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TEST PLAN OPTIMIZATION FOR AN EXPLORER-SIZE SPACECRAFT

by J. H. Boeckel and A. R. Timmins

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Greenbelt, Md.

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ABSTRACT

Although GSFC policy has required both a prototype (qualification model) and a flight (acceptance model) spacecraft, rising costs have caused a reexamination of this approach. In both the Interplanetary Monitoring Platform (IMP) and the Radio Astronomy Explorer (RAE) projects, a single spacecraft (termed proto-flight) was qualified and then successfully launched. The analysis discussed herein was conducted, using Monte Carlo techniques, to estimate whether this concept is truly cost-effective. The results of the study show a savings of approximately $1 million, using the proto-flight approach. It also shows that rigorous subsystem testing is effective in reducing costs if initial hardware quality is poor. The analysis reported herein assumes that each test approach treated produces equivalent spacecraft launch-readiness. Whether this assumption is true has not been determined; however, it could be expected to have some limitations.

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INTRODUCTION

The test philosophy at Goddard Space Flight Center has always emphasized complete spacecraft systems tests as a final check to demonstrate that the spacecraft is ready for launch. However, project managers have had considerable flexibility in conducting their programs. This has resulted in a minor amount of subsystem testing in some programs and substantial subsystem testing in others. In addition, the number of spacecraft in each program has varied considerably. Usually, a new program has included an engineering model, a prototype model, and two flight model spacecraft. In a subsequent launch in the same program, the number of spacecraft to be tested was reduced. As the funds available for a complete program declined, it was necessary to investigate ways to reduce costs. One approach was the use of a so-called "proto-flight" spacecraft. This approach used a single spacecraft that was tested to prototype levels and subsequently launched. The Interplanetary Monitoring Platform (IMP) project personnel pioneered the use of a single spacecraft. However, questions on its performance relative to other test approaches could not be answered on the basis of only one trial. The present study provides information for judging comparative performance.

The amount of hardware purchased is a basic determinant of program cost. Other factors such as amount and level of subsystem testing, combinations of subsystem and systems tests, delays, and levels of hardware quality also affect costs. Because of the effects of these factors, it became desirable to study different ways of conducting a test and evaluation program from the standpoints of cost and reliability, taking into account the expected variability in hardware quality. Because of the large number of interacting factors, such a study cannot be based upon a single program or a small number of spacecraft; experience with one or two specific projects does not provide an adequate guide concerning the costs involved. For adequate comparison, a large number of programs must be available for analysis. To provide such a basis, a mathematical cost model was developed in which the variables of cost, time, hardware quality, and test effectiveness could be studied, using large sample-sizes generated in a computer program, the General Purpose Systems Simulator (GPSS III). This program permitted the observation of total cost variation as caused by the random occurrence of failures and delays in a large number of "projects" conducted under a given philosophy.

THE COST MODEL

The GPSS III, as adapted for the present purpose, runs 2000 spacecraft programs using Monte Carlo techniques. Each step in the testing uses a probability distribution for selected failure rates. The output of the GPSS III is a distribution of cost and time for each of the six phases of a project life cycle as follows:

Phase I Development and Fabrication
Phase II Subsystem Test
Phase III Integration
Phase IV System Test
Phase V Prelaunch
Phase VI Space Flight

The inputs to the cost model may be varied as desired. Details of the cost model are presented in Appendix A.

This investigation concerns an Explorer-size spacecraft program, i.e., a spacecraft weighing up to approximately 500 pounds and launched by a Delta vehicle. Even with this limitation, one quickly recognizes that there is a considerable variation in total project costs within an Explorer program. This variation is accommodated by the cost model.

Since historical cost data were not available in the form necessary for use in the model, the costs used are the best engineering judgments available with respect to each of the phases. Total program costs derived compare favorably with experience on typical explorer projects such as IMP F&G ($7.5 million each) and RAE-A ($8.1 million).

SCOPE OF STUDY

Table 1 lists failure data from the systems tests of six IMP spacecraft. It shows that the probability of failure of a particular subsystem ranged from 0.1 to 0.5. This result provides a basis for assuming the failure probability in systems tests in the model.

