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Technical Report No. 32-961

A Space Mission Success Evaluation Model

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JET PROPULSION LABORATORY
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ABSTRACT

High among the considerations involved in the planning of space missions is the probable success of the mission. The determination of this value can lead to answers to such important questions as: (1) Is the probable return sufficiently high to justify the planned allocation of resources and is the risk (probability of an insufficient return) satisfactorily low? (2) How should the currently available resources be allocated to maximize the probable success? (3) Which of the multitude of possible changes in design will give the greatest increase in probable return for the least expenditure of additional resources? The approach presented shows a technique for determining a quantitative measure of success, a procedure for evaluating this measure both a priori and a posteriori, a systematic technique for collecting and displaying the necessary input information, and a method for determining the optimal allocation of resources.

I. INTRODUCTION

The basic intent of mission success modeling is the provision of an additional analytical tool to assist project management in making the right decisions regarding the course of a mission. To provide this assistance, an overall mission success effort, as presented in this report, consists of two stages:

1. The development of a realistic analytical model of the project to allow accurate computation of the probable success of the missions comprising the project.
2. The usage of the model to determine how the probable success can be maximized within the existing and planned resources.

There are, of course, many other uses of the model resulting from stage 1 in addition to its use in stage 2 (see Figs. 1-5).

The mission success evaluation model can be constructed at whatever level of detail is feasible. Early in the planning stages of a mission, it may be most reasonable to go into no more detail than consideration of major systems and phases. As designs evolve, more detail can be considered until the model takes into account all applicable hardware and software for systems, subsystems, and components, and all functional requirements, flight phases, and ground operations that affect the project.

Most projects are comprised of several systems. The *Surveyor* project, for example, is comprised of the launch vehicle, the spacecraft, the mission operations, and the tracking and data acquisition systems.

In past projects, the flight systems have been the major source of concern in the determination of the probabilities of success. However, due to the increasing complexity of the ground operations required to support a mission, there is considerable concern that the ground systems may significantly degrade the probability of mission success. Thus, it is becoming more and more important that ground systems be included in mission success models.

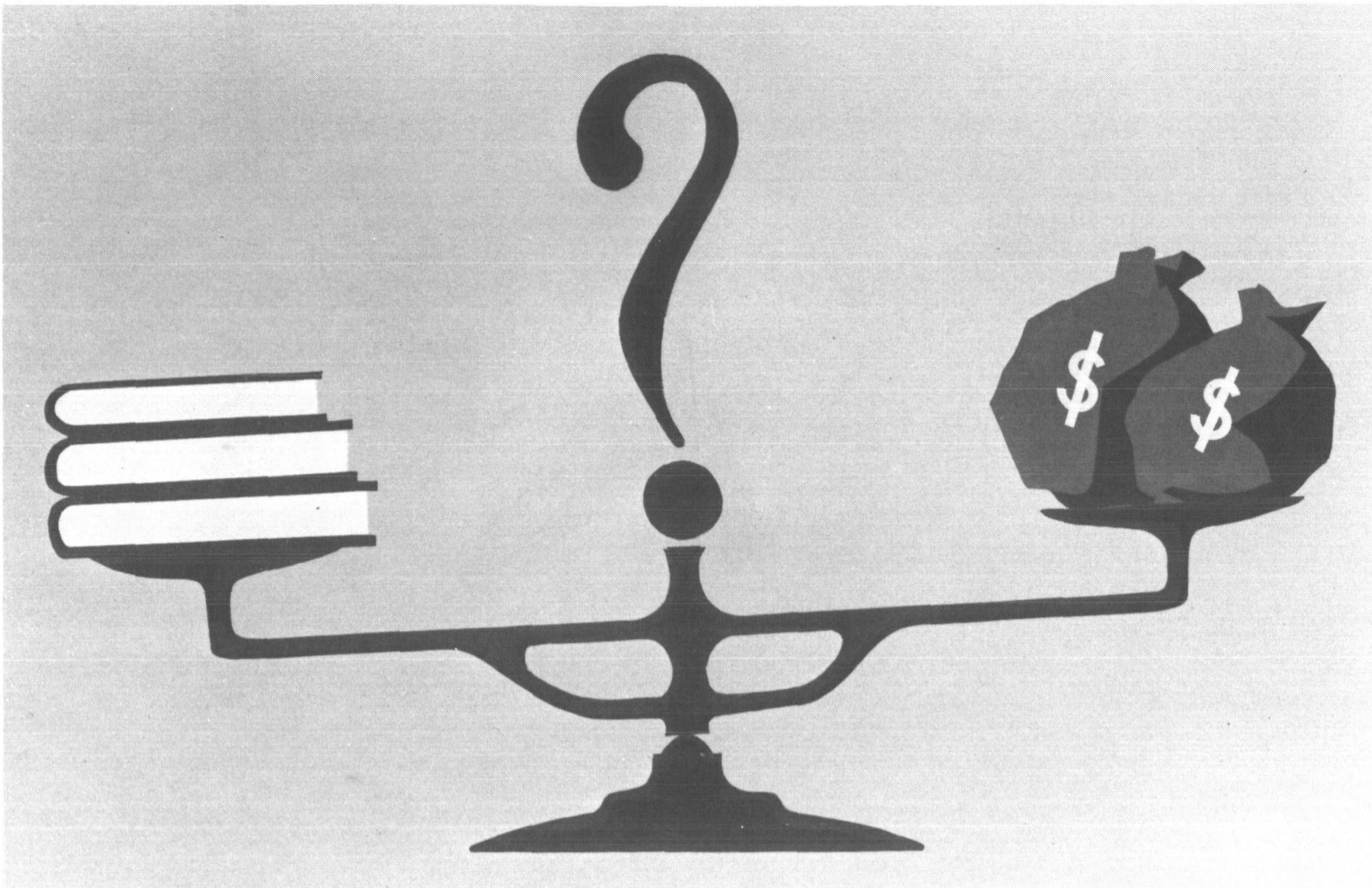


Fig. 1. Why study mission success?

To achieve maximum usefulness for the model, it is imperative that test data be accounted for and that all likely functional modes of operation be considered.

The second and more important stage of the mission success effort involves usage of the model to determine how to maximize the probable success of each mission and all missions within the existing and planned resources. An extended development of this stage of the mission success effort is beyond the scope of this report. Such development will provide the relationship between resource allocations and probable mission success. By using the mission success evaluation model resulting from stage 1, stage 2 can be divided into the following steps:

1. Perform sensitivity analyses to determine the relationships between the probabilities of proper performance of subsystems, components, etc., and the probable mission success. Sensitivity analyses indicate how particular system and subsystem designs affect the probabilities of mission success and identify weak areas in the design; they also can provide an increased awareness of the functional relationships among and within the various systems.

2. Extend this development to incorporate consideration of the effects of varying the allocation of existing and planned resources.

Step 2 is far more extensive and requires consideration of the interrelationships among the various resource allocations. The relationships between probability of success changes and resource expenditures must then be developed and an optimization procedure applied. This type of analysis is particularly important to management, since it will provide a quantitative tool for optimally allocating such resources as funds, time, and manpower to weak areas. Furthermore, it will indicate the consequences of various value judgments and provide a further understanding of the relationships among the elements of the project (Fig. 4).

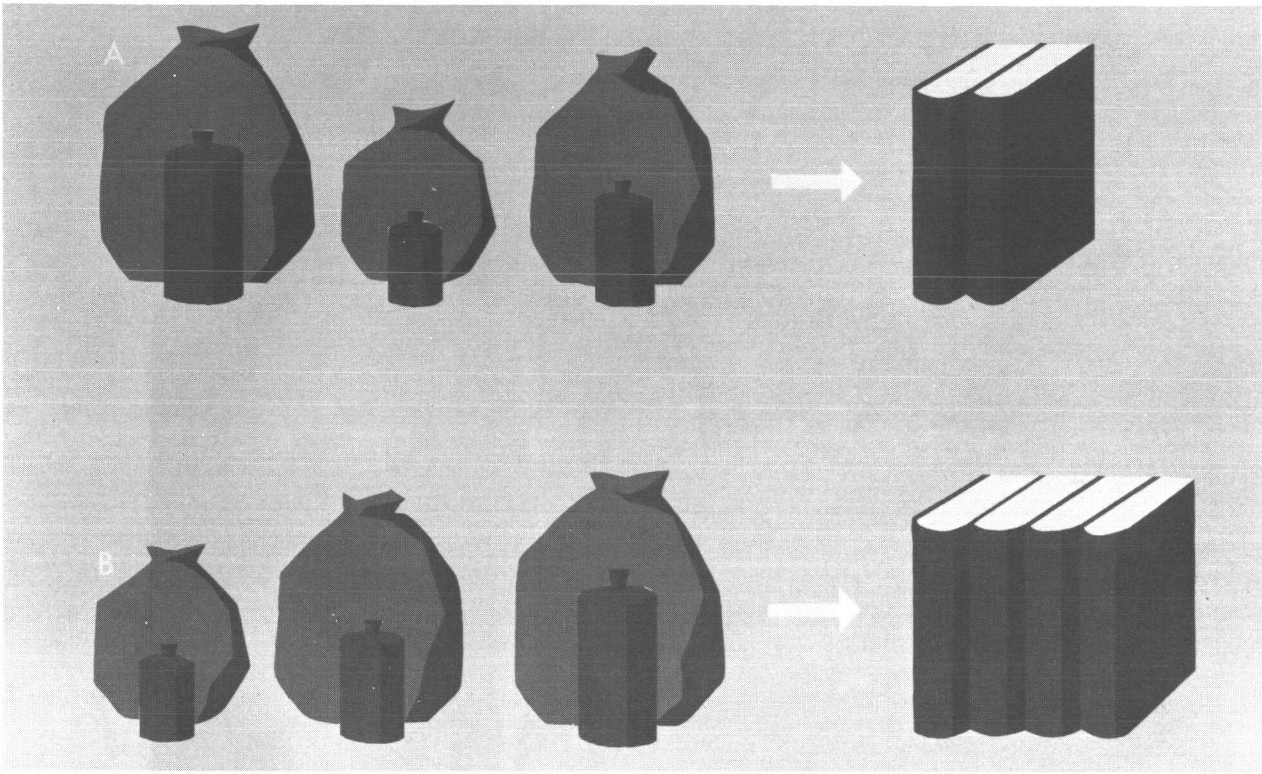


Fig. 2. Is the current allocation of resources optimal?

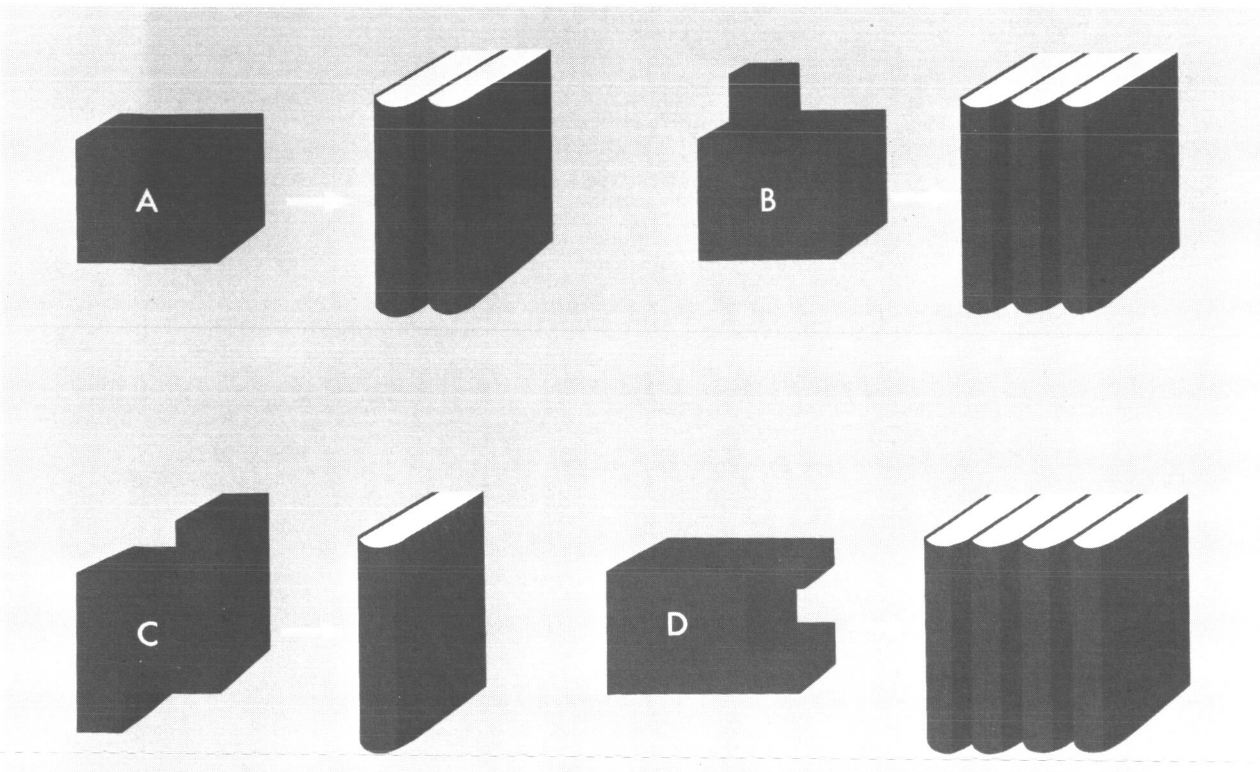


Fig. 3. Which changes should be made?

