Cr 86085

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STABILIZATION AND CONTROL SYSTEM POWER SENSITIVITY STUDY

By William C. Clemmens, Leif N. Dahl,
Otto L. Jourdan, Joseph A. Miller,
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June 1968

Honeywell Document
No. 21031-FR

Prepared under Contract No. NAS 12-633 by

HONEYWELL INC.

Aerospace and Defense Group
Minneapolis, Minnesota and St. Petersburg, Florida

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Honeywell Inc.
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SUMMARY

This report covers the work performed by Honeywell Inc. under Contract NAS 12-633, "ERC Power Study." The study included the following tasks to provide information to identify the sensitivity of the stabilization and control (SCS) reliability to power-off failure rates:

Task 1. Use 1965 Honeywell Guidance, Navigation and Control (GN&C) Mission Abort Reliability Simulator (MARS) computer data: (1) to conduct a search to identify device failures resulting from block power switching (i.e., equipment energized but not functionally required), and (2) to determine aborts and crew losses which resulted.

Task 2. Conduct a study to determine the effect on subsystem failure rates, if any, of: (1) the number of times power is applied and removed during the life of the equipment, and (2) the length of storage (de-energized) time.

The results of this study show that the seriousness of the penalties resulting from nonoptimum power distribution is integrally related to both mission profile and vehicle operation. This being the case, future power studies should be sufficiently detailed to take these two factors into account. By the use of computer programs it seems possible to identify and eliminate many of the deficiencies that may otherwise occur in future systems.

Computerized Mission Simulations

Computerized mission simulations show a direct relationship between subsystem failures and nonoptimum power distribution. For example, as shown in the navigation and control MARS failure data listed below, 8 percent of the lunar polar orbit (LPO) and 23 percent of the lunar landing mission (LLM) device failures were unwarranted, since the failures occurred in equipment energized but not required:

Description	LPO	LLM
No. of mission simulations	100	5000
Total device failures	88 (0.88 failure/ mission)	667 (0.133 failure/ mission)
Failures of equipment on but not required	7	153
Unwarranted failures	8%	23%
Aborts	23	76

The literature survey conducted as part of this study revealed that a significant amount of information relating to nonoperating conditions is available from prior studies; however, information available on the effects of power on - off cycling is very limited.

Subsystem Failure Rate Study

The limited information available and reviewed in the subsystem failure rate study revealed that the power-off failure rate is approximately 1/30 of the power-on failure rate and that the failure rate due to 1 on - off power cycle is approximately equivalent to the failure rate due to 10 hours of power-on time. Study results are as follows:

- On - off failure rate (λ on - off)
  1) One on - off cycle is equivalent to 10 hours operating time (best estimate based on available data).
  2) The small number of relevant failures (4 out of 434 Test Discrepancy Reports limited the confidence of resulting data.
  3) A survey of 4000 to 10,000 Test Discrepancy Reports (TDR's) is required for reasonable confidence in operating time equivalent.
- Off failure rate (λ off)
  1) λ off = 1/30 λ on (best estimate from study).
  2) λ off found to range from 1/10 to 1/50 of λ on.
- Mission sensitivity to λ off
  1) State Interpretive Program (SIP) analysis did not show significant reliability improvement to changing failure rates in LPO missions.
  2) Reexamination of MARS data tends to support SIP results for LPO missions.

3) State Interpretive Program analysis of a mission using space-fixed vehicle control (mission 4) indicates significant reliability improvement due to de-energized equipment.

4) Sensitivity is a function of vehicle operation and mission profile.

Recommendations

Recommendations for immediate follow-on to this study include: (1) rerun of the MARS study with redundant paths de-energized to obtain complete abort data; (2) preliminary development of a computer program to provide an efficient tool for design evaluation; and (3) a power conditioning tradeoff study to provide a basis for future power conditioning and distribution design. This latter task would include study of filters and switching, fault protection, and regulation and conversion.

INTRODUCTION

Background

Historically, the distribution of power in a vehicle has been established on an arbitrary basis. Frequently, one person is charged with the limited responsibility of providing power only to the vehicle ac and dc busses. This is done with a minimum understanding of the life and reliability requirements of the various subsystems and with a minimum of effort expended on time-consuming tradeoff studies. Once power is available at the vehicle bus, the subsystem suppliers process it to satisfy a criterion which may or may not be desirable from a total system standpoint. A major reason for this relegation of power distribution to a secondary role in the design process is the natural emphasis that is placed upon pivotal design factors such as stability and functional operating characteristics early in the design phases of a program.

To avoid arbitrary design decisions and to improve power distribution in future programs, it is important that studies be conducted that will provide basic design criteria that can be easily incorporated as part of the early design on operational programs.

Scope

The scope of this study is limited to identifying the sensitivity of SCS reliability to the power-off failure rate. It is to be recognized that this study is only a small portion of the work which is required to develop a methodology for overall power distribution design.

The scope of this study and how it relates to the overall methodology development is shown in Figure 1. From this figure it is apparent that in addition to tasks completed, additional tasks will be required before desired goals can be obtained.

The results of Task 1 and Task 2 indicate the significance of the equipment operational status. The parametric study conducted on the SCS demonstrates the sensitivity of the subsystem reliability to power-off failure rates.

The approach used in this study involves the use of the Apollo guidance and control system as a model for developing the methodology for future power distribution systems. Appendix A, Figures A-1 through A-5, illustrate the relationship of the system being studied to the overall Apollo power distribution system.

ANALYSIS OF BLOCK POWER SWITCHING

This section describes the analysis performed to evaluate the effects of block power switching. Part 1 of this analysis involved conducting a search to identify the device failures resulting from block power switching (failures occurring to devices during mission phases when they were energized but not required). In Part 2, abort missions and crew loss missions were analyzed to determine the effect of the device failures found in Part 1. The output from two separate computer runs during the 1965 Honeywell Guidance, Navigation and Control Study was used in this analysis.

MARS Computer Program Description

General. - The MARS (Mission Abort Reliability Simulator) computer program is a FORTRAN-language program written for a large-scale digital computer. It uses Monte-Carlo techniques to simulate missions such as space flights using nominal preplanned profiles or variably induced short profiles, and determines the probabilities of mission success and crew survival. As with actual missions conducted on a real-time basis, possible abort decisions are time-variable.

Abort determinations are based on component failures and are made at the end of each simulated mission phase. The MARS computer program can also be used to calculate system reliability for a variety of conventional reliability models, thereby freeing the reliability engineer from tedious hand calculations. Above all, it provides a tool for assessing reliability on systems so complex that a realistic analysis would be impossible to do by hand.

Purpose. - The MARS computer program provides results from a large number of simulated missions, making the following useful information available:

- Percentage of successful missions
- Percentage of missions with crew surviving

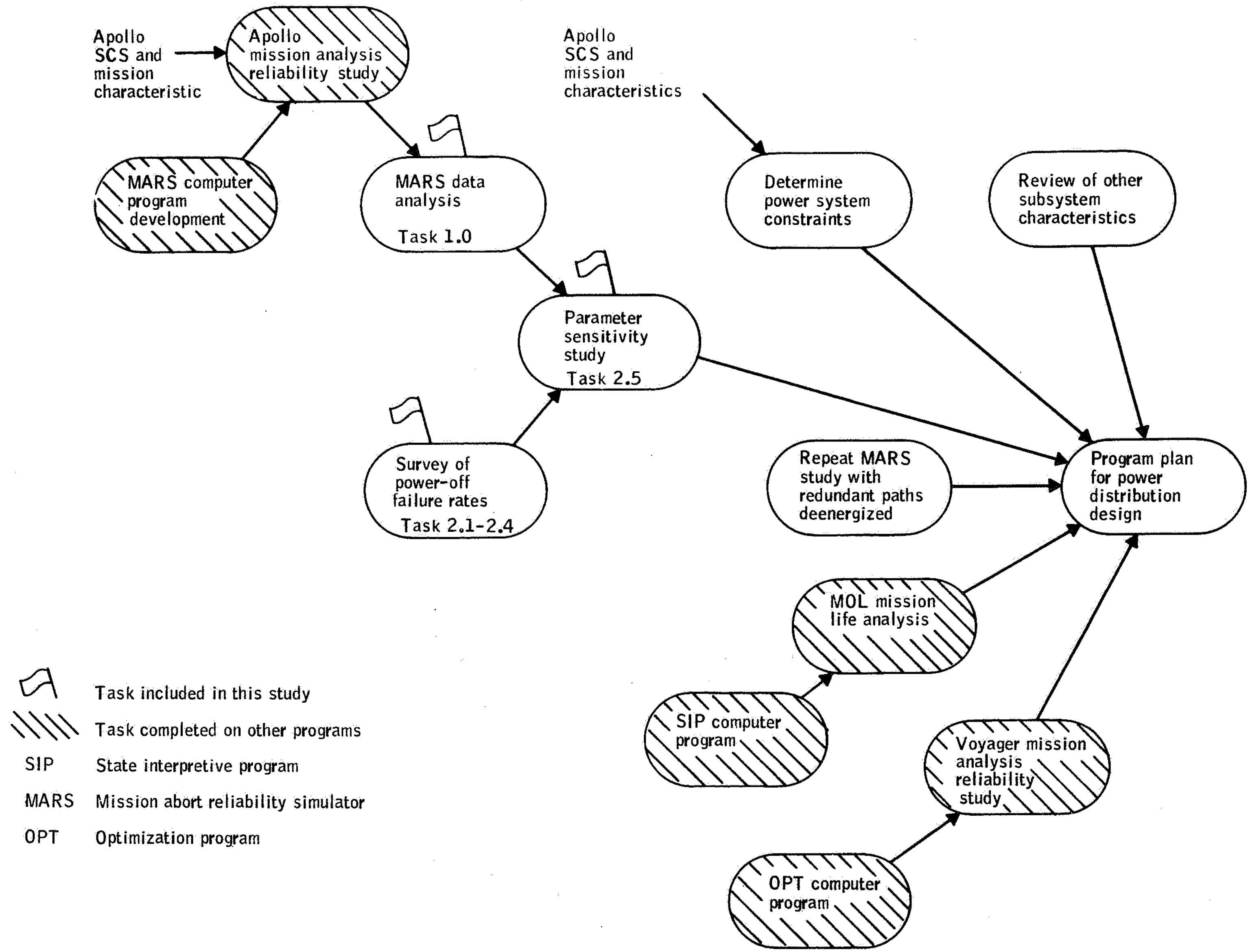


Figure 1. Task Relationship Diagram

- Probabilities of crew survival and mission success at specified confidence levels
- Number of aborted missions
- Number of safely aborted missions
- Distribution of component failures during all missions
- Failures contributing to and causing aborted missions
- Component failures causing system failure
- Component probabilities of success and other data for each phase of the mission

Distinguishing features. -- The MARS computer program:

- Can handle systems using standby redundancy
- Can consider nonrepair periods (phases during which standby spares cannot be used if available)
- Keeps track of cumulative failures during a mission, thus realistically lowering the probability of system success for later phases when there is equipment lost in earlier phases
- Determines limits on reliability at different confidence levels
- Allows system success diagrams to be described by simple algebraic formulas
- Can consider cases of mission abort
- Can consider multicomponent integrated systems
- Can consider multiphase missions

Mission simulation. -- In simulating a mission, the computer makes use of initially computed reliability values for each component for each phase and a random number generator which produces numbers between 0 and 1. By comparing random numbers to the reliability values of each component in the first phase, the computer determines which components are operating and which components have failed by the end of phase 1. The system success diagram for phase 1 can be tested by substituting ones or zeros to represent operating or failed components respectively in the algebraic formula for the first phase and evaluating it. This indicates either a failed system during phase 1 resulting in termination of the mission or a system still operating. In the latter case the simulation procedure is repeated for the second phase, and so on, until either the system fails or the final phase of the mission is sucessfully completed.

Abort missions. -- For missions where aborting is an alternative, the MARS computer program considers the situation after each successful phase simulation. It asks: Has component failure weakened the system to the point where one more component failure in at least one remaining phase could cause system failure? If the answer is yes, the mission is aborted at that time and mission simulation continues as above but through an abbreviated sequence of phases having different phase times. The purpose of the abort is to attempt to save the crew (if it is a manned space flight) but results automatically in mission failure.

Inputs. -- The following MARS computer program data is required for a computer run:

- Component symbolic names and nomenclature
- Failure rates and the number of standby spares available for each component
- Mission phase times and nonrepair periods
- Phase severity factors (to be multiplied by the failure rates)
- De-energized components (components that cannot fail during particular phases)
- Mission phase times for aborted missions
- Algebraic formulas describing system success diagrams for each phase

Outputs. -- Outputs from the MARS computer program include the following:

- Simulation results, after specified numbers of simulations. This includes number of aborts, number of successful aborts, number of aborts resulting in crew loss, number of other missions resulting in crew loss, probability of mission success, and probability of crew survival.
- Tabulation of all component failures by phase
- Useful information pertaining to each aborted mission
- Useful information pertaining to missions other than aborts that resulted in failure

Reliability Model

The reliability model for the MARS computer program is based on pictorial equipment block representations of the equipment required for functional success. Logic statements are derived from the reliability model to provide computer-code notations for alternate combinations of equipment required for successful performance of a given control function. The model is not intended to show signal flow paths as such, but only the requirement of operational readiness and the logical relation to that of another device.

To arrive at these success diagrams, inquiry is first aimed at defining the control functions required of the mission. Since control functions vary throughout the mission, the mission is separated into mission phases, each of which requires a mode of control distinct from the mode on an adjacent phase. With phase-oriented functions, the equipment array required for vehicle control during such phases can be determined by equipment descriptions and the interrelationships of equipment, i.e., functional redundancy.

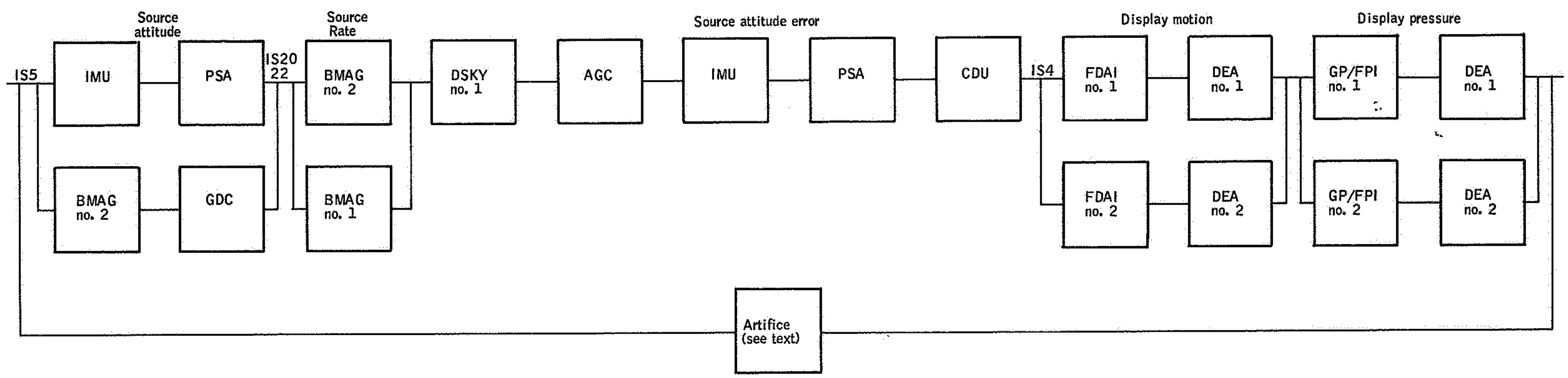
Once functional success diagrams are constructed which can be associated with the continuation of phases from launch through entry for any mission, i.e., lunar landing missions or lunar polar orbit missions, a large part of the computer inputs will have been provided.

In developing the success diagrams for an LLM or an LPO mission, a generalized lunar mission can be considered. This generalized mission is chiefly concerned with the transit portion of the mission, since regardless of the on-site nature of a lunar expedition, the out-bound and in-bound portions are identical when viewed from the aspect of vehicle stabilization and control.

Insofar as transit is concerned, then, only seven functional success diagrams are required:

- Launch to earth orbit insertion translunar injection
- Earth orbit orientation for transposition and docking
- Transposition and docking with SIVB separation
- Preparation for SPS thrusting/pre-entry
- SPS thrusting
- Coast
- Entry

These functional success diagrams (obtained from ref. 1) are included herein as Figures 2 through 8.



Equipment "on", not required

- CEA-RJC
- ASCP
- Manual translation control
- Manual rotation control no. 1
- Manual rotation control no. 2
- SCS DAA-A
- SCS DAA-B
- SCS DAA-C
- SCS DAA-D
- SAA-A
- SAA-B
- CEA-TVC
- CEA-MTVC

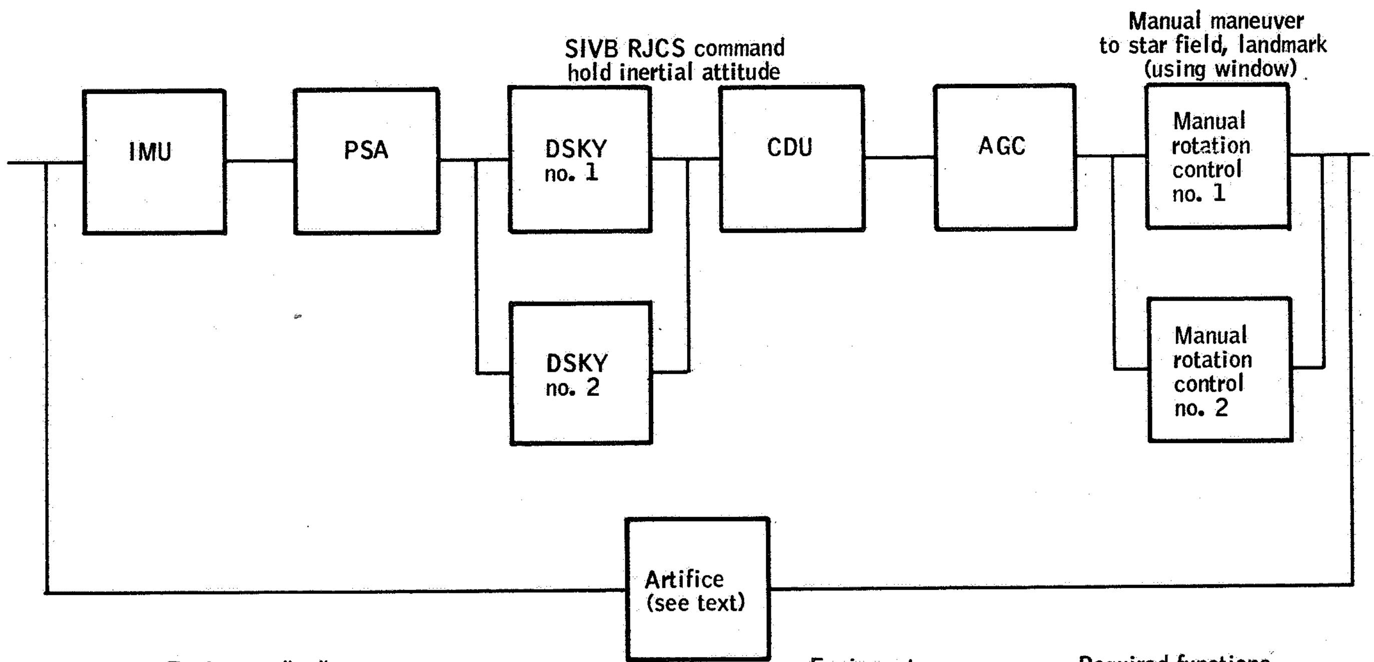
Equipment "off"

- DSKY no. 2
- RSI

Required functions

1) Monitor rates
2) Monitor total attitude
3) Monitor attitude errors
4) Monitor SII and SIVB fuel pressures (SIVB only during TLI)

Figure 2. GN&C - LLM Stabilization and Control Success Diagram. Mission Phase: Launch to Earth Orbit Insertion/ Translunar Injection



Equipment "on" not required

BMAG no. 1
BMAG no. 2
CEA-RJC
CEA-TVC
CEA-MTVC
ASCP
FDAI no. 1
FDAI no. 2
DEA no. 1
DEA no. 2
DAA-A
DAA-B
DAA-C
Translation control
DAA-D

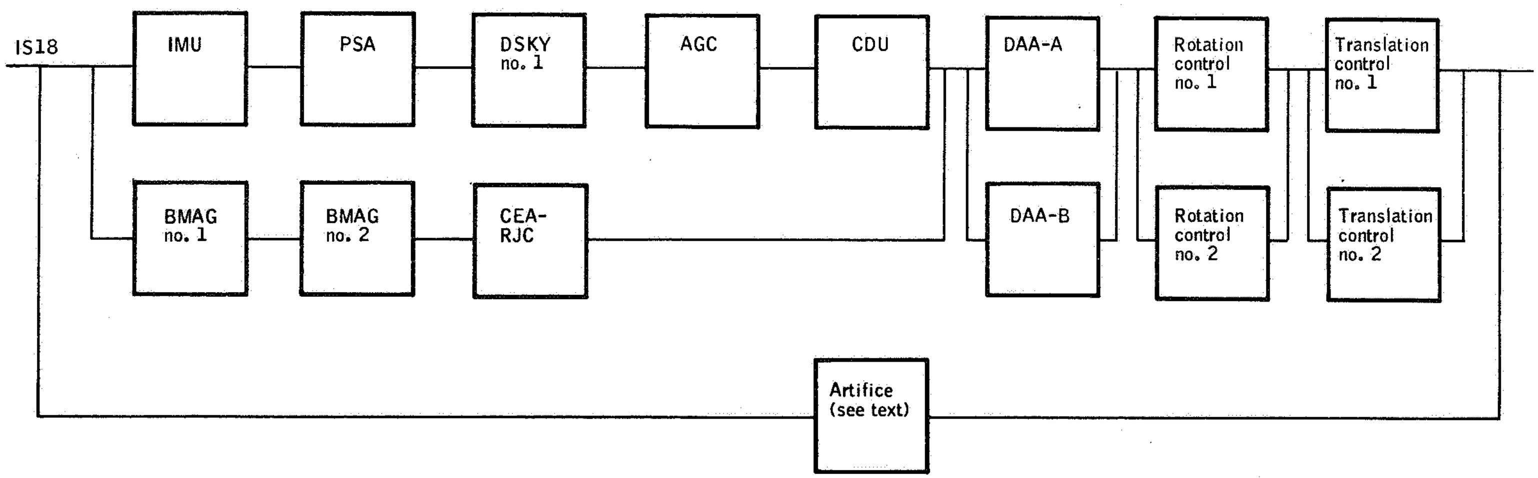
Equipment "off"

SAA-A
SAA-B
GP/FPI no. 1
GP/FPI no. 2
RSI

Required functions

1. Maneuver to star field or landmark and hold attitude through SIVB RJCS (for navigation sightings near earth, orientation for TLI, and orientation for transposition/dock

Figure 3. GN&C - LLM Stability and Control Success Diagram. Mission Phase: Earth Orbit/Orientation for Transposition and Docking



