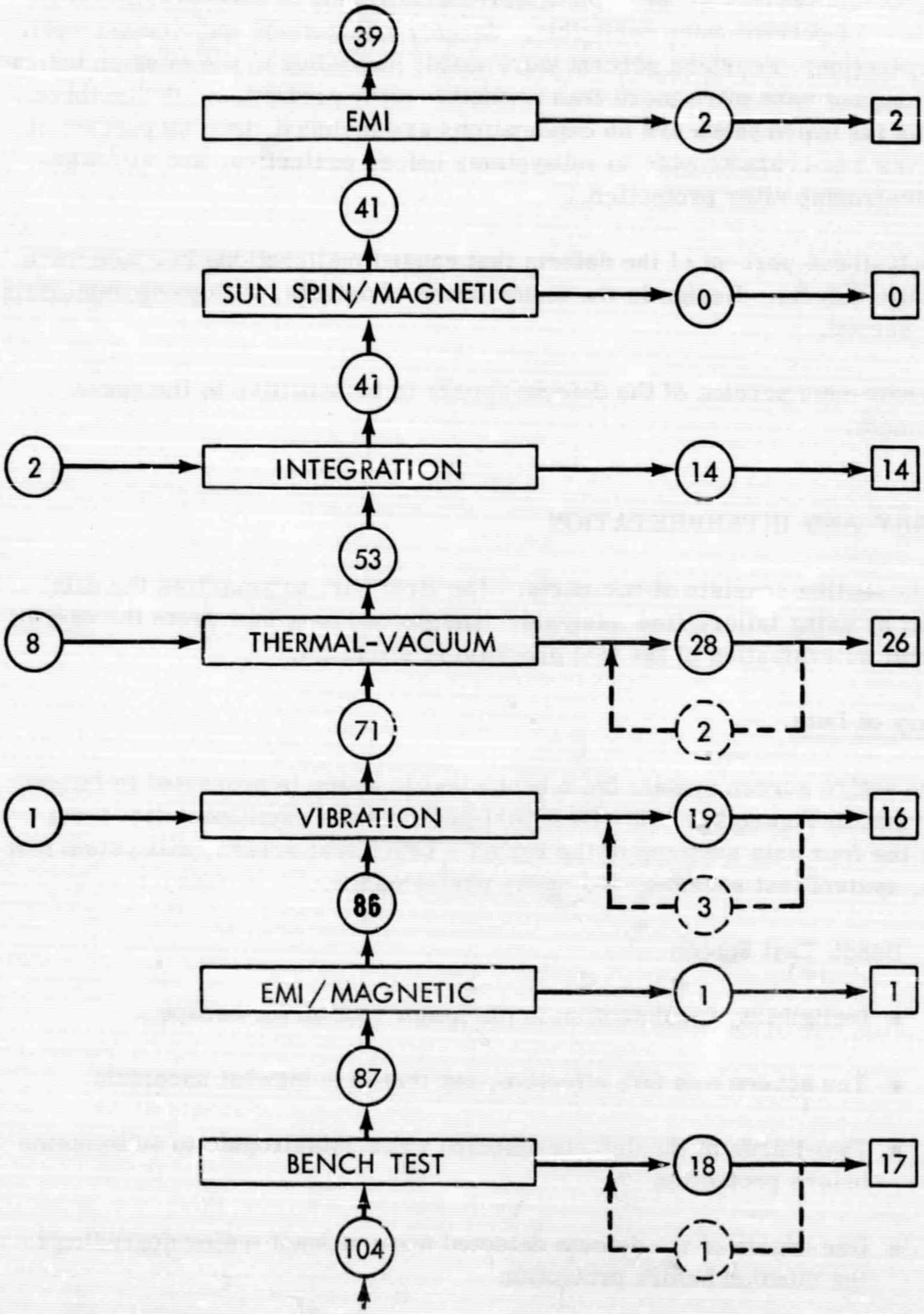

Figure 24A. IMP-I Screen Performance in Failure Flow Format