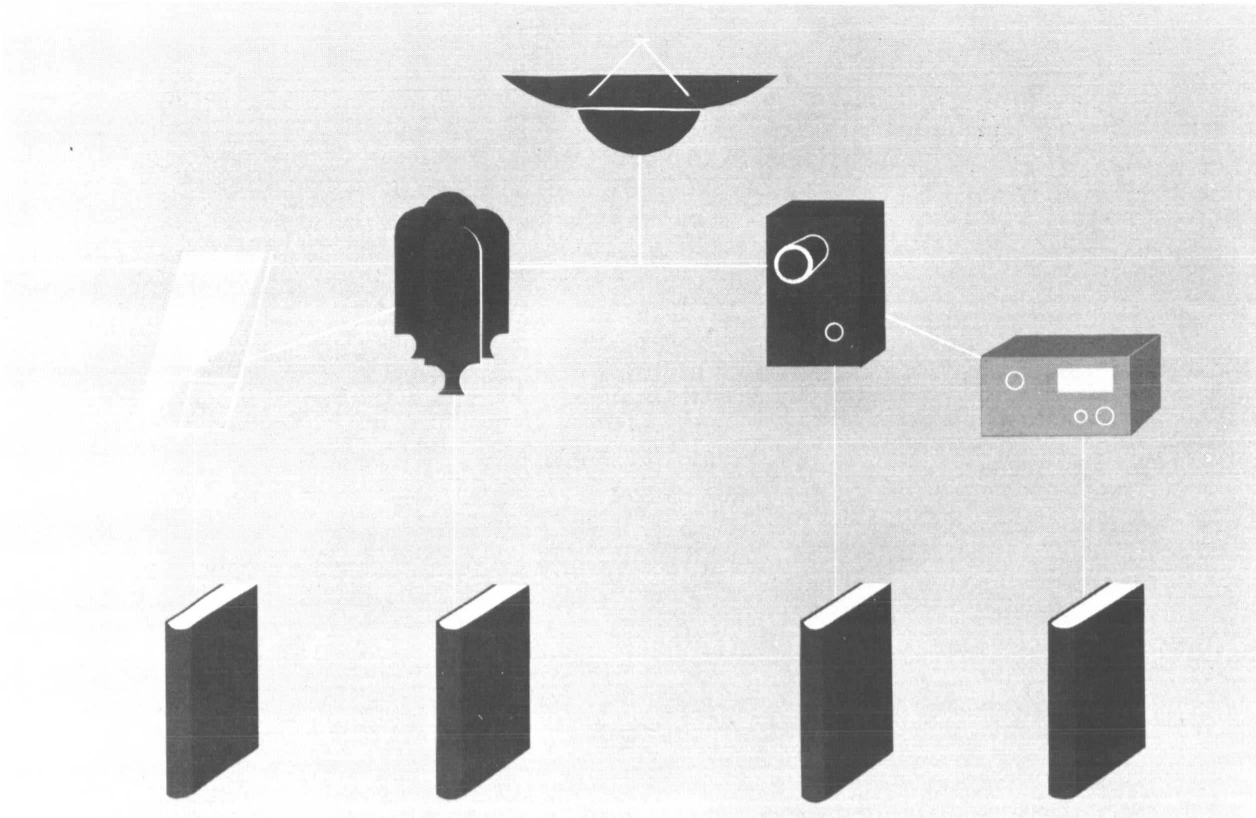


Fig. 4. Better understanding of the mission

Los Angeles Times

LARGEST CIRCULATION IN THE WEST, 839,735 DAILY, 1,165,396 SUNDAY

VOL. LXXXV | FIVE PARTS—PART ONE | MONDAY MORNING, MAY 9, 1966 | 104 PAGES | DAILY 10c

SPACE MISSION MANAGER GIVES ODDS 3 TO 2

Drizzles Expected to Continue Today

Thunderstorms and High Winds Prevail in Desert

plaining of back pain were shown to be suffering from muscular deficiencies, rather than pathological disorders.

The muscle-deficient sufferers were otherwise healthy, except for the pain. When they took the six K-W tests previously mentioned, they failed one or more.

They simply didn't have either the muscle strength or muscle flexibility to handle

proved under exercise and a check 10 years later showed that so long as they exercised, they kept strong, resilient muscles and remained free of pain.

Many of these patients had localized and exquisitely tender spots in the muscles. Such spots can occur in different parts of the body, but they are frequently in the neck, shoulders, upper or lower backs, or the hip muscles. They are called trigger points because they trigger pain.

They can be caused by constant or acute strain of the muscles, or by muscle spasm. They are, in a sense, like scar tissue. They are extremely painful and can trigger pain by triggering muscle tension or spasm.

They usually appear if minor episodes of back pain go untreated. Once formed, the episodes of pain will often reoccur and may increase frequency and intensity

chronic back pain caused by weakness or tension we feel the muscles gently with our fingers to detect any trigger points. If there are none, exercise therapy can start once pain subsides, usually after about a week.

We use ethyl chloride spray and other physical therapy to help relieve the pain.

If we find trigger points, we mark the locations on the skin. Then we inject each trigger point with procaine. This kills the pain. But more important, both the needle and the injected fluid break up the trigger point by the force of hydraulic pressure. Once the trigger point is eliminated, the patient can begin corrective exercises.

Sometimes a doctor may find another kind of tenderness—by gently rolling a patient's skin between his fingers. If the skin itself is very sensitive, it is known as fibrositis. It responds well

Ky Acts to Stifle Any Agitation Over Pledge to Stay in Power

well publicized problem that seems to strike celebrities so often.

A "slipped disc" is caused when the ligamentous disc covers tear or give so that the soft contents ooze out and press on nerves.

Trigger points and discs can be confused because they show similar symptoms. Both produce radiating pain in either the upper or lower back and down the backs of legs and arms. But that's the end of the similarity. Discs can cause loss of reflexes, loss of sensation, numbness or weakness. Trigger points cannot.

Some people still think they have

came to the clinic with pain in his back and right leg. He had already been through two operations for spinal fusion and removal of a disc. Yet the pain persisted.

There was no doubt he had disc trouble, but to avoid surgery again, we thought it would be worthwhile to try different treatment. Mr. C. agreed.

First he had to take a month's leave of absence from his job as a manufacturing firm executive. This eliminated tension from work. We used the first month to deal with painful trigger points in his back

ing program. Adding to this was a program of rest at home, a surgical corset, and muscle relaxant drugs. There were three exercise sessions at the clinic each week, plus exercise at home on non-clinic days.

It took more than six months to get his muscles back to normal and to slowly wean him away from the supporting corset.

There are many factors that can cause back pain — underexercise, tension, glandular imbalance, severe injury. But other factors like overweight, flat feet, unequal leg length, poor sleeping or seating facilities can play a part.

Fortunately, much back pain can be prevented or remedied.

Next: Exact Dosage Vital in Exercising.

(Condensed from 'Backache, Stress & Tension'

Fig. 5. Information for the press

II. OBJECTIVE HIERARCHY

An essential element in rational project, mission, and system design is a clear understanding of the goals, or objectives, that are being sought. This requires not only knowledge of the ultimate goals, but also an understanding of the more immediate goals that must be met to achieve those ultimate goals. The mission success evaluation model described in this report relies heavily on the objectives determined for the mission.

It is recognized that the objective hierarchy for a project can consist of an arbitrary number of levels. However, for the purposes of this report, only project, mission, and flight objectives will be assumed to be sufficient (see Fig. 6).

A. Project Objectives

The project objectives are the philosophically worded, general goals that the project is intended to fulfill. For example, the *Surveyor* project objectives are:

1. To accomplish successful soft landings on the Moon as demonstrated by operations of the spacecraft subsequent to landing.
2. To provide basic data in support of the *Apollo* project.
3. To perform operations on the lunar surface that will contribute new scientific knowledge about the Moon and provide further information in support of *Apollo*.

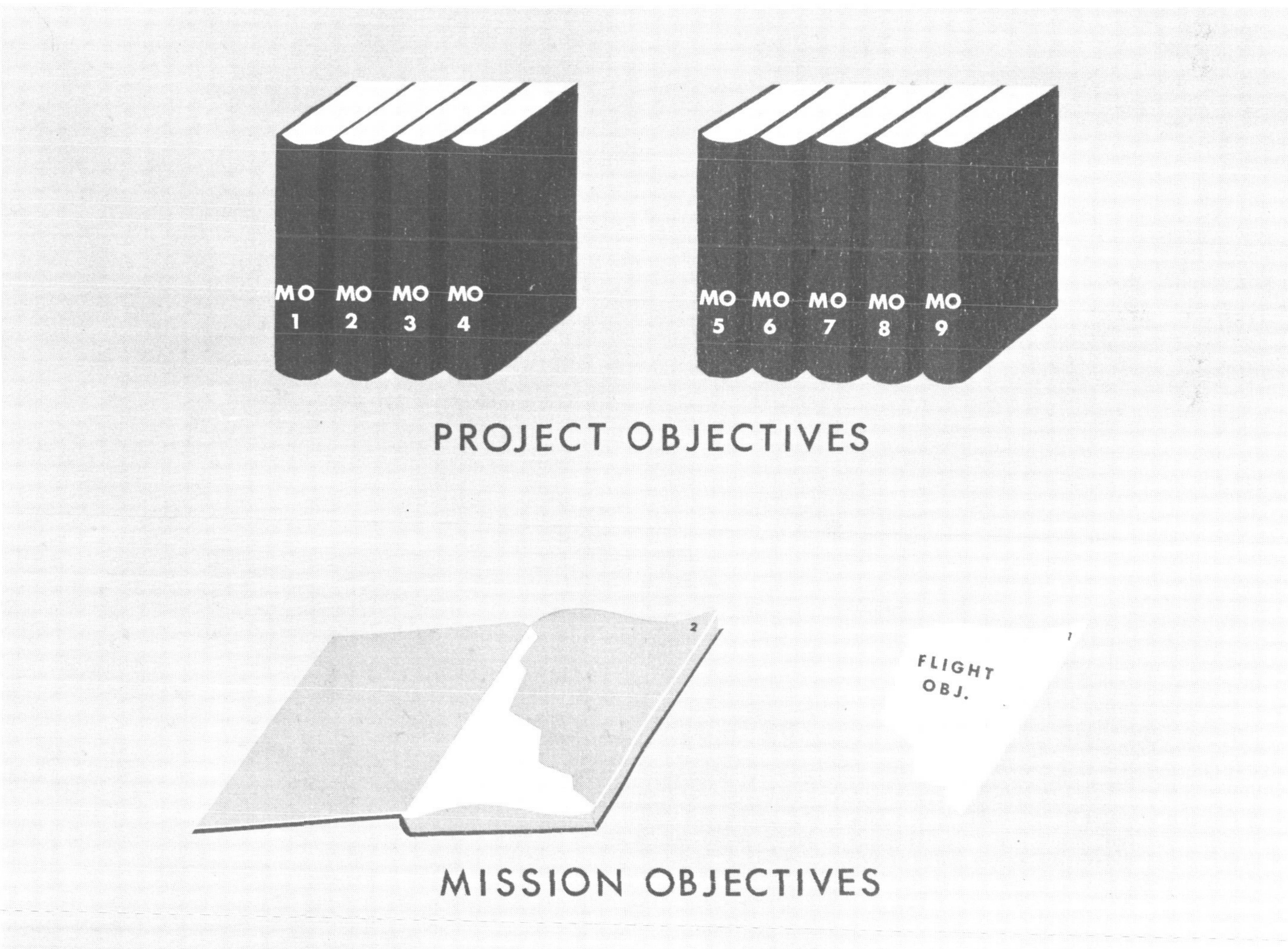


Fig. 6. Hierarchy of objectives

As a further example, the *Voyager* project objectives are:

1. To obtain information relevant to the existence and nature of extraterrestrial life on Mars.
2. To obtain information relevant to the atmospheric surface, and body characteristics of Mars by performing unmanned surface and orbital experiments.
3. To further knowledge of the interplanetary medium by obtaining scientific and engineering measurements while the spacecraft is in transit between Earth and Mars.

B. Mission Objectives

The mission objectives are the specific scientific and engineering objectives that a particular mission is intended to fulfill. They provide an orderly sequence of progressive accomplishment leading to the achievement of the project objectives consistent with the limitations imposed by available resources, launch schedules, booster capabilities, and so on. It is on the basis of the achievement of mission objectives that the success of a mission will be determined. For example, the mission objectives for *Surveyor I* were:

1. To demonstrate successful operation of the launch vehicle, spacecraft, spacecraft operations, Deep Space Instrumentation Facilities (DSIF), and ground communications from launch through completion of the midcourse maneuver.
2. To demonstrate successful spacecraft operation from the completion of the midcourse maneuver through landing.
3. To perform postlanding functions.

The *Voyager* mission objectives are yet to be fully defined. However, to assure a high level of success in achieving the *Voyager* objectives, it will be necessary, in the first mission, to develop and to gain experience in the use of the basic capability to place scientific instruments in orbit about Mars, conduct observations of Martian phenomena over extended periods of time, and transmit the results of these observations to Earth. In addition, it will be necessary to develop and provide experience in the use of the basic capability to enter the Martian atmosphere, descend to the Martian surface, and conduct observations relating to critical Mars landing design parameters.

C. Flight Objectives

The flight objectives are the explicit, detailed events and functions that must be accomplished to achieve the mission objectives. Each individual flight objective is to be so defined that accomplishment can be readily determined. The quantitative degree of accomplishment of each mission objective is then determined by the accomplishment of its subordinate flight objectives. A few hundred flight objectives will normally be required to fully describe a mission. As an example of the level of detail of flight objectives, three examples from the *Surveyor* project follow:

1. Demonstrate proper operation of the spacecraft/launch vehicle mechanical, electrical, and RF interfaces throughout the launch to separation interval of flight.
2. Demonstrate the capability of the flight control subsystem to perform acquisition and lock on the star Canopus.
3. Determine spacecraft transverse and angular rates at touchdown.

III. ASSUMPTIONS

Any mathematical model intended to be a realistic abstraction of a phenomenon that exists in the real world must depend on a number of assumptions. Because they deal with the very nature of modeling, many such assumptions invariably go unstated. An example of such an assumption is embodied in the use of a probability to describe a single nonreplicable event. If the probability of success is to be thought of as the fraction of times in a very large number of replications of the project that the particular space mission would have been successful, at which level is the replication to take place? Are we to consider a vast number of identical pieces of space hardware subjected to random variations from a nominal environment? Are we to consider a vast number of random variations from nominal components subjected to random variations from a nominal environment? Or, are we to consider a vast number of different hardware configurations resulting from random variations in the abilities of designers, design review teams, and so on? These questions will not be answered here. Indeed, the very basic assumptions, which are usually tacit in probability studies, will remain tacit here.

The assumptions presented in the following subsections are concerned with establishing relationships that will allow the model to be consistently applied to a mission.

A. Interpretation of Objectives

The primary purpose of this subsection is to delineate the assumed nature and relationship among the defined levels of objectives (i.e., project, mission, and flight); project and mission objectives are not stated explicitly enough to allow a ready determination of requirements for their achievement.

Since the separate missions in a project are intended to lead to the eventual achievement of the project objectives, they can be defined in terms of mission objectives; mission objectives, in turn, are made more explicit by the publication of detailed lists of flight objectives. These flight objectives are the detailed mission obligations that must be realized to achieve the mission objectives. To completely identify the flight objectives, and to properly emphasize the mission objectives, each flight objective is given a priority rating according to which mission objective it supports.

To establish a definite, quantitative connection between the mission and flight objectives, it is assumed that the accomplishment of all associated flight objectives is necessary and sufficient for the achievement of each mission objective.