Equipment "on", not required

FDAI no. 1
FDAI no. 2
DEA
GDC
ASCP
DAA-C
DAA-D
CEA TVC
CEA MTVC

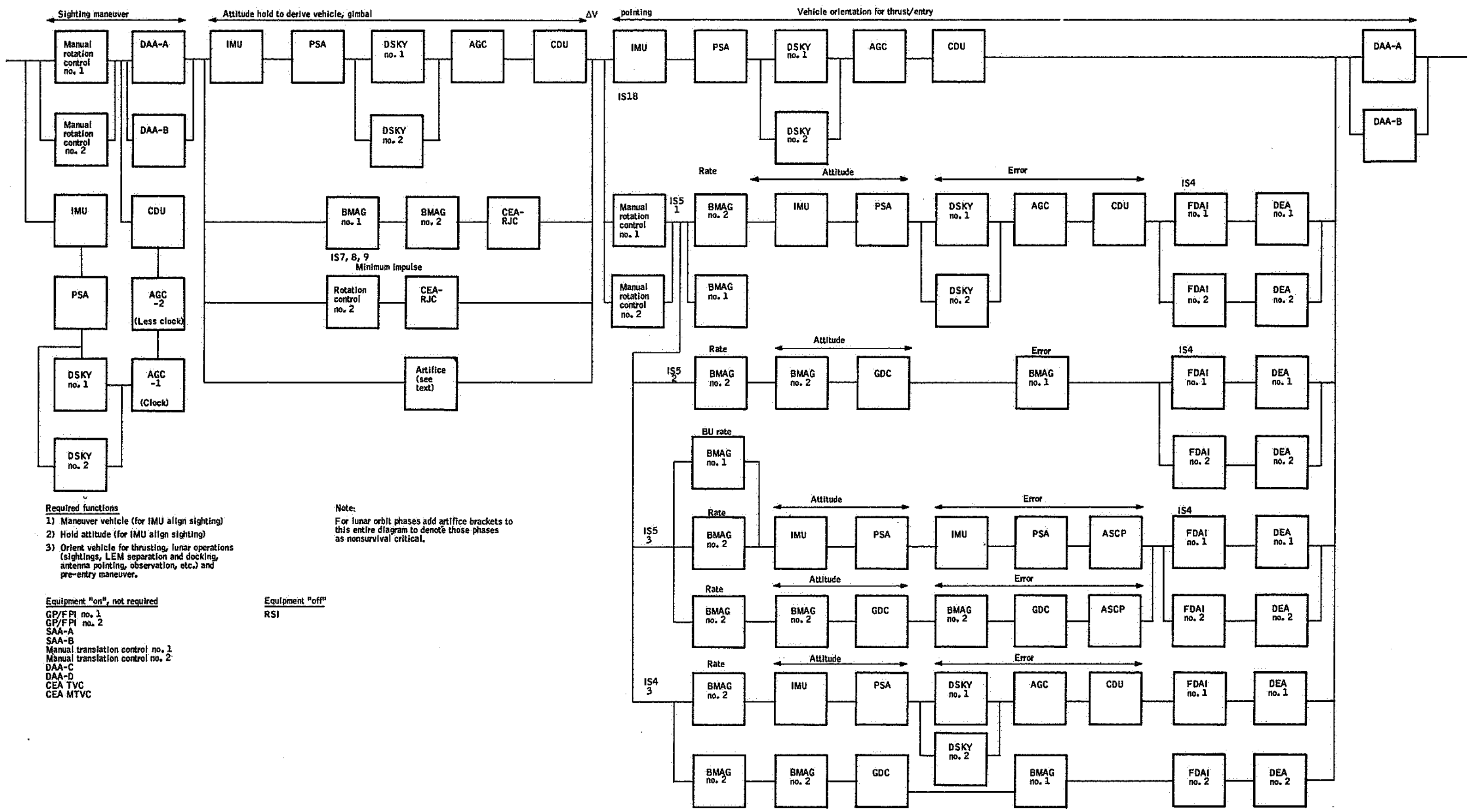
Equipment "off"

SAA A
SAA B
DSKY no. 2
GP/FPI no. 1
FP/FPI no. 2
RSI

Required functions

1) Automatic attitude hold through CSM RJCS
2) Manual translations and
3) Manual rotations (window and exterior lights used for attitude reference)

Figure 4. GN&C - LLM Stability and Control Success Diagram. Mission Phase: Transposition and Docking with SIVB Separation



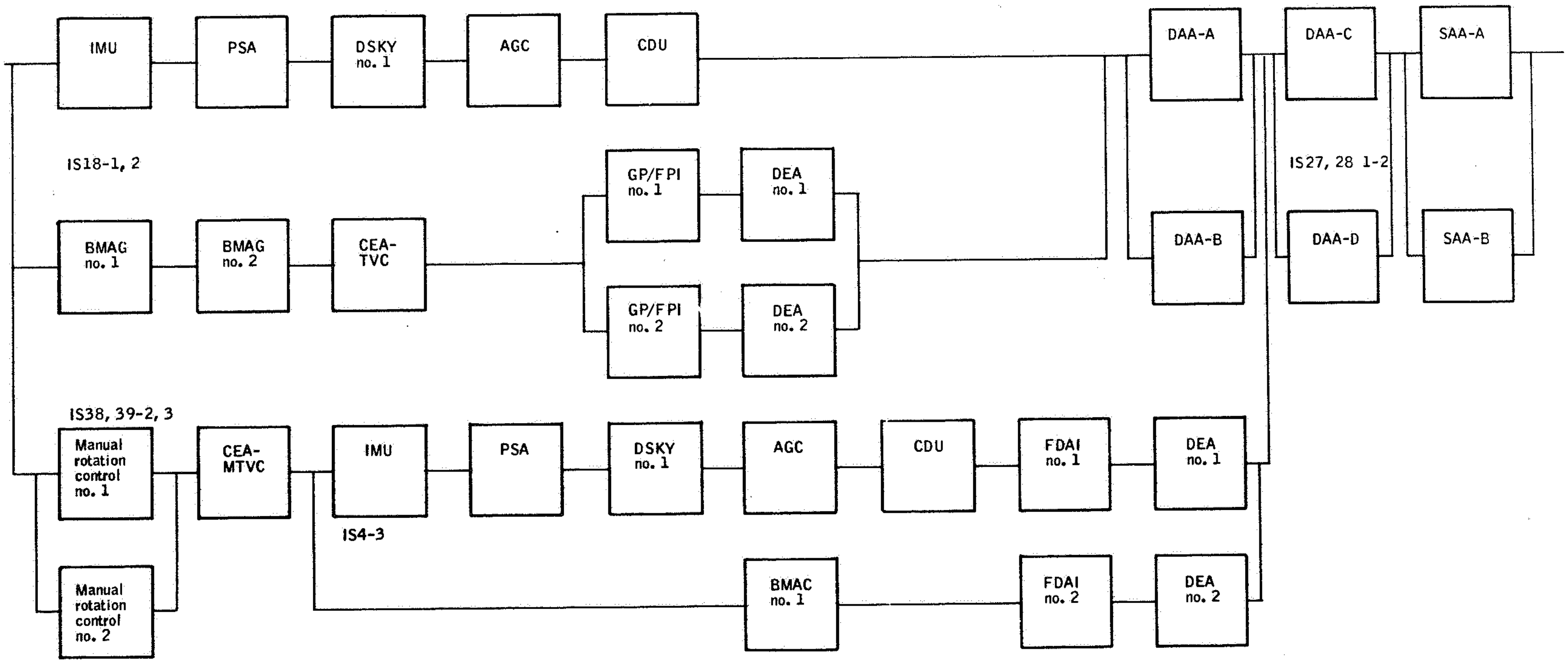
Required functions
1) Maneuver vehicle (for IMU align sighting)
2) Hold attitude (for IMU align sighting)
3) Orient vehicle for thrusting, lunar operations (sightings, LEM separation and docking, antenna pointing, observation, etc.) and pre-entry maneuver.

Note:
For lunar orbit phases add artifice brackets to this entire diagram to denote those phases as nonsurvival critical.

Equipment "on", not required
GP/FPI no. 1
GP/FPI no. 2
SAA-A
SAA-B
Manual translation control no. 1
Manual translation control no. 2
DAA-C
DAA-D
CEA TVC
CEA MTVC

Equipment "off"
RSI

Figure 5. GN&C - LLM Stabilization and Control Success Diagram, Mission Phase: Preparation for SPS Thrusting/Pre-entry

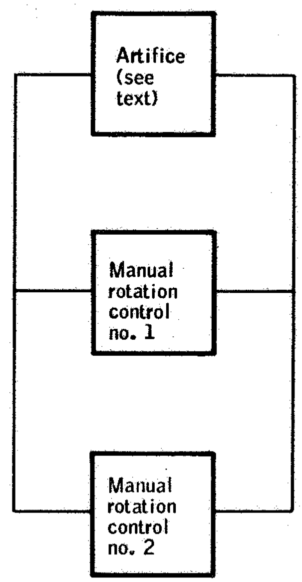


Equipment "on", not required
ASCP
GDC
Manual translation control no. 1
Manual translation control no. 2
CEA-RJC

Equipment "off"
DSKY no. 2
RSI

Required functions
1) Trim gimbals
2) Hold thrust vector, P/Y auto (G&N)or (SCS) manual
3) Hold roll attitude

Figure 6. GN&C - LLM Stabilization and Control Success Diagram. Mission Phase: SPS Thrusting



Equipment "on", not required

AGC clock

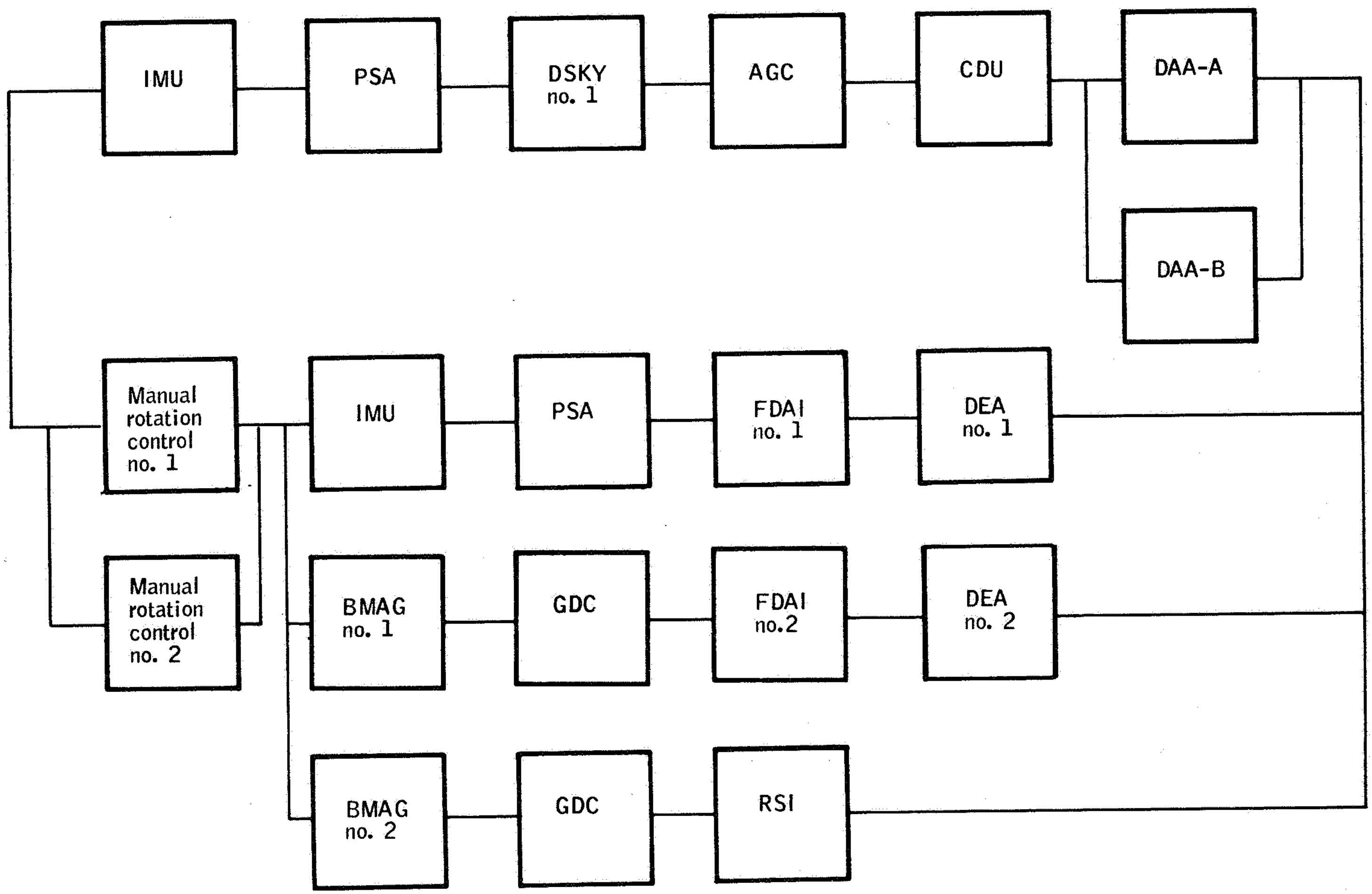
Equipment "off"

IMU	DAA-B
PSA	DAA-C
CDU	DAA-D
AGC (less clock)	CEA TVC
DSKY no. 1	CEA MTVC
DSKY no. 2	SAA-A
BMAG no. 1	SAA-B
BMAG no. 2	ASCP
GDC	GP/FPI no. 1
CEA RJC	GP/FPI no. 2
DEA no. 1	FDAI no. 1
DEA no. 2	FDAI no. 2
DAA-A	Manual translation control no. 1
	Manual translation control no. 2

Required functions

1) Manual maneuver for communication (S-band), and thermal control, I.E., emergency directions for translunar between lunar operations and transearth

Figure 7. GN&C - LLM Stabilization and Control Success Diagram. Mission Phase: Coast



Equipment "on", not required

DAA-C
DAA-D
Translation control no. 1
Translation control no. 2
ASCP
CEA-TVC
CEA-MTVC

Equipment "off"

SAA-A
SAA-B
DSKY no. 2
GP/FPI no. 1
GP/FPI no. 2

Required functions

1. Control lift vecter (roll vehicle automatically or manually with roll attitude displayed)

Figure 8. GN&C - LLM Stabilization and Control Success Diagram.
Mission Phase: Entry

The GN&C equipment considered in these diagrams is summarized in Table I, along with predicted device failure rates. In general, it consists of all the G&N less optics, the entire SCE complement of equipment, and the roll stability indicator portion of the entry monitor system.

On each diagram, notations are made of other equipment "on" but not required and also equipment "off". These notations are required computer inputs so as to provide conditional probabilities. For example, in one phase a device may not be required for success in that phase but is powered "on" and is required in the next phase. To realistically assess the probability of the device performing in that next phase, the probability of its being available must be considered, and that is the conditional probability being accounted for in the previous phase. These notations of device energizations are derived from a study of the power switching portion of the main display console. For example, if one device is required in the success diagram, then additional devices must be indicated to be in the energized state if they also receive power from the same power switch. Alternatively, if a device is shown to be off, the device failure rate is correspondingly considered to be zero.

As a consequence of the mission abort and crew survival criteria it is necessary in some instances to insert a computer artifice device around success paths or portions thereof (ref. 1). The following considerations are offered for the artifice device unique to each diagram:

Figure 2 — Launch through earth orbit/translunar injection. Surrounding the entire success diagram is the computer artifice of unity reliability to indicate that an interruption of this diagram does not result in crew loss. Therefore, this phase diagram is processed by the Honeywell H1800 computer only to determine the need for aborting the mission.

Figure 3 — Earth orbit orientation for transposition and docking. The H1800 computer artifice device (unity reliability) again is shown to indicate that loss of the GN&C in this phase does not result in crew loss.

Figure 4 — Transposition and docking with SIVB separation. The artifice designates this diagram as nonsurvival critical.

Figure 7 — Coast. The H1800 computer artifice designates this phase as nonsurvival critical.

Ref. 1 illustrates how these success diagrams are applied to specific missions (LLM and LPO), along with other diagrams unique to each of these missions.

TABLE I
GUIDANCE, NAVIGATION, AND CONTROL EQUIPMENT

Code	Name	Failures per 10^6 hours
G&N		
G&N IMU	Inertial measuring unit	125
IMU CDU	Coupling data unit	181
IMU PSA	Power servo assembly	116
G&N AGC (operate)	Apollo guidance computer - less clock	286
DSKY 1	Display and keyboard assembly - 1	200
DKSY 2	Display and keyboard assembly - 2	200
G&N AGC clock (standby)	Apollo guidance computer - clock	96
SCS		
BMAG 1	Body-mounted attitude gyro - 1	180
BMAG 2	Body-mounted attitude gyro - 2	180
GDC	Gyro display coupler	129
CEA RJC	Control electronic assy. - reaction jet control	16
CEA TVC	Control electronic assy. - thrust vector control	19.2
CEA MTVC	Control electronic assy. - manual thrust vector control	18.7
FDAI 1	Flight director attitude indicator - 1	120
FDAI 2	Flight director attitude indicator - 2	120
DEA (chan. 1, 2)	Display electronics assembly	43/43
GP/FPI (chan. 1, 2)	Gimbal position fuel pressure indicator	12/12
AS/CP	Attitude set control panel	21
TRANS. CON 1/2	Translation control	1.5/1.5
ROT. CON. 1/2	Rotation control	12/12
DAA A, DAA B	Driver amplifier assembly - reaction jet	17/17
SAA (chan. 1, 2)	Servo amplifier assembly	14/14
DAA - C/D	Driver amplifier assembly - engine valve	1.5/1.5
EMS		
RSI	Roll stability indicator	13

Evaluation of Mission Simulations

Evaluation of mission simulations was accomplished by using the output from two separate computer runs made during the 1965 Honeywell Guidance, Navigation and Control Study. One of these runs simulated 100 lunar polar orbit missions, while the other simulated 5000 lunar landing missions. The printout from these runs provided a tabulation of device failures from which it was possible to isolate the device failures occurring to devices during a mission phase when they were energized but not required.

The LPO run printout was used in analyzing abort and crew loss missions. Each device failure of the type isolated in the above mentioned task was studied to determine whether it occurred during a simulated mission which resulted in abort. For those that did, it was then determined whether or not that failure had any effect on the decision to abort. This was accomplished by making use of computer printout data and the reliability phase block diagram.

Results of Analysis

The LPO run had 88 device failures in 100 mission simulations. Of these, seven failed while energized and not required. Table II is a compilation of these failures. The LLM run resulted in 667 device failures in 5000 missions, but 153 of them were in the energized but not required category when they failed. Table III is a compilation of LLM failures. Tables IV and V show the devices energized and not required in each phase for the LPO and LLM runs respectively. For identification of the symbolic device names in these tables, refer to the MARS computer program data in Appendix B.

Of the seven failures that occurred to devices while energized and not required, two occurred during simulated missions which resulted in abort. In each of these missions an abort would have been required even in the absence of these failures due to other failures that occurred during the same mission. The fact that these two particular failures were not the cause of abort in these particular missions does not imply that they were unimportant. Failures of this type could be the cause of aborting depending on when they fail and what else fails.

Table VI lists simulation results for both the LPO and the LLM runs.

Conclusions

Results of the analysis show that approximately 23 percent (153 out of 667) of the device failures that occurred during the 5000 LLM simulations could be attributed to equipment that was energized but not required at the time of the failure. This is a significant number and indicates the possibility of a considerable improvement in reliability. The LPO mission simulation indicated eight percent (seven out of 88) of the device failures occurred when they were energized but not required. The difference in results is attributed to variations in mission profile and system/power configuration. The impact of the potential failure reduction on system reliability will be evaluated by means of additional MARS computer program simulations planned as a part of the next study phase.

TABLE II
LUNAR POLAR ORBIT MISSION FAILURES

LPO mission

100 mission simulations

88 total device failures

7 device failures resulting from equipment energized but not required

Phase	Elapsed time (hrs)	Y1	Z1	A2	T2	X2	Totals
		Device designation					
1	.19						
2	3.00						
3	3.09						
4	3.34						
5	3.67						
6	4.92						
7	4.925						
8	55.325						
9	56.325						
10	56.3285						
11	68.1285						
12	69.1285						
13	69.1305						
14	70.1305						
15	70.2105						
16	406.2105	1	1	1		1	4
17	407.2105						
18	407.2155						
19	743.2155				2	1	3
20	744.2155						
21	744.2435						
22	763.2435						
23	764.2435						
24	764.2477						
25	808.2477						
26	809.2477						
27	809.2487						
28	831.2487						
29	832.2487						
30	832.2493						
31	833.2493						
32	833.4293						
Totals	833.4293	1	1	1	2	2	7

TABLE III
LUNAR LANDING MISSION FAILURES

LLM mission

5000 mission simulations

667 total device failures

153 device failures resulting from equipment energized but not required

Phase	Elapsed time (hrs)	T1	V1	W1	X1	Z1	A2	B2	F2	G2	H2	O2	P2	Q2	R2	S2	T2	U2	V2	X2	Totals
		Device designation																			
1	.19							2		1											3
2	3.00		3	2				1			1	1	4	3						1	16
3	3.09																				
4	3.34																				
5	3.67												1								1
6	4.92																				
7	4.925																				
8	55.325	8																			8
9	56.325																				
10	56.3285																				
11	68.1285	3																			3
12	69.1285																				
13	69.1305																				
14	70.1305																				
15	70.2105																				
16	72.4905									1						1					2
17	72.5065																				
18	94.8065					3	4		1	1					2	1					12
19	193.8065	20																			20
20	246.8065	10			29	3	2										2	4	1	7	58
21	246.8345				1																1
22	265.8345	6																			6
23	266.8345								1												1
24	266.8387																				
25	310.8387	11																			11
26	311.8387					1															1
27	311.8397																				
28	333.8397	10																			10
29	334.8397																				
30	334.8403																				
31	335.8403																				
32	336.0203																				
Totals	336.0203	68	3	2	30	7	6	3	2	3	1	1	5	3	2	2	2	4	1	8	153

TABLE IV
LUNAR POLAR ORBIT MISSION - EQUIPMENT
ENERGIZED/NOT REQUIRED

LPO mission - equipment energized / not required.

Phase	
1	Y1, X2, V2, W2, T2, U2, B2, C2, D2, E2, F2, G2, Z1, A2
2	V1, W1, Y1, Z1, X2, P2, Q2, H2, O2, B2, C2, D2, E2, V2, W2
3	Same as 1
4	Same as 2
5	P2, Q2, H2, O2, X1, X2, D2, E2, Z1, A2
6	R2, S2, F2, G2, V2, W2, D2, E2, Z1, A2
7	X2, X1, V2, W2, Y1
8	T1
9	Same as 6
10	Same as 7
11	Same as 8
12	Same as 6
13	Same as 7
14	Same as 6
15	Same as 8
16	D2, E2, T2, U2, V2, W2, Y1, Z1, A2, X2
17	Same as 6
18	Same as 7
19	Same as 16
20	Same as 6
21	Same as 7
22	Same as 8
23	Same as 6
24	Same as 7
25	Same as 8
26	Same as 6
27	Same as 7
28	Same as 8
29	Same as 6
30	Same as 7
31	Same as 6
32	D2, E2, V2, W2, X2, Z1, A2

TABLE V
LUNAR LANDING MISSION - EQUIPMENT ENERGIZED/NOT REQUIRED

LLM mission - equipment energized/not required.