Table 1

Failure Data From Systems Tests of IMP Spacecraft.

IMP spacecraft	Number of failures		Probability of failure P_{f_s}
	Subsystems	Experiments	
A - Prototype	7	4	0.4
B - Flight	4	1	0.2*
C - Flight	1	1	0.1
D - Flight	8	6	0.5
E - Flight	5	7	0.4
F - Proto-flight	3	3	0.2

*No. of subsystems 20
No. of experiments 9
Total units 29

Example for $P_{f_s} = \frac{5}{29} = 0.17$.

The variables studied included hardware quality, subsystem test effectiveness, subsystem and system test failure probability, and test plan. The range of each variable was as follows:

1. Hardware quality: 0.25 to 0.95 failure probability
2. Systems test failure probabilities: 0.07 to 0.90
3. Subsystem test failure probabilities: 0.03 to 0.73
4. Ratio of subsystem-to-system test effectiveness: 0.2 to 1.0
5. Test plans: three

Table 2 lists the matrix and specified values used for all the variables. One premise used in setting up Table 2 was that testing did not eliminate all failures in a spacecraft. A conservative space failure rate residual of 0.05 per subsystem was used. For instance, with a hardware failure probability of 0.95, the combined failure probability in subsystem and system testing was 0.90.

Three cases were studied to examine the effect of the test plan on total project costs. Equal quantities of subsystem hardware were provided for each case. The three cases were as follows:

1. Case I — Two complete sets of subsystems were tested as subsystems. One set was integrated into a flight spacecraft that was tested at prototype levels. No backup spacecraft was provided.

2. Case II — No subsystem tests were performed. One prototype and one flight spacecraft were subjected to environmental tests.

3. Case III — One set of subsystems was subjected to environmental tests and integrated into a prototype spacecraft. The flight spacecraft used subsystems that had not been subjected to environmental test. Both spacecraft systems were subjected to environmental tests.

Subsystem test effectiveness was studied at three levels.

1. Good — The subsystem test was made equal to the system test in effectiveness.
2. Medium — The subsystem test was made one-half as effective as the systems test.
3. Poor — The subsystem test was made one-fifth as effective as the systems test.

As indicated in Table 2, this parameter was investigated at three levels under Case I only.

The effect of systems test failure probability on the cost to launch was studied as a function of hardware quality and test plan. The matrix includes the effect of prior subsystem tests on the system test failure probability.

Each computer run provides 25 tables of data. Each table gives the distribution of the results of 2000 spacecraft programs with respect to time, cost, or frequency of some part of the life cycle of the program. Approximately 20 individual cases were run for the purpose of this study. It is clear that many comparisons and analyses can be made from the available data. For example, test costs could be examined separately.

Table 2

Summary of Variables Investigated.

Hardware quality (P_F = probability of failure)	Failure probability in test (P_f) ss = subsystem test; s = system test	Test Plan						
		Case I			Case II		Case III	
		Two sets of subsystems and one spacecraft (proto-flight)			No. subsystem tests; one prototype and one flight spacecraft		One set of subsystem tests; one prototype and one flight spacecraft	
		Subsystem Test Effectiveness			Prototype spacecraft	Flight spacecraft	Prototype spacecraft	Flight spacecraft
		Good*	Medium*	Poor*				
0.95	$P_{f_{ss}}$	0.73	0.43	0.18	-	-	0.43	-
	P_{f_s}	0.17	0.47	0.72	0.90	0.30	0.47	0.30
0.75	$P_{f_{ss}}$	0.56	0.33	0.13	-	-	0.33	-
	P_{f_s}	0.14	0.37	0.57	0.70	0.23	0.37	0.23
0.50	$P_{f_{ss}}$	0.34	0.21	0.08	-	-	0.21	-
	P_{f_s}	0.11	0.24	0.37	0.45	0.15	0.24	0.15
0.25	$P_{f_{ss}}$	0.13	0.08	0.03	-	-	0.08	-
	P_{f_s}	0.07	0.12	0.17	0.20	0.07	0.12	0.07

