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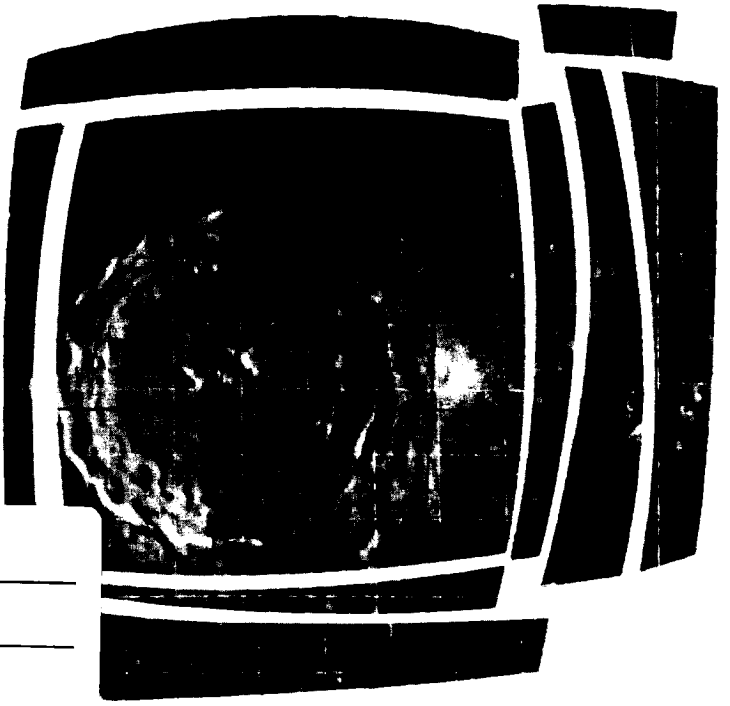

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LUNAR ROVING VEHICLE, PHASE I

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SUBMITTED TO

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

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VOLUME IV
RELIABILITY

APRIL 1964

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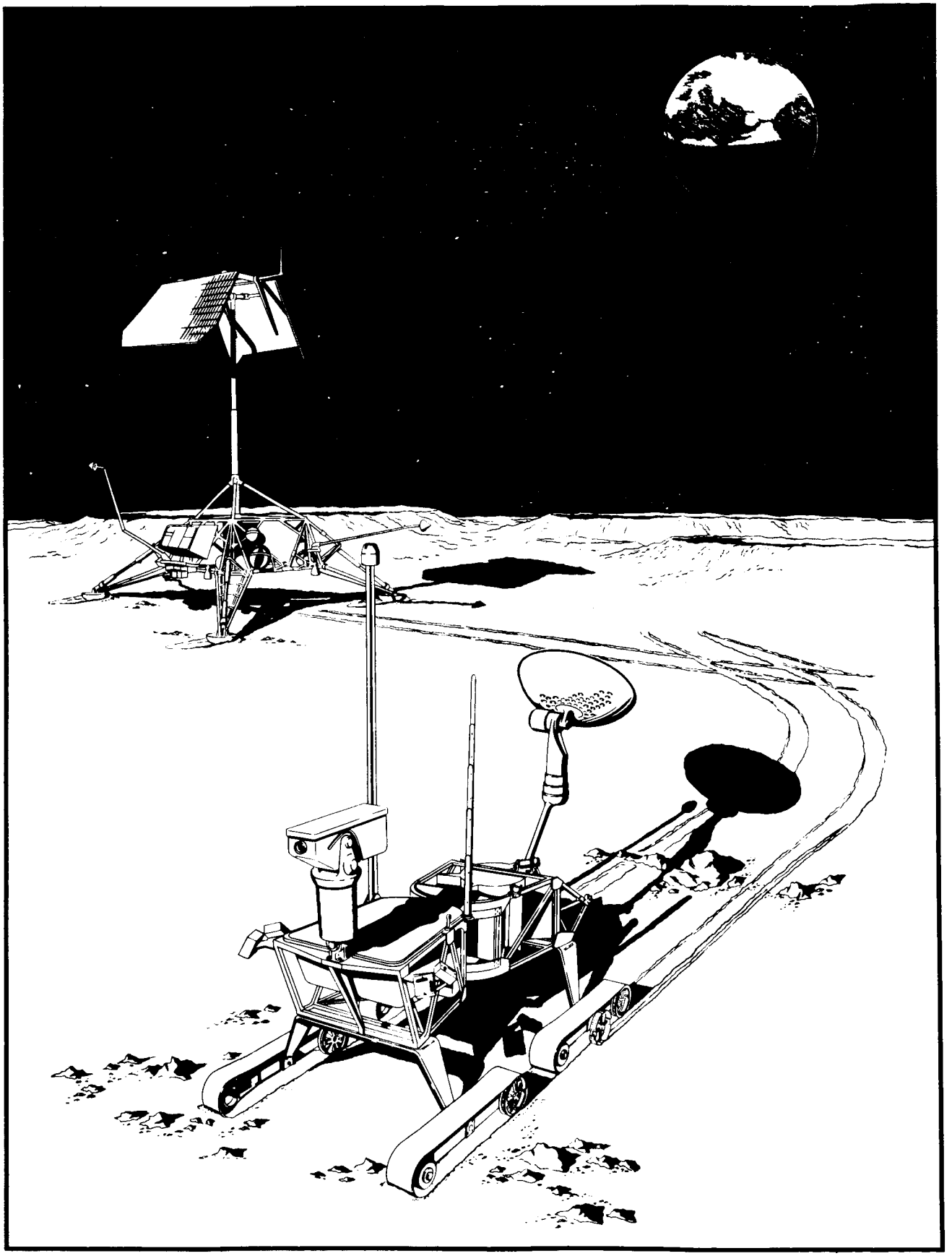

FOREWORD

As part of the continuing program of unmanned exploration of space, and to increase the effectiveness of the manned space program for exploring the moon, the Jet Propulsion Laboratory of the California Institute of Technology issued six-month study contracts to investigate the feasibility of a small, unmanned, lightweight, remotely controlled roving vehicle to be incorporated in the surveyor spacecraft to extend its data-gathering capabilities on the lunar surface. Specifically, the study program was to determine the feasibility of a 100-lb Surveyor Lunar Roving Vehicle (SLRV) system in gathering sufficient scientific information by surveying the lunar surface near the Surveyor spacecraft landing point to certify the area, in terms of specific hazards, as a potential Apollo LEM landing site.

This Final Technical Report, submitted in five volumes, presents the results and conclusions of the study program conducted by The Bendix Corporation under JPL Contract No. 950656. The volumes are organized to correspond to the specific objectives of the program: to conduct an analysis, to generate a preliminary design, and to fabricate and demonstrate an engineering test model in support of the over-all program objectives.

The results of Bendix's study show that the SLRV concept is not only feasible, but can make substantial contributions to the unmanned exploration of the moon in support of the manned Apollo program. The SLRV characteristics, the problems, and the initial trade-offs have been determined in sufficient detail to permit the definition of specific objectives and criteria for a follow-on development program. Program conclusions and recommendations are included in Volume V.

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VOLUME I – PROGRAM SUMMARY

VOLUME II – MISSION AND SYSTEM STUDIES

VOLUME III – PRELIMINARY DESIGN AND SYSTEM DESCRIPTION

Book 1 – System Description and Performance Characteristics

Book 2 – Validation of Preliminary Design

→ VOLUME IV – RELIABILITY

VOLUME V – SYSTEM EVALUATION

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SECTION I

INTRODUCTION

This volume of the Final Technical Report presents the results of the Phase I SLRV study program in accordance with the portion of Article 1, Section (a)(1)(iv) of the Statement of Work of JPL Contract No. 950656, Modification No. 1, which pertains to the preparation of failure mode and reliability data. This volume includes the SLRV reliability design effort conducted since the Second Bimonthly Technical Progress Report and summarizes the reliability efforts and results reported in the First and Second Bimonthly Technical Progress Reports (BSR 844 and BSR 879). This effort included updating and/or completion of system and subsystem reliability in the following areas:

1. Goals
2. Predictions
3. Block diagrams
4. Mathematical models
5. Analysis of mode of failure
6. Criticality rankings of failure modes

In addition, the effect of degraded modes of operation on system reliability are discussed.

SECTION 2

SLRV RELIABILITY

2.1 SYSTEM STUDIES

2.1.1 Parametric Studies

Bendix's approach enabled design decisions to be based on both performance and reliability criteria. It differs from conventional reliability techniques in that the subsystem design concepts are selected on a basis of reliability considerations before design freeze or the initiation of detailed preliminary design. Moreover, mission requirements and operating profiles did not have to be established until the reliability parametric data were weighed to determine their effect on the total system.

2.1.2 Reliability Block Diagram

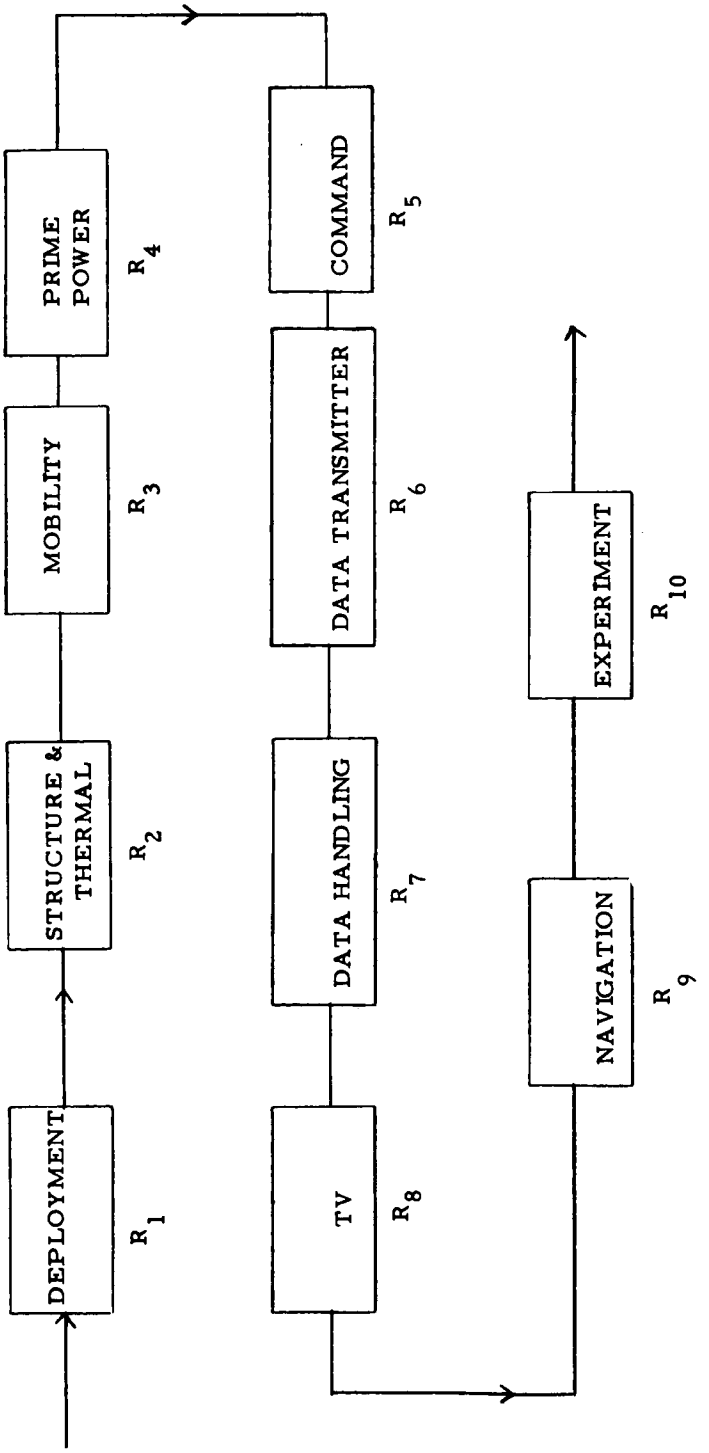
The reliability block diagram for the SLRV system is shown in Figure 2.1-1. In establishing this diagram, it has been assumed that the reliability of all static components such as supports, flanges, screws, etc., are near unity. As a consequence of this assumption, the system reliability is given by:

$$R_s(t, c) = \prod_{i=1}^{10} R_i(t, c)$$

where R_i is the specific subsystem reliability with t in hours and c in cycles. The specific reliability equations for each of the subsystems are delineated in detail in the applicable subsystem sections of this report.

2.1.3 Reliability Predictions

The primary SLRV system requirement is to survey 19 landing points. Based upon eight different lunar soil models that have been postulated and programmed into the computer, it has been determined that the average mission length will be 4.5 months.



$$R_{SLRV} = \prod_{i=1}^{10} R_i$$

Figure 2.1-1 SLRV Reliability Block Diagram

The probability of successfully surveying 19 landing points is 29.3%.

The mission profile data used in calculating the reliability for the SLRV system is shown in Tables 2.1-1 and 2.2-2. It has been assumed that only the 210-ft antenna is available with DSIF control 12 hours per day, 12 days per 28-day lunar periods.

The transmitter is energized during DSIF vehicle control time, except that in the first earth month the transmitter will also be energized during the lunar night DSIF control hours.

Table 2.1-3 and Figure 2.1-2 show that the reliability percentages of the SLRV system for 1, 2, 3, and 4.5 months of mission time is respectively 76.3, 58.9, 44.9, and 29.3.

The three subsystems contributing the most to system failure as shown in Table 2.1-3 are ranked as follows:

1. TV
2. Mobility
3. Data transmitter.

Failure mode analysis shows that the track in mobility, vidicon tube in TV, and coax switch in the data transmitter are the most critical items in the system.

2.1.4 Reliability Goals

It was shown in the first bimonthly report that the reliability goal for SLRV (P_{SR}) was a function of mission effectiveness (E), the probability of site acceptance (P_{SA}), and the probability of site identification (P_{SI}).

$$P_{SR} = \frac{}{P_{SA} \cdot P_{SI}}$$

where

E = 0.40 (see Vol. V, Section 2 for development.)

TABLE 2.1-1

MISSION PROFILE DATA

No. of 28 Day Lunar Periods	1	2	3	4.5
Total Earth Hours	672	1344	2016	3024
DSIF Control Hours	144	288	432	648
Travel - (km)	5.4	10.8	16.2	24.3
TV-Pictures (k)	5.5	11.0	16.5	24.8
Probe Cycles	230	460	690	1035
Transmitter (Hours)	280	424	568	784

TABLE 2-2

TRAVERSE AND LANDING POINT PROFILE DATA

ITEM	ONE TRAVERSE	ONE LANDING POINT	TOTAL
TV Pictures	200	1200	1400
Time (Hours)	11	27	38

TABLE 2. 1-3

GOALS AND PREDICTIONS

System	PREDICTION (%)				GOAL (%)
	1 Month	2 Month	3 Month	4. 5 Month	4. 5 Months
SLRV	76. 29	58. 95	44. 86	29. 26	50. 0
Prime Power	99. 47	98. 93	98. 40	97. 62	98. 6
TV	91. 0	82. 7	75. 2	63. 3	77. 3
Data Handling	98. 8	98. 4	97. 9	97. 2	98. 4
Command	95. 7	91. 5	87. 5	81. 5	89. 1
Data Transmitter	94. 13	89. 26	84. 71	78. 21	87. 0
Mobility	95. 2	90. 6	86. 2	80. 0	87. 8
Navigation	99. 76	99. 54	97. 8	96. 7	98. 1
Experiment	99. 7	99. 4	99. 1	98. 8	99. 3
Deployment	99. 9	99. 9	99. 9	99. 9	99. 9
Structure & Thermal	99. 9	99. 9	99. 9	99. 9	99. 9

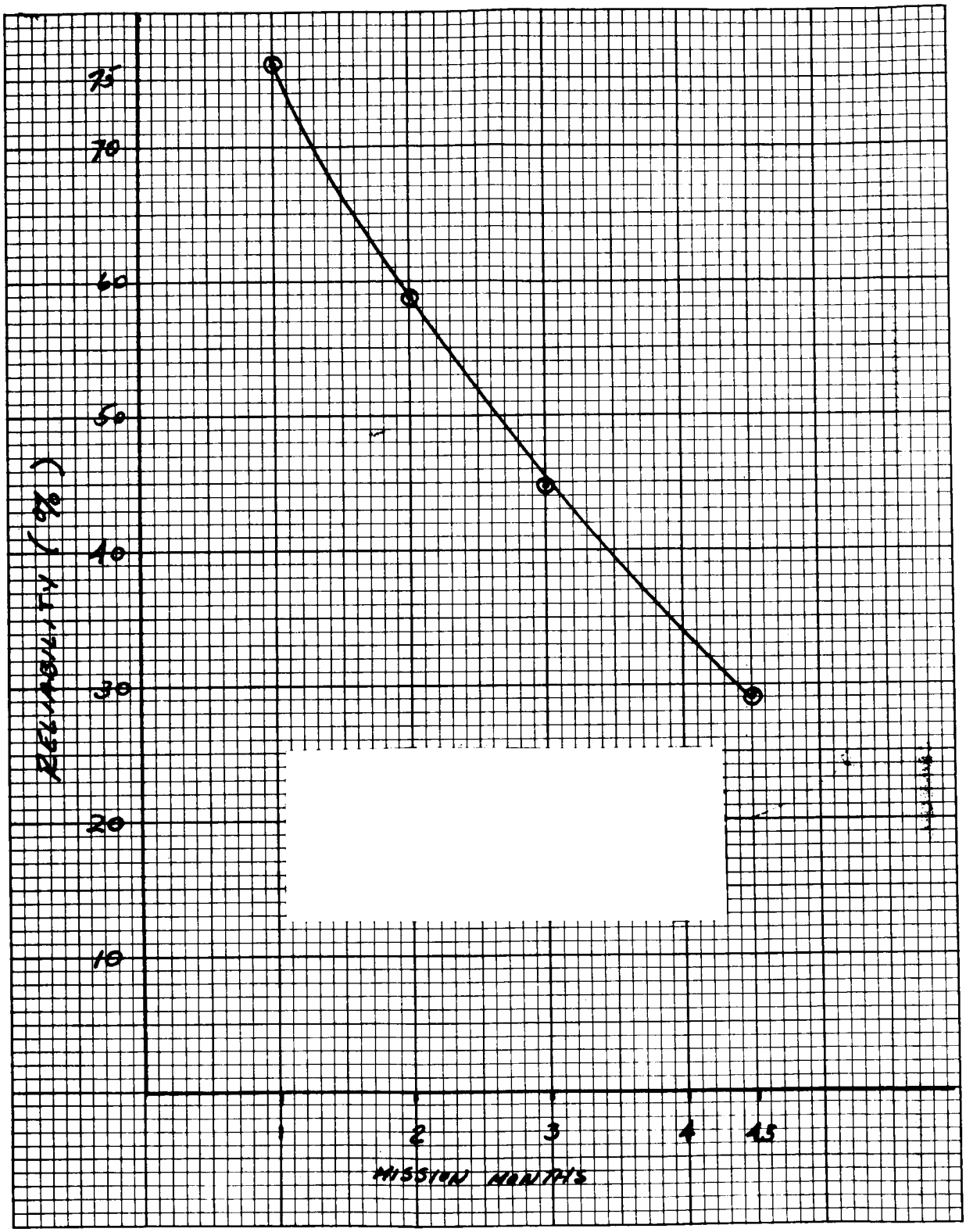


Figure 2. 1-2 System Reliability vs Mission Months

$$P_{SA} = 1$$

$$P_{SI} = 0.8.$$

Then

$$P_{SR} = \frac{0.4}{0.8} = .5, \text{ SLRV reliability goal.}$$

The preliminary subsystem goals are established based upon the SLRV system goal of 0.50. These subsystem goals will be revised during Phase II to reflect a cost effectiveness relationship, i.e., the cost to achieve a ΔR in each of the subsystems.

The technique used to establish the preliminary subsystem reliability goals is as follows:

1. Establish the λ t for the system

2. To obtain the subsystem goal, multiply the subsystem prediction λ t by the ratio of the system λ t goal to the system λ t prediction

$$\lambda t_{(SSG)} = \lambda t_{(SSP)} \times \frac{(\lambda t_{(SG)})}{\lambda t_{(SP)}}.$$

Then,

$$R_{SSG} = e^{-\lambda t_{SSG}}.$$

Figure 2.1-3 presents the SLRV Goal Tree for a mission time of 4.5 months. This mission period is the time required to survey 19 landing points.

2.1.5 Failure Mode Analysis

Failure mode analysis was conducted in accordance with the techniques described in the Bendix Systems Division SLRV System Assurance Program Document SLRV-SA-1.

The purpose of this analysis is to be able to rank the potential failure modes so that they can be investigated in the order of their level of criticalness. The order is determined by the quantitative product of the probability that a failure mode will occur and the degree of degradation resulting from the failure.

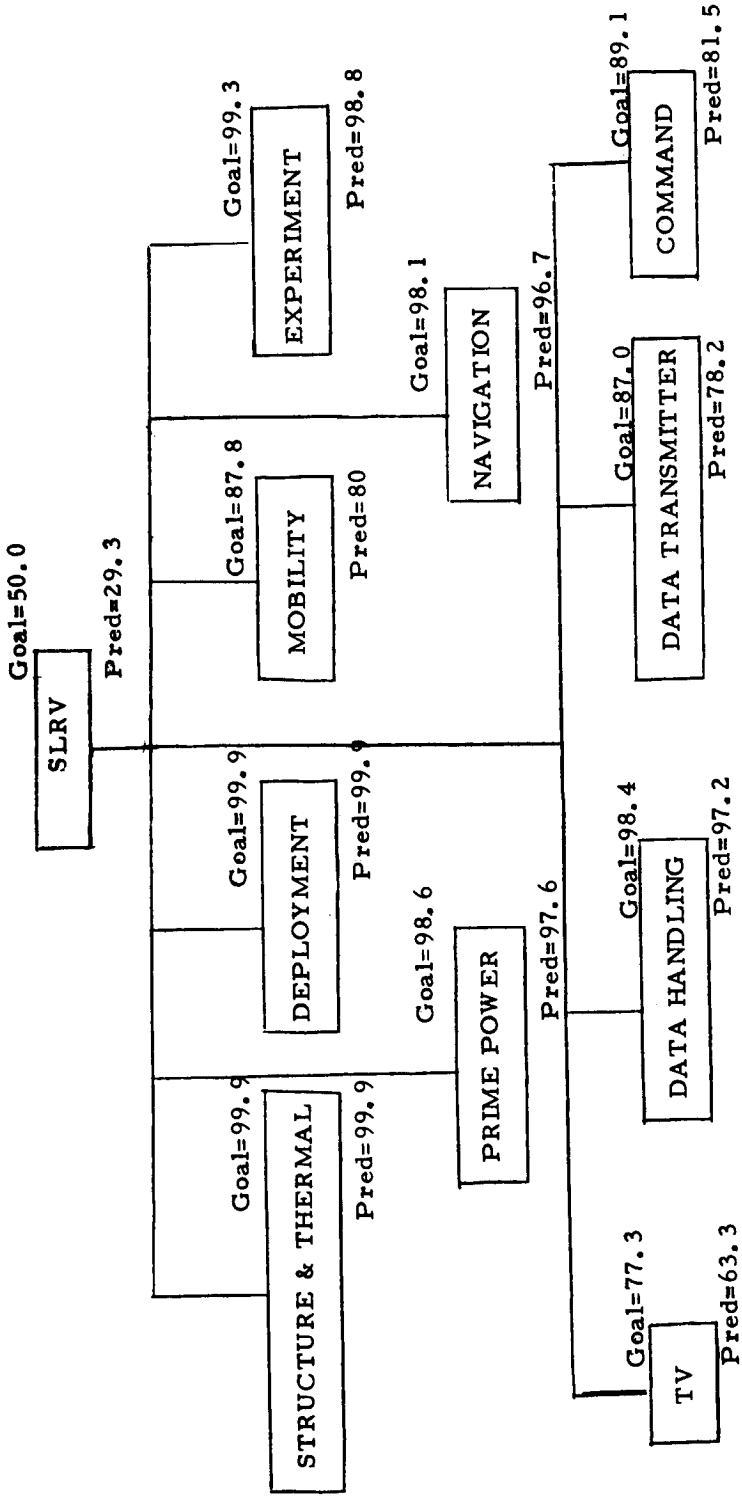


Figure 2.1-3 Reliability Prediction and Goal Tree for Mission Time of 4.5 Months

A component failure mode is defined as the manner in which a given component can fail. A component can fail, depending on the number of parts it contains and the stresses (electrical, mechanical, and/or environmental) experienced by the parts while operating in the expected environment. Each part within the component constitutes a potential failure. The manner in which the part fails under the given stresses may represent a possible failure mode of the component. Therefore, a failure mode analysis of a component is an analysis of its constituent parts to determine which of the failure modes will result in catastrophic failure or performance degradation of the component.

Once all conceivable failure modes of a component have been ascertained, a determination of the likelihood or probability of their occurrence under the particular operating condition is required to define the major failure modes. The likelihood of occurrence of a failure in a particular mode is given by

$$P = 1-e^{-\lambda t}$$

where

P = likelihood of occurrence

λ = rate of occurrence of the particular failure mode

t = operating time

e = base of the natural logarithms.

The rate of occurrence of a failure mode of a part is related to its failure rate through the following relationship:

$$\lambda_T = \sum_{i=1}^{k} \lambda_i \text{ for time (or cycle) sensitive devices}$$

where

λ_T = total failure rate of the time (or cycle) sensitive parts

λ_i = part failure rate due to the ith failure mode

K = number of failure modes.

The failure modes having the highest probability may be defined as the major failure modes.

The purpose of a failure effects analysis is to ascertain the degree of degradation resulting from the occurrence of one or more of the failure modes determined in the failure mode analysis. Since the component may fail either catastrophically or through performance degradation, the criticalness of a failure mode will be determined by the combination of the probability of failure and the degree of resultant degradation. Therefore, a major failure effect is defined as one having a severe or catastrophic effect on the performance of a subsystem and the over-all system in its mission.

Listed below are five categories of degradation into which the degrading effects on performance resulting from the occurrence of a failure mode may fall. The severity of each mode will be determined by the level to which it applies to the functional failure of the system, subsystem, component, and part in that order.

% of Reliability Degradation

A_e = 0.75 degraded to catastrophic (1.0) (likely abort)

B_e = 0.50 to < 0.75 degraded (continued operation in degraded mode)

C_e = 0.25 < 0.50 degraded (continued operation in degraded mode)

D_e = 0 to < 0.25 degraded (continued operation in degraded mode)

E_e = no effect

Subsequent to the failure mode and effects analyses, the potential failures representing serious deterrents to reliable performance of the component must be identified prior to implementing a reliability improvement effort. Such failures may be termed critical and can be defined as potential failures having a severe effect on component performance as well as high probability. The degree of criticalness of a potential failure is measured by the product of its quantitative probability of failure and the amount of degradation resulting from its occurrence.

The levels of criticalness will be presented in the order of decreasing importance. In implementing a reliability improvement effort, it will be determined which deficiencies represent the major deterrents to reliable performance, and effort will be concentrated on these. For example, the highest numerical product will be assigned a criticality number of 1, the next higher 2, etc. Since these criticality numbers are initially determined at the subsystem level, they will be re-examined by Bendix to establish a final criticality ranking based upon their influence on system reliability. Therefore, it is conceivable that a criticality ranking of "1" at the subsystem level could be modified to a ranking of "10" at the system level, depending upon the degree of change in system probability of success.

The most critical items in the SLRV system are shown in Table 2. 1-4 and are ranked in order of decending criticality.

It is recognized that failures of parts may either cause mission abort or extend the mission time to complete the survey of 19 landing points.

The computer evaluation program was used to assess the effect on reliability of those failures that extended the mission length, but still permitted the mission to be completed.

The following failures (see Table 2. 1-5), classified as partial because they did not abort the mission, were programmed into the computer at time t = 0 and t = 500 hours.

One hundred mission runs were programmed for each of the failures. Catastrophic failures could occur during each run. Analytically, their relative critical ranking, based upon probability of failure and estimated affect on mission, is shown in Table 2. 1-5.

The results of the computer run are shown in Table 2. 1-6. With failures programmed at time t = 0 and t = 500 hours, we find that our analytical critical ranking of the data transmitter coax switch agrees with the computer run; i. e., the reliability decrease is greater for the coax switch failure than for the other subsystems. However, the computer results enable us to rerank the other items in descending order as follows:

TABLE 2. 1-4

FAILURE MODE CRITICALITY RANKING CHART

SUBSYSTEM	COMPONENT	MODE OF FAILURE	PROBABILITY OF FAILURE x EFFECT	CRITICALITY RANKING
Mobility	Track	Tear	148×10^{-3}	1
TV	Vidicon	Open Heater or Insufficient Cathode Emission	60×10^{-3}	2
Transmitter	Coax Switch	Solenoid open or Short in Omni or Steerable Ant. Position	50.7×10^{-3}	3
TM Data Handling	TWT	Drift	35.5×10^{-3}	4
	Penetrometer Load Cell Input Function	Short	34.7×10^{-3}	5
Transmitter	Coax Switch	High Contact Resistance in Omni or Steerable Ant. Position	30.7×10^{-3}	6
TM Data Handling	RF Ranging Input Function	Short	26×10^{-3}	7
Command	Camera Azimuth RT Output Function	Open or Short	23.5×10^{-3}	8
	Camera Azimuth LT Output Function	Open or Short	23.5×10^{-3}	9
	TWT High Voltage ON-Output Function	Open or Short	22.8×10^{-3}	10

TABLE 2. 1-5

RELATIVE ANALYTICAL CRITICAL RANKING

Item	Component	Probability of Failure x Degradation	Criticality Ranking
Data Transmitter	Coax Switch	46×10^{-3}	1
Command	TV Decoder TV Pan Function	23.5×10^{-3}	2
TV	Video Preamp and Controls	17×10^{-3}	3
Mobility	Drive Motor (4 motors)	12×10^{-3}	4
Command	TV Decoder 50° FOV Function	11×10^{-3}	5
NAV	RF Ranging 2 Mc Phase Comparator	1.34×10^{-3}	6

TABLE 2. 1-6

DEGRADED MODE ANALYSIS

Subsystem	Component Failure	Mission Effect	Total Travel Increase-Km		Total Travel Increase Hrs		Reliability Decrease %	
			t = 0	t = 500	t = 0	t = 500	t = 0	t = 500
Navigation	RF Ranging 2 Mc Phase Computer	Loss of fine ranging must return to Surveyor after each landing point survey.	48	44	6189	5526	33	31
Mobility	Traction Drive Mechanism Drive Motor	Obstacle climbing capability reduced to 11. 5 cm cannot operate in soil less than 10 PSI per foot.	10	9. 5	1500	1350	9	10
Data Transmitter	Coax Switch	Cannot use steerable antenna. Data rate reduced. TV has 256 lines per frame.	14	12	10, 700	9450	39	37
Command	TV Decoder 50° FOV	Lose 50° FOV more pictures required.	7 (decrease	6 (decrease	2680	2340	20	17
TV	TV Decoder TV Pan	Loss of Azimuth TV Pan	3	3	2300	2000	19	15
	Control Circuitry of TV-Section I	Loss of Resolution more pictures required.	14	12	2200	1875	17	13

NOTE: System reliability decreases were based upon a system failure rate that has since been updated and reflected throughout this report.

Subsystem	Degraded Mode Analytical Ranking	Degraded Mode Revised Ranking
Data Transmitter	1	1
Command - TV Pan	2	4
TV	3	5
Mobility	4	6
Command - 50° fov	5	3
Navigation	6	2

The failures described above are typical of the many failures that would be programmed to permit reranking of part criticality. It is planned to continue this task during Phase II, so that a cost effectiveness factor can be established for each item.

2.1.6 Heavier Than 100-lb Vehicle

The foregoing discussion, including supporting studies in the subsystem sections of this report, has been devoted to a vehicle weighing no more than 100 lb. It is recognized that reliability improvement can be achieved at the expense of weight and power penalties.

Figure 2.1-4 delineates the cumulative increase in reliability with cumulative increased weight. Curve 1 is the reliability of the basic 100-lb SLRV system. The remaining curves are as follows:

1. No. 2: Basic with TV control circuitry redundant. The specific circuitry, consisting of 81 microcircuits, is shown in the Section 1 portion of the TV reliability block diagram. Reliability increases 6.3% for a 0.25-lb increase in weight.

2. No. 3: Curve number 2 with redundant command circuitry — specifically, redundant communications and penetrometer decoder, TV decoder, and mobility decoder. This results in a 12.6% cumulative increase in reliability over curve number 1 with a weight penalty of 0.5 lb. The command redundancy additional weight is only 0.25 lb.

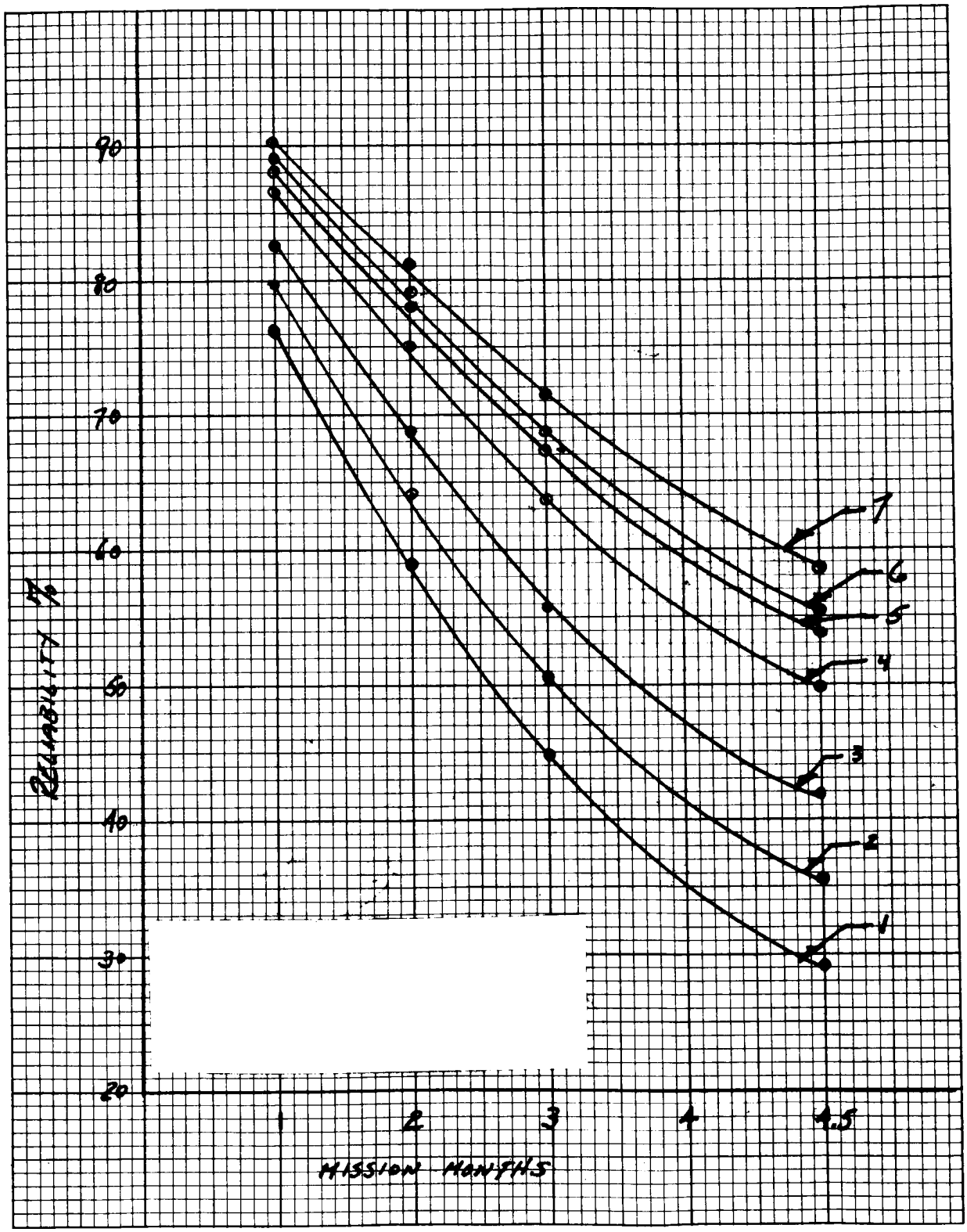


Figure 2. 1-4 Reliability vs Mission Months With Increased Redundancy

3. No. 4: Curve number 3 with a redundant coax switch in the data transmitter. Cumulative reliability increase is 20.5% with a cumulative weight penalty of 1 lb.