Phases 1 - 14 same as for the LPO mission.

Phase	
15	Same as 7
16	Same as 6
17	V2, W2, X1, H2, O2, P2, Q2, X2, D2, E2, Z1, A2
18	Same as 6
19	Same as 8
20	D2, E2, V2, W2, T2, U2, X1, Z1, A2, T1, X2

Phases 21 - 32 same as for the LPO mission.

TABLE VI
SIMULATION RESULTS FOR LPO AND LLM RUNS

Number of simulations	Aborts	Successful aborts	Crew loss aborts	Other crew losses[a] phases 1-18	Other crew losses[b] phases 19-32	Mission success reliability	Crew survival probability
100 (LPO)	23	22	1	0	1	0.760000	0.980000
5000 (LLM)	76	76	0	0	1	0.9846	0.9998

a. Crew loss resulting from system failure which prevents abort procedures from being implemented.

b. Abort procedures are not applicable to these mission phases.

FAILURE RATE DETERMINATION

Honeywell Equipment Data Survey

A detailed survey of Honeywell equipment data was conducted in an effort to correlate the number and/or type of equipment failures with either the number of power applications or the time intervals between power application and the length of time power was applied. Initial surveys disclosed that operational logs and failure summaries were readily available on the Apollo SCS, but that such data for other Honeywell programs would be more difficult to obtain.

The two major sources for equipment operational logs are: (1) the End Item Data Book (EIDB), and (2) the Assembly Configuration List (ACL). The ACL contains data on the initial build, calibration, and checkout of hardware up to the time it is turned over to the quality department to acceptance test for delivery to the customer. The EIDB contains data on initial acceptance testing and any subsequent rework, modification, or retrofit checks and tests at Honeywell. Altogether, these logs provided data on 39, 647 device operating hours, 4462 cyclings of power application to the devices, and 531, 910 device nonoperating or storage hours.

General. -- Equipment data on the number of power applications and the time intervals between power applications was relatively easy to obtain. The more difficult task was in relating the experienced failures to power cycling or storage conditions. Before relating failures, it was necessary to establish the ground rules for classifying a discrepant condition as a failure. The primary concern in this study was to associate power application cycling with device failures and not with mission failures; therefore all elements of redundancy and backup were ignored. In addition, those failures due to conditions external to the device under study were excluded from consideration. Unstable device operation due to improper mating of the interface connector, or to a fault in the external cabling, or a relay failure in the peripheral equipment could not properly be considered failure of the device even though the device might no longer be able to be used. Within these general guidelines, the following situations were considered failures:

- Loss of device output
- Serious distortion of device output
- Significant out-of-spec condition of device output
- Loss of power to other devices

Once a device failure was identified, it became necessary to determine its relationship to power cycling or storage conditions. The failures were reviewed in light of the following questions:

- Was the failure caused by turning-on the device?
- Was the failure caused by turning-off the device?
- Was the failure caused by having the device in a non-operational status (in "storage")?

Data analysis. -- Using the established criteria, 5 failures were considered relevant to this study. Four were attributed to the on-off element of power cycling, and 1 was attributed to a condition which developed from storage of the device. Table VII lists the results of a survey of device production operational logs and acceptance testing operational logs for 16 units each of 5 different devices and 31 units of a sixth device.

Data summaries. -- Several data summaries were prepared; first for each serially numbered device for each type of test or check, second for the devices for each type of test or check, and third a total summary for the devices. The device summaries are available in Honeywell's Reliability Data Center along with Xerox copies of the device operating logs. They are not included in this report for reasons of brevity. The results of these summaries are reflected in Table VII.

The summaries by topic type are:

1) On-Offs: The quantity of times the device was turned on then off, i. e., the number of cycles of power application to the device.

2) On time in hours: The quantity of device operating hours during performance checks and tests.

3) Off time during performance checks (in hours): The quantity of off hours within a type of test. During a production check or acceptance test the device may be turned off because of operator time schedules, test equipment requirements or availability, malfunction or failure investigation, rework, or the test may require so many hours on and so many hours off.

4) Off time between performance checks (in months and days): The quantity of off time between types of tests.

5) TDR (Test Discrepancy Report) and on-off relationship: This relationship means that the time of occurrence of the TDR coincided and may have been caused by the on or have caused the off.

Investigation and review of the individual TDRs resulted in obtaining the data shown in Figure 9.

TABLE VII
SUMMARY OF RECORDED DATA

Device	Parts count	Failure rate[a], failures per 10^6 hours	Device "on" time hours	Power Cycles		"Off" time	
				Device cycles	Part cycles	Device hours	Part hours
A	2 476	74.1	5 339	411	1 017 636	119 346	295 500 696
B	1 580	46.5	4 186	283	447 140	84 166	132 982 280
C	1 348	31.4	2 773	272	366 656	78 597	105 948 756
D	850	29.4	3 299	313	266 050	101 777	86 510 450
E	2 071	132.5	8 319	847	1 754 137	24 505	50 749 855
F1	803	177.6	9 253	1 574	1 263 922	64 843	52 068 929
F2	803	177.6	6 478	762	611 886	58 676	47 116 828
Total	9 931	669.1	39 647	4 462	5 727 427	531 910	770 877 794

[a]These are the predicted device failure rates based on high reliability parts used in a space environment.

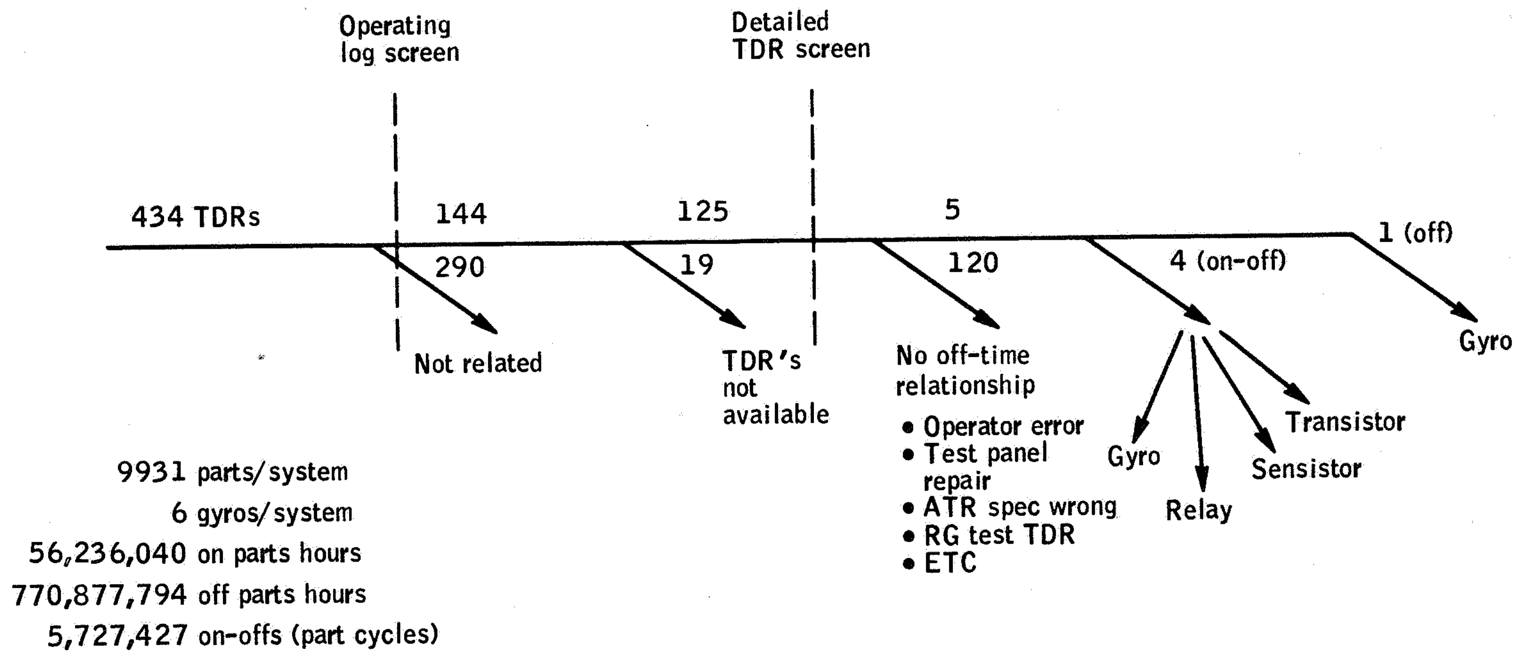


Figure 9. Screening of Test Discrepancy Reports

Results and conclusions. -- In reviewing these results it should be noted that the identifications of the 4 significant failures represent the review and judgement of a single senior reliability analyst familiar with Apollo equipment in particular and flight control equipment in general. It is assumed that these 4 failures were due only to cycling and not to any other cause. It was also assumed that the operating failure rates did not include failures due to cycling, or due to nonoperating time. Based upon these assumptions the following calculations were made:

- Device failure rate due to power cycling:

$$\frac{4 \text{ failures}}{4462 \text{ device power cycles}} = 896 \text{ failures}/10^6 \text{ cycles}$$

- Device failure rate due to storage (nonoperating) time:

$$\frac{1 \text{ failure}}{531,910 \text{ device storage hours}} = 1.88 \text{ failures}/10^6 \text{ hours}$$

- Piece-part failure rate due to power cycling:

$$\frac{4 \text{ failures}}{5,727,427 \text{ part cycles}} = 0.698 \text{ failure}/10^6 \text{ cycles}$$

- Piece-part failure rate due to storage (nonoperating) time:

$$\frac{1 \text{ failure}}{770,877,794 \text{ part storage hours}} = 0.0013 \text{ failure}/10^6 \text{ hours}$$

The average operational piece-part failure rate can also be determined and from this information the operating-to-nonoperating failure rate ratio can be obtained.

- Average operating piece-part failure rate:

$$\frac{669.1 \text{ failures}/10^6 \text{ hours}}{9,931 \text{ parts}} = 0.0674 \text{ failure}/10^6 \text{ hours}$$

- Operating-to-nonoperating failure rate ratio:

$$\frac{0.0674}{0.0013} = 51.8 \text{ to } 1$$

The significance of the failure rate due to cycling can also be shown by a comparison with the operating failure rate. This results in a operating-to-cycling failure rate ratio of

$$\frac{0.0674}{0.698} = 0.0966 \text{ to } 1$$

Therefore, based on the observed data, the failure rate due to power cycling is approximately 10 times the failure rate due to operating time. This indicates that as the number of on-off cycles is increased for any given mission, the failure rate due to cycling could be much more important than the failure rate due to operating time.

In evaluating these results it is also important to consider the limitations of the data. The limitations of the data (due to the number of hours and failures recorded) are significant in the case of the storage failure rate due to the inclusion of only one failure. However, by comparing the ratio of 51.8 to 1 with the range of data $\left(\frac{30.2 \text{ to } 53.9}{1}\right)$ derived from the literature search, it appears reasonable that a worst case failure rate ratio between operating and nonoperating time is in the approximate magnitude of 30 to 1 (see literature survey).

The large amount of data required to identify significant failures is indicated in Figure 9. Out of 434 TDRs reviewed, only 5 were determined to be related to on-off cycling or storage conditions. The limitations of the data prevent the development of failure rates for individual piece parts due to power cycling or storage conditions; however, an estimate has been made of the average failure rate observed, without regard to the type of component.

Vendor Information Survey

A survey of piece-part vendors was conducted as a part of the effort to determine piece-part failure rates due to power on-off cycling and storage time. In addition to vendor contacts, the Parts Reliability Information Center/Apollo Parts Information Center (PRINCE/APIC) was contacted for available information. The survey provided a limited amount of power on-off cycling information and no information on the effects of storage time on piece-part failure rates. No pertinent information was available from PRINCE/APIC.

Effect of power on-off cycling. -- Communication with the manufacturers of piece parts has indicated that power on-off cycling is approximately equivalent to small-increment high-temperature cycling. It is believed that power cycling of piece parts would detect any thermal expansion discrepancies of the components. Although no specific information related to the effect on piece-part failure rates was available from the vendors, the Honeywell Component Applications and Standards (CA&S) group was able to provide additional information in support of the relationship to thermal expansion problems.

Current information indicates that wedge-type bonds in semiconductor devices are highly sensitive to low-frequency power cycling. Specific tests conducted verify that thermal expansion and contraction actually move the lead and die which results in flexing the thin portions of the lead and causes failure. The basic wedge bonding process (Ref. 2) illustrates that too much wedge pressure can cause a very thin mechanical connection of the lead and die. In addition, high mechanical stress and crystalization can occur at this point. If the lead wire is flexed after the connection has been made, the additional stress may result in failure of the device.

Test data also indicates that this failure mode is possible when the device is used in a switching application at either high power (above 85 percent rated) or near rated current. Movement of the internal emitter and base wires has been observed with low repetition rate, high-current pulses applied in the forward direction of the emitter-base junction. In the case of the aluminum-to-aluminum wedge bond transistor, it has been shown that complete bond failure may result from lead movement due to current pulses. The actual movement of the aluminum bonding wire is attributed to the thermal effect of heating and cooling the wire.

The relationship between thermal cycling and power on-off cycling has also been indicated as an important factor at the equipment level. In some cases an internal temperature rise of 50°C (Ref. 3) may be expected each time the equipment is turned on. Recent reliability tests performed by Collins Radio Company proved that failures have occurred as a direct result of temperature cycling.

Conclusions. -- The survey of piece-part vendors identified failure modes associated with on-off power cycling but it did not produce quantitative failure rate data. Vendor communications have indicated that power cycling will detect thermal expansion discrepancies and recommendations have been made to perform burn-in and temperature cycling until piece parts are fully stabilized.

Because of the relationship between power on-off cycling and temperature cycling, it is apparent that field reliability improvements could be achieved by means of effective temperature cycling of equipment to screen out marginal piece parts. Reliability testing, including temperature cycling and power on-off cycling, should be included as a part of each hardware development and production program. The significance of the tests in MIL-STD-781A should not be neglected as a means of identifying equipment sensitivity to power on-off cycling.

Literature Survey

A survey of available literature was conducted as a part of the effort to determine the effect on subsystem failure rates due to the length of nonoperating time and the number of times power is applied and removed during the life of the equipment. In addition to reviewing published symposium papers and technical magazine articles, the Honeywell Aerospace library conducted a search of the Applied Science and Technology Index, Electrical Engineering Abstracts, International Aerospace Abstracts, Engineering Index, NASA STAR Index, DDC Index, and the library Card Catalog and Uniterm File.

Several significant papers and articles were identified as a result of the literature search and the references considered most applicable are listed in the bibliography at the end of this report.

General.-- If the reliability of a system is defined as the probability of survival for a specified period of time, it may be expressed as

$$P(s) = P_o \cdot P_{no} \cdot P_{cyc}$$

where

$P(s)$ = the probability of system survival

P_o = the probability of survival during operating time

P_{no} = the probability of survival during nonoperating time

and

P_{cyc} = the probability of surviving the on-off cycles

The probability of success is then obtained from the product of the probabilities of success for each condition.

If only random failures are considered, the probability for each condition will include a constant failure rate corresponding to the generally accepted prediction technique for most electronic equipment based on the exponential distribution. This requires that components such as switches, lamps, relays, motors, bearings, etc., be replaced prior to their wearout period. If the constant failure rate can be determined for each probability of survival, then the probability of system success can be obtained.

The literature search has shown that nonoperating data in excess of 760 billion part-hours is available. It is therefore possible to approximate a constant failure rate from the component part failure data by using the common relationship

$$\lambda = \frac{F}{nt}$$

where

λ = the failure rate

F = the number of failures

n = the total number of components

and

t = time (or on-off cycles)

The failure rate can also be expressed in terms of the component mean-time-between-failures (MTBF) or the mean-cycles-between-failures (MCBF). The MTBF is the reciprocal of the failure rate:

$$MTBF = \frac{1}{\lambda}$$

Effect of power on-off cycling. -- Only a limited amount of literature is available on the effect power on-off cycling has on the equipment failure rate. It is often assumed that turn-on/turn-off transients do not cause failures (Ref. 4) or that the failure rate due to cycling is not significant. These assumptions may be valid if the equipment under consideration is expected to see only a few on-off cycles and if specific design considerations were taken to minimize power supply transients and to ensure that all component parts are properly applied within their own stress rating.

It is readily apparent that component parts such as relays, switches, etc., are highly sensitive to the number of operations (or cycles) and that this characteristic should be included in the failure rate estimation (Ref. 5). Additional information on power on-off cycling effects has been provided by the survey of Honeywell experience and available vendor information (also by Ref. 2).

Effect of storage time. -- As in the case of power on-off cycling, the effect storage has on the equipment failure rate may or may not be significant. The obvious need for reliability data on operating failure rates has resulted in a tendency to minimize the importance of potential problems due to storage failures. Nonoperating failure rates and failure modes have become increasingly significant with the advent of new weapons that are left unattended for long periods of time and as long space missions require high ratios of nonoperating to operating time. Several significant papers and articles are currently available regarding nonoperating failure rates and sufficient evidence has been acquired to support the existence of storage failure rates.

Over 760 billion part-hours of nonoperating experience data (Ref. 6) have been accumulated by Martin Marietta Corporation. A summary of the hours related to the military standard and high reliability parts is presented in Table VIII.

TABLE VIII
NONOPERATING PARTS DATA

Part Classification	Part Hours (millions of hours)
Military standard	76, 244.7115
Select military standard	52, 464.4324
High reliability	631, 500.8144
Total	760, 209.9583

The detailed data presented by Martin Marietta Corporation has enabled the preparation of the nonoperating failure rates of Table IX. These failure rates illustrate typical values for the storage (equipment packaged for preservation) and dormant (equipment connected in an operational system but not significantly stressed) conditions for each piece part listed. A high level of confidence should not be placed on the specific values, since many of the failure rates are limited by the number of hours recorded or are based upon only a few failures. In cases where the available data severely limited the piece-part failure rate, the failure rate has been omitted from the table.

The nonoperating failure rate data also provides a means of obtaining representative operating-to-nonoperating failure rate ratios. Many companies have used operating-to-nonoperating failure rate ratios in the range of 10:1 and 15:1 for reliability predictions. Failure rate ratios are apparently influenced by several factors which affect the nonoperating failure rate, with the most drastic reduction in failure rate attributed to extensive parts screening. The study completed by Martin Marietta Corporation indicates that the average operating-to-nonoperating failure rate ratio is about 15:1 (no justification is given in support of the operating failure rate).

A dormant-to-storage failure rate ratio can be determined from the total part hours available for electronic equipment. The average failure rate for high reliability parts in the dormant condition was found to be 0.00125 failure per million hours and for the storage condition 0.00039 failure per million hours (Ref. 6). This results in a dormant-to-storage failure rate ratio of 3.2 to 1.

The average operational piece-part failure rate for the total SCS (previously discussed) is based on individual piece-part failure rates obtained from Honeywell experience data. If the rate of 0.0674 failures per million operating hours is compared with the rate of 0.00125 failure per million nonoperating hours, a significant operating-to-nonoperating ratio of 53.9 to 1 is obtained. This ratio may be somewhat high due to the inclusion of parts other than those generally considered electronic piece parts. If the average operational failure rate is calculated for equipment containing primarily electronic piece parts (i.e., omit device F1 and F2 of Table VII),the failure rate is found to be

$$\frac{313.9 \text{ failures}/10^6 \text{hours}}{8325 \text{ parts}} = 0.0377 \text{ failure}/10^6 \text{ hours}$$

This results in an operating-to-nonoperating failure rate ratio of 30.2 to 1 for the electronic parts.

Conclusions. -- Until such time when a sufficient number of hours and failures have been recorded to provide a significant degree of confidence in the required piece-part failure rates, it is recommended that ratios (or application factors) be used to modify the failure rate to enable reliability predictions to be made for equipment under nonoperating conditions. These nonoperating application factors should be applied to the failure rate for only the specific periods of time the equipment is to remain in a dormant or storage condition. From the results available from this study, the factor would be in the approximate magnitude of 1/30.

TABLE IX
NONOPERATING FAILURE RATES
(FAILURES/10^6 HOURS)

Piece part	Storage failure rates: Military standard	Storage failure rates: Selected military standard	Storage failure rates: High reliability	Dormant failure rates: Military standard	Dormant failure rates: Selected military standard	Dormant failure rates: High reliability
Capacitors	.0021		.00007			.00066
Ceramic	<.0010					
Glass			<.00019			.00008
Mica	.0095					
Paper	.0030		<.00049			<.00018
Tantalum, foil, wet	.0042		<.00059			.00048
Tantalum, slug, wet	.0671					.06870
Tantalum, solid	.0444		<.00020			.00063
Diodes	.0031	.0011	.00049			.00101
High-power rectifier (Si)			<.00090			.00056
Medium-power rectifier (Si)	.0099		<.00040			.00123
Medium-power zener (Si)			.00246			.06390
Low-power rectifier (Si)	.0007	.0005	.00029			.00042
Low-power rectifier (Ge)	.0162					
Low-power zener (Si)	.0023	.0042	.00336			.00548
General-purpose		.0008				.00043
General-purpose zener		.0095				
Low-power micro						.00848
Medium-power micro						.07840
Inductive devices						
Coils	.0013					
Power	.0672					
Filters	.0643					
Assembly	.4480					
Microcircuits	.0230			.0908	.1200	.04090
DCTL	.1290					
DTL	.0503					.03980
RCTL					.1770	
RTL	.0174				.1160	
Linear						.05290
Relays	.0586	<.0272				
Armature	.1350					
Resistor	.0009	.0016	.00007			.00018
Fixed	.0011		.00007			.00018
Carbon composition	.0001	<.0007	.00004			.00009
Film	.0041		.00076			.00140
Carbon film	.0057		.00322			.00599
Metal film			<.00033			.00027
Wirewound	.0024		<.00040			.00072
Power wirewound			<.00048			
Precision wirewound	.0036		<.00213			.00145
Variable wirewound	.0047					
Switches	.1780					
Pressure	.3230					
Inertial	.2370					
Transformers	.0139					
Transistors	.0182	.0073	.00135			.00470
High-power alloy (Si)	.0162					.42000
High-power alloy (Ge)			.00661			.02080
High-power mesa (Si)	.1520					
Medium-power mesa (Si)	.0310	.0021				
Low-power mesa (Si)		.0117	.00058			.00210
Low-power alloy (Si)	.0749					
Low-power alloy (Ge)	.0268		.00281			.00545
Low-power mesa (Si)	.0277					
Low-power planar (Si)	.0240					
General		.0077				

Special consideration should also be given to ensure that the limitations of the piece parts are not exceeded. Specific design criteria should be established to provide a review of equipment possessing shelf life or cyclical life limitations. If the exponential distribution is to be used in the reliability predictions, all equipment subject to wearout must be replaced prior to the expected end of life. The approximate lifetime of individual parts highly sensitive to wearout may be calculated as indicated in Ref. 7. It should be emphasized that nonoperating failure rates (or application factors) do not include consideration for equipment wearout characteristics but are only representative of the expected random equipment failures.

