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NUCLEAR PROPULSION SYSTEMS & MISSION ANALYSIS RESEARCH

Reliability Model of a Monopropellant Auxiliary Propulsion System

AMS Report No. 997

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25 June 1971

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ABSTRACT

A mathematical model and computer code have been developed to compute the reliability of a monopropellant blowdown spacecraft orbit adjustment propulsion system as a function of time. The reliability model interfaces with a computer code that models the performance of a blowdown (unregulated) monopropellant auxiliary propulsion system. The computer code acts as a performance model and as such gives an accurate time history of the system operating parameters. The basic timing and status information is passed on to and utilized by the reliability model which establishes the probability of successfully accomplishing each required orbit adjustment.

The mathematical model and computer code were developed as a background effort to verify the concepts prior to writing a reliability model based on the current NERVA propulsion system.

ACKNOWLEDGEMENTS

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by Joel S. Greenberg

I. INTRODUCTION

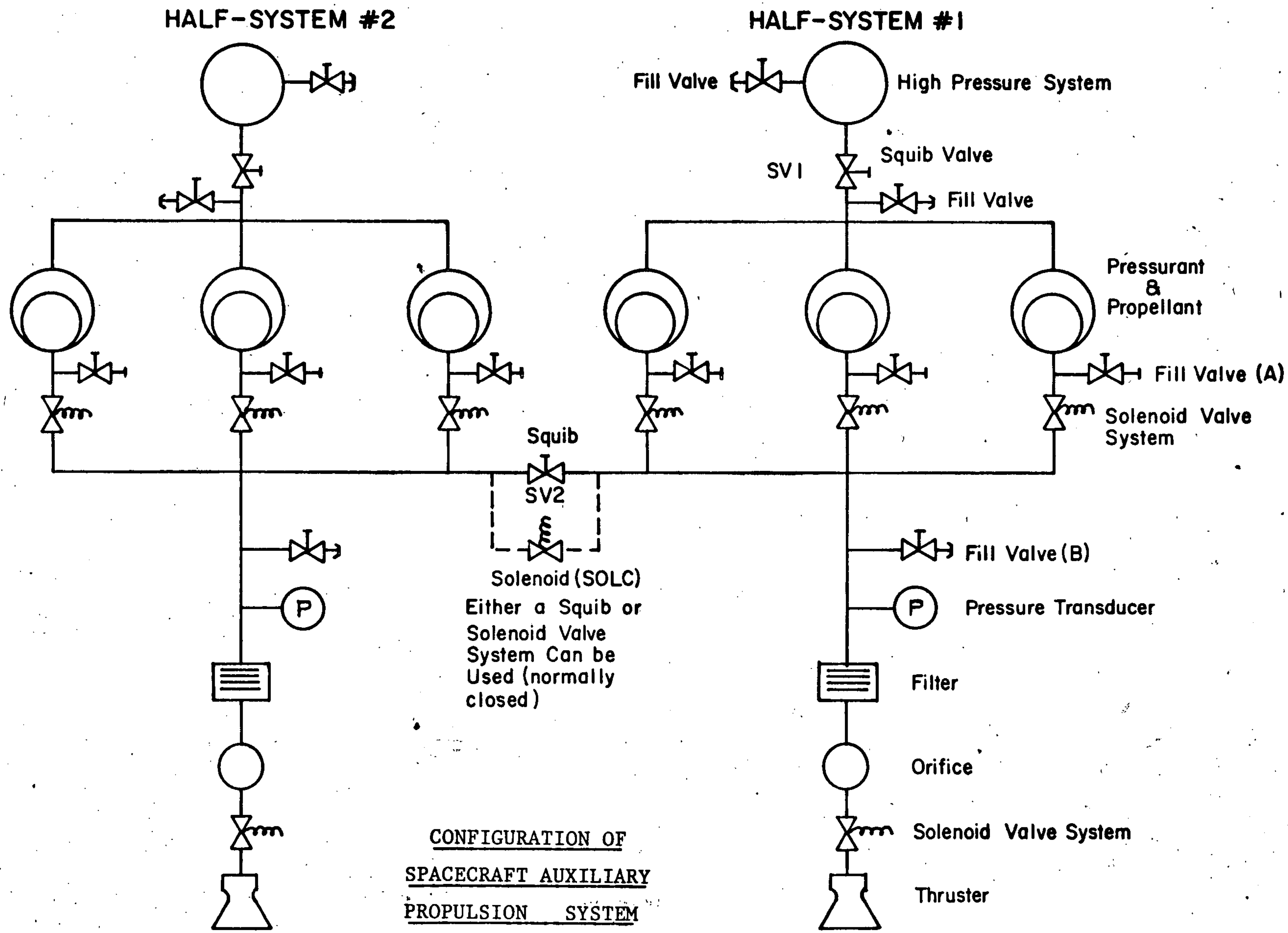
A measure of how well a system performs or meets its design objectives is provided by the concept of system reliability. In general, reliability can be defined as the probability of successful system operation in the manner and under the conditions of intended use. Since space systems are normally designed to achieve multiple time dependent objectives, it is important to establish the reliability of achieving these objectives so that appropriate design trade-offs can be made. In order to demonstrate the importance of evaluating the reliability of multiple time dependent objectives and the basic techniques employed, a relatively simple mission was considered. Specifically, a mathematical model and associated computer code has been developed which computes the reliability of a monopropellant blowdown hydrozine spacecraft auxiliary propulsion system as a function of time. The propulsion system is used to adjust or modify the spacecraft orbit over an extended period of time. The multiple orbit corrections are the multiple objectives which the auxiliary propulsion system is designed to achieve. Thus the reliability model computes the probability of successfully accomplishing each of the desired orbit corrections. To accomplish this, the reliability model interfaces with a computer code that models the performance of a blowdown (unregulated) monopropellant auxiliary propulsion system. The computer code acts as a performance model and as such gives an accurate time history of the system operating parameters. The basic timing and status information is passed on to and utilized by the reliability model which establishes the probability of successfully accomplishing the orbit corrections.

II. GENERAL PROPULSION SYSTEM DESCRIPTION

Monopropellant auxiliary propulsion systems are generally low thrust systems which are used for spacecraft attitude control and station keeping. Figure 1 illustrates the blowdown hydrazine propulsion system which has been modeled. The system consists of two identical monopropellant half-systems which are interconnected through a valve system such that the propellant from either half-system can be expended via either thruster. The half-system interconnecting valve system is normally in the closed position. The initial pressure in the propellant tank is such that the ullage gas will expand (blow-down) against the propellant, forcing it through the system during thrust periods until the propellant is depleted. The blow-down mode may be staged. That is, a pressurant tank may be placed in series with the main propellant tanks and at a predetermined propellant tank pressure the associated squib valve opens and the system is repressurized (i.e., blowdown occurs). Thus, sufficient pressure is maintained during normal operation to ensure that the desired amount of propellant can be expended.

The general propulsion system configuration which is modeled is as indicated in Figure 1. Within this configuration a number of alternatives are possible. These alternatives may be summarized as follows:

(a) A single stage blow-down system may be considered. This implies the elimination of the high pressure system and its associated squib valve.



CONFIGURATION OF SPACECRAFT AUXILIARY PROPULSION SYSTEM

FIGURE 1

(b) All squib valves are considered to consist of n valves in parallel.

(c) The high pressure system can consist of m high pressure tanks in a parallel arrangement.

(d) The half-system interconnecting valve system can consist of either squib or solenoid valves.

(e) Either a single fill valve can be used for each pressurant and propellant tank or a single propellant fill valve can be used for each half-system.

(f) Solenoid valve systems can consist of either a single valve, dual series valves, dual parallel valves, quad or quad connected valves.

III. PERFORMANCE MODEL*

The performance model[1] and associated computer code (the entire computer code for both the performance and reliability models is contained in Appendix I) yields an accurate time history of the propulsion system operating parameters. The mathematical equations used to represent the components are the basic orifice flow equation, thermodynamic expansion equation, and the various equations relating the rocket engine parameters. In order to run the performance program, the system hardware must be completely defined. The basic performance input data is summarized in Table I. Additional information describing thruster characteristic performance curves and specific

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*The performance model was developed by Ralph Lake of RCA's Astro Electronic Division as part of course (E581- 1970/71) requirements at Princeton University.

TABLE I

PERFORMANCE INPUT DATA

Input Variable	Description
VEJIN	Effective jet velocity (m/sec)
Z	Compressibility factor
CFIN	Nozzle thrust coefficient
DEN	Propellant density (kg/m^3)
AT	Nozzle thrust area (m^2)
PFIL	Initial tank pressure (n/m^2)
STG	Number of blowdown stages
CD	Orifice coefficient (all components)
A	Orifice area (all components)
P	Gas expansion exponent
DPT	Initial tank internal pressure drop (n/m^2)
PMO	Initial propellant mass (kg)
VTK	Tank volume (m^3)
VTINT	Volume of internal tank construction (m^3)
PW	Pulse width (sec)
WSC	Spacecraft mass (kg)
L	Number of maneuvers to be considered
ULV	High pressure ullage volume (m^3)
DELV	Velocity increment for each maneuver (m/sec)
PRES	Repressurization point pressure (n/m^2)
PCMIN	Minimum operating chamber pressure (n/m^2)
PCIN	Base point chamber pressure (n/m^2)
DP	System tubing diameter (m)

TABLE I

PERFORMANCE INPUT DATA

Input Variable	Description
TMAX	Temperature of propellant at input (°R)
TLNCH	Ambient propellant temperature at launch (°R)
RGAS	Gas constant
G	Gravitation constant
DT	Computation loop time increment (sec)

component parameters must also be provided (for example, effective jet velocity vs. chamber pressure, nozzle thrust coefficient vs. chamber pressure).

The performance model deals with the flow restrictors (valves, orifice, filters) and sizes the trim orifice to achieve the desired base point parameters for beginning of life operation. For a given mission, the velocity increment schedule, the thruster pulse width and number of blowdown stages are the primary inputs. Efficiency factors for the thruster depend on both operating pressure and the pulse width. These factors are introduced during an iteration process in terms of the effective jet velocity versus chamber pressure and thruster efficiency versus pulse number.* The model iterates the pulsing performance until the required velocity increment for that (K^{th}) maneuver is reached. The model keeps track of the number of impulses required to accomplish the manuever.

The model iterates the gas expansion process with time (in terms of the blowdown conditions) to determine the propellant flow rate and calculates tank pressure, chamber pressure, propellant remaining, effective jet velocity, specific impulse, thrust, mass flow rate, total impulse, and burn time. When the propellant mass decreases to zero the iteration terminates. The program may also be terminated if the system goes below the minimum operating chamber pressure. All of the above parameters are printed out for each of the maneuvers.

*All curves are input in table form and a subroutine (STINT) is utilized to interpolate and return the correct values to the main program.

The output (see Appendix II) lists the important system operating parameters as a function of the maneuver. This allows the propulsion system performance to be monitored as a function of time and indicates whether or not the modeled system fulfills the mission requirements.

IV. RELIABILITY MODEL (2-7)

General

The term reliability, as used herein, denotes the probability that a component, subsystem, or system (as the case may be) will perform its intended functions adequately under defined operating conditions at a designated time for a specified operating period. Reliability predicts mathematically the equipments behavior under expected operating conditions. Reliability is synonymous with probability of survival or probability of success.

The starting point of reliability analysis is the determination or specification of the intended functions and successful operation or adequate performance (i.e., the definition of success). To judge adequate performance involves the observation of inadequate performance in operation; therefore, the observation of malfunctions and failures which violate the requirement for an "adequate performance." The frequency of failures and malfunctions is an important parameter used in the mathematical formulation of reliability. This parameter is referred to as the failure rate. It is usually measured in terms of the number of failures per unit time or cycle of operation.

The reliability model considers both random or chance failures and wear-out failures. Random or chance failures are characterized by a failure rate which is independent of time (i.e., a constant). Under this condition the probability distribution of time to failure is given by

$$f(t) = \lambda \exp(-\lambda t)$$

where the failure rate λ may be statistically estimated by experiment. Reliability, that is the probability that the device is functioning properly at time t, is given by

$$R(t) = 1 - \int_{\emptyset}^{t} f(t)\, dt = \exp(-\lambda t)$$

where λ is the constant chance failure rate and t is the operating time for which it is desired to determine the reliability, R(t). The exponential distribution is independent of device age. When the number of operating cycles is more meaningful than time, the reliability equation can be written as

$$R(c) = \exp(-\lambda t)$$

where R(c) is the reliability at c operating cycles, or the probability of survival through c cycles.

The normal density function is used to characterize wearout failures and is of the form

$$f(T) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T-M)^2}{2\sigma^2}\right]$$

where T is the component or device age, M is the expected or mean life, and σ is the standard deviation of the lifetimes. The reliability or probability of survival to time T is thus given by

$$R(T) = 1 - \int_{\emptyset}^{t} f(t)\, dt = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{t}^{\infty} \exp\left[-\frac{(t-M)^2}{2\sigma^2}\right] dt$$

Since chance and wearout phenomena usually occur simultaneously, it is necessary to evaluate their combined effects. Thus it is desired to evaluate the reliability of a mission having a duration of t hours and employing a component that has an age of T hours at the beginning of the mission. The combined probability of failure in t equals the probability of failing of chance and /or wearout in the interval t, at the age of T. Therefore,

$$Q(t) = Q_c(t) + F_w(t) - Q_c(t) \cdot F_w(t)$$

where Q(t) is the probability of failing at time t, $Q_c(t)$ is the probability of failing at time t due to chance failures, and $F_w(t)$ is the probability of failing at time t due to wearout. $F_w(t)$ is the a posteriori or conditional probability of a failure given survival to an age T. Therefore, it can be shown(2) that the probability of successful operation is given by

$$R(t) = e^{-\lambda t} \frac{\int_{T+t}^{\infty} e^{-(T-M)^2/2\sigma^2} dT}{\int_{T}^{\infty} e^{-(T-M)^2/2\sigma^2} dT}$$

A similar expression can be written in terms of cycles of operation.

System reliability is normally a calculated or computed quantity. It is based upon consideration of the components used in the system, how they are used, their modes of failure, and their probability of successful operation. Component reliabilities are normally obtained from tests which yield information about failure rates. System reliability is thus an extrapolation of the component reliabilities using a mathematical model to describe the system operation.

From basic probability theory it can be seen that the probability of successful operation of n components connected in series is

$$R_s(t) = R_1(t) \cdot R_2(t) \cdots R_n(t) = \exp\left(-\sum_{i=1}^{n} \lambda_i t\right)$$

This is called the "product law of reliabilities" for components operating in a serial arrangement. A similar equation can be developed for components operating in parallel (i.e., in order to have a system failure all parallel components must fail). Therefore the probability of no failures is

$$Q_p(t) = Q_1(t) \cdot Q_2(t) \cdot \cdots \cdot Q_n(t) = \prod_{i=1}^{n} Q_i(t)$$

where $Q_i(t)$ = probability of no failure = $1 - R_i(t)$. This is termed the "product law of unreliabilities in parallel operation." This can also be written as

$$R_p(t) = 1 - \prod_{i=1}^{n} \left[1 - R_i(t)\right]$$

where $R_p(t)$ represents the probability of successful operation (i.e., at least one of the components operating satisfactorily).

These are thus the basic reliability concepts which are utilized in the reliability model described in the following section.

Mathematical Model

The mathematical model to be described in detail computes the reliability of the monopropellant blowdown spacecraft auxiliary propulsion system illustrated in Figure 1. The model establishes the probability of performing each of a series of orbit corrections. The model is based upon the following assumptions:

a. The propulsion system consists of two symmetric half-systems which are interconnected through a valve system (normally closed). The interconnecting valve system is opened when one of the components in the thruster system (fill valve, pressure transducer, lines, filter, orifice, valve system, thruster) in use fails.

b. The valve systems which control the propellant flow (in series with the propellant tanks) are normally closed and must therefore open to allow propellant flow.

c. Each half-system contains three propellant tanks with associated valve systems. All three valves are normally closed and are opened simultaneously to allow propellant flow. Therefore, when there is no failure, propellant is drawn in equal amounts from the three propellant tanks.

d. The useable propellant of a single half-system is expended before the second half-system is utilized. This implies that repressurization of a single half-system is performed prior to using the second half-system.

e. If a leak develops in the pressurant system, the associated half-system propellant system fails.

Definitions of all input variables (for the reliability model) are given in Table II.

As discussed previously, the reliability model is designed to interface with the performance model. This imposes several constraints upon the reliability model. The performance model is implemented such that the performance of each half-system is evaluated independently. Thus the performance model must be cycled through twice - once for each half-system. When the first half-system is being evaluated HALFZ = 1 and when the second half-system is being evaluated HALFZ = 2.

Since the total propellant mass is distributed equally between the two half-systems,

$$PMO = PMO/2$$

<u>When</u> HALFZ = 1

<u>Then</u> WSC = as input

$PM1_k = PM_k$

$PM2_k = PMO$

TABLE II

RELIABILITY MODEL - INPUT DATA

Term	Dimension	Max. Value	Definition
TIMEZ (K)	1ØØ	XXXX.XX	Time (days) of occurance of K orbit correction.
NBZ	1	XX	Average number of brazed joints per thruster engine assembly.
NPZ	1	XX	Two symetric half-systems are considered with each half system consisting of three propellant tank groups. NPZ represents the number of propellant tanks per group.
NS1Z	1	XX	Number of parallel squib valves in high pressure system.
NS2Z	1	XX	Number of parallel squib valves in half-system connecting value system. When CONVZ=SOL then set NS2Z=0.
NSCZ	1	XX	Number of catalyst screens per thruster.
NTZ	1	XX	Number of high pressure tanks per half-system.
NWHPZ	1	XXX	Number of weld connections (per half-system) between the high pressure squib valve and the pressurant and propellant tanks.
NWPZ	1	XXX	Number of weld connections (per propellant tank sys.) between propellant tank and propellant tank solenoid valve system.
NWTZ	1	XXX	Number of weld connections (per half-system) between propellant tank solenoid valve systems and thruster.

TABLE II

RELIABILITY MODEL - INPUT DATA (contd)

Term	Dimension	Max. Value	Definition
VSC	1	"S", "DS", "DP", "Q", "QC"	Specification of type of valve system configuration to be used for the half-system connecting solenoid valve system. Only required when CONVZ="SOL".
VSP	1	"S", "DS", "DP", "Q", "QC"	Specification of type valve system configuration to be used for the propellant solenoid valve system.
VST	1	"S", "DS", "DP", "Q", "QC"	Specification of type of valve system configuration to be used for the thruster solenoid value system.
CONVZ	1	"SQ" or "SOL"	Specification of the type of valve to be used for connecting the two half-systems. "SQ" refers to squib and "SOL" refers to solenoid.
SPFVZ	1	"Y" or "N"	When SPFVZ = Y, a single propellant fill valve will be used for each half-system. When SPFVZ=N, a single propellant fill valve will be used for each propellant tank.
MBZ	1	XXX	Average or mean number of cycles for bladder failure rate due to wear out phenomena.
STDZ	1	XXX	Standard deviation (cycles) of bladder wear out failures.
PFSZ	1	.XXXXXX	Probability of a squib firing successfully when required.
LCZ	1	XXX.XXXX	Random or chance failure rate of valve caps (failures/10^6 hours).

TABLE II

RELIABILITY MODEL - INPUT DATA (contd)

Term	Dimension	Max. Value	Definition
LCLZ	1	XXX.XXXX	Randon or chance failure rate of solenoid valve for failing in a closed position (failure/10^6 cycles).
LOPZ	1	XXX.XXXX	Random or chance failure rate of solenoid valve for failing in an open position (failures/10^6 cycles).
LVSZ	1	XXX.XXXX	Random or chance failure rate of solenoid valve for excessive leakage past the valve seat (failures/10^6 hours).
LVZ	1	XXX.XXXX	Random or chance failure rate of fill valves (quick disconnect) (failures/10^6 hours).
LWZ	1	XXX.XXXX	Random or chance failure rate of welded connections (failures/10^6 hours).
LPZ	1	XXX.XXXX	Random or chance failure rate of pressure transducer (failure/10^6 hours).
LFZ	1	XXX.XXXX	Random or chance failure rate of filter media (failure/10^6 hours).
LBRZ	1	XXX.XXXX	Random or chance failure rate of brazed joints (failures/10^6 hours).
LSCZ	1	XXX.XXXX	Random or chance failure rate of catalyst envelope screens (failures/10^6 hours).
LBZ	1	XXX.XXXX	Random or chance failure rate of bladder (failures/10^6 hours).