4. No. 5: Curve number 4 with a 30% increase in track thickness. Cumulative reliability increase is 24.6% with a cumulative weight penalty of 2 lb.

5. No. 6: Curve number 5 with a TWT redundant in the transmitter. Cumulative reliability increase is 26.1% with a cumulative weight penalty of 4.0 lb.

6. No. 7: Curve number 6 with a redundant vidicon tube in the TV. Cumulative reliability increase is 29.4% with a cumulative weight penalty of 7.5 lb.

As a result of this analysis, it can be clearly seen that an increase of 30% in SLRV reliability can be achieved for a weight increase of less than 10 lb through the use of selective redundancy. Further increases can be obtained by the complete use of high reliability parts. Raytheon's prediction (see Section 2.2.2) was predicated on the use of non-high-reliability parts. Their prediction of 63.3% (using standard parts) for a 4.5-month mission has a considerable effect on the system reliability of 29%.

2.1.7 Conclusions

The reliability analysis of the SLRV system during Phase I has resulted in the following conclusions:

1. The reliability goal of 0.50 for a mission period required to survey 19 landing points can be achieved with selective redundancy at a weight penalty of 1 lb. This goal can be surpassed with additional redundancy through more extensive use of high reliability parts with an additional weight penalty of 3 lb.

2. The subsystems contributing most to system failure are TV, data transmitter, and mobility. Reliability efforts will be concentrated in these areas during Phase II.

3. The three most critical items in the system are:

   a. Track in mobility subsystem

   b. Vidicon tube in TV

   c. Coax switch in data transmitter.

4. The computer evaluation program has provided a tool for reranking the criticality of parts whose failure does not cause mission abort but permits the mission to be completed in a degraded mode of operation. The effect on system reliability as a result of increased mission time is the factor employed in reranking the criticality of parts. This task will be continued during Phase II.

2.2 INFORMATION

2.2.1 Data Transmitter Parametric Studies

2.2.1.1 First Bimonthly Report

In the first bimonthly report, the SLRV concepts were evaluated for the TWT-type direct transmitter and associated antennas for a direct mode of transmitter operation, SLRV to ground station. The variables which were investigated for reliability were as follows:

1. Transmitter complexity
2. TWT redundancy
3. Operating time
4. Temperature effects
5. Vehicle speeds
6. Vehicle range.

The two basic concepts examined were a transmitter with a fixed omniantenna and a transmitter with a steerable parabolic dish antenna.

It was shown that the transmitter using the fixed omniantenna had a higher reliability than the one with a steerable antenna due to the increased complexity of the steerable antenna configuration. In summary, it was concluded that:

1. The fixed antenna configuration had a higher inherent reliability.
2. There was a significant increase in reliability for transmitter operation at 85°C as compared to operation at 125°C.
3. There was a significant gain in reliability in the use of a standby TWT in the transmitter.
4. A reduction in vehicle travel speed produced a decrease in reliability due to increased mission time.

5. A significant gain in reliability could be achieved in continuous day-night operation missions.

2. 2. 1. 2 Second Bimonthly Report

In the second bimonthly report, parametric reliability studies were performed for transmitter subsystem configurations of directional vs dual mode and for solid state vs TWT or Amplitron type circuits.

The parametric reliability study for a directional type transmitter (with fixed omni- and steerable antennas) vs dual mode type transmitter (with fixed omniantenna, indirect transmitter and surveyor link) was made for an ambient operating temperature of 55°C. The directional transmitter was shown to have a higher reliability and shorter mission time than the dual mode configuration. This was due to the greater complexity and lower TV data transmission rate for the dual mode transmitter.

In the parametric reliability study of the solid state transmitter circuit vs a TWT or Amplitron type, it was shown that the solid state circuit had a 2% higher reliability, considering a typical mission not exceeding 1000 hours. The difference becomes more a function of constant rate for extended missions.

The slightly higher reliability of the solid state transmitter design, however, was shown to be offset by the SLRV system weight and power constraints. For a 0. 5-watt transmitter design it was shown that the solid state circuit was less efficient, resulting in twice the weight of a TWT circuit, i. e., 12 lb vs 6 lb. At the 2-watt output level selected for the SLRV system design, the solid state components are not available for a practicable design.

Subsequent to the above parametric studies, a TWT type transmitter configuration using switchable antennas, fixed omni- and steerable, was decided upon for the SLRV.

2. 2. 1. 3 Reliability of Transmitter Subsystem

Since the last (2nd) bimonthly report, the transmitter subsystem has been updated from the version used in the previous reliability study. Therefore, this section will include the new reliability block diagram and mathematical model.

The reliability block diagram for the transmitter subsystem is shown in Figure 2.2-1. This diagram assumes a total mission success with both antenna systems operating. Therefore, they are shown in series with the other units of the transmitter. A partial success or degraded mode of operation could be achieved with either one of the antenna systems operating.

The resulting reliability diagrams are shown in Figures 2.2-2 and 2.2-3. It should be pointed out, however, that the probability of mission success for either degraded mode is now equal to the product of the reliability of the transmitter subsystem (Figure 2.2-1) up to the time of the degraded mode operation and the reliability of the transmitter subsystem operating in the degraded mode (Figures 2.2-2 or 2.2-3) for the time required or complete the mission.

This section will only include the reliability mathematical model for achieving the primary mission.

As shown in Figure 2.2-1, the reliability of the transmitter subsystem is given by the expression

$$L = L_1 \times L_2 \times L_3 \times L_4 \times L_5 \times L_6 \times L_7 \times L_8 \times L_9 \times L_{10} \times L_{11} \times L_{12} \times L_{13} \times L_{14} \times L_{15} \times L_{16} \times L_{17} \times L_{18} \times L_{19} \times L_{20} \times L_{21} \quad (2.2\text{-}1)$$

where

L_1 through L_{21} are the individual reliabilities of the subunits.

The values for L_1 through L_{21} are obtained by using the equation

$$R = e^{-\lambda t} \quad (2.2\text{-}2)$$

where

R = reliability

λ = total failure rate of subunit parts

t = operating time of subunit during mission.

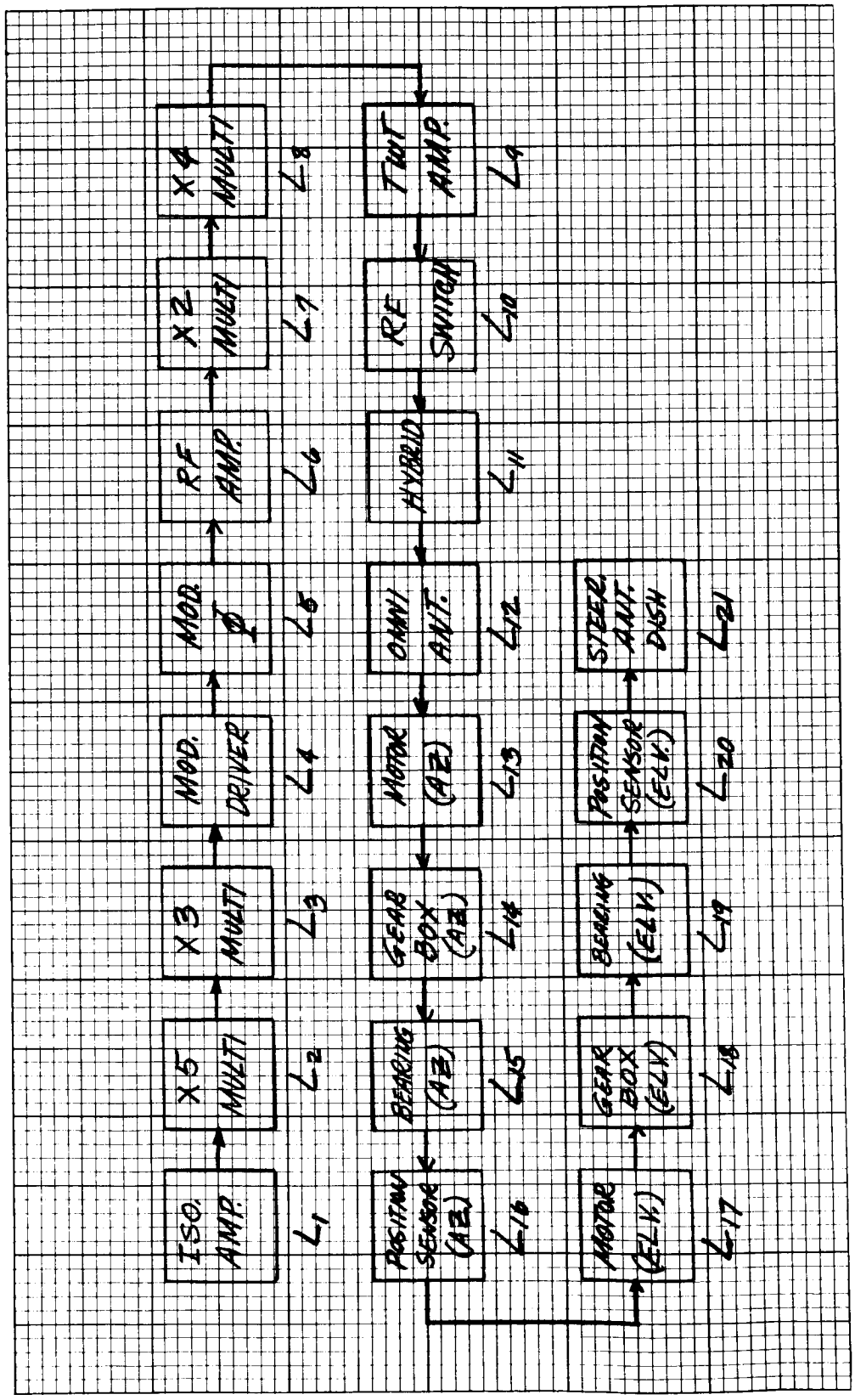


Figure 2.2-1 Transmitter Subsystem Reliability Block Diagram

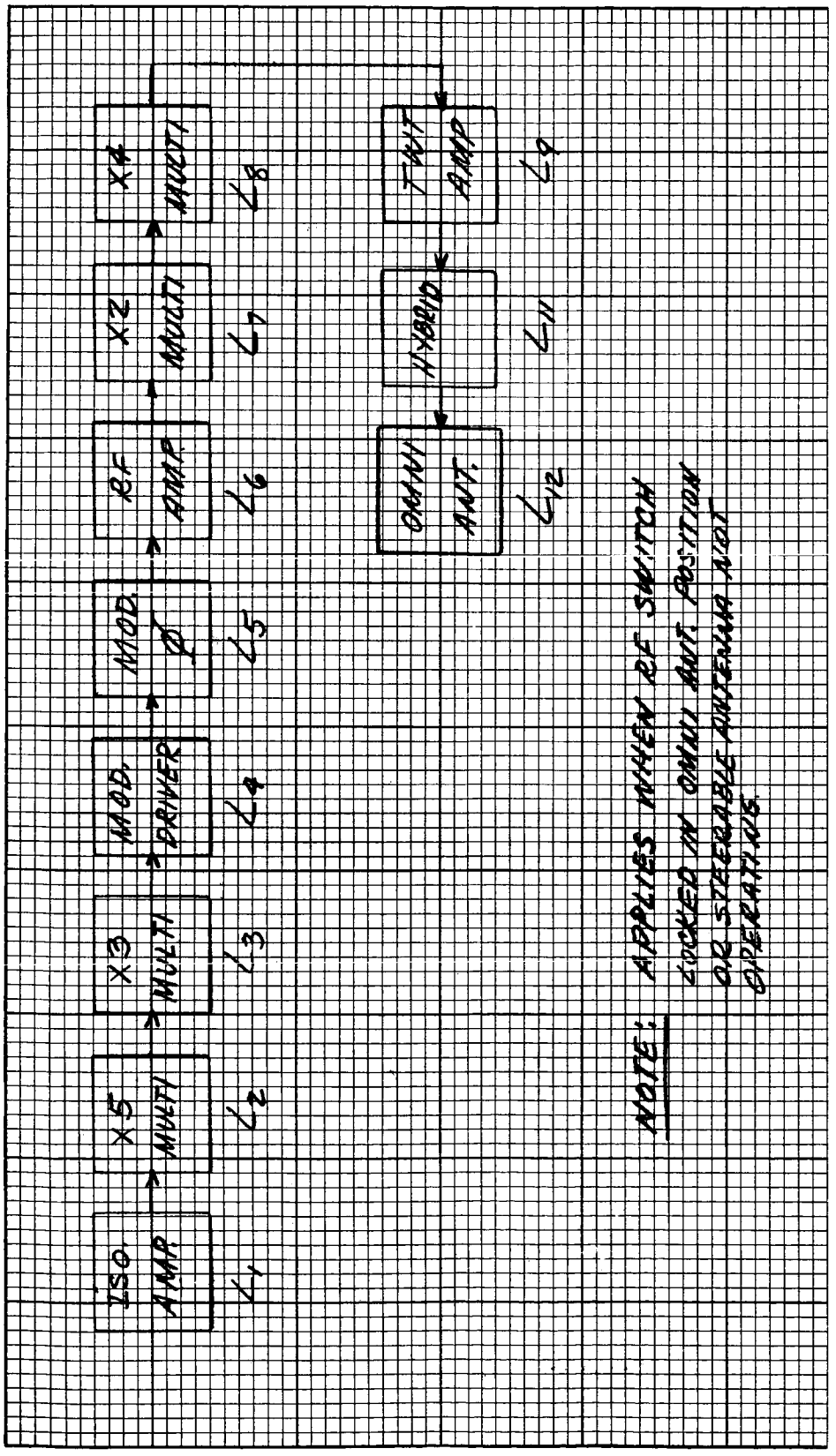


Figure 2.2-2 Transmitter Subsystem Reliability Block Diagram for Partial Mission Success With Omniantenna Operation

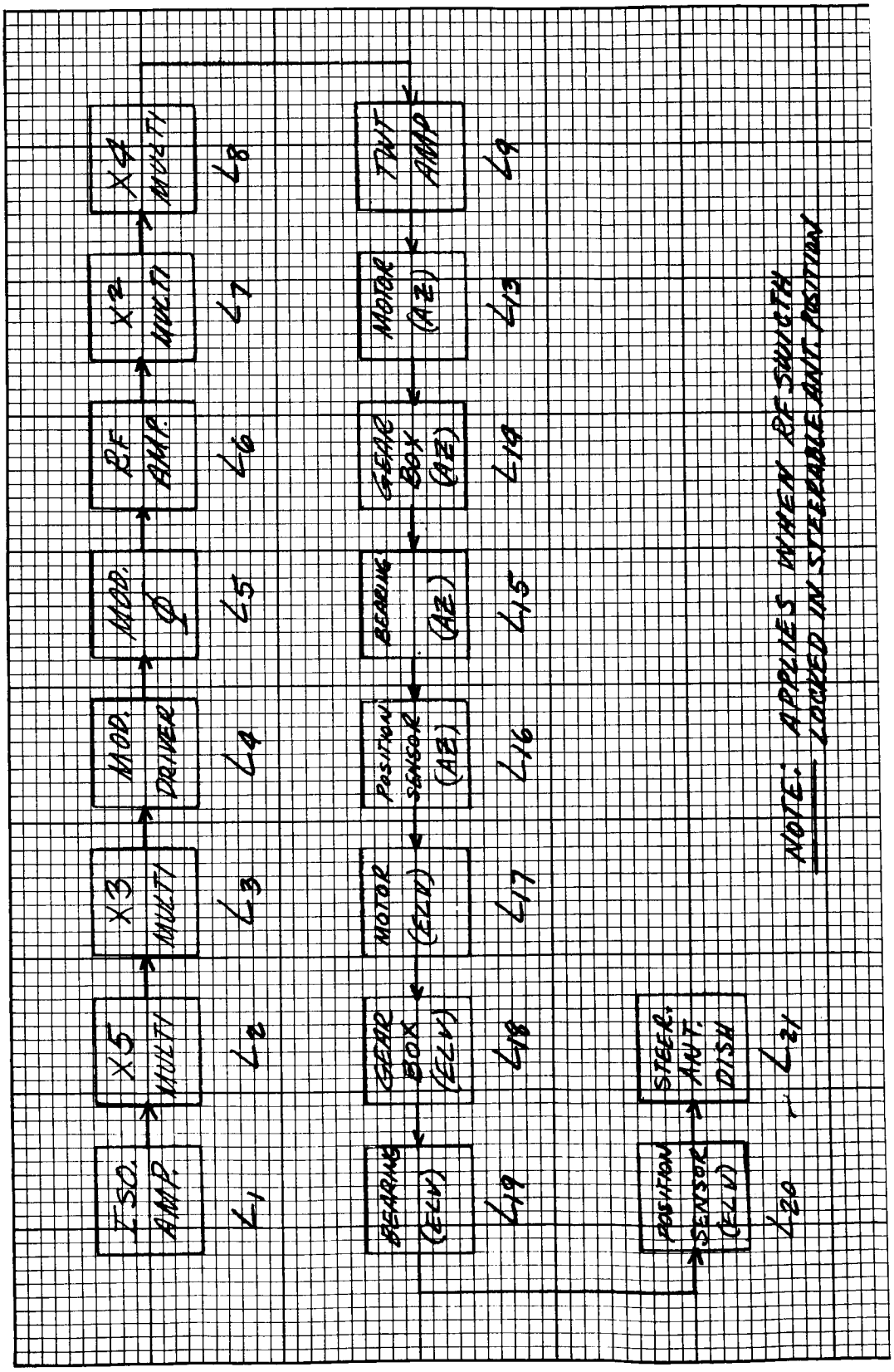


Figure 2.2-3 Transmitter Subsystem Block Diagram for Partial Mission Success With Steerable Antenna

Using Equation (2.2-2), the reliabilities of the subunits are given by the following:

$$L_1 = e^{-\lambda_1 t_1} \qquad L_{12} = e^{-\lambda_{12} t_3}$$

$$L_2 = e^{-\lambda_2 t_1} \qquad L_{13} = e^{-\lambda_{13} t_4}$$

$$L_3 = e^{-\lambda_3 t_1} \qquad L_{14} = e^{-\lambda_{14} t_4}$$

$$L_4 = e^{-\lambda_4 t_1} \qquad L_{15} = e^{-\lambda_{15} t_4}$$

$$L_5 = e^{-\lambda_5 t_1} \qquad L_{16} = e^{1\lambda_{16} t_4}$$

$$L_6 = e^{-\lambda_6 t_1} \qquad L_{17} = e^{-\lambda_{17} t_5}$$

$$L_7 = e^{-\lambda_7 t_1} \qquad L_{18} = e^{-\lambda_{18} t_5}$$

$$L_8 = e^{-\lambda_8 t_1} \qquad L_{19} = e^{-\lambda_{19} t_5}$$

$$L_9 = e^{-\lambda_9 t_1} \qquad L_{20} = e^{-\lambda_{20} t_5}$$

$$L_{10} = e^{-\lambda_{10} t_2} \qquad L_{21} = e^{-\lambda_{21} t_6}$$

$$L_{11} = e^{-\lambda_{11} t_3}$$

Substitution of the above into Equation (2.2-1) and combining terms yields the following equation:

$$L = e^{-\sum_{i=1}^{i=9} \lambda_i t_1} \times e^{-\lambda_{10} t_2} \times e^{-(\lambda_{11} + \lambda_{12}) t_3} \times e^{-\sum_{i=13}^{i=16} \lambda_i t_4} \times e^{-\sum_{i=17}^{i=20} \lambda_i t_5} \times e^{-\lambda_{21} t_6} \quad . \tag{2.2-3}$$

Using the failure rate data derived for the transmitter subsystem shown on the Reliability Prediction Worksheets and assuming a 4.5-month mission, the following values are then obtained for failure rates and times:

$\lambda_1 = 0.1106 \times 10^{-5}$

$\lambda_2 = 0.1206 \times 10^{-5}$

$\lambda_3 = 0.2116 \times 10^{-5}$

$\lambda_4 = 0.0626 \times 10^{-5}$

$\lambda_5 = 0.2552 \times 10^{-5}$

$\lambda_6 = 0.0766 \times 10^{-5}$

$\lambda_7 = 0.2526 \times 10^{-5}$

$\lambda_8 = 0.0036 \times 10^{-5}$

$\lambda_9 = 3.6150 \times 10^{-5}$

$\lambda_{10} = 2 \times 10^{-5}$/cycle

$\lambda_{11} = 0.0010 \times 10^{-5}$

$\lambda_{12} = 0.0400 \times 10^{-5}$

$\lambda_{13} = 1.1000 \times 10^{-5}$

$\lambda_{14} = 0.4300 \times 10^{-5}$

$\lambda_{15} = 0.1720 \times 10^{-5}$

$\lambda_{16} = 0.0760 \times 10^{-5}$

$\lambda_{17} = 1.1000 \times 10^{-5}$

$\lambda_{18} = 0.4300 \times 10^{-5}$

$\lambda_{19} = 0.1720 \times 10^{-5}$

$\lambda_{20} = 0.0760 \times 10^{-5}$

$\lambda_{21} = 0.3520 \times 10^{-5}$

$$t_1 = 784 \text{ hrs}$$

$$t_2 = 10,400 \text{ cycles}$$

$$t_3 = 627 \text{ hrs}$$

$$t_4 = 3.9 \text{ hrs}$$

$$t_5 = 3.9 \text{ hrs}$$

$$t_6 = 157 \text{ hrs}$$

Substituting the above values into Equation (2.2-3) gives the following expression for the total transmitter reliability

$$L = e^{-0.03673} \times e^{-0.20800} \times e^{-0.00026} \times e^{-0.00007} \times e^{-0.00007} \times e^{-0.00055} \qquad (2.2\text{-}4)$$

$$\therefore L = e^{-0.2457} = 0.7821. \qquad (2.2\text{-}5)$$

The low reliability value for the transmitter is due mainly to the large failure rate of the RF switch used to select the transmitting antenna. It is felt, however, that the failure rate could be reduced through selection of a more reliable switch or through redesign of the present switch.

The reliability of the transmitter subsystem in terms of mission months is shown in Table 2.2-1.

2.2.1.4 Failure Mode Analysis for Transmitter Subsystem

This section contains the failure mode analysis for the SLRV Transmitter Subsystem for the determination of the failure mode(s) and failure rates for each part, the failure mode probability, the degradation effect of part failure mode on subsystem mission, and the level of criticalness for

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Isolation Amplifier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C1-C6	Cap.	MICA				55	50	2	.0060	6	.0360	TRA-8734	
L1-L6	RF Coil					55	--	2	.0100	6	.0600	"	
Q1	Trans.	Planar	Fairchild	2N917		55	50	3	.0146	1	.0146	"	

SUB-UNIT TOTAL FAILURE RATE .1106

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION X5 Multiplier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C7-C12	Cap.	MICA				55	50	2	.0060	6	.0360	TRA-873-4	
L5-L11	RF Coil					55	--	2	.0100	7	.0700	"	
Q2	Trans.	Planar	Fairchild	2N917		55	50	3	.0146	1	.0146	"	

SUB-UNIT TOTAL FAILURE RATE .1206

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION X3 Multiplier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C13-20	Cap.	MICA				55	50	2	.0060	8	.0480	TRA-873-4	
L12-L19	RF Coil					55		2	.0100	8	.0800	" =	
R1, R2, R3	Resistor Comp.					55	50	2	.0270	3	.0810	"	
CR1	Diode	Si	Microwave Assoc. MA43210		Varactor	55	50	2	.0026	1	.0026	"	

SUB-UNIT TOTAL FAILURE RATE .2116

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Modulator Driver SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C21, C22,													
C23	Cap.	MICA				55	50	2	.0060	3	.0180	TRA-873-4	
L21, L22,													
L23	RFCoil					55	--	2	.0100	3	.0300	"	
Q3	Trans.	Planar	Fairchild	2N918		55	50	3	.0146	1	.0146	"	

SUB-UNIT TOTAL FAILURE RATE .0626

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Modulator, Phase SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C24-C33	Cap.	MICA				55	50	2	.0060	10	.0600	TRA-873-4	
L23-L29	RF Coil					55	--	2	.0100	7	.0700	"	
R4-R7	Resistor	Comp.				55	50	2	.0270	4	.1080	"	
CR2	Diode	Si			Varactor	55	50	2	.0026	1	.0026	"	
Q4	Trans.	Planar		2N918		55	50	3	.0146	1	.0146	"	

SUB-UNIT TOTAL FAILURE RATE .2552

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION RF Amplifier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C41, C43	Cap.	MICA				55	50	2	.00600	2	.0120	TRA-873-4	
L33, L34													
L35, L36													
L38	RFCoil					55	--	2	.0100	5	.0500	"	
Q5	Trans.	Planar	Fairchild	2N918		55	50	3	.0146	1	.0146	"	

SUB-UNIT TOTAL FAILURE RATE .0766

SUB-UNIT MTBF HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION X2 Multiplier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
C34, C35													
C36, C37													
C38, C39													
C40, C42	Cap.	MICA				55	50	2	.0060	8	.0480	TRA-873-4	
L30, L31													
L32, L37	RFCoil					55	--	2	.0100	4	.0400	"	
R8-R13	Resistor	Comp.				55	50	2	.0270	6	.1620	"	
CR4	Diode	Si	Microwave Assoc.	MA4322	Varactor	55	50	2	.0026	1	.0026	"	

SUB-UNIT TOTAL FAILURE RATE .2526

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION X4 Multiplier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
SL-1	Strip-Line		Bendix			55			.0010	1	.0010	RADC	
CR3	Diode	Si	Sylvania	D4611K		55		2	.0026	1	.0026	TRA-873-4	

SUB-UNIT TOTAL FAILURE RATE .0036

SUB-UNIT MTBF HOURS)

*INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION RF Power Amplifier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
V-1	TWT		Hughes	314H	RF Amp.				3.6150	1	3.6150	Hughes Reliability Report	

SUB-UNIT TOTAL FAILURE RATE 3.6150

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION RF Switch SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE % / 1000 cy	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE % / 1000 cy	REF. FAILURE RATE SOURCE	COMMENTS
S1	Switch	RF	Electronic Speciality Co.						2.000	1	2.000	Vendor Spec.	

SUB-UNIT TOTAL FAILURE RATE 2.000

SUB-UNIT MTBF HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Omni Antenna SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
ANT-2	Antenna	Omni	Bendix						.0400	1	.0400	TRA-873-4	
HY-1	Hybrid	Strip-											
		Line	Bendix						.0010	1	.0010	RADC	

SUB-UNIT TOTAL FAILURE RATE .0410

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Steerable Antenna Dish SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE % /1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
ANT-1	Antenna	Dish							3520	1	.3520	AVCO	

SUB-UNIT TOTAL FAILURE RATE .3520

SUB-UNIT MTBF HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. ____ REV. ____ DATE ____

SUB-UNIT DESIGNATION Azimuth Control, Steerable Antenna SCHEMATIC No. ____ REV. ____ DATE ____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
MTR-1	Motor								1.1000	1	1.1000	BSR-844	
GB-1	Gearbox								0.4300	1	0.4300	AVCO	
BR-1	Bearing								0.1720	1	0.1720	AVCO	
R14	Potentiometer				Sensor		50	3	0.0760	1	0.0760	TRA-873-4	

SUB-UNIT TOTAL FAILURE RATE 1.7780

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV Transmitter Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Elevation Control, Steerable Antenna SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
MTR-2	Motor								1.1000	1	1.1000	BSR-844	
GB-2	Gearbox								0.4300	1	0.4300	AVCO	
BR-2	Bearing								0.1720	1	0.1720	AVCO	
R15	Potentio-												
	meter				Sensor		50	3	0.0760	1	0.0760	TRA-873-4	

SUB-UNIT TOTAL FAILURE RATE 1.778

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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TABLE 2.2-1

DATA TRANSMITTER RELIABILITY

Unit	Desig.	Reliability Per Mission Months			
		1	2	3	4.5
Isolation Amp.	L_1	.9997	.9996	.9994	.9992
X5 Multiplier	L_2	.9997	.9995	.9994	.9991
X3 Multiplier	L_3	.9994	.9991	.9988	.9983
Mod. Driver	L_4	.9998	.9997	.9996	.9995
Modulator	L_5	.9993	.9989	.9986	.9980
RF Amplifier	L_6	.9998	.9997	.9996	.9994
X2 Multiplier	L_7	.9993	.9989	.9986	.9980
X4 Multiplier	L_8	.9999	.9999	.9999	.9999
TWT RF Amp.	L_9	.9899	.9848	.9797	.9721
RF Switch	L_{10}	.9548	.9117	.8705	.8122
Hybrid	L_{11}	.9999	.9999	.9999	.9999
Omni Antenna	L_{12}	.9999	.9999	.9998	.9997
Motor, Az.	L_{13}	.9999	.9999	.9999	.9999
Gear Box, Az.	L_{14}	.9999	.9999	.9999	.9999
Bearing, Az.	L_{15}	.9999	.9999	.9999	.9999
Position Sensor, Az.	L_{16}	.9999	.9999	.9999	.9999
Motor, Elv.	L_{17}	.9999	.9999	.9999	.9999
Gear Box, Elv.	L_{18}	.9999	.9999	.9999	.9999
Bearing, Elv.	L_{19}	.9999	.9999	.9999	.9999
Position Sensor, Elv.	L_{20}	.9999	.9999	.9999	.9999
Steer. Ant. Dish	L_{21}	.9999	.9998	.9996	.9994
Data Transmitter Subsystem	L	.9413	.8926	.8471	.7821

each part (the product of probability of failure and the degradation effect). The analysis was made for the transmitter subsystem configuration, which includes the steerable antenna and fixed omniantenna, as shown in the block diagram of Figure 2.2-4.

The data derived from the analysis is contained in Tables 2.2-2 and 2.2-3. The following paragraphs will discuss the derivation of together with possible methods for decreasing the high criticalness of some of the parts.

Table 2.2-2 delineates for each part of the transmitter subsystem the part failure rate, the failure mode ratio, and part failure rate for the failure mode. The sources for the part failure rates are noted at the end of Table 2.2-1. The failure mode ratio values represent the ratio of failures in each mode to the total expected failures of the part. Thus, the product of the failure mode ratio and the total failure rate of the part will give the part failure rate for that particular failure mode. The values used for the failure mode ratio were in most cases taken from TRA-873-74, section 6, dated 1 September 1961. However, where information was not available for failure mode(s) or failure mode ratio for parts, an assumed failure mode ratio was used. The data derived in Table 2.2-2 is used for derivation of the data in Table 2.2-3.

Table 2.2-3 delineates, for each part of the transmitter subsystem, the failure mode, the failure mode failure rate, the operating time or cycles during an SLRV mission, the probability of failure, the percent degradation of subsystem as related to part failure, the level of criticalness, and the criticality index number. The part failure mode and failure mode failure rates are taken from Table 2.2-2.

The operating time values were obtained from an analysis of the schedule of operations for the SLRV for point survey and traverse to each point. The assumed schedule of operations is shown in Table 2.2-4. It was assumed that the transmitter will be operating for the total time of 857 hours. In addition, it was assumed that for the first month of operation the transmitter will be operated also during the first lunar night and two additional days (days not suitable for TV transmission) for telemetry purposes. This additional time brings the total time to about 1000 hours, assuming operation with the DSIF 210-ft antenna at 11 hours per day.