B. Interpretation of Numerics

The probability that a particular subsystem will successfully perform its intended function (Fig. 7) depends on the probability:

1. That the components will not fail in the specified environments due to random causes (i.e., the reliabilities of the components).
2. That the specified environments adequately represent the conditions that will be encountered (i.e., the degree of knowledge of the environments).
3. That the subsystem will operate as planned if the components work and the specified environments are adequate (i.e., the systems or component interaction effects).
4. That the subsystem is capable of performing its intended function if it operates as designed (i.e., the adequacy of the design).

The first three probability factors are accounted for in the input numerics required for the mission success evaluation model. Each input numeric calls for a reliability estimate tempered by subjective evaluation of non-random factors, such as degree of knowledge of the flight environment, past experience with similar hardware, design state of the art, and so on. It should be noted, however, that this combining of probability factors introduces a further approximation: all events with which probabilities are associated are treated as though they were probabilistically independent, which is not invariably the case.

The four probability factors are not always as discrete as the listing implies. For example, a poor design could lead to component microenvironments considerably outside of specified bounds.

In particular cases, some facet of the expected environment may be insufficiently known (such as the bearing strength of the Lunar surface or the density of the Martian atmosphere), so that one or more parameters must be introduced and displayed in the results.

The fourth probability factor (adequacy of design) is extremely important. As a rule, this factor is either close to unity or to zero, depending on whether the particular subsystem can or can not perform its intended function.[1] It is assumed that there will be sufficient ground testing

[1] As an example of the fourth probability factor, and its inevitable interaction with the second, consider three designs for a bowl. All have the conventional shape of a soup bowl, but one is made of wax, one of wood, and one of steel. If the *intended function* is the holding of cereal, then any of the three is *adequately* designed. On the other hand, if the intended function is the holding of hot soup or of sulfuric acid, then one or more of the bowls is not adequately designed, and the fourth probability factor is quite low. If, however, the intended function is the holding of cereal but the wax bowl is placed on a stove, then the environment to be encountered was incorrectly specified, and the second probability factor is quite low. Such distinctions, however, are unnecessary in practice.

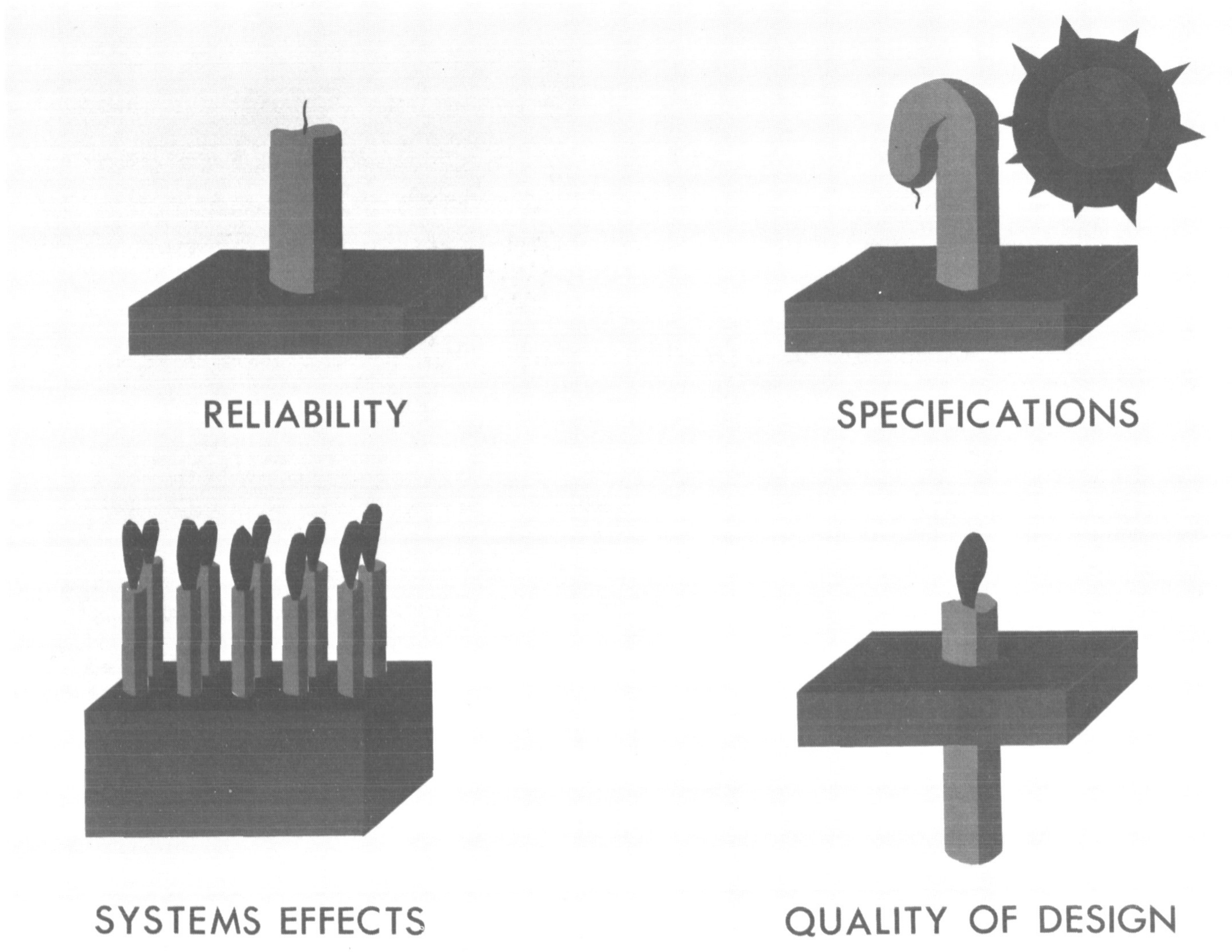


Fig. 7. Component probability factors

and design verification to ensure that each subsystem is so designed that, if it works, it will properly perform its intended function. Further, it is assumed that the functional requirements placed on the subsystems are so defined that the missions will be executed perfectly if all the subsystems properly perform their intended functions.

Before the assumption that the fourth probability factor is unity for all elements of a project can be considered valid, considerable testing and design verification must be accomplished. The intent of the mission success effort is to determine which elements of the project are weak, and can profitably be improved, rather than those which cannot work properly and must be fixed.

C. *Simplification of Weighting Factor Determinations*

To evaluate the degree of mission success, it is necessary to associate a relative weight with the accomplishment of each flight objective. Ideally, the relative weight assigned to each of the various flight objectives should be determined by the value of its accomplishment. Unfortunately, such a determination would be highly impractical, for to arrive at the proper weighting factors, it would not only be necessary to compare each objective with (on the average) half the other objectives, but also to compare groups of objectives with other groups of objectives. In fact, 2^N (where there are N flight objectives for a particular mission) comparisons might be required for complete assurance that the assignments had been consistently made.

Recognizing that success is obtained only by achievement of a number of flight objectives, it is reasonable to simplify by dividing the flight objectives into several sets and assigning the same weight (value) to each flight objective in a given set. If the flight objectives are written with this intent in mind, there can be close correspondence between the weighting factors and priority allocations assigned to the various flight objectives, so that the resulting model is very realistic. It will be assumed that there are three mission objectives, with three corresponding priority assignments, and, further, that all flight objectives corresponding to each mission objective have the same weight (i.e., w_1, w_2, and w_3, respectively).

IV. MISSION SUCCESS EVALUATION MODEL FRAMEWORK

As discussed in Section II, a small number of broad mission objectives are defined for each mission. Each mission objective is then made explicit by the delineation of a large number of detailed flight objectives. Finally, the success of the mission is quantitatively described in terms of the accomplishment of flight objectives.

A mission that achieves its primary mission objective is to be considered successful. Since all first priority flight objectives have been equated to the achievement of the primary mission objective (see Section III-A), accomplishment of all first priority flight objectives is required for a successful flight. Such a success is termed a *flight success*.

It is, however, desirable to introduce additional terms to describe various degrees of mission success that can occur. For example, if all of the project objectives are achieved, the mission is certainly a *project success*, whether or not all the first priority flight objectives have been achieved. Further, it is desirable to have a quantitative assessment of the degree of accomplishment of flight objectives; the *measure of performance* (defined below) is a measure of this achievement. If a sufficient number of first, second, and third priority flight objectives are accomplished, so that the level of accomplishment is at least as high as that of a flight success, but such that the primary mission objective is not achieved, the mission should still be considered a *technical success*.

A. Measure of Performance

The measure of performance, μ, is defined only for completed flights and provides a technical assessment of the degree of accomplishment of flight objectives. That is, it represents a quantitative a posteriori measure of the accomplishment of the mission. The measure of performance is defined as

$$\mu = \frac{\text{(sum of weights of accomplished flight objectives)}}{\text{(sum of weights of all flight objectives)}}$$

The maximum value of μ is unity, obtained if, and only if, every flight objective is accomplished. In fact, even if the project objectives were achieved, μ might be less than unity. If this measure is used to compare missions with differing objectives, the μ's for each would be normalized to the possible relative values, rather than to unity.

For the prediction of success of an anticipated flight, *the probable measure of performance*, *m*, is defined, providing an a priori estimate of the accomplishment of the mission. It represents the expected value or mathematical expectation of the measure of performance. Hence, it is known only in a probabilistic sense, and is defined as

$$m = \frac{\Sigma\, p_j W_j}{\Sigma\, W_j}$$

where

j ranges over all the flight objectives

p_j = the probability of meeting flight objective j

W_j = the weighting factor for flight objective j

Because of the identification between priority allocations and weighting factor assignments, it may be noted that W_j has one of the three values w_1, w_2, or w_3 according to whether flight objective j has first, second, or third priority, respectively.

1. Weighting of Flight Objectives

Before determining the relative weights of the various priorities of flight objectives, some preliminary considerations are in order. First, since the weights are to be used specifically to evaluate the combined achievement of a number of first, second, and third priority flight objectives, the concern of this subsection is the achievement of a so-called technical success. Further, it is necessary to realize that the value associated with the accomplishment of a flight objective (FO) is an incremental, rather than cumulative, quantity. That is, if FO_y can only be accomplished after FO_x, the value of accomplishing FO_y is the value accrued after FO_x is accomplished. The value of FO_y cannot be the cumulative value of reaching that point in the mission, for in the definition of the measure of performance, the values of FO_x and FO_y are added, and the value of FO_x would then be added twice.

There are a number of alternative procedures that could be used to determine the relative weighting factors for the flight objectives. All alternative procedures, of course, require the use of judgment at some point. The first of these procedures requires obtaining the answers to the following questions: How many first priority flight objectives (η_1, say) are required, by themselves, for the mission to be considered a technical success? If one less than this number were accomplished, how many second priority flight objectives (η_2) would be required, in addition, for the mission to be considered a technical success? And finally, if one less first priority flight objective than would be needed for technical success along with one less second priority flight objective than would make up the difference were accomplished, how many third priority flight objectives (η_3) would also be required for the mission to be considered a technical success? The numerical values of η_1, η_2, η_3 are not necessarily integers.

These questions can be expressed as equations, and the equations solved for the relative weights. First, let us note that the equation defining μ is

$$\mu = \frac{n_1 w_1 + n_2 w_2 + n_3 w_3}{N_1 w_1 + N_2 w_2 + N_3 w_3}$$

where

N_1, N_2, N_3 are the number of first, second, and third priority flight objectives,

n_1, n_2, n_3 are the number of first, second, and third priority flight objectives actually accomplished, and

w_1, w_2, w_3 are the weights assigned to first, second, and third priority flight objectives.

Then, the equations that will yield the weights are

$$\frac{\eta_1 w_1}{N_1 w_1 + N_2 w_2 + N_3 w_3} = \frac{(\eta_1 - 1) w_1 + \eta_2 w_2}{N_1 w_1 + N_2 w_2 + N_3 w_3} = \frac{(\eta_1 - 1) w_1 + (\eta_2 - 1) w_2 + \eta_3 w_3}{N_1 w_1 + N_2 w_2 + N_3 w_3}$$

The resultant relative weights are

$$\frac{w_2}{w_1} = \frac{1}{\eta_2}$$

and

$$\frac{w_3}{w_1} = \frac{1}{\eta_2 \eta_3}$$

The quantity η_1, or equivalent information, is needed at a later point to establish the level of accomplishment necessary for a technical success.

An alternative procedure for determination of the relative weights is to obtain answers to these questions: How much more valuable is it to achieve the primary and the secondary mission objectives than to achieve solely the primary mission objective (ρ_{12}, say)? How much more valuable is it to achieve all the mission objectives than to achieve solely the primary mission objective (ρ_{123}, say)? It is still necessary to know the level of achievement necessary for the mission to be considered a technical success. If desired, these questions can be rephrased in terms of the values of achievement of the individual mission objectives. Thus, if the ratio of the value of achieving the secondary mission objective to the value of achieving the primary mission objective is denoted by ρ_2, and the same ratio comparing the tertiary and primary mission objectives is denoted by ρ_3, then

$$\rho_2 = \rho_{12} - 1$$

and

$$\rho_3 = \rho_{123} - \rho_{12} = \rho_{123} - \rho_2 - 1$$

The mathematical translation of the questions is shown by

$$\frac{N_1 w_1 + N_2 w_2}{N_1 w_1} = \rho_{12}$$

and

$$\frac{N_1 w_1 + N_2 w_2 + N_3 w_3}{N_1 w_1} = \rho_{123}$$

The resultant relative weights are

$$\frac{w_2}{w_1} = \frac{N_1}{N_2} \rho_2$$

and

$$\frac{w_3}{w_1} = \frac{N_1}{N_3} \rho_3$$

If it is desired that the ratio of the value of achieving the tertiary mission objective to the value of achieving the secondary mission objective (which is ρ_3/ρ_2) be equal to the ratio of the value of achieving the secondary mission objective to the value of achieving the primary mission objective (namely ρ_2), then $\rho_3/\rho_2 = \rho_2$. To determine ρ_2, the iterative equation

$$\rho_{2(k+1)} = \frac{\rho_{123} - 1}{1 - \rho_{2(k)}}$$

may be solved.

Another possible procedure also relies on the identification of priority allocations with mission objectives. The relative weight assigned to each second priority flight objective (i.e., w_2/w_1) can be plotted vs the relative value of the primary mission objective (i.e., $1/\rho_{123}$). The weight is taken relative to the weight assigned to each first priority flight objective, while the value is taken relative to the total value of the flight. To construct the plot, it is necessary to assume a relationship involving the relative weight assigned to the third priority flight objectives (w_3/w_1), or the relative value of the secondary or tertiary mission objectives. By the choice of appropriate conditions, the range of reasonable values can be narrowed to a small area on the plot, and the final relative weights chosen by use of engineering judgment.