__When__ HALFZ = 2

__Then__ $WSC = WSC + PM1_k$ Where $PM1_{\emptyset} = PMO$

$PM1_k = PM1_{k-1}$

Prior to output, set $PM_k = PM1_k + PM2_k$

WSC is the mass of the spacecraft, PM_k is the propellant remaining at the completion of the K^{th} orbit correction in the half-system under consideration, and $PM1_k$ and $PM2_k$ represent the propellant in the first and second half-systems, respectively. It should be noted that when HALFZ = 2, the spacecraft mass must be initialized to take into account propellant remaining in the first half-system.

A schedule of velocity increments for each orbit correction is a necessary input for the performance computations. Similarly, the time ($TIMEZ_k$) of each of the K orbit corrections is a necessary input for the reliability computations. Since the input data is specified in days and the computations are performed in terms of hours,

$$TIMEZ_k = 24.\emptyset \cdot TIMEZ_k$$

The performance model keeps track of which half-system is in use. The determination of the half-system in use is based upon the assumption that a half-system will be used until all usable propellant is expended. This includes the repressurization cycle. Therefore,

__When__ first half-system is in use

__Then__ HALFZ = 1

__When__ second half-system is in use

__Then__ HALFZ = 2

It is necessary, as will be seen in the following pages, to have knowledge as to when repressurization takes place. To achieve this the variable

MODE is defined. MODE is equal to zero prior to repressurization and equal to 2 after repressurization. MODE1 and MODE2 refer to the repressurization status of half-systems 1 and 2 respectively. The value of MODE is available from the performance portion of the model. Thus,

<u>When</u> HALFZ = 1 <u>and</u> MODE = ∅

<u>Then</u> MODE1 = ∅ <u>and</u> MODE2 = ∅

<u>When</u> HALFZ = 1 <u>and</u> MODE = 2

<u>Then</u> MODE1 = 2 <u>and</u> MODE2 = ∅

<u>When</u> HALFZ = 2 <u>and</u> MODE = ∅

<u>Then</u> MODE1 = 2 <u>and</u> MODE2 = ∅

<u>When</u> HALFZ = 2 <u>and</u> MODE = 2

<u>Then</u> MODE1 = 2 <u>and</u> MODE2 = 2

It is assumed that all fill valves used in the system are capped and are of the quick disconnect type. In order to have a failure both the fill valve and the cap must fail. Therefore, the reliability of the fill valves, $RFVZ_k$, at the completion of the K^{th} orbit correction is

$$RFVZ_k = 1.\emptyset - \left[1.\emptyset - \exp(-LVZ \cdot TIMEZ_k \cdot 1\emptyset^{-6})\right] \cdot \left[1.\emptyset - \exp(-LCZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

where LVZ and LCZ are the chance failure rates of fill valves and valve caps (failures per $1\emptyset^6$ hours), respectively.

The reliability of the high pressure tank system, RTZ_k, is given by

$$RTZ_k = \exp\left[-NTZ \cdot LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

where it is assumed that the failure mode is due to leakage through the weld joints. NTZ and LWZ are the number of parallel high pressure tanks per half-system and the random or chance failure rate of welded connections (failures per $1\emptyset^{6}$ hours), respectively. Similarly the reliability of the propellant tank weld ring is

$$RPTZ_k = \exp\left[-LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6} \right]$$

The reliability of the squib valve system (SV1) attached to the high pressure tanks is given by

$$RSV1Z = 1.\emptyset - (1.\emptyset - PFSZ)^{NS1Z}$$

where PFSZ is the probability of a squib firing successfully when required and NS1Z is the number of squibs in parallel.

There are a number of connections in the system which consist of weld (or brazed) joints. The welded connections have been broken down into three groups namely (a) those between the squib valve (SV1) and the pressurant and propellant tanks, (b) those between the propellant tank and the associated solenoid valve system, and (c) those between the propellant tank solenoid valve system and the thruster. The reliability of these three groups of connections are

$$RLHPZ_k = \exp\left[-NWHPZ \cdot LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6} \right]$$

$$RLPPZ_k = \exp\left[-NWPZ \cdot LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6} \right]$$

$$RLTZ_k = \exp\left[-NWTZ \cdot LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6} \right]$$

where NWHPZ, NWPZ, NWTZ are the number of connections in each of the above three groups, respectively.

The reliability of the half-system connecting valve system depends upon whether squib or solenoid valves are used. When squib valves are used, i.e.,

<u>When</u> CONVZ = "SQ" (or not "SOL")

<u>Then</u>

$$RSV2Z_k = 1.\emptyset - (1.\emptyset - PFZ)^{NS2Z}$$

where NS2Z is the number of squib valves in parallel and CONVZ is the input variable which specifies whether a squib (SQ) or a solenoid (SOL) system is to be used.

The reliability of solenoid valves depends upon both time and the number of cycles of operation. The solenoid valve system used for the half-system valve requires only one cycle of operation, i.e., it is normally closed and is required to open only when the thruster system in use fails. The failure modes of a solenoid valve are failure to open when required, failure to close when required, and excessive leakage past the valve seat. It is assumed that leakage past the valve seat is time dependent and the other two failure modes are cycle dependent.

The probability of a single solenoid valve not failing closed in a single cycle of operation, RCSZ, is given by

$$RCSZ = \exp\left[-LCLZ \cdot 1\emptyset^{-6}\right]$$

and the probability of no open failure or leak past the valve seat in a single cycle of operation, $ROSZ_k$, is given by

$$ROSZ_k = \exp\left[-LOPZ \cdot 1\emptyset^{-6} - LVSZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

LCLZ and LOPZ are the random or chance failure rates (failures per $1\emptyset^6$ cycles) of a solenoid valve failing in a closed and open position, respectively. LVSZ is the failure rate (failures per $1\emptyset^6$ hours) of a solenoid valve due to excessive leakage past the valve seat.

The solenoid valves may be arranged in a number of different configurations. A number of configurations are considered by the reliability model; namely the single valve ("S"), dual series ("DS"),dual parallel ("DP"), quad system ("Q"), and quad connected ("QC") systems. These configurations are illustrated in Appendix III where reliability equations are derived in terms of the basic single valve reliability equations. Therefore, the reliability of the valve system is given by

<u>When</u> VSC = "S"

<u>Then</u>

$$RSOLCZ_k = ROSZ_k + RCSZ - 1.\emptyset$$

<u>When</u> VSC = "DS"

<u>Then</u>

$$RSOLCZ_k = RCSZ^2 - [1.\emptyset - ROSZ_k]^2$$

<u>When</u> VSC = "DP"

<u>Then</u>

$$RSOLCZ_k = ROSZ_k^{\,2} - [1.\emptyset - RCSZ]^2$$

<u>When</u> VSC = "Q"

<u>Then</u>

$$RSOLCZ_k = [1.\emptyset - (1.\emptyset - ROSZ_k^{\,2})]^2 - [1.\emptyset - RCSZ^2]^2$$

<u>When</u> VSC = "QC"

<u>Then</u>

$$RSOLCZ_k = [1.\emptyset - (1.\emptyset - RCSZ)^2]^2 - [1.\emptyset - ROSZ_k^{\,2}]^2$$

where VSC is the input variable which specifies the particular solenoid valve configuration to be used. It should be noted that RCSZ is not subscripted since only one cycle of operation is required.

The reliability of the pressure transducer is assumed to depend primarily upon the time of actual use. The time of actual use, TIM_k, is the thrust time* and is computed by the performance portion of the model. Thus, the reliability of the pressure transducer is given by

<u>When</u> HALFZ = 1

<u>Then</u>

$$RPD1Z_k = \exp\left[-LPZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6}\right]$$

$$RPD2Z_k = 1.\emptyset$$

<u>When</u> HALFZ = 2

<u>Then</u>

$$RPD1Z_k = RPD1Z_{k-1} \qquad \text{where } RPD1Z_\emptyset = 1.\emptyset$$

$$RPD2Z_k = \exp\left[-LPZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6}\right]$$

where LPZ is the random or chance failure rate (failure/$1\emptyset^6$ hours) of the pressure transducer. $RPD1Z_k$ and $RPD2Z_k$ are the reliabilities of the pressure transducers in half-systems 1 and 2, respectively.

It is assumed that the reliabiiity of the filter assembly, $RF1Z_k$ and $RF2Z_k$ for half-systems 1 and 2, respectively, are a function of both absolute time and use time. Absolute time must be considered because of the possibility of failure of a welded connection. Therefore, the reliability of the filter assemblies is given by

---

*Since the performance model considers each half-system seperately, TIM_k is the thrust time associated with the half-system being evaluated. TIM_k is initialized to zero after completion of the performance evaluation of the first half-system.

<u>When</u> HALFZ = 1

<u>Then</u>

$$RF1TZ_k = \exp\left[-LFZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6}\right]$$

$$RF1Z_k = RF1TZ_k \cdot \exp\left[-LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

$$RF2Z_k = \exp\left[-LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

<u>When</u> HALFZ = 2

<u>Then</u>

$$RF1TZ_k = RF1TZ_{k-1} \qquad \text{where } RF1TZ_\emptyset = 1.\emptyset$$

$$RF1Z_k = RF1TZ_k \cdot \exp\left[-LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

$$RF2Z_k = \exp\left[-LFZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6} - LWZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

where LFZ is the chance failure rate (failures/$1\emptyset^6$ hours) of the filter media.

The performance portion of the model computes the number of impulses or cycles (J_k) required to achieve the velocity increment of the k^{th} orbit correction. The total number of cycles of operation of half-systems 1 and 2 ($CYCL1Z_k$ and $CYCL2Z_k$, respectively) are thus given by

<u>When</u> HALFZ = 1

<u>When</u> k = 1

<u>Then</u> $CYCL1Z_k = J_k$

$CYCL2Z_k = \emptyset$

<u>When</u> k > 1

<u>Then</u> $CYCL1Z_k = CYCL1Z_{k-1} + J_k$

$CYCL2Z_k = \emptyset$

<u>When</u> HALFZ = 2

<u>When</u> k = 1

<u>Then</u> $CYCL1Z_k = \emptyset$

$CYCL2Z_k = J_k$

__When__ $k > 1$

__Then__ $CYCL1Z_k = CYCL1Z_{k-1}$

$CYCL2Z_k = CYCL2Z_{k-1} + J_k$

The reliability equations for the thruster solenoid valve systems are similar to the half-system connecting valve. The single exception is that the thruster solenoid valves will experience many cycles of operation. The probability of no closed failure of a single valve is

$$RC1Z_k = \exp\,[-LCLZ \cdot CYCL1Z_k \cdot 10^{-6}]$$

$$RC2Z_k = \exp\,[-LCLZ \cdot CYCL2Z_k \cdot 10^{-6}]$$

and the probability of no open failure or leak past the valve seat (of a single valve) is

$$RO1Z_k = \exp\,[-LOPZ \cdot CYCL1Z_k \cdot 10^{-6} - LVSZ \cdot TIMEZ_k \cdot 10^{-6}]$$

$$RO2Z_k = \exp\,[-LOPZ \cdot CYCL2Z_k \cdot 10^{-6} - LVSZ \cdot TIMEZ_k \cdot 10^{-6}]$$

where RC1Z AND RO1Z refer to the first half-system and RC2Z and RO2Z refer to the second half-system. As before, several different valve system types are allowed. These are specified by VST. The valve system reliability is given by RST1Z for the first half-system and RST2Z for the second half-system. Therefore (refer to Appendix III),

__When__ VST = "S"

__Then__

$$RST1Z_k = RO1Z_k + RC1Z_k - 1.0$$

$$RST2Z_k = RO2Z_k + RC2Z_k - 1.0$$

__When__ VST = "DS"

__Then__

$$RST1Z_k = RC1Z_k^{\,2} - [1.0 - RO1Z_k]^2$$

$$RST2Z_k = RC2Z_k^{\,2} - [1.0 - RO2Z_k]^2$$

__When__ VST = "DP"

__Then__

$$RST1Z_k = RO1Z_k^{\,2} - [1.\emptyset - RC1Z_k]^2$$

$$RST2Z_k = RO2Z_k^{\,2} - [1.\emptyset - RC2Z_k]^2$$

__When__ VST = "Q"

__Then__

$$RST1Z_k = [1.\emptyset - (1.\emptyset - RO1Z_k)^2]^2 - [1.\emptyset - RC1Z_k^{\,2}]^2$$

$$RST2Z_k = [1.\emptyset - (1.\emptyset - RO2Z_k)^2]^2 - [1.\emptyset - RC2Z_k^{\,2}]^2$$

__When__ VST = "QC"

__Then__

$$RST1Z_k = [1.\emptyset - (1.\emptyset - RC1Z_k)^2]^2 - [1.\emptyset - RO1Z_k^{\,2}]^2$$

$$RST2Z_k = [1.\emptyset - (1.\emptyset - RC2Z_k)^2]^2 - [1.\emptyset - RO2Z_k^{\,2}]^2$$

In a similar manner, the reliability of the pressurant and propellant tank solenoid valve system can be established.

__When__ VSP = "S"

__Then__

$$RSP1Z_k = RO1Z_k + RC1Z_k - 1.\emptyset$$

$$RSP2Z_k = RO2Z_k + RC2Z_k - 1.\emptyset$$

__When__ VSP = "DS"

__Then__

$$RSP1Z_k = RC1Z_k^{\,2} - [1.\emptyset - RO1Z_k]^2$$

$$RSP2Z_k = RC2Z_k^{\,2} - [1.\emptyset - RO2Z_k]^2$$

__When__ VSP = "DP"

__Then__

$$RSP1Z_k = RO1Z_k^{\,2} - [1.\emptyset - RC1Z_k]^2$$

$$RSP2Z_k = RO2Z_k^{\,2} - [1.\emptyset - RC2Z_k]^2$$

When VSP = "Q"

Then

$$RSP1Z_k = [1.\emptyset - (1.\emptyset - RO1Z_k)^2]^2 - [1.\emptyset - RC1Z_k{}^2]^2$$

$$RSP2Z_k = [1.\emptyset - (1.\emptyset - RO2Z_k)^2]^2 - [1.\emptyset - RC2Z_k{}^2]^2$$

When VSP = "QC"

Then

$$RSP1Z_k = [1.\emptyset - (1.\emptyset - RC1Z_k)^2]^2 - [1.\emptyset - RO1Z_k{}^2]^2$$

$$RSP2Z_k = [1.\emptyset - (1.\emptyset - RC2Z_k)^2]^2 - [1.\emptyset - RO2Z_k{}^2]^2$$

In the above equations, $RSP1Z_k$ refers to the first half-system and $RSP2Z_k$ refers to the second half-system and VSP is the input variable which specifies the type of valve configuration to be considered.

The thrusters contain a number of catalyst screens with failure rate LSCZ. The reliability of the catalyst screens is a function of usage time. The thruster also contains a number of brazed joints (failure rate given by LBRZ) and weld joints. The reliability of the two thrusters is given by $RTH1Z_k$ and $RTH2Z_k$. Therefore,

When HALFZ = 1

Then

$$RTHZ_k = \exp[-NSCZ \cdot LSCZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6}]$$

$$RTH1Z_k = RTHZ_k \cdot \exp[(-NBZ \cdot LBRZ \cdot TIMEZ_k - 2 \cdot LWZ \cdot TIMEZ_k) \cdot 1\emptyset^{-6}]$$

$$RTH2Z_k = \exp[(-NBZ \cdot LBRZ \cdot TIMEZ_k - 2 \cdot LWZ \cdot TIMEZ_k) \cdot 1\emptyset^{-6}]$$

When HALFZ = 2

Then

$$RTHZ_k = RTHZ_{k-1} \qquad \text{where } RTHZ_\emptyset = 1.\emptyset$$

$$RTH1Z_k = RTHZ_k \cdot \exp[(-NBZ \cdot LBRZ \cdot TIMEZ_k - 2 \cdot LWZ \cdot TIMEZ_k) \cdot 1\emptyset^{-6}]$$

$$RTH2Z_k = \exp[(-NBZ \cdot LBRZ \cdot TIMEZ_k - 2 \cdot LWZ \cdot TIMEZ_k - NSCZ \cdot LSCZ \cdot \frac{TIM_k}{36\emptyset\emptyset} \cdot 1\emptyset^{-6}]$$

The last component to be considered is the pressurant and propellant tank bladder. The function of the badder is to separate the pressurant and the propellant. The bladder can fail due to the random or chance failure rate, LBZ, of holes developing in the bladder. The bladder is also subject to wearout phenomena since the bladder is forced to contract and expand for several cycles of operation. Prior to the need for repressurization of the first half-system, that is

<u>When</u> MODE1 < 2

<u>Then</u>

$$RB1Z_k = \exp\left[-NPZ \cdot LBZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

$$RB2Z_k = RB1Z_k$$

When repressurization of the first half-system is required, the reliability equations become

<u>When</u> MODE1 = 2 <u>and</u> MODE2 < 2

<u>Then</u>

$$RB1Z_k = \left\{\exp\left[-NPZ \cdot LBZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]\right\} \cdot \left\{\int_2^{\infty}\left[\exp(-(AZ - MBZ)^2 / (2.\emptyset \cdot STDZ^2))\right] \cdot dAZ\right\} / \left\{\int_1^{\infty}\left[\exp(-(AZ - MBZ)^2 / (2.\emptyset \cdot STDZ^2))\right] \cdot dAZ\right\}$$

$$RB2Z_k = \exp\left[-NPZ \cdot LBZ \cdot TIMEZ_k \cdot 1\emptyset^{-6}\right]$$

where the ratio of the integrals indicates the probability of a second successful contract/expand cycle given that it survived the first. The first cycle is due to the initial filling of the tanks. When repressurization is required of the second half-system, the reliability equations are given by

__When__ MODE1 = 2 __and__ MODE2 = 2

__Then__

$$RB1Z_k = \left\{ \exp\left[-NPZ \cdot LBZ \cdot TIMEZ_k \cdot 10^{-6}\right]\right\}$$
$$\cdot \left\{ \int_2^{\infty} \left[\exp\left(-(AZ - MBZ)^2 / (2.0 \cdot STDZ^2)\right)\right] \cdot dAZ \right\}$$
$$/ \left\{ \int_1^{\infty} \left[\exp\left(-(AZ - MBZ)^2 / (2.0 \cdot STDZ^2)\right)\right] \cdot dAZ \right\}$$

$$RB2Z_k = RB1Z_k$$

In the above equations it is assumed that wearout phenomena are adequately characterized by the normal distribution where MBZ is the expected number of cycles and STDZ is the standard deviation of the number of cycles to failure.

Before getting into the general system reliability equations, two configuration decisions must be made. A decision (SPFVZ) must be made as to whether the configuration will contain a single propellant fill valve for each half-system or a single valve per propellant tank. A decision (CONVZ) must also be made as to the type of valve system to be used for the half-system connecting valve. Therefore,

__When__ SPFVZ = "Y" (i.e., a single propellant fill valve is to be used for each half-system)

__Then__

$$RFV1Z_k = 1.0$$

$$RFV2Z_k = RFVZ_k$$

__When__ SPFVZ = "N" (i.e., a single propellant fill valve is to be used for each propellant tank)

__Then__

$$RFV1Z_k = (RFVZ_k)^{NPZ}$$

$$RFV2Z_k = 1.0$$

When CONVZ = "SQ" or not "SOL" (i.e., specifications of the type of valve system connecting the two half-systems)

Then

$BZ_k = RSV2Z_k$

When CONVZ = "SOL"

Then

$BZ_k = RSOLCZ_k$

The overall system reliability can now be determined in terms of the reliability of the various components and the specific arrangement of the components. In general three basic situations are considered:

(a) repressurization is not required for either half-system

(b) repressurization is required for the first half-system,

(c) repressurization is required for both half-systems.