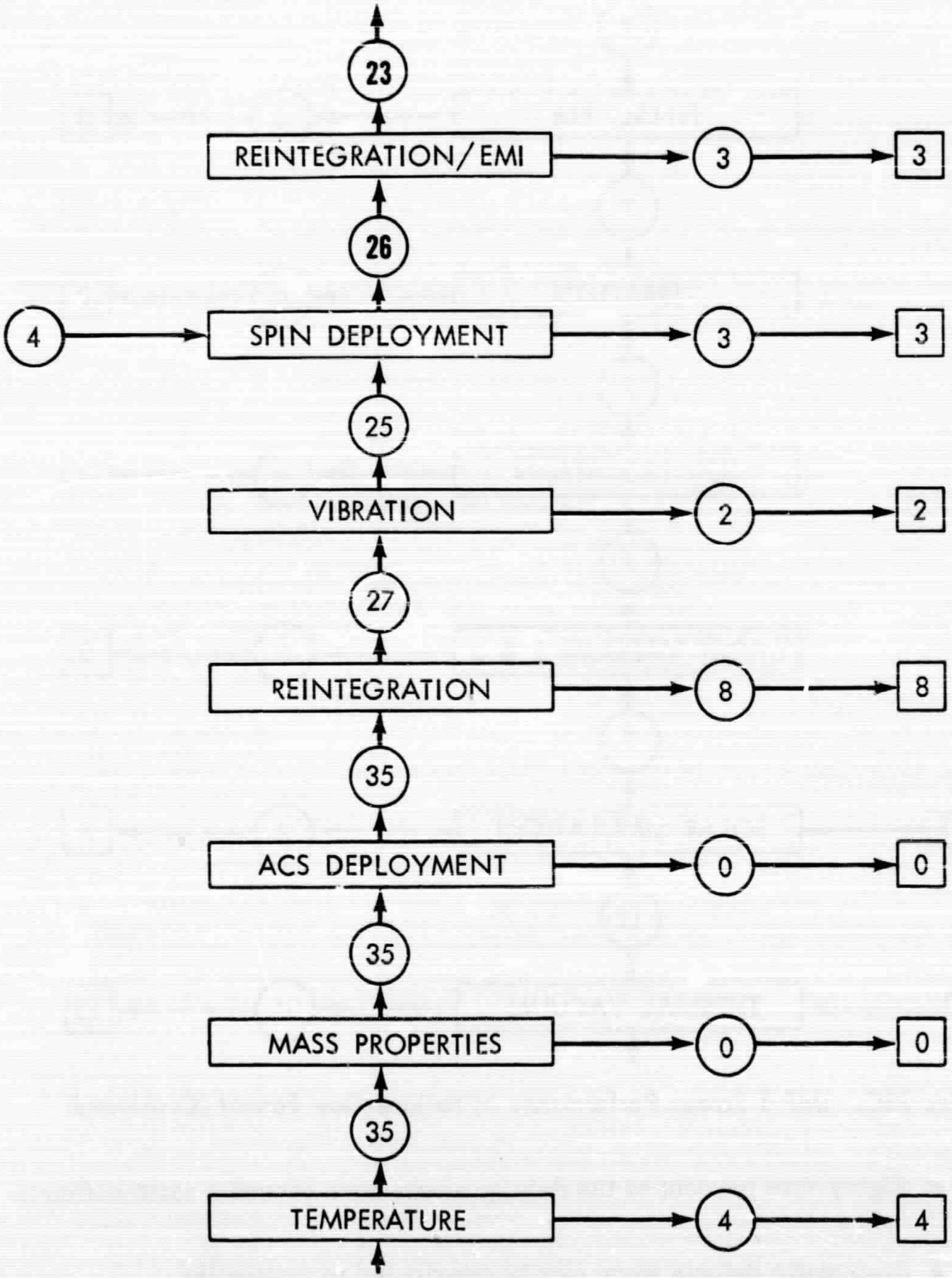

Figure 24B. IMP-I Screen Performance in Failure Flow Format (Continued)