ANALYSIS OF SCS SENSITIVITY

Analysis of the guidance, navigation and control system was conducted with the aid of Honeywell's State Diagram Interpretive Program (SIP) to determine the sensitivity of the system to failure rate changes. A system configuration which could be used for a lunar polar orbit mission was used as a basis for this study. Four mission time profiles were used, each having a total length equal to that of a lunar polar orbit mission. No attempt was made to optimize the system redundancy configuration. Data runs were made for each mission to compare the effect of several values of standby failure rate on the system predicted reliability.

Analysis with the aid of the Generalized Reliability Interpretive Program (GRIP) was initiated. Problems encountered while attempting to make the program operational for this system and mission phase profile prevented the use of GRIP in this study.

SIP Analysis

Computer program description. -- Within the past several years the state-space approach has gained prominence in the analysis of large and complex systems. The approach is based on the classical Markov methods that have been known for a considerable time but have found only a limited application in reliability work. Using the state-space approach considerably simplifies the analytical workload by employing computer methods in their full capacity.

The State Diagram Interpretive Program is a digital computer program which will:

- Interpret a given state diagram
- Compute state probabilities as a function of time
- Compute system reliabilities as a function of time
- Compute system figures of merit as a function of time

This computer program enables reliability and design engineers to study the effects of deteriorating part failure rates on system reliability over the time period of any given mission or operating period. Although the program solves the state differential equations to provide this data, the program user is not required to formulate these equations. He must only describe the state diagram, the initial conditions, and the kind of data output desired.

Reliability model. -- The reliability success diagram for the system of this study is shown in Figure 10. The state diagram derived from this model which is solved for the system reliability is shown in Figure 11. The system

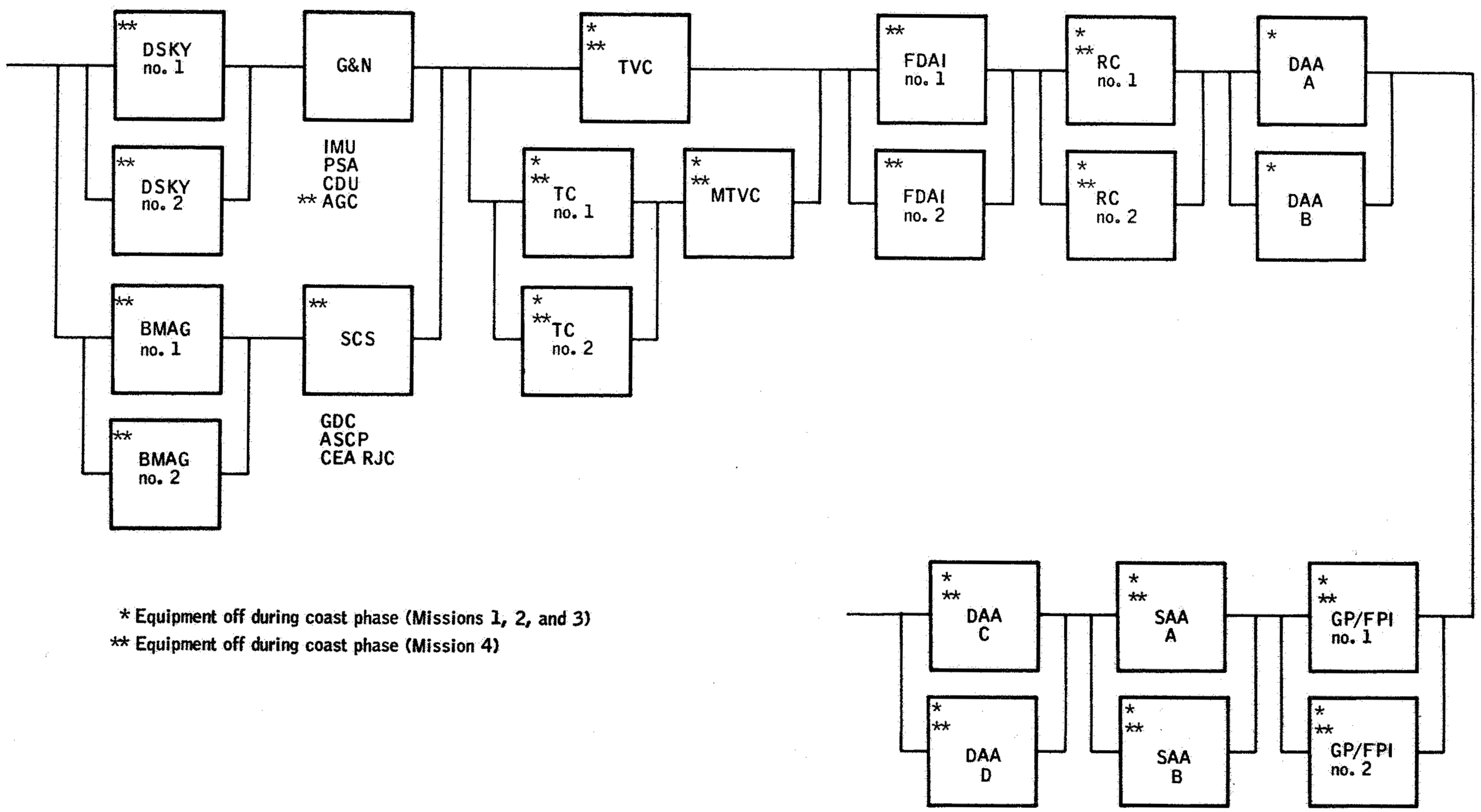
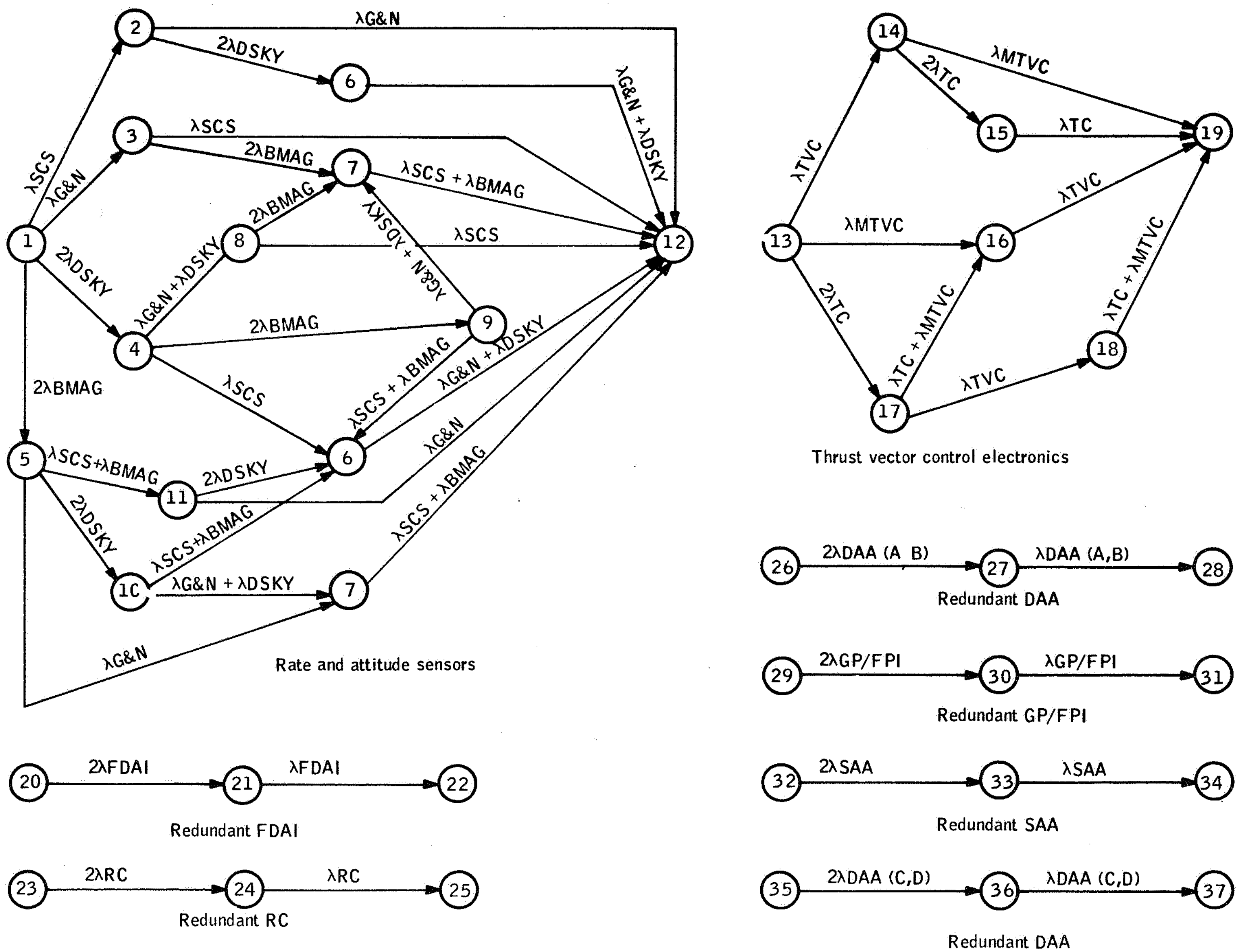


Figure 10. GN&C Reliability Success Diagram (SIP)



Note: abbreviations are defined in Appendix B

Figure 11. GN&C State Diagram

configuration shown is basically a guidance and navigation system for monitoring and controlling spacecraft attitude with a stabilization and control system providing backup redundancy. Several combinations of existing components were made in order to simplify the generation of the state diagram. In all cases the combination was logically made where groups of hardware always work together. The blocks labeled FDAI and GP/FPI include the display electronics assembly (DEA) associated with their respective operation. The block labeled G&N is made up of the following components:

IMU - Inertial measurement unit

PSA - Power servo assembly

CDU - Coupling data unit

AGC - Apollo guidance computer

The block labeled SCS is made up of the following components:

GDC - Gyro display coupler

ASCP - Attitude set control panel

RJC - Reaction jet control

The active failure rates for each component are shown in Table X.

TABLE X
GN&C ACTIVE COMPONENT FAILURE RATES

Code	Name	Failure rate, failures/10^6 hours
G&N	Guidance and navigation	804
SCS	Stabilization and control system	166
DSKY	Display and keyboard assembly	200
BMAG	Body-mounted attitude gyro	180
FDAI	Flight director attitude indicator	141.5
RC	Rotation control	12
DAA - A/B	Driver amplifier assembly - reaction jet	17
DAA - C/D	Driver amplifier assembly - engine valve	1.5
SAA - A/B	Servo amplifier assembly	14
GP/FPI	Gimbal position/fuel pressure indicator	33.5
TVC	Thrust vector control	19.2
MTVC	Manual thrust vector control	18.7
TC	Translation control	1.5

Analyses. -- Three mission profiles were analyzed by this study, each having a total length of 833 hours which corresponds to the length of a lunar polar orbit mission. A fourth 833-hour mission corresponding to a prolonged space-fixed coast-type flight was analyzed.

The first mission assumed that the spacecraft is being fully controlled during 75 percent of the mission and is coasting during the remaining 25 percent of the time wherein only monitor of spacecraft attitude takes place. The spacecraft experiences 4 periods of alternating control and coast followed by a short period of control simulating re-entry. A severity factor of 2 was applied to the failure rates during all controlling phases.

The second mission simulated was one where the control and coast time are made 50 percent of the mission time each. In addition, a short period at the beginning and end of the mission account for launch and re-entry respectively. A severity factor of 2 was applied to the failure rates only during launch and entry.

The third mission simulated corresponds to the lunar polar orbit mission described in Ref. 1 wherein control is maintained for 2 percent of the total time and coast time makes up 98 percent of the mission time. The same launch and entry conditions were applied as for mission 2.

A fourth mission was developed to simulate an alternate configuration which would allow a greater percentage of the equipment to be in a nonoperating condition. This mission uses a spacecraft with the antenna pointed toward the earth and with power applied to the IMU, PSA, and reaction control electronics. The simulated mission requires use of all guidance and control equipment for 2 percent of the total time and attitude control only for the remaining 98 percent of the mission time. A severity factor of 1 was used for this mission analysis.

Four simulations were made of each mission with different failure rates applied to the unused equipment during the coast phase. The "active rate" run assumes that the unused equipment remains powered up and that full operating failure rate applies. Three runs were then made wherein the unused equipment was powered off and a failure rate of zero, 1/15 active rate, and 1/30 active rate respectively was assigned to this equipment.

Conclusions and recommendations. -- The results obtained from these computer runs are shown in Table XI. It appears from this data that for missions 1, 2, and 3 the value of failure rate used for equipment in the standby condition has little effect on the calculated reliability. The difference between zero standby failure rate and active rate for standby was in the order of 0.000890 to 0.001254 for missions 2 and 3. This difference increased to 0.05193 for mission 1, but the controlling factor in this run was not standby failure rate but a severity factor applied to all operating failure rates during system operation. The fourth mission illustrates that for an alternate configuration, if sufficient quantities of unused equipment can be shut off, significant improvements in mission reliability can be obtained. A difference of 0.086543 between the zero standby failure rate and the active rate was observed for mission 4.

TABLE XI
GN&C SYSTEM RELIABILITY SUMMARY

Description	System reliability
Mission 1 (duty cycle 75%) (severity 2[a] during all control periods)	
Unused equipment failure rates = 0	.780167
= 1/30 active rate	.779658
= 1/15 active rate	.779576
= Active rate	.728237
Mission 2 (duty cycle 50%) (severity 2[a] during boost and entry)	
Unused equipment failure rates = 0	.914048
= 1/30 active rate	.914023
= 1/15 active rate	.913998
= Active rate	.913158
Mission 3 (duty cycle 2%) (severity 2[a] during boost and entry	
Unused equipment failure rate = 0	.914412
= 1/30 active rate	.914408
= 1/15 active rate	.914402
= Active rate	.913158
Mission 4 (duty cycle 2%) (severity 1 during all periods)	
Unused equipment failure rate = 0	.999701
= 1/30 active rate	.998342
= 1/15 active rate	.995798
= active rate	.913158

[a]Severity factor is the K factor applied to the equipment failure rates. It reflects the degree of environmental stress associated with the mission.

It should be noticed that as the nonoperating failure rate is reduced to the area of 1/30 λ on to zero, the change in system reliability is less significant.

These results indicate that the specific system configuration must be considered before conclusions can be reached as to the importance of applying nonoperating failure rates. Mission 1 indicates that the most significant factor in the predicted system reliability is the severity factor applied to the failure rates. This factor could be adjusted to obtain a predicted reliability of the same magnitude as presented in the MARS computer program data of Appendix B; however, the intent of this study was not to verify a reliability prediction, but to demonstrate the effect of power off failure rates. For this reason additional effort was not expended to obtain an exact representation of the severity factor used in the MARS computer analysis. Also, since the severity factor was applied only to boost and entry on missions 2 and 3, the results of these mission simulations cannot be compared with the results of the mission 1 simulation.

The results of missions 2 and 3 indicate no significant change in the system reliability due to a change in the equipment duty cycle. This lack of a change in reliability is due to the percentage of the equipment (represented by the predicted failure rate) that can be switched off for the 98 percent coast time period. If a larger percentage of the equipment can be turned off, then a significant improvement in mission reliab lity can be obtained.

The fourth mission illustrates the operation of an alternate configuration of the guidance and control equipment and its associated sensitivity to failure rate variation. This configuration is more realistic for the LPO mission, since this type of mission will probably be conducted as a part of an application-type program.

The results of this study show that turning off unused equipment appears to be profitable from a mission standpoint. These results are not conclusive, since it was beyond the scope of this study to modify the failure rates of the hardware. This modification would involve adding necessary switching circuit components to either the power distribution system or to the subsystems themselves.

It was also apparent as a result of this effort that a computer program more completely oriented to the relationship of power systems to mission objectives is required.

Further studies are therefore recommended to (1) more completely evaluate the effect of power on-off operation on a typical system, and (2) do preliminary development of a power system - mission-oriented computer program. These studies are more completely described in the recommendation section of this report.

GRIP Analysis

Computer program description. -- System probability of success can be calculated from a reliability success diagram when the probability of success, or the failure rate for each block in the diagram is known. Such calculations, formerly tedious, are greatly simplified by the use of the Generalized Reliability Interpretive Program (GRIP). Analysis and calculation of the system success is accomplished through the use of the probability tree method of calculating reliability. The program input is taken directly from the reliability success diagram and consists of the block numbers which form the outputs for each block along with the block probability of success or the block failure rate and mission time. The GRIP program then derives the success path equations and evaluates the system probability of success.

Reliability model. -- The system configuration and mission phase time profile used in this study is that of the lunar polar orbit mission described in Ref. 1. This was a 32-phase mission to the moon and back covering a total time period of 833 hours. To reduce the amount of repetitive calculations, several identical phases which occurred throughout the mssion were combined to give the 19-phase mission used in this study. The mission phase descriptions are shown in Table XII.

Eight separate hardware configurations are used during the performance of this mission. The reliability success block diagrams for these configurations are shown in Figures 12 through 19. The block numbers are those used as input data to the GRIP computer program. Block probabilities were used in this study and were computed separately for each block in each phase from the failure rate, severity factor, and time shown in Table XII.

Results of analysis. -- Difficulties encountered during the execution of this program prevented the acquisition of any useful data. The major difficulty appears to be that the program cannot handle the mission complexity within the constraints of computer storage and reasonable running time.

Conclusions and recommendations. -- The GRIP computer program represents an attractive method of reliability block diagram evaluation. The current program contains some severe limitations and therefore could not be used for the analysis of the block diagrams considered. It is recommended that a program of this type be developed to provide a systematic method for design evaluation. This could be accomplished by modification of the GRIP program to allow the use of larger block diagrams and to minimize the required program running time.

CONCLUSIONS

This study indicates that specific penalties result from power distribution on a "block" power switching basis. In addition, representative power off failure rates established and used in this study illustrate the sensitivity of the stabilization and control system reliability to nonoperating conditions.

TABLE XII
LUNAR POLAR ORBIT MISSION PROFILE

Block number	Block name	Failure rate $\times 10^{-5}$																				
			1	2	1	2	3	4	5	6	4	6	8	4	5	8	4	5	6	4	7	Block diagram number
			1	2	3	4	5	6	7	8	9	10	1	12	13	14	15	16	17	18	19	Phase number
			15	1	5	1	1.2	1	5	1	1	5	1	1	5	1	1	5	1	1	2	Severity factor
			0.19	2.81	0.09	0.25	0.33	3.25	0.0105	62.2	1.0	0.08	336.0	1.0	0.005	336.0	4.0	0.0338	85.0	1.0	0.18	Time, hours
1,41	IMU	12.5								O									O			
2,42	PSA	11.6								O		O							O			
3,43	CDU	18.1								O		O							O			
4,44	AGC	38.2								X		X							X			
5,45	DSKY 1	20.0								O		O							O			
6,46	DSKY 2	20.0	O		O		O		O	O		O			O			O	O		O	
7	Dummy	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
8,38,48	BMAG 1	18.0		X		X				O		O	O			O			O			
9,39,49	BMAG 2	18.0		X		X				O		O							O			
10	GDC	12.9		X		X	X		X	O		O			X			X	O			
11	CEA-RJC	1.6	X	X	X	X			X	O		O	X		X	X		X	O		X	
12	CEA-TVC	1.92	X	X	X	X	X	X		O	X	O	X	X		X	X		O	X	X	
13	CEA-MTVC	1.87	X	X	X	X	X	X		O	X	O	X	X		X	X		O	X	X	
14	FDAI 1	12.0		X		X	X			O		O	O			O			O			
15	DEA 1	2.15		X		X	X			O		O	O			O			O			
16	FDAI 2	12.0		X		X	X			O		O	O			O			O			
17	DEA 2	2.15		X		X	X			O		O	O			O			O			
18	GP/FPI 1	1.2		O		O	O	X		O	X	O	O	X		O	X		O	X	O	
19	DEA 3	2.15		O		O	O	X		O	X	O	O	X		O	X		O	X	O	
20	GP/FPI 2	1.2		O		O	O	X		O	X	O	O	X		O	X		O	X	O	
21	DEA 4	2.15		O		O	O	X		O	X	O	O	X		O	X		O	X	O	
22, 52	ASCP	2.1	X	X	X	X	X		X	O		O	X		X	X		X	O		X	
23	TC 1	0.15	X	X	X	X		X	X	O	X	O	X	X	X	X	X	X	O	X	X	
24	TC 2	0.15	X	X	X	X		X	X	O	X	O	X	X	X	X	X	X	O	X	X	
25	RC 1	1.2	X		X								X			X						
26	RC 2	1.2	X		X								X			X						
27	SAA-A	1.4	X	O	X	O	O	X		O	X	O	O	X		O	X		O	X	O	
28	SAA-B	1.4	X	O	X	O	O	X		O	X	O	O	X		O	X		O	X	O	
29	DAA-A	1.7	X	X	X	X				O		O							O			
30	DAA-B	1.7	X	X	X	X				O		O							O			
31	DAA-C	0.15	X	X	X	X	X	X		O	X	O	X	X		X	X		O	X	X	
32	DAA-D	0.15	X	X	X	X	X	X		O	X	O	X	X		X	X		O	X	X	
33	RSI	1.3	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		