The probability of having a working thruster system available for use when using the first half-system is

$$RE1Z_k = 1.\emptyset - \left\{1.\emptyset - RFV2Z_k \cdot RPD1Z_k \cdot RF1Z_k \cdot RST1Z_k \cdot RTH1Z_k \cdot RLTZ_k\right\} \cdot \left\{1.\emptyset - BZ_k \cdot RFV2Z_k \cdot RPD2Z_k \cdot RF2Z_k \cdot RST2Z_k \cdot RTH2Z_k \cdot RLTZ_k\right\}$$

and represents the probability of thruster system #1, or thruster system #2 and half-system interconnecting valve functioning properly. Similarly, the probability of having a working thruster system available for use when using the second half-system is

$$RE2Z_k = 1.\emptyset - \left\{1.\emptyset - BZ_k \cdot RFV2Z_k \cdot RPD1Z_k \cdot RF1Z_k \cdot RST1Z_k \cdot RTH1Z_k \cdot RLTZ_k\right\} \cdot \left\{1.\emptyset - RFV2Z_k \cdot RPD2Z_k \cdot RF2Z_k \cdot RST2Z_k \cdot RTH2Z_k \cdot RLTZ_k\right\}$$

The probability of successful operation of a propellant tank and its associated fill valve, solenoid valve, and lines is given by $R1Z_k$ for the first half-system and $R2Z_k$ for the second half-system. Therefore,

$R1Z_k = RB1Z_k \cdot RFV1Z_k \cdot RSP1Z_k \cdot RLPPZ_k$

$R2Z_k = RB2Z_k \cdot RFV2Z_k \cdot RSP2Z_k \cdot RLPPZ_k$

$Q1Z_k = 1.\emptyset - R1Z_k$

$Q2Z_k = 1.\emptyset - R2Z_k$

The reliability of the high pressure tank, fill valve, and squib valve system is given by $DEL1Z_k$ and $DEL2Z_k$ and depends upon the need for repressurization. Therefore,

<u>When</u> MODE1 < 2

<u>Then</u>

$DEL1Z_k = 1.\emptyset$

$DEL2Z_k = 1.\emptyset$

<u>When</u> MODE1 = 2 <u>and</u> MODE2 < 2

<u>Then</u>

$DEL1Z_k = RFVZ_k \cdot RTZ_k \cdot RSV1Z$

$DEL2Z_k = 1.\emptyset$

<u>When</u> MODE1 = 2 <u>and</u> MODE2 = 2

<u>Then</u>

$DEL1Z_k = RFVZ_k \cdot RTZ_k \cdot RSV1Z$

$DEL2Z_k = DEL1Z_k$

Since there are multiple propellant and pressurant tanks and redundant thruster systems, the reliability of the system is a function of the propellant requirement as a function of time. The model computes the propellant required for each maneuver and thence establishes the reliability in terms of the probability of the propellant being available. The possible ways of achieving six different outcomes, or propellant levels, are considered. Specifically, the probability of having 1/6, 1/3, 1/2, 2/3, 5/6, and full propellant capability at any instant of time is determined. The way of achieving these outcomes is illustrated in Figures 2-7 where the following nomenclature applies:

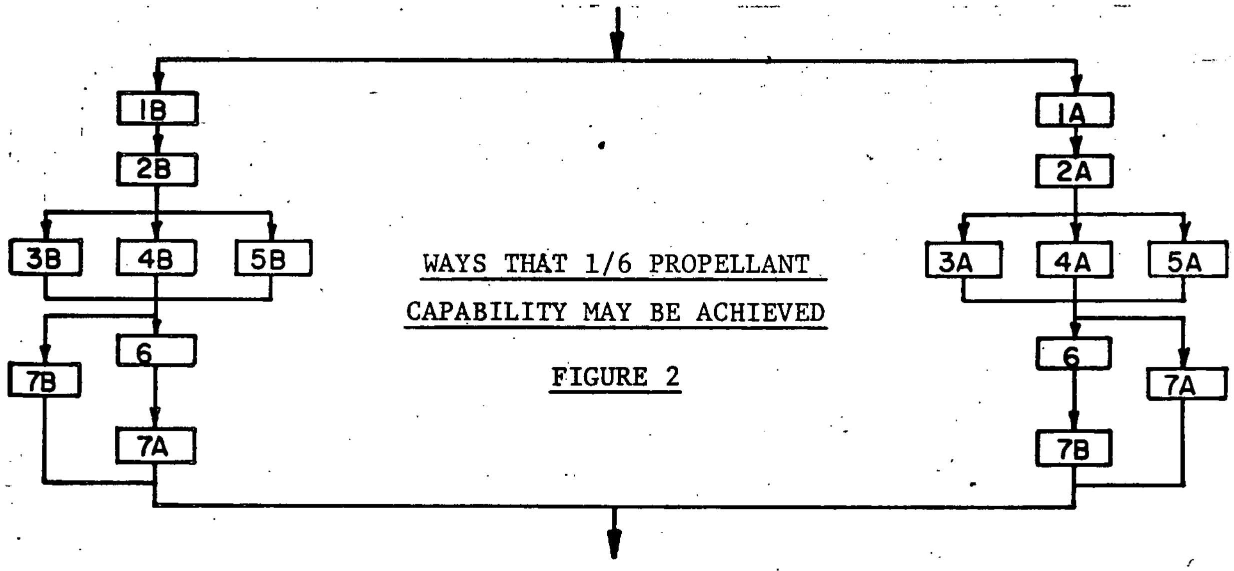
- A & B - refers to half-system one and two.
- 1A, & 1B - refers to high pressure tank system, fill valve, and squib valve system.
- 2A, & 2B - refers to fill valve, lines between squib and propellant tanks, and propellant tanks.
- 3A, 4A, 5A, 3B, 4B, 5B - refers to the propellant tank bladder, fill valve (A), solenoid valve system, and lines between propellant tanks and fill valve (B). There are six tank systems; three per half.
- 6 - refers to the half-system connecting valve system.
- 7A, 7B - refers to fill valve (B), pressure transducer, filter, orifice, solenoid valve system, and thruster.

Using figures 2-7 as a guide, the probability of having different levels of propellant available when needed and functioning properly can be established as

$$GZ_k = RLHPZ_k \cdot RFVZ_k \cdot RPTZ_k$$

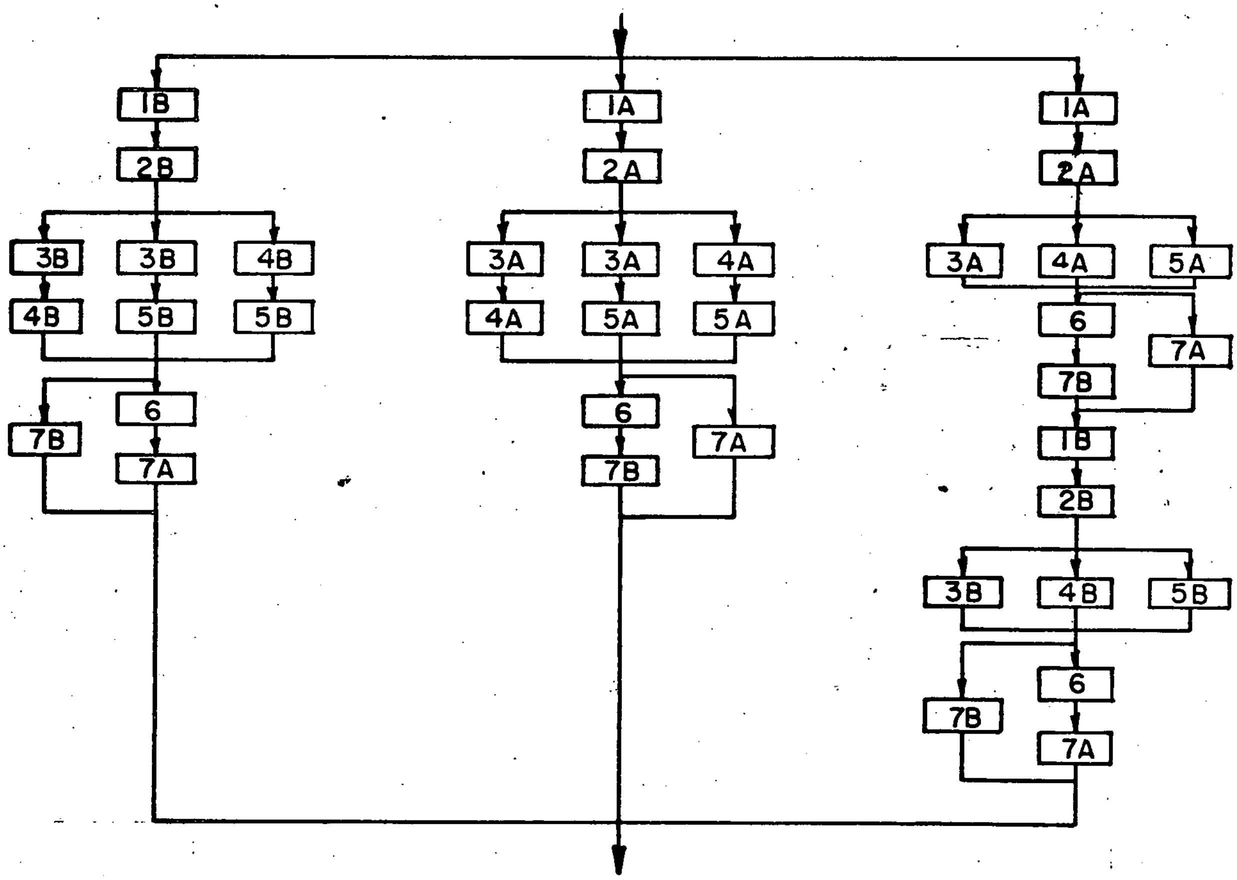
$$\begin{aligned} PFZ_{k,1} = \left\{3.\emptyset \cdot GZ_k\right\} \cdot \Big\{ & R1Z_k \cdot Q1Z_k^{\,2} \cdot RE1Z_k \cdot DEL1Z_k \cdot [1.\emptyset - GZ_k \cdot DEL2Z_k \\ & + GZ_k \cdot DEL2Z_k \cdot Q2Z_k^{\,3}] + R2Z_k \cdot Q2Z_k^{\,2} \cdot RE2Z_k \cdot [1.\emptyset - GZ_k \cdot DEL1Z_k \\ & + GZ_k \cdot DEL1Z_k \cdot Q1Z_k^{\,3}]\Big\} \end{aligned}$$

$$\begin{aligned} PFZ_{k,2} = \left\{3.\emptyset \cdot GZ_k\right\} \cdot \Big\{ & R1Z_k^{\,2} \cdot Q1Z_k \cdot RE1Z_k \cdot DEL1Z_k \cdot [1.\emptyset - GZ_k \cdot DEL2Z_k \\ & + GZ_k \cdot DEL2Z_k \cdot Q2Z_k^{\,3}] + R2Z_k^{\,2} \cdot Q2Z_k \cdot RE2Z_k \cdot DEL2Z_k \cdot [1.\emptyset - GZ_k \\ & \cdot DEL1Z_k + GZ_k \cdot DEL1Z_k \cdot Q1Z_k^{\,3}] + 3.\emptyset \cdot R1Z_k \cdot R2Z_k \cdot Q1Z_k^{\,2} \\ & \cdot Q2Z_k^{\,2} \cdot RE1Z_k \cdot RE2Z_k \cdot DEL1Z_k \cdot DEL2Z_k \cdot GZ_k\Big\} \end{aligned}$$



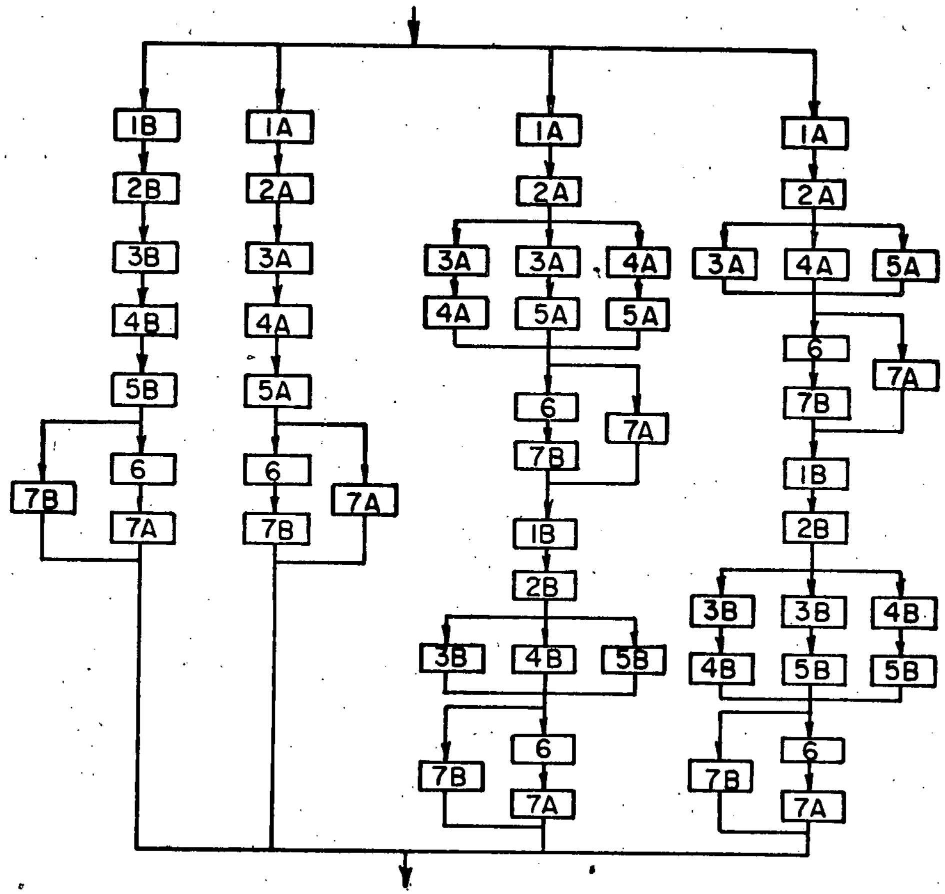
WAYS THAT 1/6 PROPELLANT CAPABILITY MAY BE ACHIEVED

FIGURE 2



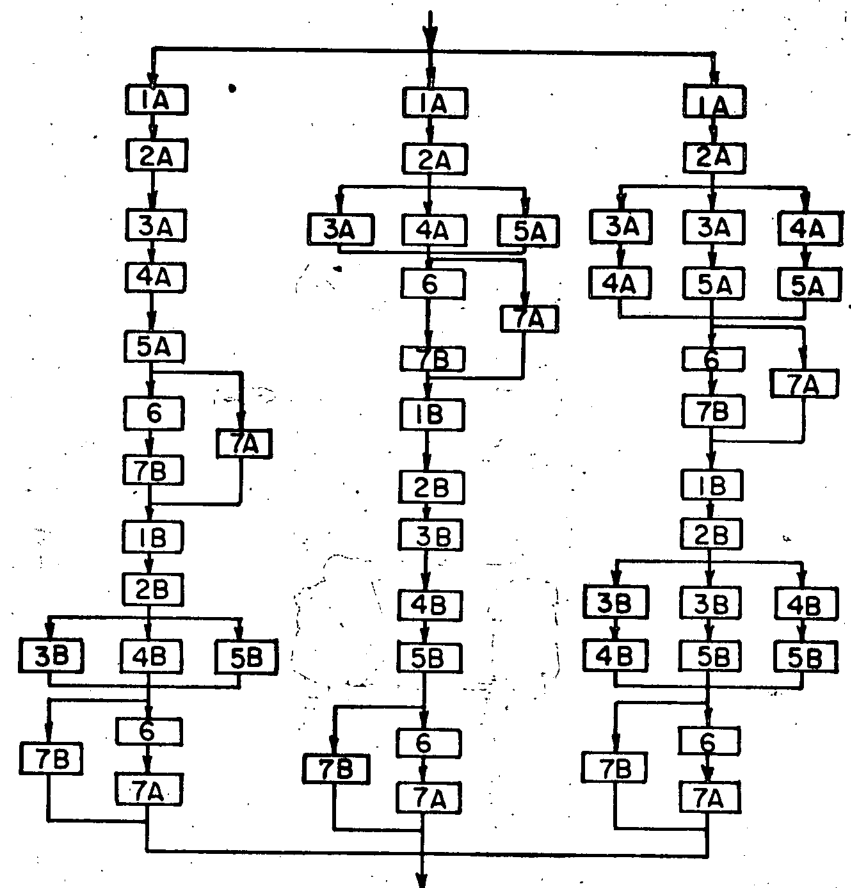
WAYS THAT 1/3 PROPELLANT CAPABILITY MAY BE ACHIEVED

FIGURE 3



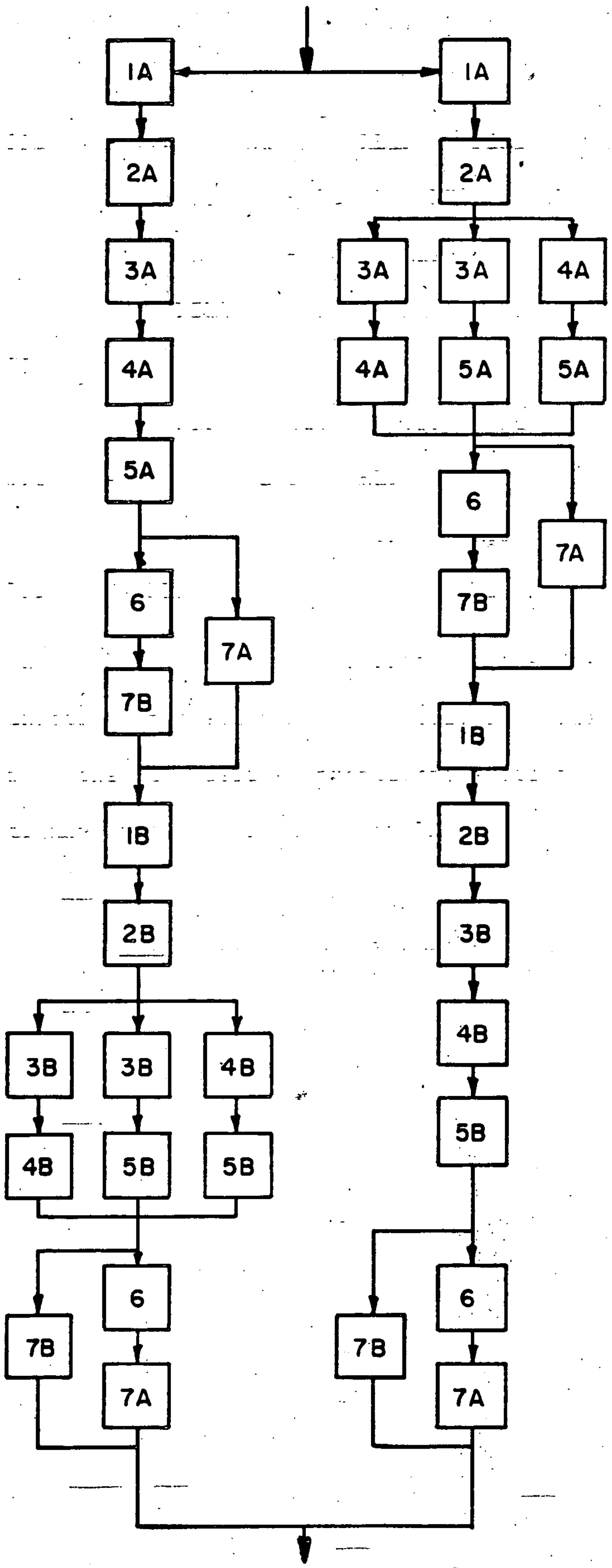
WAYS THAT 1/ 2 PROPELLANT CAPABILITY MAY BE ACHIEVED

