Electric Propulsion Design Optimization Methodology

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This paper presents a methodology for maximizing the performance and economic advantages offered by solar-electric propulsion for many interplanetary missions. The optimum design, which includes the optimum thruster module size, is chosen as the one giving minimum system mass subject to the condition that the system reliability is greater than or equal to a given number, while satisfying the requirements of operating point variations, voltage regulation, and impedance matching.

Introduction

SINCE the application of low-thrust propulsion systems to interplanetary missions requires long duration (~10,000 hr) component operation, reliability for long-term operation must become an important factor in system design. The effects of operating point variations on the system mass and reliability must be considered, particularly when a solar power source is used for interplanetary missions. Since a mass penalty is generally incurred when a component must be designed to operate over a range rather than at a fixed point, methods for reducing the component operating point variation must be investigated.

System Design Methodology

Reference 1 described a thruster system in the form of an array of operating and standby thruster modules. (Standby redundancy is the most natural mode for ion engines.) The virtue of this modularized thruster system configuration is that it permits a systematic weight-reliability tradeoff. For a specific mission (i.e., trajectory, power level, etc.) this tradeoff yields a minimum thruster system mass under the constraint of a required thruster system reliability. The numbers of operating and standby thruster modules are treated as variables. To illustrate the tradeoff, first suppose that one (large) thruster module is used for a mission. Assuming that its reliability is insufficient, standby thrusters of equal size must be included; however, these standby thrusters represent unacceptably large (100's of %) mass penalties. If the operating thruster system consists of two or more thruster modules, standby modules represent smaller mass penalties. On the other hand, the use of too many small thruster modules will increase the mass and failure rate of the operating thruster array prohibitively; hence a true tradeoff is present. In summary, the results of Ref. 1 offer solutions to two important propulsion system design problems: 1) increasing thruster system reliability and 2) answering the inevitable question of what size thruster should be employed.

Increasing the reliability of the power conditioning system was also considered in Ref. 1. The mode of redundancy stressed there was duplication of the diodes in the rectifier banks. This choice was justifiable because a single high-power, high-voltage (beam) supply was used. Subsequently it has been shown[2] that a beam supply consisting of operating and redundant inverter-rectifier modules is more advantageous(from a weight-reliability standpoint).

The design of an electric propulsion system is considerably more complicated when the electric power available to the thruster system varies during the mission, as is the case in solar electric missions. It is shown in Ref. 2 that some of the problems associated with having a thruster system operate over a range of power levels are reduced if a modularized thruster system design is employed. Instead of requiring a single high-power thruster to vary its power over the entire range exhibited by the power source, gross power regulation can be provided by switching single thruster modules in and out of the operating array. A further advantage is that on decreasing power missions thruster modules which are switched off can be considered standbys for the remainder of the missions. On deep space probe missions (Mars, Jupiter) these extra standbys bring about a significant increase in mission reliability of the thruster system.

The criterion for switching thruster modules to accommodate power source variations is based on the desire to increase the power transfer from the source to the load. The condition for maximum power transfer (i.e., that the load impedance match the source impedance) is discussed in Ref. 2; it is shown that since the thruster system load is approximately a constant current line, the large power variations in a solar array on an interplanetary mission will appear as fluctuations in bus voltage unless continuous control on the load (beam) current is employed during a mission.

The final electric propulsion system designs presented in Refs. 1 and 2 reflect weight-reliability tradeoffs which are

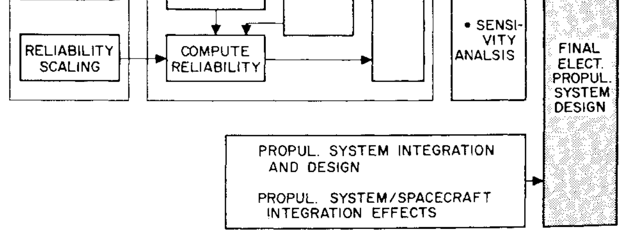

Fig. 1 Block diagram of propulsion system design approach.

Presented as Paper 69-254 at the AIAA 7th Electric Propulsion Conference, Williamsburg, Va., March 3–5, 1969; submitted April 10, 1969; revision recieved October 29, 1969.

This work was partially supported by Marshall Space Flight Center under Contract NAS 8-21447.