To arrive at the operating time distribution between the omni- and steerable antenna modes of transmitter operation, it was assumed that

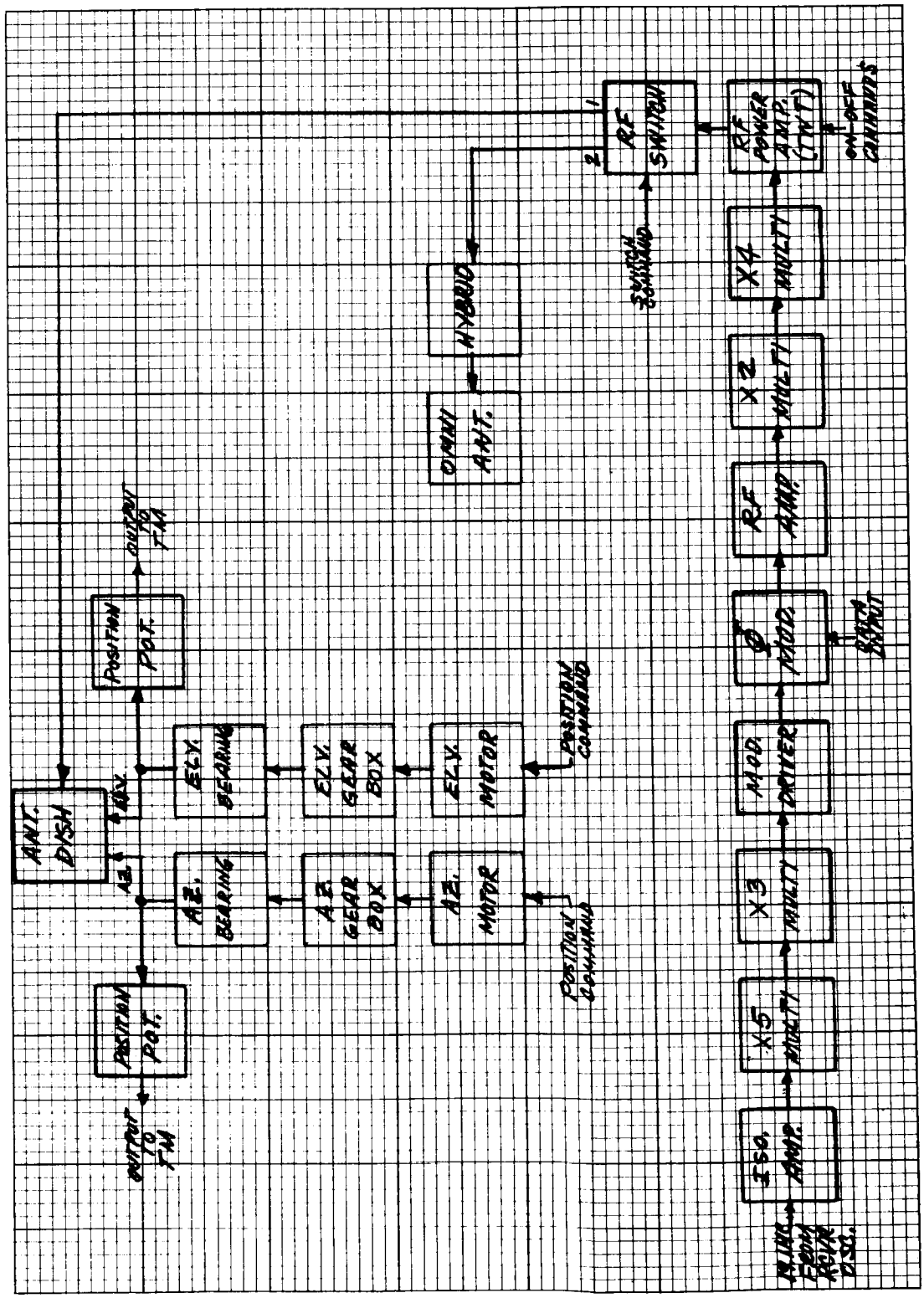


Figure 2.2-4 Transmitter Subsystem Block Diagram

TABLE 2.2-2

TRANSMITTER SUBSYSTEM PARTS FAILURE RATE FOR MODE OF FAILURE

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode Ratio			Part Failure Rate in Failure Mode ($X10^{-5}$)		
					Open	Short	Drift	Open	Short	Drift
C1	Capacitor, F. M.	Iso. Amp.	50	.0060	.70	.30		.0042	.0018	
C2	"	"	50	.0060	.70	.30		.0042	.0018	
C3	"	"	50	.0060	.70	.30		.0042	.0018	
C4	"	"	50	.0060	.70	.30		.0042	.0018	
C5	"	"	50	.0060	.70	.30		.0042	.0018	
C6	"	"	50	.0060	.70	.30		.0042	.0018	
L1	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L2	"	"	--	.0100	.10		.90	.0010		.0090
L3	"	"	--	.0100	.10		.90	.0010		.0090
L4	"	"	--	.0100	.10		.90	.0010		.0090
L6	"	"	--	.0100	.10		.90	.0010		.0090
Q1	Transistor	"	50	.0146	.20	.10	.70	.0029	.0015	.0102
C7	Capacitor, F. M.	X5 Multi.	50	.0060	.70	.30		.0042	.0018	
C8	"	"	50	.0060	.70	.30		.0042	.0018	
C9	"	"	50	.0060	.70	.30		.0042	.0018	
C10	"	"	50	.0060	.70	.30		.0042	.0018	
C11	"	"	50	.0060	.70	.30		.0042	.0018	
C12	"	"	50	.0060	.70	.30		.0042	.0018	
L5	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L7	"	"	--	.0100	.10		.90	.0010		.0090
L8	"	"	--	.0100	.10		.90	.0010		.0090
L9	"	"	--	.0100	.10		.90	.0010		.0090

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode Ratio			Part Failure Rate in Failure Mode ($X10^{-5}$)		
					Open	Short	Drift	Open	Short	Drift
L10	RF Coil	X5 Multi.	--	.0100	.10		.90	.0010		.0090
L11	"	"	--	.0100	.10		.90	.0010		.0090
Q2	Transistor	X5 Multi.	50	.0146	.20	.10	.70	.0029	.0015	.0102
C13	Capacitor, F. M.	X3 Multi.	50	.0060	.70	.30		.0042	.0018	
C14	"	"	50	.0060	.70	.30		.0042	.0018	
C15	"	"	50	.0060	.70	.30		.0042	.0018	
C16	"	"	50	.0060	.70	.30		.0042	.0018	
C17	"	"	50	.0060	.70	.30		.0042	.0018	
C18	"	"	50	.0060	.70	.30		.0042	.0018	
C19	"	"	50	.0060	.70	.30		.0042	.0018	
C20	"	"	50	.0060	.70	.30		.0042	.0018	
L12	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L13	"	"	--	.0100	.10		.90	.0010		.0090
L14	"	"	--	.0100	.10		.90	.0010		.0090
L15	"	"	--	.0100	.10		.90	.0010		.0090
L16	"	"	--	.0100	.10		.90	.0010		.0090
L17	"	"	--	.0100	.10		.90	.0010		.0090
L18	"	"	--	.0100	.10		.90	.0010		.0090
L19	"	"	--	.0100	.10		.90	.0010		.0090
R1	Resistor, F. C.	"	50	.0270	.10		.90	.0027		.0243
R2	"	"	50	.0270	.10		.90	.0027		.0243
R3	"	"	50	.0270	.10		.90	.0027		.0243
CR1	Diode	"	50	.0026	.10	.30	.60	.0003	.0008	.0016
C21	Capacitor, F. M.	Mod. Driver	50	.0060	.70	.30		.0042	.0018	
C22	"	"	50	.0060	.70	.30		.0042	.0018	

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode Ratio			Part Failure Rate in Failure Mode ($X10^{-5}$)		
					Open	Short	Drift	Open	Short	Drift
C23	Capacitor, F. M.	Mod. Driver	50	.0060	.70	.30		.0042	.0018	
L20	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L21	"	"	--	.0100	.10		.90	.0010		.0090
L22	"	"	--	.0100	.10		.90	.0010		.0090
Q3	Transistor	"	50	.0146	.20	.10	.70	.0029	.0015	.0102
C24	Capacitor, F. M.	Modulator	50	.0060	.70	.30		.0042	.0018	
C25	"	"	50	.0060	.70	.30		.0042	.0018	
C26	"	"	50	.0060	.70	.30		.0042	.0018	
C27	"	"	50	.0060	.70	.30		.0042	.0018	
C28	"	"	50	.0060	.70	.30		.0042	.0018	
C29	"	"	50	.0060	.70	.30		.0042	.0018	
C30	"	"	50	.0060	.70	.30		.0042	.0018	
C31	"	"	50	.0060	.70	.30		.0042	.0018	
C32	"	"	50	.0060	.70	.30		.0042	.0018	
C33	"	"	50	.0060	.70	.30		.0042	.0018	
L23	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L24	"	"	--	.0100	.10		.90	.0010		.0090
L25	"	"	--	.0100	.10		.90	.0010		.0090
L26	"	"	--	.0100	.10		.90	.0010		.0090
L27	"	"	--	.0100	.10		.90	.0010		.0090
L28	"	"	--	.0100	.10		.90	.0010		.0090
L29	"	"	--	.0100	.10		.90	.0010		.0090
R4	Resistor, F. C.	"	50	.0270	.10		.90	.0027		.0243
R5	"	"	50	.0270	.10		.90	.0027		.0243

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode Ratio			Part Failure Rate in Failure Mode ($X10^{-5}$)		
					Open	Short	Drift	Open	Short	Drift
R6	Resistor, F. C	Modulator	50	.0270	.10		.90	.0027		.0243
R7	"	"	50	.0270	.10		.90	.0027		.0243
CR2	Diode	"	50	.0026	.10	.30	.60	.0003	.0008	.0016
Q4	Transistor	"	50	.0146	.20	.10	.70	.0029	.0015	.0102
C41	Capacitor, F. M.	RF Amp.	50	.0060	.70	.30		.0042	.0018	
C43	"	"	50	.0060	.70	.30		.0042	.0018	
L33	RF Coil	"	50	.0100	.10		.90	.0010		.0090
L34	"	"	--	.0100	.10		.90	.0010		.0090
L35	"	"	--	.0100	.10		.90	.0010		.0090
L36	"	"	--	.0100	.10		.90	.0010		.0090
L38	"	"	--	.0100	.10		.90	.0010		.0090
Q5	Transistor	RF Amp	50	.0146	.20	.10	.70	.0029	.0015	.0102
C34	Capacitor, F. M.	X2 Multi.	50	.0060	.70	.30		.0042	.0018	
C35	"	"	50	.0060	.70	.30		.0042	.0018	
C36	"	"	50	.0060	.70	.30		.0042	.0018	
C39	"	"	50	.0060	.70	.30		.0042	.0018	
C38	"	"	50	.0060	.70	.30		.0042	.0018	
C39	"	"	50	.0060	.70	.30		.0042	.0018	
C40	"	"	50	.0060	.70	.30		.0042	.0018	
C42	"	"	50	.0060	.70	.30		.0042	.0018	
L31	RF Coil	"	--	.0100	.10		.90	.0010		.0090
L31	"	"	--	.0100	.10		.90	.0010		.0090
L32	"	"	--	.0100	.10		.90	.0010		.0090
L39	"	"	--	.0100	.10		.90	.0010		.0090
R8	Resistor, F. C.	"	50	.0270	.10		.90	.0027		.0243

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode Ratio			Part Failure Rate in Failure Mode ($X10^{-5}$)		
					Open	Short	Drift	Open	Short	Drift
R9	Resistor, F. C.	X2 Multi.	50	.0270	.10		.90	.0027		.0243
R10	"	"	50	.0270	.10		.90	.0027		.0243
R11	"	"	50	.0270	.10		.90	.0027		.0243
R12	"	"	50	.0270	.10		.90	.0027		.0243
R13	"	"	50	.0270	.10		.90	.0027		.0243
CR4	Diode	"	50	.0026	.10	.30	.60	.0003	.0008	.0016
SL-1	Stripline	X4 Multi.	--	**** .0010	.50	.50		.0005	.0005	
CR3	Diode	"	50	.0026	.10	.30	.60	.0003	.0008	.0016
V-1	TWT	RF Pwr. Amp	--	* **** 3.6150			1.0			3.615

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode	Failure Mode Ratio	Part Failure Rate In Failure Mode ($X10^{-5}$)
S1	Switch, R. F.	Output		.2/10^4cycles NOTE-1	Solenoid inoperative in position 1	.25	.50
					Solenoid inoperative in position 2	.25	.50
					High contact resistance position 1	.15	.30
					High contact resistance position 2	.15	.30
					Open on wiper	.05	.10
					Short on wiper	.05	.10
					Open on position 1	.025	.05
					Open on position 2	.025	.05
					Short on position 1	.025	.05
					Short on position 2	.025	.05
ANT-2	Antenna Dipole	Omni Antenna	--	.0400	Open	.50	.0200
					Short	.50	.0200
HY-1	Hybrid	Omni Antenna	--	.0010****	Open	.50	.0005
					Short	.50	.0005
ANT-1	Antenna, Dish	Steer. Ant.	--	.3520**	Open	.50	.1760
					Short	.50	.1760
BR-1	Bearing, Az.	Steer. Ant.	--	.1720**	Binding	1.00	.1720
R14	Potentiometer Az.	Steer. Ant	50	.0760	Open	.10	.0076
					Drift	.90	.0684

TABLE 2.2-2 (CONT.)

Part Ref. Desig.	Part Name	Stage Used In	Part Derating %	*Part Failure Rate %/1000 hrs a 55°C	Failure Mode	Failure Mode Ratio	Part Failure Rate In Failure Mode ($X10^{-5}$)
MTR-1	Motor, Az.	Steer. Ant	--	1.1000 ***	Worn Brushes	.50	.5500
					Beinding Brgs.	.30	.3300
					Shorts	.10	.1100
					Opens	.10	.1100
BR-2	Bearing, Elv.	Steer. Ant	--	.1720 **	Binding	1.00	.1720
R15	Potentio-meter, Az.	Steer. Ant	50	.0760	Open	.10	.0076
					Drift	.90	.0684
MTR-2	Motor, Elv.	Steer. Ant	--	1.1000 ***	Worn Brushes	.50	.5500
					Binding Bearings	.30	.3300
					Shorts	.10	.1100
					Opens	.10	.1100
GB-1	Gear Box, Az.	Steer. Ant	--	.4300 **	Binding Gears	.70	.3010
					Binding Bearings	.30	.1290
GB-2	Gear Box, Az.	Steer. Ant	--	.4300 **	Binding Gears	.70	.3010
					Binding Bearings	.30	.1290

* Unless otherwise noted, failure rates from TRA-873-4
** From AVCO Reliability Engineering Data Book dated 4/62
*** From BSR-844, First Bi-monthly Report page G38
**** From RADC Reliability Note Book dated 12/61
***** From Hughes Reliability Report
NOTE-1 Electronic Specialty Co.

TABLE 2.2-3

TRANSMITTER SUBSYSTEM PARTS LEVEL OF CRITICALNESS

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Iso. Amp.	C1	Open	.0042	1000	4.2	100	4.2	11
	C2	Short	.0018		1.8	100	1.8	15
		Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C3	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C4	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C5	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C6	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	L1	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L2	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L3	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L4	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
Iso. Amp.	L6	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
Iso. Amp.	Q1	Open	.0029		2.9	100	2.9	12
		Short	.0015		1.5	100	1.5	17
		Drift	.0102		10.2	100	10.2	9

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
X5 Multi	C7	Open	.0042	1000	4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C8	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C9	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C10	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C11	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C12	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	L5	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L7	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
X5 Multi	L8	Open	.0010		1.0	100	1.0	19
		Drift	.0090	1000	9.0	10	0.9	20
	L9	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L10	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. $(1-e^{-\lambda t})$ x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
X5 Multi	L11	Open	.0010	1000	1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
X5 Multi	Q2	Open	.0029		2.9	100	2.9	12
		Short	.0015		1.5	100	1.5	17
		Drift	.0102		10.2	100	10.2	9
X3 Multi	C13	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C14	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C15	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C16	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C17	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C18	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C19	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C20	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	L12	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
X3 Multi	L13	Open	.0010	1000	1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L14	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L15	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L16	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L17	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L18	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L19	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
X3 Multi	R1	Open	.0027	1000	2.7	100	2.7	13
		Drift	.0243		24.3	0	0	33
	R2	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
	R3	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
X3 Multi	CR1	Open	.0003	1000	0.3	100	0.3	28
		Short	.0008		0.8	100	0.8	22
		Drift	.0016		1.6	100	1.6	16

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Mod Driver	C21	Open	.0042	1000	4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C22	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C23	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	L20	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L21	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L22	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
Mod Driver	Q3	Open	.0029		2.9	100	1.5	12
		Short	.0015		1.5	100	1.5	17
		Drift	.0102		10.2	100	10.2	9
Modulator	C24	Open	.0042	1000	4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C25	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C26	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C27	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Modulator	C28	Open	.0042	1000	4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C29	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C30	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C31	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C32	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C33	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
Modulator	L23	Open	.0010	1000	1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L24	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L25	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L26	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	10	0.9	20
	L27	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L28	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Modulator	L29	Open	.0010	1000	1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	R4	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	100	24.3	6
	R5	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	100	24.3	6
	R6	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	100	24.3	6
	R7	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	100	24.3	6
	CR2	Open	.0003		0.3	100	0.3	28
		Short	.0008		0.8	100	0.8	22
		Drift	.0016		1.6	100	1.6	16
	Q4	Open	.0029		2.9	100	2.9	12
		Short	.0015		1.5	100	1.5	17
		Drift	.0102		10.2	100	10.2	9
RF Amp.	C41	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C43	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	L33	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L34	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L35	Open	.0010		1.0	100	1.0	19

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
RF Amp.	L35	Drift	.0090	1000	9.0	0	0	33
	L36	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L38	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	Q5	Open	.0029		2.9	100	2.9	12
		Short	.0015		1.5	100	1.5	17
		Drift	.0102		10.2	100	10.2	9
X2 Multi	C34	Open	.0042	1000	4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C35	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C36	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C37	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C38	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C39	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	0	0	33
	C40	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15
	C42	Open	.0042		4.2	100	4.2	11
		Short	.0018		1.8	100	1.8	15

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
X2 Multi	L30	Open	.0010	1000	1.0	100	1.0	19
		Drift	.0090		9.0	5	0.45	25
	L31	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L32	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	L37	Open	.0010		1.0	100	1.0	19
		Drift	.0090		9.0	0	0	33
	R8	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	0	0	33
	R9	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
	R10	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
	R11	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
	R12	Open	.0027		2.7	100	2.7	13
		Drift	.0243		24.3	0	0	33
	R13	Open	.0027		2.7	75	2.03	14
		Drift	.0243		24.3	50	12.15	8
	CR4	Open	.0003		0.3	100	0.3	28
		Short	.0008		0.8	100	0.8	22
		Drift	.0016		1.6	100	1.6	16

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
X4 Multi	SL-1	Open	.0005	1000	0.5	100	0.5	24
		Short	.0005		0.5	100	0.5	24
X4 Multi	CR3	Open	.0003		0.3	100	0.3	28
		Short	.0008		0.8	100	0.8	22
		Drift	.0016		1.6	100	1.6	16
RF Power Amp. (TWT)	V-1	Drift	3.615	1000	3546.0	100	3546.0	1
Output	S1	Solenoid inoperative in position 1 (Steer. Ant)	.50/cy	10,400cy	5068.)	50	2534.0	2
		Solenoid inoperative in position 2 (omni Ant)	.50/cy	10,400cy	5068.)	50	2534.0	2
		High contact resistance in position 1 (Steer Ant)	.30/cy	10,400cy	3072.)	50	1536.0	3

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Output	S1	High contact resistance in position 2 (Omni Ant)	.30/cy	10,400 cy	3072.0	50	1536.0	3
		Open on wiper	.10/cy	10,400cy	1034.0	100	1034.0	4
		Short on wiper	.10/cy	10,400cy	1034.0	100	1034.0	4
		Open in position 1 (Steer Ant)	.05/cy	10,400cy	519.0	50	258.5	5
		Open in position 2 (Omni Ant)	.05/cy	10,400cy	519.0	50	258.5	5
		Short in position 1 (steer ant)	.05/cy	10,400cy	519.0	50	258.5	5
		Short in position 2 (omni ant)	.05/cy	10,400cy	519.0	50	258.5	5

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Omni Ant.	ANT-2	Open	.0200	800	16.0	50	8.0	10
		Short	.0200	800	16.0	50	8.0	10
Omni Ant.	HY-1	Open	.0005	800	0.40	50	0.20	30
		Short	.0005	800	0.40	50	0.20	30
Steer. Ant.	ANT-1	Open	.1760	200	35.2	50	17.6	7
		Short	.1760	200	35.2	50	17.6	7
	BR1	Binding	.1720	5	0.86	50	0.43	26
	R14	Open	.0076	5	0.04	10	0.004	32
		Drift	.0684	5	0.34	10	0.034	31
	MTR-1	Worn Brushes	.5500	5	2.75	50	1.375	18
		Bearings Binding	.3300	5	1.65	50	0.825	21
		Shorts	.1100	5	0.55	50	0.275	29
		Opens	.1100	5	0.55	50	0.275	29
	BR2	Binding	.1720	5	0.86	50	0.43	26
	R15	Open	.0076	5	0.04	10	0.004	32
		Drift	.0684	5	0.34	10	0.034	31
	MTR-2	Worn Brushes	.5500	5	2.75	50	1.375	18

TABLE 2.2-3 (CONT.)

Stage Used In	Part Ref. Desig.	Failure Mode	Failure Mode Failure Rate (λ) x 10^{-5}	Operating Time In Hours (t)	Prob. ($1-e^{-\lambda t}$) x 10^{-5}	Deg. %	Level of Criticalness x 10^{-5}	Criticality No.
Steer. Ant.	MTR-2	Binding Bearings	.3300	5	1.65	50	0.825	21
		Shorts	.1100	5	0.55	50	0.275	29
		Opens	.1100	5	0.55	50	0.275	29
	GB-1	Binding Gears	.3010	5	1.5	50	0.75	23
		Binding Bearings	.1290	5	0.65	50	0.325	27
	GB-2	Binding Gears	.3010	5	1.5	50	0.75	23
		Binding Bearings	.1290	5	0.65	50	0.325	27

TABLE 2.2-4

ASSUMED SCHEDULE OF OPERATIONS FOR SLRV

FUNCTION	OPERATING TIME IN MINUTES	
	POINT SURVEY	TRAVERSE (To next point)
Travel	173	155
Penetrometer Readings	96	--
TV Slewing	124	28
TV Transmission	118	24
Steerable Antenna Slewing	10	9
Decision	558	333
TOTAL	1079	549

Total Time = 19(1079 x 1.8* + 549 x 1.4*) = 51400 min.

(19 points) = 857 hours

*Correction factors taking into account irregular travel paths and unsuitable points.

transmissions through the omniantenna will be made during vehicle travel, steerable antenna slewing, and during the ground decision time; and that operation with the steerable antenna will be made for TV and penetrometer data transmissions and TV slewing.

For the operating time or cycles of the transmitter RF switch, it was assumed that the switch will be operated each time the SLRV starts and stops for transmissions (through the omniantenna if the vehicle is moving, and through the steerable antenna when the vehicle is stopped for taking of pictures or penetrometer readings).

The probability of failure for each part was determined by substitution of the values for the part failure mode failure rate and operating time into the expression

$$P_F = 1-e^{-\lambda t}$$

where

P_F = probability of failure

λ = failure mode failure rate

t = part operating time or cycles.

The values for the % Degradation column of Table 2.2-3 were arrived at by taking each part of the transmitter subsystem for each failure mode of that part and determining what the degradation effect would be on the transmitter performance with respect to power output and data transmission rate.

The level of criticalness values are obtained from the product of the failure mode probability and the degradation. The associated index number indicates the relative level of the criticality of the part with respect to the other parts of the subsystem, with the smaller numbers being the highest part criticality and the larger numbers being the lowest part criticality.

The following discussion will be limited to the analysis of the six most critical items. These are shown in the chart of Table 2.2-5.

TABLE 2.2-5

TRANSMITTER SUBSYSTEM FAILURE MODE ANALYSIS EXCERPT

Item	Malfunction	Failure Probability	Percent Degradation	Criticality Level Index No.
TWT(V1)	Drift	.03546	100	1
RF Switch (S1)	Solenoid Inoperative in steerable antenna position (1).	.05068	50	2
	Solenoid inoperative in omni antenna position (2).	.05068	50	2
	High contact resistance in steerable antenna position (1).	.03072	50	3
	High contact resistance in omni antenna position (2).	.03072	50	3
	Open on wiper	.01034	100	4
	Short on wiper	.01034	100	4
	Open in steerable antenna position (1).	.00519	50	5
	Open in omni antenna position (2).	.00519	50	5
	Short in steerable antenna position (1).	.00510	50	5
	Short in omni antenna position (2).	.00519	50	5

TABLE 2.2-5 (CONT.)

Item	Malfunction	Failure Probability	Percent Degradation	Criticality Level Index No.
Resistor (R4)	Drift	.00024	100	6
Resistor (R5)	Drift	.00024	100	6
Resistor (R6)	Drift	.00024	100	6
Resistor (R7)	Drift	.00024	100	6
Steerable	Open	.00035	50	7
Antenna (ANT-1)	Short	.00035	50	7
Resistor (R2)	Drift	.00024	50	8
Resistor (R3)	Drift	.00024	50	8
Resistor (R9)	Drift	.00024	50	8
Resistor (R10)	Drift	.00024	50	8
Resistor (R11)	Drift	.00024	50	8
Resistor (R13)	Drift	.00024	50	8
Transistor (Q1)	Drift	.00010	100	9
Transistor (Q2)	Drift	.00010	100	9
Transistor (Q3)	Drift	.00010	100	9
Transistor (Q4)	Drift	.00010	100	9
Transistor (Q5)	Drift	.00010	100	9

In Table 2.2-5, the TWT is shown to have the highest criticality. This is due to the high failure probability and percent degradation. However, it should be pointed out that the failure rate, used for the determination of the probability, is based on the Hughes "Life and Reliability Report on Space Traveling - Wave Tubes" dated May 1963. This report indicated that there were no failures in the tubes tested and that an MTBF of 27,860 hours was predicated based on assumed random failures and Poisson distribution. Therefore, these tubes can very well have a life expectancy exceeding the MTBF of 27,860 hours which would then decrease the value of the failure probability and criticality level. The malfunction of the TWT was assumed to be due to drift, i.e., change in the tube characteristics. This was based on the fact that no representative failures had occurred and that in a properly designed vacuum tube, the wearout life is determined by the eventual reduction of electron emission from the cathode. The 100% degradation was assigned to the TWT failure, because it is the output amplifier stage of the transmitter and the failure would be catastrophic for the mission. A method to improve the TWT criticality would be to provide selective switching redundancy. This would mean providing a standby TWT with a switch for inserting it into the circuit. Whether this type of redundancy could be used is limited by the constraints of physical size and weight of the transmitter subsystem.

The RF Switch, in Table 2.2-5, is shown to have a criticality, for its various failure modes, covering a range from 2 through 5. The high criticality is due mostly to the high probability of failure. The probability of failure for this switch was based on the manufacturer minimum life expectancy rating of 50,000 cycles. This particular switch was chosen because of its latching feature, low power requirements for switching and low insertion loss. However, it is felt that a switch meeting the above requirements could be found having a longer life expectancy of between 250,000 to 500,000 cycles or the manufacturer could redesign the present switch for the required life expectancy. The degradation figures assigned to the various failure modes for the RF switch are based on the following:

1. If the solenoid is inoperative when the switch is in the steerable or omniantenna position, the degradation is assumed to be 50% for either position. This is due to increased mission time (using the steerable antenna only) caused by the requirement for orientation of the steerable antenna now for all transmissions and due to the reduction in bit rate when using the omniantenna.

2. For an open or short on the wiper of the switch, the degradation is 100% because of no transmitter output; a catastrophic condition.

3. For high contact resistance or open or shorts in either position of the switch, the reason specified in (1) above is also applicable.

Resistors R4, R5, R6, and R7 have a criticality index number of 6 as shown in Table 2.2-5. This is a result of the high failure probability of these fixed composition resistors for the drift condition, and the 100% degradation due to the drift. These resistors are used in the modulator stage of the transmitter as biasing resistors, and drifting of these resistors will cause a change in the modulation characteristics and modulator output. A possible improvement for this condition would be to use resistor types, such as carbon film, having less tendency for the drift condition or by derating of parts.

The steerable antenna dish (ANT-1) is shown in Table 2.2-5 to have a criticality index of 7. The failure modes for this antenna were assumed, and the failure rate for the antenna was halved for each failure mode. The percent degradation was taken as 50% for each failure mode, since an open or short of the antenna will terminate RF transmission and require switching to the omniantenna at the reduced bit rate. Improvements for this type of failure will require an analysis of the physical design of the antenna.

The next parts in order of criticality are fixed composition resistors R2, R3, R9, R10, R11, and R13. These resistors are used as biasing resistors for the X3 and X2 multipliers. They have a high probability of failure due to drift which would result in a reduction in output from the multiplier stages and consequently a decrease in transmitter output. A 50% degradation or 3-db decrease in power was assumed. However, a detailed analysis after part values have been assigned may indicate a greater loss. An improvement for the drift condition would be similar to that stated above for resistors R4, R5, R6, and R7.

Transistors Q1, Q2, Q3, Q4, and Q5 of the transmitter are next in order of criticality for malfunction due to drift. A drift in this case is defined as a change in the characteristics of the transistor resulting in reduced gain. These transistors are used in series stages of the transmitter, and a reduction in output from any one of the stages will effect a reduction in transmitter output. For the present analysis, this reduction is assumed to be catastrophic or 100% degradation. Possible ways of decreasing the criticality would be through selection of transistors having a low drift failure rate, derating, and redundancy.

2.2.2 Television

The reliability aspects of the present TV subsystem design are an integral part of the design and development processes.

2.2.2.1 Parametric and Option Analysis

As part of the parametric and option analysis, parametric reliability tradeoff data were generated to provide criteria which could be applied to various design options and approaches. The basic and most important data generated for tradeoff use in option analyses included the following:

1. The sensitivity of electronics parts reliability to operating temperature.

2. The relative complexities, adaptabilities, stabilities, and tolerance limits of analog and digital circuits required to perform a given function and their resultant reliabilities.

3. A reliability comparison of the various construction techniques, namely discrete parts, micromodules, and microcircuits (monolithic and discrete-chip types).

4. A comparison of the two basic classes of panning systems: mirror drive and camera drive.

5. A reliability analysis of the four basic functions relating to picture taking: field of view, aperture, focus, and exposure.

In a number of options, the aspect of reliability was secondary because of the low reliability of sensitivity to the options when compared to factors such as performance capabilities, weight, power consumption, and optical limitations. In many instances, the difference in reliability between various configurations was obviously insignificant since essentially the same parts and components were used in different options but were only distributed in differing arrangement. A continual consideration and analysis was made of parts contemplated for any option.

Summary of Selected Tradeoff Studies

The basic and most important data subjects generated during the parametric and option analysis phase are listed above. A brief summary of selected tradeoff studies is presented here.

The effects of temperature on electronic reliability were investigated to determine a suitable operating temperature range without imposing difficult constraints on the thermal control system. The operating temperature range selected was 10°C to 50°C with a non-operating temperature minimum of -40°C.

The lower operating limit was set at 10°C because circuit performance and efficiency begin to deteriorate below this temperature, and because failure rate data are limited below this temperature. The upper limit was set primarily by the vidicon which has a maximum temperature limit of 70°C. In this region, and above, the failure rate of component parts rapidly increases with temperature.

The majority of comparisons found in literature circuitry are based upon discrete-part technology rather than integrated circuits. For discrete, conventional parts, the expected reliability gain (digital over analog) is about 10:1.

For micro-module technology (extremely small discrete parts) one source of data indicates a reliability gain of about 4:1 (failure rate of 0.077%/1000 hrs for digital vs 0.37%/1000 hrs for analog; per transistor active element group).

For microcircuit technology, documented and proven reliability exists only for digital circuits. This type of monolithic construction provides the highest reliability gains which have been proved, and are available off-the-shelf.

In summary, the following general statements can be made relative to digital and analog circuits:

1. More complexity is required to perform the same function with digital than with analog techniques

2. Microcircuitry can be applied more readily to digital systems

3. Digital circuits will generally operate over wider temperature ranges than analog circuits and with more stability

4. Part tolerances must be kept within tighter tolerances with analog circuitry

5. Failure rates of digital circuits are conservatively 1/2 to 1/3 those of analog circuits.

Application of the findings, failure rate ratios, and guidelines to preliminary camera circuits, with certain functions which could be accomplished by either digital or analog circuits, resulted in the following summations of failure rates for the TV subsystem:

Digital failure rate: 26.4%/1000 hr

Analog failure rate: 17.8%/1000 hr

Two basic panning options were considered. The first consisted of an azimuth-elevation mount in which the camera rotated in both elevation and azimuth. In the second option, a reflecting mirror rotated in elevation, and the camera and mirror assembly rotated together in azimuth.

On the basis of the parts and items contemplated for use, and the assumed operational duty cycles, there was no significant difference in reliability between the two options.

2.2.2.2 Preliminary Reliability Analysis and Report

The preliminary reliability report of 13 February 1964 from Raytheon Company presented a reliability block diagram of the TV subsystem design as it existed at that time, a reliability analysis relating to the block diagram, and a preliminary parts control program. The specific reliability of the complete system was shown based on the parts content and the analysis, development, and definition of camera motion-control parameters.

The reliability effort previously defined was continuing as part of the design effort. The work was increasingly oriented to the selection, analysis, and judgment of parts and components which could satisfy the developing needs of design and performance.

2.2.2.3 Stereoptic System Analysis

Since the start of the program, considerable attention had always been directed to vidicons — their capabilities, limitations, and particularly their reliability. The critical relation of the vidicon served to stress the absence of an authoritative and documented failure rate for vidicons. Considering the unavailability of a failure rate and the concern over the degree of confidence desired, a closer look at a stereoptic system was initiated.

The stereoptic system analyzed employs fixed lenses and eliminates the rotating Galilean telescope turret. This eliminates two undesirable failure modes. First, the turret control mechanism may fail while the turret is between two FOV positions and prevent transmission of the scene. A fixed lens ensures that the optical path is never obstructed. Second, elimination of the turret removes inaccurate rotational positioning of the turret due to wear and possible environmental factors. This failure mode causes boresight errors in imaging the scene on the vidicon faceplate with resultant errors in surveying and perhaps in photogrammetry.

The use of two vidicons in a stereo (basically redundant) arrangement enhances mission reliability. Considering only the vidicon itself, the reliability of two in parallel is given by the equation $R_p = 1 - (1-R)^2$, where R_p is the reliability of two vidicons in parallel and R is the reliability of one vidicon. Failures are taken as having an exponential distribution.

The stereo system does away with the lens turret gearhead motor but requires a motor for the second vidicon iris. This, however, is not a one-for-one exchange in reliability. The failure mode of an iris control motor is less critical than the failure modes of a lens turret motor. Failure of an iris motor results in degraded performance while failure of a lens turret motor can result in either degradation or a catastrophic failure.

Concern over the vidicon may be lessened after conducting investigations into data and vidicon reliability information generated by other contractors in their respective vidicon improvement programs for various space projects.

2.2.2.4 Interim TV Subsystem Design

The interim TV subsystem design (reported in Raytheon Report BR-2848-1, 28 February 1964) took advantage of the analyses and results

of the work accomplished up to that date. The decisions and choices of specific approaches, such as thermal control design range, were based on the findings of the tradeoff study and subsequent analyses. While the use of potentiometers for camera pan and tilt control readout instead of brush type shaft encoders were largely predicted on reliability requirements, investigations were underway on the technical feasibility of changing to the use of the latter. Encoders were considered to offer many advantages over analog systems from the viewpoint of readout accuracy and PCM data transmission systems.

2. 2. 2. 5 Interim TV Subsystem Reliability Report

The interim TV subsystem reliability report from Raytheon included the following:

1. A reliability block diagram
2. A reliability analysis associated with the block diagram and contents thereof
3. Failure mode analysis
4. A preferred parts list for space applications.

2. 2. 2. 6 Reliability Block Diagram and Mathematical Model

Figure 2. 2.-5 shows the reliability block diagram, the failure rate for each block, and the mathematical model for the final TV subsystem design.