FIGURE 4

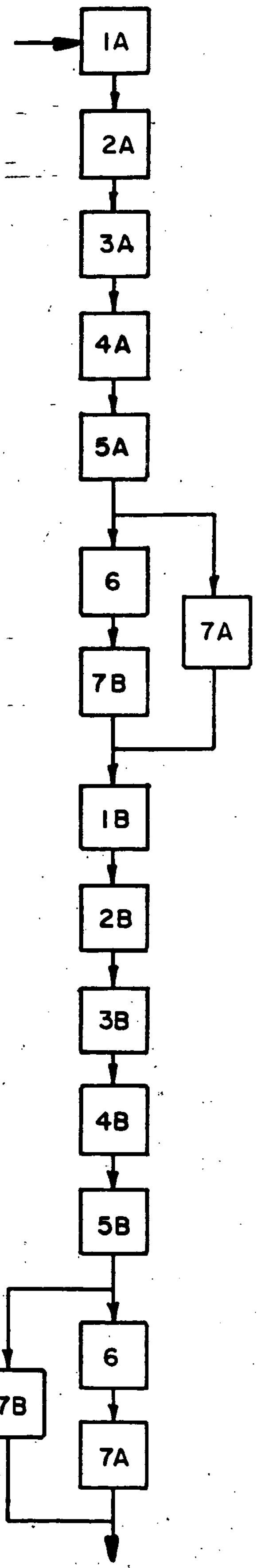


WAYS THAT 2/3 PROPELLANT CAPABILITY MAY BE ACHIEVED

FIGURE 5



WAYS THAT 5/6 PROPELLANT CAPABILITY MAY BE ACHIEVED
FIGURE 6



WAYS THAT TOTAL PROPELLANT CAPABILITY MAY BE ACHIEVED
FIGURE 7

$$PFZ_{k,3} = \{GZ_k\} \cdot \{R1Z_k^3 \cdot RE1Z_k \cdot DEL1Z_k \cdot [1.\emptyset - GZ_k \cdot DEL2Z_k + GZ_k \cdot DEL2Z_k \cdot Q2Z_k^3] + R2Z_k^3 \cdot RE2Z_k \cdot DEL2Z_k \cdot [1.\emptyset - GZ_k \cdot DEL1Z_k + GZ_k \cdot DEL1Z_k \cdot Q1Z_k^3] + 9.\emptyset \cdot R1Z_k \cdot R2Z_k \cdot Q2Z_k \cdot RE1Z_k \cdot RE2Z_k \cdot DEL1Z_k \cdot Q1Z_k \cdot DEL2Z_k \cdot GZ_k \cdot [R1Z_k \cdot Q2Z_k + Q1Z_k \cdot R2Z_k]\}$$

$$PFZ_{k,4} = \{3.\emptyset \cdot RE1Z_k \cdot RE2Z_k \cdot GZ_k^2 \cdot DEL1Z_k \cdot DEL2Z_k \cdot R1Z_k \cdot R2Z_k\} \cdot \{R1Z_k^2 \cdot Q2Z_k^2 + Q1Z_k^2 \cdot R2Z_k^2 + 3.\emptyset \cdot R1Z_k \cdot Q1Z_k \cdot Q2Z_k \cdot R2Z_k\}$$

$$PFZ_{k,5} = \{3.\emptyset \cdot RE1Z_k \cdot RE2Z_k \cdot GZ_k^2 \cdot DEL1Z_k \cdot DEL2Z_k \cdot R1Z_k^2 \cdot R2Z_k^2\} \cdot \{R1Z_k \cdot Q2Z_k + Q1Z_k \cdot R2Z_k\}$$

$$PFZ_{k,6} = RE1Z_k \cdot RE2Z_k \cdot GZ_k^2 \cdot DEL1Z_k \cdot DEL2Z_k \cdot R1Z_k^3 \cdot R2Z_k^3$$

where $PFZ_{k,i}$ is the probability of the system functioning properly and having exactly i propellant tanks available. Therefore, the probability of having more than the desired propellant available when needed and the system functioning properly is given by PMZ_k.

__When__ HALFZ = 1

__Then__ $PMZ_k = PM1_k + PM2_k$

__When__ HALFZ = 2

__Then__ $PMZ_k = PM2_k$

__When__ $PMZ_k \geq \frac{5.\emptyset}{6.\emptyset} \cdot PMO \cdot 2.\emptyset$ (i.e., at least 1 propellant tank available)

__Then__ $PZ_k = \sum_{IZ=1}^{6} PFZ_{k,IZ}$

__When__ $\frac{5.\emptyset}{6.\emptyset} \cdot PMO \cdot 2.\emptyset > PMZ_k \geq \frac{2.\emptyset}{3.\emptyset} \cdot PMO \cdot 2.\emptyset$ (i.e., at least 2 propellant tanks available)

__Then__ $PZ_k = \sum_{IZ=2}^{6} PFZ_{k,IZ}$

__When__ $\frac{2.\emptyset}{3.\emptyset} \cdot PMO \cdot 2.\emptyset > PMZ_k \geq \frac{1.\emptyset}{2.\emptyset} \cdot PMO \cdot 2.\emptyset$ (i.e., at least 2 propellant tanks available)

__Then__ $PZ_k = \sum_{IZ=3}^{6} PFZ_{k,IZ}$

When $\frac{1.\emptyset}{2.\emptyset} \cdot PMO \cdot 2.\emptyset > PMZ_k \geq \frac{1.\emptyset}{3.\emptyset} \cdot PMO \cdot 2.\emptyset$ (i.e., at least 4 propellant tanks available)

Then $PZ_k = \sum_{IZ=4}^{6} PFZ_{k,IZ}$

When $\frac{1.\emptyset}{3.\emptyset} \cdot PMO \cdot 2.\emptyset > PMZ_k \geq \frac{1.\emptyset}{6.\emptyset} \cdot PMO \cdot 2.\emptyset$ (i.e., at least 5 propellant tanks available)

Then $PZ_k = \sum_{IZ=5}^{6} PFZ_{k,IZ}$

When $\frac{1.\emptyset}{6.\emptyset} \cdot PMO \cdot 2.\emptyset > PMZ_k \geq \emptyset$ (i.e., all 6 propellant tanks available)

Then $PZ_k = PFZ_{k,6}$

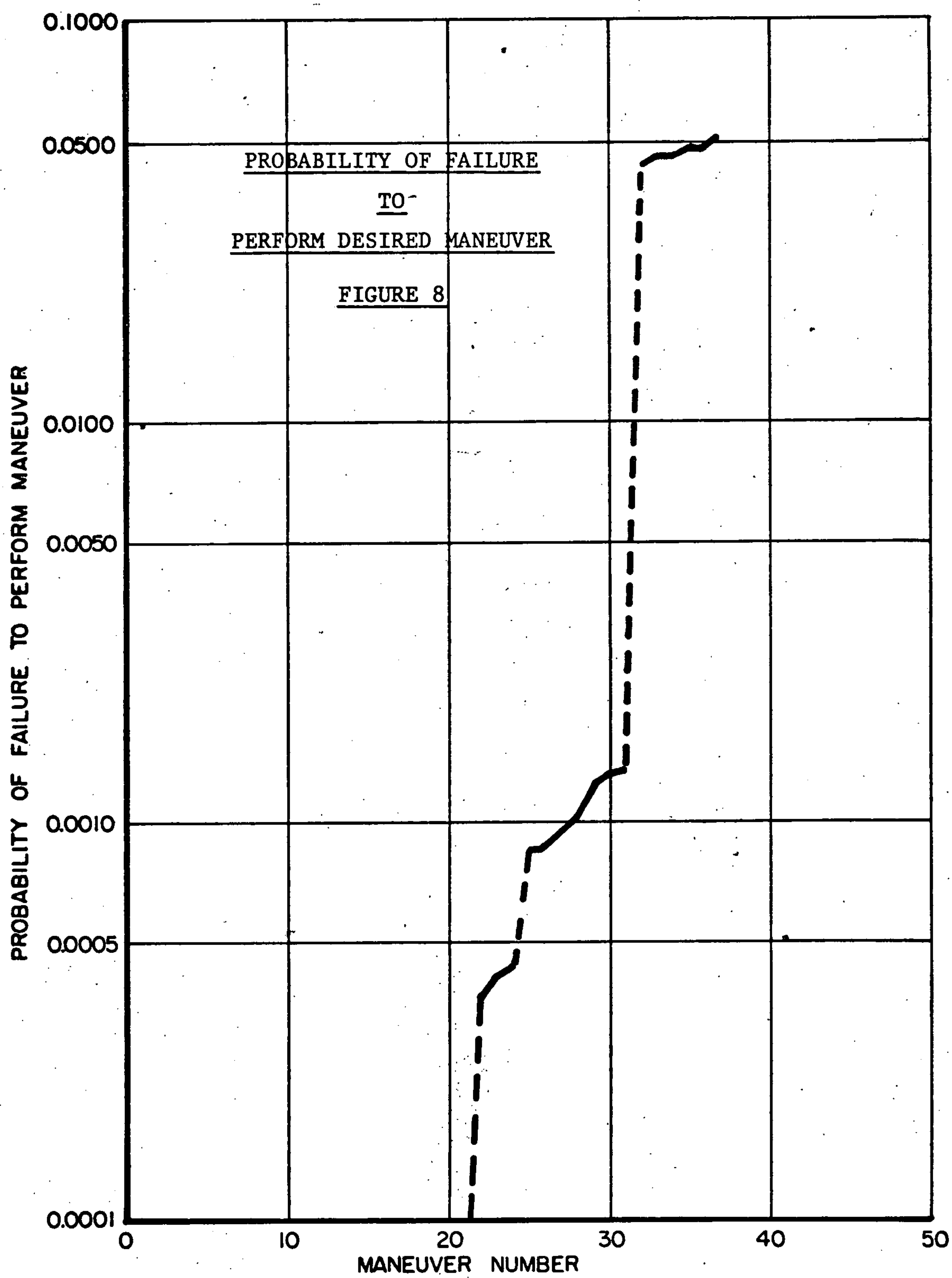
In other words, PMZ_k is the reliability of the orbit correction system as a function of the orbit correction maneuver. The overall system reliability takes into account the specific operations of the auxiliary propulsion system; i.e., thrust duration, number of impulses to achieve desired velocity increments, magnitude and timing of velocity increments, etc. The reliability model considers each of the k maneuvers as a different outcome and establishes the probability of achieving each outcome taking into account the various ways in which the outcome can be achieved.

Typical Results

In order to demonstrate the type of results available from this model, a typical mission profile was assumed along with propulsion system characteristics. The set of input data is printed out and is attached as part of Appendix II. The mission evaluated consisted of 39 orbit corrections spaced over a period of approximately one year. Several of the orbit corrections are spaced at intervals of one-half an orbit period while others are seperated by tens of days. The computed results are also shown in Appendix II. Only 37 maneuvers are possible due to the performance of the propulsion system. The results of the reliability computations are summarized in Figure 8 which indicates the probability of failing to perform the desired maneuver in terms of the maneuver number. This is one minus the probability of success or the "unreliability" of the system. The specific numbers are unimportant. What is important is the rapid manner in which the probability of a failure increases as the number of maneuvers increases. The reason for this is that early in the mission only one or more propellant tanks need function successfully. In the latter stages of the mission, maneuvers can only be performed if all six propellant tanks have and continue to function properly! The large propability increments (k=21, 25, 32) are due to the requirement of additional propellant tanks being available. The small changes in the probability of failure between maneuvers no. 25 & 26, 29 & 30, etc., are due to the fact that the maneuvers occur within a time interval of 1/2 an orbit period (i.e., a perigee followed by an apogee correction).

GENERAL DISCUSSION

A general methodology for evaluating the reliability of a propulsion system as a function of time or mission objective has been described. The method requires the interaction of a propulsion system performance model with a reliability model. The performance model provides basic timing and cycle data required for the reliability computations and the reliability model provides the basic structure for the manner in which the various mission outcomes or objectives can be achieved. The reliability model thence performs the reliability computations, in terms of


PROBABILITY OF FAILURE
TO
PERFORM DESIRED MANEUVER
FIGURE 8
PROBABILITY OF FAILURE TO PERFORM MANEUVER
0.1000
0.0500
0.0100
0.0050
0.0010
0.0005
0.0001
0
10
20
30
40
50
MANEUVER NUMBER

specific equipment configurations, providing probability of success data for achieving each of the desired mission objectives.

When a mission consists of multiple time distributed mission objectives (for example, the previously discussed orbit correction system), the normal procedure for evaluating system reliability at a single point in time loses significance. The reliability of the system after t hours is still an important indicator of overall system performance. However, it is also important to establish the probability of successfully achieving each desired mission objective within the t hours.

The availability of data indicating the probability of successfully achieving each of the desired mission objectives can provide valuable insights for the comparison of system alternatives. In particular, if the relative importance of the various mission objectives is established, a figure of merit can be computed and used to assist with the ranking and comparison of alternatives. The figure of merit is of the form

$$F = \sum_{k} PZ_k \cdot IMP_k$$

where IMP_k is the relative importance of achieving the k^{th} mission objective. It is normally desirable to chose that system configuration which maximizes F. When cost constraints become important, the above can be utilized to establish a measure of cost effectiveness (CE) such that

$$CE = \frac{F}{C}$$

where C is the total cost associated with the system configuration under study. The objective is to chose that system configuration which maximizes the value of CE. When costs are spread over a significant period of time, present value concepts should be used so as to take into account the timing of expenditure of funds.

REFERENCES

(1) Lake, R., "A Mathematical Model for the Performance of a Spacecraft Auxiliary Propulsion System," RCA PRAE-71-TR-014 dated May 21, 1971.

(2) Greenberg, J., "Space System Comparison and Evaluation - Basic Concepts", ASAR Memo No. 71, Aerospace Systems Laboratory, Princeton University 28 May, 1971.

(3) Holcomb, L.B., "Satellite Auxiliary-Propulsion Selection Techniques," NASA Technical Report 32-1505, Jet Propulsion Laboratory, Nov. 1, 1970.

(4) Rau, J.G., Optimization and Probability in Systems Engineering Van Nostrand Reinhold Co., 1970.

(5) Polovko, A.M., Fundamentals of Reliability Theory, Academic Press, 1968.

(6) Barlow, R., Proschan, F., Mathematical Theory of Reliability, John Wiley & Sons, Inc. 1967.

(7) Bazovsky, I., Reliability Theory and Practice, Prentice-Hall, Inc., 1961.

APPENDIX A: Program Listing

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      REAL LVZ,LCZ,NTZ,LWZ,NWHPZ,LCLZ,LOPZ,LVSZ,LPZ,LFZ,
     1NSCZ,LSCZ,NBZ,LBRZ,NPZ,LBZ,NWTZ,NWPZ
      REAL*8 MBZ,STDZ,RT2S,ERFC2,ERFC1,ERFC21,DERFC
      INTEGER CYCL1Z,CYCL2Z
      INTEGER HALFZ
      DATAKS/'S'/,KDS/'DS'/,KDP/'DP'/,KQ/'Q'/,KN/'N'/,KSQ/'SQ'/
      DIMENSION ORF(10),DELP(10),DELPE(10),DELV(100),CD(10),A(10),
     1STI(100),STIME(100),SDELV(100),STDEL(100),STIM(100)
      DIMENSION RFVZ(100),RTZ(100),RPTZ(100),RLHPZ(100),
     1TIMEZ(100),RF1TZ(100),RPD1Z(100),RPD2Z(100),PFZ(100,6),
     2RF1Z(100),RF2Z(100), CYCL1Z(100),CYCL2Z(100),PZ(100),
     3RE1Z(100),RE2Z(100),RSP1Z(100),RST1Z(100),RST2Z(100),
     4RSP2Z(100),RTH1Z(100),RTH2Z(100),RB1Z(100),RB2Z(100),BZ(100),
     5RLPPZ(100),RLTZ(100),RTHZ(100)
      NAMELIST/INDATL/VEJIN,Z,CFIN,DEN,AT,PFIL,STG,CD,A,DT,DTI,P,DPT,
     1PMO,VTK,VTINT,PW,WSC,L,ULV,DELV,PRES,PCMIN,PCIN,DP,TMAX,TLNCH,
     2RGAS,G
      NAMELIST/INDATG/TIMEZ,LVZ,LCZ,NTZ,LWZ,NS1Z,PFSZ,
     1NWHPZ,CONVZ,NS2Z,LCLZ,LOPZ,LVSZ,VSC,LPZ,LFZ,NSCZ,
     2LSCZ,NBZ,LBRZ,NPZ,LBZ,MBZ,STDZ,NWTZ,NWPZ,SPFVZ,VSC,VST,VSP
      WRITE(6,70)
   70 FORMAT('1INPUT DATA')
C FOR STEADY STATE MODE USE PW=1.0E+10 SEC.
      READ (5,INDATL)
      WRITE(6,INDATL)
      READ(5,INDATG)
      WRITE(6,INDATG)
C  AT INPUT DIVIDE THE FOLLOWING VARIABLES BY 2
      PMO=PMO/2.
      VTK=VTK/2.
      ULV=ULV/2.
      VTINT=VTINT/2.
C  COMPLEMENT OF THE ERROR FUNCTION
      RT2S=1.414 13562 3731D0*STDZ
      ERFC2=DERFC((2.D0-MBZ)/RT2S)
      ERFC1=DERFC((1.D0-MBZ)/RT2S)
      ERFC21=ERFC2/ERFC1
      CALL STINT(0.,0.,0.,0.,-1,NGRIPE,0,0)
      IF(NGRIPE.NE.0)GO TO 100
      WRITE(6,86)
   86 FORMAT(' END DATA',///)
      WRITE(6,83)
   83 FORMAT(' LIST OF VARIABLES WITH CORRESPONDING UNITS',/)
      WRITE(6,82)
   82 FORMAT(' AT=THROAT AREA(SQ MET)PGO=INIT TANK PRES(N/SQ MET)  STG=S
     1TAGE NUMBER CD=ORIFICE COEF A=ORIFICE OR VALVE FLOW AREA (SQ MET)'
     2/'WSC=SPACECRAFT MASS  (KG) ULV=GAS BOT VOLUME (CU MET)DELV=DELTA
     3V(MET/SEC)')
      WRITE (6,84)
   84 FORMAT(' Z=COMPRES FACT CF=THRUST COEF  DEN=PROP DENS (K/CU MET)
     1DT=LOOP TIME INCR(SEC)DTI=LOOP2 TIME INC (SEC)  P=PRES BOT EXPAN
     2EXP'/' DPT=INTERNAL TANK PRES DROP (N/SQ MET)  PMO=PRCP MASS (KG)
     3R=PROP TANK RADIUS (MET)  PW=PULSE WIDTH (SEC)')
      WRITE(6,81)
   81 FORMAT('VTK=TANK VOL(CU MET)VTINT=INTERNAL TANK DISPLACEMENT (CU
     1MET)  VG2 + VG3 = 2ND ST6 GAS VOL (CUMET) A(2)=ORIFICE AREA (CUMET
```

```
      2)')
       PMI=PMO
C*** THIS ROUTINE ADJUSTS THE TANK PRESSURE FOR LAUNCH TEMPERATURE
       TEMP=TMAX
       CALL STINT(TEMP,0.,0.,DEN,1,NGRIPE,5,5)
       IF(NGRIPE.NE.0) GO TO 100
       DENO=DEN
       VOLG=VTK-VTINT-PMO/DENO
       DEN=0.
       TEMP=TLNCH
       CALL STINT(TEMP,0.,0.,DEN,1,NGRIPE,5,5)
       IF(NGRIPE.NE.0) GO TO 100
       DELVOL=(PMO/DENO)*(1.-DENO/DEN)
       VGO=VOLG+DELVOL
       PGO=PFIL*VOLG*TLNCH/(TMAX*VGO)
       C2=Z/DEN
C     THIS ROUTINE SIZES THE FLOW ORIFICE
       VEJ=VEJIN
       CF=CFIN
       AP=.7853975*DP*DP
       PG=PGO
       DPT=DPT*6897.4862
       DO 131 M=1,5000
       SUMA=0.
       DO 10 I=1,10
       IF(CD(I).EQ.0.) GO TO 101
       IF(A(I).EQ.0.) GO TO 101
       ORF(I)=CD(I)*CD(I)*A(I)*A(I)
    10 SUMA=SUMA+(1.-ORF(I)/(AP*AP))/(ORF(I)*2.*DEN)
   101 C3=SUMA
       KM=I-1
       CSTAR=VEJ/CF
       C1=CSTAR/AT
       CONST=(C1*C1)-4.*C3*(DPT-PG)
       FM=(-C1+SQRT(CONST))/(2.*C3)
       IF(FM.LE.0.)GO TO 114
       PC=FM*C1
       CALL STINT(PC,0.,0.,VEJ,1,NGRIPE,2,2)
       IF(NGRIPE.NE.0) GO TO 100
       CALL STINT(PC,0.,0.,CF,1,NGRIPE,3,3)
       IF(NGRIPE.NE.0) GO TO 100
       IF(PC.GE.PCIN)GO TO 133
       A(1)=A(1)+.5E-08
       IF(A(1).LE.AP) GO TO 131
       A(1)=AP
       GO TO 133
   131 CONTINUE
   133 DOR=SQRT(A(1)*1.274324)
       DO 129 N=1,KM
       DELP(N)=(FM*FM)*(1.-ORF(N)/(AP*AP))/(ORF(N)*2.*DEN)
   129 DELPE(N)=DELP(N)/6897.4862
       KI=1
       HALFZ=1
       MODE1=0
       MODE2=0
     2 VEJ=VEJIN
```