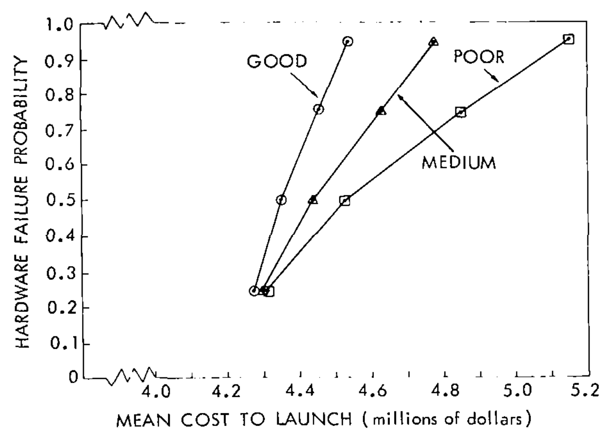
*Good - Subsystem tests equal to systems tests in effectiveness
Medium - Subsystem tests one-half as effective
Poor - Subsystem tests one-fifth as effective.

For the purpose of this study, the criterion used for comparison of the many variables is the cost to launch. This criterion is the most important one from the standpoint of the project manager since his interest is not served by minimizing costs of one phase of the program if it does not provide a savings for the overall program.

RESULTS OF STUDY

Subsystem Test Effectiveness

Figure 1 presents data on the relationship of subsystem test effectiveness to hardware quality and the mean cost to launch. For this part of the study, one set of subsystems and one spacecraft were the basis for the cost data. With good hardware (failure probability, $P_f = 0.25$), variations in subsystem test effectiveness caused no significant difference in the mean cost to launch. With fair hardware (failure probability of 0.5), the difference between a good subsystem test and a poor subsystem test amounted to approximately $180,000 in the mean cost to launch. Inability to find faults at the subsystem level delayed their discovery until systems tests were conducted. As the number of failures found in the more costly systems test increased, the mean cost to launch increased. With very poor hardware (failure probability of 0.95) the subsystem test effectiveness could make a difference of $600,000 in the mean cost to launch.



Note: GOOD - Subsystems tests equal to systems tests in effectiveness.
MEDIUM - Subsystem tests half as effective.
POOR - Subsystem tests one fifth as effective.

Figure 1—Effect of hardware quality and subsystem test effectiveness on cost to launch, based on a test plan for one set of subsystems and one Explorer spacecraft.

Test Plan

Subsystem test effectiveness compared to systems test effectiveness is influenced by the adequacy of system interface simulation as well as by the comparative duration of the two tests. The normal subsystem test time for a prototype subsystem test in an Explorer-type program is 2 days for a thermal-vacuum test, compared to about 13 days (Reference 1) for a systems test. These considerations, in addition to a separate study of subsystem tests (Reference 2), resulted in using the "medium" subsystem test effectiveness in Figure 1 as being representative of the subsystem test effectiveness at Goddard Space Flight Center.

Three test plans, identified as Case I, II, and III in Table 2, were investigated. Figure 2 shows the effect of hardware quality and test plan on the mean cost to launch. Case I is more economical under all circumstances investigated. With good hardware quality, Case I is more economical than Case II or III by $850,000, and the cost savings increase as the hardware quality decreases. If hardware quality is very poor (failure probability of 0.95) the cost savings of Case I increases to $1.1 million compared to Case III and $1.6 million compared to Case II.

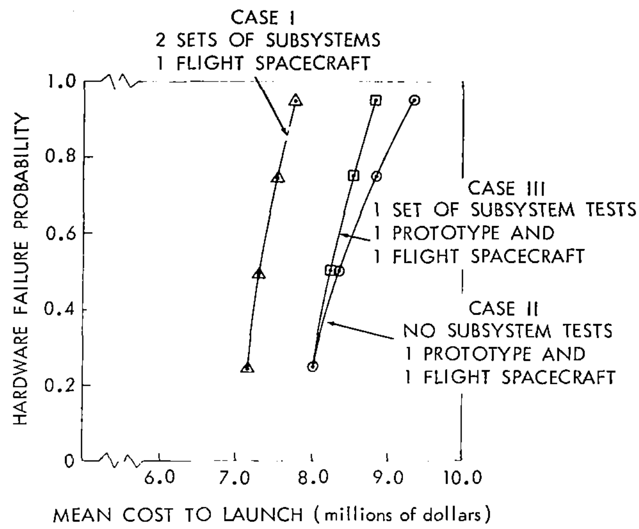


Figure 2—Effect of hardware quality and test plan on cost to launch.