The equations that govern this approach follow. Let

$N_1 w_1 = V_P$, the value of the primary mission objective

$N_1 w_1 + N_2 w_2 = V_S$, the value of the primary and secondary mission objectives

$N_1 w_1 + N_2 w_2 + N_3 w_3 = V_T$, the value of all mission objectives

Note that

$$\rho_{123} = \frac{V_T}{V_P}$$

$$\rho_{12} = \frac{(V_S - V_P)}{V_P}$$

$$\rho_3 = \frac{(V_T - V_S)}{V_P}$$

$$\rho_2 = \frac{(V_S - V_P)}{V_P}$$

Then, if the additional relationship is $w_3 = r\, w_2$, solution of these equations gives

$$\frac{w_2}{w_1} = \frac{N_1 (\rho_{123} - 1)}{N_2 + N_3 r} \tag{1}$$

Or, if the relationship is $w_2/w_1 = a$, then

$$\frac{w_3}{w_1} = \frac{N_1}{N_3} (\rho_{123} - 1) - \frac{N_2}{N_3} a \tag{2}$$

Finally, if the relationship is $w_3/w_2 = w_2/w_1$, then the following iterative solution may be used to find the ratio. Let $w_3/w_2 = w_2/w_1 = a$, then

$$a_{(k+1)} = \frac{N_1 (\rho_{123} - 1)}{N_2 + N_3 a_{(k)}} \tag{3}$$

2. Numerical Values of Weights

In subsection 1, the decisions that are required to arrive at numerical values for the relative weighting factors are formulated in several ways. The first formulation requires consideration of the number of lower priority flight objectives that must be accomplished to obtain as much value as an additional higher priority flight objective. The second formulation requires consideration of the incremental values obtained by achievement of the secondary and tertiary mission objectives. The third formulation requires consideration of the relationship between the relative weights of the second and third priority flight objectives and of the relationship between the value of achieving the primary mission objective and the value of achieving all mission objectives.

Figure 8 has been prepared for use with the third formulation, and also may be used to ascertain some of the mission implications if some other formulation is used for the determination of the weights. It has been prepared from Eqs. (1), (2), and (3), a count of flight objectives, and an assumption that achievement of the primary mission objective be given a value at least as

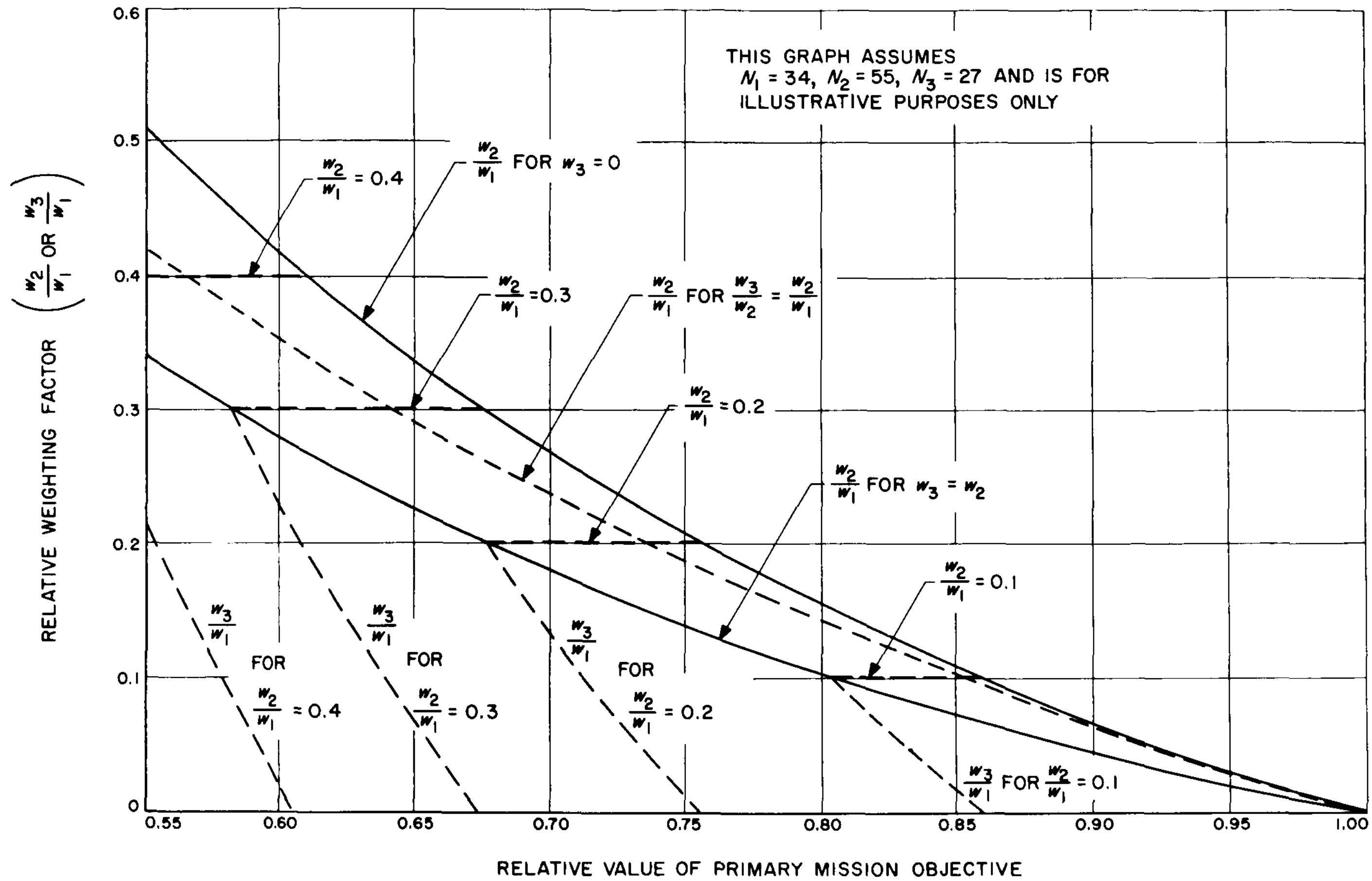


Fig. 8. Relationship between relative weighting factors and relative values of mission objectives

large as the value assigned to the combined achievement of all the other mission objectives.

If it is further assumed that third priority flight objectives cannot be assigned a value more than that of second priority flight objectives, then the choice of w_2/w_1 and ρ_{123} must lie above the lower solid line in Fig. 8. Recognition of the fact that third priority flight objectives cannot be given a weight less than zero requires the choice to be below the upper solid line.

An assumption that the second priority flight objectives are as much more important than the third priority flight objectives as the first priority flight objectives are than the second (i.e., $w_3/w_2 = w_2/w_1$) leads to the dotted curve.

It should be pointed out that there may be different numbers of flight objectives defined for each mission objective. Consequently, the relative flight objective weighting factors do not necessarily bear the same simple relationships as the relative values of the mission objectives (Table 1). Table 1 shows the relative weights that result from several different considerations.[2]

3. Critical Measure of Performance

The critical measure of performance, μ_s, is defined to be the minimum value of the measure of performance, μ, which is high enough for the mission to be termed a technical success. The term technical success was introduced for use in describing those missions that achieve a level of performance as high as that of a flight success but without achieving the primary mission objective. Consequently, the critical measure of performance is numerically identical to the relative value of the primary mission objective.

Furthermore, since achievement of the primary mission objective requires the accomplishment of all first priority flight objectives, and provides an equivalent level of performance to that of a technical success if no second

[2] Assumed numbers of flight objectives are $N_1 = 34$, $N_2 = 55$, $N_3 = 27$.

Table 1. Example of weighting factor choices

Case	Values of mission objectives			Relative weights		η_2	η_3	Comments
	$1/\rho_{123}$	ρ_2/ρ_{123}	ρ_3/ρ_{123}	w_2/w_1	w_3/w_1			
I	0.700	0.227	0.073	0.200	0.132	5.00	1.51	$1/\rho_{123} = 0.70$ $\rho_3/\rho_2 = \rho_2/1$
II	0.476	0.476	0.048	0.618	0.126	1.62	4.90	$10\rho_3 = \rho_2 = 1$
III	0.333	0.333	0.333	0.618	1.26	1.62	0.49	$\rho_3 = \rho_2 = 1$

or third priority flight objectives are accomplished, the value of η_1, the number of first priority flight objectives required, by themselves, to give a level of performance equal to that of a technical success, is the total number of first priority flight objectives (i.e., $\eta_1 = N_1$).

B. Degrees of Mission Success

The three types of successful missions that have been presented are: (1) *flight success* — achievement of the primary mission objective (or, equivalently, achievement of all first priority flight objectives), (2) *project success*— achievement of all project objectives, and (3) *technical success* — achievement of a number of first, second, and third priority flight objectives whose combined value is as high as that of a flight success, but does not satisfy the primary mission objective.

Two additional terms for successful missions are: (1) *partial project success* — achievement of at least one, but not all project objectives, and (2) *perfect mission* — achievement of all mission objectives (or, equivalently, achievement of all flight objectives).

For completeness, the terms for lower levels of success are defined as: (1) *complete failure* — accomplishment of no flight objectives, (2) *unsuccessful mission* — accomplishment of at least one second or third priority flight objective, but no first priority flight objective, and (3) *qualified success* — accomplishment of at least one first priority flight objective.

Figure 9 whimsically illustrates the concept behind the measure of performance, degrees of mission success, and the definition of weighting factors. The weighting factors determine the placement of the cups on the right-hand side of the balance. The number of achieved objectives of each priority determines the content of each of the cups. The setting of the slide required to bring about a balance determines the measure of performance, μ. Three degrees of success are shown.

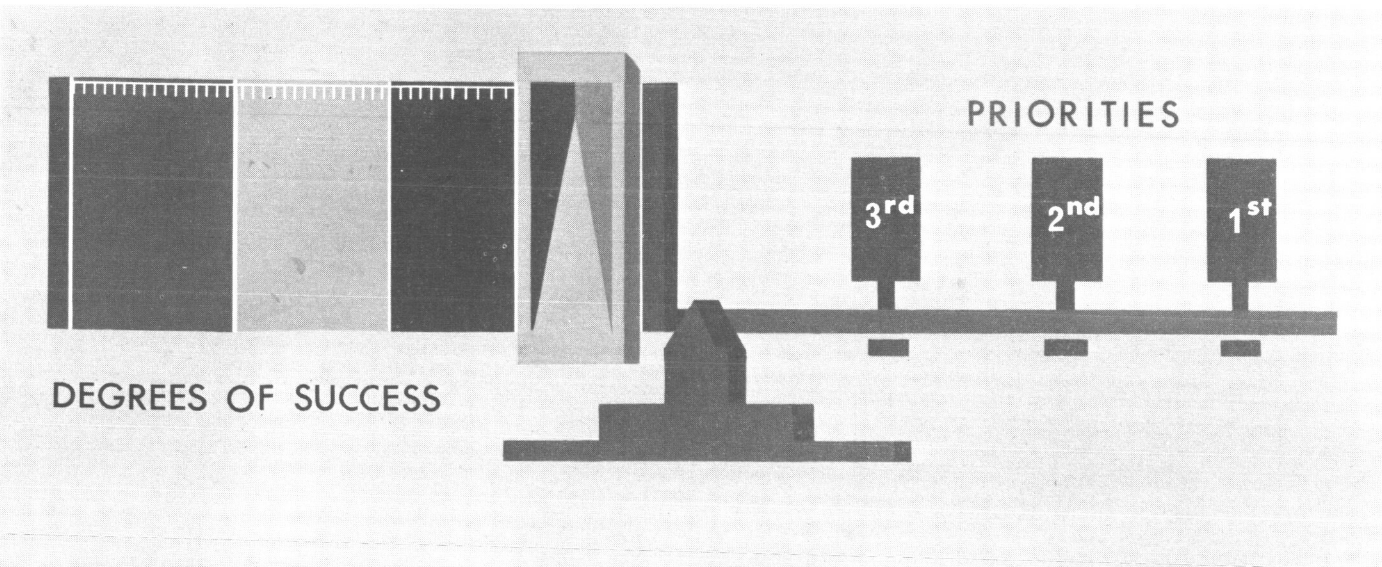


Fig. 9. Measure of performance

Using symbols defined in subsections 1 and 3, Table 2 summarizes the hierarchy of the various degrees of mission success. As previously stated, the measure of performance, μ, is a quantitative assessment of the accomplishment of all priorities of flight objectives. Each term in this table supersedes those above it, except that the terms *partial project success* and *project success* may be used in conjunction with any of the terms *technical success, flight success,* or *perfect mission.*

C. *Subsystem/Objective Matrix*

A block diagram showing the functional interconnections of subsystems is the traditional source for the equations expressing the probabilities of accomplishing objectives. However, the model described here requires consideration of several score objectives. As the traditional technique would require a detailed block diagram with several score sets of connecting lines, or several score block diagrams, the subsystem/objective (S/O) matrix has been developed as an auxiliary tool. This tool is used to indicate and present the same information in a more tractable form. An example is given in the Appendix, Table A-3.

The systems and subsystems of a mission are delineated in sufficient detail in the S/O matrix that the block diagram representing any of the objectives can be constructed from the items listed. Then, columns in the right hand side of the matrix are filled in for each objective according to a block diagram notation to indicate the functional connection of the items.

1. Block Diagram Notation

By means of the block diagram notation, series-parallel block diagrams can be described by symbols applied to a list of the blocks in the diagram. That is, an equivalent functional block diagram can be constructed (or reconstructed) from the list. In most cases, however, construction of the block diagram is not necessary in writing the probability equations.

Blocks that are required under standard operating conditions are given the designation S to denote a *standard* or *series* path. If alternate paths are available, they are identified by the addition of other letters to the paralleled blocks, as well as by the use of these same additional letters to identify the blocks on the alternate paths. Decision blocks are indicated by numbers, and the resultant paths by Y (for yes) or N (for no).

Figure 10 and Table 3 illustrate application of this tool in describing a single objective path. Figure 11 and Table 4 provide a simplified illustration of S/O matrix construction.