```
      IERR=0
      CF=CFIN
      TIM=0.
      SUM=0.
      ICTR=0
      TDEL=0.
      TI=0.
      MODE=0
      RESTIM=0.
      PM=PMO
C*** L IS THE NUMBER OF MANUEVERS
      DO 40 K=KI,L
      TIMEP=0.
      BTIME=RESTIM
      RESTIM=0.
      DELTAV=0.
      DELN=0.
C   THIS LOOP IS ONE PULSE
      DO 30 J=1,10000
      BTIME=BTIME+TIMEP
C   THIS IS THE FIRST STAGE OF BLOWDOWN
      DO 20 I=1,10000
      IF(MODE.EQ.2) GO TO 115
      IF(HALFZ.EQ.2) GO TO 112
      MODE1=0
      MODE2=0
  113 IF(STG.EQ.1.) GO TO 15
      IF(PG-PRES) 11,11,15
   11 VGO=VGO+SUM*C2+ULV
      PGO=PFIL
      SUM=0.
      PMO=PM
      MODE=2
C   THIS IS BOTH STAGES OF BLOWDOWN
   15 CSTAR=VEJ/CF
      C1=CSTAR/AT
C THE EXPONENT WAS EXPERIMENTALLY DETERMINED
      PG=PGO*(VGO/(VGO+SUM*C2))**P
      PCT=(PMI-PM)/PMI
C   THE TANK INTERNAL PRESSURE GRADIENT IS A FUNCTION OF REMAINING PROPELLANT
      CALL STINT(PCT,0.,0.,DPT,1,NGRIPE,1,1)
      DPT=DPT*6897.486
      IF(NGRIPE.NE.0) GO TO 100
      CONST=(C1*C1)-4.*C3*(DPT-PG)
      IF(CONST.LE.0.) WRITE(6,65)
   65 FORMAT(' LOOK UP ERROR')
      FM=(-C1+SQRT(CONST))/(2.*C3)
      IF(FM.LE.0.) GO TO 21
      SUM=SUM+DT*FM
      PM=PMO-SUM
      IF(PM.LE.0.) GO TO 21
      TIME=DT*I
      TIMEP=TIME
      PC=FM*C1
      IF(PC.LE.PCMIN) GO TO 21
C   THIS CURVE VARIES FOR DIFFERENT THRUSTERS
```

```
      CALL STINT(PC,0.,0.,CF,1,NGRIPE,3,3)
      IF(NGRIPE.NE.0)GO TO 100
      CALL STINT(PC,0.,0.,VEJ,1,NGRIPE,2,2)
      IF (NGRIPE.NE.0)GO TO 100
C   THIS CURVE VARIES FOR DIFFERENT PULSE MODES
      IF(PW.EQ.1.E+10)GO TO 8
      PN=J
      CALL STINT(PN,0.,0.,EFF,1,NGRIPE,4,4)
      IF(NGRIPE.NE.0)GO TO 100
      VEJ=VEJ*EFF
    8 BIT=FM*VEJ*DT
      TI=TI+BIT
      THR=FM*VEJ
      SPI=VEJ/9.8
      IF(PW.NE.1.E+10)GO TO 9
      DELTAV=DELTAV+VEJ*ALOG((WSC+PM+FM*DT)/(WSC+PM))
      IF(DELTAV.GE.DELV(K))GO TO 31
    9 IF(MODE.EQ.2)GO TO 111
C   THIS FOR FIRST BLOWDOWN
      IF(K.NE.1)GO TO 111
      IF(J.NE.1)GO TO 111
      IF(I.NE.1)GO TO 111
      POR=FM*FM*(1.-ORF(1)/(AP*AP))/(ORF(1)*2.*DEN)
      PINLET=PG-DPT-POR
      WRITE(6,69)
   69 FORMAT('1INITIAL CONDITIONS',//)
      WRITE(6,59)A(1)
   59 FORMAT(' ORIFICE AREA = ',E11.4,' SQ MET',/)
      WRITE(6,62)DOR
   62 FORMAT(' ORIFICE DIAMETER = ',E11.4,' SQ MET',/)
      WRITE(6,64)PRES
   64 FORMAT(' PRESSURE AT REPRESSURIZATION = ',E12.4,' N/SQ MET',/)
      IF(A(2).NE.0.)WRITE(6,60)DELPE(1)
   60 FORMAT(' ORIFICE PRES DROP = ',F5.0,' PSI',/)
      IF(A(2).NE.0.)WRITE(6,58)PINLET
   58 FORMAT(' PINLET = ',E12.4,' N/SQ M',/)
      WRITE(6,61)
   61 FORMAT(' MANEUVER',6X,'PROP',12X,     'TANK',12X,     'CHAM',14X,
     1       'THRUST',16X,             'VEJ',15X,          'ISP',11X,     'FLOW'
     2,/,'  NUMBER',7X,'LEFT',12X,     'PRES',12X,      'PRES',68X,'RATE
     3',/,15X,'(KG)',10X,'(N/SQ M)',8X,'(N/SQ M)',14X,'(N)',15X,'(M/SEC)
     4',12X,'(SEC)',8X,'(KG/SEC)'/)
      WRITE(6,71)K,PM,PG,PC,THR,VEJ,SPI,FM
   71 FORMAT(4X,I3,4X,3(E12.4,4X),E17.4,4X,E17.5,4X,F10.2,4X,E12.4,/)
  111 IF(I*DT.GE.PW)GO TO 19
      GO TO 20
  112 MODE1=2
      MODE2=0
      GO TO 113
  115 IF(HALFZ.EQ.2)GO TO 116
      MODE1=2
      MODE2=0
      GO TO 15
  116 MODE1=2
      MODE2=2
      GO TO 15
```

```
   20 CONTINUE
   19 PBIT=SUM*VEJ
      DELTAV=DELTAV+VEJ*ALOG((WSC+PM+FM*DT)/(WSC+PM))
      IF(DELTAV.GE.DELV(K)) GO TO 31
   30 CONTINUE
      RESTIM=BTIME+TIMEP
   31 NJ=J
      IF(HALFZ.EQ.2) GO TO 1000
C NUMBER OF CYCLES OF THE DELTA V THRUSTERS;HALFZ=1
      IF(K.EQ.1) GO TO 1010
      CYCL1Z(K)=CYCL1Z(K-1)+NJ
      CYCL2Z(K)=0
      GO TO 1064
 1010 CYCL1Z(K)=NJ
      CYCL2Z(K)=0
      GO TO 1064
C  NUMBER OF CYCLES OF THE DELTA V THRUSTERS;HALFZ=2
 1000 IF(K.EQ.1) GO TO 1016
      CYCL1Z(K)=CYCL1Z(K-1)
      CYCL2Z(K)=CYCL2Z(K-1)+NJ
      GO TO 1064
 1016 CYCL1Z(K)=0
      CYCL2Z(K)=NJ
 1064 TDEL=TDEL+DELTAV
      POR=FM*FM*(1.-ORF(1)/(AP*AP))/(ORF(1)*2.*DEN)
      PINLET=PG-DPT-POR
      IF(ICTR.EQ.0) GO TO 16
      IF(ICTR.GE.54) GO TO 16
    6 WRITE(6,71) K,PM,PG,PC,THR,VEJ,SPI,FM
      ICTR=ICTR+2
C  SAVE THE FOLLOWING VARIABLES FOR LATER PRINTING
      STI(K)=TI
      IF(NJ.GT. 1) STIME(K)=BTIME
      IF(NJ.EQ.1) STIME(K)=TIME
      SDELV(K)=DELTAV
      STDEL(K)=TDEL
      IF(NJ.GT. 1) TIME=BTIME
      TIM=TIM+TIME
      STIM(K)=TIM
      NK=K
      TIMEZ(K)=24.*TIMEZ(K)
C RELIABILITY OF FILL VALVES
 1001 RFVZ(K)=1.-(1.-EXP(-LVZ*TIMEZ(K)*1.0E-6))*(1.-EXP(-LCZ*TIMEZ(K)
     1*1.0E-06))
C RELIABILITY OF HIGH PRESSURE TANK SYSTEM
      RTZ(K)=EXP(-NTZ*LWZ*TIMEZ(K)*1.0E-06)
C RELIABILITY OF SQUIB VALVE SYSTEM (SV1)
      RSV1Z=1.-(1.-PFSZ)**NS1Z
C PROPELLANT TANK WELD RING RELIABILITY
      RPTZ(K)=EXP(-LWZ*TIMEZ(K)*1.0E-06)
C RELIABILITY OF WELDED CONNECTIONS BETWEEN SQUID VALVE (SV1)
C     AND PRESSURANT AND PROPELLANT TANKS
      RLHPZ(K)=EXP(-NWHPZ*LWZ*TIMEZ(K)*1.0E-06)
C RELIABILITY OF SQUIB VALVE SYSTEM (SV2)
      IF(CONVZ.NE.KSQ) GO TO 1002
      RSV2Z=1.-(1.-PFSZ)**NS2Z
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      GO TO 1003
C RELIABILITY OF SOLENOID VALVE SYSTEM (SOLC)
 1002 RCSZ=EXP(-LCLZ*1.0E-06)
      ROSZ=EXP(-LOPZ*1.0E-06 -LVSZ*TIMEZ(K)*1.0E-06)
      IF(VSC.EQ.KS)GO TO 1004
      IF(VSC.EQ.KDS)GO TO 1005
      IF(VSC.EQ.KDP)GO TO 1006
      IF(VSC.EQ.KQ)GO TO 1007
C  QUAD CONNECTED VALVE SYSTEM
      RSOLCZ=(1.-(1.-RCSZ)*(1.-RCSZ))**2-(1.-ROSZ*ROSZ)**2
      GO TO 1008
C  SINGLE VAIVE SYSTEM
 1004 RSOLCZ=ROSZ+RCSZ-1.
      GO TO 1008
C  DUEL SERIES VALVE SYSTEM
 1005 RSOLCZ=RCSZ*RCSZ-(1.-ROSZ)*(1-ROSZ)
      GO TO 1008
C  DUEL PARALLEL VALVE SYSTEM
 1006 RSOLCZ=ROSZ*ROSZ-(1.-RCSZ)*(1.-RCSZ)
      GO TO 1008
C  QUAD VAIVE SYSTEM
 1007 RSOLCZ=(1.-(1.-ROSZ)*(1.-ROSZ))**2-(1.-RCSZ*RCSZ)**2
C RELIABILITY OF PRESSURE TRANSDUCER
 1008 IF(HALFZ.EQ.2)GO TO 1009
C  HALFZ EQUALS ONE
      RPD1Z(K)=EXP(-LPZ*(TIM/3600.)*1.0E-06)
      RPD2Z(K)=1.
C RELIABILITY OF FILTER ASSEMBLY;HALFZ=1
      RF1TZ(K)=EXP(LFZ*(TIM/3600.)*1.0E-06)
      RF1Z(K)=RF1TZ(K)*EXP(-LWZ*TIMEZ(K)*1.0E-06)
      RF2Z(K)=EXP(-LWZ*TIMEZ(K)*1.0E-06)
      GO TO 1011
C HALFZ EQUALS TWO
 1009 IF(K.EQ.1)GO TO 1012
      RPD1Z(K)=RPD1Z(K-1)
      GO TO 1013
 1012 RPD1Z(K)=1.
 1013 RPD2Z(K)=EXP(-LPZ*(TIM/3600.)*1.0E-06)
C RELIABILITY OF FILTER ASSEMBLY;HALFZ=2
      IF(K.EQ.1)GO TO 1014
      RF1TZ(K)=RF1TZ(K-1)
      GO TO 1015
 1014 RF1TZ(K)=1.
 1015 RF1Z(K)=RF1TZ(K)*EXP(-LWZ*TIMEZ(K)*1.0E-06)
      RF2Z(K)=EXP(-LFZ*(TIM/3600.)*1.0E-06 -LWZ*TIMEZ(K)*1.0E-06)
C RELIABILITY OF THRUSTER SOLENOID VALVE SYSTEM
C     PROBABILITY OF NO CLOSED FAIIURE OF A SINGLE VALVE
 1011 RC1Z=EXP(-LCLZ*CYCL1Z(K)*1.0E-06)
      RC2Z=EXP(-LCLZ*CYCL2Z(K)*1.0E-06)
C     PROBABILITY CF NO OPEN FAILURE OR LEAK PAST VALVE SEAT
      RO1Z=EXP(-LOPZ*CYCL1Z(K)*1.0E-06-LVSZ*TIMEZ(K)*1.0E-06)
      RO2Z=EXP(-LOPZ*CYCL2Z(K)*1.0E-06-LVSZ*TIMEZ(K)*1.0E-06)
      IF(VST.EQ.KS)GO TO 1017
      IF(VST.EQ.KDS)GO TO 1018
      IF(VST.EQ.KDP)GO TO 1019
      IF(VST.EQ.KQ)GO TO 1020
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C   QUAD CONNECTED VALVE SYSTEM
          RST1Z(K)=(1.-(1.-RC1Z)*(1.-RC1Z))**2-(1.-RO1Z*RO1Z)**2
          RST2Z(K)=(1.-(1.-RC2Z)*(1.-RC2Z))**2-(1.-RO2Z*RO2Z)**2
          GO TO 1021
C   SINGLE VALVE SYSTEM
 1017     RST1Z(K)=RO1Z+RC1Z-1.
          RST2Z(K)=RO2Z+RC2Z-1.
          GO TO 1021
C   DUEL SERIES VALVE SYSTEM
 1018     RST1Z(K)=RC1Z*RC1Z-(1.-RO1Z)*(1.-RO1Z)
          RST2Z(K)=RC2Z*RC2Z-(1.-RO2Z)*(1.-RO2Z)
          GO TO 1021
C   DUEL PARALLEL VALVE SYSTEM
 1019     RST1Z(K)=RO1Z*RO1Z-(1.-RC1Z)*(1.-RC1Z)
          RST2Z(K)=RO2Z*RO2Z-(1.-RC2Z)*(1.-RC2Z)
          GO TO 1021
C   QUAD VAIVE SYSTEM
 1020     RST1Z(K)=(1.-(1.-RO1Z)*(1.-RO1Z))**2-(1.-RC1Z*RC1Z)**2
          RST2Z(K)=(1.-(1.-RO2Z)*(1.-RO2Z))**2-(1.-RC2Z*RC2Z)**2
C   THRUSTER RELIABILITY
 1021     IF(HALFZ.EQ.2)GO TO 1022
          RTHZ(K)=EXP(-NSCZ*LSCZ*(TIM/3600.)*1.0E-06)
          RTH2Z(K)=EXP((-NBZ*LBRZ*TIMEZ(K)-2.*LWZ*TIMEZ(K))*1.0E-06)
          RTH1Z(K)=RTHZ(K)*RTH2Z(K)
          GO TO 1023
 1022     IF(K.EQ.1)GO TO 1024
          RTHZ(K)=RTHZ(K-1)
          GO TO 1025
 1024     RTHZ(K)=1.
 1025     TEMP=(-NBZ*LBRZ*TIMEZ(K)-2.*LWZ*TIMEZ(K))*1.0E-06
          RTH1Z(K)=RTHZ(K)*EXP(TEMP)
          RTH2Z(K)=EXP(((TEMP/1.0E-06)-NSCZ*LSCZ*TIM/3600.)*1.0E-06)
C   PROPELLANT TANK BLADDER RELIABILITY
 1023     IF(MODE1.EQ.2)GO TO 1026
          RB1Z(K)=EXP(-NPZ*LBZ*TIMEZ(K)*1.0E-06)
          RB2Z(K)=RB1Z(K)
          GO TO 1027
 1026     IF(MODE2.EQ.2)GO TO 1028
          RB1Z(K)=(EXP(-NPZ*LBZ*TIMEZ(K)*1.0E-06))*ERFC21
          RB2Z(K)=EXP(-NPZ*LBZ*TIMEZ(K)*1.0E-06)
          GO TO 1027
 1028     RB1Z(K)=(EXP(-NPZ*LBZ*TIMEZ(K)*1.0E-06))*ERFC21
          RB2Z(K)=RB1Z(K)
C   RELIABIIITY OF PRESSURANT AND PROPELLANT TANK SOLENOID VALVE SYSTEM
 1027     IF(VSP.EQ.KS)GO TO 1029
          IF(VSP.EQ.KDS)GO TO 1030
          IF(VSP.EQ.KDP)GO TO 1031
          IF(VSP.EQ.KQ)GO TO 1032
C   QUAD CONNECTED VALVE SYSTEM
          RSP1Z(K)=(1.-(1.-RC1Z)*(1.-RC1Z))**2-(1.-RO1Z*RO1Z)**2
          RSP2Z(K)=(1.-(1.-RC2Z)*(1.-RC2Z))**2-(1.-RO2Z*RO2Z)**2
          GO TO 1033
C   SINGLE VAIVE SYSTEM
 1029     RSP1Z(K)=RO1Z+RC1Z-1.
          RSP2Z(K)=RO2Z+RC2Z-1.
          GO TO 1033
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C  DUEL SERIES VALVE SYSTEM
 1030 RSP1Z(K)=RC1Z*RC1Z-(1.-RO1Z)*(1.-RO1Z)
      RSP2Z(K)=RC2Z*RC2Z-(1.-RO2Z)*(1.-RO2Z)
      GO TO 1033
C  DUEL PARALLEL VALVE SYSTEM
 1031 RSP1Z(K)=RO1Z*RO1Z-(1.-RC1Z)*(1.-RC1Z)
      RSP2Z(K)=RO2Z*RO2Z-(1.-RC2Z)*(1.-RC2Z)
      GO TO 1033
C  QUAD VALUE SYSTEM
 1032 RSP1Z(K)=(1.-(1.-RO1Z)*(1.-RC1Z))**2-(1.-RC1Z*RC1Z)**2
      RSP2Z(K)=(1.-(1.-RO2Z)*(1.-RO2Z))**2-(1.-RC2Z*RC2Z)**2
C  RELIABILITY OF WELDED CONNECTIONS BETWEEN PROPELLANT TANK
C     SOLENOID VALUE AND THRUSTER
 1033 RLTZ(K)=EXP(-NWTZ*LWZ*TIMEZ(K)*1.0E-06)
C  RELIABILITY OF WELDED CONNECTIONS BETWEEN PROPELLANT TANK
C     AND SOLENOID VALVE SYSTEM
      RLPPZ(K)=EXP(-NWPZ*LWZ*TIMEZ(K)*1.0E-06)
C  GENERAL SYSTEM RELIABILITY
 1003 IF(SPFVZ.EQ.KN)GO TO 1034
      RFV1Z=1.
      RFV2Z=RFVZ(K)
      GO TO 1035
 1034 RFV1Z=RFVZ(K)**NPZ
      RFV2Z=1.
 1035 IF(CONVZ.NE.KSQ)GO TO 1036
      BZ(K)=RSV2Z
      GO TO 1037
 1036 BZ(K)=RSOLCZ
C  REPRESSURIZATION NOT REQUIRED FOR EITHER HALF-SYSTEM
 1037 RE1Z(K)=1.-(1.-RFV2Z*RPD1Z(K)*RF1Z(K)*RST1Z(K)*RTH1Z(K)*
     1RLTZ(K))*(1.-BZ(K)*RFV2Z*RPD2Z(K)*RF2Z(K)*RST2Z(K)*
     2RTH2Z(K)*RLTZ(K))
      RE2Z(K)=1.-(1.-BZ(K)*RFV2Z*RPD1Z(K)*RF1Z(K)*RST1Z(K)*RTH1Z(K)
     1*RLTZ(K))*(1.-RFV2Z*RPD2Z(K)*RF2Z(K)*RST2Z(K)*RTH2Z(K)*
     2RLTZ(K))
C  REPRESSURIZATION REQUIRED FOR FIRST HALF-SYSTEM
      R1Z=RB1Z(K)*RFV1Z*RSP1Z(K)*RLPPZ(K)
      R2Z=RB2Z(K)*RFV2Z*RSP2Z(K)*RLPPZ(K)
C  REPRESSURIZATION REQUIRED FOR BOTH HALF-SYSTEMS
      Q1Z=1.-R1Z
      Q2Z=1.-R2Z
      IF(MODE1.EQ.2)GO TO 1038
      DEL1Z=1.
      DEL2Z=1.
      GO TO 1039
 1038 IF(MODE2.EQ.2)GO TO 1040
      DEL1Z=RFVZ(K)*RTZ(K)*RSV1Z
      DEL2Z=1.
      GO TO 1039
 1040 DEL1Z=RFVZ(K)*RTZ(K)*RSV1Z
      DEL2Z=DEL1Z
C  PROBABILITY OF HAVING DEFFERENT LEVELS OF PROPELLANT
C     AVAILABLE WHEN NEEDED AND FUNCTIONING PROPERLY
 1039 GZ=RLHPZ(K)*RFVZ(K)*RPTZ(K)
      PFZ(K,1)=(3.*GZ)*(R1Z*Q1Z*Q1Z*RE1Z(K)*DEL1Z*(1.-GZ*
     1DEL2Z+GZ*DEL2Z*Q2Z*Q2Z*Q2Z)+R2Z*Q2Z*RE2Z(K)*
```