The reliability of the TV subsystem, R_{TV}, is the product of the reliability of the time-dependent items, R(t), and the reliability of the cyclic item, $R(\lambda c)$, as expressed by:

$$R_{TV} = R(t) \S R(\lambda c)$$

Investigations to date, of parts and items in the TV subsystem design, show no apparent area where wearout failure conditions are expected in terms of the operating time and number of cycles of actuation expected for the missions presently contemplated. Therefore, the failures will be chance failures only and have an exponential distribution as defined by the

equation $R(t) = e^{-\lambda t}$ for time-dependent parts and $R(\lambda c) = e^{-\lambda / \text{cycle} \times \text{number of cycles}}$ for cyclic items. The cyclic formula is used for time-dependent parts which operate briefly on a low duty-cycle basis in conjunction with the taking of each picture such as the digital electronic circuits for converting picture information, as well as electromechanical items such as a motor which operates for a few seconds when tilting the camera. The reliability formula for both the truly cyclic items, such as the shutter solenoid, and the low duty-cycle items, can be basically expressed as a function of picture taking by the equation

$$R(\lambda c) = e^{-(\lambda c/\text{picture}) \times (\text{number of pictures})}$$

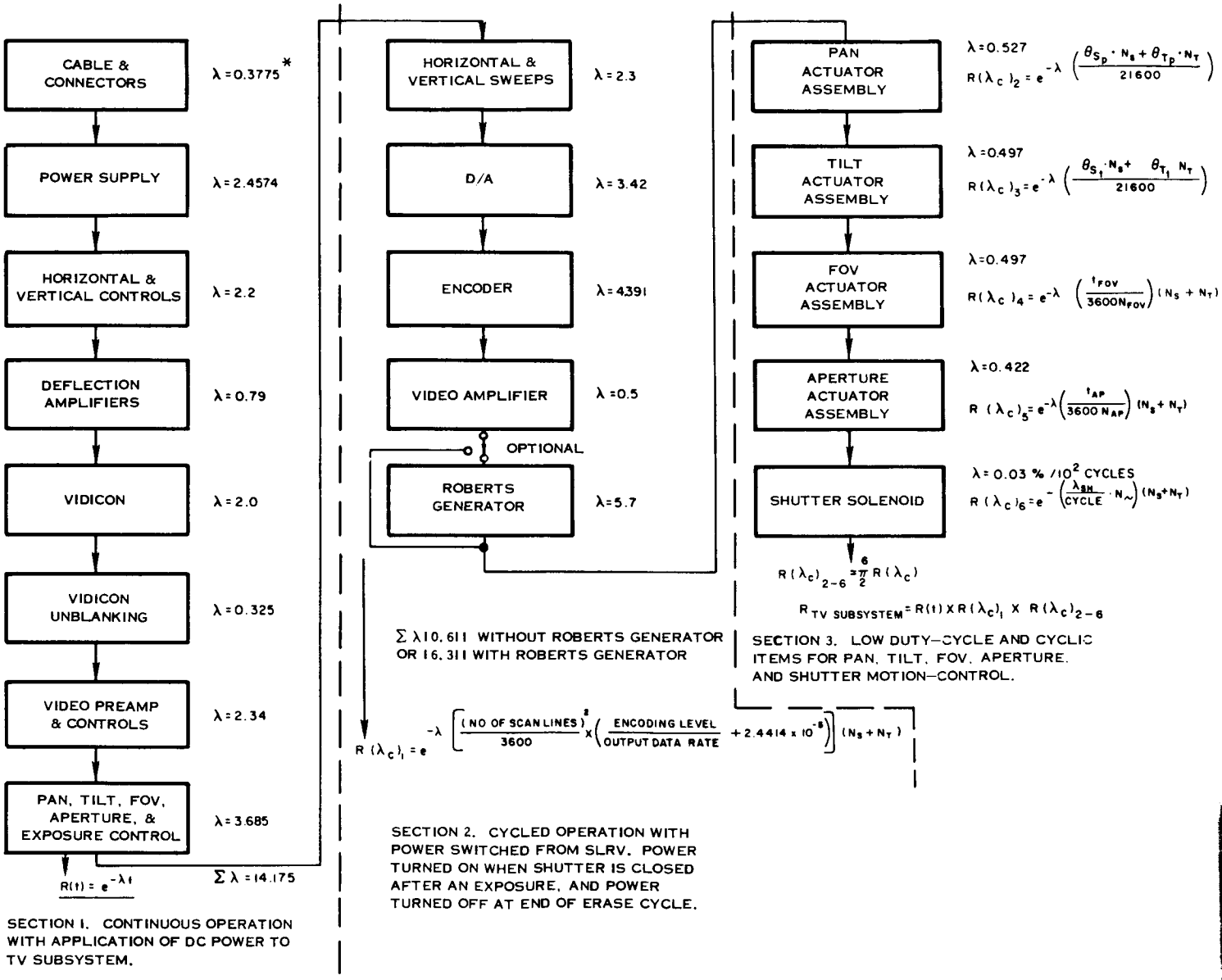
The need and potential for redundancies have been directed mainly at the vidicon in two areas: (1) the use of two vidicons in a stereoptic configuration, and (2) some considerations of redundancy in switching the vidicon heater. These are not shown in Figure 2.2-5 because: (1) the final design is a monoptic design, and (2) the addition of vidicon heater switching parts and circuits need not have any discernible degrading effect on overall reliability.

2.2.2.7 Reliability Analysis

Figure 2.2-5 shows the reliability block diagram to be divided into three sections corresponding to the three basic ways of expressing time, t, in the reliability mathematical models. These variations arise from the partial switching performed to limit power demands on the SLRV, and the intermittent performance needed of certain parts and items in relation to the taking of each picture.

Section 1 covers the items to which electrical power is continuously applied during the entire mission, including lunar nighttime. As such, the time, t, in the reliability equation is made equal to the operating time for any selected portion of the SLRV mission.

The vidicon, although in Section 1, can be switched off when photographic activity has ended for the lunar day as the lunar night approaches. This is described in Section 2.2.2.8. It will be seen that the switching circuit and relay do not contribute to the total failure rate of the TV subsystem and need not be included in the reliability block diagram.


CABLE & CONNECTORS
λ = 0.3775 *
POWER SUPPLY
λ = 2.4574
HORIZONTAL & VERTICAL CONTROLS
λ = 2.2
DEFLECTION AMPLIFIERS
λ = 0.79
VIDICON
λ = 2.0
VIDICON UNBLANKING
λ = 0.325
VIDEO PREAMP & CONTROLS
λ = 2.34
PAN, TILT, FOV, APERTURE, & EXPOSURE CONTROL
λ = 3.685
R(t) = e^{-λt}
Σ λ = 14.175
SECTION 1. CONTINUOUS OPERATION WITH APPLICATION OF DC POWER TO TV SUBSYSTEM.
* λ = FAILURE RATE IN PERCENT PER 1000 HOURS
HORIZONTAL & VERTICAL SWEEPS
λ = 2.3
D/A
λ = 3.42
ENCODER
λ = 4391
VIDEO AMPLIFIER
λ = 0.5
OPTIONAL
ROBERTS GENERATOR
λ = 5.7
Σ λ 10.611 WITHOUT ROBERTS GENERATOR OR 16.311 WITH ROBERTS GENERATOR
R(λc)1 = e^{-λ [(NO OF SCAN LINES)/3600)^2 X (ENCODING LEVEL / OUTPUT DATA RATE + 2.4414 x 10^-6)] (Ns + NT)}
SECTION 2. CYCLED OPERATION WITH POWER SWITCHED FROM SLRV. POWER TURNED ON WHEN SHUTTER IS CLOSED AFTER AN EXPOSURE, AND POWER TURNED OFF AT END OF ERASE CYCLE.
PAN ACTUATOR ASSEMBLY
λ = 0.527
R(λc)2 = e^{-λ ((θSp · Ns + θTp · NT) / 21600)}
TILT ACTUATOR ASSEMBLY
λ = 0.497
R(λc)3 = e^{-λ ((θST · Ns + θTT · NT) / 21600)}
FOV ACTUATOR ASSEMBLY
λ = 0.497
R(λc)4 = e^{-λ (tFOV / 3600 NFOV) (Ns + NT)}
APERTURE ACTUATOR ASSEMBLY
λ = 0.422
R(λc)5 = e^{-λ (tAP / 3600 NAP) (Ns + NT)}
SHUTTER SOLENOID
λ = 0.03 % / 10^2 CYCLES
R(λc)6 = e^{- (λSH / CYCLE · N~) (Ns + NT)}
R(λc)2-6 = π/2 R(λc)
RTV SUBSYSTEM = R(t) X R(λc)1 X R(λc)2-6
SECTION 3. LOW DUTY-CYCLE AND CYCLIC ITEMS FOR PAN, TILT, FOV, APERTURE, AND SHUTTER MOTION-CONTROL.

λ = failure rate in %/1000 hours

R(t) = reliability of time-dependent items

e = base of natural logarithms

$R(\lambda c)$ = reliability of cycled circuits, low duty-cycle and cyclic items

N_S = number of site pictures

N_T = number of traverse pictures

θS_p = average panning angular movement of camera per site picture, degrees

θT_p = average panning angular movement of camera per traverse picture, degrees

θS_t = average tilting angular movement of camera per site picture, degrees

θT_t = average tilting angular movement of camera per traverse picture, degrees

t_{FOV} = average time required to change FOV, seconds

N_{FOV} = average number of pictures taken with one FOV setting before changing to another FOV

t_{AP} = average time required to change aperture, seconds

N_{AP} = average number of pictures taken with one aperture setting before changing to another aperture

λ_{SH} = failure rate of shutter control items per cycle of operation

$N_{\sim}$ = number of shutter control operations per picture

Figure 2.2-5 Reliability Block Diagram and Mathematical Model

#2

Section 2 covers the items which operate in a specific cycle. The power is controlled from the SLRV and is switched off when the functions are not required in order to minimize electrical demands on the SLRV power supply. The reliability equation in basic terms can be stated as follows:

$$R(\lambda c)_1 = e^{-\lambda \left(\frac{\text{time}}{\text{cycle}}\right) (\text{number of cycles})}$$

1. Roberts Generator - The Roberts Generator can be switched in or out on command by the operator. The total failure rate of Section 2 is given for both modes of operation.

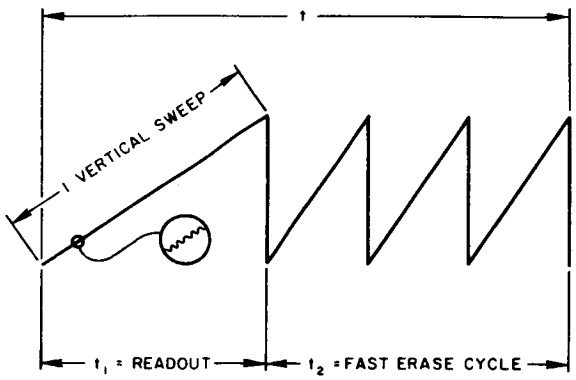
2. Determination of Time, t - The computation of the reliability of Section 2 involves the time term, t, which is the time period beginning from the time power is turned on when the shutter is closed after an exposure and extending up to the end of the erase cycle, at which time the power is turned off. This time, t, is variable since it is a function of: (1) the number of elements per picture, (2) the number of encoding levels, and (3) the output data rate. Figure 2.2-6 shows the time elements and equations for determining time t for Section 2. The basic equation for computing the time it takes to scan one frame is as follows:

$$t = \frac{\text{elements}}{\text{picture}} \times \frac{\text{bits}}{\text{element}} \times \frac{1}{\text{clock rate}}$$

In a square picture format with equal horizontal and vertical resolution, the number of elements per picture is also numerically equal to the square of the number of scan lines.

The variables applicable to the computation of time and reliability are:

	Primary Mode	Emergency Mode
Number of Lines:	512	256
Encoding Levels:	4	2
Output Data Rate:	122,800 bits/sec	960 bits/sec



$$t = t_1 + t_2$$

$$t = \left[\frac{(\text{NUMBER OF SCAN LINES})^2 \times (\text{ENCODING LEVELS})}{\text{OUTPUT DATA RATE} \times 3600} + \frac{(\text{NUMBER OF SCAN LINES})^2 \times (\text{NUMBER OF ERASURES})}{\text{ERASE SWEEP RATE} \times 3600}\right] \text{HOURS}$$

$$t = \frac{(\text{NUMBER OF SCAN LINES})^2}{3600} \times \left[\frac{\text{ENCODING LEVELS}}{\text{OUTPUT DATA RATE}} + (2.4414 \times 10^{-5})\right] \text{HRS}$$

OUTPUT DATA RATE = 122,880 BITS / sec., OR 960 BITS / sec.

ERASE SWEEP RATE = 122,880 BITS / sec.

Figure 2. 2-6 Section 2, Time Elements and Equations

Section 3 covers the low duty-cycle and cyclic items which are activated in preparation for, or during, the taking of a picture. The reliability equations (excepting that of the shutter solenoid) in basic terms can also be stated as follows:

$$R(\lambda c)_x = e^{-\lambda\left(\frac{\text{time}}{\text{cycle}}\right)(\text{number of cycles})}$$

For the cyclic shutter solenoid, the equation in basic terms is:

$$R(\lambda c)_6 = e^{-\left(\frac{\text{failure rate}}{\text{cycle}}\right)\left(\frac{\text{number of cycles}}{\text{picture}}\right)(\text{number of pictures})}$$

The variables applicable to the computation of time and reliability are:

N_S: 0 to 16, 625

N_T: 0 to 6, 688

Although the other terms in the reliability equations have been assigned specific values according to the present design and contemplated mission data, the general terms have been retained to permit computations for different design parameters, if desired, or when changes occur in mission profile data.

The parts and items contained in each block of the reliability block diagram are itemized in the Reliability Prediction Worksheets immediately following.

The failure rates and explanatory data for the various items contained within each block, along with the failure rate sources, are summarized in Table 2.2-6. These failure rates are not high reliability part failure rates and do not include any factor for lunar environment.

The failure rates are based on a derating of 50% at a maximum temperature of 70°C. In the future program, breadboard tests will be conducted to check transient effects to ensure that parts are not overstressed. Transient effects will be taken into account by suitably increasing failure rates when necessary on the basis of transient duration, duty cycle, type of part, packaging techniques and thermal design.

Reliability of TV Subsystem Sections

The reliability of the TV subsystem sections can be computed from the equations given in Figure 2.2-5 by using the desired or appropriate values for the variables. The reliability of the different sections are computed and combined wherever practicable and meaningful. Table 2.2-7 gives the reliability of the TV and its components for 1, 2, 3, and 4.5 months of operation.

The reliability of the continuously-operating items in Section 1 is shown in Figure 2.2-7. Reliability is plotted as a function of operating time to accommodate the different mission profiles of the various Bendix SLRV system concepts.

The reliability of the cyclic-operation items in Section 2 is shown in Figure 2.2-8 as a function of: (1) number of pictures, and (2) number of "surveyed sites". The total failure rate used includes the Roberts Generator although use of the Roberts Generator is optional. Reliability is plotted for only the primary mode of operation.

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * 70 max	PART DERATING * 50%	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
Cable and Connector:													
	Cable								.0475	1	0.0475	AVCO	
	Conn. - 55 Pins								.006/PIN	1	0.3300	TRA	
											0.3775		
Power Supply:													
	Transformer								0.08	1	0.08	TRA	
	Transistor								0.073	4	0.292	TRA	
	Zener Diode								0.053	2	0.106	TRA	
	Diode								0.053	14	0.742	TRA	
	Inductor								0.05	3	0.150	TRA	
	Capacitor								0.0625	3	0.1875	TRA	
	Resistor								0.045	20	0.9	TRA	
											2.4575		
Hor. and Vert. Controls:													
	μ-CKT**		Signetics	"G"					0.1	20	2.0	Vendor	
	μ-CKT		GI	"PC"					0.1	2	0.2	Vendor	
											2.2		
Deflection Amplifiers:													
	μ-CKT	To-5	GI						0.1	4	0.4	Vendor	
	Potentiometer								0.075	4	0.3	TRA	
	Resistor								0.045	2	0.09	TRA	
											0.79		

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

** μ-CKT = Microcircuit

Sig. = Signetics
GI = General Instruments
TRA = TRA-873-74

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C + 70 max	PART DERATING + 50%	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
VIDICON:													
	VIDICON		GEC						2.0	1	2.0	TRA	
VIDICON Unblanking:													
	μ-CKT		SIG	SC-160					0.1	1	0.1	Vendor	
	μ-CKT	TO-5	GI						0.1	1	0.1	Vendor	
	Resistor								0.045	1	0.045	TRA	
	Transformer								0.08	1	0.08	TRA	
											0.325		
Video Preamp and Controls:													
Preamp:													
	μ-CKT		GI	PC					0.1	2	0.2	Vendor	
Gain Control													
	μ-CKT	TO-5	GI						0.1	3	0.3	Vendor	
	μ-CKT		SIG	SE-101					0.1	6	0.6	Vendor	
	Resistor								0.045	7	0.315	TRA	
Threshold Control:													
	μ-CKT	TO-5	GI						0.1	2	0.2	Vendor	
	μ-CKT		SIG	SE-101					0.1	4	0.4	Vendor	
	Resistor								0.045	5	0.225	TRA	
Mode Control:													
	μ-CKT	TO-5	GI						0.1	1	0.1	Vendor	
											2.340		

SUB-UNIT TOTAL FAILURE RATE _____

SUB-UNIT MTBF (HOURS) _____

* INDICATE ESTIMATED OR ACTUAL

Section 1

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
Pan, Tilt, FOV, Aperture, and Exposure Control													
Pan, Tilt, FOV, and Aperture Motor Control:										4			
	μ-CKT	TO-5	GI						0.1	4	0.4	Vendor	
	Capacitor								0.03	2	0.06	TRA	
	Resistor								0.073	1	0.073	TRA	
											0.533		
										X4=	2.132		
	Exposure Control:												
	μ-CKT	To-5	GI						0.1	15	1.5	Vendor	
	Diode	Photo							0.053	1	0.053	TRA	Diode F.R.
											3.685		

SUB-UNIT TOTAL FAILURE RATE _____

SUB-UNIT MTBF (HOURS) _____

* INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * 70 max	PART DERATING * 50%	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
Hor. and Vert. Sweeps:													
	μ-CKT		SIG	"G"					0.1	23	2.3	Vendor	
D/A:													
	μ-CKT		SIG	"G"					0.1	18	1.8	Vendor	
	Resistor								0.045	36	1.62	TRA	
											3.42		
Encoder:													
	μ-CKT		SIG	"G"					0.1	27	2.7	Vendor	
	μ-CKT		GI	"PC"					0.1	7	0.7	Vendor	
	Resistor								0.045	15	0.675	TRA	
	Capacitor								0.03	3	0.09	TRA	
	Transformer								0.08	1	0.08	TRA	
	Transistor								0.073	2	0.146	TRA	
											4.391		
Video Amp:													
	μ-CKT		GI	"PC"					0.1	5	0.5	Vendor	
Roberts Generator:													
	μ-CKT		SIG	"G"					0.1	57	5.7	Vendor	

SUB-UNIT TOTAL FAILURE RATE _____

SUB-UNIT MTBF (HOURS) _____

*INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystems SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C 70 max	PART DERATING 50%	NUMBER OF TERMINALS	PART FAILURE RATE % /1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
Pan Actuator Assy.													
	Motor	DC	Globe						0.16	1	0.16	TRA	
	Gear Train								0.063	1	0.063	AVCO	
	Bearing								0.065	3	0.195	AVCO	
	"O" Ring								0.002	2	0.004	AVCO	
	Potentiometer		Markite						0.075	2	0.15	TRA	
											0.572		
Tilt Actuator Assy:													
	Motor	DC	Globe						0.16	1	0.16	TRA	
	Gear Train								0.063	1	0.063	AVCO	
	Bearing								0.065	3	0.195	AVCO	
	"O" Ring								0.002	2	0.004	AVCO	
	Potentiometer		Markite						0.075	1	0.075	TRA	
											0.497		
FOV Actuator Assy:													
	Motor	DC	Globe						0.16	1	0.16	TRA	
	Gear Train								0.063	1	0.063	AVCO	
	Bearing								0.065	3	0.195	AVCO	
	"O" Ring								0.002	2	0.004	AVCO	
	Potentiometer		Markite						0.075	1	0.075	TRA	
											0.497		

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION SLRV TV Subsystems SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * 70 max	PART DERATING * 50%	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
Aperture Actuator Assy:													
	Motor	DC	Globe						0.16	1	0.16	TRA	
	Gear Train								0.063	1	0.063	AVCO	
	Bearing								0.065	3	0.195	AVCO	
	"O" Ring								0.002	2	0.004	AVCO	
											0.422		
Shutter Solenoid:													
	Solenoid								0.03/ 10^3 Cycles	1		AVCO	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

TABLE 2.2-6

FAILURE RATES AND FAILURE RATE SOURCES

Item	Failure Rate percent/1000 hours*
1) Source: TRA-873-74	
a) Resistor - Fixed metal film; 1/4 and 1/2 watt rating; 100 K to 1 meg values.	0.045
b) Resistor, Variable, composition, 50-500 K.	0.075
c) Capacitor - Fixed solid tantalum.	0.0625
d) Capacitor - Paper.	0.024
e) Capacitor - General purpose ceramic.	0.030
f) Capacitor - (Metalized Film) Paper-Plastic.	0.0025
g) DC Motor, Insulation "A", brush device, rotational speed taken as 100 rpm due to low duty cycle.	0.160
h) Coil - Inductor (Grade 5); encapsulated construction; class "T" Insulation; hot spot temperature 20°C above ambient.	0.05
i) Transformer (Pulse & Blocking Oscillator) Grade 5.	0.08
j) Diode-Silicon; general purpose.	0.053
k) Transistor-Silicon; medium power.	0.073
l) Cathode Ray Tube (for Vidicon)	2.00

*Note: Failure Rates determined on basis of operating parts at 50 percent rating.

TABLE 2.2-6 (CONT.)

Item	Failure Rate percent/1000 hours*
m) Connector, Electrical	0.0002 (per contact)
n) Relay - Coil	
- Individual Contact Set	$0.21/10^4$ Operations
- Redundant Contact Sets (2 in parallel)	Determined by Number of Operations
2) Source: AVCO	
a) Gear Box	0.063
b) "0" Ring	0.002
c) Bearing	0.065
d) Solenoid Rotary	0.03 percent/10^3 Cycles
e) Cable	0.0475
3) General Instruments	
"PC" type microcircuit.	0.1
4) Signetics	
0.25" x 0.25" x 0.70" microcircuit package.	0.1
5) Texas Instruments	
Microcircuits, "SN" type.	0.1

TABLE 2. 2-7

TV SUSBSYSTEM RELIABILITY

Item	Reliability 1 Mo.	2 Mo.	3 Mo.	4 Mo.	Remarks
Cable & Connectors	.9975	.9950	.9925	.9886	Continuous Energization
Power Supply	.9836	.9675	.9519	.9287	
Horizontal & Vertical Controls	.9853	.9708	.9566	.9656	
Deflection Amplifiers	.9947	.9894	.9842	.9765	
Vidicon	.9866	.9735	.9605	.9413	
Vidicon Unblanking	.9979	.9957	.9935	.9902	
Video Preamp & Controls	.9844	.9690	.9530	.9324	
Pan, Tilt, FOV Aperture & Exposure Controls	.9756	.9518	.9286	.8949	
Horizontal & Vertical Sweeps	.9995	.9989	.9985	.9977	Power on when shutter is closed after exposure. Power off at end of erase cycle.
D/A	.9993	.9985	.9977	.9965	
Encoder	.9987	.9980	.9970	.9955	
Roberts Generator	.9987	.9974	.9961	.9942	
Pan Actuator Assy.	.9999	.9999	.9999	.9999	Low duty cycle and cyclic items.
Tilt Actuator Assy.	.9999	.9999	.9999	.9999	
F. O. V. Actuator Assy.	.9999	.9999	.9999	.9999	
Aperture Actuator Assy.	.9999	.9999	.9999	.9999	
Shutter Solenoid	.9967	.9934	.9901	.9851	
TV Subsystem	.9100	.8270	.7520	.6333	

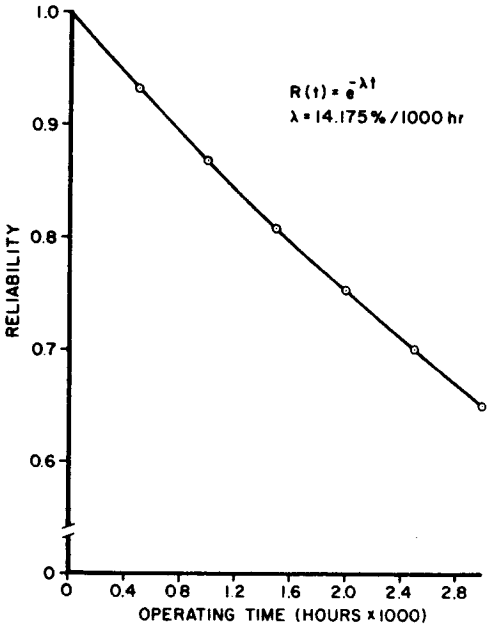

Figure 2. 2-7 Reliability System 1, Continuously Operating Items

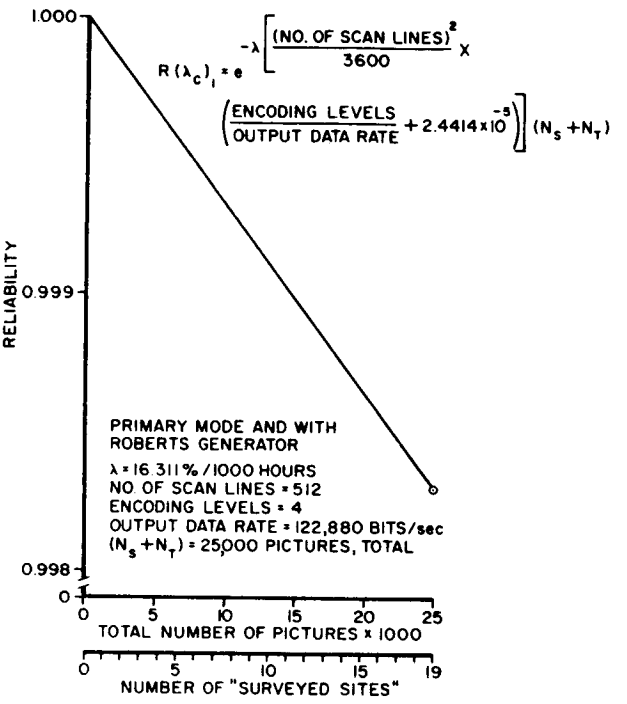

Figure 2. 2-8 Reliability of Section 2, Cyclic-Operation Items

A total of 25, 000 pictures is required for a complete mission — 20, 000 for site survey and 5, 000 for intersite traverse. These figures include allowances for false starts.

A surveyed site is defined here as consisting of one intersite traverse plus one site survey. A surveyed site provides for false starts also, and the pictures due to false starts are arbitrarily averaged out over the required 19 good sites. Thus the number of pictures in a surveyed site is found by dividing 25, 000 by 19, which gives 1315.

The reliability of the low duty-cycle and cyclic items (Section 3), as expressed by the equations and data shown in Figure 2. 2- 5 , is determined by selecting specific parametric values based on the final system design and present mission concepts.

1. Pan and Tilt Control Systems - The pan and tilt control system equations for $R(\lambda c)_2$ and $R(\lambda c)_3$ are the same, and the systems are discussed together since certain aspects are common to each.

   The average required pan and tilt angular movement of the camera was based on a 40-degree field-of-view lens. With such a lens, an average angular camera movement of 30 degrees per site picture and 20 degrees per traverse picture was given. For this analysis, it is assumed that the total angular camera movement is equally divided between panning and tilting.

   The parametric values for determining $R(\lambda c)_2$ and $R(\lambda c)_3$ are as follows:

   θS_p = 15 degrees

   θT_p = 10 degrees

   θS_t = 15 degrees

   θT_t = 10 degrees

   The reliability of the pan and tilt control systems as a function of the number of "surveyed sites" is shown in Table 2.2-8 , and combined with other low duty-cycle and cyclic items of Section 3 in Figure 2.2-9 . The reliability is also shown as a function of number of pictures. This is made possible by making a minor approximation. For a site picture, the average camera movement is 15 degrees while for a traverse picture, the average movement is 10 degrees. With a fixed rate of camera angular motion of 6 degrees per second, slightly more time is required to complete the required camera movement for a site picture than for a traverse picture. Although a group of intersite traverse pictures is taken and then followed by a group of site pictures, it may be taken that the site and traverse pictures are interleaved by a ratio of 1.054/263, (since 1,054 pictures are required for one site, and 263 are required for one intersite traverse). From this, 4 site pictures are taken for every 1 traverse picture and are interleaved in that order. This concept of interleaving makes it

TABLE 2.2-8

RELIABILITY OF SECTION 3, LOW DUTY-CYCLE AND CYCLIC ITEMS

Block		Reliability
Pan Actuator Assembly	$R(\lambda c)_2$	0.999907
Tilt Actuator Assembly	$R(\lambda c)_3$	0.999919
F0V Actuator Assembly	$R(\lambda c)_4$	0.999974
Aperture Actuator Assembly	$R(\lambda c)_5$	0.999985
Shutter Solenoid	$R(\lambda c)_6$	0.985110
Overall Reliability: $R(\lambda c)_{2-6} = \prod_{2}^{6} R(\lambda c)$ =		0.984898

NOTE:	Number of Site Pictures	=	20,000
	Number of Traverse Pictures	=	5,000
	Total number of pictures	=	25,000

convenient to plot reliability as a function of number of pictures, yielding negligible errors in between the discrete, integral numbers of "surveyed sites".

2. Field-of-View Control System - The parametric values used for determining $R(\lambda c)_4$ are as follows:

t_{FOV} = 15 seconds

N_{FOV} = 20 (it is estimated that FOV will be changed every 20 pictures, or 1/20 operation per picture)

The reliability of the FOV control system is shown in Table 2.2-8 , and combined with other low duty-cycle and cyclic items of Section 3 in Figure 2.2-9.

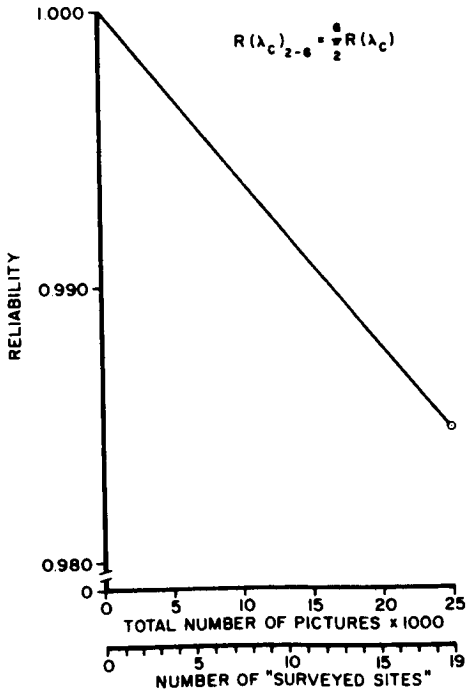

Figure 2.2-9 Reliability of Section 3, Low Duty-Cyclic and Cyclic Items

3. Aperture Control System - The parametric values used for determining $R(\lambda c)_5$ are as follows:

   t_{AP} = 5 seconds

   N_{AP} = 10 (it is estimated that the aperture will be changed once every 10 pictures, or 1/10 operation per picture).

   The reliability of the aperture control system is shown in Table 2.2-8 and combined with other low duty-cycle and cyclic items of Section 3, in Figure 2.2-9.

4. Shutter Solenoid - The parametric values used for determining $R(\lambda c)_6$ are as follows:

   λ_{SH} = 0.03×10^{-5} failures/cycle (0.03 percent/1000 cycles)

   $N_{\sim}$ = 2 operations per picture

   The reliability of the shutter solenoid is shown in Table 2.2-8 and combined with other low duty-cycle and cyclic items of Section 3, in Figure 2.2-9.

Table 2.2-8 shows extremely high reliabilities for $R(\lambda c)_2$, $R(\lambda c)_3$, $R(\lambda c)_4$, and $R(\lambda c)_5$ because the motors are operated for very short periods and accumulate a relatively low number of operating hours over the span of a mission. The normal determination of failure rates for motors includes consideration of duty cycle to arrive at operating time. However, when a motor is repeatedly started and run for very short periods, it is felt that the straight, time-dependent failure rate becomes less and less realistic. The failure rate should most probably be multiplied by some factor which reflects the increasing effects of a failure mode attributable to motor starts. An investigation will be made in the next program phase to determine if such a factor can be established.

Reliability of TV Subsystem

By means of the reliability block diagram, mathematical model, and failure rates given in Figure 2.2-5, and the parametric values given in the text, the reliability of the TV subsystem may be obtained for any chosen operating time and any given number of site and traverse pictures (or "surveyed sites" as defined herein).

The reliabilities of Section 2 (as shown in Figure 2. 2- 8) and Section 3 (as shown in Figure 2. 2- 9) are combined for convenience in Figure 2. 2-10. Thus, the reliability of the TV subsystem may also be obtained by multiplying the reliabilities from Figures 2. 2-7 and 2. 2-10 for any given operating time and number of pictures, or sites surveyed, recognizing the conditions and definitions about which Figures 2. 2- 8 , 2. 2- 9 , and 2. 2-10 were generated.

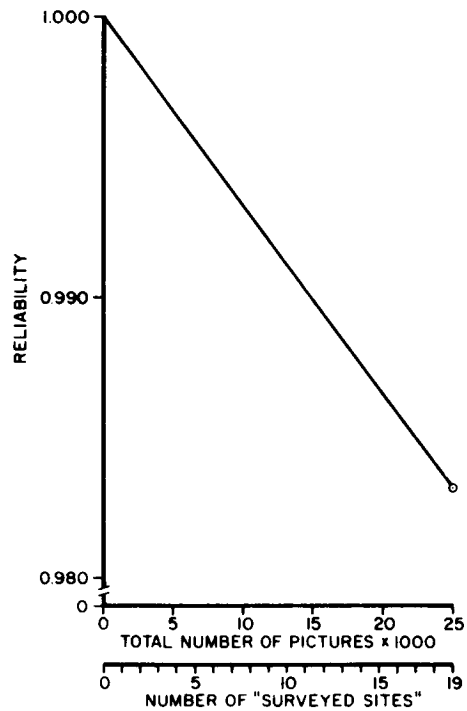

Figure 2. 2-10 Combined Reliability of Section 2 and Section 3 (Figures 2. 2-8 and 2. 2-9)

2. 2. 2. 8 Reliability Aspects of Critical Parts and Items

Reliability aspects of critical parts and items, and design features, are discussed to give additional background and a better understanding of the TV subsystem and some of the design decisions which affected the final design.

Vidicon

The vidicon is considered to be one of the most critical items in the TV subsystem. Unfortunately, vidicons are low-population items and because

of the lack of statistical data, there are no known vidicon failure rates in the various available failure rate data sources. To date, a generic failure rate of 2%/1000 hours for CRTs and kinescopes has been used since these are the nearest comparable items to the vidicon.

To attain the high degree of confidence in the vidicon for this project, future work must include careful investigation, analysis of test data that become available, a test program, and, probably, a product improvement program if shown to be desirable and technically profitable in succeeding program phases. The scope of this effort will become defined after an investigation into the vidicon data and reliability findings generated by various contractors in their vidicon improvement programs for previous and current space programs.

Test data furnished by General Electrodynamics Corporation (GEC) on their vidicons and heater/cathode assemblies are summarized as follows:

1. Continuous Operation - Test data on 25 heater/cathode assemblies operated continuously showed total hours run, ranging from 588 hours to 2472 hours grouped as follows:

   a. 588-1000 hours: 4 assemblies

   b. 1000-2000 hours: 12 assemblies

   c. 2000-2472 hours: 9 assemblies

   The assemblies tested represented succeeding new batches of manufacture. No failures occurred. A few assemblies were removed from test because of declining emission but most tests were terminated because the test facilities were limited and assemblies were removed to make room for newer batches.

2. Cyclic Operation - Test data on 4 assemblies operated in a cyclic mode consisting of 1 minute on and 4 minutes off, an extremely rugged test, showed the following:

   a. 2 failed at 1634 hours (heater failure)

   b. 1 removed from test at 6625 hours and was still operating satisfactorily

c. 1 removed from test at 6731 hours and was still operating satisfactorily.

3. Cyclic Operation - Four vidicons were tested in a cyclic mode consisting of 4 minutes on and 1 minute off with the following results:

   a. 1 survived 2000 hours

   b. 2 survived 5000 hours

   c. 1 was still operating satisfactorily at 10,000 hours when the test was terminated.

GEC stated that the main failure mode of the vidicon is failure of the heater.

A "standard" commercial TV vidicon has an expected life of 3000 hours, as a conservative figure, according to technical information from Raytheon's Industrial Tube Division, but in space applications employing slower read-out rates may experience shorter life because of the possibility of deterioration in the photosensitive material.

GEC stated that while deterioration of photosensitive material may take place in commercial vidicons, their test data and experience have shown no such failure mode to be evident in the 1344 and similar type vidicons.

The vidicon (Section 1 of Figure 2.2-5), which can be switched off when photographic activity has ended for the lunar day and the lunar night approaches), is considered to be the most critical item in the TV subsystem due to the absence of an authoritative, documented failure rate for vidicons. Certain facts are known about the GEC vidicon:

1. The main failure mode is failure of the heater/cathode element

2. In an "off-on" power switching cyclic test, the failure mode is opening of the heater

3. In a continuous power "on" run, the failure mode is exhaustion of the cathode with emission falling off below an acceptable limit.

GEC has expressed "good" confidence in the ability of the vidicon to successfully complete a mission of 3400 hours duration. The test data supplied by GEC heater/cathode assemblies for both continous and cycled test runs indicate good life. However, it would have been preferable if more of the tests were continued for longer periods and more tests to end-of-life were run.