2. Inclusion of Failure Modes and Alternate Objectives

The mission model represented by the S/O matrix must include all identified failure modes, nonstandard procedures, and alternate modes of operation to accurately and completely describe the mission. Indeed, if the model is to be used as an aid during operations, failure to include such paths would seriously impair its usefulness. On the other hand, such alternate paths as

Table 2. Degrees of mission success

Defining criteria	Resulting criteria				Degree of success
	n_1	n_2	n_3	μ	
$\mu = 0$	$n_1 = 0$	$n_2 = 0$	$n_3 = 0$	–	Complete failure
$n_1 = 0, \mu > 0$	–	$0 \leq n_2 \leq N_2$	$0 \leq n_3 \leq N_3$	–	Unsuccessful, but not complete failure
$1 \leq n_1 < N_1, \mu < \mu_s$	–	$0 \leq n_2 \leq N_2$	$0 \leq n_3 \leq N_3$	$\mu > 0$	Qualified success
$n_1 < N_1, \mu \geq \mu_s$	$n_1 \geq 0$	$0 \leq n_2 \leq N_2$	$0 \leq n_3 \leq N_3$	$\mu < 1$	Technical success
$n_1 = N_1, \mu < 1$	–	$0 \leq n_2 \leq N_2$	$0 \leq n_3 \leq N_3$	$\mu \geq \mu_s$	Flight success
$\mu = 1$	$n_1 = N_1$	$n_2 = N_2$	$n_3 = N_3$	–	Perfect mission
At least one, but not all project objectives achieved	The accomplishment of some of the flight objectives may be unverified; compensating errors may even have saved the mission.				Partial project success
All project objectives achieved	Same as partial project success				Project success

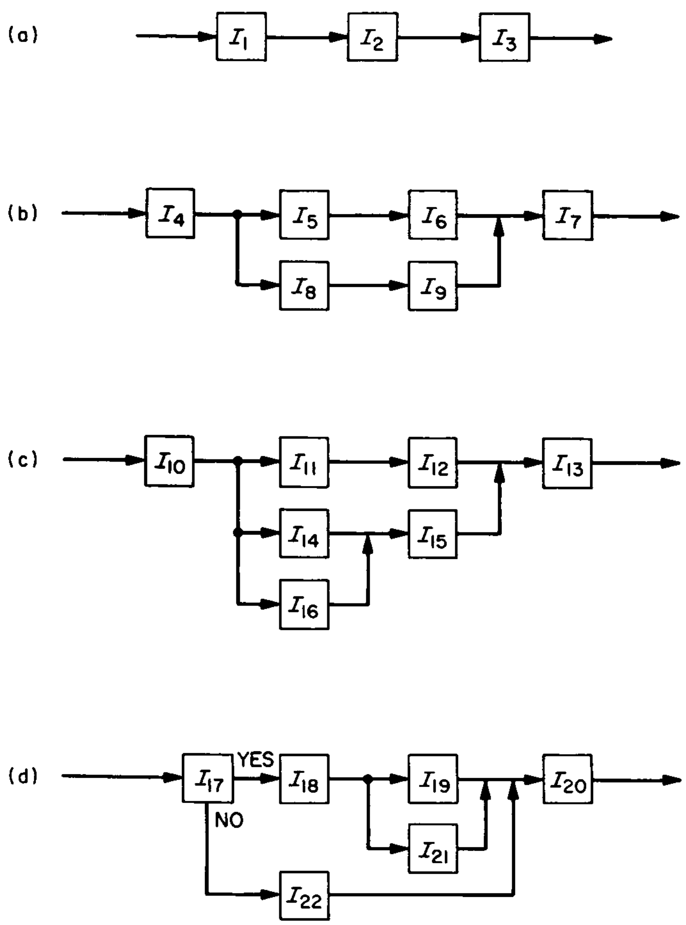


Fig. 10. Block diagrams for Table 3

are very unlikely to be encountered need not be included if the model is to be used strictly for mission evaluation during nonreal time.

D. *Estimates of Probability of Success on Successive Flights*

Space programs generally consist of several flights. Many project success models do not take into account the fact, demonstrated by past programs, that the probability of success increases with successive flights. Successive flights are labeled, in the discussions that follow, by upper case letters in alphabetical sequence.

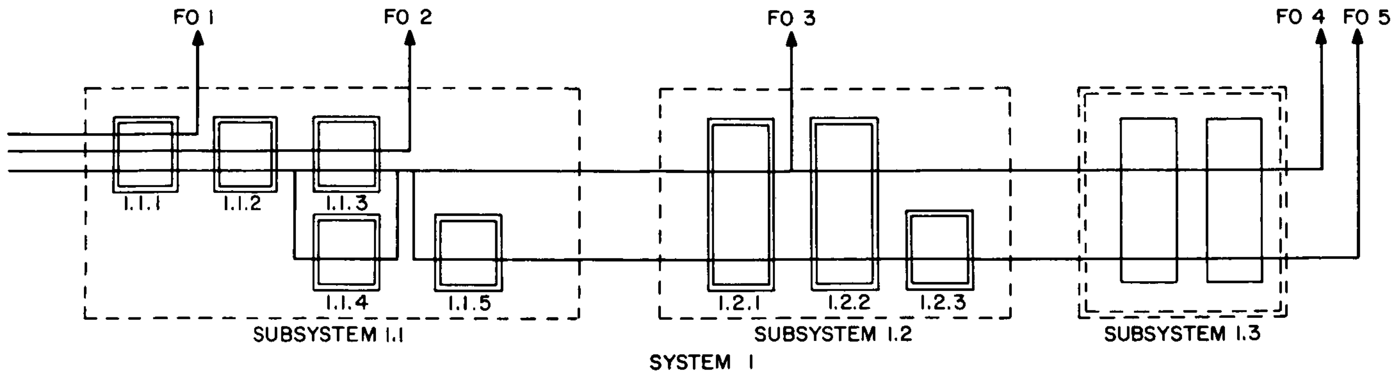
For the model developed here, it will be assumed that there are three possible outcomes from each deep-space flight test (that is, from each flight) for each S/O matrix item. Each of these possible outcomes has a different implication with regard to revisions of the estimates of probabilities of proper performance. The assumed totality of outcomes is as follows (see Fig. 12):

Table 3. Use of block diagram notation

Figure	Item	Symbol	Comment
10(a)	I_1	S	This item is required in series on the standard path
10(a)	I_2	S	Same as I_1
10(a)	I_3	S	Same as I_1
10(b)	I_4	S	Same as I_1
10(b)	I_5	SA	This item is on the standard path, but an alternate path also exists (namely path A)
10(b)	I_6	SA	Same as I_5
10(b)	I_7	S	Same as I_1
10(b)	I_8	A	This item is in series on alternate path A
10(b)	I_9	A	Same as I_8
10(c)	I_{10}	S	Same as I_1
10(c)	I_{11}	SB	This item is on the standard path, but there is an alternate path B
10(c)	I_{12}	SB	Same as I_{11}
10(c)	I_{13}	S	Same as I_1
10(c)	I_{14}	BC	This item is on alternate path B, but it also has an alternate path (namely path C)
10(c)	I_{15}	B	Similar to I_8
10(c)	I_{16}	C	This item is in series on alternate path C
10(d)	I_{17}	S1	Decision blocks are denoted by numbers, and this decision occurs in the standard path
10(d)	I_{18}	1Y	This item is required in series on the path that leads from the yes response to decision 1
10(d)	I_{19}	1YD	Same as I_{18} except that alternate path D is available
10(d)	I_{20}	S	Both paths from decision 1 have come together, and this item is required in series on the standard path
10(d)	I_{21}	D	Similar to I_8
10(d)	I_{22}	1N	This item is required in series on the path that leads from the no response to decision 1

1. There can be knowledge that the S/O matrix item performed successfully. In this case, the estimate of the probability of success of the S/O matrix item should be revised upward for the next mission by an amount that depends on the increase in confidence (in the nonstatistical sense) in the capability of the item to perform as required.

2. There can be knowledge that the S/O matrix item did not perform successfully. In this case, the estimate of the probability of success of the item should be revised downward, left the same, or revised upward, depending on whether the same design and



COMPONENTS ARE INDICATED BY SOLID LINES AND SUBSYSTEMS BY DASHED LINES. LINES ARE DOUBLED TO INDICATE S/O MATRIX ITEMS. ITEMS 1.1.1 AND 1.1.5 MIGHT BE THE SAME COMPONENT, BUT AS REQUIRED FOR DIFFERENT TIME PERIOD.

Fig. 11. S/O matrix items for five objectives

Table 4. S/O matrix for Fig. 3

Item No.	Flight test objectives				
	1	2	3	4	5
1.1.1	S	S	S	S	S
1.1.2		S	S	S	S
1.1.3		S	SA	SA	SA
1.1.4			A	A	A
1.1.5					S
1.2.1			S	S	S
1.2.2				S	S
1.2.3					S
1.3				S	S

hardware are to be used again, or whether the item is to be redesigned. A new design would presumably use the new data gained from the failure and, perhaps, have a larger allocation of weight.

3. Finally, there can be no knowledge about the success of the item. In this case, there is no reason for changing the a priori estimate of the probability of S/O matrix item success.

Consider the performance of an item in the S/O matrix. Let

$p_\alpha =$ The probability of S/O matrix item success on the mission α. This probability will usually be conditional upon success of earlier S/O matrix items.

$p_{\alpha'/\alpha} =$ The probability of S/O matrix item success on the mission following mission α (i.e., mission α') assuming knowledge of success on mission α.

Further, let

$p^*_\alpha =$ The probability that the diagnostic tools available will be able to provide enough data to determine whether the item was successful on mission α. This includes the probability of reaching the point in the mission sequence where the item is required and the probability that, if necessary, the data obtained by onboard sensors can be transmitted to, and received by, the ground.

To obtain numerical values for p_α with $\alpha =$ A, B, $\cdots$, it is certainly within the accuracy of obtainable estimates to fit curves through the points p_A and $p_{B/A}$ and extrapolate. Then, only the two numbers p_A and $p_{B/A}$ are required as input for each S/O matrix item.[3] These quantities are, respectively, the estimated probabilities that the S/O matrix items will perform successfully on mission A and the estimated probabilities that the S/O matrix items will perform successfully on mission B given a known successful performance on mission A. The extrapolation curves should be convex upward, and should monotonically and asymptotically approach a constant less than or equal to unity. A form that meets these requirements is

[3]There is some doubt that even these numbers can be reliably obtained.

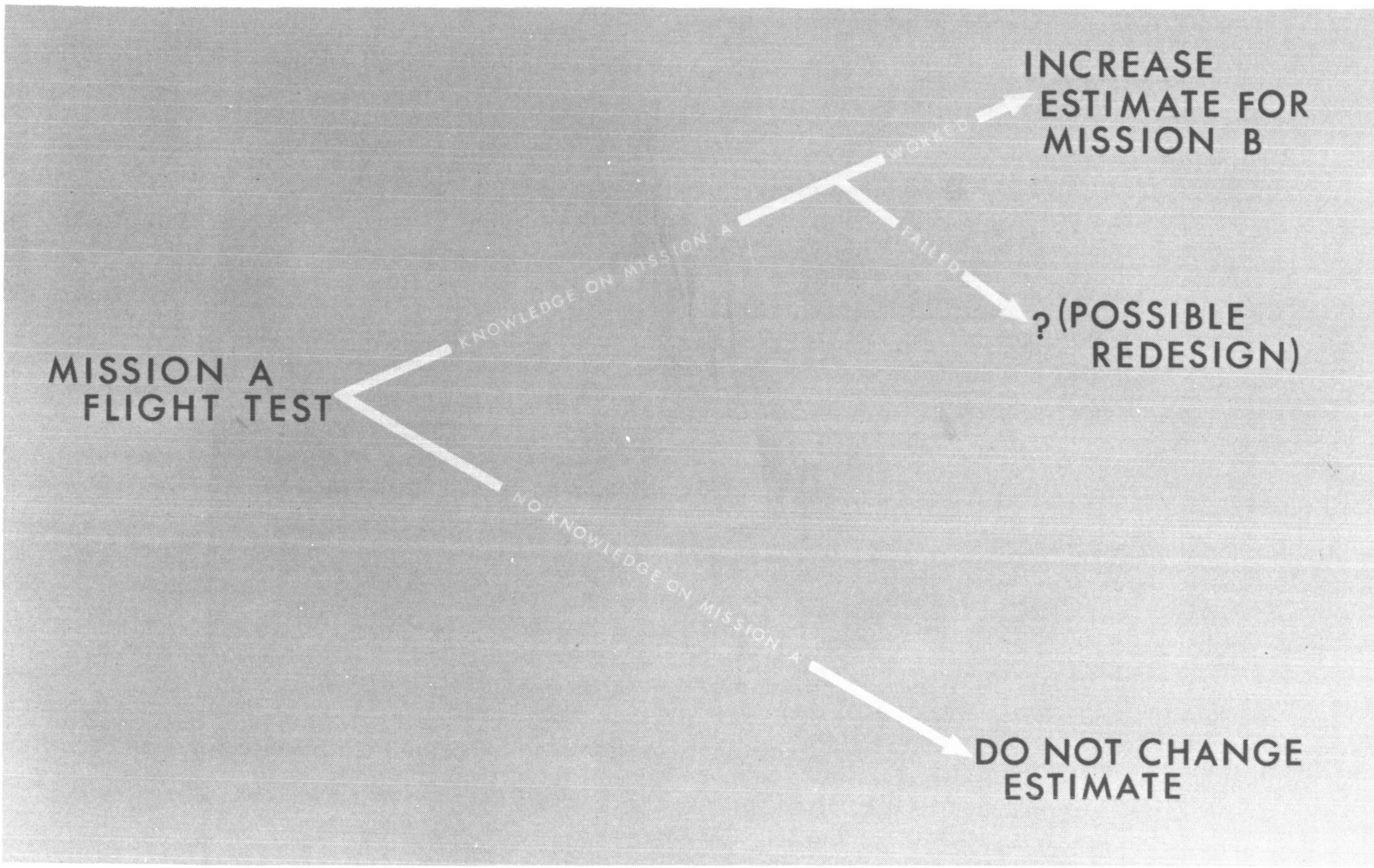


Fig. 12. Growth of estimated reliability

$$p_n = (1 - e^{c-nb})\, p_\infty$$

where n is the excess of known successes over known failures, and p_∞ is the limiting value of the probability as n approaches ∞; this form is common in the field of learning curves. The extrapolation constants b and c are found by identifying p_0 (that is, p_n with $n = 0$) with p_A and p_1 (similarly, p_n with $n = 1$) with $p_{B/A}$. (For simplicity, p_∞ is assumed to be unity.) Then

$$c = \ln(1 - p_A)$$

and

$$b = \ln \frac{1 - p_A}{1 - p_{B/A}}$$

The best estimate for p_α is p_n, where n depends on how many more known successes than known failures the particular S/O matrix item will have had prior to mission α. However, since it is not known what will have occurred on the missions prior to mission α, it is necessary to consider a weighted average of all the possible p_n's, where the weighting is based on the probabilities of occurrence of each possibility.

The estimation of $p_{\alpha'}$ (where α' is used to indicate the mission following mission α) can be considered as a stochastic process, with the following transition probabilities:

1. The probability of $p_\alpha = p_n$ becoming $p_{\alpha'} = p_{n+1}$ on the mission following mission α is the probability of a known success: $p_\alpha^* \, p_n$.