```
     2(1.-GZ*DEL1Z+GZ*DEL1Z*Q1Z*Q1Z*Q1Z))
      PFZ(K,2)=(3.*GZ)*(R1Z*R1Z*Q1Z*RE1Z(K)*DEL1Z*(1.-GZ*DEL2Z+
     1GZ*DEL2Z*Q2Z*Q2Z*Q2Z)+R2Z*R2Z*Q2Z*RE2Z(K)*DEL2Z*
     2(1.-GZ*DEL1Z+GZ*DEL1Z*Q1Z*Q1Z*Q1Z)+3.*R1Z*R2Z*Q1Z
     3*Q1Z*Q2Z*Q2Z*RE1Z(K)*RE2Z(K)*DEL1Z*DEL2Z*GZ)
      PFZ(K,3)=GZ*(R1Z*R1Z*R1Z*RE1Z(K)*DEL1Z*(1.-GZ*DEL2Z+
     1GZ*DEL2Z*Q2Z*Q2Z*Q2Z)+R2Z*R2Z*R2Z*RE2Z(K)*DEL2Z*(1.-GZ
     2*DEL1Z+GZ*DEL1Z*Q1Z*Q1Z*Q1Z)+9.*R1Z*R2Z*Q1Z*Q2Z
     3*RE1Z(K)*RE2Z(K)*DEL1Z*DEL2Z*GZ*(R1Z*Q2Z+Q1Z*R2Z))
      PFZ(K,4)=(3.*RE1Z(K)*RE2Z(K)*GZ*GZ*DEL1Z*DEL2Z*R1Z*R2Z)
     1*(R1Z*R1Z*Q2Z*Q2Z+Q1Z*Q1Z*R2Z*R2Z+3.*R1Z*R2Z*
     2Q1Z*Q2Z)
      PFZ(K,5)=(3.*RE1Z(K)*RE2Z(K)*GZ*GZ*DEL1Z*DEL2Z*R1Z*R1Z*
     1R2Z*R2Z)*(R1Z*Q2Z+Q1Z*R2Z)
      PFZ(K,6)=RE1Z(K)*RE2Z(K)*GZ*GZ*DEL1Z*DEL2Z*R1Z*R1Z*R1Z
     1*R2Z*R2Z*R2Z
C   PROBABILITY OF HAVING MORE THAN THE DESIRED PROPELLANT
C     AVAILABLE WHEN NEEDED AND THE SYSTEM FUNCTIONING PROPERLY
      IF(HALFZ.EQ.2)GO TO 1041
      PMZ=PM+PMO
      GO TO 1042
 1041 PMZ=PM
 1042 FSE=(5./6.)*PMO*2.
      TTE=(2./3.)*PMO*2.
      OTE=(1./3.)*PMO*2.
      OSE=(1./6.)*PMO*2.
      IF(PMZ.GE.FSE)GO TO 1043
      IF(PMZ.LT.FSE.AND.PMZ.GE.TTE)GO TO 1044
      IF(PMZ.LT.TTE.AND.PMZ.GE.PMO)GO TO 1045
      IF(PMZ.LT.PMO.AND.PMZ.GE.OTE)GO TO 1046
      IF(PMZ.LT.OTE.AND.PMZ.GE.OSE)GO TO 1047
      IF(PMZ.LT.OSE.AND.PMZ.GE.0.)GO TO 1048
      WRITE(6,1049)PMZ
 1049 FORMAT(1X,'PMZ IS IN ERROR PMZ=',F10.6)
      CALL EXIT
C   AT LEAST ONE PROPELLANT TANK AVAILABLE
 1043 IZI=1
      GO TO 1050
C   AT LEAST TWO PROPELLANT TANKS AVAILABLE
 1044 IZI=2
      GO TO 1050
C   AT LEAST THREE PROPELLANT TANKS AVAILABLE
 1045 IZI=3
      GO TO 1050
C   AT LEAST FOUR PROPELLANT TANKS AVAILABLE
 1046 IZI=4
      GO TO 1050
C   AT LEAST FIVE PROPELLANT TANKS AVAILABLE
 1047 IZI=5
      GO TO 1050
C   ALL SIX PROPELLANT TANKS AVAILABLE
 1048 PZ(K)=PFZ(K,6)
      GO TO 1065
 1050 PZ(K)=0.
      DO 1052 IZ=IZI,6
 1052 PZ(K)=PZ(K)+PFZ(K,IZ)
```

```
      GO TO 1065
   16 ICTR=0
      WRITE(6,54)
      WRITE(6,61)
      GO TO 6
   21 IERR=1
      GO TO 31
 1065 IF(IERR.EQ.1)GO TO 3
   40 CONTINUE
    3 IF(HALFZ.EQ.2)GO TO 7
      HALFZ=2
      KI=NK+1
      J=0
      WSC=WSC+PM
      GO TO 2
    7 INK=0
   66 ICTR=0
      IK=INK+1
      WRITE(6,72)
   72 FORMAT(1H1,7X,'MANEUVER',10X,'TOTAL',17X,'BURN',20X,'DELTA',18X,
     1'TOTAL',16X,'TOTAL',/,9X,'NUMBER',10X,'IMPULSE',16X,'TIME',22X,
     2'V',19X,'DELTA V',13X,'BURN TIME',/,25X,'(N-SEC)',15X,'(SEC.)',
     318X,'(M/SEC)',16X,'(M/SEC)',15X,'(SEC)',/)
      DO 18 K=IK,NK
      WRITE(6,74)K,STI(K),STIME(K),SDELV(K),STDEL(K),STIM(K)
   74 FORMAT(10X,I3,8X,E12.4,8X,E16.6,8X,E17.4,8X,E14.4,8X,F10.0,/)
      ICTR=ICTR+2
      INK=K
      IF(ICTR.GE.54)GO TO 66
   18 CONTINUE
C    OUTPUT K VARIABLES
      INK=0
 1051 ICTR=0
      IK=INK+1
      WRITE(6,1053)
 1053 FORMAT(1H1,4X,'MANEUVER',2X,'TIME',5X,'SYSTEM',4X,
     1'LEVEL OF SYSTEM AVAILABILITY (NO. OF PROP. TANKS)',6X,
     2'RELIABILITY OF ',/,6X,'NUMBER',3X,'(HRS)',4X,'RELIAB',
     36X,'1',8X,'2',8X,'3',8X,'4',8X,'5',8X,'6',7X,'THRUST SYSTEM',
     4/,8X,'K',6X,'TIMEZ',6X,'PZ',4X,'PFZ(K,1)',1X,'PFZ(K,2)',
     51X,'PFZ(K,3)',1X,'PFZ(K,4)',1X,'PFZ(K,5)',1X,'PFZ(K,6)',4X,
     6'RE1Z(K)',1X,'RE2Z(K)',/)
      DO 1054 K=IK,NK
      WRITE(6,1055)K,TIMEZ(K),PZ(K),(PFZ(K,KK),KK=1,6),RE1Z(K),
     1RE2Z(K)
 1055 FORMAT(7X,I3,3X,F9.1,7(1X,F8.6),2X,2(1X,F8.6)/)
      ICTR=ICTR+2
      INK=K
      IF(ICTR.GE.54)GO TO 1051
 1054 CONTINUE
      INK=0
 1056 ICTR=0
      IK=INK+1
      WRITE(6,1057)
 1057 FORMAT(1H1,4X,'MANEUVER',3X,'NUMBER OF ',5X,'FILL',3X,
     1'HI PRESS PROP TANK',4X,'PROP TANK',9X,'BLADDER',11X,
```

```
     2'PRESSURE',/,6X,'NUMBER',5X,'CYCLES',7X,'VALVES',4X,
     3'TANK',3X,'WELD RING',3X,'VALVE SYSTEM',5X,'RELIABILITY',
     48X,'TRANSDUCER',/,8X,'K',5X,'CYCL1Z CYCL2Z',4X,'RFVZ',5X,
     5'RTZ',7X,'RPTZ',5X,'RSP1Z',4X,'RSP2Z',5X,'RB1Z',4X,'RB2Z',
     65X,'RPD1Z',3X,'RPD2Z',/)
      DO 1058 K=IK,NK
      WRITE(6,1059)K,CYCL1Z(K),CYCL2Z(K),RFVZ(K),RTZ(K),RPTZ(K),
     1RSP1Z(K),RSP2Z(K),RB1Z(K),RB2Z(K),RPD1Z(K),RPD2Z(K)
 1059 FORMAT(7X,I3,3X,2(1X,I6),2F9.6,1X,F9.6,1X,2F9.6,
     12F9.6,2F9.6,/)
      ICTR=ICTR+2
      INK=K
      IF(ICTR.GE.54)GO TO 1056
 1058 CONTINUE
      INK=0
 1060 ICTR=0
      IK=INK+1
      WRITE(6,1061)
 1061 FORMAT(1H1,4X,'MANEUVER',7X,'FILTER',10X,'THRUSTER',9X,
     1'THRUSTER',6X,'HALF-SYS',2X,'WELD CONNECTION RELIAB',/,
     26X,'NUMBER',7X,'ASSEMBLY',7X,'VALVE SYSTEM',6X,
     3'RELIABILITY',4X,'CON. VALV',2X,'HP SYS',2X,'PRO SYS',1X,
     4'THR SYS',/,8X,'K',8X,'RF1Z',4X,'RF2Z',5X,'RST1Z',4X,
     5'RST2Z',4X,'RTH1Z',4X,'RTH2Z',5X,'BZ',6X,'RLHPZ',4X,
     6'RLPPZ',4X,'RLTZ',/)
      DO 1062 K=IK,NK
      WRITE(6,1063)K,RF1Z(K),RF2Z(K),RST1Z(K),RST2Z(K),RTH1Z(K),
     1RTH2Z(K),BZ(K),RLHPZ(K),RLPPZ(K),RLTZ(K)
 1063 FORMAT(7X,I3,3X,2F9.6,2F9.6,2F9.6,F9.6,
     13F9.6,/)
      ICTR=ICTR+2
      INK=K
      IF(ICTR.GE.54)GO TO 1060
 1062 CONTINUE
      CALL EXIT
  100 WRITE(6,63)
   63 FORMAT(' READ IN ERROR')
      CALL EXIT
  114 WRITE(6,68)C3,C1,PG
   68 FORMAT(' FM IS LE 0., C3 = 'E16.6,'  C1 = ',E16.6,'  PG = ',E16.6)
      CALL EXIT
   54 FORMAT(1H1,25X)
      END
```

```
      SUBROUTINE STINT (ARG1,ARG2,ARG3,PCT,KEY,NGRIPE,MINTBL,MAXTBL)
      DATA K002PX/5 /
      DATA K001PX/6 /
      DIMENSIONNUMPTS(38),L1(37),L2(37),L3(37),STG(1765),DUMMY(10)
      DIMENSION NAME (9)
C     DIMENSIONNUMPTS(38),L1(37),L2(37),L3(37),STG(1765),DUMMY(10)
C     DIMENSION NAME (9)
      EQUIVALENCE (NAT,L3(1))
C**** SIZE OF STG IS CALCULATED BY SUM OF ((1+N(ARG1))*(1+N(ARG2)))
      NGRIPE=0
      IF(KEY) 1,1,70
    1 NG=1
      NORMAL=1
      WRITE (K001PX,1357)
 1357 FORMAT (34H0  TABLE        DATE        CONTENTS)
      GO TO 55
 2000 NG=2
      NORMAL=2
 3000 RETURN
  775 NGRIPE=1
      RETURN
  776 NGRIPE=2
      WRITE (K001PX,9000)ARG1,ARG2,ARG3,MINTBL,MAXTBL
      RETURN
 9000 FORMAT (20H0 ERROR IN TLU,ARG1=F12.5,6H ARG2=F12.5,6H ARG3=F12.5,
     18H MINTBL=I4,8H MAXTBL=I4)
C     GRUMMEN  AIRCRAFT ROUTINE FOLLOWS
C     BEGINNING OF STINT
   55 NUMTBL=1
      NUMPTS(1)=0
  102 READ  (K002PX,57) DA1,DA2,DA3,K,L1(NUMTBL),L2(NUMTBL),NAME,ISEQ
   57 FORMAT (A2,A3,A3,I4,2I2,9A4,18X,I2)
      WRITE (K001PX,1157) K,DA1,DA2,DA3,NAME
 1157 FORMAT (I8,5X,A2,A3,A3,5X,9A4)
  104 IF(ISEQ) 69,58,69
   58 IF (K)  99,99,1159
 1159 IF (K-37)    59, 59,1103
   59 L8=L1(NUMTBL)
      N1=(L8-1)/9+1
      DO 68 IS=1,N1
      NAT=(IS-1)*9+1
      IF (IS-N1) 60,61,60
   60 L4=NAT+8
      GO TO 62
   61 L4=L8
   62 L5=NUMPTS(NUMTBL)+1
      L6=L5+NAT
      L7=L5+L4
      JJ=0
      L9=L2(NUMTBL)
      LM=L5+L8
      LN=LM+L9
  105 READ  (K002PX,64) (DUMMY(K),K=1,10),ISEQ
      WRITE(K001PX,44) (DUMMY(K),K=1,10),ISEQ
   44 FORMAT(10E12.4,3X,I2)
   64 FORMAT (10E7.0,I2)
```

```
  107 STG(L5)=DUMMY(1)
      K=2
      DO 65 J=L6,L7
      STG(J)=DUMMY(K)
   65 K=K+1
      IF (ISEQ-((IS-1)*(L9+1)+JJ+1)) 69,66,69
   66 L6=LN+NAT
      L7=LN+L4
      L5=LN+1+JJ
      IF (JJ-L9) 67,68,69
   67 JJ=JJ+1
      LN=LN+L8
      GO TO 105
   68 CONTINUE
  109 LEE=NUMPTS(NUMTBL)+(L8+1)*(L9+1)
      IF (LEE-1765) 1100,1100,1101
 1100 IF (NUMTBL-37)  1102,108,1103
 1102 NUMPTS(NUMTBL+1)=LEE
  108 NUMTBL=NUMTBL+1
      GO TO 102
 1101 WRITE (K001FX,1111)LEE
      GO TO 775
 1103 WRITE (K001FX,1113)NUMTBL
      GO TO 775
 1111 FORMAT (17H TOO MANY POINTS  I8)
 1113 FORMAT (17H TOO MANY TABLES  I8)
   69 GO TO (775,776,776),NG
   70 IF (MINTBL-MAXTBL) 71,100,69
   71 DO 73 NAT=MINTBL,MAXTBL
      L4=NUMPTS(NAT)+1
      IF (ARG3-STG(L4)) 72,74,73
   72 IF(NAT-MINTBL)69,69,75
   73 CONTINUE
      GO TO 69
   75 L5=1
      L6=2
      L7=L4
  101 DO 97 L8=L5,L6
      L4=NUMPTS(NAT)+1
      L9=L1(NAT)
      LM=L9+L4
      DO 77 LN=1,L9
      JJ=L4+LN
 2626 IF (ARG1-STG(JJ)) 76,78,77
   76 IF (LN-1) 69,69,79
   77 CONTINUE
      GO TO 69
   78 N1=-1
      GO TO 80
   79 N1=+1
   80 K=L2(NAT)
      DO 82 I=1,K
      IDATE=LM+I
      IF (ARG2-STG(IDATE)) 81,83,82
   81 IF (I-1) 69,69,84
   82 CONTINUE
```

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```
0107          GO TO 69
0108       83 IS=-1
0109          GO TO 85
0110       84 IS=+1
0111       85 ISEQ=LM+L2(NAT)+LN+(I-1)*L9
0112          J=ISEQ-L9
0113          K8=LM+(I-1)
0114          K9=L4+LN-1
0115          IF (N1+IS) 86,88,91
0116       86 IF (STG(ISEQ)-999.E20) 87,69,69
0117       87 FCT=STG(ISEQ)
0118          GO TO 95
0119       88 IF (N1) 89,69,93
0120       89 IF (AMAX1(STG(ISEQ),STG(J))-999.E20) 90,69,69
0121       90 FCT=STG(ISEQ)-(STG(IDATE)-ARG2)*(STG(ISEQ)-STG(J))/(STG(IDATE)
             1-STG(K8))
0122          GO TO 95
0123       91 IF (AMAX1(STG(ISEQ),STG(J),STG(ISEQ-1),STG(J-1))-999.E20) 92,
             169,69
0124       92 FCT=((STG(IDATE)-ARG2)*((STG(JJ)-ARG1)*STG(J-1)-(STG(K9)-ARG1)
             1*STG(J))-(STG(K8)-ARG2)*((STG(JJ)-ARG1)*STG(ISEQ-1)-(STG(K9)-
             2ARG1)*STG(ISEQ)))/((STG(IDATE)-STG(K8))*(STG(JJ)-STG(K9)))
0125          GO TO 95
0126       93 IF (AMAX1(STG(ISEQ),STG(ISEQ-1))-999.E20) 94,69,69
0127       94 FCT=STG(ISEQ)-(STG(JJ)-ARG1)*(STG(ISEQ)-STG(ISEQ-1))/(STG(JJ)-
             1STG(K9))
0128       95 GO TO (96,98,99),L8
0129       96 DUMMY(1)=FCT
0130       97 NAT=NAT-1
0131       98 FCT=DUMMY(1)-(STG(L7)-ARG3)*(DUMMY(1)-FCT)/(STG(L7)-STG(L4))
0132       99 GO TO (2000,3000),NORMAL
0133      100 NAT=MINTBL
0134       74 L5=3
0135          L6=3
0136          GO TO 101
        C     END STINT  TABLE LOOK-UP
0137          END
```