Even though the vidicon test data and failure mode analyses point to satisfactory life capabilities, the present philosophy is to be conservative and minimize accumulated vidicon operating time by switching power off during the lunar night. This arrangement conserves heater/cathode life for expenditure during the lunar day only when the TV subsystem is actively engaged in picture taking. As more test data become available from the vendor and, if deemed necessary, from special Raytheon tests, an extra margin of confidence may be attained at which the conservative approach of switching heater power off during lunar night time may be discarded along with the parts and circuits required for this function.

The subject of switching vidicon heater power is related to one of the thermal control design requirements. The temperature of the TV subsystem can be maintained within the desired limits during the lunar night by means of power dissipated by certain circuits which are continuously powered, along with the one watt of power dissipated by the vidicon heater. To conserve heater/cathode life, as previously discussed, a design based on reliability considerations was then adopted to switch off the vidicon heater and switch in resistors which would dissipate the required one watt of power.

Figure 2.2-11 shows two circuits for switching vidicon heater and heater resistors. Circuit a, employing a single relay, is used in the present design. Redundant contacts are used for increased reliability. The series-parallel arrangement of resistors, properly sized, provides better reliability than a single resistor, along with the advantage of dispersing the source of heat. Examination of this circuit shows that the relay can be neglected in the reliability analysis. The reliability of the relay is given by the equation:

$$R = e^{-(\lambda_b t_b + \lambda * N)}$$

where:

$\lambda_b t_b$ = expected number of coil failures

λ_b = coil failure rate = $0.025\%/10^3$ hr

t_b = time power is applied to coil

$\lambda * N$ = expected number of failure for redundant relay contacts

$\lambda *$ = failure rate for redundant contacts (λ for single contact set = $0.21\%/10^4$ operations - from TRA-873-74)

N = number of relay operations in mission.

The term $\lambda_b t_b$ would ordinarily be somewhat significant since power is to be applied during lunar nights. However, if the relay coil fails, the result is that power will be applied to the vidicon heater for the remainder of the lunar night(s) and there is no effect on TV subsystem operation. In this case the heater will be operating instead of turned off in accordance with the present conservative approach. The term $\lambda * N$ can be neglected since the failure rate for two contact sets in parallel, operated twice for each lunar night, is insignificant.

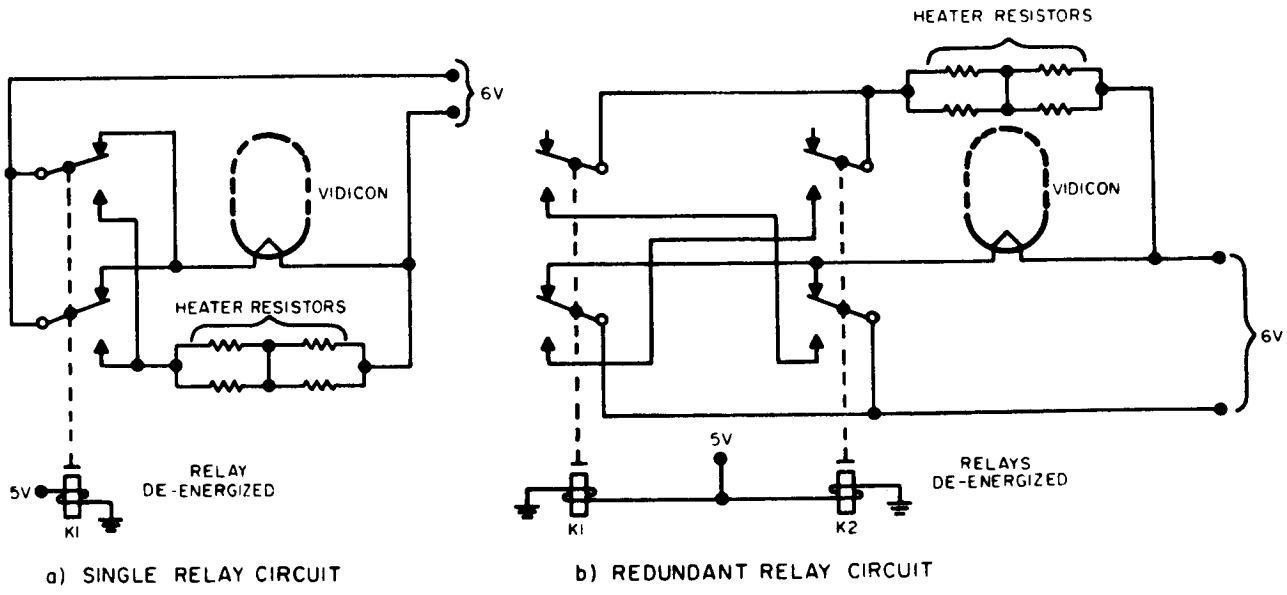

Figure 2.2-11 Vidicon Heater Switching Circuits

A remote possibility is that the relay armature would not spring back for proper contact operation and reapply power to the vidicon heater when SLRV operation is to resume. If this possibility were of concern, a solution could be provided by a redundant relay circuit such as shown by circuit b of Figure 2.2-11. While this circuit ensures that the vidicon heater will have power when desired, the switching of current to the heater resistors requires operation of both relays.

Sealed Motion-Control Drives

The TV subsystem, as presently designed, requires the use of motors and potentiometers. These types of parts are not normally capable of operation in hard vacuum and it is planned to seal them, along with gear trains, in a container having controlled leakage rates. The output shaft is sealed by "O" rings and a suitable lubricant.

Construction of the sealed drives will be at the laboratory and they will be installed as a unit at the manufacturing facility. Although great care and control will be effected in assembling these items, precautions must be taken during subsequent handling, installation, and testing to ensure the integrity of the seals.

Although the electronics and electromechanical devices can be readily checked for proper operation at the last scheduled checkout prior to installation in the vehicle or countdown, the effectiveness of the seals cannot be easily determined. Obviously, an extremely high degree of confidence must be assured in the ability of the sealed packages to function properly in hard vacuum. To this end, the next program phase will require investigation into the feasibility of checking gas pressure, leakage rates, or some other parameter at the last scheduled checkout prior to launch.

Drive Motors

The DC motor has been selected for all the TV subsystem motion control systems because of its efficiency and the availability of DC power. Use of less efficient AC motors would also require a converter in the TV subsystem or an AC source in the vehicle which would mean more circuitry, a decrease in reliability, and more heat to dump out due to added circuits and less efficient motors.

The present design of the TV subsystem is based on the use of Globe Industries' Model X-116 subminiature DC motor. This motor was selected on the basis of small size, weight, and suitable electrical characteristics. This motor provides considerably more torque than is required in the various motion control systems so, as a result, the motor is applied conservatively with a good safety margin.

The performance and design features of the Globe motor, as they relate to reliability, are as follows:

1. Failure Rate - No specific failure rate for the X-116 motor is available. Therefore, the standing of this motor relative to the generic failure rate obtained from TRA-873-74 cannot be ascertained.

2. Brush Life - The brush life of the commercially available X-116 motor is 100-500 hours in a standard atmosphere, continuous operation. The life obtained depends on the loading and rotational speed. Globe Industries provided data on the Model XA-0740 (similar to the X-116 except for a rectangular cross-section) brush life in standard atmosphere as follows:

   a. 500 hours under conservative loading

   b. 300 hours at 800 rpm and maximum continuous loading

   c. 600 hours at 5000 rpm

   d. 100 hours at 12,000 rpm

   Although the brush life appears adequate in view of the actual torque requirements and accumulated operating time for a mission, improved brushes may be incorporated for motors intended for the TV subsystem.

3. Vacuum - This motor is not intended to be operated in hard vacuum. The motor, along with gear trains and potentiometers used in the camera control systems, will be sealed into containers having controlled leakage rates.

4. Shock and Vibration - The X-116 motor is limited to shock and vibration of not more than 5g. This limit is due to the structure of the body case and end bell attachments. Raytheon has determined that a metal sleeve suitably fitted over the length of the motor will enable the motor to withstand 25 g shock and vibration.

Potentiometers

Potentiometers are considered to be critical items in the TV subsystem as are all other electromechanical items.

The present design of the TV subsystem is based on the use of Markite Corporation conductive plastic potentiometers. These potentiometers were selected on the basis of satisfying system electrical, environmental, mechanical, and reliability requirements.

The primary TV subsystem electrical, environmental, and mechanical requirements for potentiometers, which are met by Markite pots, are high resolution, high accuracy (or linearity), stability under environmental conditions, and physical dimensions suitable for the intended applications.

The Markite potentiometers have performance and design features, described below, which are desirable from the viewpoint of reliability.

1. Failure Rate - No specific failure rates are available for these potentiometers so the typical generic failure rate found in TRA-873-74 is used.

2. Life - Useful life is measured in many millions of revolutions although no such number of revolutions is needed for the TV subsystem.

3. Failure Mode - The possibility of catastrophic failures (opens or shorts) should be extremely low due to the large cross-sectional area of the molded, one-piece, continuous, resistive element. The high wiper forces (usually 50-70 grams) maintain electrical continuity under high g shock, acceleration, and vibration. Typical test data show continuous contact during conditions of 70 g vibration at 5 to 2000 cps, 100 g shock and 100 g

acceleration in all planes. The use of precision stainless steel ball bearings, both front and back, minimizes the possibility of seizing or wearout as may be experienced in ordinary bearings.

4. Radiation - Markite potentiometers will function to 10^8 and probably 10^9 rads radiation.

5. Vacuum - Although the potentiometers will be sealed into containers having controlled leakage rates for space usage; Markite states that the potentiometers can withstand, and not be harmed, by 8 days of exposure at 10^{-8} Torr. Additional information relative to the test in which the statement is based is being sought.

Reliability Aspects of Telescope

The Galilean telescope drum axis was reoriented from its original position for reliability purposes. In the present orientation the drum rotation is in a vertical plane. In the event of a failure mode wherein the proper lens is selected but not indexed within specifications, the resultant pointing error will be in the tilt plane rather than the pan plane. Pointing accuracy in the pan plane is considered more essential since this affords maximum design accuracy in navigation. Tilt pointing errors are considered less harmful to mission success than pan pointing errors.

Reliability Aspects of Iris Design

For varying the aperture, a modified iris has been designed in preference to the previous design of moveable fixed apertures. The latter has an undesirable failure mode wherein a catastrophic failure can occur while changing aperture openings with the result that the image cannot be transmitted by the optical system. Failure of the modified iris system will not cause the optics to be obstructed. Such a failure will result in a fixed aperture which can be compensated to some degree by selecting a suitable exposure time although the depth of field may not necessarily be at an optimum.

2.2.2.9 Failure Mode Analysis

A failure mode analysis of the TV subsystem was conducted by determining the various modes of failure, the probability of occurrence of

each mode of failure, and the resultant degradation to the TV subsystem. The purpose of the analysis is to rank the failure modes in critical order and define the major failure modes. Appropriate effort may then be logically directed in implementing reliability improvements.

Detail Analysis

Selection of items for failure mode analysis is based on the functional blocks of the reliability block diagram, Figure 2.2-5 . Items for analysis included functional groupings of various types of parts, groupings of integrated circuits, groupings of discrete parts, and separate, various discrete parts.

The failure mode analysis data are presented in Tables 2.2-9 to 2.2-12. The five highest critical failure modes in descending order of criticality are summarized by the following:

1. Vidicon - open heaters or insufficient cathode emission
2. 16 microcircuits of video preamplifier controls - open
3. 22 microcircuits of horizontal and vertical controls - open
4. 4 microcircuits of tilt control - open or shorted
5. 15 microcircuits of exposure control - open or shorted.

In the next phase of the program, the failure modes of the higher criticalities will be examined for means to lower or eliminate the failure modes. Possible means include use of improved parts, simpler circuits, alternate and better ways of accomplishing a given function, and redundancies.

It should be stressed again that the failure rates used in this analysis are not high reliability part failure rates. Therefore, the actual TV subsystems to be constructed, will employ high reliability parts and will have better reliability than that shown here.

The present design is based on Section 1 being powered continuously, including the time during the lunar night when no photographic activity is taking place. Further study will be made of the possibility of switching off power for Section 1 items and switching in heater resistors during DSIf off-time for increasing reliability while maintaining a suitable temperature. This study is necessary since the thermal control system will be involved.

TABLE 2.2-9

FAILURE MODE ANALYSIS DATA

Block Diagram Item	Mode of Failure	Failure Effect	Probability of Failure (λt)	Effect Index Number	Combined Product	Criticality Ranking
SECTION D-1. Assumed Mission Parameters: t = 2000 hours						
1. CABLE & CONNECTOR:						
1A. Connector (55 pin)	Open pin for a single contact	Ground loop with noise and distortion of raster, to catastrophic	6.6×10^{-3}	0.7	4.62×10^{-3}	9
2. POWER SUPPLY						
2A. Switching transistors	Short or open	No voltage output from the Power Supply.	3×10^{-3}	1	3×10^{-3}	17
2B. Zener diode	Short, open, or drift	Oscillation stops. No voltage output from the Power Supply.	1.02×10^{-3}	1	1×10^{-3}	24
2C. Inductor (3)	Open	No voltage output from the Power Supply	0.3×10^{-3}	1	0.3×10^{-3}	35
2D. Diode Rectifier	Open or short	Reduced output voltage from Power Supply. Increased ripple and noise.	6×10^{-3}	0.5	3×10^{-3}	16
2E. Regulator (2 transistors, zener diode, 6 resistors)	Open or short	Power Supply voltages out of limits.	9.4×10^{-3}	0.5	4.7×10^{-3}	8
2F. Capacitor (3)	Short	No voltage output from Power Supply	4×10^{-3}	1	4×10^{-3}	11
2G. Bleeder Resistor (11)	Open	Slight change, to no voltage.	3.5×10^{-3}	0.7	2.45×10^{-3}	19
	Drift	Slight change in output voltage.	1.5×10^{-3}	0.2	0.3×10^{-3}	36
3. HOR. & VERT. CONTROLS						
3A. Control Circuits (20 GI & 2 Sig. modules)	Short	Partial loss	13×10^{-3}	0.3	3.9×10^{-3}	12
	Open	Total loss of corresponding control circuit.	31×10^{-3}	0.3	9.3×10^{-3}	3*

Note: *Ranked in highest criticality group.

TABLE 2.2-10

FAILURE MODE ANALYSIS DATA

Block Diagram Item	Mode of Failure	Failure Effect	Probability of Failure (λt)	Effect Index Number	Combined Product	Criticality Ranking
4. DEFLECTION AMPS.						
4A. Amplifier circuits (4 GI modules)	Short	Non-linearity of reduced gain.	2.4×10^{-3}	0.5	1.2×10^{-3}	21
	Open	No deflection.	5.6×10^{-3}	1	5.6×10^{-3}	6
4B. Potentiometer (2)	Open	Loss of deflection centering	3×10^{-3}	1	3×10^{-3}	15
5. VIDICON	Open heater or insufficient cathode emission	Catastrophic	40×10^{-3}	1	40×10^{-3}	1*
6. VIDEO PREAMP & CONTROLS						
6A. Video Preamp. (2 GI modules)	Short	Loss of gain	1.2×10^{-3}	0.5	0.6×10^{-3}	26
	Open	Loss of signal	2.8×10^{-3}	1	2.8×10^{-3}	18
6B. Control Circuits (16 microcircuit modules)	Short	Partial loss.	9.6×10^{-3}	0.5	4.8×10^{-3}	7
	Open	Total loss of corresponding control circuit	22.4×10^{-3}	0.5	11.2×10^{-3}	2*
7. PAN, TILT, FOV, APERTURE EXPOSURE CONTROLS:						
7A. Pan Control (4 microcircuits)	Open or short	Camera driven against stops at + or - 200° in pan.	8×10^{-3}	0.4	3.2×10^{-3}	13
7B. Tilt Control (4 microcircuits)	Open or short	Camera tilted against stops, either full up or full down.	8×10^{-3}	0.9	7.2×10^{-3}	4*

Note: *Ranked in highest criticality group.

TABLE 2.2-11

FAILURE MODE ANALYSIS DATA

Block Diagram Item	Mode of Failure	Failure Effect	Probability of Failure (λt)	Effect Index Number	Combined Product	Criticality Ranking
7C. FOV Control	Open or short	Galilean telescope drum driven against stops and FOV remains fixed.	8×10^{-3}	0.5	4×10^{-3}	10
7D. Aperture Control (4 microcircuits)	Open or short	Aperture driven to and fixed at widest or smallest aperture. Loss of flexibility.	8×10^{-3}	0.3	2.4×10^{-3}	20
7E. Exposure Control (15 microcircuits)	Open or short	Partial loss to total loss of control circuit. Loss of photographic flexibility.	30×10^{-3}	0.2	6×10^{-3}	5*
SECTION D-II Assumed Mission Parameters:		1. 25,000 pictures 2. 15 seconds of video circuit time per TV picture. 3. Approximately 100 hours total time for video circuit operation.				
8. HOR. & VERT. SWEEP CIRCUITS: (23 Sig. modules)	Short	Raster distorted	0.7×10^{-3}	0.5	0.35×10^{-3}	32
	Open	Raster distorted	1.6×10^{-3}	0.5	0.8×10^{-3}	25
9. D/A CIRCUITS						
9A. 18 SIG. Modules	Short	Ranging from small loss to 1/2 loss of picture.	0.54×10^{-3}	0.3	0.16×10^{-3}	37
	Open		1.25×10^{-3}	0.3	0.375×10^{-3}	31
9B. Resistor (36)	Open	As above.	1.6×10^{-3}	0.3	0.48×10^{-3}	28
10. ENCODER						
10A. Comparator (4 microcircuits)	Short	No encoding	0.15×10^{-3}	1	0.15×10^{-3}	38
	Open	No encoding	0.15×10^{-3}	1	0.35×10^{-3}	33
10B. Encoding Circuits (29 microcircuits)	Short	Loss of flexibility	0.87×10^{-3}	0.5	0.43×10^{-3}	30
	Open	Loss of flexibility	2×10^{-3}	0.5	1×10^{-3}	23
10C. Resistor (15)	Open or short	Incorrect coding	0.68×10^{-3}	0.7	0.47×10^{-3}	29

Note: Ranked in highest criticality group.

TABLE 2.2-12

FAILURE MODE ANALYSIS DATA

Block Diagram Item	Mode of Failure	Failure Effect	Probability of Failure (λt)	Effect Index Number	Combined Product	Criticality Ranking
11. VIDEO AMP. (5 microcircuits)	Open	Loss of signal	0.35×10^{-3}	1.0	0.35×10^{-3}	34
	Short	Loss of gain	0.15×10^{-3}	0.5	0.08×10^{-3}	39
12. ROBERTS GENERATOR (57 microcircuits)	Short	Loss of flexibility.	1.7×10^{-3}	0.3	0.5×10^{-3}	27
	Open	Loss of flexibility.	4×10^{-3}	0.3	1.2×10^{-3}	22
SECTION D-3 Assumed Mission Parameters: 1. 25,000 pictures, (5,000 traverse, 20,000 site survey) 2. θS_p, θS_t = 15° camera swing, average, per site picture. θT_p, θT_t = 10° camera swing, average, per site picture. 3. Rate of camera swing = 6°/second						
13. PAN ACTUATOR ASSY. (16.2 hours):						
13A. Motor	Inoperative	Fixed pan angle	0.03×10^{-3}	0.4	0.01×10^{-3}	42
13B. Bearing	Freeze-up	Fixed pan angle	0.03×10^{-3}	0.4	0.01×10^{-3}	43
13C. Potentiometer	Open	No pan angle read-out	0.03×10^{-3}	0.2	0.006×10^{-3}	44
14. TILT ACTUATOR ASSY. (16.2 hours):						
14A. Motor	Inoperative	Fixed tilt angle	0.03×10^{-3}	0.9	0.027×10^{-3}	40
14B. Bearing	Freeze-up	Fixed tilt angle	0.03×10^{-3}	0.9	0.027×10^{-3}	41
15. FOV ACTUATOR ASSY. (5.2 hours):						
15A. Motor	Inoperative	Fixed FOV	0.008×10^{-3}	0.5	0.004×10^{-3}	46
15B. Bearing	Freeze-up	Fixed VOV	0.01×10^{-3}	0.5	0.005×10^{-3}	45
16. APERTURE ACTUATOR ASSY. (3.5 hours):						
16A. Motor	Inoperative	Fixed aperture	0.0056×10^{-3}	0.3	0.002×10^{-3}	47
16B. Bearing	Freeze-up	Fixed aperture	0.0068×10^{-3}	0.3	0.002×10^{-3}	48
17. SHUTTER ACTUATOR ASSY.						
17A. Solenoid	Short or open	Shutter fixed open. Loss of flexibility	15×10^{-3}	0.2	3×10^{-3}	14

Several aspects of the failure mode analysis procedure are reviewed here (see Tables 2.2-9 through 2.2-12).

The rate of occurrence of a failure mode of a time (or cycle) sensitive part is related to its failure rate through the following relationship:

$$\lambda_T = \sum_{i=1} \lambda_i$$

where

λ_T = total failure rate of the time (or cycle) sensitive part

λ_i = part failure rate due to the ith failure mode

k = number of failure modes.

The ratio of failures in each failure mode to the total expected failures of the part were obtained from several sources: TRA-873-74 for the more common parts, Bendix Systems Division for integrated circuits, and engineering estimates for parts not otherwise covered. In developing estimates, use was made of Section 6.1, "Environmental Effect on Part Failures", of TRA-873-74.

The Mode-of-Failure column data (Tables 2.2-9 through 2.2-12) was based on the above. Failure modes which were considered insignificant, with a very remote possibility of occurrence, were not subject to further analysis.

The probability of failure (λt) was determined by the product of the total failure rate of the part, the rate of occurrence of a particular failure mode, and the total operating time (or number of actuations for cyclic items).

The Effect Index Number is the level of degradation suffered by the TV subsystem as a consequence of a particular failure mode. An Effect Index Number of 1 corresponds to total failure or mission abort, while a number approaching zero has no effect on the mission.

The Combined Product is the product of Probability of Failure and Effect Index Number.

The Criticality Ranking is the ranking of failure modes in order of descending order of importance — ranking of 1 being the most critical failure mode of the TV subsystem.

2. 2. 2. 10 Parts and Materials Control Program

The broad objective of the parts and materials control program is to eliminate or minimize potential reliability problems associated with component parts and materials including the choice of types, specification, qualification, and application. (As used herein, qualification means all methods of determination of suitability, as opposed to qualification testing.)

Since the TV subsystem will be produced in limited numbers, heavy emphasis will not be placed on reduction of numbers of types of parts or microcircuits.

Selection

In order to facilitate and control proper choices of parts, an approved parts list has been prepared for use in the TV subsystem, and about 85 percent of the parts and circuits required should be available from this list.

Specifications

It is not anticipated that a large number of parts, circuits, and materials specifications will be required since existing high reliability specifications will be satisfactory in most cases.

Where additional requirements or modification of specifications are required, individual purchase orders can be supplemented to achieve the objectives.

Qualification

Qualification of parts, circuits and materials will be based upon prior usage in space programs and a history of good reliability. However, verification test program will be required on a limited number of items, either because of lack of usage history, use in an unusual application, or both.

Screening Aging Tests

Regardless of the type of part under consideration, manufacturing conditions for the part are never constant. Therefore, it must be recognized that potentially defective parts are likely to be present in any lot of parts regardless of the type. Therefore, it is planned that all part types will receive a nominal run-in (burn-in) at near full capacity and at elevated ambient temperature.

In addition to these nominal run-ins, special screening tests will be instituted on certain types of parts where such tests are considered to be effective in eliminating "early" failures.

Additional Considerations

As the television subsystem design and development progresses, it may be determined that certain types of parts are not capable of meeting the reliability requirement of the subsystem. In those cases, a detailed analysis will be made to determine the causes of the inadequacy, and recommendations will be made to improve the reliability of the part through a suitable reliability improvement program.

2. 2. 2. 11 Preferred Parts List and Application Guidelines

Preferred Parts List and Application Guidelines, presented in Tables 2. 2-13 through 2. 2-24, form a preliminary document developed to provide initial guidance to SLRV TV subsystem designers. These will be revised periodically to pace the advancement of the program and design phase of the TV subsystem.

Basic guidelines for the design of the TV subsystems are as follows:

1. Avoid the use of parts containing liquids, such as wet slug tantalum capacitors, aluminum electrolytic capacitors, etc.

2. Limit the use of electromechanical, rotary or switching devices such as potentiometers, motors, relays, switches, etc.

3. Use only lubricants indicated.

TABLE 2.2-13

MINIMUM ENVIRONMENTAL REQUIREMENTS FOR PARTS FOR TV SUBSYSTEM APPLICATION

Environment	Operating
Shock	50 g, 11 ± 1 ms (3 axes) in MIL-STD-202
Vibration	
Sinusoidal	5 - 20 0.5 in. double amplitude 20 - 57 ± 10g 57 - 99 0.6 in. double amplitude 99 - 3000 ± 30g
Random	50 - 2000 cps at $0.3g^2$/cps
Acceleration	When conditions are considered to be more severe than the requirements noted above, then the acceleration requirements will be specified in the purchase specifications.
Temperature	-65°C to + 85°C*, -65°C to + 125°C* (non operating)
Acoustic Noise CPS above 2×10^{-4} dynes CM^2	37.5 - 9600 cps at 150 db
Pressure	Operation at maximum rated voltage at 2.5 mm Hg without arc over
Vacuum	Stabilized at 1×10^{-8} mm Hg for 50 hours min
Moisture	MIL-STD-202, Method 106A
Radiation	Integrated flux 2×10^{13} electrons/cm
Electrons	Energy level - 1 mev
Gamma Ray	DOSE: 7×10^6 Rads

*Measured at the part case

TABLE 2.2-14

Standard Resistance Values for the 10 to 100 Decade

A	B	A	B	A	B	A	B	A	B	A	B
10.0	10.0	14.7	14.7	21.5	21.5	31.6	31.6	46.4	46.4	68.1	68.1
10.1	--	14.9	--	21.8	--	32.0	--	47.0	--	69.0	--
10.2	10.2	15.0	15.0	22.1	22.1	32.4	32.4	47.5	47.5	69.8	69.8
10.4	--	15.2	--	22.3	--	32.8	--	48.1	--	70.6	--
10.5	10.5	15.4	15.4	22.6	22.6	33.2	33.2	48.7	48.7	71.5	71.5
10.6	--	15.6	--	22.9	--	33.6	--	49.3	--	72.3	--
10.7	10.7	15.8	15.8	23.2	23.2	34.0	34.0	49.9	49.9	73.2	73.2
10.9	--	16.0	--	23.4	--	34.4	--	50.5	--	74.1	--
11.0	11.0	16.2	16.2	23.7	23.7	34.8	34.8	51.1	51.1	75.0	75.0
11.1	--	16.4	--	24.0	--	35.2	--	51.7	--	75.9	--
11.3	11.3	16.5	16.5	24.3	24.3	35.7	35.7	52.3	52.3	76.8	76.8
11.4	--	16.7	--	24.6	--	36.1	--	53.0	--	77.7	--
11.5	11.5	16.9	16.9	24.9	24.9	36.5	36.5	53.6	53.6	78.7	78.7
11.7	--	17.2	--	25.2	--	37.0	--	54.2	--	79.6	--
11.8	11.8	17.4	17.4	25.5	25.5	37.4	37.4	54.9	54.9	80.6	80.6
12.0	--	17.6	--	25.8	--	37.9	--	55.6	--	81.6	--
12.1	12.1	17.8	17.8	26.1	26.1	38.3	38.3	56.2	56.2	82.5	82.5
12.3	--	18.0	--	26.4	--	38.8	--	56.9	--	83.5	--
12.4	12.4	18.2	18.2	26.7	26.7	39.2	39.2	57.6	57.6	84.5	84.5
12.6	--	18.4	--	27.1	--	39.7	--	58.3	--	85.6	--
12.7	12.7	18.7	18.7	27.4	27.4	40.2	40.2	59.0	59.0	86.6	86.6
12.9	--	18.9	--	27.7	--	40.7	--	59.7	--	87.6	--
13.0	13.0	19.1	19.1	28.0	28.0	41.2	41.2	60.4	60.4	88.7	88.7
13.2	--	19.3	--	28.4	--	41.7	--	61.2	--	89.8	--
13.3	13.3	19.6	19.6	28.7	28.7	42.2	42.2	61.9	61.9	90.9	90.9
13.5	--	19.8	--	29.1	--	42.7	--	62.6	--	92.0	--
13.7	13.7	20.0	20.0	29.4	29.4	43.2	43.2	63.4	63.4	93.1	93.1
13.8	--	20.3	--	29.8	--	43.7	--	64.2	--	94.2	94.2
14.0	14.0	20.5	20.5	30.1	30.1	44.2	44.2	64.9	64.9	95.3	95.3
14.2	--	20.8	--	30.5	--	44.8	--	65.7	--	96.5	--
14.3	14.3	21.0	21.0	30.9	30.9	45.3	45.3	66.5	66.5	97.6	97.6
14.5	--	21.3	--	31.2	--	45.9	--	67.3	--	98.8	--

TABLE 2.2-15

WEIGHT AND DENSITY OF MICROCIRCUIT PACKAGES

Company	Volume	Density	Weight
1) T.I.	1/4" x 1/8" x 1/32"	$7 \times 10^6/ft^3$	0.005 Gram
2) Fairchild	TO-5 (0.330" Dia x 0.250"h)	$3\text{-}5 \times 10^5/ft^3$	1.2 - 1.3 Gram
3) Signetics	TO-5 or 0.330" Dia x 0.250"h 0.25" x 0.25" x 0.070"	$5 \times 10^6/ft^3$	0.18 Gram
4) Westinghouse	0.25" x 0.25" x 0.035"	$5\text{-}8 \times 10^5/ft^3$	0.05 - 0.07 Gram
5) IRC	TO-5	$0.3\text{-}5 \times 10^6/ft^3$	2-5 Gram Stackup
6) Servomechanisms (Thin Film)	0.35" x 0.35 x 0.30"	$2\text{-}5 \times 10^5/ft^3$	0.008 lb ($0.2\ lb/in^3$)
7) Miniature Discreet (Cordwood)	--	$5\text{-}6 \times 10^4/ft^3$	

TABLE 2.2-16

DIGITAL MICROCIRCUITS

Function	Vendor	Catalog No.	Military No.	f_d max n sec	I_{cbo} μa	f_a mc	P mw	Package	Remarks
Gate NOR-NAND	T.I.	SN-512	--	130	100	0.6	7	Flat-Pack	
Gate NOR-NAND with C.F.	T.I.	SN-513	--	130	100	0.6	7	Flat-Pack	
Flip-Flop	T.I.	SN-510	--	300	100	0.6	7	Flat-Pack	
Flip-Flop with C.F.	T.I.	SN-511	--	300	100	0.6	7	Flat-Pack	
Gate Dual NOR-NAND	T.I.	SN-514	--	80	100	0.6	7	Flat-Pack	
Gate OR	T.I.	SN-515	--	100	100	0.6	7	Flat-Pack	
Buffer	F.A.	MLB	--	35	100	0.8	15	TO-5	
Flip-Flop	F.A.	MLF	--	35	100	0.8	30	TO-5	
Gate	F.A.	MLG	--	35	100	0.8	15	TO-5	
Half-Adder	F.A.	MLH	--	70	100	0.8	45	TO-5	
Half-Shift Register	F.A.	MLS	--	70	100	0.8	75	TO-5	
Flip-Flop	G.I.	NC-8/ PC-8	--	30	200	20	200	TO-5 or Flat Pack	
Steering Gate	G.I.	NC-9/ PC-9	--	30	200	20	200	TO-5 or Flat-Pack	
Flip-Flop Reset	G.I.	PC-13	--	30	200	20	200	TO-5 or Flat-Pack	
Gate NOR Single 4 Input	G.I.	NC-10	--	22	150	12	170	TO-5	
Gate NOR Dual 3 Input	G.I.	PC-14	--	22	150	12	170	Flat-Pack	
Gate NOR Single 6 Input	G.I.	PC-10	--	22	150	12	170	Flat-Pack	
Gate NAND Single 4 Input	G.I.	NC-11	--					TO-5	
Gate NAND Dual 3 Input	G.I.	PC-15	--	16	100	15	60	Flat-Pack	
Gate NAND Single 6 Input	G.I.	PC-11	--					Flat-Pack	
Buffer	G.I.	NC/PC-12	--		70	12	200	TO-5 or Flat Pack	
Gate NOR-NAND Single 3 Input	Signetics	SE101G SE101K	--	60	100	1	6	G = TO-5 K = Flat-Pack	

TABLE 2.2-16 (CONT.)

Function	Vendor	Catalog No.	Military No.	f_d max n sec	I_{cbo} μa	f_a mc	P mw	Package	Remarks
Gate NOR-NAND Single 4 Input	Signetics	SE-102G SE-102K	-- --	60	100	1	6	G = TO-5 K = Flat-Pack	
Diode & Gate	Signetics	SE-105-104T	--	60	100	1	6	Flat-Pack	
Power Gate	Signetics	SE-110	--	35	200	1	50	Flat-Pack	
Shift Register	Signetics	SE-122 SE-123 SE-120T SE-121T	--	--	100	8	16	Flat-Pack	
Ripple Counter	Signetics	SE-124	--	--	100	8	16	Flat-Pack	
Line Driver	Signetics	SE-150	--	35	200	--	50	Flat-Pack	
One-shot Multi-vibrator	Signetics	SE-160	--	--	150	1	25	Flat-Pack	
Buffer.	Signetics	SE-130T	--	50	200	1	60	Flat-Pack	
Exclusive OR	Signetics	SE-140T	--	35	100	1	60	Flat-Pack	
High-Speed NAND-NOR	Signetics	SE-201G SE-201K	--	8	50	20	6	G = TO-5 K = Flat-Pack	
Gate NAND	Raytheon	--	--	--	100	0.8	15	TO-5	
J-K Flip-Flop	T.I.	SN-530	--	--	--	5	30	Flat-Pack	
5 Input NAND Gate	T.I.	SN-531	--	--	--	5	30	Flat-Pack	
5 Input NAND Gate	T.I.	SN-532	--	--	--	5	30	Flat-Pack	
Dual 3 Input NAND Gate	T.I.	SN-533	--	--	--	5	30	Flat-Pack	
2 & 3 Input NAND Gate	T.I.	SN-534	--	--	--	5	30	Flat-Pack	
Clock Driver/Buffer	T.I.	SN-535	--	--	--	5	30	Flat-Pack	

TABLE 2.2-17

ANALOG MICROCIRCUITS

Function	Vendor	Catalog No.	Military No.	Power	V_B	I_c	f_{co}	Z_{in} ohm	Z_{out} ohm	Package	Remarks
RF Amp	Westinghouse	WM 1101	--	30 db Gain	12	4 ma	6 mc	300	1.3K	Flat-Pack	
Osc-Mix	Westinghouse	WM 1102	--	30 db	12	4 ma	8 mc	300	1.3K	Flat-Pack	
IF Amp	Westinghouse	WM 1103		30 db	12	4 ma	10 mc	300	1.3K	Flat-Pack	Function of Xtal
Video Amp	Westinghouse	WM 1106		30 db	12	4 ma	12 mc	300	1.3K	Flat-Pack	Function of load
Audio Amp	Westinghouse	WM 1105		3 w Dis.	12	10 ma	0.5 mc	--	--	Flat-Pack	5% distortion
		WM 1205		3 w	12	10 ma	0.5 mc	--	--	Flat-Pack	10% distortion
Power Audio Amp	Westinghouse	WM 1109		13 w	60	1.2 a	20 kc	--	--	Round 0.980" D	
Impedance Transformer	Westinghouse	WM 1111		--	8	1.5	5 mc	20M	1K	Flat-Pack	
Impedance Transformer	Westinghouse	WM 1211		--	8	1.5	5 mc	20M	1K	TO-5	
Two-stage Darlington	Westinghouse	WM 1110		50 mw		H_{fe} 1500	2 mc	--	--	Flat-Pack	
Operational Amplifiers	Texas Instr.	SN-521	--	28 mw	62		0-50kc	12 K	12K	Flat-Pack	
		SN-522	--	72 mw	62		0-50kc	10 K	1.6K	Flat-Pack	
Video Amp	General Instr.	NC/PC-101	--	--	25		20 mc band-width	1.2 K	500	TO-5 Flat-Pack	

TABLE 2.2-18
RESISTORS, FIXED

Specification	Type	Vendor	Resistance Range	Tolerance %	PPM/°C	Voltage V_{max}	Power P_{max}
MIL-R 38101/1	Film	IRC	10-150K	±1.0	100	250	1/8 at 100°C
MIL-R 38101/2	Power Wirewound	Dale	0.1-6K	±1.0	20	200	2.0 at 125°C
MIL-R 38101/3	Precision Wirewound	Ultronix	10-1.1 meg	±0.02	15	600	1.0 at 125°C
MIL-R 38101/4	Precision Wirewound	Ultronix	0.1-240K	±1.0	15	300	1/4 at 125°C
MIL-R 38101/5	Precision Wirewound	Ultronix	0.1-400K	±1.0	15	300	1/2 at 125°C
MIL-R 38101/6	Precision Wirewound	Ultronix	0.1-1.1 meg	±0.1	15	600	1/8 at 125°C
MIL-R 38101/7	Precision Wirewound	Ultronix	0.1-100K	±0.1	15	150	1/8 at 125°C
MIL-R 38101/8	Precision Wirewound	Ultronix	1.0-240K	±0.1	15	300	1/4 at 125°C
MIL-R 38101/9	Precision Wirewound	Ultronix	1.0-400K	±0.1	15	300	1/2 at 125°C
MIL-R 38101/10	Precision Wirewound	Ultronix	1.0-1.0 meg	±0.1	15	600	1 at 125°C
MIL-R 38101/11	Precision Wirewound	Ultronix	1.0-240K	±0.02	15	300	1/4 at 125°C
MIL-R 38101/12	Precision Wirewound	Ultronix	1.0- 60K	±0.01	20	150	1/8 at 125°C

TABLE 2.2-18 (CONT.)