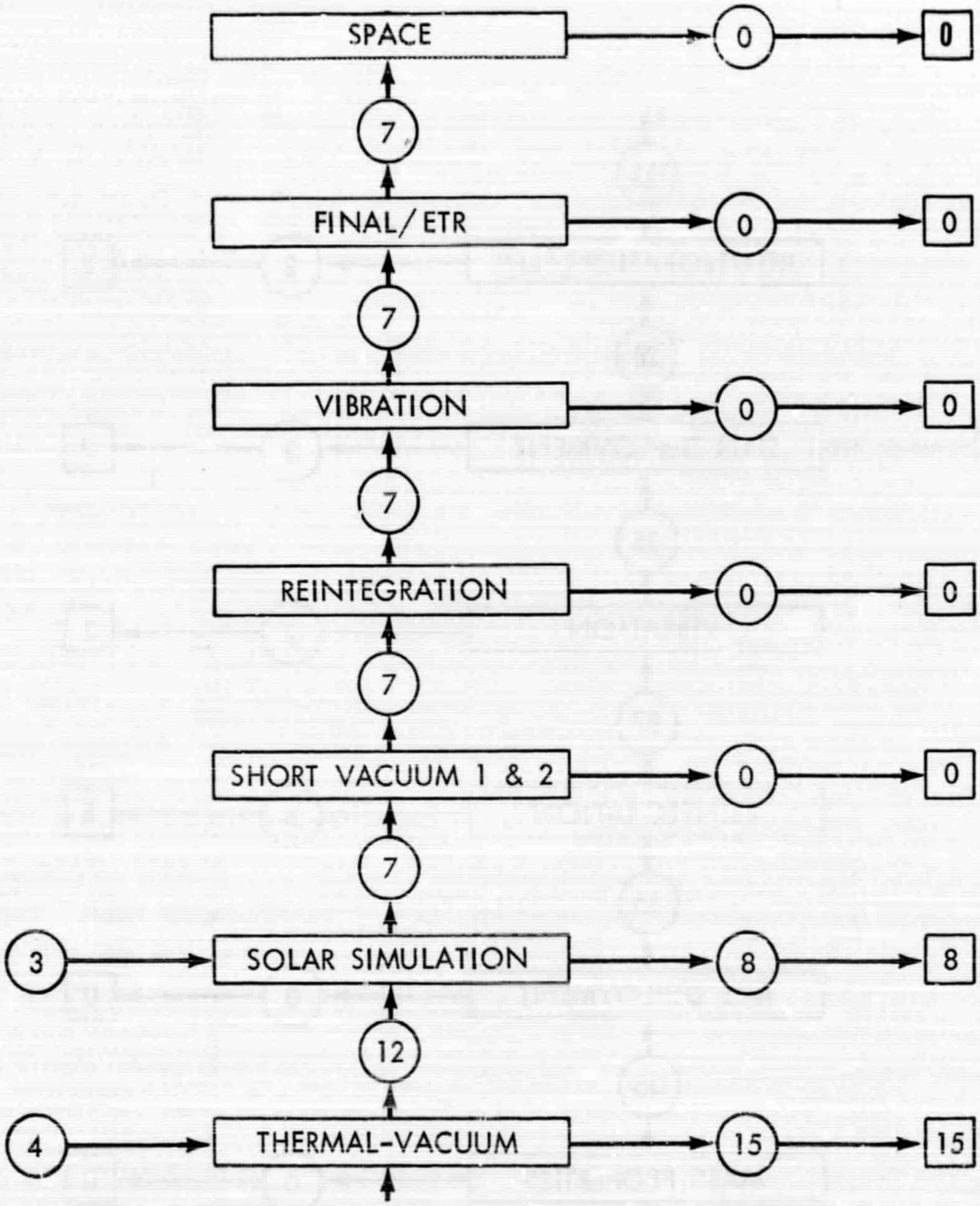

Figure 24C. IMP-I Screen Performance in Failure Flow Format (Continued)

- Eighty-five percent of the defects would have caused a malfunction in space
- Systematic defects were evenly distributed in criticality
- Design was the major cause of defects
- The percentage of parts/materials defects seemed high

2. Subsystem Test Screen

- Ineligibility is the major reason for escape
- The screen was 46 percent effective
- There were more minor criticality to subsystem before protection defects than major
- Protection had little effect on criticality
- The major criticality defects had a high probability of causing a space malfunction
- Systematic defects were evenly distributed in criticality
- Fabrication/assembly was the major cause
- The percentage of parts/materials caused defects was higher than in bench test
- Most of the defects detected in vibration were sensitive to the vibration environment
- Less than half of the defects detected in thermal-vacuum were sensitive to the thermal-vacuum environment

3. System Test Screen

- Screens with the most comprehensive functional checkout had the highest percentage of escapes due to inadequacy, but also had the highest detection rate
- Ineligibility is the major reason for escape
- The screen was 92 percent effective
- Forty-two percent of the defects were at least major degrading to subsystems before protection
- There were very few mission critical defects detected during system test

- Protection had little effect on criticality

- Most of the defects had a high probability of causing a space malfunction

- Systematic defects were evenly distributed in criticality

- Design was the major cause of defects; fabrication/assembly was the second most prevalent cause; parts/materials was third

- All of the defects detected in vibration were sensitive to the vibration environment, but only forty percent of the defects detected in thermal-vacuum were sensitive to thermal-vacuum

4. Space

   - There were seven malfunctions in space

   - Ineligibility was the major reason for escape to space

   - Sixty percent were catastrophic to subsystems before protection

   - Fifty percent were catastrophic after protection

   - Design was the major cause; parts/materials was second

Interpretation of the Data

This second part interprets the data presented in the first part, indicates some cautions and improvements with respect to a test program, and shows some of the useful features of failure flow analysis.

- Ineligibility is consistently the major reason for escape on a screen by screen basis. Considering each of the screen systems - bench, subsystem, and system - separately, this is reasonable. Most of the screens are designed to detect particular kinds of defects. A defect is ineligible for detection if it is a different kind of defect from the kind for which the screen was designed.