Test Costs

Two of the principal cost inputs for the three cases are the subsystem and system test costs. These costs were examined extensively as a function of test effectiveness and hardware quality, and the results were summarized in Figure 3. With very poor hardware, the need for a highly effective subsystem test is evident. In the most extreme case shown, the cost savings may amount to $1.75 million for an effectiveness ratio of 1.0 compared to 0.2. With good hardware, the cost savings of good subsystems testing becomes relatively small.

Hardware Quality

Figures 1 and 2 show decreased program costs for improved hardware quality. However, the model does not assign a cost penalty for improved quality. It is an independent variable and "comes for free". In reality, however, quality increases cost. There are two attacks on the quality problem:

1. Standard quality assurance through workmanship, documentation, and design review.
2. Pretesting under environmental stress before initiating the formal test program.

Either of these approaches costs money. As indicated in Figure 2, the maximum benefit to be obtained through improved quality is approximately $1 million for this model program. Therefore, extra quality assurance and pretest are not cost-effective if they cost more than $1 million. However, one must recognize that some types of failures may escape detection by present test methods and can be eliminated only through quality assurance measures.

Test Delays

Another consideration in determining the best test plan is the time required to complete the program. Delays may be caused by late delivery of hardware, failures in subsystem and system testing, and unavailability of subsystems to complete integration or delivery to the launch site. These delays were combined for study as follows:

1. All delays up to the start of systems tests

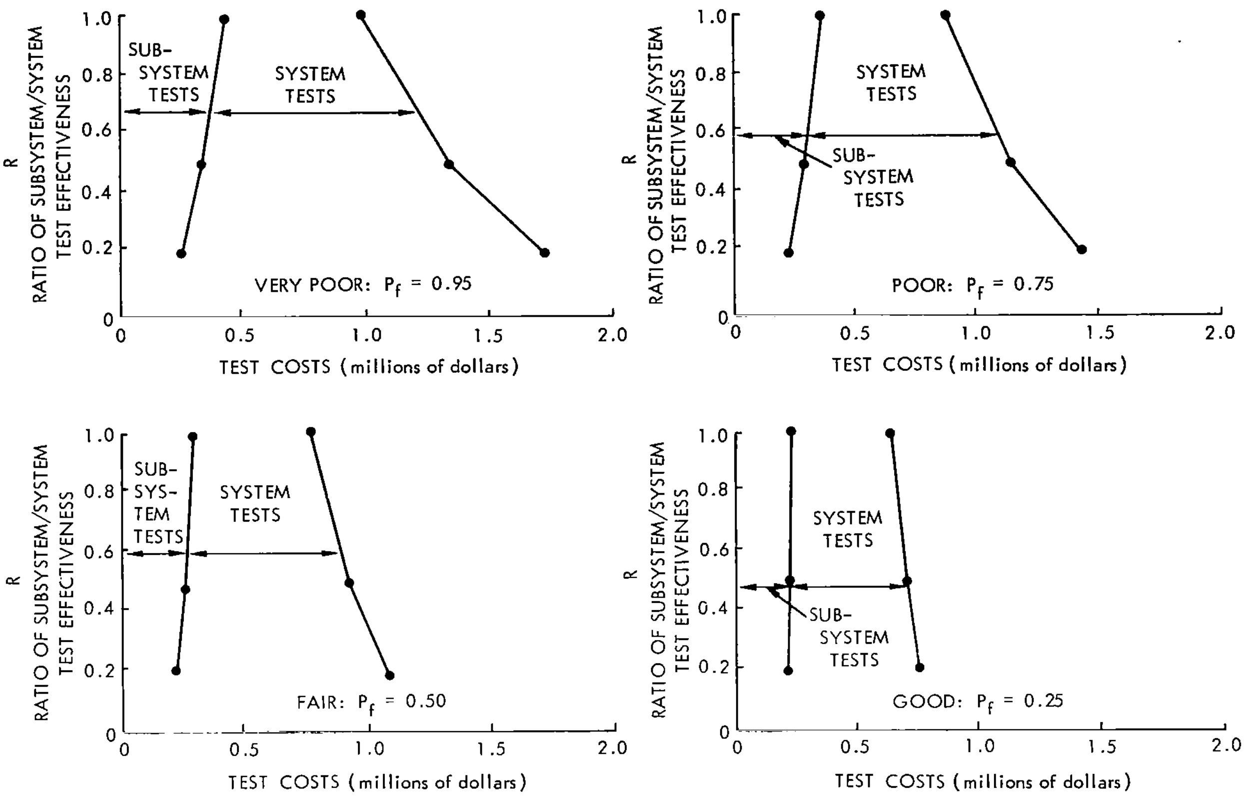


Figure 3—Effect of subsystem-to-system test effectiveness ratio on test costs for several levels of hardware quality, based on one set of subsystems and one spacecraft.

2. Delays caused by system test failures
3. Delays in shipping to the launch site because one or two subsystems had not arrived.

The three types of delays are depicted in Figure 4 as a function of test effectiveness and hardware quality. Figure 4 shows:

1. The delays preceding the start of system tests are not very sensitive to variation in hardware quality, and less sensitive to R (ratio of subsystem-to-system test effectiveness).

2. The delay in system tests can vary significantly, depending principally on hardware quality. For a representative R value of 0.5, there could be 14 weeks of delay for very poor hardware, compared to 4 weeks for good hardware.

3. The "good" subsystem test effectiveness ratio causes larger delays in shipping to the launch site. This results from the ground rule that system tests begin when 23 of 25 subsystems have been integrated. Thus, the system test may be completed before the last two subsystems have completed their subsystems tests. The chances of this happening increase with an increase in R.

Variation From Mean Costs

The data presented thus far have been cited on the basis of the mean cost to launch. However, for a specific program, the cost to launch could vary from the mean, depending on chance. In order to make the best program decisions, a project manager needs to know how much chance alone might affect his program. The cost model provides such information by giving frequency/cost distributions for each phase of the life cycle. Figure 5 is an example of such a distribution.

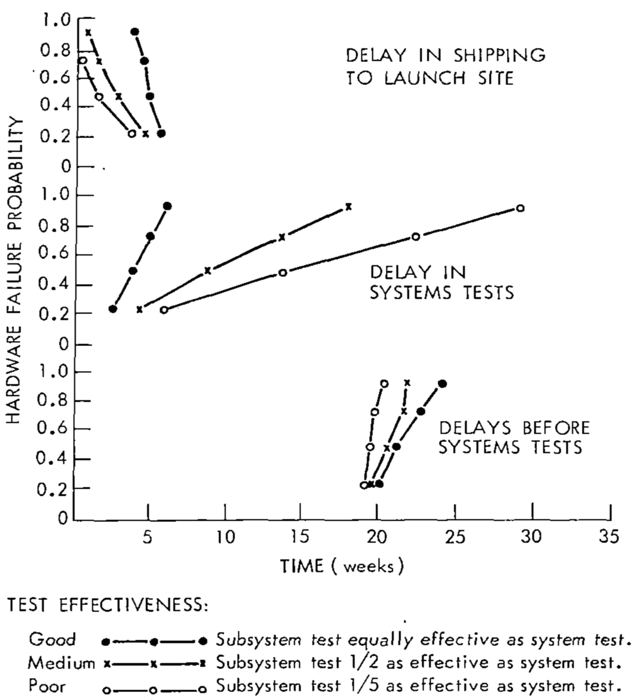


Figure 4—Summary of delays in a spacecraft program as a function of hardware quality and test effectiveness.