Specification	Type	Vendor	Resistance Range	Tolerance %	PPM/°C	Voltage V_{max}	Power P_{max}
MIL-R 38101/13	Power Wirewound Subminiature		0.5- 1K	±1.0	±20	25	1 at 125°C
MIL-R 38101/14	Power Wirewound Subminiature		0.1-216K	±1.0	±20	52	2.25 at 25°C
MIL-R 38101/15	Power Wirewound Subminiature		0.1-4.12K	±1.0	±20	112	4.0 at 25°C
MIL-R 38101/16	Power Wirewound Miniature	Dale	0.1- 12K	±1.0	±20	400	5.0 at 25°C
MIL-R 38101/17	Power Wirewound Subminiature		0.1-12.4K	±1.0	±20	275	7.0 at 25°C
MIL-R 38101/18	Power Wirewound Miniature	Dale	1.0- 40K	±1.0	±20	1000	10 at 25°C
MIL-R 38101/19	Metal Film Subminiature		50-200K	±1.0	±50	200	0.1 at 100°C
MIL-R 38101/20	Metal Film Subminiature		50-100K	±1.0	±50	200	0.05 at 100°C
MIL-R 38101/21	Film	Corning Glass	51-150K	±2.0	±200	150	1/8 at 70°C
MIL-R 38101/22	Film	Corning Glass	51-300K	±2.0	±200	250	1/3 at 70°C
MIL-R 38101/23	Film	Corning Glass	51-620K	±2.0	±200	250	1 at 70°C

TABLE 2.2-19
CAPACITORS, FIXED

Military Specification	Type	Vendor	Capacitance Range C	Tolerance %	Volts V_{max}	D. F. Max %	Leakage ma
MIL-C 38102/1	Glass	Corning	1-3900 pf	± 1 to ±10	350	0.08	0.05 at 25°C
MIL-C 38102/2	Paper	J. E. Fast	0.0018 to 1.0 mf	±10 to ±20	600	0.5	0.03 at 25°C
MIL-C 38102/4	Solid Tant.	Sprague G. E.	0.047 to 68.0 mf	±10 ±20	50	6.0	27.0 at 25°C
MIL-C 38102/9	Polystyrene		0.01 1.0 mf	± 1.0 to ±10.0	200	0.10	--
MIL-C 11272	Porcelain	Vitramon	0.5 to 6.800 pf	± 2	500	--	--
MIL-C 5	Mica	El-Menco	2 to 1000 pf	± 1	500	0.001	--
MIL-C 11015	Stand-off & Feed-thru CK-70 CK-80	Erie	50 to 1500 pf	±10 ±20	500	--	--
MIL-C 5	(dc-dc Converter Filter) Mica	Sprague 210M	to 1 mf	± 5 ±10	to 6000	0.15	--
MIL-C 38102/5	Foil Plain Tant. Polarized	Sprague G. E.	2.0 to 100.0	±10 ±20	150	7.0	5 ma at 25°C
MIL-C 38102/6	Foil Plain Tant. Nonpolarized	Sprague G. E.	1.2 to 100	±10 ±20	150	7.0	5 ma at 25°C
MIL-C 38102/7	Foil Etched Tant. Polarized	Sprague G. E.	450 mf	-15, +30 -15, +50 -15, +75	150	15.0	15 ma at 25°C

TABLE 2.2-20

DIODES, SEMICONDUCTOR

Military Specification	Type	Vendor	Power W	I_o A	V_R	I_z	V_z	V_{KGM}	I_{GKM}	P_{GM}	Package
MIL-S 38103/104	Medium Power Si	G. E.									
MIL-S 38103/105	Power Si	G. E.	35	20	400						Stud mount
MIL-S 38103/106	High Power Si	Westinghouse	330	240	150						Stud mount
MIL-S 38103/107	Reg. 250 mw Si	Continental Device	250 mw			37 ma	6.7				0.300" length 0.125" dia.
MIL-S 38103/108	Reg. 250 mw Si	Continental Device	250			20 ma	12.8				0.300" length 0.125" dia.
MIL-S 38103/109	Reg. 250 mw Si	Continental Device	250 mw			100 ma	50.0				0.300" length 0.125" dia.
MIL-S 38103/110	Ref. Precision Si	Transitron	250 mw			37 ma	6.7				0.300" length 0.125" dia.
MIL-S 38103/111	Ref. Precision Si	Continental Device	250			28 ma	9.0				0.327" dia. 0.710" length
MIL-S 38103/112	Reg. 750 mw Si	Motorola	750 mw			105 ma	7.1				0.225" dia. 0.350" length
MIL-S 38103/113	Reg. 750 mw Si	Motorola	750 mw			55 ma	13.6				0.225" dia. 0.350" length

TABLE 2.2-20 (CONT.)

Military Specification	Type	Vendor	Power W	I_o A	V_R	I_z	V_z	V_{KGM}	I_{GKM}	P_{GM}	Package
MIL-S 38103/115	Reg. 750 mw Si	Motorola	750 mw			75 ma	10.0				0.225" dia. 0.350" length
MIL-S 38103/116	Rectifier Controlled Si	G. E.	--	16				5 V	2 A	5 W	Stud mount
MIL-S 38103/117	Rectifier Controlled Si	Solid State									
MIL-S 38103/119	Power Si	G. E.		12	400						Stud mount
MIL-S 38103/120	Gen. Purpose Low-Leakage Si	PSI	600 mw	400 ma	225						0.300" length 0.125" dia.
MIL-S 38103/121	Computer Si	FA Cont. Dev. PSI Raytheon	250 mw	100 ma	50						0.300" length 0.125" dia.
MIL-S 38103/122	Computer Si										
MIL-S 38103/123	Gen. Purpose Si										
MIL-S 38103-124	Medium Power Si										
MIL-S 38103/125	Power Si		15.0	12	100						0.635" dia. 0.165" thick
MIL-S 38103/126	Regulator Si		1.0			125 ma	6.8				0.085" dia. 0.160" length

TABLE 2.2-20 (CONT.)

Military Specification	Type	Vendor	Power W	I_o A	V_R	I_z	V_z	V_{KGM}	I_{GKM}	P_{GM}	Package
MIL-S 38103/127	Regulator Si		1.0			90 ma	9.0				0.085" dia. 0.160" length
MIL-S 38103/128	Regulator Si		1.0			65 ma	12.0				0.085" dia. 0.160" length
MIL-S 38103/129	Power		45.0	40	175						Stud mount

Note: If a diode type cannot be selected from this list, the designer is requested to use those in MIL-STD-701.

TABLE 2.2-21
TRANSISTORS

Military Sp cification	Type	Vendor	BV_{ceo}	BV_{cbo}	BV_{ces}	BV_{ebo}	I_c	I_b	P_c	Package
MIL-S 38103/501	NPN Si Switch	G.E.								
MIL-S 38103/505	Switch PNP Ge	Motorola T.I.								
MIL-S 38103/506	Power PNP Ge	Delco Motorola								
MIL-S 38103/508	Switch PNP Si	FA T.I. Motorola Hughes								
MIL-S 38103/509	Video Amp PNP Ge	Motorola T.I.								
MIL-S 38103/510	Small Signal NPN Si	G.E.								
MIL-S 38103/511	Switch NPN Si	FA Raytheon T.I.								
MIL-S 38103/512	Switch PNP Ge	Motorola T.I.	-16 V	-40 V	-40 V	-5 V	-100 ma	-100 ma	150 mw	0.230" dia. 0.210" high
MIL-S 38103/513	Video Amp PNP Ge		-16 V	-40 V	-40 V	-2 V	-100 ma	-100 ma	150 mw	0.230" dia. 0.210" high
MIL-S 38103/514	Power NPN Si		100 V	135 V		7 V	12A	5A	2W	0.635" Disc 0.165" Thick

TABLE 2.2-21 (CONT.)

Military Specification		Vendor	BV_{ceo}	BV_{cbo}	BV_{ces}	BV_{ebo}	I_c	I_b	P_c	I_e	V_{B_2E}	Package
MIL-S 38103/515	Dual Switch PNP Si		-25 V	-40 V		-5 V	-100 ma	-50 ma	250 mw			Flat-Pack 1/4"X1/8"X 3/64"
MIL-S 38103/516	Dual Switch PNP Si		-20 V	-35 V		-4 V	-100 ma	-50 ma	250 mw			Flat-Pack 1/4 X1/8"X 3/64"
MIL-S 38103/517	General Purpose NPN Si											
MIL-S 38103/518	Low Level Pair NPN Si											
MIL-S 38103/519	Low Level Pair NPN Si											
MIL-S 38103/520	Switch PNP Si											
MIL-S 38103/521	Switch PNP Si											
MIL-S 38103/522	Dual Switch NPN Si											
MIL-S 38103/523	Dual Switch NPN Si											
MIL-S 38103/524	General Purpose NPN Si		100 V	160 V		8 V	20 A	5 A	3W			Stud-mt.
MIL-S 38103/525	Power NPN Si		100 V	160 V		8 V	15 A	5 A	2W			0.70" Disc 0.20" Thick
MIL-S	Unijunction	GE							600	70	60	TO-5

Note: If a transistor type cannot be selected from this list the designer is requested to use those in MIL-STD-701.

TABLE 2.2-22

CONNECTORS

Military Specification	Type	Vendor	Shell Material	Insert Material	Contact Material	Contact Plating
MIL-C 26482	Round Minia.	Bendix PY Series	Aluminum	Compressed Glass	Beryllium Copper	Gold over Nickel
	RF	Amphenol				
	Rectangular	Cannon	Steel Nickel plated	Diallyl Phthalate	Brass	Gold over Nickel

TABLE 2. 2-23

INDUCTIVE DEVICES (FIXED)

Military Specification	Type	Vendor	Core Material	Wire	Vacuum Impregnate	Molding Material
MIL-T-27	Trans-formers	Raytheon Wheeler	Powdered Iron		Varnish MIL-V-173	
MIL-C-15305	R. F. Chokes	Delevan Jeffers	Phenolic or Iron		Varnish MIL-V-173	

INDUCTIVE DEVICES (ROTARY)

Military Specification	Type	Vendor	Metals	Bearings	Lubricant(1)	
MIL-R-20708	Servos	Kearfott	Stainless Steel	Stainless Steel	Molykote Type Z Duroid 5813	

Note: (1) Oil and grease lubricants evaporate rapidly in a vacuum. Lubricants must be approved by Reliability.

TABLE 2.2-24

WIRE

Military Specification	Type	Vendor	Insulation	Jacket	Z Ω	Cap pf	Remarks
MIL-C-17C	Coax	RG-141A/U	Teflon	Teflon	50	29	Lo-loss Hi Temp.
MIL-W-16878	Hookup	Surprenant Hi-Temp. W. L. Gore	Teflon				600 V Insulation

4. Avoid the use of parts plated with cadmium or zinc unless, as used, there is no potential for failure or degradation because of associated sublimation processes.

5. The heat transfer of an operating device in vacuum is only through the modes of conduction and radiation. The power rating of such a device should be reduced 30% comparative to its operation in a normal atmosphere, unless adequately heat-sinked.

Table 2.2-13 is provided as a basic starting point for environmental requirements for parts for the TV subsystem and therefore, the requirements specified therein are minimum requirements.

In order to promote standardization, the resistance values shown in Table 2.2-14 are considered preferred nominal values. Each decade of resistance shall have its preferred nominal values though only those for one decade are shown. The B columns give the preferred nominal values for resistors with purchase tolerance of 1.0 percent. The A columns give the preferred nominal values for resistors with a tolerance of less than 1.0 percent.

Resistance values other than those shown in Table 2.2-14 shall not be considered preferred nominal values.

2.2.3 TM Data Handling Subsystem

2.2.3.1 Summary of Parametric Study

A reliability parametric study was conducted on the TM Data Handling Subsystem (see BSR-887). In this study, the reliability versus temperature, time, and number of both critical and non-critical inputs was calculated. Based upon the results of this study, and the thermal considerations obtaining in the subsystem, an operating temperature for the subsystem of 55°C was established. Additionally, the number of both critical and non-critical inputs was held to a minimum in the final configuration. Preliminary calculation indicated that the non-redundant system offered relatively low reliability, and therefore selective redundancy was employed. Specifically, parallel redundancy has been employed in both the A/D converter and in the clock divider. Triplicated input majority voting was employed in the A/D converter, selector logic, and in the row and column drivers of the programmer. The entire parametric study was based on the assumption that all logic functions would be implemented using Texas Instrument micro circuits, similar to the SN series. The failure rates assumed are those determined by Texas Instruments and published in their 1962 reliability report.

2.2.3.2 Functional Description & Block Diagram

A reliability block diagram of the TM Data Handling Subsystem is shown in Figure 2.2-12. The telemetry data processor is designed to accept digital inputs, low level (0 to 50 mv) analog inputs, high level (0 to 5 v) analog inputs, and to convert these signals into a digital form appropriate to the transmitter. The various input signals are time multiplexed under the command of the programmer and provide a PCM split phase output to the transmitter. Time synchronization of these signals is provided by the clock divider, which in turn is driven by the receiver oscillator.

2.2.3.3 Reliability Mathematical Model

The reliability of the subsystem, assuming all inputs must function, is simply the product of the reliabilities of the individual subunits. In this case, however, the majority of the TM inputs are of a housekeeping nature, and the loss of any or all of these functions is not detrimental to mission success.

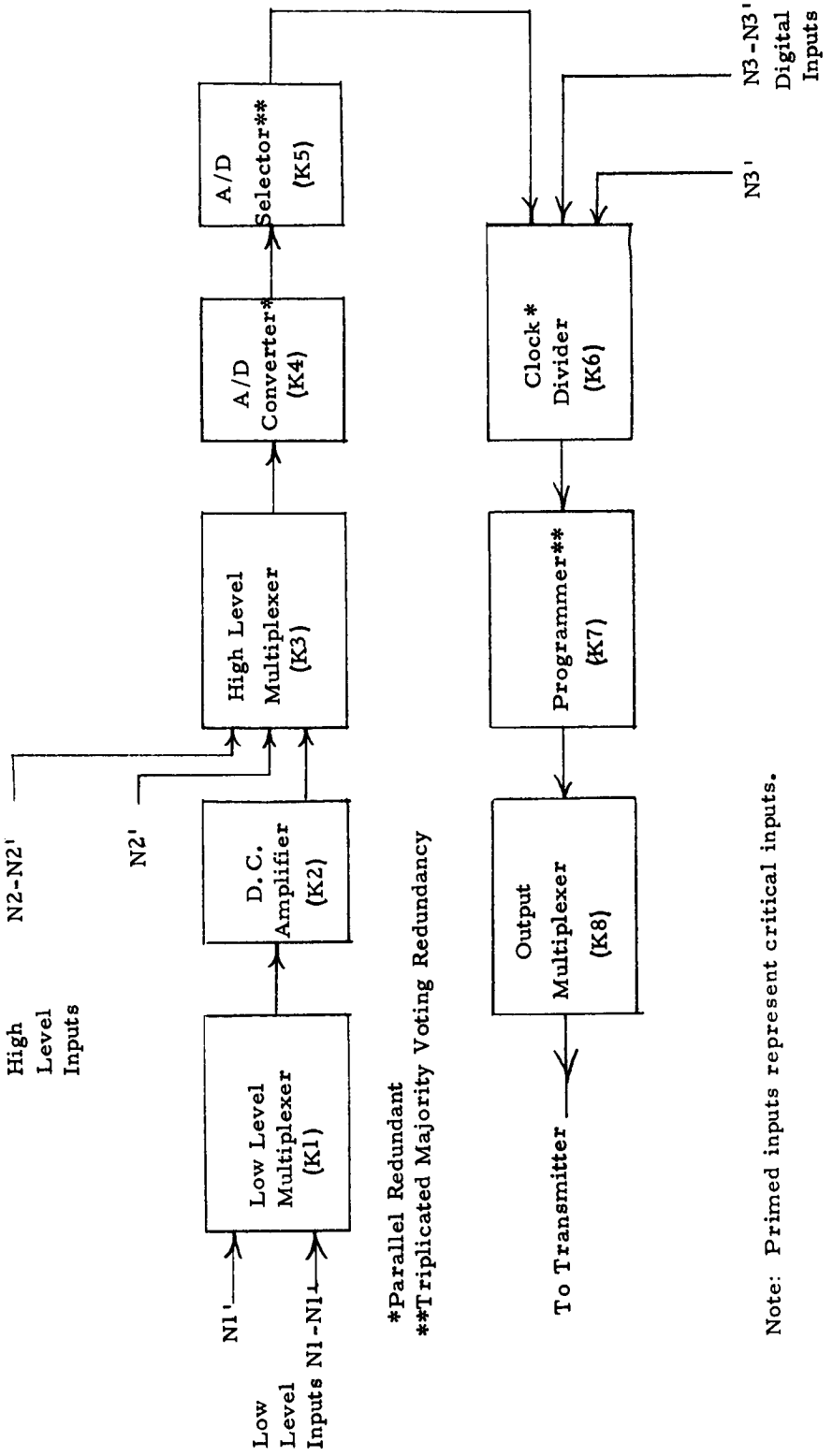

Figure 2.2-12 TM Data-Handling Subsystem Reliability Block Diagram

Preliminary design has indicated that the TM Data Handling Subsystem will have the following inputs:

1. DC Low Level - 12 total - none critical to mission
2. DC High Level - 70 total - four critical to mission
3. Digital - 74 total - four critical to mission.

The resultant subsystem reliability will therefore be:

$$R = K3 \times K4 \times K5 \times K6 \times K7 \times K8$$

where the K's represent the reliability of the various subunits in terms of survival of those inputs critical to the mission. K1 and K2 have been omitted from this equation because they pertain to subunits which handle only low-level inputs, and low-level inputs are not critical to the mission.

The model for this system is developed as described in the ensuing sections.

High Level Multiplexer (K3)

This unit is comprised of a number of analog switches which sequentially connect, upon command from the programmer, one of the high level input signals to a common output bus. To accommodate 70-DC high level signals, 71 analog switches must be provided. The additional switch is required to provide an input line for the low level signals, which have been previously multiplexed.

The analog switch will have a failure rate twice that of a TI micromodule (λ) and the failure mode will be short/open in a 1:1 ratio. The failure rate then, for the four analog switches in the signal paths of the four signals critical to mission success will be

$$\lambda_R = 4 \times (2\lambda) = 8\lambda.$$

However, there are 67 other analog switches in parallel with the output bus, and a short on any of these switches will cause failure. The failure rate caused by this effect will then be

$$\lambda_s = 67\ (2\lambda)\ \frac{1}{2}.$$

The failure rate for the multiplexer will then be

$$\lambda_T = \lambda_R = \lambda_s$$

$$= 8\lambda + 67\lambda = 75\lambda$$

where λ is the failure rate of a TI micromodule.

The multiplexer reliability may now be expressed as

$$K3 = \epsilon^{-75\lambda t} .$$

A/D Converter (K4)

The A/D converters used in this subsystem have an individual component complement of 19 TI modules of failure rate λ, 9 analog switches of failure rate 2λ, 19 resistors of failure rate $\lambda/6$, and one comparator of failure rate 2λ, resulting in a total failure rate per converter of

$$\lambda t = 19\lambda + 9(2\lambda) + 19(\lambda/6) + 2\lambda \approx 42\lambda .$$

An individual converter will then have a reliability of

$$K4' = \epsilon^{-42\lambda t} .$$

However, the subsystem employs two A/D converters in a parallel redundant configuration with a resultant reliability of

$$K4 = \left[1 - \left(1 - K4' \right)^2 \right] .$$

which reduces to

$$K4 = 2\epsilon^{-42\lambda t} - \epsilon^{-84\lambda t} .$$

A/D Selector (K5)

The A/D selector requires ten TI micromodules to implement the required logic functions. However, triplicated majority voting logic is employed.

The equation describing the reliability of this type of redundancy is

$$R = \left[\left(Pg^2 Pf \right)^2 \left(3 - 2 Pg^2 Pf \right) \right]^N$$

where

Pg = reliability of gate function = $\epsilon^{-\lambda t/2}$

Pf = reliability of logic function = $\epsilon^{-\lambda t}$

N = number of logic functions to be implemented

λ = failure rate of TI micromodule.

Substituting

$$R = K5 = \left[\left[\left(\epsilon^{-\lambda t/2} \right)^2 \epsilon^{-\lambda t} \right]^2 \left[3 - 2 \left(\epsilon^{-\lambda t/2} \right)^2 \epsilon^{-\lambda t} \right]^{10} \right]$$

which reduces to

$$K5 = \left(3\epsilon^{-4\lambda t} - 2\epsilon^{-6\lambda t} \right)^{10} .$$

Clock Divider (K6)

The clock for this subsystem is comprosed of two units in a parallel redundant configuration. Each clock is comprised of four TI modules of failure rate λ, one inductor of failure rate 0.95λ, two capacitors with a total failure rate 0.019λ, and one resistor of failure rate 0.068λ. The total failure rate for one clock is

$$\lambda_t = 5.04\lambda$$

and the reliability of a single clock may be written as

$$K6' = \epsilon^{-5.04\lambda t} .$$

The reliability of the redundant combination is

$$K6 = \left[1 - (1 - K6')^2 \right] .$$

Substituting and reducing

$$K6 = 2\epsilon^{-5.04\lambda t} - \epsilon^{-10.08\lambda t} .$$

Programmer (K7)

To facilitate this discussion a block diagram of the programmer is shown in Figure 2.2-13. In this diagram, f_1 through f_n are the row drivers and f_1' through f_m' are the column drivers. Because of their criticality, the preliminary design has provided for triplicated majority voting logic in both row and column drivers.

The crosspoint gates are represented as CG, through CG_{nm} and, because of the relatively large number, no redundancy is provided. The reliability of the programmer may be expressed as the product of the row drivers (R_R), the column drivers (R_C), and the crosspoint gates (R_{CG}).

$$K7 = R_R \cdot R_c \cdot R_{CG}$$

This sytem has 156 total inputs, and will therefore require that there be at least that many crosspoint gates. This programmer, therefore, is provided with a 13 x 13 matrix. This indicates that there are 13 row drivers, 13 column drivers, and 169 crosspoint gates.

The reliability for both row and column drivers may be determined. Triplicated majority rating logic is used, and the resultant reliability for the drivers will be

$$R_R = R_c = (3\epsilon^{-4\lambda t} - 2\epsilon^{-6\lambda t})^{13}$$

Referring to Figure 2.2-12 it is readily apparent that the failure rate of the CG function is that of CG, itself plus the probability that any CG associated (in either row or column) will fail short. Oepn failures in associated CGs have no effect.

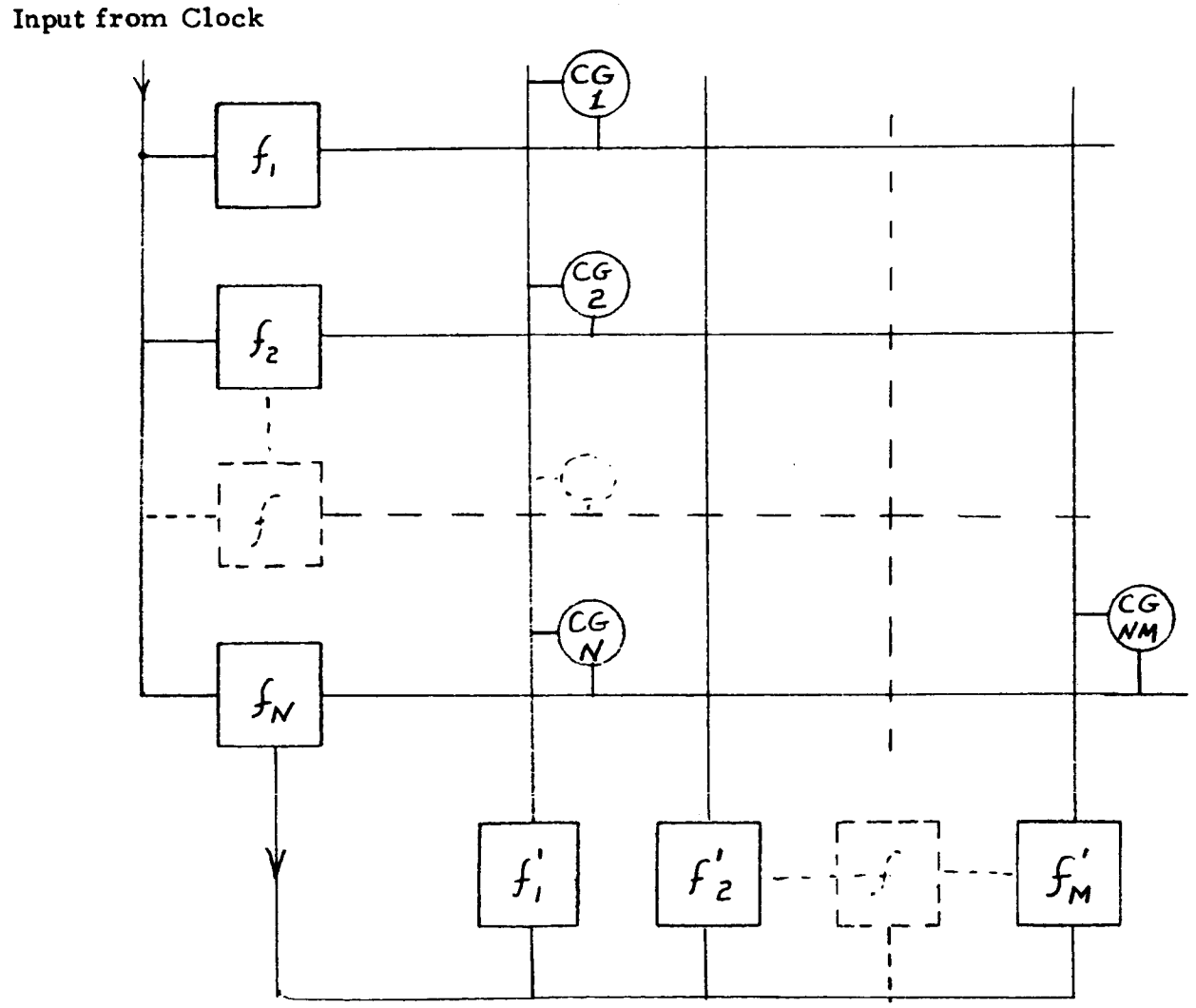

Figure 2.2-13 Programmer Block Diagram

Letting

Failure rate of CG = $\lambda / 2$

$\frac{\text{Fail Short}}{\text{Fail Open}}$ (of CGs) = 3/7

λ = failure rate of TI micromodule

then

$$\text{CG function failure rate} = \lambda/2 + 12(.3)\lambda/2 + 12\left(\frac{.3\lambda}{2}\right) = 4.1\lambda.$$

Because only eight functions are critical to the mission, the CG reliability may be written as

$$R_{CG} = \epsilon^{-8(4.1)\lambda t} = \epsilon^{-32.8\lambda t}.$$

and the total programmer reliability is then

$$K7 = (3\epsilon^{-4\lambda t} - 2\epsilon^{-6\lambda t})^{26} \epsilon^{-32.8\lambda t}.$$

Output Multiplexer (K8)

The output multiplexer is composed of a number of digital gates, one being required for each digital input to the subsystem plus one additional gate to accommodate the output of the A/D converter. Although only five of these gates are in the signal path, the remaining 151 gates are in parallel with the output, and a short in any of these gates will cause system failure. An individual gate is 1/2 of a TI module and will therefore have a failure rate of $\lambda / 2$. The failure ratio short/open is 3/7 as before. The output multiplexer failure rate may be written as

$$\lambda_t = 5\lambda/2 + 151(0.3)\lambda/2 = 25.15.$$

Therefore

$$K8 = \epsilon^{-25.15\lambda t}.$$

The resulting mathematical model for the TM Data Handling System is:

$$R = K3 \times K4 \times K5 \times K6 \times K7 \times K8$$

$$= e^{-75\lambda t}(2e^{-42\lambda t} - e^{-84\lambda t})(3e^{-4\lambda t} - 2e^{-6\lambda t})^{10}$$

$$(2e^{-5.04\lambda t} - e^{-10.08\lambda t})(3e^{-4\lambda t} - 2e^{-6\lambda t})^{26}$$

$$e^{-32.8\lambda t}\, e^{-25.15\lambda t}.$$

2. 2. 3. 4 Reliability Prediction

The TM Data Handling Subsystem Reliability versus time is shown in Table 2. 2-25. This subsystem reliability was determined assuming that there would be twelve low-level DC analog inputs, seventy high-level DC analog inputs, and seventy-four digital inputs. Of the foregoing it is also assumed that there will be four high-level analog inputs critical to the mission and four digital inputs critical to the mission. There will be no low-level analog inputs critical to the mission. Therefore, the overall reliability for the data handling subsystem does not incorporate the reliability of the low level multiplexer or the DC amplifier (they are applicable only to the low level analog signals).

2. 2. 3. 5 Failure Mode Effect and Criticality Analysis

This subsystem comprised a relatively large number (300) of microcircuits employed primarily as a digital logic system. Because logic modules not in the signal path can adversely affect modules in the signal path, the criticality analysis is based separately on the reliability of each individual input function. The results of this analysis are presented in Tables 2. 2-26 through 2. 2-28, and 2. 2-29 through 2. 2-30. The overall function reliability is computed as the product of the reliability of circuitry peculiar to the input function and the reliability of circuitry not peculiar to the input function. A detailed example of the methods used to determine criticality ranking is given in Section 2. 2. 4. 5.