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carried out separately for the thruster, power conditioning, and tankage subsystems. In Ref. 3 a technique is developed which under certain conditions permits a simultaneous optimization of all three subsystems (thruster, power conditioning, and tankage) in such a way that the over-all propulsion system mass is minimized subject to the constraint that the over-all system reliability exceeds a given value. When this weight-reliability tradeoff is applied to the over-all propulsion system, the optimum allocation of reliability (and therefore redundancy) among the subsystems can be found.

The over-all propulsion system design approach which has been developed is summarized in Fig. 1. As shown, the final result is a detailed electric propulsion system design which has been optimized for a specific mission and integrated with a specific spacecraft. The total effort which must be performed to obtain the final designs is divided into two general tasks: 1) computer simulation, design optimization, and sensitivity analysis of the major propulsion subsystems, and 2) propulsion system integration and propulsion system/spacecraft integration.

This paper will be limited to the discussion of a design optimization computer program which has been developed to carry out task 1. It should be noted, however, that the integration studies (task 2) are important in developing design constraints which are necessary to make all the subsystems and spacecraft compatible. A well-balanced over-all propulsion system design can be expected when tasks 1 and 2 are pursued simultaneously.

Bus-current and voltage vs time curves (at maximum power transfer) are inputs into a subroutine which calculates all of the thruster module and power supply module switching times. Provision has also been made so that each power supply has a variable module size and variable number of modules in standby.

Subsystem masses are based on the component mass versus power level scaling laws. The switching times are also inputs to this subroutine for the purpose of calculating mass penalties due to source voltage and current variations.

The reliability subroutine is the most complex, due to the elaborate switching capabilities which are provided. Component reliability vs power level scaling laws and the switching sequences are the inputs to the reliability subroutine. The output provides not only the over-all system reliability, but also the individual subsystem reliabilities.

The only remaining input required for the computer simulation is a trial set of system variables. Outputs such as masses, reliabilities, switching times, and current and voltage variations in modules will then be obtained for this set.

The final step is to compare many trial designs and systematically find the one with minimum mass. Various levels of system optimization, depending on the number of quantities to be varied simultaneously, can be performed. Either independent subsystem optimizations or system optimization based on proper reliability allocation among the subsystems can be obtained. Since the scaling laws used as inputs to the computer program are based on detailed subsystem analysis, the resulting outputs can immediately be related to specific subsystem designs.

Modeling of System Mass and Reliability

The electric propulsion system configuration chosen for simulation by the computer program is shown in Fig. 2. The reservoir subsystem is represented generally as having T tanks containing the propellant required for the mission and S tanks containing redundant propellant. All the tanks are connected to the thruster subsystem through a common manifold; the reservoir subsystem is considered independent of the other subsystems (with respect to module switching).

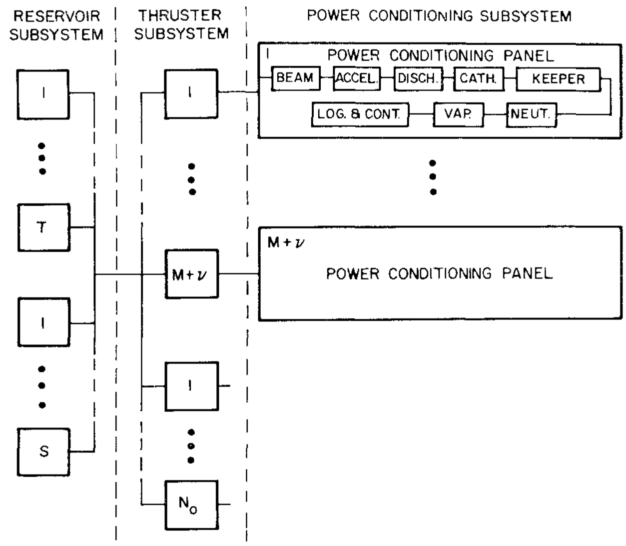

Fig. 2 Block diagram of ion propulsion system.

In the general thruster subsystem configuration shown, it is assumed that at the beginning of a mission there are M operating thruster modules and N_0 thruster modules in standby. A number ν of additional (turn-on) modules are also provided in the event that the power available to the thruster subsystem increases during a mission. Accordingly, thruster modules are switched on or off in relation to power source fluctuations. When thruster modules are switched off and are no longer needed, due to reduced power, they are considered standbys for the remainder of the mission.