APPENDIX B: Printout of Input Data and Computed Results

PROPULSION SYSTEM PERFORMANCE INPUT DATA

```
INPUT DATA
&INDATL
VEJIN=  2257.0000    ,Z=  1.0000000    ,CFIN=  1.7399998    ,DEN=  997.37280    ,AT= 0.55864693E-05,PFIL=  4138570.0    ,STG=
 1.0000000     ,CD= 0.60999995    , 0.60999995    , 0.0          , 0.0          , 0.0          , 0.0          , 0.0
 0.0           , 0.0           , 0.0          ,A= 0.80354823E-07, 0.0        , 0.0          , 0.0          , 0.0
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          ,DT=  1.0000000    ,DTI=  100.00000    ,P=
 1.0499992     ,DPT=  3.0000000    ,PMO=  231.50000    ,VTK= 0.27726996    ,VTINT= 0.0    ,PW= 0.99999990E 10,WSC=
 401.69995     ,L=          39,ULV= 0.38234498E-02,DELV=  7.0000000    ,  7.7849998    ,  8.6099997    ,  70.839996    ,
 7.8499994     ,  9.2099991    ,  7.7199993    ,  8.4499998    ,  81.299988    ,  7.9599991    ,  6.5999994    ,  7.9599991    ,
 6.0599995     ,  88.199997    ,  8.0000000    ,  6.8199997    ,  7.8299999    ,  8.3399992    ,  75.959991    ,  7.7699995    ,
 2.7099991     ,  2.5999994    ,  85.613998    ,  2.5999994    ,  78.649994    ,  2.5199995    ,  5.4799995    ,  1.8999996    ,
 3.1599998     ,  6.7599993    ,  13.469999    ,  116.07300    ,  26.449997    ,  29.049988    ,  26.48999C    ,  29.339996    ,
 26.519989     ,  29.379990    ,  27.996994    ,  27.996994    ,  27.996994    ,  27.996994    , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
PRES=  1241550.0    ,PCMIN=  393156.00    ,PCIN=  1724400.0    ,DP= 0.25000000    ,TMAX=  564.00000    ,TLNCH=  510.00000    ,RGAS=
 1266.5320     ,G=  9.7999992
&END
```

RELIABILITY INPUT DATA

```
&INDATG
TIMEZ=  20.000000    ,  21.000000    ,  33.000000    ,  34.000000    ,  34.039993    ,  48.000000    ,  49.000000    ,
 69.000000     ,  70.000000    ,  70.039993    ,  84.000000    ,  85.000000    ,  99.000000    ,  100.00000    ,  100.03999    ,
 113.00000     ,  114.00000    ,  128.00000    ,  129.00000    ,  129.03999    ,  147.00000    ,  162.00000    ,  179.00000    ,
 199.00000     ,  211.00000    ,  211.03999    ,  224.00000    ,  238.00000    ,  272.00000    ,  278.00000    ,  284.00000    ,
 300.00000     ,  314.00000    ,  314.03979    ,  328.00000    ,  328.03979    ,  342.00000    ,  342.03979    ,  356.00000    ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          , 0.0          ,
 0.0           , 0.0           , 0.0          , 0.0          , 0.0          ,LVZ=  3.6999998    ,LCZ= 0.49999997E-01,NTZ=
 1.0000000     ,LWZ= 0.29999998E-02,NS1Z=          1,PFSZ= 0.99989998    ,NWHPZ=  10.000000    ,CONVZ=-0.73586394E 41,NS2Z=
         1,LCLZ= 0.12499999E-01,LOPZ= 0.12499999E-01,LVSZ= 0.10999995    ,VSC= -57920.250    ,LPZ=  35.000000    ,LFZ=
 0.29999995    ,NSCZ=  7.0000000    ,LSCZ= 0.20000000E-01,NBZ=  12.000000    ,LBBZ= 0.99999993E-03,NPZ=  1.0000000    ,LBZ=
 1.0000000     ,MBZ=  50.000000000000000    ,STEZ=  10.000000000000000    ,NWTZ=  10.000000    ,NWPZ=  10.000000    ,SPPVZ=
-0.36680823E 48,VSC= -57920.250    ,VST= -55104.250    ,VSP= -55104.250
&END
```

PERFORMANCE INPUT DATA

```
  TABLE      DATE       CONTENTS
    1      01-03-71           DPT VS PG FOR METAL DIAPHRAM
 0.0         0.0          0.9000E 00  0.9100E 00  0.9200E 00  0.9300E 00  0.9400E 00  0.9500E 00  0.9600E 00  0.9700E 00   1
 0.0         0.3000E 01   0.5000E 01  0.5500E 01  0.6000E 01  0.6500E 01  0.9000E 01  0.2500E 02  0.5000E 02  0.8300E 02   2
 0.0         0.9800E 00   0.1000E 01  0.0         0.0         0.0         0.0         0.0         0.0         0.0          3
 0.0         0.1500E 03   0.2000E 03  0.0         0.0         0.0         0.0         0.0         0.0         0.0          4
    2      02-24-71          VEJ VS PC FOR INTL III
 0.0         0.1720E 06   0.4134E 06  0.6897E 06  0.8622E 06  0.1000E 07  0.1124E 07  0.1241E 07  0.1379E 07  0.1482E 07   1
 0.0         0.1860E 04   0.1992E 04  0.2081E 04  0.2130E 04  0.2159E 04  0.2188E 04  0.2208E 04  0.2228E 04  0.2238E 04   2
 0.0         0.1586E 07   0.1689E 07  0.1000E 09  0.0         0.0         0.0         0.0         0.0         0.0          3
 0.0         0.2248E 04   0.2252E 04  0.2257E 04  0.0         0.0         0.0         0.0         0.0         0.0          4
    3      02-24-71          CF VS PC FOR INTL III
 0.0         0.0          0.2470E 06  0.5173E 06  0.6897E 06  0.8622E 06  0.1173E 07  0.1483E 07  0.1724E 07  0.1931E 07   1
 0.0         0.1000E 01   0.1150E 01  0.1463E 01  0.1559E 01  0.1616E 01  0.1725E 01  0.1719E 01  0.1709E 01  0.1691E 01   2
 0.0         0.1000E 11   0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0          3
 0.0         0.1691E 01   0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0          4
    4      02-08-71           EFF VS PULSE NUMBER
 0.0         0.1000E 01   0.2000E 01  0.3000E 01  0.4000E 01  0.5000E 01  0.6000E 01  0.8000E 01  0.1000E 02  0.1200E 02   1
 0.0         0.2000E 00   0.4560E 00  0.5820E 00  0.6700E 00  0.7400E 00  0.7900E 00  0.8600E 00  0.9070E 00  0.9400E 00   2
 0.0         0.1600E 02   0.2000E 02  0.1000E 08  0.0         0.0         0.0         0.0         0.0         0.0          3
 0.0         0.9730E 00   0.1000E 01  0.1000E 01  0.0         0.0         0.0         0.0         0.0         0.0          4
    5      05-25-71                  PROPELLANT DENSITY
 0.0         0.4920E 03   0.5280E 03  0.5370E 03  0.5820E 03  0.0         0.0         0.0         0.0         0.0          1
 0.0         0.1026E 04   0.1009E 04  0.1005E 04  0.9837E 03  0.0         0.0         0.0         0.0         0.0          2
    0
END DATA
```

LIST OF VARIABLES WITH CORRESPONDING UNITS

AT=THROAT AREA(SQ MET) PGO=INIT TANK PRES(N/SQ MET) STG=STAGE NUMBER CD=ORIFICE COEF A=ORIFICE OR VALVE FLOW AREA (SQ MET)
SC=SPACECRAFT MASS (KG) ULV=GAS BOT VOLUME (CU MET) DELV=DELTA V (MET/SEC)
Z=COMPRES FACT CF=THRUST COEF DEN=PROP DENS (K/CUMET) DT=LOOP TIME INCR(SEC) DTI=LOOP2 TIME INC (SEC) P=PRES BOT EXPAN EXP
DPT=INTERNAL TANK PRES DROP (N/SQ MET) PMO=PROP MASS (KG) R=PROP TANK RADIUS (MET) PW=PULSE WIDTH (SEC)
TK=TANK VOL(CU MET) VTINT=INTERNAL TANK DISPLACEMENT (CU MET) VG2 + VG3 = 2ND STG GAS VOL (CUMET) A(2)=ORIFICE AREA (CUMET)

INITIAL CONDITIONS

ORIFICE AREA = 0.2004E-06 SQ MET

ORIFICE DIAMETER = 0.5053E-03 SQ MET

PRESSURE AT REPRESSURIZATION = 0.1242E 07 N/SQ MET

MANEUVER NUMBER	PROP LEFT (KG)	TANK PRES (N/SQ M)	CHAM PRES (N/SQ M)	THRUST (N)	VEJ (M/SEC)	ISP (SEC)	FLOW RATE (KG/SEC)
1	0.1157E 03	0.3585E 07	0.1727E 07	0.1675E 02	0.22522E 04	229.81	0.7439E-02

(PRIOR TO START OF MANEUVER NO. 1)

MANEUVER NUMBER	PROP LEFT (KG)	TANK PRES (N/SQ M)	CHAM PRES (N/SQ M)	THRUST (N)	VEJ (M/SEC)	ISP (SEC)	FLOW RATE (KG/SEC)
1	0.1141E 03	0.3339E 07	0.1662E 07	0.1590E 02	0.22510E 04	229.69	0.7062E-02
2	0.1121E 03	0.3095E 07	0.1575E 07	0.1509E 02	0.22465E 04	229.23	0.6719E-02
3	0.1100E 03	0.2865E 07	0.1489E 07	0.1430E 02	0.22384E 04	228.41	0.6386E-02
4	0.9275E 02	0.1772E 07	0.1055E 07	0.9924E 01	0.21722E 04	221.65	0.4569E-02
5	0.9086E 02	0.1700E 07	0.1025E 07	0.9584E 01	0.21651E 04	220.93	0.4427E-02
6	0.8849E 02	0.1618E 07	0.9904E 06	0.9191E 01	0.21572E 04	220.12	0.4261E-02
7	0.8652E 02	0.1555E 07	0.9634E 06	0.8889E 01	0.21514E 04	219.53	0.4132E-02
8	0.8443E 02	0.1493E 07	0.9362E 06	0.8589E 01	0.21456E 04	218.94	0.4003E-02
9	0.6427E 02	0.1078E 07	0.7343E 06	0.6456E 01	0.20934E 04	213.61	0.3084E-02
10	0.6224E 02	0.1048E 07	0.7186E 06	0.6297E 01	0.20889E 04	213.15	0.3014E-02
11	0.6060E 02	0.1025E 07	0.7063E 06	0.6173E 01	0.20854E 04	212.79	0.2960E-02
12	0.5865E 02	0.9993E 06	0.6922E 06	0.6032E 01	0.20814E 04	212.39	0.2898E-02
13	0.5718E 02	0.9807E 06	0.6823E 06	0.5927E 01	0.20783E 04	212.07	0.2852E-02
14	0.3541E 02	0.7671E 06	0.5618E 06	0.4669E 01	0.20396E 04	208.13	0.2289E-02
15	0.3355E 02	0.7530E 06	0.5533E 06	0.4584E 01	0.20369E 04	207.85	0.2250E-02
16	0.3198E 02	0.7415E 06	0.5463E 06	0.4514E 01	0.20347E 04	207.62	0.2218E-02
17	0.3004E 02	0.7277E 06	0.5379E 06	0.4430E 01	0.20320E 04	207.34	0.2180E-02
18	0.2772E 02	0.7119E 06	0.5281E 06	0.4333E 01	0.20289E 04	207.02	0.2136E-02
19	0.8514E 01	0.6030E 06	0.4558E 06	0.3543E 01	0.20056E 04	204.65	0.1767E-02
20	0.6585E 01	0.5938E 06	0.4159E 06	0.3126E 01	0.19928E 04	203.35	0.1569E-02
21	0.6251E 01	0.5922E 06	0.3931E 06	0.2898E 01	0.19809E 04	202.13	0.1462E-02
22	0.1151E 03	0.3489E 07	0.1714E 07	0.1637E 02	0.22522E 04	229.81	0.7269E-02
23	0.9403E 02	0.1824E 07	0.1076E 07	0.1017E 02	0.21772E 04	222.16	0.4670E-02
24	0.9338E 02	0.1797E 07	0.1065E 07	0.1004E 02	0.21746E 04	221.90	0.4618E-02
25	0.7352E 02	0.1236E 07	0.8156E 06	0.7293E 01	0.21165E 04	215.97	0.3446E-02
26	0.7290E 02	0.1224E 07	0.8097E 06	0.7231E 01	0.21148E 04	215.80	0.3419E-02
27	0.7138E 02	0.1195E 07	0.7952E 06	0.7081E 01	0.21107E 04	215.38	0.3355E-02
28	0.7085E 02	0.1186E 07	0.7904E 06	0.7031E 01	0.21093E 04	215.24	0.3333E-02
29	0.6998E 02	0.1170E 07	0.7825E 06	0.6949E 01	0.21071E 04	215.01	0.3298E-02
30	0.6815E 02	0.1139E 07	0.7664E 06	0.6784E 01	0.21025E 04	214.54	0.3227E-02
31	0.6474E 02	0.1085E 07	0.7380E 06	0.6494E 01	0.20944E 04	213.72	0.3100E-02
32	0.3601E 02	0.7718E 06	0.5646E 06	0.4697E 01	0.20405E 04	208.22	0.2302E-02
33	0.2968E 02	0.7253E 06	0.5364E 06	0.4415E 01	0.20315E 04	207.29	0.2173E-02
34	0.2182E 02	0.6746E 06	0.5055E 06	0.4092E 01	0.20216E 04	206.28	0.2024E-02
35	0.1509E 02	0.6364E 06	0.4823E 06	0.3831E 01	0.20141E 04	205.52	0.1902E-02
36	0.8095E 01	0.6010E 06	0.4537E 06	0.3521E 01	0.20049E 04	204.59	0.1756E-02
37	0.6251E 01	0.5922E 06	0.3931E 06	0.2898E 01	0.19809E 04	202.13	0.1462E-02

MANEUVER NUMBER	TOTAL IMPULSE (N-SEC)	BURN TIME (SEC.)	DELTA V (M/SEC)	TOTAL DELTA V (M/SEC)	TOTAL BURN TIME (SEC)
1	0.3808E 04	0.234000E 03	0.7006E 01	0.7006E 01	234.
2	0.8143E 04	0.280000E 03	0.7807E 01	0.1481E 02	514.
3	0.1288E 05	0.323000E 03	0.8633E 01	0.2344E 02	837.
4	0.5098E 05	0.323900E 04	0.7085E 02	0.9430E 02	4076.
5	0.5510E 05	0.422000E 03	0.7855E 01	0.1022E 03	4498.
6	0.6022E 05	0.546000E 03	0.9210E 01	0.1114E 03	5044.
7	0.6447E 05	0.470000E 03	0.7724E 01	0.1191E 03	5514.
8	0.6896E 05	0.516000E 03	0.8458E 01	0.1275E 03	6030.
9	0.1116E 06	0.580100E 04	0.8131E 02	0.2089E 03	11831.
10	0.1158E 06	0.666000E 03	0.7969E 01	0.2168E 03	12497.
11	0.1192E 06	0.553000E 03	0.6604E 01	0.2234E 03	13050.
12	0.1233E 06	0.668000E 03	0.7963E 01	0.2314E 03	13718.
13	0.1263E 06	0.510000E 03	0.6069E 01	0.2375E 03	14228.
14	0.1710E 06	0.859200E 04	0.8821E 02	0.3257E 03	22820.
15	0.1748E 06	0.824000E 03	0.8008E 01	0.3337E 03	23644.
16	0.1780E 06	0.703000E 03	0.6824E 01	0.3405E 03	24347.
17	0.1819E 06	0.889000E 03	0.7834E 01	0.3483E 03	25236.
18	0.1866E 06	0.107700E 04	0.8341E 01	0.3567E 03	26313.
19	0.2252E 06	0.988000E 04	0.7596E 02	0.4326E 03	36193.
20	0.2290E 06	0.113300E 04	0.7775E 01	0.4404E 03	37326.
21	0.2297E 06	0.222000E 03	0.1256E 01	0.4417E 03	37548.
22	0.1437E 04	0.870000E 02	0.2616E 01	0.2616E 01	87.
23	0.4819E 05	0.371100E 04	0.8563E 02	0.8824E 02	3798.
24	0.4961E 05	0.140000E 03	0.2615E 01	0.9086E 02	3938.
25	0.9217E 05	0.504500E 04	0.7866E 02	0.1695E 03	8983.
26	0.9347E 05	0.179000E 03	0.2528E 01	0.1720E 03	9162.
27	0.9669E 05	0.452000E 03	0.5480E 01	0.1775E 03	9614.
28	0.9780E 05	0.158000E 03	0.1908E 01	0.1794E 03	9772.
29	0.9962E 05	0.262000E 03	0.3160E 01	0.1826E 03	10034.
30	0.1035E 06	0.562000E 03	0.6768E 01	0.1894E 03	10596.
31	0.1106E 06	0.108400E 04	0.1347E 02	0.2028E 03	11680.
32	0.1698E 06	0.100000E 05	0.1161E 03	0.3189E 03	21680.
33	0.1826E 06	0.283900E 04	0.2645E 02	0.3454E 03	24519.
34	0.1985E 06	0.376100E 04	0.2906E 02	0.3744E 03	28280.
35	0.2120E 06	0.344400E 04	0.2650E 02	0.4009E 03	31724.
36	0.2260E 06	0.382900E 04	0.2934E 02	0.4303E 03	35553.
37	0.2297E 06	0.111600E 04	0.7203E 01	0.4375E 03	36669.

MANEUVER NUMBER K	TIME (HRS) TIMEZ	SYSTEM RELIAB PZ	LEVEL OF SYSTEM AVAILABILITY (NO. OF PROP. TANKS) 1 PFZ(K,1)	2 PFZ(K,2)	3 PFZ(K,3)	4 PFZ(K,4)	5 PFZ(K,5)	6 PFZ(K,6)	RELIABILITY OF THRUST SYSTEM RE1Z(K)	RE2Z(K)
1	480.0	1.000000	0.000000	0.000000	0.000032	0.000004	0.002958	0.997006	1.000000	1.000000
2	504.0	1.000000	0.000000	0.000000	0.000033	0.000004	0.003106	0.996856	1.000000	1.000000
3	792.0	1.000000	0.000000	0.000000	0.000052	0.000010	0.004873	0.995065	1.000000	1.000000
4	816.0	1.000000	0.000000	0.000000	0.000054	0.000011	0.005020	0.994915	1.000000	1.000000
5	817.0	1.000000	0.000000	0.000000	0.000054	0.000011	0.005026	0.994909	1.000000	1.000000
6	1152.0	1.000000	0.000000	0.000000	0.000076	0.000021	0.007074	0.992828	1.000000	1.000000
7	1176.0	1.000000	0.000000	0.000000	0.000078	0.000022	0.007220	0.992680	1.000000	1.000000
8	1656.0	1.000000	0.000000	0.000001	0.000110	0.000043	0.010139	0.989707	1.000000	1.000000
9	1680.0	1.000000	0.000000	0.000001	0.000111	0.000045	0.010285	0.989559	1.000000	1.000000
10	1681.0	1.000000	0.000000	0.000001	0.000111	0.000045	0.010291	0.989552	1.000000	1.000000
11	2016.0	1.000000	0.000000	0.000001	0.000134	0.000064	0.012319	0.987482	1.000000	1.000000
12	2040.0	1.000000	0.000000	0.000001	0.000135	0.000066	0.012464	0.987334	1.000000	1.000000
13	2376.0	1.000000	0.000001	0.000001	0.000158	0.000089	0.014490	0.985262	1.000000	1.000000
14	2400.0	0.999998	0.000001	0.000001	0.000160	0.000091	0.014634	0.985114	1.000000	1.000000
15	2401.0	0.999999	0.000001	0.000001	0.000160	0.000091	0.014640	0.985109	1.000000	1.000000
16	2712.0	0.999998	0.000001	0.000002	0.000180	0.000115	0.016507	0.983195	1.000000	1.000000
17	2736.0	0.999998	0.000001	0.000002	0.000182	0.000118	0.016652	0.983047	1.000000	1.000000
18	3072.0	0.999998	0.000001	0.000002	0.000205	0.000148	0.018661	0.980984	1.000000	1.000000
19	3096.0	0.999998	0.000001	0.000002	0.000206	0.000150	0.018804	0.980837	1.000000	1.000000
20	3097.0	0.999999	0.000001	0.000002	0.000207	0.000150	0.018810	0.980831	1.000000	1.000000
21	3528.0	0.999997	0.000001	0.000003	0.000236	0.000195	0.021377	0.978190	1.000000	1.000000
22	3888.0	0.999622	0.000003	0.000004	0.000373	0.000236	0.023509	0.975877	1.000000	1.000000
23	4296.0	0.999591	0.000003	0.000005	0.000403	0.000287	0.025916	0.973388	1.000000	1.000000
24	4776.0	0.999555	0.000004	0.000006	0.000438	0.000354	0.028734	0.970466	1.000000	1.000000
25	5064.0	0.999135	0.000005	0.000007	0.000459	0.000398	0.030418	0.968717	1.000000	1.000000
26	5065.0	0.999135	0.000005	0.000007	0.000459	0.000398	0.030423	0.968712	1.000000	1.000000
27	5376.0	0.999061	0.000005	0.000008	0.000482	0.000448	0.032235	0.966826	1.000000	1.000000
28	5712.0	0.998978	0.000006	0.000009	0.000507	0.000505	0.034185	0.964793	1.000000	1.000000
29	6528.0	0.998763	0.000007	0.000011	0.000568	0.000657	0.038890	0.959873	1.000000	1.000000
30	6672.0	0.998723	0.000007	0.000012	0.000579	0.000685	0.039716	0.959007	1.000000	1.000000
31	6816.0	0.998682	0.000008	0.000012	0.000590	0.000715	0.040540	0.958142	1.000000	1.000000
32	7200.0	0.955839	0.000008	0.000014	0.000619	0.000796	0.042732	0.955839	1.000000	1.000000
33	7536.0	0.953826	0.000009	0.000015	0.000645	0.000871	0.044642	0.953826	1.000000	1.000000
34	7537.0	0.953821	0.000009	0.000015	0.000645	0.000871	0.044647	0.953821	1.000000	1.000000
35	7872.0	0.951819	0.000010	0.000016	0.000671	0.000948	0.046544	0.951819	0.999999	0.999999
36	7873.0	0.951814	0.000010	0.000016	0.000671	0.000949	0.046549	0.951814	0.999999	0.999999
37	8208.0	0.949815	0.000011	0.000018	0.000697	0.001029	0.048439	0.949815	0.999999	0.999999

PFZ(K,n) = probability of exactly n propellant tanks available and the remainder of the system functioning successfully.