TABLE 2.2-25

TM DATA HANDLING

Item	Reliability 1 Mo.	2 Mo.	3 Mo.	4.5 Mo.	Remarks
Low Level Multiplexer	.9979	.9957	.9936	.9904	These items not included in total reliability because no low level signals are critical to mission.
D.C. Amplifier	.9993	.9987	.9980	.9970	
High Level Multiplexer	.99859	.99833	.99510	.99020	
A/D Converter	.9998	.9996	.9994	.9991	Incorporates parallel redundancy.
A/D Selector	.9999	.9998	.9997	.9996	Incorporates triplicated majority voting logic.
Clock	.99949	.99997	.99995	.99992	Incorporates parallel redundancy.
Programmer	.99328	.99262	.99205	.99150	Incorporates triplicated majority voting logic.
Output Multiplexer	.99660	.99430	.99300	.99200	
Total Reliability	.98820	.98469	.97934	.97258	

TABLE 2.2-26

TM DATA HANDLING SUBSYSTEM (A)

Input Function	Modules in Signal Path Peculiar to Function		Reliability of Circuitry Peculiar to Function	Reliability of Circuitry Not Peculiar to Function	Overall Function Reliability
	Series	Parallel			
Sun Sensor	14	5 1/3	.9917	.9913	.98307
Odometer	4	2	.9976	.9913	.9889
RF TDM Abort	3	4	.9977	.9913	.9890
RR " "	3	4	.9977	.9913	.9890
LF " "	3	4	.9977	.9913	.9890
LR " "	3	4	.9977	.9913	.9890
R Chassis Lock	3	4	.9977	.9913	.9890
L " "	3	4	.9977	.9913	.9890
C " "	3	4	.9977	.9913	.9890
Direct/Omni Ant. Select	3	4	.9977	.9913	.9890
A/D Conv. Select	3	4	.9977	.9913	.9890
Address Decoder Select	3	4	.9977	.9913	.9890
Command Accept/Reject	3	4	.9977	.9913	.9890
Inclinometer	1	69	.9926	.9725	.9653
RF Ranging	1	69	.9926	.9725	.9653
RF TDM Speed	1	69	.9926	.9725	.9653
RR " "	1	69	.9926	.9725	.9653
LF " "	1	69	.9926	.9725	.9653
LR " "	1	69	.9926	.9725	.9653

TABLE 2.2-27

TM DATA HANDLING SUBSYSTEM (B)

Input Function	Modules in Signal Path Pecular to Function		Reliability of Circuitry Pecular to Function	Reliability of Circuitry Not Pecular to Function	Overall Function Reliability
	Series	Parallel			
RF TDM Voltage	1	69	.9926	.9725	.9653
RR " "	1	69	.9926	.9725	.9653
LF " "	1	69	.9926	.9725	.9653
LR " "	1	69	.9926	.9725	.9653
32 ea. Thermal	1	69	.9926	.9725	.9653
Penet. Load Cell	1	69	.9926	.9725	.9653
" Payout Pot.	1	69	.9926	.9725	.9653
" Motor Temp.	1	69	.9926	.9725	.9653
" Probe Tip temp.	1	69	.9926	.9725	.9653
Penet. Housing temp.	1	69	.9926	.9725	.9653
RTG Output Volt.	1	69	.9926	.9725	.9653
Conv. Reg. Input Volts	1	69	.9926	.9725	.9653
Cal. Voltage	1	69	.9926	.9725	.9653
Internal Pressure RTG	1	69	.9926	.9725	.9653
Receiver VCO Cont. Volts	1	69	.9926	.9725	.9653
Receiver AGC Volts	1	69	.9926	.9725	.9653

TABLE 2.2-28

TM DATA HANDLING SUBSYSTEM (C)

Input Function	Modules in Signal Path Pecular to Function		Reliability of Circuitry Pecular to Function	Reliability of Circuitry Not Pecular to Function	Overall Function Reliability
	Series	Parallel			
Receiver Lock-on Signal	1	69	.9926	.9725	.9653
Receiver VCO Output	1	69	.9926	.9725	.9653
TWT Helix Current	1	69	.9926	.9725	.9653
TWT Cathode Current	1	69	.9926	.9725	.9653
TWT Helix Voltage	1	69	.9926	.9725	.9653
TWT Collector Volt.	1	69	.9926	.9725	.9653
TWT Anode Voltage	1	69	.9926	.9725	.9653
TWT Heater Voltage	1	69	.9926	.9725	.9653
Antenna Angle - A3	1	69	.9926	.9725	.9653
" " E1	1	69	.9926	.9725	.9653
RF TDM Current	2	80	.9850	.9596	.9452
RR " "	2	80	.9850	.9596	.9452
LF " "	2	80	.9850	.9596	.9452
LR " "	2	80	.9850	.9596	.9452
RTG Output "	2	80	.9850	.9596	.9452
Conv. Reg. Input Current	2	80	.9850	.9596	.9452
6 Msc. Current	2	80	.9850	.9596	.9452

TABLE 2.2-29

TM DATA HANDLING SUBSYSTEM (D)

Input Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10-3	Criticality Ranking
Sun Sensor	No bearing info.	None	.0179	catastrophic	1.00	17.9	3
Odometer	Loss of range info if not LOS	Use RF Ranging if LOS	.0111	+75%	.50	5.55	6
RF TDM Abort	" "	" "	.0110	0	.01	0.11	9
RR " "	" "	" "	.0110	0	.01	0.11	9
LF " "	Loss of function info	None	.0110	0	.01	0.11	9
LR " "	" "	" "	.0110	0	.01	0.11	9
R Chassis Lock	" "	" "	.0110	0	.01	0.11	9
L " "	" "	" "	.0110	0	.01	0.11	9
C " "	" "	" "	.0110	0	.01	0.11	9
Direct/Omni Ant. Select	" "	" "	.0110	0	.01	0.11	9
A/D Conv. Select	" "	" "	.0110	0	.01	0.11	9
Address Decoder	" "	" "	.0110	0	.01	0.11	9
Select Command Accept/Reject	" "	" "	.0110	0	.01	0.11	9
Inclinometer	No local gravity reference	Use sun sensor	.0347	+63%	.40	13.88	5
RF Ranging	No precision ranging	Use odometer	.0347	+150%	.75	26.03	2

TABLE 2.2-30

TM DATA HANDLING SUBSYSTEM (E)

Input Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
RF TDM Speed			.0347	0	.01	26.03	9
RR " "			.0347	0	.01	26.03	9
LF " "			.0347	0	.01	26.03	9
LR " "			.0347	0	.01	26.03	9
RF " Voltage		None	.0347	0	.01	26.03	9
RR " "			.0347	0	.01	26.03	9
LF " "			.0347	0	.01	26.03	9
LR " "			.0347	0	.01	26.03	9
32 ea. Thermal	No bearing strength meas.	None	.0347	0	1.00	34.7	9
Penet. Load cell	No bearing strength meas.	None	.0347	catastrophic	1.00	34.7	1
" Payout Pot.	No penetrometer extension meas.	Assume penet. constant velocity	.0347	0	.01	0.347	8
" Motor temp.			.0347	0	.01	0.347	8
" Probe Tip Temp.			.0347	0	.01	0.347	8
Penet. Housing temp.			.0347	0	.01	0.347	8
RTG Output volt.			.0347	0	.01	0.347	8
Conv. Reg. Input Volts			.0347	0	.01	0.347	8

2. 2. 3. 6 Reliability Worksheets

The following pages are a number of reliability worksheets pertaining to this subsystem. The quantities shown for the various components are those required for a single subunit. The quantities must be adjusted to reflect any redundancy incorporated in the subunit (e. g., in the case of a parallel redundant subunit, twice as many components will be required as are shown on the worksheet). The subunit failure rates shown are for a totally non-redundant unit and should not be used when redundancy is employed.

2. 2. 3. 7 Conslusions

The criticality analysis described in Section 2. 2. 3. 5 provides a useful tool for the improvement of system reliability. Initial efforts to improve subsystem reliability will be concentrated on those items whose relative criticality ranking is highest. For example, an examination of Tables 2. 2-29 through 2. 2-32 shows that the three most critical input functions to the TM Data Handling Subsystem are:

1. Penetrometer load cell.

2. RF ranging.

3. Sun Sensor.

It is anticipated that future efforts on the Data Handling Subsystem will be directed toward improving the reliability of these input functions. With regard to these specific functions, certain conclusions and recommendations may be determined from the information presented in Tables 2. 2-29 through 2. 2-32.

Penetrometer Load Cell

This input function is first in criticality ranking because of its effect on the mission: soil bearing strength measurements must be made. A failure in this area could be catastrophic.

The input in question is a high-level DC analog voltage and must, therefore, propagate through almost the entire Data Handling Subsystem,

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Clock Divider SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-	SN	Texas			55	80	7	.02641	26	.687		
	circuit		Inst.										
					Note: Triplicated majority voting logic is employed to provide redundancy in the sub-unit, and the total failure rate is presented for information only.								

SUB-UNIT TOTAL FAILURE RATE .687

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Programmer SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-	SN	Texas			55	80	7	.02641	159	4.199		
	circuit		Inst.										

Note: Redundancy, in the form of triplicated majority voting logic is employed in this subsystem, and sub-unit total failure rate is presented for information only.

SUB-UNIT TOTAL FAILURE RATE 4.199

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Output Multiplexer SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro	SN	Texas			55	80	7	.02641	139	3.671		
	circuit		Inst.										

SUB-UNIT TOTAL FAILURE RATE 3.671

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION A/D Converter SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-circuit	SN	Texas Inst.		Logic	55	80	7	.02641	13	.343		
	Resistor	Film				55	50	2	.001	27	.027		
	Capacitor	Glass				55	80	2	.001	4	.004		
	Transistor	Si				55	80	3	.004	8	.032		
	Diode	Si				55	80	2	.003	3	.009		

Note: Two A/D converters will be employed in a parallel redundant configuration and sub-unit total failure rate is shown for information only.

SUB-UNIT TOTAL FAILURE RATE .415

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Low Level Multiplexer & D.C. Amplifier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Integrated Si		National	NS-3000	Switch	55	50	4	.005*	12	.060		*estimated
	Chopper		Semiconductor										
	Resistor	Film				55	80	2	.001	12	.012		
	Transformer		UTC	DI-T37		55	80	4	.01	12	.12		
	Micro-	SN	Texas Inst.		D.C. Amp.	55	80	7	.02641	1	.02641		
	circuit												

SUB-UNIT TOTAL FAILURE RATE .218

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION TM Data Handling Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION High Level Multiplexer SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Integrated		National	NS-3000	Switch	55	80	4	.005*	70	.350		*estimated
	Chopper		Semiconductor										
	Resistor	Film				55	80	2	.001	70	.070		
	Transformer		UTC	DI-T37		55	80	4	.01	70	.70		

SUB-UNIT TOTAL FAILURE RATE 1.120

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

TABLE 2.2-31

TM DATA HANDLING SUBSYSTEM (F)

Input Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Cal. Voltage			.0347	0	.01	0.347	8
Internal Pressure RTG		None	.0347	0	.01	0.347	8
Receiver VCO Cont. volts			.0347	0	.01	0.347	8
Receiver AGC volts			.0347	0	.01	0.347	8
Receiver Lock-on Signal			.0347	0	.01	0.347	8
Receiver VCO Output			.0347	0	.01	0.347	8
TWT Helix current			.0347	0	.01	0.347	8
" Cathode "			.0347	0	.01	0.347	8
TWT Helix voltage			.0347	0	.01	0.347	8
TWT collector volt.			.0347	0	.01	0.347	8
" Anode "			.0347	0	.01	0.347	8
" Heater "			.0347	0	.01	0.347	8
Antenna Angle-A3	Loss of direct-	Use omin	.0347	+100%	.50	17.35	4
" " E1	ional antenna	antenna	.0347	+100%	.50	17.35	4

TABLE 2.2-32

TM DATA HANDLING SUBSYSTEM (G)

Input Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
RF TDM current			.0548	0	.01	0.548	7
RR " "			.0548	0	.01	0.548	7
LF " "			.0548	0	.01	0.548	7
LR " "		None	.0548	0	.01	0.548	7
RTG Output "			.0548	0	.01	0.548	7
Conv. Reg. Input current			.0548	0	.01	0.548	7
6 Msc. current			.0548	0	.01	0.548	7

as contrasted to digital inputs, which pass through about one half as many subunits. If, for example, this measurement could be converted to a digital measurement, its relative criticality ranking could be changed from 1 to perhaps 3 or 4.

RF Ranging

The loss of this function, although not catastrophic, ranks second in criticality ranking. This relatively high ranking is due to the sizable increase in mission time incurred by failure of this function. Also, this function is a DC analog input. The most straightforward method of improving the criticality ranking of this function would be, as in the previous case, to convert to digital format.

Sun Sensor

The sun sensor provides the only bearing information available, and is therefore critical. The high criticality ranking of this input function is due almost entirely to the effect of function failure on the mission and not to the probability of function failure. In a case of this type, where the function is already in digital form (with its attendant high reliability), the most probable method of reducing criticality would be to provide a duplicate input function in the TM Data Handling Subsystem at minimum increase in weight and power.

Considering the relatively high reliability (0.97258) of the TM Data Handling Subsystem, any improvement in this subsystem would provide only a negligible improvement in overall system reliability. Therefore, major reliability effort will be concentrated on subsystems which will result in considerable improvement in the overall system reliability.

2.2.4 Command Subsystem

2.2.4.1 Summary of Parametric Studies.

A reliability parametric study of this subsystem was conducted, the results of which are given in BSR 887, Section 4.4. In this study, the reliability vs temperature, time, and the number of output functions were calculated. Preliminary studies indicated the need for an improvement in over-all reliability. As a result, redundancy has been employed in a number of subunits of this subsystem. It was also determined that an operating temperature of 55°C was consistent with the expected operating environment. These preliminary studies assumed that all logic functions would be implemented with Texas Instrument Co. microcircuits, and all reliability calculations were based upon TI microcircuit failure rates.

2.2.4.2 Functional Description and Block Diagram

The block diagram of the command subsystem is shown in Figure 2.2-14. The function of the command subsystem is to receive coded data from the ground station, decode these data, and convert the decoded data into controlled signals to the proper output decoder for subsequent transmission to the pertinent device (TV subsystem, mobility subsystem, etc.). A preliminary investigation of reliability indicated the need for some redundancy in those elements which are common to all output functions. Therefore, the switch control and address decoder-selector are implemented with triplicated majority voting redundancy, and the address decoder employs parallel redundancy. The three output decoders, because they are not in series with all output functions, are nonredundant in this configuration.

2.2.4.3 Reliability Mathematical Model

The command subsystem is comprised of eight major elements, viz,, receiver, switch control, two address decoders (in a parallel redundant configuration), an address decoder-selector, communications and penetrometer decoder, steering control decoder, and TV decoder. A reliability block diagram of the system is shown in Figure 2.2-14.

This analysis will develop mathematical models for the Command Subsystem.

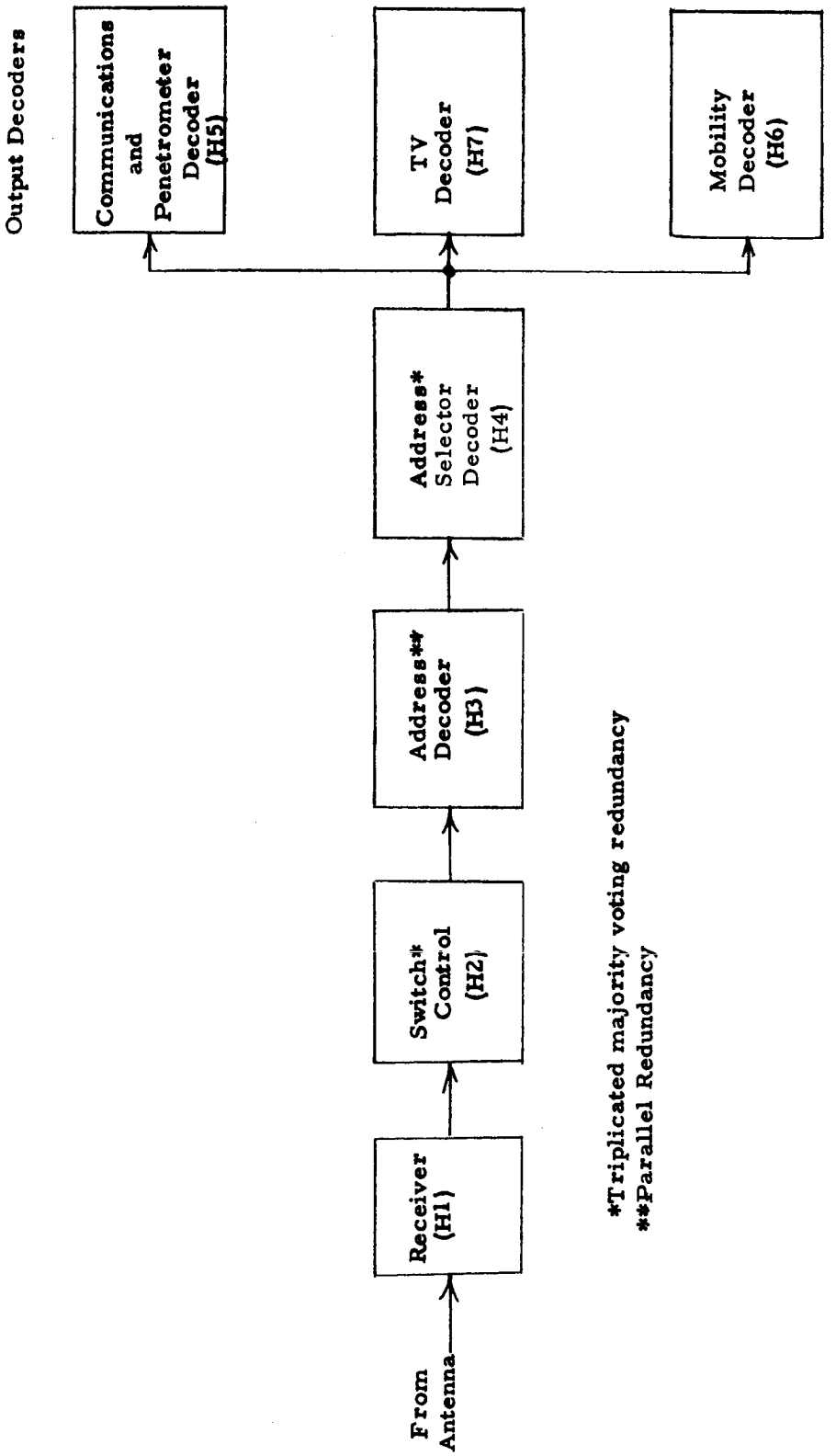

Figure 2.2-14 Command Subsystem Reliability Block Diagram

The basic equation for subsystem reliability is

$$H_t = H_1 \times H_2 \times \left[1-(1-H_3)^2\right] \times H_4 \times H_5 \times H_6 \times H_7 \quad (2.2\text{-}6)$$

where:

H_t = subsystem reliability, assuming all command functions must operate.

H_1 = reliability of receiver

H_2 = reliability of switch control

$\left[1-(1-H_3)^2\right]$ = reliability of parallel redundant address decoder

H_4 = reliability of address decoder selector

H_5 = reliability of communications and penetrometer decoder

H_6 = reliability of steering control decoder

H_7 = reliability of TV decoder.

The individual item reliability calculations are as follows:

Receiver (H_1)

The reliability calculations are based upon a receiver complexity as outlined in LRVP-896 and containing the following items:

Item	Quantity	Failure Rate Designation
Transistor	30	$\lambda 1$
Resistor	102	$\lambda 2$
Capacitor	76	$\lambda 3$

Item	Quantity	Failure Rate Designation
Coil (RF)	17	$\lambda 4$
Crystal	2	$\lambda 5$
Stripline	1	$\lambda 6$
Varactor	2	$\lambda 7$
Diode	4	$\lambda 8$
TI Type SN Module	7	λ

The reliability equation for the receiver may then be written as:

$$H_1 = e^{-(30\lambda_1 + 102\lambda_2 + 76\lambda_3 + 17\lambda_4 + 2\lambda_5 + \lambda_6 + 2\lambda_7 + 4\lambda_8 + 7\lambda)t} \quad (2.2\text{-}6a)$$

High reliability components have failure rates (at 55°C) as shown below, and these failure rates are equated to equivalent TI module failure rates as shown:

$\lambda = 0.02641$

$\lambda_1 = 0.0041 = 0.155\lambda$

$\lambda_2 = 0.0009 = 0.034\lambda$

$\lambda_3 = 0.00025 = 0.009\lambda$

$\lambda_4 = 0.005 = 0.189\lambda$

$\lambda_5 = 0.02 = 0.757\lambda$

$\lambda_6 = 0.001 = 0.038\lambda$

$$\lambda_7 = 0.002 = 0.076\lambda$$

$$\lambda_8 = 0.002 = 0.076\lambda.$$

Substituting these equivalencies into Equation (2.2-6a), the receiver reliability may not be written as

$$H_1 = e^{-21.023\,\lambda t}. \qquad (2.2\text{-}7)$$

Switch Control

The switch control, upon receipt of a command from the receiver, selects one of the two address decoders. In the non-redundant configuration, the switch control will require two TI modules. Because this is an item critical to the operation of the command subsystem, triplicated majority voting redundancy is employed. The equivalent reliability for a unit having triplicated majority voting on input lines may be expressed

$$R = \left[(P_g{}^2 P_f)^2 \ (3-2P_g{}^2 P_f)\right]^N \qquad (2.2\text{-}8)$$

where

P_g = reliability of vote-taking function

P_f = reliability of logic function

N = no. of logic functions to be implemented.

In this case, let

$$P_g = e^{-\lambda t/2}$$

$$P_f = e^{-\lambda t}$$

$$N = 2$$

λ = TI module failure rate.

Substituting these values in Equation (2. 2-8) and reducing, the reliability of the switch control may be expressed as

$$H_2 = (3e^{-4\lambda t} - 2e^{-6\lambda t})^2. \qquad (2.2\text{-}9)$$

Address Decoder

It is assumed that the address decoder will contain 40 TI modules. The equation for the reduant configuration, assuming all modules are necessary for operation, will be

$$H_3 = \left[1 - (1 - e^{-40\lambda t})^2\right] = 2e^{-40\lambda t} - e^{-80\lambda t} \qquad (2.2\text{-}10)$$

Address Decoder Selector

The address decoder selector will probably require 21 TI modules in the nonredundant configuration. Utilizing triplicate majority voting, Equation (2. 2-8) will apply:

$$P_g = e^{-\lambda t/2}$$

$$P_f = e^{-\lambda t}$$

$$N = 21$$

λ = TI module failure rate.

The reliability for the redundant address decoder selector may be expressed as

$$H_4 = \left[3e^{-4\lambda t} - 2e^{-6\lambda t}\right]^{21}. \qquad (2.2\text{-}11)$$

Because the output decoders to be discussed in the following paragraphs are all driven from a common source, it will be assumed that each output decoder will employ some buffering element in each of the eight input lines to reduce the probability of interaction between

decoders in the event of a "short" on an input line. The following three subsections consider the reliability of the output decoders assuming no interaction (i.e., all command functions must operate).

Communications and Penetrometer Decoder

This unit is composed of 36 TI modules to perform the logic functions plus four TI modules as buffers. The math model may then be expressed as

$$H_5 = e^{-40\lambda t}. \qquad (2.2\text{-}12)$$

Steering Control Decoder

This decoder requires 78 TI modules to perform the required logic functions and four additional buffer modules. The resultant reliability is

$$H_6 = e^{-82\lambda t}. \qquad (2.2\text{-}13)$$

TV Decoder

The 16 logic functions of this decoder require 68 TI modules. The four additional modules required for buffering (or isolation) increase the total count to 70, resulting in the equation

$$H_7 = e^{-70\lambda t}. \qquad (2.2\text{-}14)$$

The reliability of the command subsystem may not be written by substituting Equations (2.2-7) and (2.2-9) through (2.2-14) into Equation (2.2-6) as follows:

$$H_t = (e^{-21.0123\lambda t})\,(3e^{-4\lambda t} - 2e^{-6\lambda t})^2 \left[1-(1-e^{-40\lambda t})^2\right] (3e^{-4\lambda t} - 2e^{-6\lambda t})^{21} (e^{-40\lambda t})\,(e^{-82\lambda t})\,(e^{-70\lambda t})$$

$$H_t = (3e^{-4\lambda t} - 2e^{-6\lambda t})^{23} (2e^{-40\lambda t} - e^{-80\lambda t})(e^{-213\lambda t})$$

2.2.4.4 Reliability Prediction

The over-all reliability of the command subsystem may be determined by taking the product of the component reliabilities. If it is assumed that all output functions must survive, the command subsystem reliability will be as shown in Table 2.2-33. It will be noted that the items other than the receiver which incorporate redundancy are extremely reliable, and improvement in over-all subsystem reliability could be best accomplished by providing some measure of redundancy in the output decoders.

The following chart indicates the improvement in the command subsystem reliability that could be realized by providing parallel redundant output decoders.

	Time - Months			
	1	2	3	4.5
Present System	0.9576	0.9153	0.8754	0.8150
Present System + Redundant Comm. & Penetrometer Decoder	.9644	.9282	.8939	.8407
" " + Redundant Mobility Decoder	.9743	.9487	.9229	.8850
" " + Redundant TV Decoder	.9694	.9377	.9075	.8594
All decoders Redundant	.9934	.9857	.9769	.9615

2.2.4.5 Failure Mode, Effect,and Criticality Analysis

The command subsystem incorporates both digital and analog circuitry; therefore, the failure mode and criticality analysis are presented in two sections. The first section pertains to the receiver which is essentially an analog device. Table 2.2-34 shows the results of this analysis on the receiver. The various functions of the receiver, e.g., the IF amplifiers, mixer, limiter, etc., are handled separately. For example, there are 16 bias resistors in the IF amplifiers. These resistors have a component failure rate as shown in the chart, and a failure

TABLE 2.2-33

COMMAND SUBSYSTEM

Item	Reliability 1 Mo.	2 Mo.	3 Mo.	4.5 Mo.	Remarks
Receiver	.9963	.9925	.9889	.9833	
Switch Control	.9998	.9996	.9994	.9992	Incorporates triplicated majority voting logic.
Address Decoder	.9999	.9998	.9995	.9991	Incorporate parallel redundancy.
Address Decoder Selector	.9979	.9958	.9936	.9916	Incorporates triplicated majority voting logic.
Communications & Penetrometer Decoder	.9929	.9859	.9789	.9686	
Steering Control Decoder	.9825	.9635	.9458	.9142	
TV Decoder	.9876	.9755	.9634	.9456	
Total Reliability	.9576	.9153	.8754	.8150	

TABLE 2.2-34(a)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
47MC & 9.5 MC IF Amplifiers	Resis.	Bias	16	.001	Short	--				
					Open	.85	0.272	1.0	.272	5
					Drift	.15	0.048	.01	.00048	65
	Cap.	Coupling	5	.001	Short	.3	0.030	.5	.015	42
					Open	.7	0.07	1.0	.07	17
					Drift	--	--			
	Cap.	Bypass	5	.001	Short	.3	0.030	1.0	.03	32
					Open	.7	0.07	.5	.035	29
					Drift	--	--			
	Cap.	Tuning	5	.001	Short	13	0.03	1.0	.03	32
					Open	.7	0.07	.05	.0035	58
					Drift	--	--			
	Coil RF	Tuning	5	.001	Short	--	--			
					Open	.1	0.05	.2	.01	46
					Drift	.9	0.45	.05	.0225	35
	Trans.	Amp.	5	.004	Short	.1	0.04	.5	.02	38
					Open	.2	0.08	.2	.016	41
					Drift	.7	0.28	.01	.0028	59
MIXER	Resis.	Bias	3	.001	Short	--	--			
					Open	.85	.051	1.0	.051	24
					Drift	.15	.009	.01	.00009	71
	Cap.	Coupling	2	.001	Short	.3	.012	.5	.006	52
					Open	.7	.028	1.0	.028	33
					Drift	--	--			

TABLE 2.2-34(b)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
MIXER	Capacitor	Bypass	1	.001	Short	.3	.006	1.0	.006	52
					Open	.7	.014	.5	.007	51
					Drift	--	--			
	Capacitor	Tuning	1	.001	Short	.3	.006	1.0	.006	52
					Open	.7	.014	.05	.007	51
					Drift	--	--			
	Coil RF	Tuning	1	.005	Short	--	--			
					Open	.1	.01	.2	.002	60
					Drift	.9	.09	.05	.0045	54
	Trans.	Amp.	1	.004	Short	.1	.008	.5	.004	56
					Open	.2	.016	.3	.0048	53
					Drift	.7	.056	.05	.00280	59
Xtal Filter					Open	.2	.08	1.0	.08	15
					Drift	.8	.32	.2	.064	19
9.5 MC Limiter	Resis.	Bias	11	.001	Short	--	--			
					Open	.85	.187	1.0	.187	6
					Drift	.15	.040	.01	.0004	66
	Cap.	Coupling	3	.001	Short	.3	.018	.5	.009	48
					Open	.7	.042	1.0	.042	26
					Drift	--	--			
	Cap.	Tuning	3	.001	Short	.3	.018	1.0	.018	39
					Open	.7	.042	.05	.021	37
					Drift	--	--			

TABLE 2.2-34(c)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
9.5 MC Limiter	Cap.	Bypass	3	.001	Short	.3	.018	1.0	.018	39
					Open	.7	.042	.5	.021	37
					Drift	--	--			
	Coil RF	Tuning	3	.005	Short	--	--			
					Open	.1	.03	.1	.03	32
					Drift	.9	.27	.05	.0135	44
	Trans.	Amp.	3	.004	Short	.1	.024	.5	.012	45
					Open	.2	.048	.2	.0096	47
					Drift	.7	.168	.01	.00168	61
	Diode	Limiter	6	.003	Short	.4	.144	1.0	.144	7
					Open	.2	.072	.05	.0036	57
					Drift	.4	.144	.01	.00144	62
9.5 MC Phase Det.	Resis.	Bias	6	.001	Short	--	--			
					Open	.85	.102	1.0	.102	12
					Drift	.15	.018	.01	.00018	69
	Cap.	Coupling	2	.001	Short	.3	.012	.5	.006	52
					Open	.7	.028	1.0	.028	33
					Drift	--	--			
	Cap.	Bypass	2	.001	Short	.3	.012	1.0	.012	45
					Open	.7	.028	.5	.014	43
					Drift	--	--			

TABLE 2.2-34(d)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
9.5 MC Phase Det.	Coil RF	Coupling & Tuning	2	.01	Short	--	--			
					Open	.1	.04	1.0	.04	27
					Drift	.9	.36	.05	.018	39
	Trans.	Amp.	2	.004	Short	.1	.016	1.0	.016	41
					Open	.2	.032	1.0	.032	31
					Drift	.7	.112	.02	.0022	60
	Diode	Demod.	4	.003	Short	.4	.096	1.0	.096	14
					Open	.2	.048	1.0	.048	25
					Drift	.4	.096	.1	.0096	47
9.5 MC VCO & 9.5 MC Buffer	Resis.	Bias	8	.001	Short	--	--			
					Open	.85	.136	1.0	.136	9
					Drift	.15	.024	.01	.00024	68
	Cap.	Coupling	5	.001	Short	.3	.03	.5	.015	42
					Open	.7	.07	1.0	.07	17
					Drift	--	--			
	Cap.	Tuning	2	.001	Short	.3	.012	1.0	.012	45
					Open	.7	.028	.5	.014	43
					Drift	--	--			
	Cap.	Bypass	1	.001	Short	.3	.006	.7	.0042	55
					Open	.7	.014	.4	.0056	52
					Drift	--	--			

TABLE 2.2-34(e)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10-5	Failure Mode	Failure Mode Ratio	Probability of Failure x 10-3	Mission Degradation	Combined Product x 10-3	Criticality Ranking
9.5 MC VCO & 9.5 MC Buffer	Crystal	Osc.	1	.02	Open	.2	.08	1.0	.08	15
					Drift	.8	.32	.4	.128	10
	Trans.	Amp.	3	.004	Short	.1	.024	1.0	.024	34
					Open	.2	.048	1.0	.048	25
					Drift	.7	.168	.05	.0084	49
	Coil RF	Tuning	2	.005	Short	--	--			
					Open	.1	.02	1.0	.02	38
					Drift	.9	.18	.05	.009	48
	Thermistor	Comp.	1	.03	Short	--	--			
					Open	.1	.06	1.0	.06	20
					Drift	.9	.54	.1	.054	23
9.5 to 342 MC Multiplier Chain	Resis.	Bias	4	.001	Short	--	--			
					Open	.85	.068	1.0	.068	18
					Drift	.15	.012	.01	.0012	63
	Cap.	Coupling	4	.001	Short	.3	.024	1.0	.024	34
					Open	.7	.056	1.0	.056	22
					Drift	--	--			
	Cap.	Fixed Tuning	8	.001	Short	.3	.048	1.0	.048	25
					Open	.7	.112	1.0	.112	11
					Drift	--	--			
	Cap.	Variable Tuning	4	.007	Short	--	--			
					Open	1.0	.560	1.0	.560	4
					Drift	--	--			

TABLE 2. 2-34(f)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
9.5 to 342 MC Multiplier Chain	Cap.	Bypass	1	.001	Short	.3	.006	.02	.00012	70
					Open	.7	.014	.02	.00028	67
					Drift	--	--			
	Coil RF	Tuning	14	.005	Short	--	--			
					Open	.1	.140	1.0	.140	8
					Drift	.9	1.26	1.0	1.26	3
	Trans.	Amp.	4	.004	Short	.1	.032	1.0	.032	31
					Open	.2	.064	1.0	.064	19
					Drift	.7	.224	.1	.0224	36
Microwave Stripline Section	Stripline		1	.01	Short	.5	.10	1.0	.10	13
					Open	.5	.10	1.0	.10	13
	Diode	Mult. & Mix	3	.003	Short	.4	.072	1.0	.072	16
					Open	.2	.036	1.0	.036	28
					Drift	.4	.072	.1	.0072	50
	Coil RF	Coupling & Tuning	1	.01	Short	--	--			
					Open	.1	.02	1.0	.02	38
					Drift	.9	.18	.05	.0090	48
Logic Section	Resis.	Coupling & Filter	34	.001	Short	--	--			
					Open	.85	.578	1.0	.0578	21
					Drift	.15	.102	.01	.00102	64

TABLE 2.2-34(g)

COMMAND SUBSYSTEM - RECEIVER

Stage	Component	Function	Quantity	Component Failure Rate x 10^{-5}	Failure Mode	Failure Mode Ratio	Probability of Failure x 10^{-3}	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Logic Section	Cap.	Coupling & Filter	20	.001	Short	.3	.120	.5	.060	20
					Open	.7	.280	.5	.140	8
					Drift	--	--			
	Diode	Clamp.	7	.003	Short	.4	.168	.1	.0168	40
					Open	.2	.084	.4	.0336	30
					Drift	.4	.168	.1	.0168	40
	Trans.	Amp.	3	.004	Short	.1	.024	1.0	.024	34
					Open	.2	.048	1.0	.048	25
					Drift	.7	.168	.01	.00168	61
	Micro-circuit	Amp.	11	.0264	Short	.3	1.742	1.0	1.742	2
					Open	.7	4.066	1.0	4.066	1
					Drift	--	--			

mode as shown in column 6. The probability of failure in a given mode is determined by multiplying the quantity of the component by its associated failure rate and the ratio of the specific failure mode under consideration. This probability of failure is determined assuming 2000 hours of operation. The next column, "mission degradation", represents the best assessment of the effect on the mission of the failure of a specific component in the mode being considered. The next column indicates the combined product of "mission degradation" and "probability of failure." The last column provides a rank of the combined product such that one will be able to assess the relative criticality of the specific components in the receiver in a specific failure mode.

The remainder of the subsystem, exclusive of the receiver, is treated as a digital logic system, and the data pertaining to this portion of the subsystem are shown in Tables 2.2-35 and 2.2-36.

To provide a meaningful failure mode analysis and to properly assess the criticality of the various logic modules, the relative subsystem reliability has been calculated for each of the output functions independently. This approach was taken because a given signal path is affected by modules not in the signal path, due to the configuration of the logic. Additionally, there are approximately 300 modules incorporated in the subsystem, and these modules are not readily identified by function or nomenclature.

The information pertaining to the communications and penetrometer functions are contained in Tables 2.2-35(a) and 2.2-36(a). Information pertinent to the TV decoder is in Tables 2.2-35(b), 2.2-36(b), and 2.2-36(c); information pertinent to the mobility decoder is provided in Tables 2.2-35(c and d) and 2.2-36(d and e).

