Table 2 Mariner Mars '71 firing data comparison

Constant current, amp	Ambient temperature, °K (°F)	No. of firings	Measured average time to burnout of bridgewire ms	Range, ms	Model prediction of time to reach 672°K (750°F), ms
3.5[a]	294 (70)	20	1.59	1.45-1.79	1.6
3.5	144 (-200)	10	2.02	1.8 -2.2	2.27
5	294 (70)	3	0.84	0.80-0.88	0.82
5	144 (-200)	4	1.08	1.05-1.1	1.1
5	366 (+200)	4	0.58	0.51-0.71	0.70

[a] Test conditions used for initial estimate of h (see Fig. 1.)

The good agreement between the predicted time to ignition and the measured time to bridgewire burnout seems to indicate that this model has some merit in spite of the many simplifying assumptions that were incorporated into the model. One of the significant aspects of this model is the interfacial boundary condition that stipulates a thermal contact conductance between the bridgewire and the pyrotechnic. This boundary condition greatly affects the temperature distribution and the heat transfer within the bridgewire-pyrotechnic system. Figure 2 shows the predicted temperature distribution within the system at 0.4 ms time intervals for the 3.5 amp firing at room temperature. A number of important points about the bridgewire-pyrotechnic system can be demonstrated with this figure. First, it can be seen that a sizable temperature difference can occur between the bridgewire and the pyrotechnic even when a very large thermal contact conductance is used. This results primarily because of the large heat flux out of the bridgewire. Second, there is very little temperature difference between the center of the bridgewire and the outside surface of the bridgewire. Finally, the heat does not diffuse past 100 μm (0.004 in.) within the pyrotechnic during the first 1.6 ms.

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Reliability Simulation for Solar Electric Propulsion Missions

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Introduction

CANDIDATE planetary, cometary, and geosynchronous missions with solar electric propulsion (SEP) are being studied for missions in the 1980's. Important aspects of any such mission studies are the system tradeoffs and reliability analyses. Such studies of alternate configurations and designs are needed to provide guidelines for hardware and subsystem requirements.

On simpler ballistic missions, a number of approximations and realistic assumptions can be used to simplify mission reliability tradeoff studies. In solar electric propulsion missions, the mission requirements are so complex that tradeoff studies become more difficult, and any simplifications must be considered with great care, for often they can affect the results. Indeed, many simplifications can no longer be made. In a typical SEP mission, a number of complexities influence mission tradeoff studies. Many of these complexities evolve from the mission requirements of providing thrust that is variable and dependent on a number of parameters. These parameters include such factors as available solar power (dependent on spacecraft-solar distance) as well as variations in hardware performance, hardware interfaces, and hardware wearout and reliability.

Some of the complexities can be summarized as follows: 1) Multiphase Missions—where different sets of hardware are required to work during the various portions or phases of the missions; 2) Complex Switching—where switching is needed for redundancy and for normal operations; and 3) Wearout Failure Modes of Components—including such items as switches and thrusters. The simplifying assumption of the constant failure rate for electronic components is not applicable to many of the components used on a SEP mission. This is because the constant failure rate assumption implies that there is no wearout.

Because of these and other complicating factors, analytical techniques are often insufficient for performing mission reliability tradeoff studies of alternate designs or configurations of a SEP spacecraft. Monte Carlo simulation provides an alternative and viable method for performing many of these analyses.

The objective of this paper is to very briefly describe the Monte Carlo method and elaborate on the complicated assumptions that can be modeled when using Monte Carlo simulation. This will be done principally by illustrating an application to an Encke Comet rendezvous mission reliability tradeoff study for interconnecting power processors and ion thrusters, the major elements of a thrust subsystem.

Monte Carlo Method

The Monte Carlo method provides a means, through the use of pseudo-random numbers, for simulating both probabilistic events and deterministic events that could occur during an actual mission. Examples of probabilistic (or random) events would be component failures and trajectory errors. Examples of deterministic events would be the

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predetermined points in time where the thrust requirements change.

Monte Carlo simulation is a very useful tool because it is often relatively easy to describe, with logical statements, what the system will do given various probabilistic and deterministic events. Yet it can be quite difficult to describe the system analytically with equations that are functions of the various probability distributions involved. The Monte Carlo method needs only the logical statements and takes care of the probability distributions in the "random" generation of the events.

Thus, a Monte Carlo simulation of a mission is one in which the mission is "flown" repeatedly (perhaps 5000 times) with the aid of a computer. All events pertinent to mission reliability are simulated on the computer, and statistics are compiled on the parameters of interest. For example, one might want to know the system reliability of two alternate configurations, which would, in the simplest type of Monte Carlo simulation, be the ratio of mission successes to total simulation trials. Another desired statistic might be the percentage of time a particular redundant unit was actually needed. By "flying" alternate configurations and designs on the same mission, the reliability of the alternate designs can be compared. Weight and power tradeoffs can then enter the analyses.