2. The probability of $p_\alpha = p_n$ becoming $p_{\alpha'} = p_n$ on the mission following mission α is the probability of failing to obtain knowledge: $1 - p_\alpha^*$.

3. The probability of $p_\alpha = p_n$ becoming $p_{\alpha'} = p_{n-1}$ on the mission following mission α is the probability of a known failure: $p_\alpha^* (1 - p_n)$, except

4. If the number of known successes of the S/O matrix item on the missions prior to mission α' is less than the number of known failures, $p_{\alpha'} = p_0$, as

it is assumed that the item would be replaced after an *extensive* redesign effort.

Thus, the transition matrix, T_α, is the body of Table 5.

Table 5. Transition probabilities

Mission α	Mission α'					
	p_0	p_1	p_2	p_3	p_4	...
p_0	$1-p_\alpha^* p_0$	$p_\alpha^* p_0$	0	0	0	...
p_1	$p_\alpha^*(1-p_1)$	$1-p_\alpha^*$	$p_\alpha^* p_1$	0	0	...
p_2	0	$p_\alpha^*(1-p_2)$	$1-p_\alpha^*$	$p_\alpha^* p_2$	0	...
p_3	0	0	$p_\alpha^*(1-p_3)$	$1-p_\alpha^*$	$p_\alpha^* p_3$	...
p_4	0	0	0	$p_\alpha^*(1-p_4)$	$1-p_\alpha^*$	...
...	...	...	...	...	...	...

Consider a row vector whose components are the probabilities that the estimate p_α is in each of the states p_0, p_1, p_2, ...; let this vector be called the *probability vector*, V_α. Consider also a column vector whose components are the probability states p_0, p_1, p_2, ...; let this vector be called the *state vector*, S. Then, the inner product of V_α and S is the weighted average desired for p_α. Thus

$$p_\alpha = V_\alpha S$$

$V_{\alpha'}$ can be obtained from V_α by post-multiplying by T_α. Thus

$$V_{\alpha'} = V_\alpha T_\alpha$$

and

$$p_{\alpha'} = V_{\alpha'} S = V_A T_A T_B \cdots T_\alpha S$$

When mission α is in the next flight in the program, each V_α contains unity in one of its positions and zero in all of its other positions (the location of the *one* depends on the past history of the item).

The state vector for each S/O matrix item for mission A is

$$V_A = (1\ 0\ 0\ 0\ .\ .\ .)$$

so that

$$P_A = 1 \cdot p_0 + 0 \cdot p_1 + 0 \cdot p_2 + \ .\ .\ .$$

Consequently, prior to mission A, the state vector for mission B is

$$V_B = V_A T_A = [(1 - p_A^* p_0)\ \ p_A^* p_0\ \ 0\ \ 0\ .\ .\ .]$$

so that

$$p_B = (1 - p_A^* p_0)\, p_0 + p_A^* p_0\, p_1 + 0 \cdot p_2 + 0 \cdot p_3 + \ .\ .\ .$$

The numbers in V_B and the value of p_B will, of course, differ from item to item, though the literal expression does not.

After completion of mission A, the state vectors for the items for mission B will be

$$V_B = (1\ 0\ 0\ 0\ .\ .\ .)$$

if the item is known to have failed on mission A or if there is no knowledge from mission A concerning the success of the item, or

$$V_B = (0\ 1\ 0\ 0\ .\ .\ .)$$

if the item is known to have been successful on mission A.

E. Possible Extensions to the Model Framework

1. Quantization of Project Objectives

The quality of scientific information obtained could be accounted for on a quantitative, rather than a qualitative basis; this could be implemented by the introduction of a quantity similar to the measure of performance previously defined. It would be necessary to define a set of scientific objectives, a value or set of values for each objective, and a set of requirements for various degrees of success. This entire procedure could be carried out in a pattern similar to that previously described.

2. Real Time Use

The mission success evaluation model could be incorporated into the set of flight programs and used as an aid in making real-time decisions during nonstandard operating conditions. For this use it would be particularly important to have alternate modes of operation included in the S/O matrix.

3. Probability of Technical Success or Better

The probability that the measure of performance will equal or exceed the critical measure of performance could be computed. This computation could be accomplished by a Monte Carlo computer program and the presently required inputs. This would constitute a more meaningful measure of effectiveness than does the probable measure of performance currently defined.

4. Further Quantization of Weights

It would be more realistic to account for the fact that all first (or all second or third) priority flight objectives are not equally valuable.

There are a number of ways that this accounting could take place. In every case, engineering judgment is required to reduce the effect of the failure to make the full number of consistency checks. Among the possible approaches are:

1. Bounds could be placed on the weights to be assigned to each priority, and engineering judgment used to place weights within those bounds.
2. Standard first, second, and third priority flight objectives could be defined (or identified from among existing flight objectives). Each flight objective could then be compared in value to the standard for its priority, and its weight be assigned on the basis of this comparison.
3. The flight objectives could be defined with an equal-value constraint imposed on the definition process.

V. APPLICATION OF THE MODEL TO THE ALLOCATION OF RESOURCES

Probably the most important single reason for expending effort on a mission success evaluation model is the development of information that can be used as a guide for the allocation of resources in such a way that the probability of mission success is maximized within the constraints imposed by available and planned resources. This development is to be carried out in two stages. The first stage requires the development of an analytic model relating the elements of the systems comprising the project to the probabilities of success. The second stage requires the usage of the model to determine optimal resource allocations.

The second stage can be considered as consisting of two steps: (1) determination of the relationships between the probabilities of proper performance of subsystems, components, etc., and the probabilities of mission success, and (2) extension of this development to incorporate consideration of the effects on the probabilities of mission success of varying resource allocations.

Table 6 gives a typical example of a sensitivity analysis, showing the contribution of a number of subsystems to the probabilities of obtaining the primary mission objective (MO 1) and the first project objective (PO 1). Assume that all of these elements are probabilistically in series, so that an increase of x% in any subsystem will give an increase of x% in the probability of success. Then, Table 6 represents the results of step (1) of the second stage.

Table 6. Subsystem contributions to the probabilities of achieving MO 1 and PO 1

System	Subsystem	Objectives	
		MO 1	PO 1
Spacecraft	Telecommunications	0.81	0.79
	Mechanisms	0.96	0.92
	Propulsion	not applicable	0.95
	Electrical power	0.75	0.74
	Flight controls	0.90	0.88
	Payload	~1	~1
Launch vehicle		0.70	0.65
Ground operations		0.98	0.95
Probabilities of achievement of objectives		0.36	0.28

From Table 6, the best apparent candidate for improvement is the launch vehicle, though it may well be that improvements in the launch vehicle are among the most expensive. Within the spacecraft system, the best apparent candidate is the electrical power subsystem, followed by the telecommunications subsystem. Improvements in the propulsion or payload subsystems are apparently not very profitable.

The subsystems that most degrade the probabilities of success can be readily identified from a listing such as Table 6; however, these subsystems are not necessarily the best candidates for improvement. Such an identification requires knowledge of which subsystems give the greatest improvement for specific additional resource allocations.

The complex relationships between design changes, reliability changes, and the additional resources required to effect such changes are rarely continuous mathematical functions. In most cases, there are critical amounts of additional resources required to effect changes, so that slightly smaller allocations will give no improvement, and slightly larger allocations will give no more improvement. Thus, for each subsystem in each system, there may be one or more discrete changes that could be made, each requiring a certain amount of each resource, and each giving a certain change in the probabilities of success. An oversimplified example of how such tradeoffs might be made is shown in Fig. 13. The oversimplification comes about because there are a vast number of dimensions and constraining relationships that must be considered.[4]

[4]Mathematical programming techniques may prove to be useful in solving this problem. Most of the constraints are linear, but the objective function *(probable return)* is not only nonlinear in some of the controllable variables, but also discretely related to most of the others. Furthermore, the probable return itself may consist of several component parts, such as the probability of achieving the various mission objectives, the probable measure of performance, and so on.

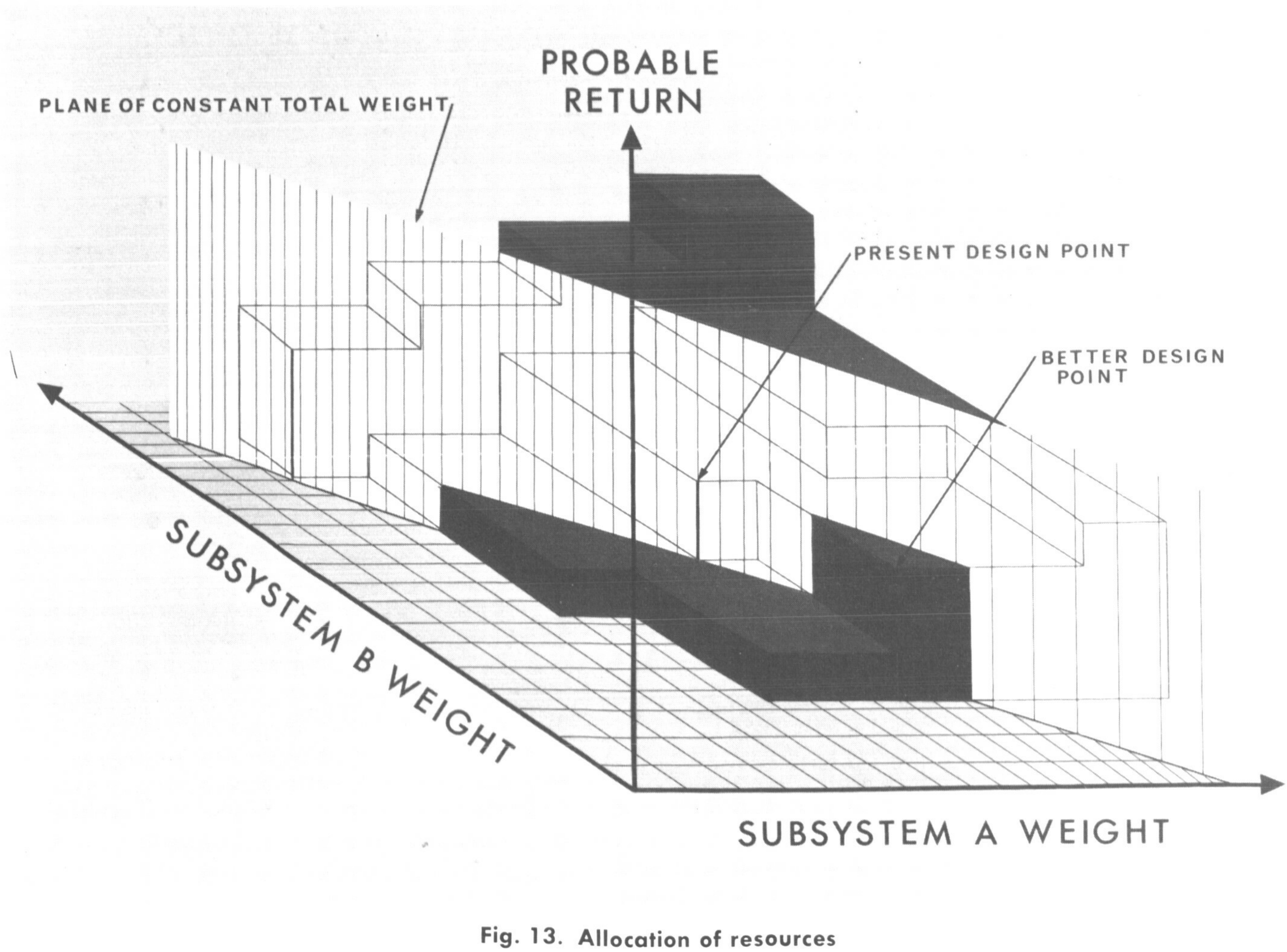


Fig. 13. Allocation of resources

A table listing individual changes would provide a relatively simple, but quite useful, guide for the allocation of resources, and could be prepared early in the second stage of the mission success effort (see Table 7).

To understand Table 7, consider as an example change plan 2, which consists of increasing the battery capacity in the electrical power subsystem on the spacecraft. This change raises the reliability of the electrical power subsystem from 0.79 to 0.81 with regard to the primary mission objective, and from 0.78 to 0.80 with regard to the first project objective; this causes the probability of success to increase from 0.41 to 0.42 for the primary mission objective, and from 0.35 to 0.36 for the project objective. To effect this change requires additional funding of $63,000, a 4-month schedule slip, an increase in weight of 3 lb, and 15 man-months of effort. In addition, there is a 10% risk that the new battery, and its associated redesigned hardware, will not be capable of performing the intended functions.

Table 7, alone, would be of considerable benefit as an aid in the allocation of resources, but it is inadequate in several respects. First, the effects of changes in the baseline resources, such as would be caused by a schedule slip of x months, cannot be identified. Second, the table does not show the effects of reducing the resources allocated to the various subsystems. Thus, though useful in itself, the table does not meet all of the goals of the stage 2 effort because it does not indicate how current and planned resources should be allocated to maximize the probabilities of success.

To determine truly optimal resource allocations, further effort will be required to consider all possible combinations of plans. It may be noted that, if there are N plans, there are 2^N possible combinations of plans.

Table 7. Sample resource allocation guide

Change plan	Subsystem	Usage of the change plans would have following effects						Additional resource allocations					Changes to be made
		Reliability				Probability of success[a]		Funds, $\$10^3$	Schedule slip, months	Weight, lb	Manpower, man-months	Risk, %	
		Current		New									
		MO 1	PO 1	MO 1	PO 1	MO 1	PO 1						
1	Electrical power	0.79	0.78	0.83	0.82	0.43	0.37	125	6	5	30	5	Add redundant battery
2				0.81	0.80	0.42	0.36	63	4	3	15	10	Increase battery capacity
3				0.89	0.88	0.46	0.39	400	18	−8	80	20	Redesign entire subsystem
4	Tele-communications	0.88	0.98	0.90	0.985	0.42	0.352	58	3	6	14	0	Add redundant antenna
5				0.90	0.985	0.42	0.352	100	6	1	24	3	Use lighter weight antenna and make redundant
6				0.92	0.99	0.43	0.353	200	12	−4	40	5	Change to thin-film circuits
7	Vehicle mechanisms	0.94	0.93	0.94	0.95	0.41	0.358	43	6	10	13	0	Strengthen shock absorbers
8				0.94	0.96	0.41	0.362	117	12	0	35	10	Redesign motor Q

[a] Current probabilities of success are $P_{MO\,1} = 0.41$, $P_{PO\,1} = 0.35$.

VI. SUMMARY

The primary objective of this report was to present an analytic model for the evaluation of space missions (both a priori and a posteriori). A quantitative measure of success, based on the accomplishment of a defined hierarchy of objectives was defined, along with procedures for determining values to be assigned to the objectives.