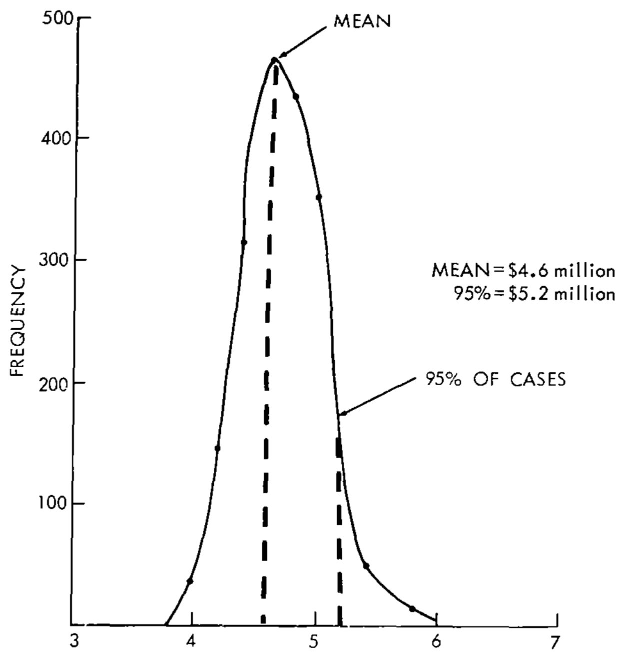


Figure 5—Distribution of cost to launch for 2000 spacecraft based on a test plan using one spacecraft and one set of subsystems ($P_{f_{ss}}$ = 0.33, P_{f_s} = 0.37).

For instance, the cost to launch would not exceed $4.6 million (for the variables listed) for 50 percent of the time and would not exceed $5.20 million for 95 percent of the time. This kind of variation exists even though the following variables were fixed:

1. Test plan—one spacecraft and one set of subsystems
2. System test failure probability—P_{f_s} = 0.37
3. Subsystem test failure probability—$P_{f_{ss}}$ = 0.33.

The main point is that each program is unique, and we are trying to determine the probabilities for the cost to be within certain bounds.

Comparison of 50-Percent and 95-Percent Values of Cost to Launch

When mean values of cost to launch are used, the test plan identified as Case I is more economical in all cases. To gain further insight into the three test plans, the 50-percent values of the cost to launch were compared with the 95-percent values. Table 3 gives this comparison. It shows again that Case I is superior in all instances to Case II and Case III. In fact, the extreme values (95 percent values) for Case I are less than the mean values for Cases II and III. Further, Case I is affected less by hardware quality than Case II and Case III. Also, the cost to launch is more sensitive to the test plan than it is to hardware quality.

Table 3

Cost To Launch In Thousands of Dollars.

Hardware	P_f	Mean values			95% values		
		Case no.			Case no.		
		I_B*	II	III	I_B*	II	III
Quality							
Very poor	0.95	7726	9324	8819	8291	10470	9891
Poor	0.75	7525	8839	8539	8090	9978	9502
Fair	0.50	7310	8342	8240	7892	9439	9295
Good	0.25	7137	8005	7980	7756	9181	9015
Cost to	0.95	108	131	123	116	146	138
Launch	0.75	105	124	119	112	139	133
as % of	0.50	103	117	115	111	132	130
$7137	0.25	100	112	112	109	128	126

*See Table 2 for identification of Cases I_B, II, and III.

Relative Costs of Program Phases

The relative costs (Table 4) are based on one spacecraft and one set of subsystems. The minimum and maximum values are taken from the spread of the mean values of the cases covered in this study. Using the foregoing representative figures, the phase I costs are shown to be greater

Table 4

Relative Costs of Program Phases.

Phase	Cost (Thousands of dollars)		
	Minimum	Maximum	Representative
I Research, development, and fabrication	2500	2700	2600
II Subsystem test	208	427	320
III Integration	380	840	610
IV System test	412	1835	1150
V Prelaunch	155	225	190

than any other phase. These data are for one set of subsystems. All programs to date have used at least two sets of subsystems; thus a more representative value for phase I would be $5 million. The cost assumptions used in the model would have to be in error by orders of magnitude to change the conclusion that phase I offers the greatest potential for maximum cost savings. Another self-evident conclusion is that the cost of integrating a second spacecraft can be traded for testing two complete sets of subsystems. The subsystem and system test phases also offer cost savings possibilities, mainly through improvement of hardware quality. This analysis shows that the system test cost can be minimized by the use of a single spacecraft in conjunction with the complete testing of two sets of subsystems.