Legend:
Blank - used
X - not used and powered
O - not powered
--- dummy block

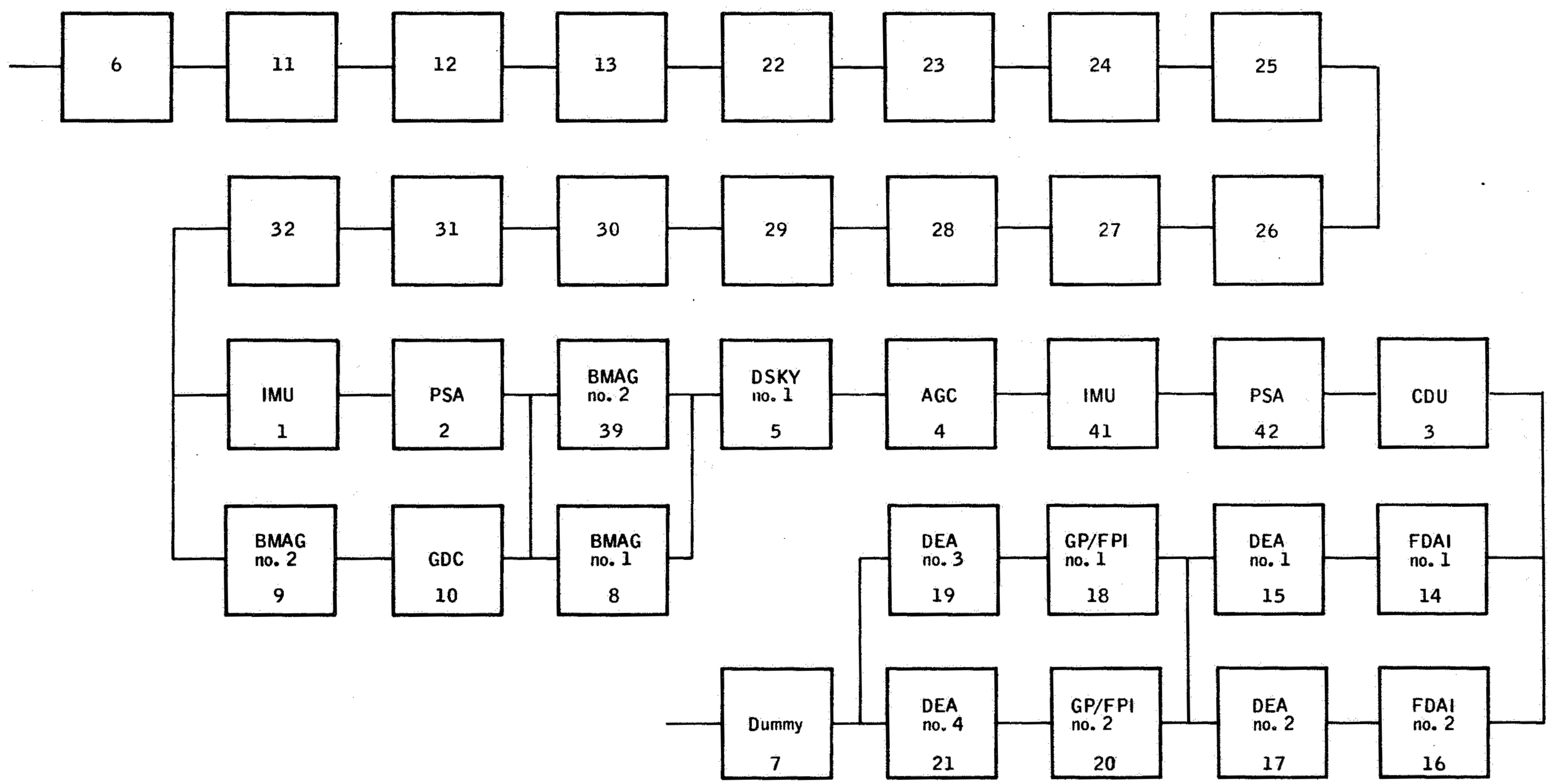


Figure 12. GRIP Block Diagram Number 1

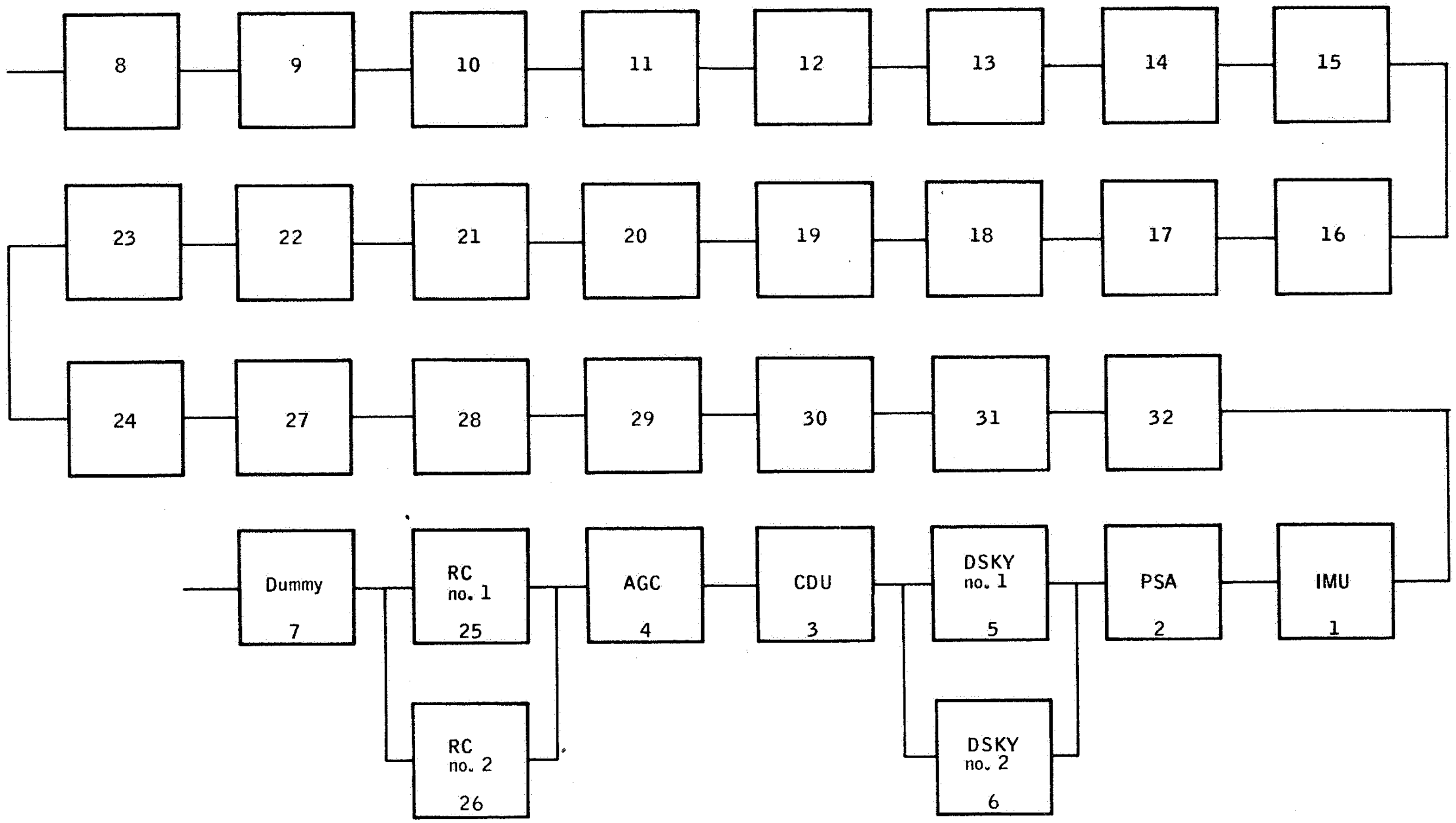


Figure 13. GRIP Block Diagram Number 2

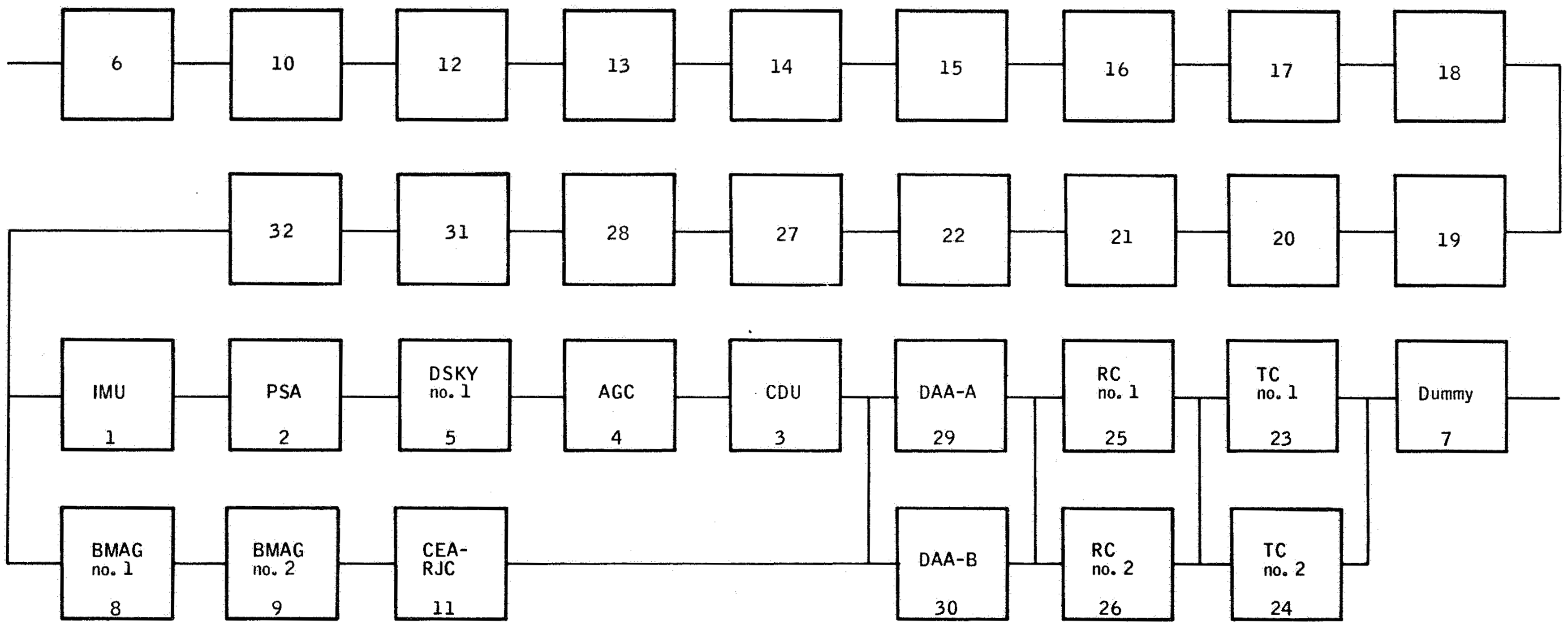


Figure 14. GRIP Block Diagram Number 3

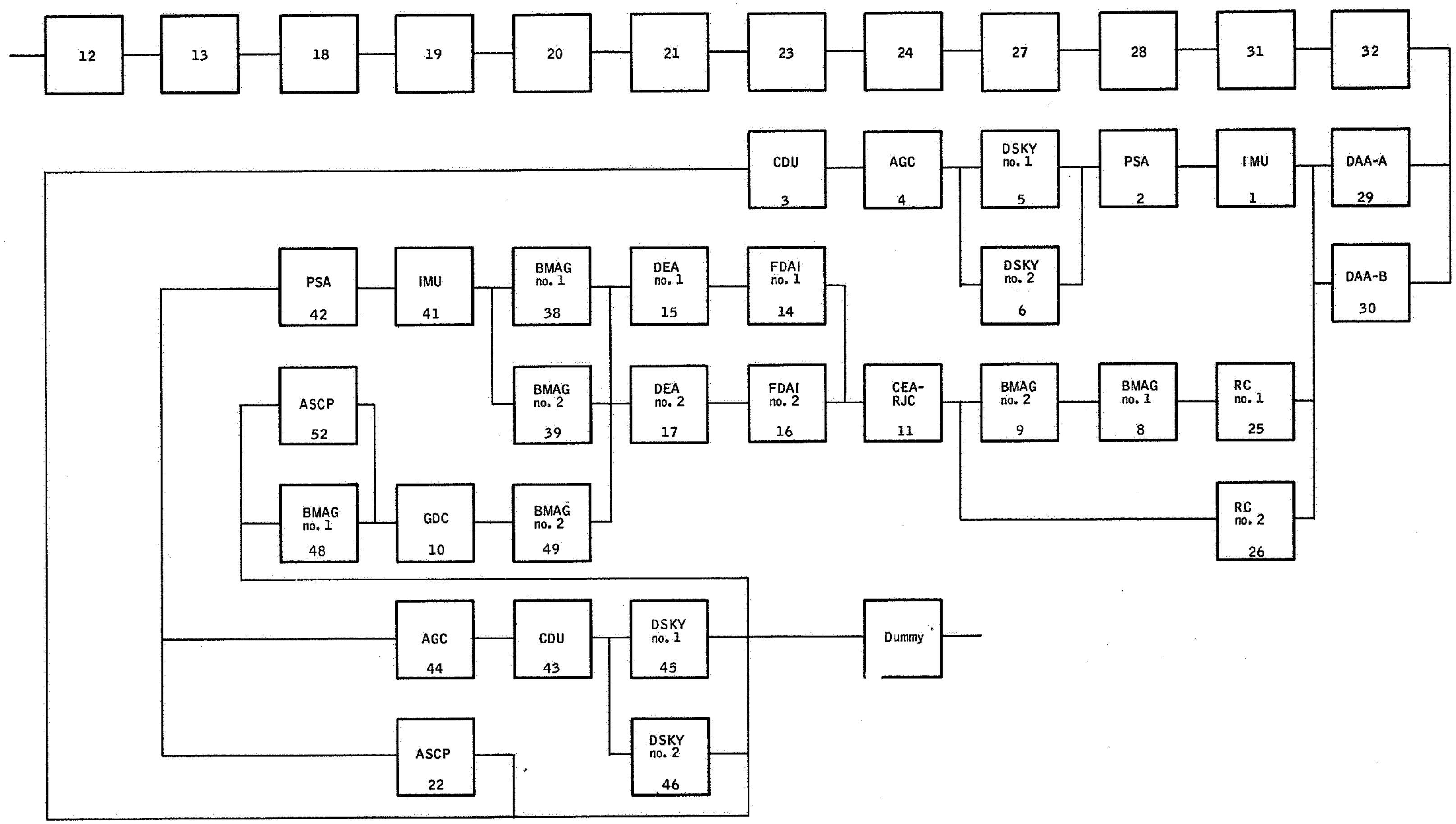


Figure 15. GRIP Block Diagram Number 4

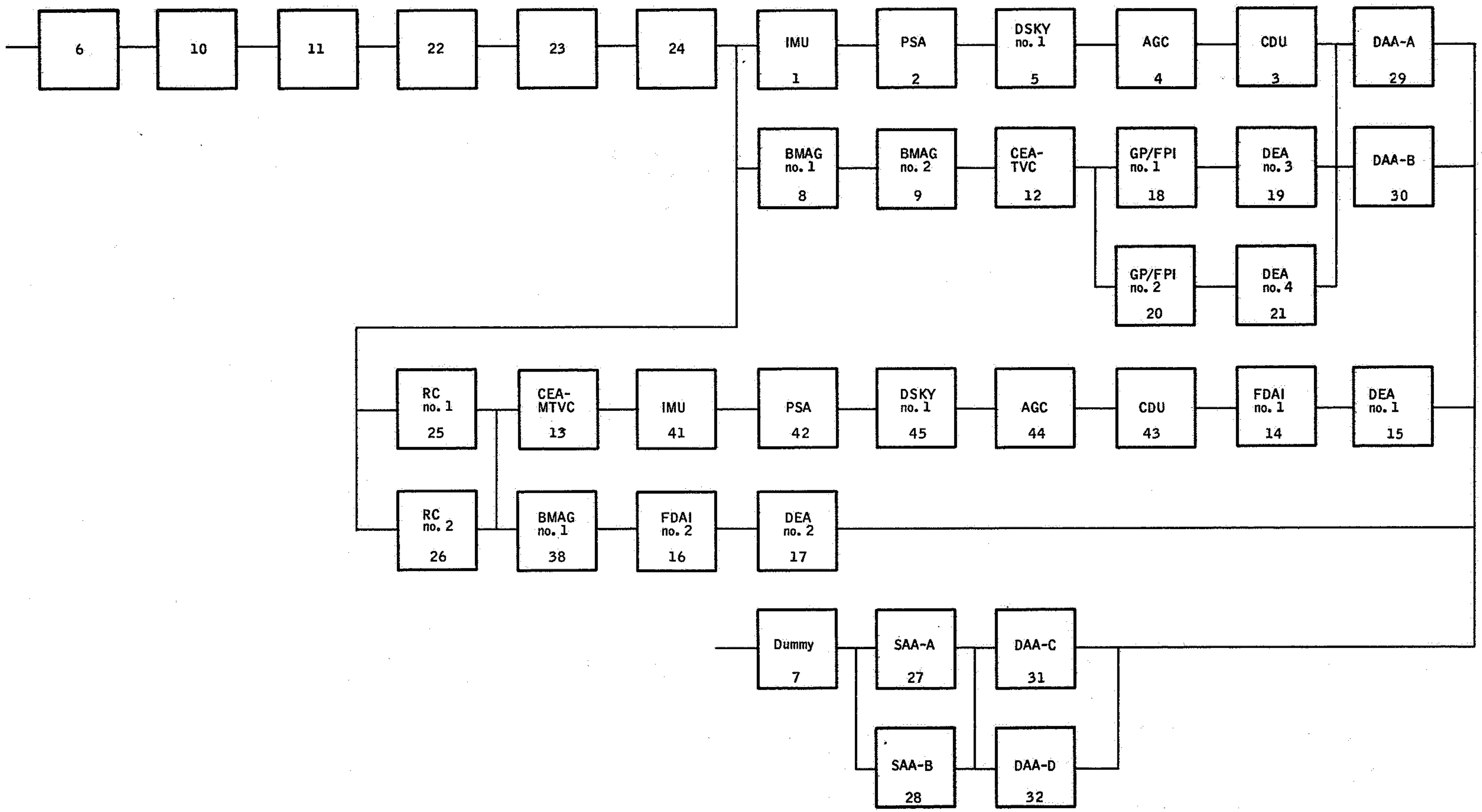


Figure 16. GRIP Block Diagram Number 5

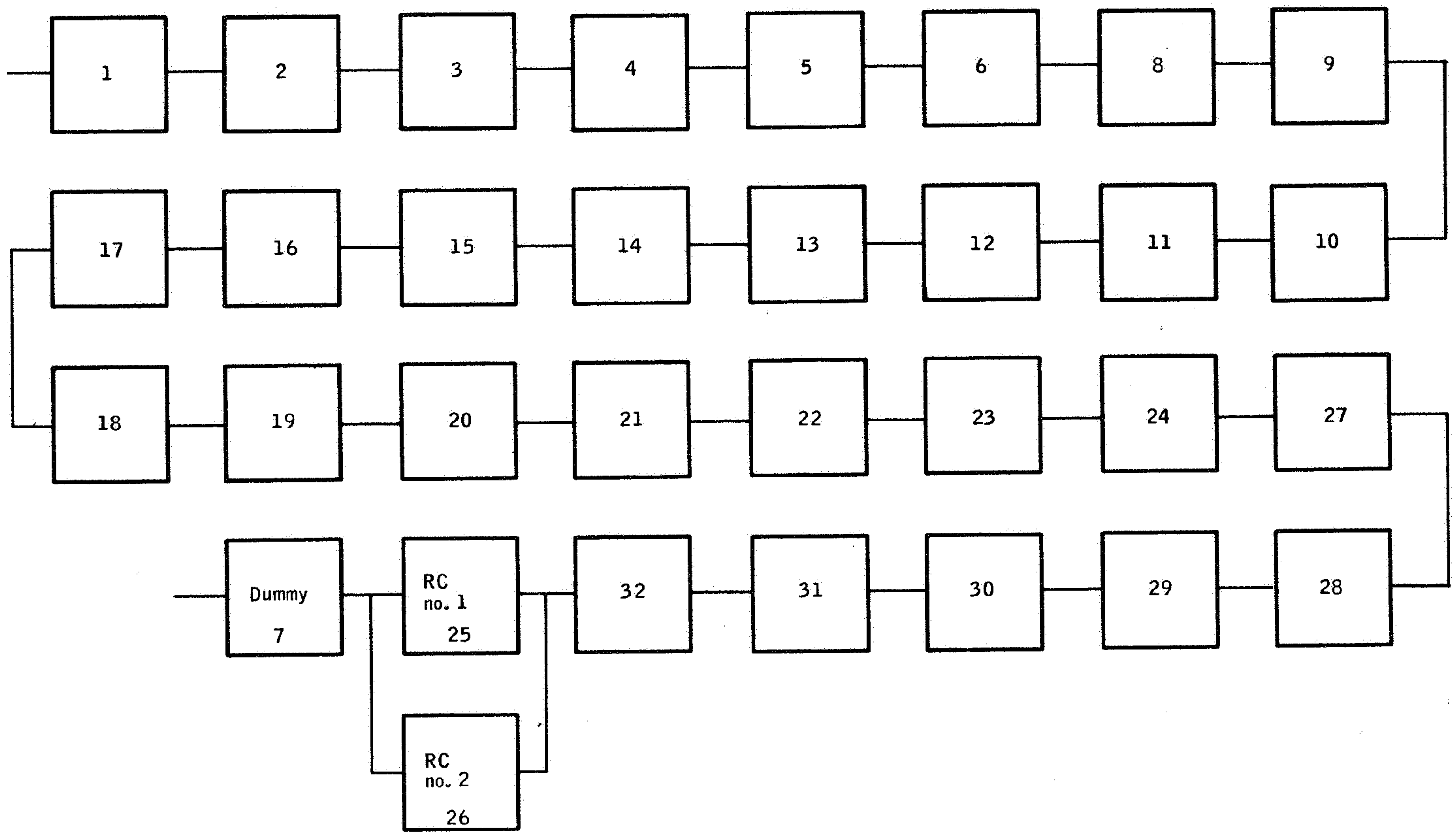


Figure 17. GRIP Block Diagram Number 6

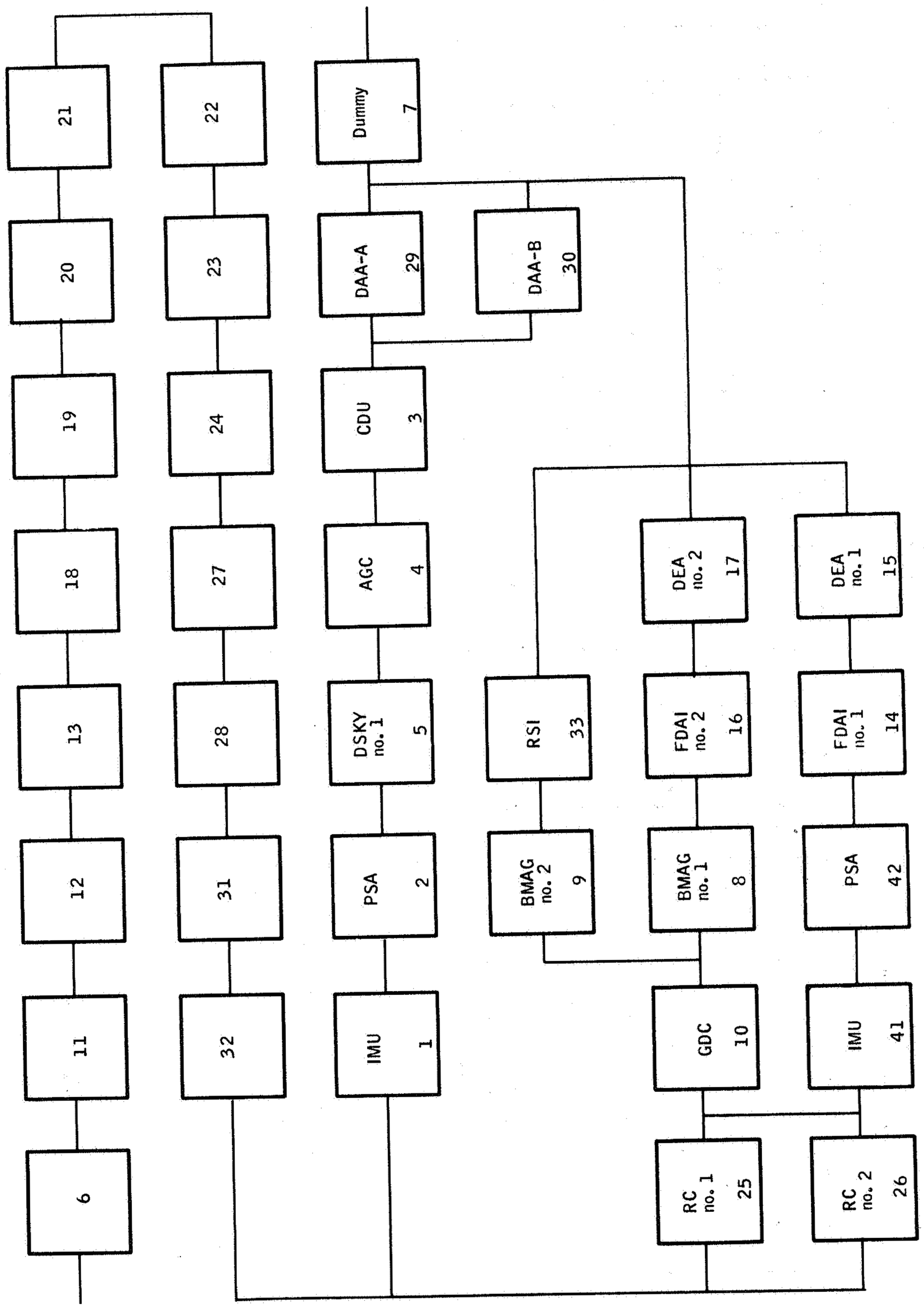


Figure 18. GRIP Block Diagram Number 7

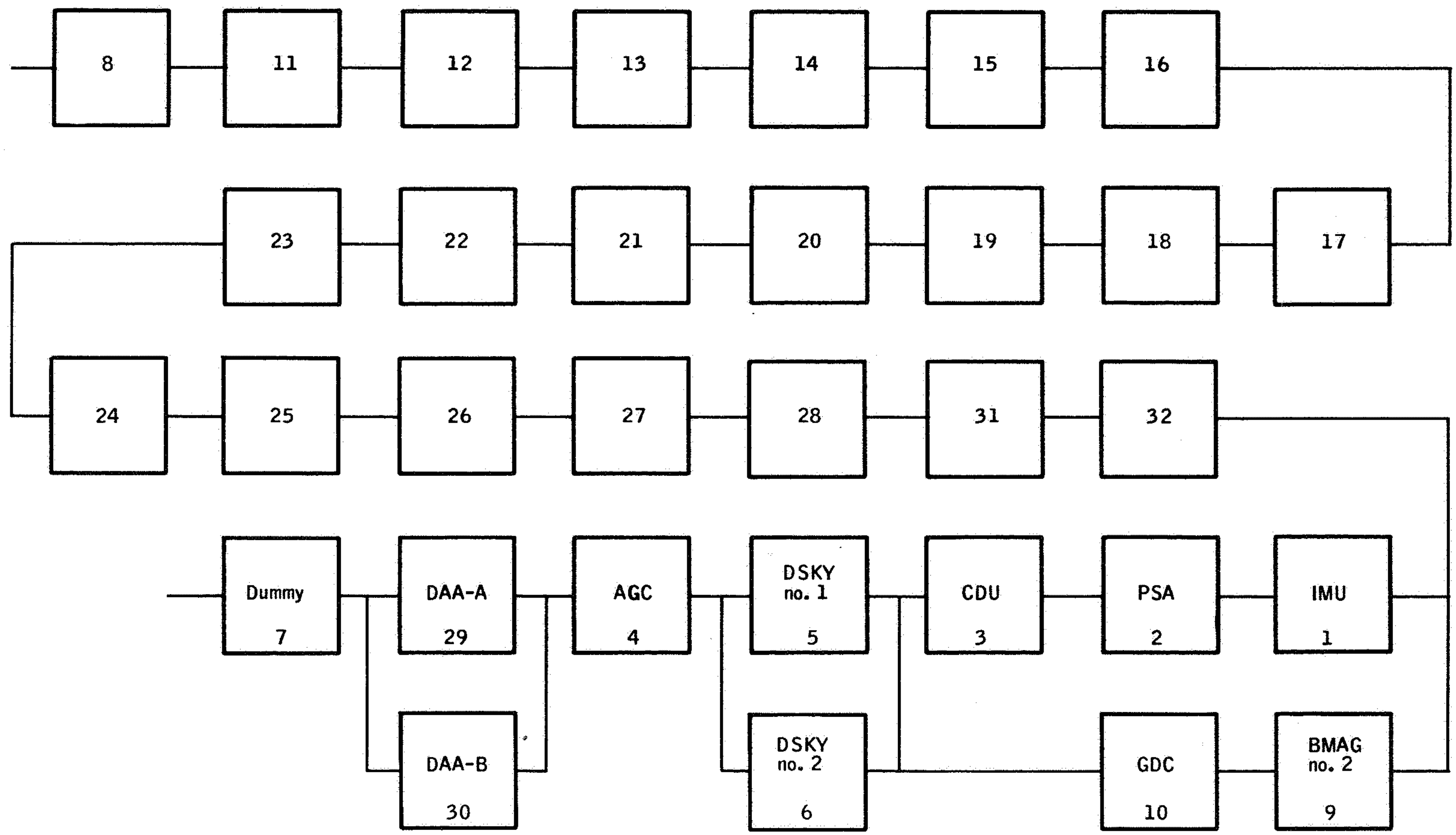


Figure 19. GRIP Block Diagram Number 8

The analysis of "block" power switching indicates that a significant number (approximately 23 percent) of the failures during the 5000 LLM simulations were due to equipment that was energized but not required at the time of the failure. Failures due to equipment energized but not required were also shown to be significant from a mission success standpoint in that 2 failures indicates in the 100 LPO simulations were directly related to 2 aborts that resulted. This analysis presents specific indications of the penalties of non-optimum power distribution.

The significance of the effect of power on-off cycling is indicated in the results of the Honeywell equipment data survey. This survey indicates that the failure rate due to cycling could be a significant factor if the equipment is cycled as often as one or more times for every 10 hours of operation. The importance of on-off cycling failure rates will depend on the specific system under consideration and the relationship between the number of cycles and the total operating time.

The vendor information survey that was conducted also indicated the significance of power on-off cycling. This survey identified a definite relationship between thermal expansion problems and power cycling at the piece-part level. Specific tests on semiconductor devices with wedge-type bonds have shown that these piece parts are highly sensitive to low-frequency power cycling. The relationship between power on-off cycling and thermal cycling has also been indicated as an important factor at the equipment level resulting in some cases in an internal temperature rise of 50°C. Reliability testing, including temperature cycling and power on-off cycling (MIL-STD-781A), should not be neglected as a means of identifying equipment sensitivity to power cycling.

Only a limited amount of literature on the effect of power on-off cycling on component failure rates has been published. Considerably more information is available in the area of equipment storage time and nonoperating component failure rates; however, many piece-part nonoperating failure rates are severely limited by the number of failures and hours recorded. Until such time when a sufficient number of hours and failures have been recorded to provide a significant degree of confidence in the required nonoperating piece-part failure rates, it is recommended that ratios (or application factors) be used to modify the operating failure rate to enable reliability predictions for equipment under nonoperating conditions.

Using the information obtained from the study of failure rates, the effects of failure rate change were evaluated on a typical system by means of a Honeywell computer analysis. This analysis indicates that for the simulated mission considered, the use of nonoperating failure rates does not significantly affect the system reliability; however, analysis of an alternate configuration indicated that nonoperating failure rates can be significant if sufficient quantities of unused equipment can be shut off.

In a general evaluation of the effects of nonoperating conditions and power on-off cycling on a particular mission, this study identified the following factors that should be considered: (1) The failure rate due to power cycling is significant if the on-off cycles occur as often as 1 or more times in a 10-hour period. (2) The failure rate due to nonoperating conditions becomes significant as the nonoperating time period increases to 30 or more hours for each operating hour of the mission. (3) It is necessary to consider other factors in addition to the failure rates for the nonoperating and power cycling conditions. These considerations must include, for example, an analysis of individual piece-part stress limitations, equipment wearout characteristics, equipment storage limitations, and specific mission environmental considerations.

RECOMMENDATIONS

In this study the scope was limited to identifying the sensitivity of the stabilization and control system reliability to power-off failure rates. The limited survey and analysis conducted during this study provided an indication of several areas in need of additional study or investigation. Some of these area of investigation are directly related to this study effort and others represent entirely new areas of investigation. Three specific study needs are identified. These are briefly discussed in the paragraphs that follow.

MARS Computer Program

The MARS computer program should be used to obtain complete abort data on LLM simulations. The MARS computer program data should be modified to show redundant paths de-energized and to evaluate tradeoffs.

This task would include a MARS computer analysis to evaluate the effects of power on-off cycling and nonoperating conditions on LLM simulation. The LLM simulation represents a mission of high reliability requirements and will provide a realistic means of determining if significant advantages are gained from turning off equipment that is not required.

Computer Program Development