The power conditioning subsystem consists of an array of $M + \nu$ power conditioning panels. One panel contains all of the power supplies necessary to operate a thruster module. Standby panels which could replace any operating panel are not provided because the switching matrix required would be prohibitively large. Only the original thruster module and the standby thruster modules can be operated by a given panel. Although it is not explicitly shown in the block diagram, the reliability of the power conditioning system is increased through redundancy in the separate supplies. For example, the beam supply consists of a parallel redundant array of inverter modules. An increase in the power conditioning subsystem reliability also occurs for missions in which switched off thruster modules and their panels are considered standbys.

Within the context of the general configuration shown in Fig. 1, there are many possible detailed designs which could satisfy reliability and power matching constraints. The optimization procedure examines these alternative designs to find the one with minimum mass. In order to test tentative designs against constraints and compare their masses, quantitative expressions are needed for the mass and reliability of the general propulsion system configuration as functions of the configuration variables. First, the (more complicated) formulation of reliability expression will be discussed.

In the reliability formulation the usual formulas for series, parallel, and standby configurations of units are widely used. A representative example is the standby redundancy formula

$$R(M,N) = e^{-M\lambda(P/M)T} \sum_{j=0}^{N} \frac{\{M\lambda(P/M)T\}^j}{j!}$$

which represents the reliability of a system of M operating modules of power level P/M each, and N in standby for a mission of length T. The expression for $R(M,N)$ is an explicit function of the configuration variables M and N and also employs the failure rate function $\lambda(p)$. This so-called

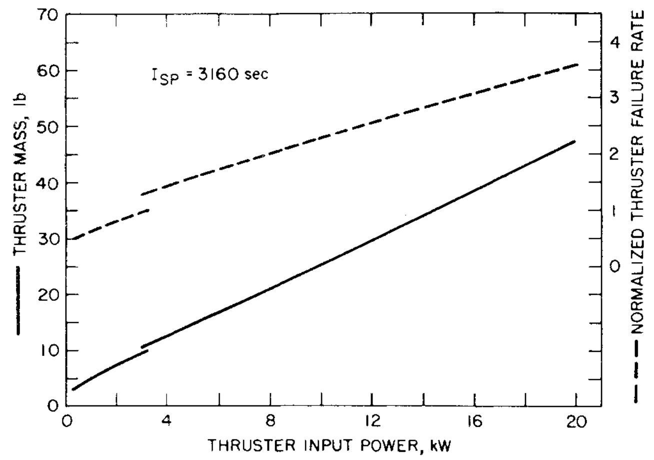

Fig. 3 Scaling for mercury hollow-cathode thruster and feed system.

"scaling" function $\lambda(p)$ gives the failure rate of a single module as a function of its power level p. For the preceding example $M\lambda(P/M)$ denotes the failure rate of an array of M modules with total power P. A considerable effort has been devoted to developing and incorporating into the formulation failure rate scaling curves for each (thruster, tank, and power supply) module used in the general configuration. Many examples are given later.

The complexity of the reliability formulation for the overall system depends on the nature of the source power profile which must be followed by the thruster array during the mission. The two cases which can presently be handled are 1) increasing power (typical of solar probe, Venus, etc., solar electric) missions and 2) decreasing power (typical of solar electric outer planet) missions. For the increasing power situations, new thrusters and power conditioning panels which are switched on during the mission can be treated by employing the idea of a variable (increasing) failure rate $\lambda(t)$. In comparison with the reliability $e^{-\lambda_0 T}$ of a mission of length T for a constant failure rate λ_0, the mission reliability becomes

$$\exp\left[-\int_0^T \lambda(t)dt\right]$$

for the case of a variable failure rate $\lambda(t)$.

On decreasing power missions, thrusters and power conditioning panels are switched into standby after a time of operation. The reliability formulation is complicated by the

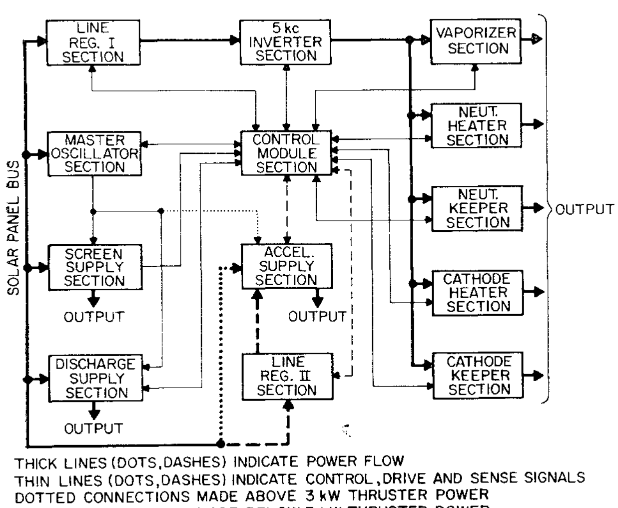

Fig. 4 Electrical block diagram of power conditioning panel.