To simulate a mission on a computer, the mission parameters and the relevant spacecraft components must all be modeled. Consideration must be given to all probabilistic and deterministic events that might affect the study. All such events then must be programed for the computer. The simulation then proceeds. Of course, Monte Carlo simulation introduces statistical errors into the numerical results. One must ensure that enough simulations have been performed to reduce this statistical error to the point where it will not influence any decisions that might be based on the analyses of the simulation. When considering tradeoff studies, the effect of statistical errors can be reduced by "correlated sampling"—that is, by assuring that abnormal random numbers affect all the designs under consideration in roughly the same way. In the computer program developed for performing the analyses of the Encke Comet rendezvous mission, five thousand trials for each of the tradeoff studies appeared to be sufficient for the desired statistical accuracy.

Example of an Application

An excellent application for the Monte Carlo simulation program was the power conditioner ion thruster interconnection tradeoff study performed during the preliminary design of an SEP spacecraft for an Encke Comet rendezvous mission of the 1980's.

A. Mission Requirements and Constraints

The Encke Comet rendezvous mission studied (Ref. 1) requires that the spacecraft thrust subsystem operate during the entire mission from Earth (1.0 AU) to 3.3 AU and back to about 1.0 AU for encounter with the comet. This fact establishes one of the complicating factors for which Monte Carlo simulation provides an easy workaround. In particular, the power (provided by the spacecraft solar arrays) available for the thrust subsystem is very dependent on the spacecraft distance from the sun, and so the number of operating thrusters varies during the mission.

Another complication related to thrusting is that the thruster must be operated in combinations that do not disturb the attitude of the spacecraft. This puts a symmetry constraint on the choice of operating thrusters.

B. Description of Considered Concepts

For the study, three possible ways of interconnecting power processors to ion thrusters were studied:

1) *Hardwired interconnection*. In this approach a power processor is directly connected to each thruster. Spares are in the form of a set, a power processor with its interconnected ion thruster. The primary advantage is that no switching circuitry is required between a power processor and a thruster that may fault the operation of either component in case of a switch failure. Disadvantages of hardwiring are: a) loss of power processor or thruster causes loss of both units; b) less flexibility, since spares are in the form of sets, a power processor and the interconnecting thruster; and c) The weight of additional power processors to make the sets of spares may be undesirable. For example, one might wish to add only spare thrusters, since they are probably the more unreliable component.

2) *Complete switching*. The approach permits interconnecting any power processor to any available thruster. This approach would employ a rotary multipositioned switch for each power processor. The switch would connect the output of the power conditioner to any ion thruster of the array. A logical circuit is required to ensure the correct interconnection between a power processor and an ion thruster.

An advantage is that spares of either power processors or ion thrusters can be added or removed for each new mission, depending on the probability of the mission success as influenced by the reliability of each component. Another advantage is that attitude-control ion thruster symmetry requirements may be satisfied more easily, since all the ion thrusters are available for interconnection. A key disadvantage is that a switch has been introduced between the power processors and the ion thrusters, a series element in the reliability flow diagram. The failure of the switch will have a degrading effect on the overall mission success.

3) *Limited switching*. In this approach, each power processor may be connected to limited number of thrusters. This makes for simpler switches, but also provides less flexibility.

So the question then becomes, for this particular mission, which of these schemes is more reliable at at minimum weight?

C. Component Failure Rates

Complicated assumptions about the component failure rates were another factor contributing to the need for a Monte Carlo simulation.

1) *Ion thruster*. There are two important failure modes of the ion thruster that need to be considered: one is random failure and the other is wearout failure. A constant failure rate was assumed for the early part of the mission and a Weibull distribution was fitted for the latter part of the mission to account for cathode and grid wearout.

2) *Power processors*. The power processor, being largely electronic, presented no complications. Dormancy considerations for the dormant or turned-off state were included, though.

3) *Switch*. By using Monte Carlo, switch wearout can be modeled. Also different assumptions were made depending on the complexity of the switch—ranging from the simplest 2-position switch for the simplest limited switching case to the 7-position switch for the complete switching case.

Also, three separate switch failure modes were considered: a) "stuck-at" failure; b) an "open" failure; and c) a "complete" failure. Conditional probabilities were assigned to each of these failure modes.