An efficient computer program should be developed for evaluating basic system functional diagrams to obtain systematic methods of design evaluation.

This task is recommended to provide a systematic method of evaluating the basic block diagram design of a system. This would indicate system reliability limitations due to nonoptimum power distribution and would indicate the areas requiring additional design consideration. The task could be accomplished by modification of the GRIP computer program to allow the use of larger block diagrams and to minimize the required program running time.

Distributed versus Central Power Conditioning Study

Recent advances in integrated microelectronic circuits and in switching-type power conditioners indicate that future central power conditioning should be limited to that required for internal power system control such as battery charging, bus isolation, and load division, whereas utilizing subsystems should be designed to use power with characteristics as inherently produced by such space power systems as fuel cells and solar cells.

A distributed power conditioning system is difficult to implement due to the long establishment of central power conditioning throughout industry and also because distributed power conditioning adds to the technical responsibility of utilizing subsystem designers. A preliminary study should consider the complete electrical requirements of 4 or 5 typical electrical systems as indicated in Figure 20 but in greater detail. Central power conditioning would be compared with distributed power conditioning on the basis of reliability, weight, volume, and cost for the complete electrical system.

Regulation, filters, fault protection, and switching are some of the mechanization factors which must be considered in a comparison of central and distributed power conditioning.

Regulation. -- The high efficiency of switching-type regulators and the use of integrated circuits in regulators has reduced the power, weight, and volume savings of central power processing. Distributed regulators can be designed for maximum efficiency at actual load, whereas central regulators are designed for maximum efficiency at peak or average load.

Filters. -- Many utilizing subsystems now contain microelectronic circuits which can be damaged by switching transients. The filters located in the central power conditioning cannot protect utilizing equipment from these voltage spikes due to the high-frequency components of the spikes. Required filter duplication with central power conditioning reduces or eliminates any weight or volume advantage. Location of filters at the utilizing equipment also provides electromagnetic interference (EMI) advantages.

Fault protection. -- Recent work at Honeywell has established the requirement for a spacecraft fault isolation device to isolate malfunctioning equipment, to protect adjacent components from damage, and to isolate shorted components from the power bus. Isolation requirements include very fast circuit interruption for some applications, provisions for manual reclosure on manned spacecraft, provisions for automatic recloses on unmanned spacecraft out of range of a ground station, and provisions for ground command override. Fuses, circuit breakers, and solid-state devices were considered, with the solid-state system being the only device capable of meeting the requirements for many applications. Disadvantages of the isolation devices include decreased reliability in nonredundant systems, power loss, increased weight and volume and serious voltage drop and ripple problems in low voltage systems. Honeywell studies indicated that combining the isolation device with required filters, regulator, and voltage conversion equipment and making

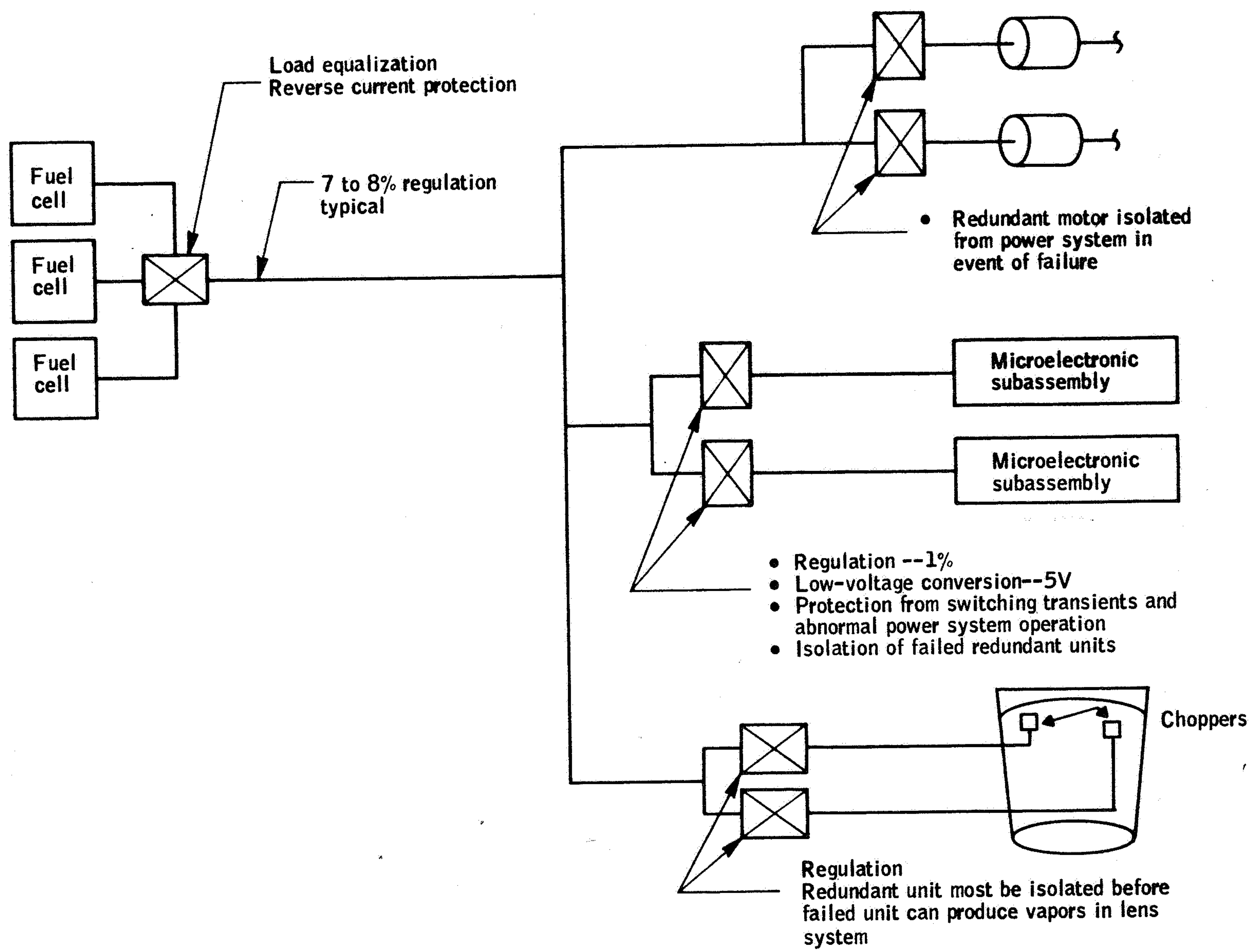


Figure 20. Electrical Requirements of a Typical System

the unit an integral part of the utilizing subsystem would avoid duplication of many components, avoid the voltage drop and ripple problem, and reduce the weight and volume requirements.

Switching. -- Reliability and system optimization considerations have indicated a requirement for switching of redundant components. In a central power conditioning system, the switches are separate devices, with attendant weight, volume, voltage drop, and other problems. In a distributed system the switch can be an integral part of the power conditioning, with all the advantages noted in the discussion of failt protection.

APPENDIX A

REPRESENTATIVE POWER DISTRIBUTION SYSTEM

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APPENDIX A

REPRESENTATIVE POWER DISTRIBUTION SYSTEM

The power distribution system considered for this study is described in this Appendix. The system presented here is representative of power systems being used on Apollo but is not necessarily the final configuration mechanized in the actual spacecraft. Figure A-1 shows the major overall power distribution system.

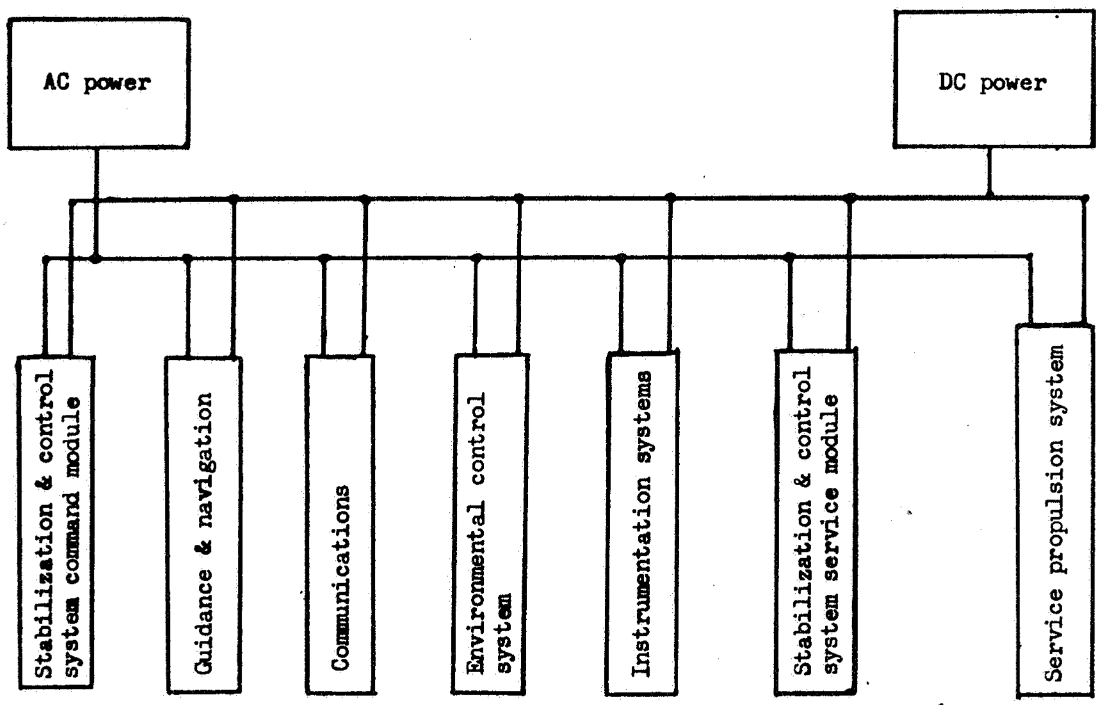

Figure A-1. Representative Power Distribution System

The ac power generation and distribution system shown in Figure A-2 consists of 3 static inverters, associated safety and inverter control circuitry, and 2 redundant, 3-phase, 115-volt busses that connect power through circuit breakers to the ac-powered components of the spacecraft.

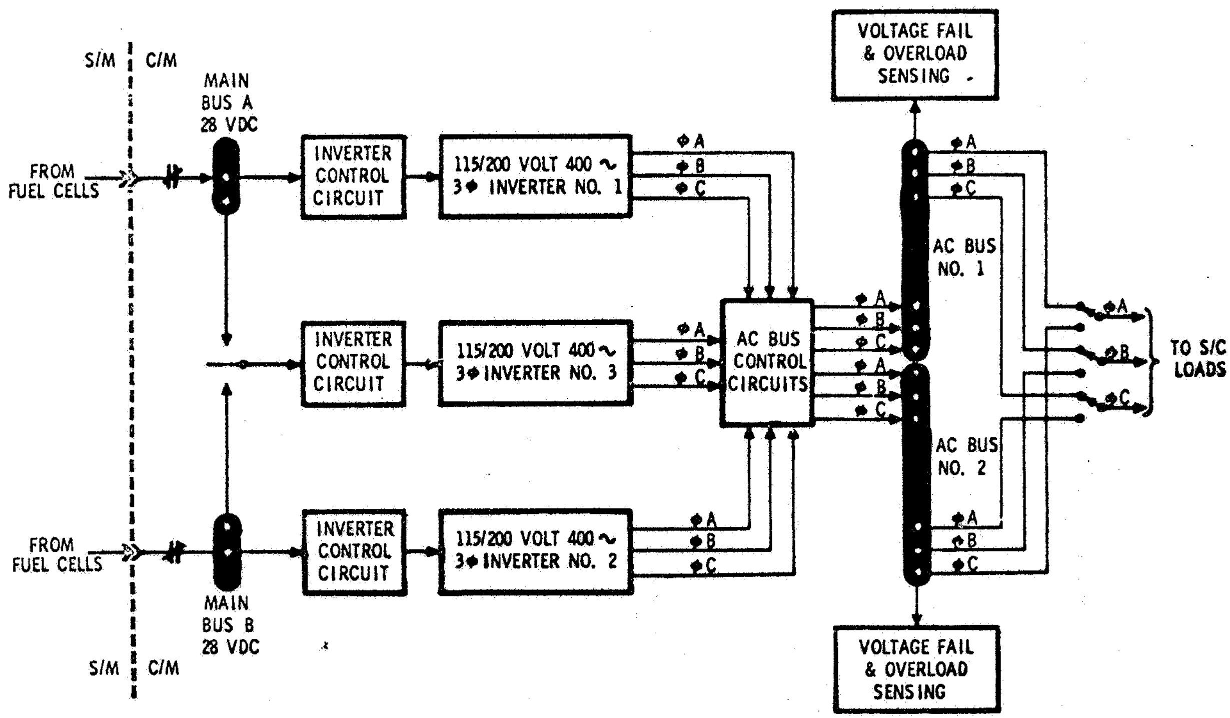

Figure A-2. AC Distribution

Figure A-3 shows the Apollo spacecraft electrical power dc distribution system. This system consists of power supplies, busses, control circuits, and protective devices. The major components with which we are concerned are the fuel cells, batteries, main and battery busses, circuit brakers, isolation diodes, and voltage and overload protection circuits.