Table 1 Comparison of subsystem designs-increasing power mission[a]

Design parameter	T	$T + BS$	$T + P$
R_g	0.96	0.96	0.96
M_S	80	125	209
O_T	6	6	2
S_T	1	1	1
R_{TS}	0.9886	0.9886	0.9925
M_{TS}	80	80	100
R_{BS}		0.9755	0.9995
M_{BS}		45	47
R_P			0.967
M_P			109

[a] Symbols: M = mass, lb; R = reliability; O = maximum number of operating modules; S = initial number of standby modules. Subscripts: T = thruster, TS = thruster subsystem; BS = beam supplies; P = power conditioning; and S = system.

increase in redundancy during the mission and because the standby panels "remember" their past operation. Because of the internal redundancy (in the individual supplies), panels can be in many possible states, depending on how much internal redundancy was used, when they are switched into standby.

The formulation of the mass of the electric propulsion system is relatively straightforward. The total system mass is simply the sum of the masses of all subsystems (i.e., thruster, power conditioning, and reservoir), which in turn are equal to the sum of the masses of their respective components. These component masses (thruster module, inverter modules, filter circuits, propellant tanks, etc.) are functions of the configuration variables (i.e., the degrees of redundancy and modularization) and in some cases also of component failure rates. The expressions for component mass are, in most cases, relationships between the component mass and its rated power as determined by the configuration variables. In some cases, however, (e.g., propellant tanks) the component mass is related to capacity or operating point variations (also functions of the variables). The relationship between the component masses and their power levels are part of the scaling information given in the next section and are basic to the system mass formulation.

Application to Solar Electric Propulsion

The methodology just presented is currently being applied to ion propulsion systems representative of the state of the art and having the configuration described earlier. Pertinent scaling studies were performed to provide information used in the mass and reliability formulations to determine component masses and failure rates. The scaling studies are discussed separately for each propulsion subsystem.

The scaling curves shown in Fig. 3 are for a mercury-bombardment ion engine employing a hollow cathode for both discharge chamber and neutralizer. The thruster uses permanent magnets, has a vaporizer to convert liquid mercury to vapor, and has a mercury vapor isolator which provides electrical isolation between the thruster and the reservoir subsystem. For an effective specific impulse of 3160 sec the thruster is scaled through a range of total input thruster power from 1 kw to 20 kw. It is assumed that for thrusters larger than 30 cm diam. (3.19 kw) an increase from one to four cathodes will be required for efficient thruster operation. This assumption causes a discontinuity in both the mass and failure rate curves. A normalized failure rate vs power curve (referenced to a power of 3.19 kw) is shown. The best current failure rate estimate for a 3.19 kw thruster is 0.00638 failures per thousand hours.[4] (These failure rates refer to random failures which occur during the predicted life expectancy of a thruster.)

The power conditioning subsystem is composed of a group of identical panels, each of which furnishes power to a single