RE1Z(K) = probability of thrust system of first half-system or second-half system and half-system value functioning successfully.

RE2Z(K) = probability of thrust system of second half-system or first half-system and half-system value functioning successfully.

MANEUVER NUMBER K	NUMBER OF CYCLES CYCL1Z	CYCL2Z	FILL VALVES RFVZ	HI PRESS TANK RTZ	PROP TANK WELD RING RPTZ	PROP TANK VALVE SYSTEM RSP1Z	RSP2Z	BLADDER RELIABILITY RB1Z	RB2Z	PRESSURE TRANSDUCER RPD1Z	RPD2Z
1	1	0	1.000000	0.999999	0.999999	1.000000	1.000000	0.999520	0.999520	0.999998	1.000000
2	2	0	1.000000	0.999999	0.999999	1.000000	1.000000	0.999496	0.999496	0.999995	1.000000
3	3	0	1.000000	0.999998	0.999998	1.000000	1.000000	0.999208	0.999208	0.999992	1.000000
4	4	0	1.000000	0.999998	0.999998	1.000000	1.000000	0.999184	0.999184	0.999960	1.000000
5	5	0	1.000000	0.999998	0.999998	1.000000	1.000000	0.999183	0.999183	0.999956	1.000000
6	6	0	1.000000	0.999997	0.999997	1.000000	1.000000	0.998849	0.998849	0.999951	1.000000
7	7	0	1.000000	0.999996	0.999996	1.000000	1.000000	0.998825	0.998825	0.999946	1.000000
8	8	0	1.000000	0.999995	0.999995	1.000000	1.000000	0.998345	0.998345	0.999941	1.000000
9	9	0	1.000000	0.999995	0.999995	1.000000	1.000000	0.998321	0.998321	0.999885	1.000000
10	10	0	1.000000	0.999995	0.999995	1.000000	1.000000	0.998320	0.998320	0.999879	1.000000
11	11	0	0.999999	0.999994	0.999994	1.000000	1.000000	0.997986	0.997986	0.999873	1.000000
12	12	0	0.999999	0.999994	0.999994	1.000000	1.000000	0.997962	0.997962	0.999867	1.000000
13	13	0	0.999999	0.999993	0.999993	1.000000	1.000000	0.997627	0.997627	0.999862	1.000000
14	14	0	0.999999	0.999993	0.999993	1.000000	1.000000	0.997603	0.997603	0.999778	1.000000
15	15	0	0.999999	0.999993	0.999993	1.000000	1.000000	0.997602	0.997602	0.999770	1.000000
16	16	0	0.999999	0.999992	0.999992	1.000000	1.000000	0.997292	0.997292	0.999763	1.000000
17	17	0	0.999999	0.999992	0.999992	1.000000	1.000000	0.997268	0.997268	0.999755	1.000000
18	18	0	0.999998	0.999991	0.999991	1.000000	1.000000	0.996933	0.996933	0.999744	1.000000
19	19	0	0.999998	0.999991	0.999991	1.000000	1.000000	0.996909	0.996909	0.999648	1.000000
20	20	0	0.999998	0.999991	0.999991	1.000000	1.000000	0.996908	0.996908	0.999637	1.000000
21	21	0	0.999998	0.999989	0.999989	0.999999	0.999999	0.996478	0.996478	0.999635	1.000000
22	21	1	0.999997	0.999988	0.999988	0.999999	0.999999	0.996119	0.996120	0.999635	0.999999
23	21	2	0.999997	0.999987	0.999987	0.999999	0.999999	0.995713	0.995713	0.999635	0.999963
24	21	3	0.999996	0.999986	0.999986	0.999999	0.999999	0.995235	0.995235	0.999635	0.999962
25	21	4	0.999995	0.999985	0.999985	0.999999	0.999999	0.994948	0.994949	0.999635	0.999913
26	21	5	0.999995	0.999985	0.999985	0.999999	0.999999	0.994947	0.994946	0.999635	0.999911
27	21	6	0.999995	0.999984	0.999984	0.999999	0.999999	0.994638	0.994638	0.999635	0.999907
28	21	7	0.999994	0.999983	0.999983	0.999998	0.999998	0.994304	0.994304	0.999635	0.999905
29	21	8	0.999992	0.999980	0.999980	0.999998	0.999998	0.993493	0.993493	0.999635	0.999902
30	21	9	0.999992	0.999980	0.999980	0.999998	0.999998	0.993350	0.993350	0.999635	0.999897
31	21	10	0.999992	0.999980	0.999980	0.999998	0.999998	0.993207	0.993207	0.999635	0.999886
32	21	12	0.999991	0.999978	0.999978	0.999997	0.999997	0.992826	0.992826	0.999635	0.999789
33	21	13	0.999990	0.999977	0.999977	0.999997	0.999997	0.992492	0.992492	0.999635	0.999762
34	21	14	0.999990	0.999977	0.999977	0.999997	0.999997	0.992491	0.992491	0.999635	0.999725
35	21	15	0.999989	0.999976	0.999976	0.999997	0.999997	0.992159	0.992159	0.999635	0.999692
36	21	16	0.999989	0.999976	0.999976	0.999997	0.999997	0.992158	0.992158	0.999635	0.999654
37	21	17	0.999988	0.999975	0.999975	0.999997	0.999997	0.991825	0.991826	0.999635	0.999644

MANEUVER NUMBER K	FILTER ASSEMBLY RF1Z	RF2Z	THRUSTER VALVE SYSTEM RST1Z	RST2Z	THRUSTER RELIABILITY RTH1Z	RTH2Z	HALF-SYS CON. VALV BZ	WELD CONNECTION RELIAB HP SYS RLHPZ	PRO SYS RLPPZ	THR SYS RLTZ
1	0.999999	0.999999	1.000000	1.000000	0.999991	0.999991	1.000000	0.999986	0.999986	0.999986
2	0.999999	0.999999	1.000000	1.000000	0.999991	0.999991	1.000000	0.999985	0.999985	0.999985
3	0.999998	0.999998	1.000000	1.000000	0.999986	0.999986	1.000000	0.999976	0.999976	0.999976
4	0.999998	0.999998	1.000000	1.000000	0.999985	0.999985	1.000000	0.999976	0.999976	0.999976
5	0.999998	0.999998	1.000000	1.000000	0.999985	0.999985	1.000000	0.999976	0.999976	0.999976
6	0.999997	0.999997	1.000000	1.000000	0.999979	0.999979	1.000000	0.999965	0.999965	0.999965
7	0.999996	0.999996	1.000000	1.000000	0.999979	0.999979	1.000000	0.999965	0.999965	0.999965
8	0.999996	0.999995	1.000000	1.000000	0.999970	0.999970	1.000000	0.999950	0.999950	0.999950
9	0.999996	0.999995	1.000000	1.000000	0.999969	0.999970	1.000000	0.999950	0.999950	0.999950
10	0.999996	0.999995	1.000000	1.000000	0.999969	0.999970	1.000000	0.999950	0.999950	0.999950
11	0.999995	0.999994	1.000000	1.000000	0.999963	0.999964	1.000000	0.999940	0.999940	0.999940
12	0.999995	0.999994	1.000000	1.000000	0.999963	0.999963	1.000000	0.999939	0.999939	0.999939
13	0.999994	0.999993	1.000000	1.000000	0.999957	0.999957	1.000000	0.999929	0.999929	0.999929
14	0.999995	0.999993	1.000000	1.000000	0.999956	0.999957	1.000000	0.999928	0.999928	0.999928
15	0.999995	0.999993	1.000000	1.000000	0.999956	0.999957	1.000000	0.999928	0.999928	0.999928
16	0.999994	0.999992	1.000000	1.000000	0.999950	0.999951	1.000000	0.999919	0.999919	0.999919
17	0.999994	0.999992	1.000000	1.000000	0.999950	0.999951	1.000000	0.999918	0.999918	0.999918
18	0.999993	0.999991	1.000000	1.000000	0.999944	0.999945	1.000000	0.999908	0.999908	0.999908
19	0.999994	0.999991	1.000000	1.000000	0.999943	0.999944	1.000000	0.999907	0.999907	0.999907
20	0.999994	0.999991	1.000000	1.000000	0.999943	0.999944	1.000000	0.999907	0.999907	0.999907
21	0.999992	0.999989	0.999999	0.999999	0.999935	0.999937	0.999999	0.999894	0.999894	0.999894
22	0.999991	0.999988	0.999999	0.999999	0.999929	0.999930	0.999999	0.999883	0.999883	0.999883
23	0.999990	0.999987	0.999999	0.999999	0.999921	0.999923	0.999999	0.999871	0.999871	0.999871
24	0.999988	0.999985	0.999999	0.999999	0.999913	0.999914	0.999999	0.999857	0.999857	0.999857
25	0.999988	0.999984	0.999999	0.999999	0.999907	0.999909	0.999999	0.999848	0.999848	0.999848
26	0.999988	0.999984	0.999999	0.999999	0.999907	0.999909	0.999999	0.999848	0.999848	0.999848
27	0.999987	0.999983	0.999999	0.999999	0.999902	0.999903	0.999999	0.999839	0.999839	0.999839
28	0.999986	0.999982	0.999998	0.999998	0.999896	0.999897	0.999998	0.999829	0.999829	0.999829
29	0.999983	0.999980	0.999998	0.999998	0.999881	0.999882	0.999998	0.999804	0.999804	0.999804
30	0.999983	0.999979	0.999998	0.999998	0.999878	0.999879	0.999998	0.999800	0.999800	0.999800
31	0.999982	0.999979	0.999998	0.999998	0.999876	0.999877	0.999998	0.999796	0.999796	0.999796
32	0.999981	0.999977	0.999997	0.999997	0.999869	0.999870	0.999997	0.999784	0.999784	0.999784
33	0.999980	0.999975	0.999997	0.999997	0.999863	0.999863	0.999997	0.999774	0.999774	0.999774
34	0.999980	0.999975	0.999997	0.999997	0.999863	0.999863	0.999997	0.999774	0.999774	0.999774
35	0.999979	0.999974	0.999997	0.999997	0.999857	0.999857	0.999997	0.999764	0.999764	0.999764
36	0.999979	0.999973	0.999997	0.999997	0.999857	0.999857	0.999997	0.999764	0.999764	0.999764
37	0.999978	0.999972	0.999997	0.999997	0.999851	0.999851	0.999997	0.999754	0.999754	0.999754

APPENDIX C: Valve Configurations

One of the weakest links in auxiliary propulsion systems is the solenoid valve. Four commonly used valve redundancy configurations are: dual series, dual parallel, quad, and quad connected. These are illustrated below along with equations for their reliability. Two basic failure modes are considered; i.e., open failures and closed failures. Both an open and a closed failure will lead to a system failure in the absence of redundancy.

In general, let

R_o = probability of no open failure

R_c = probability of no closed failure

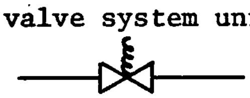
$Q_o = 1-R_o$ = probability of open failure

$Q_c = 1-R_c$ = probability of closed failure

$Q_s = Q_o + Q_c$ = probability of failure of a single valve

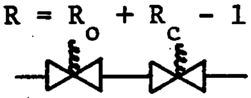
R = valve system reliability

Q = valve system unreliability

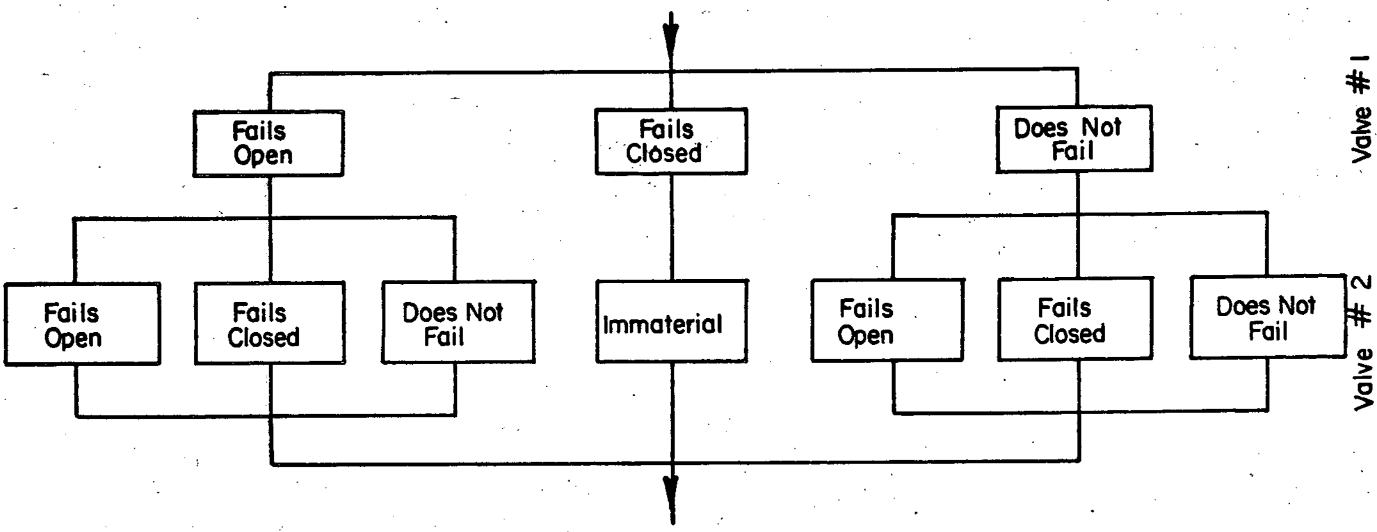
Single Valve 

$$R = 1 - Q_s = 1 - Q_o - Q_c = 1 - (1 - R_o) - (1 - R_c)$$

$$R = R_o + R_c - 1$$

Dual Series 

The various possible outcomes are shown below

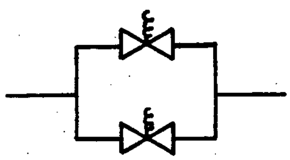


Therefore,

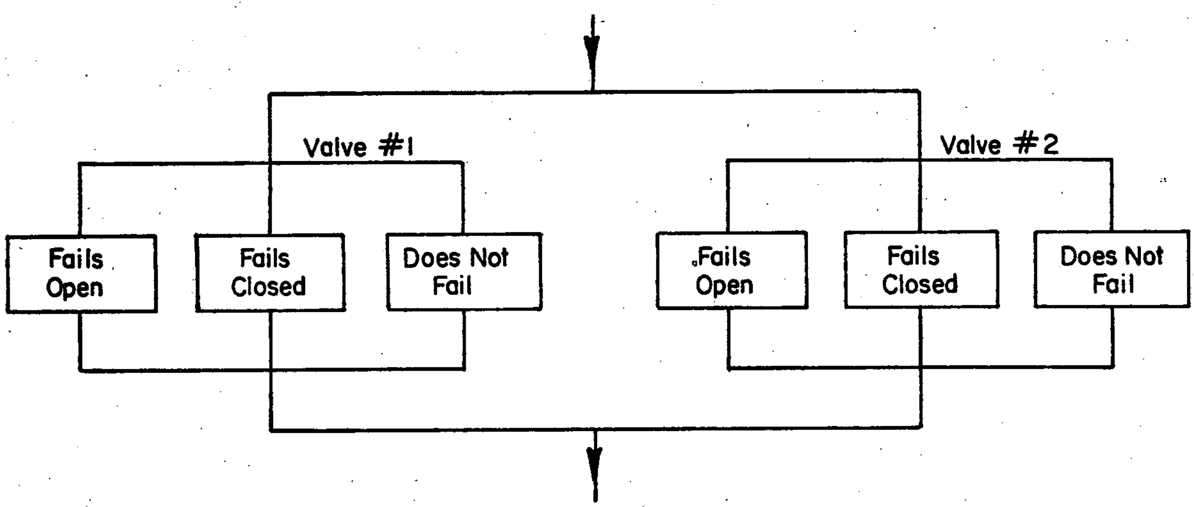
$$R = (1 - Q_o - Q_c)^2 + (1 - Q_o - Q_c)\, Q_o + Q_o(1 - Q_o - Q_c)$$

$$R = R_c^{\,2} - (1 - R_o)^2$$

Dual Parallel



The various possible outcomes are shown below



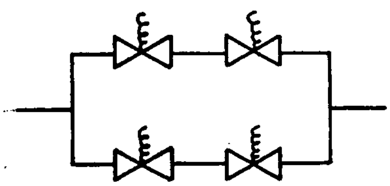
A system failure will occur if either valve fails in the open position or if both valves fail in the closed position. Therefore,

$$R = 1 - \left[1 - (1 - Q_o)^2 + Q_c^2\right]$$

$$R = R_o^2 - (1 - R_c)^2$$

where $1 - (1 - Q_o)^2$ is the probability of an open failure and Q_c^2 is the probability of a closed failure.

<u>Quad</u>



The various possible outcomes can be structured in a manner similar to that shown above. It should be noted that the probability of a system failure is the sum of the probability of a failure due to an open valve arrangement and that due to a closed valve arrangement. Therefore,

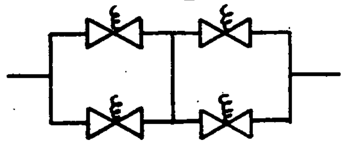
$$\text{probability of closed failure} = \left[1 - (1 - Q_c)^2\right]^2$$

$$\text{probability of open failure} = 1 - (1 - Q_o^2)^2$$

$$R = 1 - \left[1 - (1 - Q_c)^2\right]^2 - 1 + (1 - Q_o^2)^2$$

$$R = \left[1 - (1 - R_o)^2\right]^2 - \left[1 - R_c^2\right]^2$$

<u>Quad Connected</u>



In a manner similar to the Quad above,

$$\text{probability of closed failure} = 1 - \left[1 - Q_c^2\right]^2$$

probability of open failure = $\left[1 - (1 - Q_o)^2\right]^2$

$$R = 1 - \left[1 - (1 - Q_o)^2\right]^2 - 1 + \left[1 - Q_c^{\,2}\right]^2$$

$$R = \left[1 - (1 - R_c)^2\right]^2 - \left[1 - R_o^{\,2}\right]^2$$