The expected mission-to-mission growth in estimated reliability was treated by a Markovian approach. A matrix format for the representation of series-parallel block diagrams was presented. Finally, the application of mission success study results to the optimal allocation of resources was considered in moderate detail.

GLOSSARY

Notation

Vectors and matrixes

V_α probability vector for mission α

T_α transition matrix from mission α

S state vector

Probabilities of success

m probable measure of performance

Probability estimates

p_α estimate of the probability of success of a particular S/O matrix item on mission α

$p_{\alpha'/\alpha}$ estimate of the probability that an S/O matrix item will be successful on the mission following mission α *given* known success on mission α

p_n estimate of the probability that an S/O matrix item will be successful given n more known successes than known failures of that item

p_∞ limiting value of p_n as n approaches ∞

p^*_α estimate of the probability of obtaining knowledge concerning the operation of an S/O matrix item on mission α

Numbers

n excess of known successes over known failures of an S/O matrix item

N_1, N_2, N_3 number of first, second, and third priority flight objectives defined for a particular mission

n_1, n_2, n_3 numbers of first, second, and third priority flight objectives actually accomplished on a particular mission

η_1 number of first priority flight objectives needed, by themselves, to make the mission a technical success

η_2 number of second priority flight objectives needed (along with one less first priority flight objective than would be sufficient) to make the mission a technical success

η_3 number of third priority flight objectives needed (along with one less first priority flight objective than would be sufficient, and one less second priority flight objective than would make up the difference) to make the mission a technical success

Other scalars

μ measure of performance

μ_s critical measure of performance

ρ_{12} ratio of value of achieving primary and secondary mission objectives to value of achieving solely the primary mission objective

ρ_{123} ratio of value of achieving all mission objectives to value of achieving solely the primary mission objective

ρ_2 ratio of value of achieving secondary mission objective to value of achieving the primary mission objective

ρ_3 ratio of value of achieving tertiary mission objective to value of achieving the primary mission objective

W_j weighting factor for flight objective j

w_1, w_2, w_3 weighting factors for first, second, and third priority flight objectives, respectively

b, c constants used in the extrapolation of the estimates of the probabilities of S/O matrix item success

Mission indicators

α generalized indication of mission being considered

α' the mission following mission α

Terminology

Block diagram notation the means used in the S/O matrix to describe the functional connection of the S/O matrix items

Complete failure failure to accomplish any flight objectives (see degrees of mission success)

Component a piece part, such as a transformer, involved in the composition of a subsystem

Composite space vehicle all hardware that purposely leaves the launch pad at lift-off (e.g., launch vehicle, spacecraft and payload)

Critical measure of performance (μ_s) the minimum value of the measure of performance that would result in a mission being termed at least a technical success (see degrees of mission success)

Degrees of mission success	a hierarchy of quantitative descriptors of mission accomplishment $\mu = 0$: complete failure $\mu > 0$, $n_1 = 0$: unsuccessful, but not complete failure $0 < \mu < \mu_s$, $1 \leq n_1 < N_1$: qualified success $\mu_s \leq \mu < 1$, $1 \leq n_1 < N_1$: technical success $\mu < 1$, $n_1 = N_1$: flight success (achieved primary mission objective) achievement of at least one, but not all, project objectives: partial project success achievement of all project objectives: project success $\mu = 1$: perfect mission
Extrapolation constants	quantities used to extrapolate the probabilities of S/O matrix item success for successive missions
First priority	see flight objectives
Flight (used as a noun)	the phase of operations beginning with launch and ending with failure or turnoff
Flight (used as an adjective)	concerning or of any or all of the hardware or software directly connected with the operational phase of a mission
Flight objectives	explicit, detailed events and functions that must be accomplished to achieve the mission objectives
Flight success	the achievement of all first priority flight objectives defined for a particular mission—allows further definition of a hierarchy of various degrees of mission success (since achievement of all first priority flight objectives has been identified with accomplishment of the primary mission objective, the flight success achievement implies the achievement of the primary mission objective—$n_1 = N_1$)
Functional element	a subsystem, component, or group of components or, an operations console operator, a flight operations computer program, etc.
Item	see S/O matrix item
Measure of performance (μ)	a quantitative assessment of the relative value of a mission
Mission	all preflight and inflight activity necessary to operate and support all flights in a single launch opportunity (The operational phase of a mission starts with the prelaunch countdown and ends at the cessation of real-time activity. The mission begins with the first activity directly applicable to one or more of the flights of that mission, and ends when all scientific and engineering

	data have been returned to Earth, decoded, and delivered to the cognizant organizations.)
Mission level activity	that which is concerned with intersystem interfaces (see system) or with overall mission plans, such as selection of trajectories, scheduling of systems tests, and determination of launch constraints
Mission objectives	the specific scientific and engineering objectives that a particular mission is intended to fulfill (it is on the basis of the achievement of mission objectives that the success of a mission is determined)
Mission success	a general term used to describe the desired accomplishments, or potentially obtainable value, of a mission (degrees of mission success are defined for more precise use)
Mission success effort	all the activity and tasks involved in the determination of mission success probabilities, values, functional models, and so on (stage 1); also, the application of the mission success evaluation model to the optimal allocation of resources (stage 2)
Mission success evaluation model	an analytical representation of a flight that is used to evaluate probable values prior to a flight and obtained values afterwards
Mission success evaluation model framework	the collection of analytical tools and information presentation methods required for mission success evaluation model
Partial project success	achievement of at least one, but not all, project objectives (see degrees of mission success)
Perfect mission	achievement of all flight objectives (see degrees of mission success)
Phase	a period of time during a flight or during a mission
Primary	see mission objectives
Probabilities of success	probabilities of achieving the various degrees of mission success
Probability of flight success	probability of achieving all first priority flight objectives defined for a mission (since achievement of all first priority flight objectives has been identified with achievement of the primary mission objective, this is also the probability of achieving the primary mission objective)
Probability of S/O matrix item success	reliability estimate tempered by subjective evaluation of nonrandom factors, such as degree of knowledge of the flight environment, past experience with similar hardware, design state of the art, and so on (also recognizes the conditional, in the probability theory sense, nature of many S/O matrix items)

Probable measure of performance (m)	a priori expected value (in the statistical sense) of the measure of performance
Program	a related series of undertakings designed to accomplish long-range scientific and/or technical goals—attainment progressively accomplished by the collective achievement of a series of individual projects
Project	a scheduled undertaking, within a program, which may involve research and development, design, construction, and operation of systems, associated intersystem interfaces, and related facilities to accomplish the assigned project goals (see project objectives)
Project objectives	the goals assigned to a project by a program—usually phrased in very general terms—goals are assigned to the missions comprising a project to provide an orderly sequence of progressive accomplishment leading to achievement of project objectives
Project success	achievement of all project objectives (see degrees of mission success)
Qualified success	accomplishment of at least one, but not all first priority flight objectives—failure to achieve a measure of performance equal to or higher than the critical measure of performance, and failure to achieve the primary mission objective or any project objective (see degrees of mission success)
Reliability	probability that a functional element will not fail due to random causes or a statistical estimate of this probability based on test data, either current or historical
Second priority	see flight objectives
Secondary	see mission objectives
Sensitivity analysis	study of the dependence of the probabilities of success on the various functional elements comprising the mission
S/O matrix	see subsystem objective matrix
S/O matrix item	see subsystem/objective matrix item
S/O matrix item success	satisfactory performance of a functional element listed in an S/O matrix during a specified phase or satisfactory performance of a specified function (i.e., successful working of the block diagram block represented by the S/O matrix item)
Subsystem	major logical and/or hardware portion of a system, such as structures, electrical power, telecommunications, propulsion, ground communication net, etc.
S/O matrix	a tool developed to indicate and present a large number of different connections of a set of functional elements in a compact and tractable fashion

S/O matrix item functional element listed in an S/O matrix or such finer breakdown as functions to be performed or times or phases at which, or during which events must occur (i.e., the level of detail in an S/O matrix to which item numbers are assigned—all S/O matrix items are probabilistically independent)

Success see degrees of mission success, mission success, and flight success

System major organizational and functional portion of the totality of effort comprising a project—system managers are responsible for the availability and performance of their systems, including the integration of all relevant subsystems (e.g., the *Surveyor* project is comprised of the launch vehicle system, the spacecraft system, the mission operations system, and the tracking and data acquisition system)

Technical success achievement of a sufficient number of first, second, and third priority flight objectives that the measure of performance equals or exceeds the critical measure of performance, but failure to achieve all first priority flight objectives (see degrees of mission success)

Tertiary see mission objectives

Third priority see flight objectives

Transition probability the probability that a quantity will change from one assumed value to another assumed value

Unsuccessful mission accomplishment of at least one second or third priority flight objective, but no first priority flight objective (see degrees of mission success)

Weight see weighting factor

Weighting factor numerical indication of the incremental value of the accomplishment of a flight objective relative to the incremental values of accomplishment of other flight objectives

APPENDIX

Typical Block Diagrams and Supporting Information

This appendix is included to illustrate the kind of information that is needed by the mission success evaluation model described in the text.

Figure A-1 shows a block diagram of a mission that is relatively simple from a modeling point of view. All that this diagram is intended to do is to illustrate how the various mission objectives are related.

Figure A-2 shows a more complicated mission, and, in fact, is similar to that currently planned for *Voyager* in 1973. The project objectives might be to obtain certain combinations of mission objectives, as shown.

The fictitious launch vehicle described in Tables A-1, A-2, and A-3 may be thought of as applying to either of the illustrated missions.

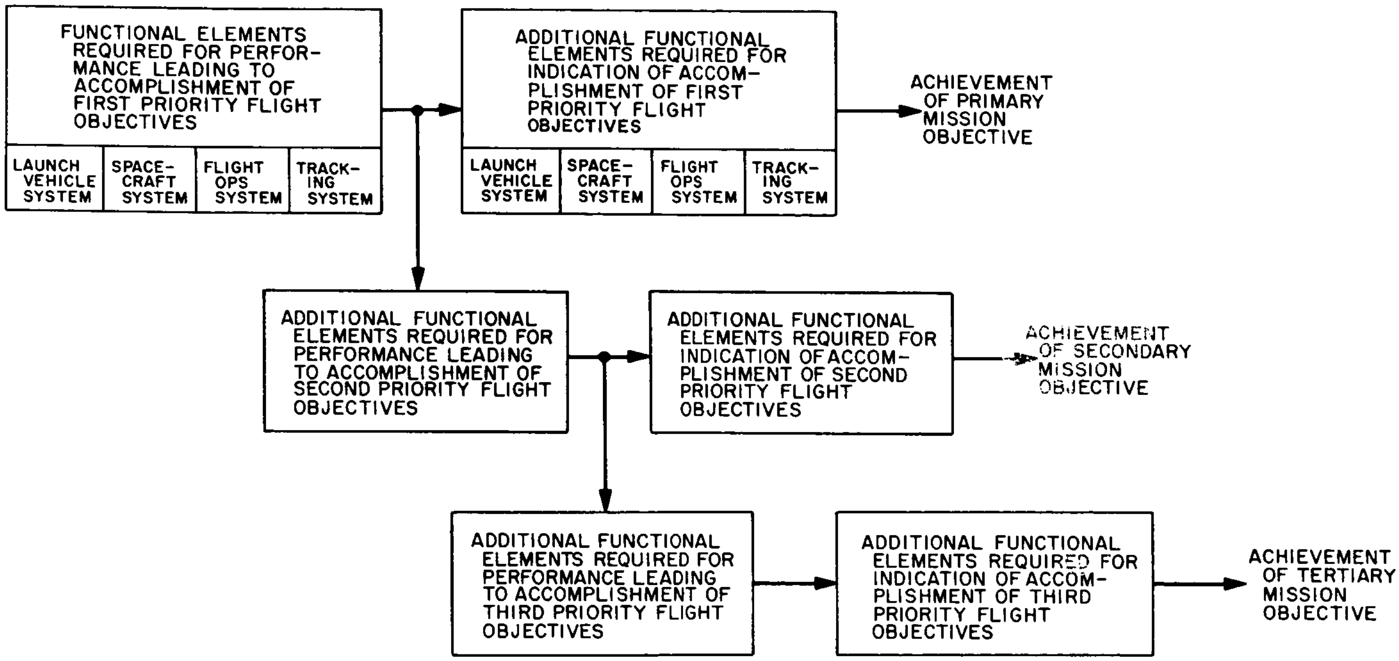


Fig. A-1. Illustrative mission block diagram for a simple mission

Table A-1. Supporting information from a typical system[a]

S/O matrix item No.	Description	P_A	$P_{B/A}$
101	*Lift off pad:* Success requires that the launch vehicle get into flight without having some completely catastrophic failure.	0.92	0.92
102	*Lift off pad within scheduled window:* Requires a launch within any established window in a launch period (i.e., this item is successful if L-O occurs at any time in a launch window in a launch period, together with no catastrophic failure at lift-off). Probabilistically, success is conditional on the success of item 101.	0.99	0.992
103	*Perform throughout powered flight:* Requires that the launch vehicle (both stages) perform sufficiently well, assuming a successful launch, that range safety does not use the *destruct* option, and that at least a highly elliptical earth orbit is obtained. Probabilistically, success is conditional on the success of items 101, 106, 110, and 119.	0.94	0.95

[a]Contained in the S/O matrix (Table A-3).