CONCLUSIONS

1. The cost model is useful in developing comparison data, using a large sample to investigate the effects of varying hardware quality, the test program plan, and test effectiveness.

2. The cost model shows that the most economical way to conduct an evaluation program on an Explorer-type spacecraft is to use a test plan that requires one spacecraft with two sets of subsystems.

3. The cost saving from an effective subsystem test program decreases as hardware quality improves.

4. There is a clear limit to the cost savings that can be achieved by improving hardware quality prior to the spacecraft testing.

FURTHER WORK

As discussed earlier, it has been assumed throughout this study that all programs resulted in equivalent performance after launch. However, there are insufficient flight data to make a judgment. Therefore, it is desirable to investigate a range of possible situations. Such an investigation, however, would require an acceptable cost model for the impact of a failure in space to serve as a basis for comparison between programs. This phase of the analysis will require considerable development and input from scientists and managers.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, December 10, 1968
124-12-03-01-51

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Appendix A

The Spacecraft Test Program Simulator

Introduction

Estimating the effect of various test philosophies on program cost requires a model of a spacecraft program. The following discussion describes the model chosen and the manipulations introduced. The mathematical modeling technique used is described in the General Purpose Systems Simulator III Users Manual (IBM Application Program H20-0163-1). With this tool, it was possible to simulate 2000 repetitions of each spacecraft program conducted with a given quality of hardware and under a given test philosophy but with variability in delay of hardware arrival, integration, and test effectiveness. Thus variability in resultant cost could be observed for a given set of input data.

The Spacecraft Program

A spacecraft of the Explorer class was chosen for analysis. It consisted of approximately 25 subsystems of which 11 were considered to be scientific experiments. Each subsystem was put through a simulated life-cycle of fabrication, integration, and testing by means of Monte Carlo techniques on a digital computer. (The Monte Carlo method consists of the use of random numbers to provide an artificial world of experience, based on assumed probability distributions for input variables, which is used for testing proposed operational schemes.) There are numerous possibilities at nearly every step in this life cycle. For example, a subsystem may fail in systems tests with a probability of 0.25. Therefore, an average of one-fourth of the subsystems in the spacecraft will fail. However, on a particular spacecraft, there is a finite (though small) probability that all subsystems might fail or that none might fail, in accord with the laws of chance. Thus the results of a total program can vary widely, depending on chance although the input assumptions of arrival distributions and failure probabilities are held constant. To study this variation, 2000 simulated programs were run for each set of input assumptions. The final results of these 2000 programs gave a distribution of possible costs related to the particular assumptions used.

The model program emphasizes the test phase of the spacecraft program. Nominal durations for life cycle phases before the introduction of variability, failure, and delays are shown in Table A1.

A secondary output of the analysis, in addition to program cost, is the delay in each of these phases as a function of the initial assumptions made on hardware quality, test effectiveness, and test philosophy.

Table A1

Project Life Cycle.

Phase	Nominal time (weeks)
Development/fabrication	40
Subsystem test	4
Integration	6
System test	8
Prelaunch	4
Time to launch	62

Development/Fabrication

The nominal time duration chosen for this phase was 40 weeks. However, experience shows that simultaneous, on-time arrival of all subsystems is very unlikely. The distribution chosen to represent the delay was log-normal, truncated at 50 weeks of delay. This means that no subsystem ever arrives ahead of schedule, the vast majority (85 percent) are no more than 20 weeks late, and none are later than 50 weeks. It was assumed that disasters represented by schedule slippages of more than 1 year would be corrected by a *deus ex machina* that could not be interpreted mathematically. The actual distribution used had a mean delay of 12-1/2 weeks, and 99 percent of the items were included before the end of 50 weeks.