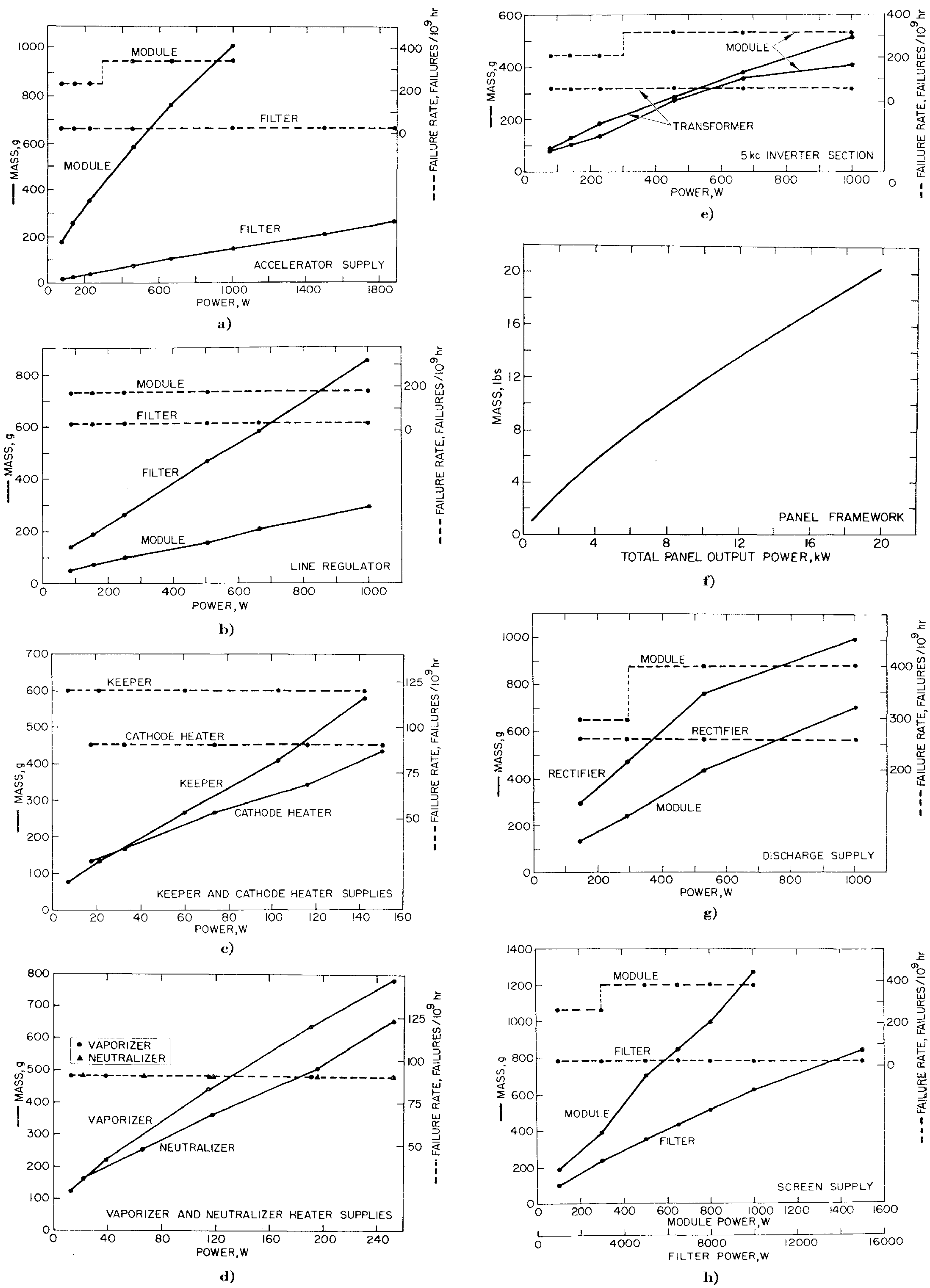

Fig. 5 Power supply scaling curves.

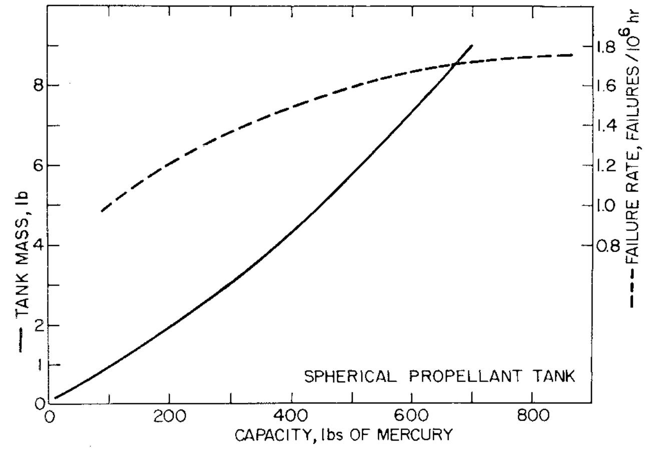

Fig. 6 Scaling curve for one stainless steel tank.