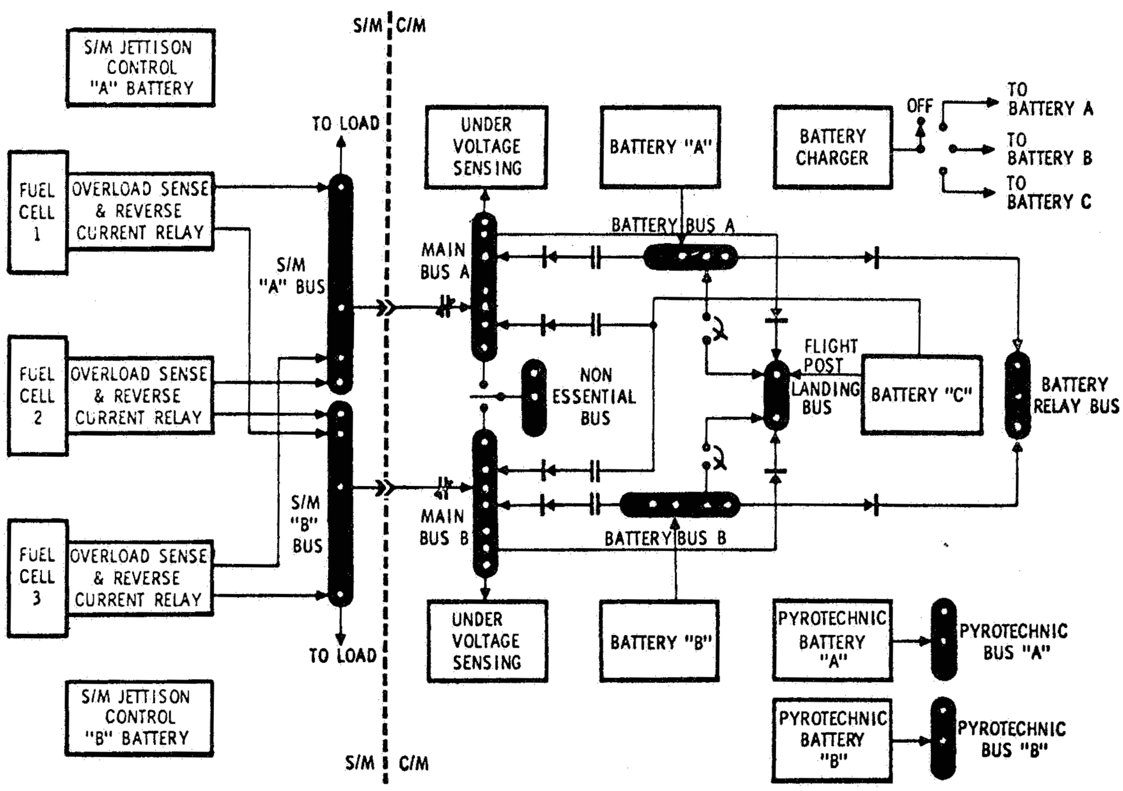

Figure A-3. DC Distribution

Appendix A

Figures A-4 and A-5 show the power distribution and conditioning within the stabilization and control system designed and supplied by Honeywell. This power is supplied through 18 circuit breakers located on the left hand circuit breaker panel. From these circuit breakers power is distributed to the SCE components through 6 power switches on the sequence controller and SCS power panel. These 6 switches are subdivided into 2 groups of 3 switches each, called group 1 and group 2. Group 2 power switches supply power to those SCS components which provide the backup capability for controlling the spacecraft during critical periods when the SPS engine is firing. Group 1 power switches supply power to the rest of the SCS.

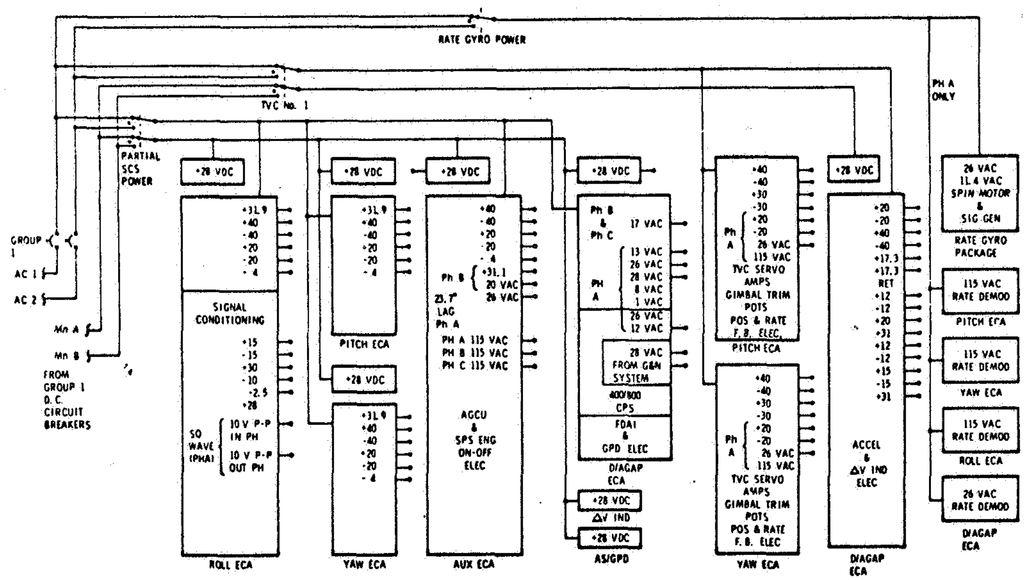

Figure A-4. Group 1 Power Distribution

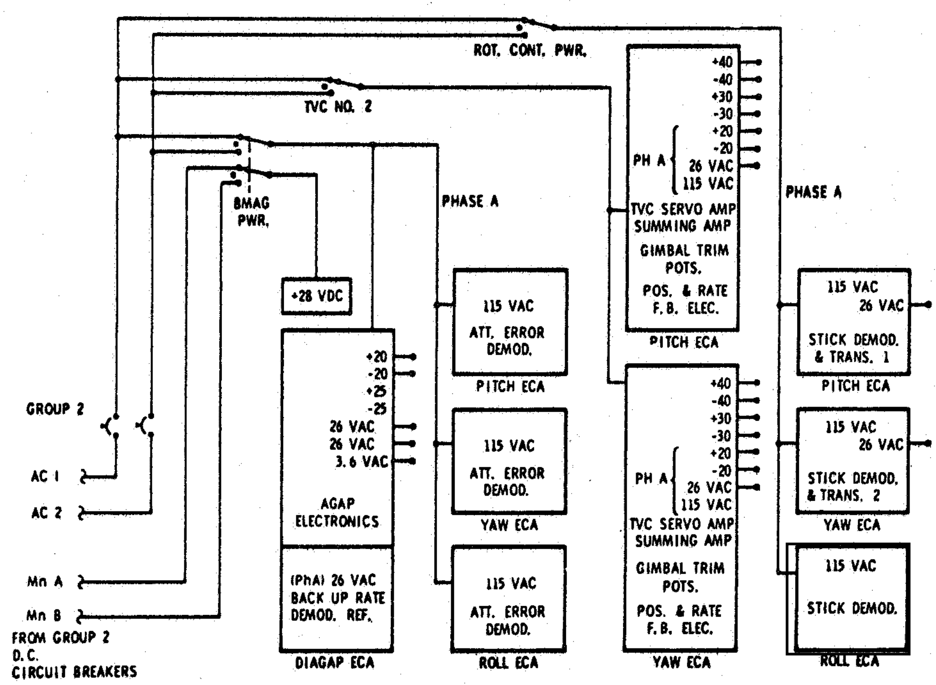

Figure A-5. Group 2 Power Distribution

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APPENDIX B

MISSION ABORT RELIABILITY SIMULATOR (MARS) DATA

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Appendix B

TABLE B-1
GUIDANCE, NAVIGATION AND CONTROL EQUIPMENT

Component	Code	Name
A1	ARTIFICE	(See page 16 of text.)
B1	IMU HTR.	Inertial measurement unit heater
C1	IMU STAB.	Inertial measurement stabilization loop
D1	IMU ACCEL.	Inertial measurement unit accelerometer loop
E1	PSA HTR.	Power servo assembly heater electronics
F1	PSA STAB.	Power servo assembly stabilization loop electronics
G1	PSA ACCEL.	Power servo assembly accelerometer loop electronics
H1	CDU COMMON	Coupling data unit circuits common to total CDU
O1	CDU IMU A/D	Coupling data unit IMU analog/digital converter
P1	CDU IMU D/A	Coupling data unit IMU digital/analog converter
Q1	CDU OPT. D/A	Coupling data unit optics digital/analog converter
R1	DSKY 1	Display and keyboard assembly - 1
S1	DSKY 2	Display and keyboard assembly - 2
T1	AGC CLOCK	Apollo guidance computer - clock
U1	AGC COMP.	Apollo guidance computer - less clock
V1	BMAG 1	Body-mounted attitude gyro - 1
W1	BMAG 2	Body-mounted attitude gyro - 2
X1	GDC	Gyro display coupler
Y1	CEA RJC	Control electronic assembly - reaction jet control
Z1	CEA TVC	Control electronic assembly - thrust vector control
A2	CEA MTVC	Control electronic assembly - manual thrust vector control
B2	DAA A	Driver amplifier assembly - reaction jet - A
C2	DAA B	Driver amplifier assembly - reaction jet - B
D2	DAA C	Driver amplifier assembly - engine valve - C
E2	DAA D	Driver amplifier assembly - engine valve - D
F2	SAA A	Servo amplifier assembly - A
G2	SAA B	Servo amplifier assembly - B
H2	DEA 1	Display electronics assembly - 1
O2	DEA 2	Display electronics assembly - 2
P2	FDAI 1	Flight director attitude indicator - 1
Q2	FDAI 2	Flight director attitude indicator - 2
R2	GP/FPI 1	Gimbal position/fuel pressure indicator - 1
S2	GP/FPI 2	Gimbal position/fuel pressure indicator - 2
T2	ROT. CON. 1	Rotation control - 1
U2	ROT. CON. 2	Rotation control - 2
V2	TR. CON. 1	Translation control - 1
W2	TR. CON. 2	Translation control - 2
X2	ASCP	Attitude set control panel
Y2	RSI	Roll stability indicator

TABLE B-2
COMPUTER OUTPUT - LPO MISSION

D2	DAA C	.0000015000	.0000015000	1.0000	0	0	.999998
E2	DAA D	.0000015000	.0000015000	1.0000	0	0	.999998
F2	SAA A	.0000140000	.0000140000	1.0000	0	0	.999986
G2	SAA B	.0000140000	.0000140000	1.0000	0	0	.999986
H2	DEA 1	.0000430000	.0000430000	1.0000	0	0	.999957
O2	DEA 2	.0000430000	.0000430000	1.0000	0	0	.999957
P2	FDAI 1	.0001200000	.0001200000	1.0000	0	0	.999880
Q2	FDAI 2	.0001200000	.0001200000	1.0000	0	0	.999880
R2	GP/FPI 1	.0000120000	.0000120000	1.0000	0	0	.999988
S2	GP/FPI 2	.0000120000	.0000120000	1.0000	0	0	.999988
T2	ROT.CON.1	.0000120000	.0000120000	1.0000	0	0	.999988
U2	ROT.CON.2	.0000120000	.0000120000	1.0000	0	0	.999988
V2	TR.CON.1	.0000015000	.0000015000	1.0000	0	0	.999998
W2	TR.CON.2	.0000015000	.0000015000	1.0000	0	0	.999998
X2	ASCP	.0000210000	.0000210000	1.0000	0	0	.999979
Y2	RSI	.0000130000	.0000130000	.0000	0	0	1.000000

PHASE 32

COMPONENT	NOMENCLATURE	FAILURE RATE	CORRECTED FAILURE RATE	OPERATING HOURS	AVAILABLE SPARES	REPLACEMENT POSSIBLE	COMPONENT RELIABILITA
A1	ARTIFICE	.0000000000	.0000000000	.1800	0	0	1.000000
B1	IMU HTR.	.0000011500	.0000023000	.1800	0	0	1.000000
C1	IMU STAB.	.0001000000	.0002000000	.1800	0	0	.999964
D1	IMU ACCEL.	.0000238500	.0000477000	.1800	0	0	.999991
E1	PSA HTR.	.0000095000	.0000190000	.1800	0	0	.999997
F1	PSA STAB.	.0000688000	.0001376000	.1800	0	0	.999975
G1	PSA ACCEL.	.0000377000	.0000754000	.1800	0	0	.999986
H1	CDU COMMON	.0000343000	.0000686000	.1800	0	0	.999988
O1	CDU IMU A/D	.0001176000	.0002352000	.1800	0	0	.999958
P1	CDU IMU D/A	.0000450000	.0000900000	.1800	0	0	.999984
Q1	CDU OPT.D/A	.0000300000	.0000600000	.1800	0	0	.999989
R1	DSKY 1	.0000200000	.0000400000	.1800	0	0	.999993
S1	DSKY 2	.0000200000	.0000400000	.0000	0	0	1.000000
T1	AGC CLOCK	.0000450000	.0000900000	.1800	0	0	.999984
U1	AGC COMP.	.0003116000	.0006232000	.1800	0	0	.999888
V1	BMAG 1	.0001800000	.0003600000	.1800	0	0	.999935
W1	BMAG 2	.0001800000	.0003600000	.1800	0	0	.999935
X1	GDC	.0001290000	.0002580000	.1800	0	0	.999954
Y1	CEA RJC	.0000160000	.0000320000	.1800	0	0	.999994
Z1	CEA TVC	.0000192000	.0000384000	.1800	0	0	.999993
A2	CEA MTVC	.0000187000	.0000374000	.1800	0	0	.999993
B2	DAA A	.0000170000	.0000340000	.1800	0	0	.999994
C2	DAA B	.0000170000	.0000340000	.1800	0	0	.999994
D2	DAA C	.0000015000	.0000030000	.1800	0	0	.999999
E2	DAA D	.0000015000	.0000030000	.1800	0	0	.999999
F2	SAA A	.0000140000	.0000280000	.0000	0	0	1.000000
G2	SAA B	.0000140000	.0000280000	.0000	0	0	1.000000
H2	DEA 1	.0000430000	.0000860000	.1800	0	0	.999985
O2	DEA 2	.0000430000	.0000860000	.1800	0	0	.999985
P2	FDAI 1	.0001200000	.0002400000	.1800	0	0	.999957
Q2	FDAI 2	.0001200000	.0002400000	.1800	0	0	.999957
R2	GP/FPI 1	.0000120000	.0000240000	.0000	0	0	1.000000
S2	GP/FPI 2	.0000120000	.0000240000	.0000	0	0	1.000000
T2	ROT.CON.1	.0000120000	.0000240000	.1800	0	0	.999996
U2	ROT.CON.2	.0000120000	.0000240000	.1800	0	0	.999996
V2	TR.CON.1	.0000015000	.0000030000	.1800	0	0	.999999
W2	TR.CON.2	.0000015000	.0000030000	.1800	0	0	.999999
X2	ASCP	.0000210000	.0000420000	.1800	0	0	.999992
Y2	RSI	.0000130000	.0000260000	.1800	0	0	.999995

TABLE B-2
COMPUTER OUTPUT - LPO MISSION (CONTINUED)

SIMULATION RESULTS

AFTER SIMULATION NO	TOTAL ABORTS	SUCCESSFUL ABORTS	CREW LOSS ABORTS	OTHER CREW LOSSES PHASES 1 - 18	OTHER CREW LOSSES PHASES 19 - 32	MISSION SUCCESS RELIABILITY	CREW SURVIVAL PROBABILITY
20	6	5	1	0	0	.700000	.950000
40	9	8	1	0	0	.775000	.975000
60	12	11	1	0	0	.800000	.983333
80	16	15	1	0	1	.787500	.975000
100	23	22	1	0	1	.760000	.980000

TIME ELAPSED = 00 HOURS, 03 MINUTES, AND 17 SECONDS.

CONFIDENCE AFTER 100 SIMULATIONS

CREW SURVIVAL PROBABILITY

CONFIDENCE LEVEL	.000001	.081212	.323314	.577946	.764882
CREW SURVIVAL PROBABILITY	.999800	.989900	.980000	.970100	.960200

MISSION SUCCESS RELIABILITY

CONFIDENCE LEVEL	-.000000	.000507	.443489	.990490	.999998
MISSION SUCCESS RELIABILITY	.989030	.874515	.760000	.645485	.530970

Appendix B

TABLE B-2
COMPUTER OUTPUT - LPO MISSION
(CONTINUED)

TABULATION OF COMPONENT FAILURES BY PHASE

PHASE	TOTAL	A1	B1	C1	D1	E1	F1	G1	H1	O1	P1	Q1	R1	S1	T1	U1	V1	W1	X1	Y1	Z1	A2
1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	46	0	0	3	1	0	6	3	1	7	1	3	0	1	1	10	0	3	1	1	1	1
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	31	0	0	3	1	0	4	0	2	3	1	0	2	0	0	4	0	2	5	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	88	0	0	6	2	0	10	3	3	11	2	3	2	1	2	14	0	6	6	1	2	1

PHASE	B2	C2	D2	E2	F2	G2	H2	O2	P2	Q2	R2	S2	T2	U2	V2	W2	X2	Y2
1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
17	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	1	0	0	0	0	0	0	[illegible]	0	0	0	2	0	0	0	1	0

TABLE B-2
COMPUTER OUTPUT - LPO MISSION
(CONTINUED)

[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
26	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	1	1	0	0	1	0	1	1	1	1	0	0	3	0	0	0	3	0

TABLE B-2
COMPUTER OUTPUT - LPO MISSION
(CONTINUED)

ABORT MISSIONS

ABORT NO	MISSION NO	LAST PHASE BEFORE ABORT	CRITICAL PHASE CAUSING ABORT	CRITICAL COMPONENT CAUSING ABORT	TOTAL FAILURES BEFORE ABORTING	FAILED COMPONENTS
1	4	16	17	W1	2	F1 Y1
2	6	16	17	O2	2	U1 H2
3	14	16	18	V1	1	O1
4	15	16	17	W1	2	F1 A2
5	16	16	17	W1	1	F1
6	19	16	17	W1	2	F1 O1
7	25	16	18	V1	1	O1
8	38	16	17	W1	1	C1
9	40	16	18	V1	1	O1
10	47	16	17	B1	1	W1
11	49	16	17	B1	1	W1
12	60	16	17	W1	2	C1 U1
13	64	5	7	V1	1	O1
14	69	16	17	B1	2	U1 W1
15	74	16	17	B1	1	X1
16	80	16	18	V1	1	O1
17	81	16	17	W1	1	F1
18	85	16	18	V1	1	H1
19	86	16	17	W1	2	C1 F1
20	89	16	18	V1	1	O1
21	93	16	18	V1	1	O1
22	97	16	17	C2	1	B2
23	100	16	18	V1	2	P1 U1

CREW LOSS ABORTS

ABORT NO	MISSION NO	LAST PHASE BEFORE ABORT	CRITICAL PHASE CAUSING ABORT	CREW LOSS PHASE	TOTAL FAILURES	FAILED COMPONENTS
1	6	16	17	23	3	U1 H2 O2

OTHER CREW LOSSES

TABLE B-2
COMPUTER OUTPUT - LPO MISSION
(CONTINUED)

OTHER CREW LOSSES

CREW LOSS MISSION NO	CREW LOSS PHASE	TOTAL FAILURES	FAILED COMPONENTS
61	20	2	C1 X1

TOTAL FAILURES FROM ALL ABORT MISSIONS (ABOVE) = 31

TOTAL FAILURES FROM ALL ABORT MISSIONS RESULTING IN CREW LOSS (ABOVE) = 3

TABLE B-2
COMPUTER OUTPUT - LPO MISSION
(CONCLUDED)

ABORT TIME MATRIX

1.0800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0200
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	1.4240	.0360	.0000
.0000	.0000	.0000	.0000	.0000	.0160	.3300					
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	1.2240	.0360	.0000	.0000
.0000	.0000	.0000	.0000	.0160	.3300						
.2500	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000	.0000	1.5160	.0900	6.0000	1.0000	.0050
2.0000	1.0000	.0020	1.0000	.1800							
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000	1.5160	.0900	7.0000	1.0000	.0050	3.0000
1.0000	.0020	1.0000	.1800								
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	1.5160	.0900	8.0000	1.0000	.0050	4.0000	1.0000
.0020	1.0000	.1800									
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	1.0160	.0900	12.0000	1.0000	.0050	5.0000	1.0000	.0020
1.0000	.1800										
50.4000	1.0000	.0035	11.8000	1.0000	.0020	1.0000	.0000	1.0160	.0000	.0000	.0000
.0000	.0000	2.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0006	1.0000
.1800											
1.0000	.0035	11.8000	1.0000	.0020	1.0000	.0000	1.0160	.0000	.0000	.0000	.0000
.0000	2.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0006	1.0000	.1800
.0035	11.8000	1.0000	.0020	1.0000	.0000	1.0160	.0000	.0000	.0000	.0000	.0000
2.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0006	1.0000	.1800	
11.8000	1.0000	.0020	1.0000	.0000	1.0160	.0000	.0000	.0000	.0000	.0000	2.0000
1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0006	1.0000	.1800		
1.0000	.0020	1.0000	.0000	1.0160	.0000	.0000	.0000	.0000	.0000	2.0000	1.0000
.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0060	1.0000	.1800			
.0020	1.0000	.0000	1.0160	.0000	.0000	.0000	.0000	.0000	2.0000	1.0000	.0042
44.0000	1.0000	.0010	22.0000	1.0000	.0006	1.0000	.1800				
1.0000	.0000	1.0160	.0000	.0000	.0000	.0000	.0000	2.0000	1.0000	.0042	44.0000
1.0000	.0010	22.0000	1.0000	.0006	1.0000	.1800					
.0000	1.0160	.0000	.0000	.0000	.0000	.0000	2.0000	1.0000	.0042	44.0000	1.0000
.0010	22.0000	1.0000	.0006	1.0000	.1800						
6.0160	.0000	.0000	.0000	1.0000	.0280	19.0000	1.0000	.0042	44.0000	1.0000	.0010
22.0000	1.0000	.0006	1.0000	.1800							
.0000	.0000	.0000	1.0000	.0280	19.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000
1.0000	.0006	1.0000	.1800								
.0000	.0000	1.0000	.0280	19.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000
.0006	1.0000	.1800									
.0000	1.0000	.0280	19.0000	1.0000	.0042	44.0000	1.0000	.0010	22.0000	1.0000	.0006
1.0000	.1800										

TABLE B-3
COMPUTER OUTPUT - LLM MISSION

D2	DAA C	.0000015000	.0000015000	1.0000	0	0	.999998
E2	DAA D	.0000015000	.0000015000	1.0000	0	0	.999998
F2	SAA A	.0000140000	.0000140000	1.0000	0	0	.999986
G2	SAA B	.0000140000	.0000140000	1.0000	0	0	.999986
H2	DEA 1	.0000430000	.0000430000	1.0000	0	0	.999957
O2	DEA 2	.0000430000	.0000430000	1.0000	0	0	.999957
P2	FDAI 1	.0001200000	.0001200000	1.0000	0	0	.999880
Q2	FDAI 2	.0001200000	.0001200000	1.0000	0	0	.999880
R2	GP/FPI 1	.0000120000	.0000120000	1.0000	0	0	.999988
S2	GP/FPI 2	.0000120000	.0000120000	1.0000	0	0	.999988
T2	ROT.CON.1	.0000120000	.0000120000	1.0000	0	0	.999988
U2	ROT.CON.2	.0000120000	.0000120000	1.0000	0	0	.999988
V2	TR.CON.1	.0000015000	.0000015000	1.0000	0	0	.999998
W2	TR.CON.2	.0000015000	.0000015000	1.0000	0	0	.999998
X2	ASCP	.0000210000	.0000210000	1.0000	0	0	.999979
Y2	RSI	.0000130000	.0000130000	.0000	0	0	1.000000