D. Mission Simulation Computer Program and Results

Several definitions of mission success have been considered for the Encke comet mission. The most desirable success is when the spacecraft follows a trajectory that encounters the comet at 40 days before Encke perihelion. A slightly degraded success occurs when encounter is at least 27 days before perihelion. The degraded case was considered for this exam-

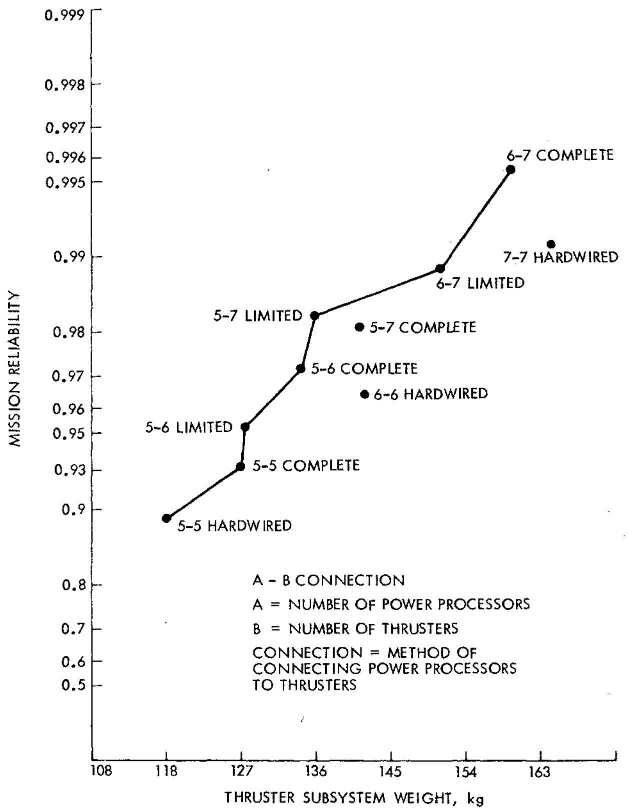

Fig. 1 Thrust subsystem weight vs mission reliability.

ple. But the point is that quite complicated definitions of success can be specified for a simulation. This is important because the definition of success has a very large impact on mission reliability and reliability tradeoff studies.

In the simulation, the mission was started with the nominal case, and as failures appeared the mission would continue as long as the degraded case could be performed. If the degraded case was achieved in the simulation, this was considered a mission success. The mission reliability (mission probability of success) was then obtained by taking the ratio of mission successes to the total number of missions simulated.

The actual performance of the simulation proceeded as follows. Failure times were generated for each component, based on the previously described failure distributions. Then, at the start of the simulation, the appropriate elements (thruster and power processors) were chosen and designated to be "active," so that operating time would be accumulated on these elements. The simulation then proceeded to the next "event," which would either be a failure or a phase change, (that is, a new scheduled thrusting requirement). For either event, new thrusters and processors would be selected and switch availability would be checked. In the event of failures, the scheduled "active" elements would not be available. In such cases, alternates were chosen, and switching and symmetry checked, until a viable configuration was found. In selecting "active" thrusters for a particular phase, the algorithms generally chose those with least accumulated active time to "even out" the operating times and to help prevent wearout. This procedure was then repeated until either the mission was complete, or until too many failures had occurred to continue the mission.

The other important factor in any reliability tradeoff study is weight. Figure 1 shows a means of presenting results that illustrates the dependence of reliability on weight. The solid line can be considered an "optimum" line in that configurations off this line are both heavier and less reliable.

Conclusions

The Monte Carlo simulations for the Encke Comet rendezvous mission have demonstrated the versatility of the Monte Carlo method for performing tradeoff studies. A great number of factors, usually too complicated to include, were used in the studies. Moreover, sensitivity studies indicated that most of the factors described above were pertinent to the results and so could not safely have been ignored. A general reliability simulation program is a very useful tool for analyzing competing designs from a reliability viewpoint.

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Model Reduction of a Nonlinear Rocket Control System

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Introduction

MODEL reduction by continued fraction is a very powerful and popular tool if it is used correctly.‡ In the original papers of Chen and Shieh, it has been pointed out that the system must be low pass in nature.[1,2] But in the limit-cycle analysis of a high order nonlinear rocket control system, one can not make sure whether the system is suitable for model reduction, although a Bode plot may help. It is the main purpose of this work to present such an application.

System Analysis

The block diagram of a flexible rocket control system is shown in Fig. 1. The linear blocks are[3]

$$TF_{\text{str.}} = [0.686(S+53)(S-53)(S^2-152.2S+14500)$$
$$\times (S^2+153.8S+14500)]/[(S^2+S+605)(S^2+45.5S+2660)$$
$$\times (S^2+2.51S+3900)(S^2+3.99S+22980)] \tag{1}$$

$$G_s(S) = 2750/(S^2+42.2S+2750) \tag{2}$$

$$G_r(S) = 7.21/(S+1.6)(S-1.48) \tag{3}$$

$$G_{sf}(S) = \frac{(S^2+70S+4000)(S^2+22S+12800)}{(S^2+30S+5810)(S^2+30S+12800)} \tag{4}$$

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‡One of the reviewers of this paper has pointed out that the method of continued fraction may sometimes reduce a stable system to an unstable one. This is a fact but will not be discussed here for lack of space. The authors are grateful to all the reviewers for their comments.