thruster module. The components used in the panel are determined by the electrical requirements of the thruster. Figure 4 is a block diagram of such a panel for the aforementioned thruster. The flow of power to various sections in the panel is indicated by the heavy lines. Line regulator No. 2 is not used for panel output powers above 3 kw. Some of the sections (or supplies) comprise redundant modules and series elements, e.g., the screen supply is composed of a parallel group of inverter modules in series with a filter element. The ranges over which each of the components is scaled is determined by the distribution of power to the thruster, assumed practical limits on the number of modules and the existing component state of the art. Figure 5 presents scaling curves for most of the elements in a power conditioning panel. In many cases the failure rates are constant with power because heavier elements were designed to yield a constant stress value. Discontinuities in the failure rate usually occur where the basic design of an element has changed. The panel frame failure rate is assumed zero. The master oscillator and control module were also scaled. Their masses and failure rates which are not functions of power are 25.2 g and 183 failures per 10^9 hr for the master oscillator, and 354 g and 505 failures per 10^9 hr for the control module.

The propellant reservoir subsystem is assumed to include one or more spherical tanks. The tanks are at present considered to be constructed of stainless steel which is known to be compatible with mercury. Titanium was considered for the design; however, because it exhibits marked stress corrosion effects in mercury, it was not used (pending further research).[5] Figure 6 shows mass and failure rate scaling for a spherical tank (excluding the pressurizer) operating at 45 psi with a 43% safety factor.

Using the above scaling laws, the computer optimization program has been applied to several system and subsystem design problems for an increasing power mission (i.e., a solar electric propulsion system on a mission to Venus). A specific impulse of 3160 sec and a maximum available solar panel power of 20 kw were assumed.

Examples of the use of the computer program are presented for three different systems. The system considered becomes successively more complex with each example. The optimum system design for each system is summarized in Table 1. When the results are presented in this manner, the variation in the subsystem designs when more and more of the system is considered is apparent. It is then obvious that the entire system must be optimized at the same time to find the correct subsystem designs; this optimization problem is not reducible, as are some, to a number of subsystem optimization problems.

In all the system design problems considered, the minimum allowed system reliability was assumed to be 0.96. In the first case only the thruster subsystem is optimized. Two effects operate to make O_T, the maximum number of operating thrusters, large. First, subsystem designs with large O_T have small operating point penalties. Second, large values of O_T imply small thrusters. Therefore, a given number of standby thrusters become less massive as O_T is increased. Because only integer variables are meaningful and allowed the optimum system design can occur at a point where the system reliability is larger than the minimum allowed reliability, R_g, as occurred in the first case.

The system for the next case considered was composed of the thruster subsystem plus the beam supply to represent the power conditioning subsystem. Since inclusion of the beam supply brings two additional variables (O_B, the number of required beam supply modules; and S_B, the number of initial redundant modules), the optimization problem becomes a four variable problem. Comparison with the previous case shows that the system mass increased due to the additional subsystem.

The system considered for the final example is composed of the complete thruster and power conditioning subsystems. The additional supplies brought into the power conditioning subsystem raises the number of variables in the optimization problem to ten. Because of the increased power conditioning subsystem complexity the system mass has again increased. Both the thruster subsystem mass and the mass of the beam supplies have increased. The slight increase in the mass of the beam supplies is due to the increased reliability demanded of that section. The increased thruster subsystem mass arises from two causes. First, a higher reliability is demanded of the subsystem. Another cause is the effect of coupling in the mass and reliability formulas. The thruster subsystem is forced by the coupling away from its optimum design to achieve the optimum design for the system. Inspection of the system configuration (Fig. 2) reveals that the coupling is due to O_T. The mass and reliability of the power conditioning subsystem is directly dependent on O_T, the maximum number of thrusters in operation, since the number of power conditioning panels equals O_T. Also, the power conditioning reliability depends upon the thruster switching times and hence O_T. Large values of O_T will lead to large values of power conditioning mass and low values of power conditioning reliability. Therefore, O_T could be expected to be small when the system optimization includes the power conditioning subsystem even though this may increase the thruster subsystem mass by driving it away from its optimum design.

Conclusions

It has been shown that an important consideration in designing an electric propulsion system is total system reliability. Specifically, high system reliability must be attained with minimal mass penalties to the system. Mathematically, the problem to be solved is one of finding that propulsion system design which provides minimum system mass while satisfying the constraint that the system reliability is greater than or equal to an assigned minimum value. It was also shown that the effects of impedance matching, and operating point variations on the problem must be considered in the formulation of the system mass and reliability functions. A method for obtaining a solution to the optimization problem has been mechanized in a digital computer program. The computer program is sufficiently general to apply to any likely system configuration. It has been applied to a particular system configuration, which was felt to best represent the state of the art. Several sample problems were illustrated for this system configuration for ion propulsion systems on an increasing power mission.