PHASE 32

COMPONENT	NOMENCLATURE	FAILURE RATE	CORRECTED FAILURE RATE	OPERATING HOURS	AVAILABLE SPARES	REPLACEMENT POSSIBLE	COMPONENT RELIABILITY
A1	ARTIFICE	.0000000000	.0000000000	.1800	0	0	1.000000
B1	IMU MTR.	.0000011500	.0000023000	.1800	0	0	1.000000
C1	IMU STAB.	.0001000000	.0002000000	.1800	0	0	.999964
D1	IMU ACCEL.	.0000238500	.0000477000	.1800	0	0	.999991
E1	PSA MTR.	.0000095000	.0000190000	.1800	0	0	.999997
F1	PSA STAB.	.0000688000	.0001376000	.1800	0	0	.999975
G1	PSA ACCEL.	.0000377000	.0000754000	.1800	0	0	.999986
H1	CDU COMMON	.0000343000	.0000686000	.1800	0	0	.999988
O1	CDU IMU A/D	.0001176000	.0002352000	.1800	0	0	.999958
P1	CDU IMU D/A	.0000450000	.0000900000	.1800	0	0	.999984
Q1	CDU OPT.D/A	.0000300000	.0000600000	.1800	0	0	.999989
R1	DSKY 1	.0000200000	.0000400000	.1800	0	0	.999993
S1	DSKY 2	.0000200000	.0000400000	.0000	0	0	1.000000
T1	AGC CLOCK	.0000450000	.0000900000	.1800	0	0	.999984
U1	AGC COMP.	.0003116000	.0006232000	.1800	0	0	.999888
V1	BMAG 1	.0001800000	.0003600000	.1800	0	0	.999935
W1	BMAG 2	.0001800000	.0003600000	.1800	0	0	.999935
X1	GDC	.0001290000	.0002580000	.1800	0	0	.999954
Y1	CEA RJC	.0000160000	.0000320000	.1800	0	0	.999994
Z1	CEA TVC	.0000192000	.0000384000	.1800	0	0	.999993
A2	CEA MTVC	.0000187000	.0000374000	.1800	0	0	.999993
B2	DAA A	.0000170000	.0000340000	.1800	0	0	.999994
C2	DAA B	.0000170000	.0000340000	.1800	0	0	.999994
D2	DAA C	.0000015000	.0000030000	.1800	0	0	.999999
E2	DAA D	.0000015000	.0000030000	.1800	0	0	.999999
F2	SAA A	.0000140000	.0000280000	.0000	0	0	1.000000
G2	SAA B	.0000140000	.0000280000	.0000	0	0	1.000000
H2	DEA 1	.0000430000	.0000860000	.1800	0	0	.999985
O2	DEA 2	.0000430000	.0000860000	.1800	0	0	.999985
P2	FDAI 1	.0001200000	.0002400000	.1800	0	0	.999957
Q2	FDAI 2	.0001200000	.0002400000	.1800	0	0	.999957
R2	GP/FPI 1	.0000120000	.0000240000	.0000	0	0	1.000000
S2	GP/FPI 2	.0000120000	.0000240000	.0000	0	0	1.000000
T2	ROT.CON.1	.0000120000	.0000240000	.1800	0	0	.999996
U2	ROT.CON.2	.0000120000	.0000240000	.1800	0	0	.999996
V2	TR.CON.1	.0000015000	.0000030000	.1800	0	0	.999999
W2	TR.CON.2	.0000015000	.0000030000	.1800	0	0	.999999
X2	ASCP	.0000210000	.0000420000	.1800	0	0	.999992
Y2	RSI	.0000130000	.0000260000	.1800	0	0	.999995

TABLE B-3
COMPUTER OUTPUT - LLM MISSION (CONTINUED)

SIMULATION RESULTS

AFTER SIMULATION NO	TOTAL ABORTS	SUCCESSFUL ABORTS	CREW LOSS ABORTS	OTHER CREW LOSSES PHASES 1 - 16	OTHER CREW LOSSES PHASES 17 - 32	MISSION SUCCESS RELIABILITY	CREW SURVIVAL PROBABILITY
500	4	4	0	0	0	.992000	1.000000
1000	14	14	0	0	0	.986000	1.000000
1500	21	21	0	0	0	.986000	1.000000
2000	28	28	0	0	1	.985500	.999500
2500	37	37	0	0	1	.984800	.999600
3000	45	45	0	0	1	.984667	.999667
3500	55	55	0	0	1	.984000	.999714
4000	61	61	0	0	1	.984500	.999750
4500	68	68	0	0	1	.984667	.999778
5000	76	76	0	0	1	.984600	.999800

TIME ELAPSED = 00 HOURS, 00 MINUTES, AND 09 SECONDS.

CONFIDENCE AFTER 5000 SIMULATIONS

CREW SURVIVAL PROBABILITY

CONFIDENCE LEVEL	.264241	.264241	.264241	.264241	.264241
CONFIDENCE LIMIT	.999800	.999800	.999800	.999800	.999800

MISSION ~~SUCCESS~~ RELIABILITY

CONFIDENCE LEVEL	.001771	.078386	.469740	.873424	.988264
CONFIDENCE LIMIT	.989030	.986815	.984600	.982385	.980170

TABLE B-3
COMPUTER OUTPUT - LLM MISSION
(CONTINUED)

TABULATION OF COMPONENT FAILURES BY PHASE

PHASE	TOTAL	A1	B1	C1	D1	E1	F1	G1	H1	O1	P1	Q1	R1	S1	T1	U1	V1	W1	X1	Y1	Z1	A2
1	30	0	0	1	1	0	3	2	0	3	1	0	0	0	1	4	1	2	3	0	0	0
2	33	0	0	0	1	0	1	0	1	2	0	0	0	0	1	6	3	2	4	0	0	1
3	4	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
4	3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	12	0	0	0	0	0	0	0	0	1	0	1	0	0	0	3	2	0	2	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	20	0	2	0	0	3	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0
9	12	0	0	1	0	0	2	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
12	10	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	3	1	1	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	7	0	0	1	0	0	0	1	0	0	0	0	0	1	0	2	0	1	0	0	0	0
15	4	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
16	23	0	0	2	0	0	3	0	0	3	0	0	0	0	2	1	3	2	1	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	209	0	0	20	1	0	5	9	4	15	5	5	2	4	7	32	15	13	6	6	3	4
19	36	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0
20	186	0	0	0	0	3	0	0	0	0	0	0	0	0	10	0	51	57	29	6	3	2
21	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
22	9	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
23	9	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	18	0	1	0	0	0	0	0	0	0	0	0	0	0	11	0	1	0	1	0	0	0
26	7	0	0	0	0	0	1	1	0	0	1	0	0	0	0	1	0	0	1	0	1	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	13	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
29	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	3	1	0	1	0	0
32	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
TOTAL	667	0	3	25	3	6	16	14	6	27	7	7	2	6	81	56	88	85	50	13	7	7

PHASE	B2	C2	D2	E2	F2	G2	H2	O2	P2	Q2	R2	S2	T2	U2	V2	W2	X2	Y2
1	2	0	0	0	0	1	0	0	3	1	1	0	0	0	0	0	0	0
2	1	0	0	0	0	0	1	1	4	3	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0
9	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	0	0

TABLE B-3
COMPUTER OUTPUT - LLM MISSION
(CONCLUDED)

17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	1	1	5	5	17	12	2	1	2	0	0	0	3	0
19	0	0	0	0	0	0	0	0	0	0	0	0	7	9	0	0	0	0
20	7	5	0	0	0	0	0	0	0	0	0	0	6	4	1	0	7	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0
23	0	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0
26	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0
29	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
32	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	12	6	0	0	2	3	8	9	36	22	3	2	20	23	1	0	11	0

APPENDIX C
STATE INTERPRETIVE PROGRAM (SIP) DATA

PRECEDING PAGE BLANK NOT FILMED.

Appendix C

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA

```
                         S/E STATE INTERPRETATION PROGRAM

               ERC  POWER  STUDY

NUMBER OF TIME INTERVALS:   3          TIME IN HOURS

PHASE  RATE    INTEGRATION INCREMENT  PRINT INCREMENT  END OF INTERVAL  K FACTOR        DESCRIPTION
  1     0              1.00                 8.00             8.00          1.00          HIGH POWER
  2     1              8.17               817.00           825.00          1.00         LOW POWER
  3     0              1.00                 8.00           833.00          1.00         HIGH POWER

COLUMN HEADINGS:  10
 ARS     TRAN    FDAI     RC     DAA 1  GP/FPI    SAA    DAA 2   SYS Q   SYS R

ANSWERS:  10
     12      19      22      25      28      31      34      37      50      60

INITIAL CONDITIONS:   8
     1 1.00000      13 1.00000      20 1.00000      23 1.00000      26 1.00000
    29 1.00000      32 1.00000      35 1.00000

ARROWS:  46
   1  2  16.600     0     .000
   1  3  80.400     0     .000
   1  4  40.000     0   40.000
   1  5  36.000     0     .000
   2  6  40.000     0   40.000
   2 12  80.400     0     .000
   3  7  36.000     0     .000
   3 12  16.600     0     .000
   4  6  16.600     0     .000
   4  8 100.400     0   20.000
   4  9  36.000     0     .000
   5  7  80.400     0     .000
   5 10  40.000     0   40.000
   5 11  34.600     0     .000
   6 12 100.400     0   20.000
   7 12  34.600     0     .000
   8  7  36.000     0     .000
   8 12  16.600     0     .000
   9  6  34.600     0     .000
   9  7 100.400     0   20.000
  10  6  34.600     0     .000
  10  7 100.400     0   20.000
  11  6  40.000     0   40.000
  11 12  80.400     0     .000
  13 14   1.920    25     .000
  13 16   1.870    26     .000
  13 17    .300    27     .000
  14 15    .300    28     .000
  14 19   1.870    29     .000
```

TABLE C-1
STATE INTERPRETIVE PROGRAM
DATA (CONTINUED)

	19	.150	30	.000
16	19	1.920	31	.000
17	16	2.020	32	.000
17	18	1.920	33	.000
18	19	2.020	34	.000
20	21	28.300	0	.000
21	22	14.150	0	.000
23	24	2.400	37	.000
24	25	1.200	38	.000
26	27	3.400	0	3.400
27	28	1.700	0	1.700
29	30	6.700	41	.000
30	31	3.350	42	.000
32	33	2.800	43	.000
33	34	1.400	44	.000
35	36	.300	45	.000
36	37	.150	46	.000

SUMS: 1

8	50	12	19	22	25	28	31	34	37	0

COMPLEMENTS: 1

60	50

S/E STATE INTERPRETATION PROGRAM

ERC POWER STUDY

PHASE: 1 - HIGH POWER

TIME	ARS SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
.00	.000000000 .000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
8.00	.000008525 .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940

TABLE C-1
STATE INTERPRETIVE PROGRAM
DATA (CONTINUED)

S/E STATE INTERPRETATION PROGRAM

ERC POWER STUDY

PHASE: 2 - LOW POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
8.00	.000008525 / .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940
825.00	.000039077 / .999765562	.000000023	.000001280	.000000009	.000193964	.000000072	.000000013	.000000000	.000234438

PHASE: 3 - HIGH POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
825.00	.000039077 / .999765562	.000000023	.000001280	.000000009	.000193964	.000000072	.000000013	.000000000	.000234438
833.00	.000095869 / .999700833	.000000092	.000005114	.000000037	.000197717	.000000287	.000000050	.000000001	.000299167

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

S/E STATE INTERPRETATION PROGRAM

FRC POWER STUDY

NUMBER OF TIME INTERVALS: 3 TIME IN HOURS

PHASE	RATE	INTEGRATION INCREMENT	PRINT INCREMENT	END OF INTERVAL	K FACTOR	DESCRIPTION
1	0	1.00	8.00	8.00	1.00	HIGH POWER
2	1	8.17	817.00	825.00	1.00	LOW POWER
3	0	1.00	8.00	833.00	1.00	HIGH POWER

COLUMN HEADINGS: 10

ARS TRAN FDAI RC DAA 1 GP/FPI SAA DAA 2 SYS Q SYS R

ANSWERS: 10

12 19 22 25 28 31 34 37 50 60

INITIAL CONDITIONS: 8

1	1.00000	13	1.00000	20	1.00000	23	1.00000	26	1.00000
29	1.00000	32	1.00000	35	1.00000				

ARROWS: 46

1	2	16.600	0	.553
1	3	80.400	0	22.370
1	4	40.000	0	40.000
1	5	36.000	0	1.200
2	6	40.000	0	40.000
2	12	80.400	0	22.370
3	7	36.000	0	1.200
3	12	16.600	0	.553
4	6	16.600	0	.553
4	8	100.400	0	42.370
4	9	36.000	0	1.200
5	7	80.400	0	22.370
5	10	40.000	0	40.000
5	11	34.600	0	1.090
6	12	100.400	0	42.370
7	12	34.600	0	1.090
8	7	36.000	0	1.200
8	12	16.600	0	.553
9	6	34.600	0	1.090
9	7	100.400	0	42.370
10	6	34.600	0	1.090
10	7	100.400	0	42.370
11	6	40.000	0	40.000
11	12	80.400	0	22.370
13	14	1.920	25	.064
13	16	1.170	26	.062
13	17	.300	27	.010
14	15	.300	28	.010
14	19	1.870	29	.062

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

	19	.150	30	.005
16	19	1.920	31	.064
17	16	2.020	32	.067
17	18	1.920	33	.064
18	19	2.020	34	.067
20	21	?8.300	0	.944
21	22	14.150	0	.471
23	24	2.400	37	.080
24	25	1.200	38	.040
26	27	3.400	0	3.400
27	28	1.700	0	1.700
29	30	6.700	41	.223
30	31	3.350	42	.112
32	33	?.800	43	.093
33	34	1.400	44	.047
35	36	.300	45	.010
36	37	.150	46	.005

SUMS: 1

8	50	12	19	22	25	28	31	34	37	0

COMPLEMENTS: 1

60	50

S/E STATE INTERPRETATION PROGRAM

ERC POWER STUDY

PHASE: 1 - HIGH POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
.00	.000000000 / .000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
8.00	.000008525 / .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940

TABLE C-1
STATE INTERPRETIVE PROGRAM
DATA (CONTINUED)

S/E STATE INTERPRETATION PROGRAM

FRC POWER STUDY

PHASE: 2 = LOW POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
8.00	.000008525 / .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940
825.00	.001123233 / .998655832	.000000445	.000024709	.000000179	.000193964	.000001392	.000000243	.000000003	.001344168

PHASE: 3 = HIGH POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
825.00	.001123233 / .998655832	.000000445	.000024709	.000000179	.000193964	.000001392	.000000243	.000000003	.001344168
833.00	.001419539 / .998342160	.000000670	.000037179	.000000269	.000197717	.000002095	.000000366	.000000004	.001657840

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

```
                              S/E STATE INTERPRETATION PROGRAM

                    ERC  POWER  STUDY

NUMBER OF TIME INTERVALS:  3          TIME IN HOURS

PHASE  RATE    INTEGRATION INCREMENT  PRINT INCREMENT  END OF INTERVAL  K FACTOR        DESCRIPTIO
  1     0               1.00                8.00             8.00          1.00          HIGH POW
  2     1               0.17              817.00           825.00          1.00          LOW POWER
  3     0               1.00                8.00           833.00          1.00          HIGH POWE

COLUMN HEADINGS:  10
  ARS     TRAN     FDAI     RC     DAA 1   GP/FPI   SAA    DAA 2   SYS Q   SYS R

ANSWERS:  10
    12      19      22      25      28      31      34      37      50      60

INITIAL CONDITIONS:   8
     1 1.00000      13 1.00000      20 1.00000      23 1.00000      26 1.00000
    29 1.00000      32 1.00000      35 1.00000

ARROWS:  46
   1   2  16.600     0   1.106
   1   3  80.400     0  44.740
   1   4  40.000     0  40.000
   1   5  36.000     0   2.400
   2   6  40.000     0  40.000
   2  12  80.400     0  44.740
   3   7  36.000     0   2.400
   3  12  16.600     0   1.106
   4   6  16.600     0   1.106
   4   8 100.400     0  64.740
   4   9  36.000     0   2.400
   5   7  80.400     0  44.740
   5  10  40.000     0  40.000
   5  11  34.600     0   2.170
   6  12 100.400     0  64.740
   7  12  34.600     0   2.170
   8   7  36.000     0   2.400
   8  12  16.600     0   1.106
   9   6  34.600     0   2.170
   9   7 100.400     0  64.740
  10   6  34.600     0   2.170
  10   7 100.400     0  64.740
  11   6  40.000     0  40.000
  11  12  80.400     0  44.740
  13  14   1.920    25    .128
  13  16   1.870    26    .125
  13  17    .300    27    .020
  14  15    .300    28    .020
  14  19   1.870    29    .125
```

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

	19	.150	30	.010
16	19	1.920	31	.128
17	16	2.020	32	.135
17	18	1.920	33	.128
18	19	2.020	34	.135
20	21	28.300	0	1.887
21	22	14.150	0	.943
23	24	2.400	37	.160
24	25	1.200	38	.080
26	27	3.400	0	3.400
27	28	1.700	0	1.700
29	30	6.700	41	.447
30	31	3.350	42	.223
32	33	2.800	43	.187
33	34	1.400	44	.093
35	36	.300	45	.020
36	37	.150	46	.010

SUMS: 1
8 50 12 19 22 25 28 31 34 37 0

COMPLEMENTS: 1
60 50

S/E STATE INTERPRETATION PROGRAM

ERC POWER STUDY

PHASE: 1 = HIGH POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
.00	.000000000 / .000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
8.00	.000008525 / .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

S/E STATE INTERPRETATION PROGRAM

FRC POWER STUDY

PHASE: 2 = LOW POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
8.00	.000008525 / .999990060	.000000023	.000001280	.000000009	.000000018	.000000072	.000000013	.000000000	.000009940
825.00	.003402979 / .996318530	.000001399	.000077425	.000000561	.000193964	.000004369	.000000764	.000000009	.003681470

PHASE: 3 = HIGH POWER

TIME	ARS / SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS Q
825.00	.003402979 / .996318530	.000001399	.000077425	.000000561	.000193964	.000004369	.000000764	.000000009	.003681470
833.00	.003896930 / .995797894	.000001780	.000098422	.000000714	.000197717	.000005558	.000000972	.000000011	.004202106

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONTINUED)

```
                              S/E STATE INTERPRETATION PROGRAM

                    ERC  POWER  STUDY

NUMBER OF TIME INTERVALS:   1          TIME IN HOURS

PHASE  RATE    INTEGRATION INCREMENT  PRINT INCREMENT  END OF INTERVAL  K FACTOR     DESCRIPTION
  1     0              83.30                 83.30           833.00         1.00     TOTAL CONTROL

COLUMN HEADINGS:  10
 ARS      TRAN     FDAI      RC     DAA 1  GP/FPI   SAA     DAA 2   SYS Q    SYS R

ANSWERS:  10
    12        19       22       25       28       31       34       37       50       60

INITIAL CONDITIONS:     8
     1 1.00000        13 1.00000        20 1.00000        23 1.00000        26 1.00000
    29 1.00000        32 1.00000        35 1.00000

ARROWS:   46
  1   2  16.600          1  16.600
  1   3  80.400          2  80.400
  1   4  40.000          3  40.000
  1   5  36.000          4  36.000
  2   6  40.000          5  40.000
  2  12  80.400          6  80.400
  3   7  36.000          7  36.000
  3  12  16.600          8  16.600
  4   6  16.600          9  16.600
  4   8 100.400         10 100.400
  4   9  36.000         11  36.000
  5   7  80.400         12  80.400
  5  10  40.000         13  40.000
  5  11  34.600         14  34.600
  6  12 100.400         15 100.400
  7  12  34.600         16  34.600
  8   7  36.000         17  36.000
  8  12  16.600         18  16.600
  9   6  34.600         19  34.600
  9   7 100.400         20 100.400
 10   6  34.600         21  34.600
 10   7 100.400         22 100.400
 11   6  40.000         23  40.000
 11  12  80.400         24  80.400
 13  14   1.920         25    .000
 13  16   1.870         26    .000
 13  17    .300         27    .000
 14  15    .300         28    .000
 14  19   1.870         29    .000
 15  19    .150         30    .000
 16  19   1.920         31    .000
```

TABLE C-1
STATE INTERPRETIVE PROGRAM
DATA (CONTINUED)

	16	2.020	32	.000
17	18	1.920	33	.000
18	19	2.020	34	.000
20	21	28.300	35	28.300
21	22	14.150	36	14.150
23	24	2.400	37	.000
24	25	1.200	38	.000
26	27	3.400	39	.000
27	28	1.700	40	.000
29	30	6.700	41	.000
30	31	3.350	42	.000
32	33	2.800	43	.000
33	34	1.400	44	.000
35	36	.300	45	.000
36	37	.150	46	.000

SUMS: 1
8 50 12 19 22 25 28 31 34 37 0

COMPLEMENTS: 1
60 50

TABLE C-1
STATE INTERPRETIVE PROGRAM DATA (CONCLUDED)

S/E STATE INTERPRETATION PROGRAM

ERC POWER STUDY

PHASE 1 - TOTAL CONTROL

TIME	ARS SYS R	TRAN	FDAI	RC	DAA 1	GP/FPI	SAA	DAA 2	SYS 0
.00	.000000000 .000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
83.30	.000907285 .998940781	.000002487	.000137306	.000000998	.000002003	.000007765	.000001358	.000000016	.001059219
166.60	.003552298 .995846510	.000009933	.000542807	.000003989	.000007999	.000030975	.000005427	.000000062	.004153490
249.90	.007816815 .990845022	.000022314	.001207073	.000008966	.000017972	.000069501	.000012197	.000000140	.009154978
333.20	.013580504 .984066006	.000039606	.002120935	.000015923	.000031904	.000123213	.000021659	.000000250	.015933994
416.50	.020722777 .975639155	.000061784	.003275470	.000024856	.000049780	.000191985	.000033803	.000000390	.024360845
499.80	.029124321 .965692642	.000088827	.004662001	.000035756	.000071582	.000275690	.000048620	.000000562	.034307358
583.10	.038668338 .954351884	.000120709	.006272090	.000048620	.000097293	.000374202	.000066100	.000000764	.045648116
666.40	.049241531 .941738566	.000157407	.008097531	.000063440	.000126897	.000487396	.000086234	.000000998	.058261434
749.70	.060734871 .927969876	.000198899	.010130342	.000080211	.000160378	.000615149	.000109013	.000001263	.072030124
833.00	.073044174 .913157935	.000245160	.012362764	.000098927	.000197717	.000757336	.000134427	.000001559	.086842065

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