The cost of each subsystem was computed at $2000 per week, uniformly for each subsystem. This cost would actually vary among subsystems during design and fabrication. However, it was felt that this variation would not have a significant effect on the interpretation of test philosophy changes.

Subsystem

After a subsystem was delivered, it was subjected to subsystem testing, nominally a 4-week phase. These tests were not defined further; however, the failure probability ($P_{f_{ss}}$) in these tests was a major input variable to the analysis. The $P_{f_{ss}}$ is a function of two factors—the quality of the hardware as delivered and the effectiveness of the test. Hardware quality is defined as the probability (P_f) that the specific subsystem will fail catastrophically at some time before the spacecraft mission is complete. Test effectiveness is the ability of the test to find the inherent flaw, i.e., $E_{ss} = P_{f_{ss}}/P_f$. When a subsystem failed, it was repaired (3 weeks) and retested (2 weeks). The probability of failure in the second test varied also but was always set at one-third of the initial failure probability. When a second failure did occur, the subsystem was again repaired (3 weeks) and retested (2 weeks). It was assumed that it always passed the third test. This truncation by guaranteed success does not conform to real life, but it was suitable for the purpose. Subsystems tests cost $2000 per week for each subsystem for both testing and repair time. The rate per week includes all project costs.

Integration

The nominal program calls for simultaneous delivery of all subsystems; however, as discussed earlier, this does not happen. The model, therefore, begins integration when 13 subsystems are available and continues for 6 weeks or until 23 subsystems arrive. It is assumed that the 23rd subsystem can be integrated in zero time. If the last two subsystems arrive during systems tests, no delay is charged; if they arrive after systems tests are complete, shipment to the launch site is delayed. This delay is charged at a rate of $40,000 per week, as is the integration itself. The rate per week, as in the case of the subsystem tests, includes all project costs.

Systems Test

Systems tests begin after integration is completed. The nominal time for these tests is 8 weeks; however, their completion is usually delayed by failures. During systems tests, each subsystem is considered to have the same probability of failure P_{f_s}. This value is variable in the model. Its magnitude depends on initial hardware quality, the effectiveness of the prior subsystem tests in correcting faults, and the residual failure rate remaining in space. Thus system test effectiveness is given by

$$E_s = \frac{P_{f_s}}{P_f - P_{f_{ss}}} .$$

In manipulating the model, the effectiveness of systems tests was always chosen as equal to, or greater than, subsystem test effectiveness. The ratio E_{ss}/E_s was varied from 1.0 to 0.2. The latter case represents rather cursory subsystem testing that would require the isolation of most faults at the systems test level.

When failures did occur, they were categorized such that one-third required a retest of the system (Type A), and two-thirds were "quick-fix" without retest (Type B). Type A failures, which added 2 weeks each to the systems test time had a failure probability of $P_{f_s}/2$ in the retest for the particular subsystem in question. If another failure occurred, another 2-week delay was incurred, and the failure probability was $P_{f_s}/4$ in the retest. If a failure occurred in this test, another 2-week delay was charged, but it was assumed that the fourth test was always successful. Type B failures (quick-fix) added 1 week each to the systems test time for repair but did not require retest.

Systems testing was charged at a rate of $40,000 per week. As before, the rate per week includes all project costs.

Shipment Delay

As discussed earlier, the model permitted systems tests to be performed with two subsystems missing. However, shipping to the launch site was delayed until they arrived. This delay was charged at $40,000 per week.

Prelaunch

The nominal time duration at the launch site was set at 4 weeks. Provision was also made for failures in this phase; they remained constant at 0.03. One week of delay was charged for each failure at a cost per week of $40,000.

Space Flight

The model provides for treating variable failure rates in space and a method of interpreting these failures in terms of cost. However, it is difficult to obtain a general agreement on this matter. In this analysis, it was assumed that every test philosophy analyzed produced equal results in terms of finding inherent failures. Therefore, "cost in space" was the same for each approach, and only "cost to launch" has been treated. Hopefully it will become possible to obtain agreement on the cost of failures in space and on the relative effectiveness of varying test philosophies so that the analysis can be extended to cover this aspect of total program cost.

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