Two important conclusions can be drawn from the results of the sample problems: 1) the scaling studies which are used as inputs to the propulsion systems design computer program are extremely important to the final solution, and 2) it is necessary, as is generally the case, to consider all subsystems simultaneously when searching for an optimum system design.

Using the aforementioned computer simulation as a basic tool, a design methodology has been formulated which will provide a spacecraft developer with a means to optimize the design of an electric propulsion system (and, therefore, to maximize mission performance) for any given application.

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FEBRUARY 1970 J. SPACECRAFT VOL. 7, NO. 2

A Vortex Valve for Flow Modulation of 5500°F Gas

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The results of developing a fluidic, no-moving part vortex valve capable of modulating the hot gas generated by a typical solid propellant are presented. The developed vortex valve has the capability of controlling a 16% aluminized, 5500°F gas flow of 1.0 lb/sec at 750 psi and for durations up to 50 sec. Seven hot gas tests were performed during the development. A materials selection was made based on an elasto-plastic thermal analysis of the vortex valve geometry. The final vortex valve demonstrated a 3.46/1 flow modulation range at a control pressure to supply pressure ratio of 1.7. A 2000°F gas was used to control the vortex valve, and it is concluded that a higher temperature control gas would improve the vortex valve modulation range.

Introduction

SOLID-PROPELLANT rockets have evolved rapidly in the last twenty years from simple uncontrolled devices to more complex units capable of thrust modulation, start-stop, and thrust vector control. The demand for more accurate control, more life and reliability and, finally, lower cost and less weight. In the effort to obtain maximum power from the solid propellant, combustion temperatures are increasing, and the combustion products are highly corrosive and erosive. Valves capable of operating in this severe environment are needed. By bleeding controlled quantities of gases from the combustion chamber, various control functions may be accomplished. Valving techniques for such purposes have been the subject of many investigations. This paper describes the development of a fluidic, no-moving-part vortex valve which has the capability of modulating the flow of solid-propellant hot gas. The vortex valve has certain operating limitations and, provided that these characteristics are acceptable to the system under consideration, the vortex valve can offer certain system advantages.

Received June 2, 1969; presented as Paper 69-424 at the AIAA 5th Propulsion Joint Specialist Conference, U.S. Air Force Academy, Colo., June 9–13, 1969; revision received October 9, 1969. The authors wish to thank the NASA Langley Research Center for permission to publish results from the work sponsored under Contract NAS1-5199. They also thank the Bendix Research Laboratories for assistance in the preparation of this paper, and the many individuals who contributed to the effort while it was in progress.

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Vortex Valve Concept

The vortex valve (Fig. 1) functions by the interaction between properly introduced control and supply flows. The supply flow is introduced radially into a cylindrical vortex chamber. In the absence of control flow, it proceeds radially toward the center outlet orifice whose size establishes maximum valve flow. Supply flow is modulated by tangential control flow that imparts a rotational component to the supply flow. Conservation of angular momentum causes the tangential velocity to increase toward the center of the valve. This generates an impedance or pressure buildup

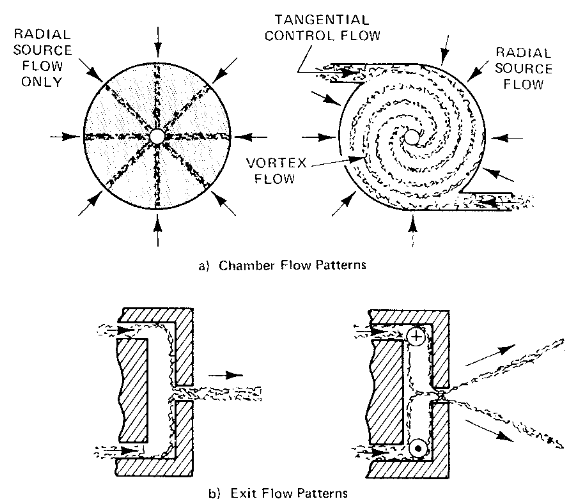

Fig. 1 Vortex valve configuration and operation.