- However, those defects that escape into space because of ineligibility for detection present an opportunity to improve the screen system. Those defects that were ineligible because there was no screen for that defect, or because they did not pass through the screen, indicate the need for a specific screen. In the case of IMP-I, a second long thermal-vacuum test, rather than the short thermal-vacuum test, may have detected some of the defects that escaped to space.

- The overall screen was 94 percent effective. If the system test screen effectiveness is constant, then it presents a way to assess the risk involved in eliminating or curtailing the subsystem test program.

- The percentage of defects that were catastrophic or major degrading to subsystems, before protection, in space was somewhat higher than it had been during test screens, 60 percent versus 46 percent. If the 46 percent had been used to predict the percent of the space malfunctions that would be at least major degrading, 60 percent would have been a fairly close result.

- The effect of protection could have been very accurately predicted, since only one of the major degrading defects in space has its criticality reduced by protection.

- The percentage of systematic defects in space, 43 percent, is not far from the 53 percent detected in system test. In fact, if the 37 percent systematic defects detected in subsystem test is also considered, 43 percent is close to the average of subsystem and system screens.

- The distribution of cause of defects in space is quite interesting. The major cause of defects detected in system screens was design, with fabrication second. The major cause of defects detected in subsystem screens was fabrication, with design second. Parts/Materials was the third most prevalent cause for both system and subsystem detections. The fact that design accounts for three of the seven space malfunctions is not surprising. What is somewhat surprising at first is that parts failures accounted for two of the seven space malfunctions. The concern expressed earlier in this report, that 15 to 25 percent defects caused by parts/materials was a high percentage, is justified by this result. This does not determine what a good percentage is, only that 15 to 25 percent is high. The low fraction of space malfunctions due to fabrication defects, one out of seven, is not in accord with the results during test. However, this could indicate that the protoflight test program has the capability to remove almost all of the fabrication defects from the flow. This particular question, whether defects were detected because of the protoflight levels, was asked during the analysis, but the question is almost impossible to answer on a defect by defect basis. In the case of IMP-I, though, there were very few fabrication defect-caused malfunctions in space, and this could be a result of the protoflight levels.

- One space malfunction, the University of Chicago experiment, could have been damaged during launch, and then degraded by the space thermal-vacuum environment until it failed. The effect of the launch environment is a weak conjecture though. Dr. Ogilvie's experiment's failure can be attributed to the space vacuum, if the analysis of the failure is correct. This means that 30 percent of the space malfunctions were possibly caused by the thermal-vacuum environment. However, one of the defects never underwent system test, and it is doubtful that the other should have been detected. These data indicate that all the environmentally sensitive defects that could have been found during test were found. Had there been a second long thermal-vacuum test, the two environmentally sensitive space malfunctions might possibly have been found.

There is some information developed in this report which can only be developed by failure flow analysis, and some information that could be developed by other means but is integrated into a unified picture by failure flow analysis.

- Failure flow analysis showed what kinds of defects were removed at any point in the test program. It showed that a number of major degrading defects that should have been detected earlier were detected far downstream in system thermal-vacuum test. If each screen has a characteristic effectiveness, which is an assumption at this point, then loading a downstream screen increases the probability of an escape, and consequently a space malfunction.

- Failure flow analysis shows that not only does the system thermal-vacuum screen detect the most defects, but it is also the most effective screen. This means that the system thermal-vacuum screen detects a higher percentage of the defects eligible for detection than any other screen.

- This study has confirmed the need for very thorough parts screening for protoflight programs.

- The area of test that could be improved to decrease the downstream loading by at least 60 percent is the functional test. Only 40 percent of the defects needed thermal-vacuum for detection, and none needed solar simulation.

In light of future programs that will have extensive subsystem tests before system test, or programs that will be limited to less than full system tests because of size, failure flow analysis has provided some vaulable information.

- The subsystem test program as performed for IMP-I was only 50 percent effective for eligible defects, and this does not include defects that required the system level for detection. This must be improved before the subsystem test screens alone can be used to assure reliable spacecraft.

- Considering the environmental sensitivity of defects detected in subsystem screens, failure flow analysis indicates that the most improvement can be made in the areas of functional tests and parts screening.

- Coupled with the low effectiveness of the subsystem test screen is the fact that nearly 50% of the defects detected during system test required the system level of assembly for detection. Before any project is started that would involve a spacecraft too large for system test, two things must be changed. First, the subsystem test program must be made more effective. Second, the number of defects that require the system level for detection must be reduced.

Failure flow analysis would have the most value if it were used on a real time basis. It gives a view of how many and what kinds of problems are occurring, and thus could lead to early elimination of some sources of defects. Failure flow analysis could give an estimate of flight readiness, and indicate what actions might achieve flight readiness in the most efficient way.

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