Table A-1. (Cont'd)

S/O matrix item No.	Description	P_A	$P_{B/A}$
104	*Provide injection within midcourse capability:* Requires that the launch vehicle perform sufficiently well that the spacecraft is injected within its midcourse correction capability. Probabilistically, success is conditional on the success of items 101, 103, 106, 110, 115, 116, and 119.	0.93	0.94
105	*Perform as programmed to separation with spacecraft:* Requires that all launch vehicle functional elements not specified elsewhere perform as programmed from launch to second stage/spacecraft separation. Probabilistically, success is conditional on the success of all other items except 111 and 118.	0.99	0.99
106	*Perform to nose-fairing jettison:* Requires that the first stage perform sufficiently well, assuming a successful launch (i.e., given success of item 101) that nose-fairing jettison can occur as programmed.	0.97	0.98
107	*Telecommunications—to nose-fairing jettison:* Requires the second stage telecommunications subsystem to perform properly from launch to nose-fairing jettison.	0.97	0.985
108	*Telecommunications—nose-fairing jettison to injection:* Requires the second stage telecommunications subsystem to perform properly from nose-fairing jettison to injection. Probabilistically, success is conditional on the success of item 107.	0.992	0.992
109	*Telecommunications—injection to retro:* Requires the second stage telecommunications subsystem to perform properly from injection to and throughout the second stage retro maneuver. Probabilistically, success is conditional on the success of items 107 and 108.	0.994	0.994
110	*Guidance—to separation:* Requires the second stage guidance subsystem to perform sufficiently well to prevent the occurrence of a range safety *destruct* command from launch to separation. Probabilistically, success is conditional on the success of items 101 and 106.	0.995	0.997
111	*Guidance—separation to retro:* Requires the second-stage guidance subsystem to perform from separation to and throughout the second stage retro maneuver. Probabilistically, success is conditional on the success of items 101, 106, and 110.	0.998	0.999
112	*C-Band beacon—MECO to separation:* Requires the second stage C-Band beacon to perform properly from main engine cutoff (MECO) to second stage/spacecraft separation.	0.9995	0.9995
113	*C-Band beacon—separation to retro start:* Requires the second stage C-Band beacon to perform properly from second stage/spacecraft separation to the start of the second stage retro maneuver. Probabilistically, success is conditional on the success of item 112.	0.9999	0.9999
114	*C-Band beacon—through retro:* Requires the second stage C-Band beacon to perform properly throughout the second stage retro maneuver. Probabilistically, success is conditional on the success of items 112 and 113.	0.9995	0.9995
115	*Separation—pre-separation commands:* Requires that the second stage provide proper pre-separation commands to the spacecraft.	0.997	0.998
116	*Separation—after MECO:* Requires that second stage/spacecraft separation commands occur after MECO. Probabilistically, success is conditional on the success of items 101, 110, and 119.	0.9997	0.9997
117	*Separation—within tolerance:* Requires that second stage/spacecraft separation occurs within specified velocity and rotation rate intervals. Probabilistically, success is conditional on the success of items 101, 103, 106, 110, 115, 116, and 119.	0.96	0.983
118	*Retro—sufficient:* Requires that the second stage retro impulse following separation be sufficient to provide a satisfactory separation distance between the second stage and the spacecraft.	0.97	0.99
119	*Nose fairing—jettison:* Requires that the nose-fairing jettison as programmed.	0.96	0.98
120	*Sensors—jettison:* Requires proper operation of those second stage sensors that indicate the jettison of the nose fairing.	~1.0	~1.0
121	*Sensors—separation:* Requires proper operation of those second stage sensors that indicate and measure the second stage/spacecraft separation event.	~1.0	~1.0
122	*Spacecraft interfaces:* Requires proper operation of the second stage/spacecraft mechanical, electrical, and RF interfaces from launch to separation.	0.97	0.995

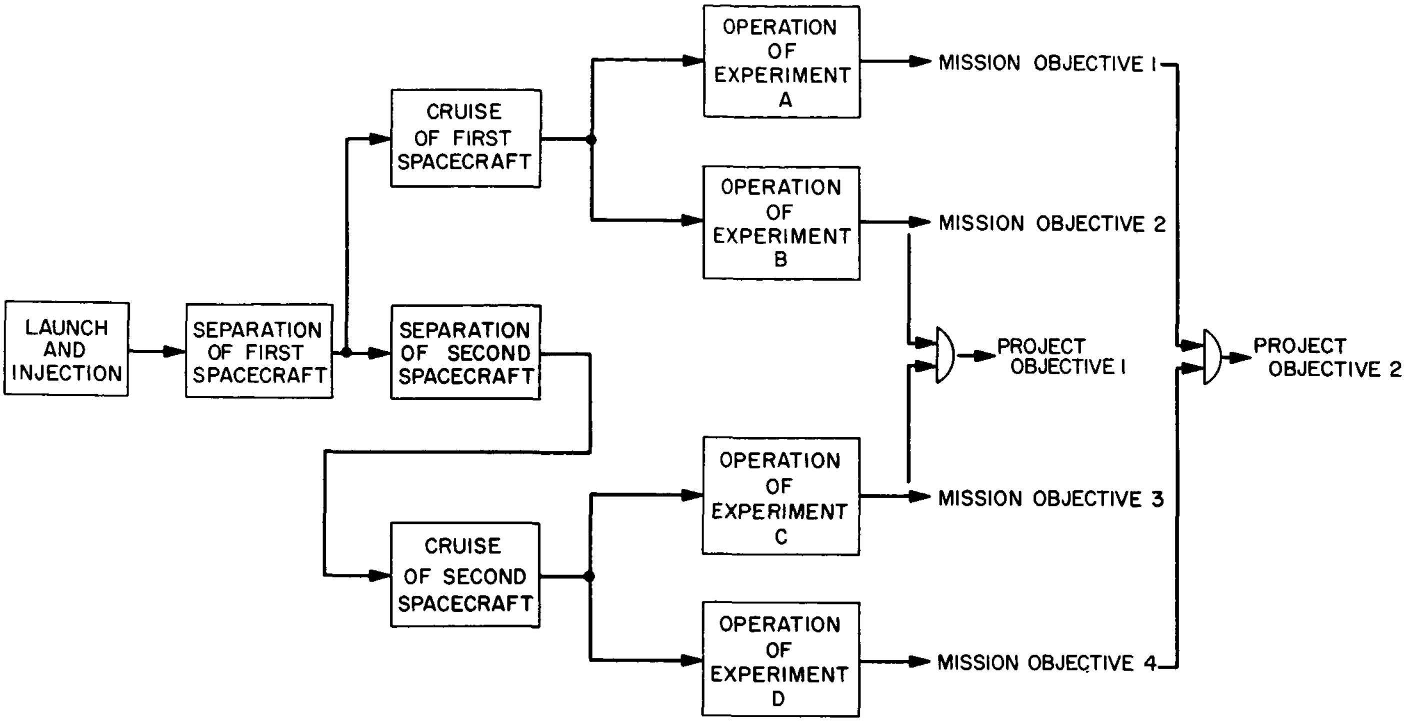


Fig. A-2. Illustrative mission block diagram for a complex mission

Table A-2. Spacecraft system S/O matrix items[a]

S/O matrix item No.	Description
A1	*Transponder—after separation:* Requires that the spacecraft S-band transponder function sufficiently well to allow tracking for a sufficient period after separation to allow determination of the injection trajectory.
A2	*Telecommunications—to nose-fairing jettison:* Requires the spacecraft telecommunication subsystem to perform from launch to nose-fairing jettison.
A3	*Telecommunications—nose-fairing jettison to separation:* Requires the spacecraft telecommunications subsystem to perform from nose-fairing jettison to separation. Probabilistically, success is conditional on the success of item A2.
A4	*Sensors—nose-fairing jettison:* Requires those spacecraft sensors that indicate the occurrence of nose-fairing jettison to perform properly.

[a] Required in parallel with one or more launch vehicle system S/O matrix items.

To further illustrate the S/O matrix, the S/O matrix items delineated in Tables A-1 and A-2 are shown in their functional relationships in the S/O matrix of Table A-3. Figure A-3 shows the block diagrams that present the equivalent information.

It will be noted that columns have been added for four *modes*. For phase 3 and beyond in the example, there are only four distinct results from the operation of the launch vehicle that are significant to the degree of partial success of the mission. To avoid simply repeating these four combinations over and over in the remainder of the S/O matrix, the combinations are denoted by the letters a, b, c, and d. Then, the remaining flight objectives are each separately identified with a mode. This procedure may be useful for several of the systems comprising a mission, or it may be a useful technique during the period prior to an accurate modeling of a system. Then, a small number of modes present an approximate picture of the system's contribution to the mission.

The launch vehicle modes used here may be described as:

Mode	*Description*
a	Perform sufficiently well that at least a low Earth orbit is obtained
b	Perform sufficiently well that at least a highly elliptical Earth orbit is obtained
c	Perform sufficiently well that at least a highly elliptical Earth orbit is obtained, and obtain a second stage/spacecraft separation
d	Launch on time, inject the spacecraft within its midcourse correction capability, execute a proper second stage/spacecraft separation, and execute an adequate second stage retro maneuver

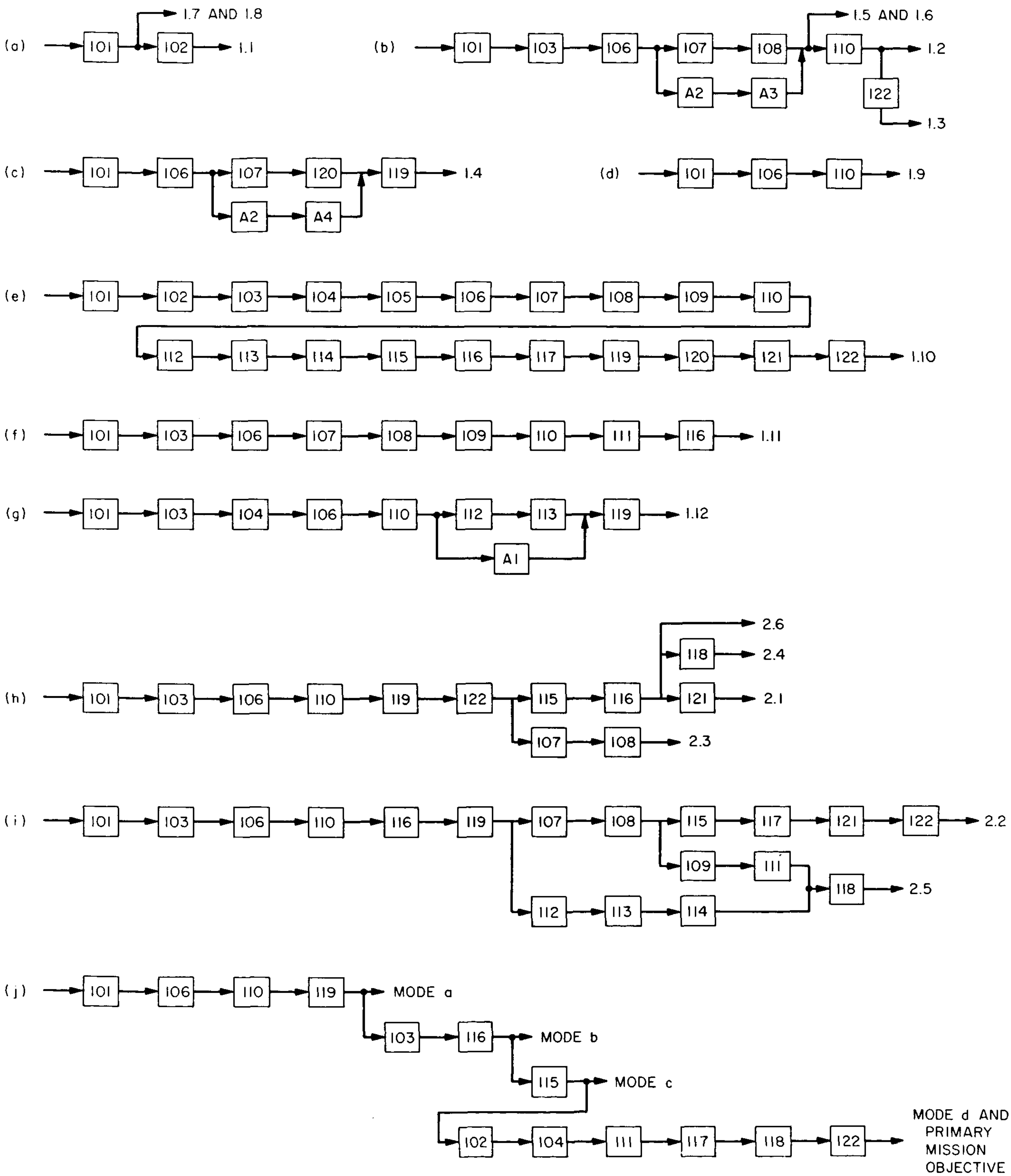


Fig. A-3. Block diagram equivalent to S/O matrix (Table A-3)

Table A-3. Illustrative S/O matrix and input data

Item No.	System	Subsystem	Configuration	P_A	$P_{B/A}$	Primary mission objective	Flight objectives 1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12	2.1	2.2	2.3	2.4	2.5	2.6	Modes a	b	c	d	Item No.
101	Launch vehicle (both stages)	Lift off pad		0.92	0.92	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	101
102		Lift off pad within scheduled window		0.99	0.992	S	S									S												S	102
103		Perform throughout powered flight		0.94	0.95	S		S	S		S	S				S	S	S	S	S	S	S	S	S		S	S	S	103
104		Provide injection within midcourse capability		0.93	0.94	S										S		S										S	104
105		Perform as programmed to separation with spacecraft		0.99	0.99											S													105
106	Launch vehicle (first stage)	Perform to nose-fairing jettison		0.97	0.98	S		S	S	S	S	S			S	S	S	S	S	S	S	S	S	S	S	S	S	S	106
107	Launch vehicle (second stage)	Telecommunications	To nose-fairing jettison	0.97	0.985			SA	SA	SA	SA	SA				S	S			S	S		SA						107
108			Nose-fairing jettison to injection	0.992	0.992			SA	SA		SA	SA				S	S			S	S		SA						108
109			Injection to retro	0.994	0.994											S	S						SA						109
110		Guidance	To separation	0.995	0.997	S		S	S						S	S	S	S	S	S	S	S	S	S	S	S	S	S	110
111			Separation to retro	0.998	0.999	S											S						SA					S	111
112		C-band beacon	MECO to separation	0.9995	0.9995											S		SA					A						112
113			Separation to retro start	0.9999	0.9999											S		SA					A						113
114			Through retro	0.9995	0.9995											S							A						114
115		Separation	Preseparation commands	0.997	0.998	S										S			S	S		S		S			S	S	115
116			After MECO	0.9997	0.9997	S										S	S		S	S		S	S	S		S	S	S	116
117			Within tolerance	0.96	0.983	S										S				S								S	117
118		Retro	Sufficient	0.97	0.99	S																S	S					S	118
119		Nose fairing	Jettison	0.96	0.98	S				S						S		S	S	S	S	S	S	S	S	S	S	S	119
120		Sensors	Nose-fairing jettison	~1.0	~1.0					SA						S													120
121			Separation	~1.0	~1.0											S			S	S									121
122		Spacecraft interfaces		0.97	0.995	S			S							S			S	S	S	S		S				S	122
A1	Spacecraft (paths parallel to launch vehicle prime paths)	Transponder	After separation															A											A1
A2		Telecommunications	To nose-fairing jettison					A	A	A	A	A																	A2
A3			Nose-fairing jettison to separation					A	A		A	A																	A3
A4		Sensors	Nose-fairing jettison							A																			A4

S: Item required in series for flight test objective
SA: Item in series has alternate path 'A'
A: Item required in series on alternate path 'A'
SB: Item in series has alternate path 'B'
B: Item required in series on alternate path 'B'

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