To best explain the method used in the determination of the criticality ranking, an example is presented showing the methods used. Referring to the output function "select omniantenna", it may be seen from Table 2.2-35(a) that there are eight series modules in the signal path peculiar to the function and 19 parallel modules. This situation is illustrated in Figure 2.2-15, where F (1) through F (8) show the eight series modules in the path of the specific output function. F' (1) through F' (19) show the 19 modules which may be considered to be in parallel with the output function. Inasmuch as the entire logic system is

TABLE 2. 2-35(a)

COMMAND SUBSYSTEM

Output Function	Modules in Signal Path Peculiar to Function		Reliability of Circuitry Peculiar to Function	Reliability of Circuitry Not Peculiar to Function	Overall Function Reliability
	Series	Parallel			
Select Omni Ant.	8	19	.9924	0.9848	.9773
Select Direct Ant.	8	19	.9924	0.9848	.9773
Ant. Az. Right	13	22	.9895	0.9848	.9745
Ant. Az. Left	13	22	.9895	0.9848	.9745
Ant. Elevation Up	13	22	.9895	0.9848	.9745
Ant. Elevation Down	13	22	.9895	0.9848	.9745
Normal TM out.	8	20	.9923	0.9848	.9772
Penetrometer TM out.	8	20	.9923	0.9848	.9772
TV TM out.	8	20	.9923	0.9848	.9772
A/D Conv. "A"	8	22	.9922	0.9848	.9771
A/D Conv. "B"	8	22	.9922	0.9848	.9771
TWT heater ON	8	20	.9923	0.9848	.9772
TWT heater OFF	8	20	.9923	0.9848	.9772
TWT HV ON	8	20	.9923	0.9848	.9772
TWT HV OFF	8	20	.9923	0.9848	.9772
Start Penetrometer Motor	7	18	.9931	0.9848	.9780
Stop " "	7	18	.9931	0.9848	.9780
Fire " Squib.	7	18	.9931	0.9848	.9780

TABLE 2.2-35(b)

COMMAND SUBSYSTEM

Output Function	Modules in Signal Path Pecular to Function		Reliability of Circuitry Pecular to Function	Reliability of Circuitry Not Pecular to Function	Overall Function Reliability
	Series	Parallel			
Open Iris	6	20	.9933	0.9848	.9782
Close Iris	6	20	.9933	0.9848	.9782
Turret CW	6	20	.9933	0.9848	.9782
Turret CCW	6	20	.9933	0.9848	.9782
Exp. Time, Manual	10	25	.9904	0.9848	.9753
Shutter, Auto	8	21	.9921	0.9848	.9770
Shutter, Manual	8	21	.9921	0.9848	.9770
Shutter Seq., Manual	9	21	.9915	0.9848	.9764
Camera Az. Right	8	24	.9916	0.9848	.9765
Camera Az. Left	8	24	.9916	0.9848	.9765
Camera El, Up	8	24	.9916	0.9848	.9765
Camera El, Down	8	24	.9916	0.9848	.9765
512 lines + 4 bits	8	20	.9923	0.9848	.9772
256 lines + 2 bits	8	20	.9923	0.9848	.9772
Roberts Gen. Enable	8	20	.9923	0.9848	.9772
Roberts Gen. Inhibit	8	20	.9923	0.9848	.9772
Video Control (Gain)	10	20	.9912	0.9848	.9761
" " "	10	20	.9912	0.9848	.9761
" " "	10	20	.9912	0.9848	.9761
Non-linear Inserts ON	8	20	.9923	0.9848	.9772
" " " OFF	8	20	.9923	0.9848	.9772
" " " Select	8	20	.9923	0.9848	.9772
" " " "	8	20	.9923	0.9848	.9772
Erase	6	20	.9933	0.9848	.9772

TABLE 2.2-35(c)

COMMAND SUBSYSTEM

Output Function	Modules in Signal Path Pecular to Function		Reliability of Circuitry Pecular to Function	Reliability of Circuitry Not Pecular to Function	Overall Function Reliability
	Series	Parallel			
Stop	5	1	.9972	0.9848	.9820
Manual N3 TDM1	7	25	.9924	0.9848	.9773
Manual N3 TDM2	7	25	.9924	0.9848	.9773
Manual N3 TDM3	7	25	.9924	0.9848	.9773
Manual N3 TDM4	7	11	.9946	0.9848	.9795
Manual N2 TDM1	7	25	.9924	0.9848	.9773
Manual N2 TDM2	7	25	.9924	0.9848	.9773
Manual N2 TDM3	7	25	.9924	0.9848	.9773
Manual N2 TDM4	7	25	.9924	0.9848	.9773
Manual Rev. TDM3	7	25	.9924	0.9848	.9773
Manual Rev. TDM4	7	25	.9924	0.9848	.9773
Abort TDM1	7	25	.9924	0.9848	.9773
Abort TDM2	7	25	.9924	0.9848	.9773
Abort TDM3	7	25	.9924	0.9848	.9773
Abort TDM4	7	25	.9924	0.9848	.9773
Auto Right	7	11	.9946	0.9848	.9795
Auto Left	7	11	.9946	0.9848	.9795
Auto Straight	7	11	.9946	0.9848	.9795
Forward	7	14	.9941	0.9848	.9790
Reverse	7	14	.9941	0.9848	.9790

TABLE 2.2-35(d)

COMMAND SUBSYSTEM

Output Function	Modules in Signal Path Pecular to Function		Reliability of Circuitry Pecular to Function	Reliability of Circuitry Not Pecular to Function	Overall Function Reliability
	Series	Parallel			
Manual Lock	7	25	.9924	0.9848	.9773
Manual Unlock	7	25	.9924	0.9848	.9773
Manual Reverse RDM1	7	11	.9946	0.9848	.9795
Manual Reverse TDM2	7	11	.9946	0.9848	.9795
Manual Go	7	13	.9943	0.9848	.9792
Override, Manual	7	14	.9941	0.9848	.9790
Override, Auto	7	14	.9941	0.9848	.9790

TABLE 2.2-36(a)

COMMAND SUBSYSTEM

Output Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Select Omni Ant.	No Omni Ant.	Use direct Ant.	.0227	+200%	.75	17.02	5
Select direct Ant.	No direct Ant.	Use Omni Ant.	.0227	+100%	.50	11.35	7
Ant. Az. Right	No Ant. Az.	Slew Vehicle	.0254	+50%	.40	10.16	9
Ant. Az. Left	Control	for Azimuth	.0254	+50%	.40	10.16	9
Ant. Elevation Up	No Antenna	Use Omni Ant.	.0254	+100%	.50	12.70	6
" " Down	elevation control	↓	.0254	+100%	.50	12.70	6
Normal TM out.	No Normal TM	None	.0228	catas.	1.00	22.8	2
Penet. TM out.	No Penet. TM	None	.0228	catas.	1.00	22.8	2
TV TM out.	no TV TM	None	.0228	catas.	1.00	22.8	2
A/D Conv. "A"	No "A" A/D conv.	Use "B" A/D Conv.	.0229	0	0	0	18
A/D Conv. "B"	" "B" " "	Use "A" A/D Conv.	.0229	0	0	0	18
TWT heater ON	No TWT	None	.0228	catas.	1.00	22.8	2
TWT heater OFF	TWT on continuously	None	.0228	0	.03	0.68	15
TWT HV ON	No TWT	None	.0228	catas.	1.00	22.8	2
TWT HV OFF	TWT HV on continuously	None	.0228	0	0	0	18
Start Penet. Motor	No. Penet. meas.	None	.0220	catas.	1.00	22.0	3
Stop " "	Lose	None	.0220	0	0	0	18
Fire " Squib.	Function	None	.0220	0	0	0	18

TABLE 2.2-36(b)

COMMAND SUBSYSTEM

Output Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Open Iris	No Iris	Operate at f:22	.0218	0	0	0	18
Close Iris	Control	" " f:7	.0218	+20%	.40	08.72	13
Turret CW	No Control of	Operate at 10°FOV	.0218	+100%	.50	10.90	8
Turret CCW	focal length	" " 50° "	.0218	+25%	.40	08.72	13
Exp. Time, Manual	No Manual Shutter	Use Auto Shutter	.0247	0	0	0	18
Shutter, Auto	No Auto Shutter	Use Manual "	.0230	0	0	0	18
Shutter, Manual	No Manual "	Use Auto "	.0230	0	0	0	18
Shutter Seq. Man.			.0236	0	0	0	18
Camera Az. Right	Unable to	Slew Vehicle	.0235	catas.	1.00	23.5	1
" " Left	Pan Camera	for pan	.0235	catas.	1.00	23.5	1
Camera El, Up	No camera	None	.0235	+50%	.40	09.40	11
" ", Down	elevation control	↓	.0235	+50%	.40	09.40	11
512 Lines + 4 bits	No 512 line pix	Use 256 line pix	.0228	+50%	.40	09.12	12
256 linex + 2 bits	" 256 " "	" 512 " "	.0228	0	0	0	18
Roberts Gen. Enable	No Roberts Gen	None	.0228	0	0	0	18
" " Inhibit	continuous Roberts Gen.	None	.0228	0	0	0	18
Video Control (Gain)	No Gain	Operate at	.0239	+20%	.40	9.56	10
Videao Control (Gain)	Control	fixed gain	.0239	+20%	.40	9.56	10
Video Control (Gain)	↓	↓	.0239	+20%	.40	9.56	10

TABLE 2.2-36(d)

COMMAND SUBSYSTEM

Output Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Non-Linear Inserts ON	No contrast control	None	.0228	+20%	.40	9.12	12
" " " OFF	Non-linear inserts in continuously	Select best contrast	.0228	0	0	0	18
" " " Select	No contrast	Switch out	.0228	+20%	.40	9.12	12
" " " "	control	non-linear inserts	.0228	+20%	.40	9.12	12
Erase	No Manual Erase	Use Auto Erase	.0228	0	0	0	18

TABLE 2.2-36(d)

COMMAND SUBSYSTEM

Output Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Stop	Unable to stop vehicle	None	.0180	catas.	1.00	1.80	4
Manual N3 TDM1		Operate	.0227	0	0	0	18
" " " 2	Lose	at N_1 or	.0227	0	0	0	18
" " " 3	Function	N_2	.0227	0	0	0	18
" " " 4	↓	↓	.0215	0	0	0	18
Manual N2 TDM1		Operate	.0227	0	0	0	18
" " " 2	Lose	at N_1 or	.0227	0	0	0	18
" " " 3	Function	N_3	.0227	0	0	0	18
" " " 4	↓	↓	.0227	0	0	0	18
Manual Rev. TDM3	Lose	None	.0227	0	0	0	18
" " " 4	Function	↓	.0227	0	0	0	18
Abort TDM1	↓	↓	.0227	0	0	0	18
" " 2	Lose	None	.0227	0	0	0	18
" " 3	Function	↓	.0227	0	0	0	18
" " 4	↓	↓	.0227	0	0	0	18
Auto Right	Lose	Revert to	.0205	+2%	.01	0.205	17
Auto Left	Auto	Manual	.0205	+2%	.01	0.205	17
Auto Straight	Mode	Mode	.0205	+2%	.01	0.204	17
Forward	Lose Forward vehicle motion	Operate vehicle reverse only	.0210	+25%	.40	8.40	14
Reverse	Lose Auto Rev.	Use Man. Mode	.0210	+2%	.01	0.21	16
Manual Lock	Lose Manual	Use Auto	.0227	0	0	0	18
" Unlock	Mode	Mode	.0227	0	0	0	18

TABLE 2.2-36(e)

COMMAND SUBSYSTEM

Output Function	Effect of Failure	Possible Remedial Action	Probability of Function Failure	Effect of Function Failure on Mission Time	Mission Degradation	Combined Product x 10^{-3}	Criticality Ranking
Manual Rev. TDM1	Lose	None	.0205	0	0	0	18
" " " 2	Function	↓	.0205	0	0	0	18
Manual Go	No Manual Mode	Use Auto Mode	.0208	0	0	0	18
Override, Manual	Lose	Use Auto Mode	.0210	0	0	0	18
" Auto	Function	Use Man. Mode	.0210	0	0	0	18

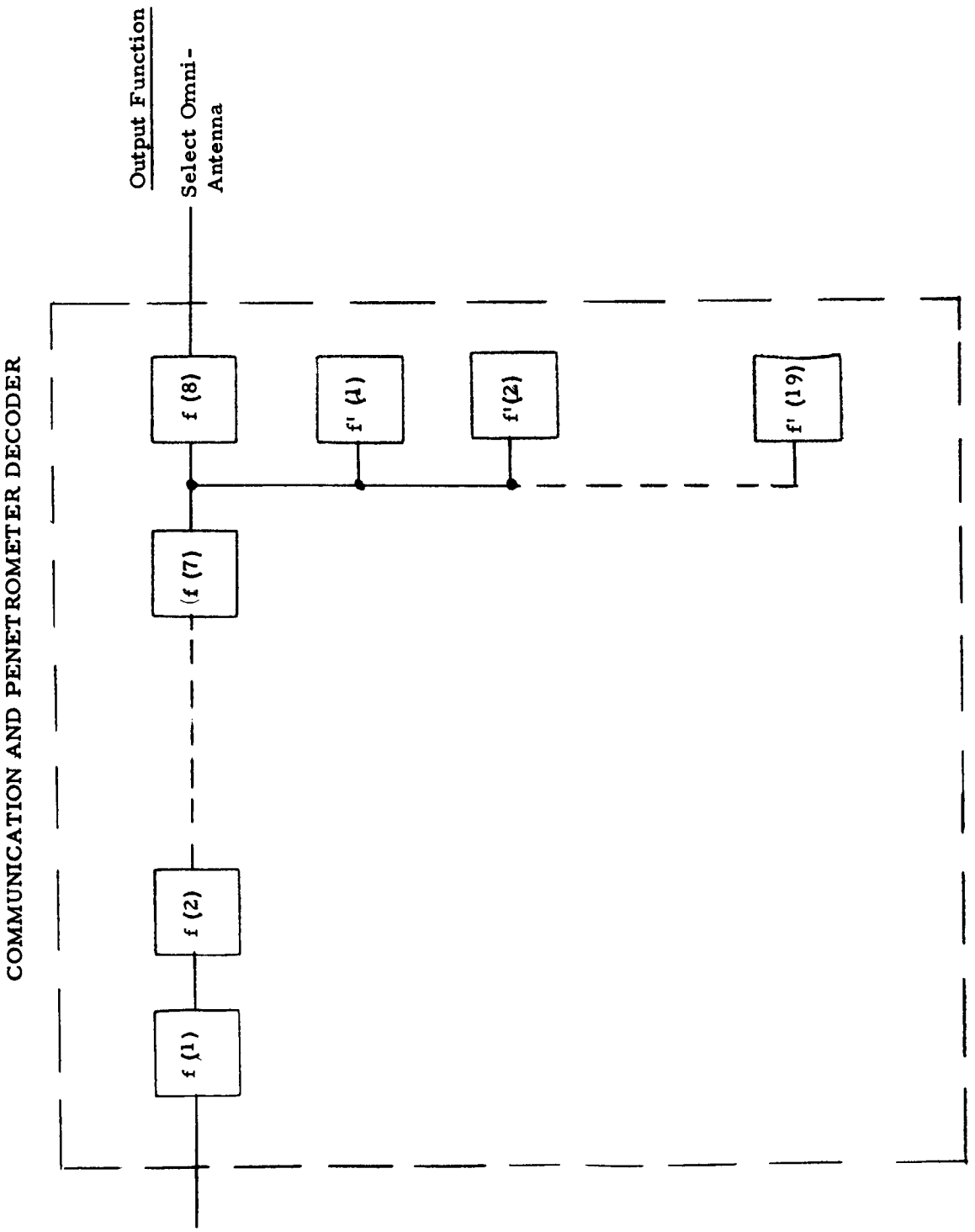

Figure 2.2-15 Communication and Penetrometer Decoder

implemented with Texas Instrument micromodules and both the total failure rate and the ratio of short-to-open failures are known, the reliability of the circuitry peculiar to this function may be written as:

$$R = e^{-(8\lambda + 0.3 \times 19\lambda)t}$$

where λ = failure rate of TI micromodule and $\frac{3}{7}$ = failure mode ratio $\frac{\text{short}}{\text{open}}$ of TI micromodule.

This then represents the reliability of the communications and penetrometer decoder with respect to the selected output function. The next item on the chart refers to the reliability of the circuitry not peculiar to the function. This would be the product of the reliability of the receiver, the switch control, address decoder, and address decoder-selector. The over-all function reliability will then be the product of the reliability of this circuitry, not peculiar to the function, times the reliability of the circuitry peculiar to the function; i.e., the series and parallel modules in the communications and penetrometer decoder. Turning now to Table 2.2-36(a) we see that the output function "select omniantenna" is listed, and the effect of this failure (no omniantenna) follows immediately. The possible remedial action in this situation would be to use the direct antenna. The probability of function failure will be equal to one minus the over-all function reliability as shown in Table 2.2-35(a). The next column "defective function failure on mission time" represents the best estimate to date of the probable over-all effect on the mission of the loss of this specific output function, assuming that any possible remedial action will be taken. The next column, "mission degradation", represents the best estimate as to the mission degradation incurred by the required additional mission time. The next column, "combined product times 10^{-3}", represents the product of "probability of function failure" times "mission degradation." This combined product is representative of the relative effect of any output function on a mission combined with its probability of failure. This combined product is then ranked, and the rank order is shown in the last column, "criticality ranking", wherein we have established the rank order of the combined product and thus indicated the relative criticality of the various output functions.

2.2.4.6 Reliability Worksheets.

Following on p. 2-186 are the reliability worksheets for this subsystem. The quantities shown for the various components are those required for a

single subunit. In the case where redundancy is employed, the quantities should be adjusted (e. g. , for parallel redundant elements, twice the indicated quantity will be required). It should also be noted that the total failure rate shown is that of a nonredundant system and is not applicable to any element incorporating redundancy.

2. 2. 4. 7 Conclusions

An examination of Tables 2. 2-35 and 2. 2-36 will provide an indication of the criticality ranking of the various output functions of the command subsystem. It will be noted that, by and large, all output functions have the same over-all probability of failure, and the primary reason for the relative criticality is the effect of a given function failure on mission time.

That portion of the command subsystem common to all output functions employs considerable redundancy, but the three output decoders are totally nonredundant. Following is a list of those output functions which are in the first four criticality ranks and a reference as to which of the output decoders provides the function:

Criticality Rank	Function	Output Decoder
1	Camera Az, Right	TV
1	Camera Az, Left	TV
2	Normal TM out	Communications and Penetrometer
2	Penetrometer TM out	Communications and Penetrometer
2	TV TM out	Communications and Penetrometer
2	TWT heater ON	Communications and Penetrometer

Criticality Rank	Function	Output Decoder
2	TWT HV ON	Communications and Penetrometer
3	Start penetrometer motor	Communications and
4	Stop	Mobility

The format of these commands and the number of circuit elements required for execution will be quite difficult to change. Therefore, other means of improving reliability should be considered.

One attractive approach which seems worthy of consideration is to employ parallel redundancy in all three output decoders. This approach will increase the over-all subsystem reliability at 4.5-months duration from the present 81.5% to 96% at the expense of about 1/4 lb.

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Command Subsystem SCHEMATIC No. ____ REV. ____ DATE ____

SUB-UNIT DESIGNATION TV Decoder SCHEMATIC No. ____ REV. ____ DATE ____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-	SN	Texas			55	80	7	.02641	52	1.373		
	circuit		Inst.										

SUB-UNIT TOTAL FAILURE RATE 1.373

SUB-UNIT MTBF (HOURS) ____

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Command Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Switching Control SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro	SN	Texas			55	80	7	.02641	40	1.056		
	circuit		Inst.										

Note: Redundancy in the form of triplicated voting is employed in this sub-unit, and the total failure rate is presented for information only.

SUB-UNIT TOTAL FAILURE RATE 1.056

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Command Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Communications and Penetrometer Decoder SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro	SN	Texas			55	80	7	.02641	53	1.400		
	circuit		Inst.										

SUB-UNIT TOTAL FAILURE RATE 1.400

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Command Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Mobility Decoder SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-	SN	Texas		Logic	55	80	7	.02641	59	1.558		
	circuit		Inst.										

SUB-UNIT TOTAL FAILURE RATE 1.558

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Command Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Address Decoder SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING % *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	micro-	SN	Texas		Logic	55	80	7	.02641	49	1.299		
	circuit		Inst.										

Note: Two address decoders will be employed in a parallel redundant configuration and sub-unit total failure rate is presented for information only.

SUB-UNIT TOTAL FAILURE RATE 1.299

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

RELIABILITY PREDICTION WORI SHEET

UNIT DESIGNATION Command Sub-system SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Command Receiver SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PAR DERA INC %	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Resistor	Film				55	50	2	.001	83	.083	TRW 873-74	
	Capacitor	Glass					80	2	.001	75	.075		
	Capacitor	Variable					80	2	.007	8	.056		
	Coil,RF						80	2	.005	25	.125		
	Coil,RF						80	4	.010	3	.030		
	Thermistor						20	2	.030	1	.030		
	Diode	Si.					80	7	.003	18	.054		
	Transistor	Si.					80	3	.004	21	.084		
	Microcircuit	SN	Texas Inst.		Amplifier		80	7	.02641	11	.290	TI	
	Stripline							1	.01	1	.01		a priori
	Antenna								.04	1	.04		
	Xtal Filter								.02	2	.04		

SUB-UNIT TOTAL FAILURE RATE 0.917

SUB-UNIT MTBF (HOURS) 109,000

*INDICATE ESTIMATED OR ACTUAL

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2.3 EXPERIMENT (PENETROMETER)

This section is a summary of work carried out on the systems assurance task for the SLRV penetrometer subsystem. The systems assurance task consists of the following five major areas of effort:

1. Component Reliability Characteristics and Parametric Studies
2. Failure Mode and Criticality Analysis
3. Reliability Block Diagram and Mathematical Model
4. Reliability Prediction
5. Parts Selection Program.

The reliability studies have been directed to emphasize lunar operation of the penetrometer subsystem based upon the penetrometer concept and design and reflected in the penetrometer engineering test model (ETM). Thus, the reliability studies contained herein are not a reliability evaluation of the ETM itself, the main purpose of which is to demonstrate the operation and feasibility of the IITRI penetrometer concept. Rather, it is an initial evaluation of the expected lunar performance of the penetrometer concept with the ETM providing the basic design inputs. This reliability study then reflects any adaptation of the penetrometer concept, as contained in the ETM, and any design and engineering considerations which must be made to obtain satisfactory lunar operation.

2.3.1 Component Reliability Characteristics and Parametric Studies

This section considers the basic reliability characteristics of the various parts and units making up the penetrometer subsystem. The applicability of particular designs or part types for a lunar mission from a reliability standpoint is discussed when necessary, and parametric representations of performance are indicated where available data allow.

2.3.1.1 Electrical-Electronic Subassemblies

There are four principal areas in the SLRV penetrometer subsystem in which electrical-electronic parts and components find application. These applications are in the: (1) LVDT (linear variable differential transformer)

which is used as the force measurement transducer, (2) switching circuitry, (3) drive motor, and (4) penetration depth measurement. The reliability factors for each will now be considered.

LVDT Unit

The LVDT unit being considered for the penetration force measurement is a DC input and output device, consisting of a self-contained electronics package for conversion and demodulation, and the differential transformer. The unit being employed in the ETM and upon which the present parametric analysis is based, (G. L. Collins Model SS-203), is a transducer designed for commercial application; with appropriate modification, it is capable of meeting the high reliability requirements for lunar vehicle application. The rated operating temperature range of the present unit is $-54^{\circ}C$ to $+121^{\circ}C$, which compares favorably with the possible range of lunar surface temperatures ($-173^{\circ}C$ to $+127^{\circ}C$), although operating restrictions do at present appear for the low temperature range.

The basic parametric study for the LVDT unit considers the failure rate as a function of the ambient operating temperature over a range of possible lunar operating temperatures. The parametric studies carried out for the LVDT have considered the use of failure rates for standard military electronic parts.[1] Table 2.3-1 indicates the failure rates applies to the various parts and the complete LVDT unit at three representative temperatures.

The following assumptions were made in the use of failure rate data for Table 2.3-1:

1. In power dissipating parts, the operating level is at 0.1 the power rating.

2. Capacitors are operated at 0.3 of rated voltage.

3. Class H insulation is utilized in the transformer with a 180° rating.

4. In the establishment of the device failure rate, all parts are considered to be in series.

[1] RADC Reliability Notebook, RADC-TR-58-111.

TABLE 2.3-1

LVDT FAILURE RATES

Part Type	Number in LVDT	Failure Rates - %/1000 hours					
		Part F.R. 0°C	Total F.R. 0°C	Part F.R. 100°C	Total F.R. 100°C	Part F.R. 125°C	Total F.R. 125°C
Resistors (Carbon Composition)	6	0.001	0.006	0.008	0.048	0.045	0.270
Transistors (Silicon)	2	0.02	0.04	0.036	0.072	0.2	0.4
Diodes (Silicon)	8	0.01	0.08	0.018	0.144	0.1	0.8
Capacitors (Solid Tantalum)	2	0.006	0.012	0.036	0.072	0.067	0.134
Transformer	1	0.05	0.05	0.053	0.053	0.07	0.07
Total LVDT F.R.			0.188		0.389		1.674

Figure 2.3-1 shows the estimated LVDT failure rate resulting from the analysis over a temperature range of 0 to 125°C.

The failure rate characteristic indicated, as determined by data in the "RADC Reliability Notebook", considers the use of standard MIL-type parts in the LVDT. However, in the interest of evaluating the possible improvement in the reliability characteristics which might be obtained through the use of high reliability parts, the use of parts with, for example, Minuteman reliability characteristics will be considered. Although little detailed and generally applicable information, such as is found for standard parts, is yet available for parts which have resulted from part improvement programs for the Minuteman, information on general trends in such part failure rates will be used. Such information is contained in the "RADC Reliability Notebook", where expected target failure rates for such electronic parts are given. Another reference used for comparing standard and high reliability part failure rates is an Advent Reliability Report. [1]

On the basis of the various sources giving comparisons of such failure rates, a modification of the LVDT failure rate characteristics was made. The electronic parts which have primarily been the subject of high reliability studies are resistors, capacitors, and semiconductor parts. Estimates of improved performance of such parts applied to the LVDT unit indicate possible failure rate reductions by a factor of 10 for resistors and semiconductors, and a factor of 2 for solid tantalum capacitors. The transformer reliability characteristics are assumed to remain the same. For comparison, the result of such a reduction in failure rates is also indicated in Figure 2.3-1. It should be noted that this is only a single estimate of improvement based on the assumed part characteristics stated above and scattered data on high reliability parts.

To illustrate the expected reliability performance of the LVDT electronic package during a lunar mission, the expected reliability trends, based upon the application of the failure rates indicated in Figure 2.3-1 in the exponential failure distribution, are shown in Figure 2.3-2. Basic mission profile data supplied by Bendix Systems Division was utilized in the development of the curves shown. This includes a total of 58 penetrations at a landing

[1] Communication Satellite, Project Advent, Final Technical Report, Section 8 - Reliability, Report of Long Life Reliability Effort During the Period 1 January through 29 May 1962. Air Force Contract AF 04(647)-476, Document No. 635D4288, Vol. 14, Air Force Space Systems Division, by General Electric, Missile and Space Division.

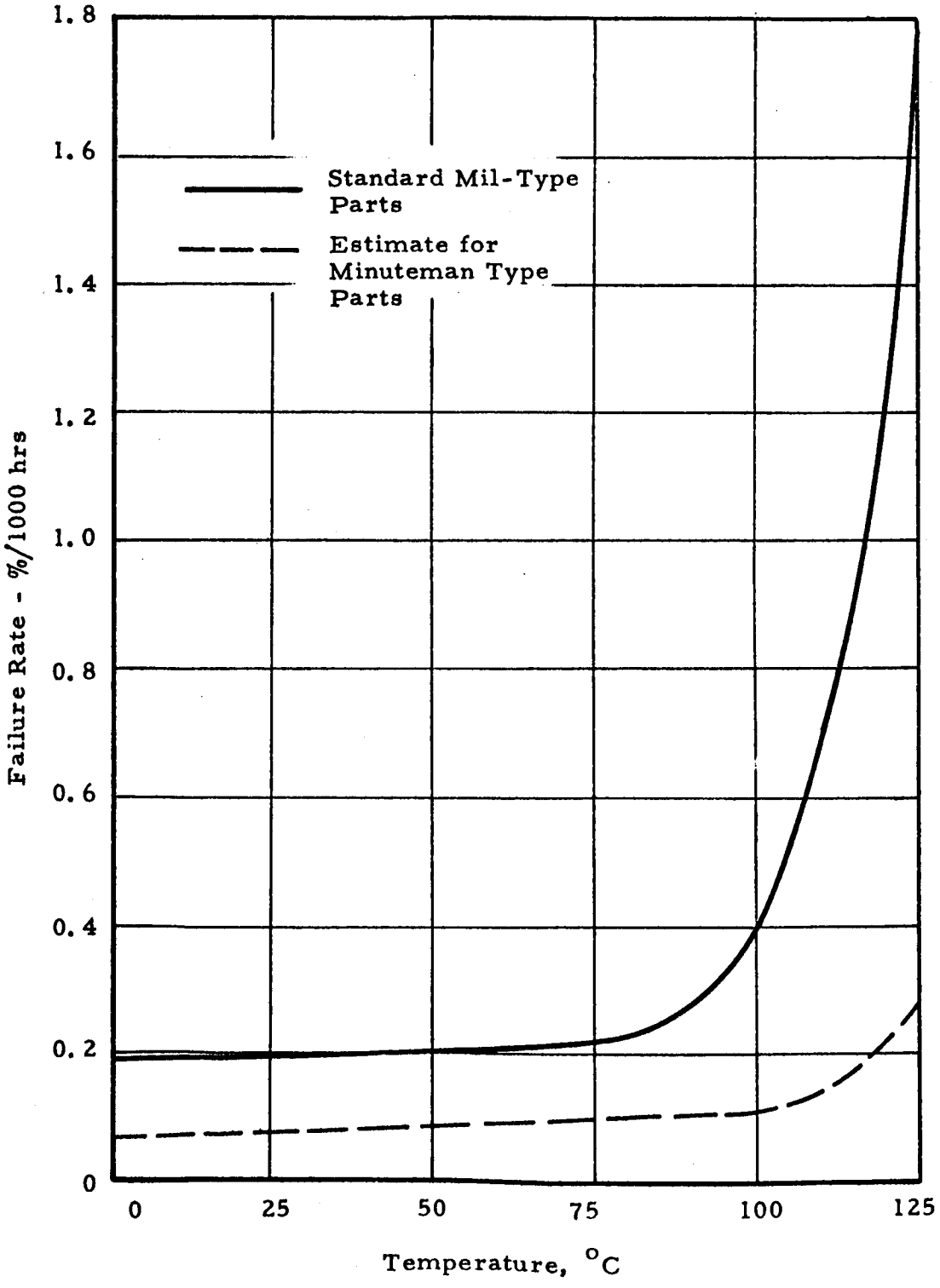


Figure 2.3-1 LVDT Electronics Package Failure Rate vs Temperature

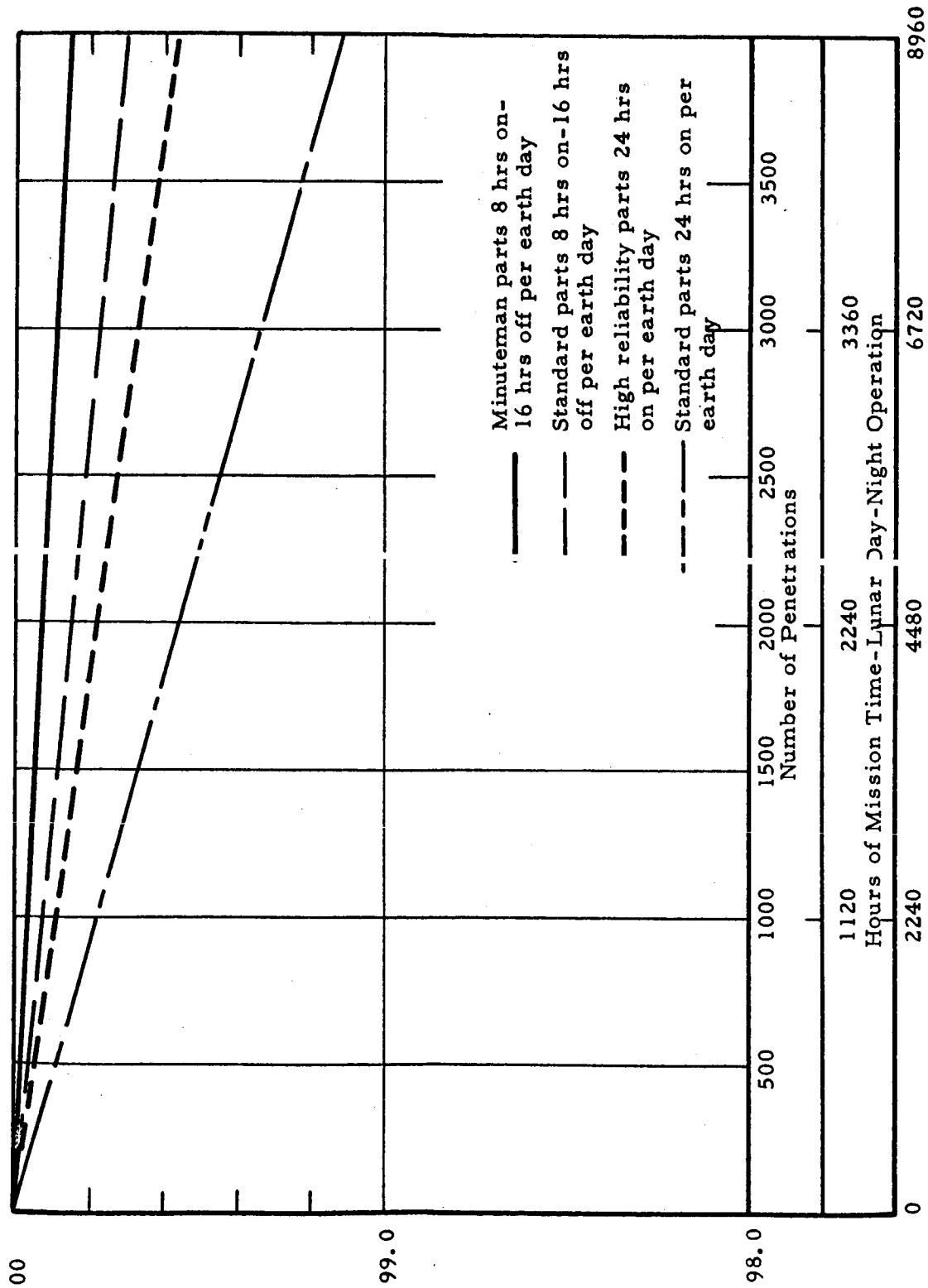


Figure 2.3-2 Reliability Characteristics LV DT Unit—Operating Temperature 60°C

point and between landing points, taking a total mission time of 65 hours. This includes a duty cycle of 8 hours of operation and 16 hours of non-operation during each earth day if a single earth tracking station is used. At this rate, 300 penetrations can be accomplished per lunar day for day-only operation, and 600 penetrations per lunar day for day-night operation. For the particular curves shown, an operating temperature of 60°C is assumed throughout the mission. This is based upon the condition that enough power is supplied during the lunar night, either through operation of supplementary heaters or, if necessary, by means of a trickle charge to maintain such a temperature. The thermal analysis for the penetrometer subsystem has indicated that the temperature will vary between approximately 10°C and 65°C under such conditions throughout the lunar day and night, and the higher temperature of 60°C was selected to apply throughout the mission. Figure 2.3-1 indicates that there is little variation in the failure rate over this temperature range, and thus the choice of 60°C is quite suitable for analysis purposes. In addition, the temperature range indicated by the thermal analysis appears to present no particular problems to the reliable operation of the LVDT unit. With regard to this present study, it is assumed that only the transformer portion of the LVDT is carried within the penetrometer probe tip and that the remainder of the electronic parts are contained within the temperature-controlled chamber in the SLRV.

In Figure 2.3-2, the prime horizontal scale is indicated as number of penetrations, which is a direct measure of the amount of penetrometer data obtained. Corresponding scales of elapsed mission time for lunar day-night and lunar day-only operation are also indicated. For the curves shown, it is assumed that for the lunar day-only operation the LVDT electronics is powered during DSIF operation hours only, and that no deterioration occurs at the storage temperatures to be encountered. In this case the reliability characteristics for day-night and day-only operation are identical when considered on the basis of number of penetrations. Two curves are shown, however, when considering the use of both standard and high reliability parts. In one case, it is assumed that the LVDT electronics are on during a complete earth day, including 8 hours of operation and 16 hours of non-operation for the SLRV vehicle and penetrometer (under the condition of a single earth tracking station). In the other case considered, the electronics are powered only during the 8-hour operational portion of the earth day. The resulting increase in reliability as a function of the number of penetrations under the condition of the shorter actual operational period are indicated. In this case, it was assumed that the resulting on-off cycle has no deteriorating effect upon the LVDT unit.

Switching Circuit

A study of failure rate-temperature characteristics similar to that presented for the LVDT unit has been carried out for the switching and control circuitry. Three circuits have been designed and analyzed and formed the basis for the parametric study discussed here. The circuit diagrams and description of operation of the three switching configurations have been presented in Interim Report No. 2, 1 February 1964. Circuit No. 1 consists of two relays, three limit switches, and two RC circuits; circuits No. 2 and 3 consist of three relays and three limit switches. The principal differences between circuit No. 2 and No. 3 are in component arrangement and operational sequence. The failure rate-temperature parametric characteristics for the three circuits are shown in Figure 2. 3-3. In this case, only the use of standard parts has been considered, as the use of electronic part types for which Minuteman reliability considerations could be made is relatively small.

Although the gross reliability characteristics of the three circuits as indicated in Figure 2. 3-3 are very similar, circuit No. 1 was selected for the ETM from an operational standpoint and is used as the basis of study in switching circuit application for the flight model. Table 2. 3-2 indicates the various part failure rates for three selected operating temperatures.

The performance of the switching circuit for a lunar mission is indicated in Figure 2. 3-4. The reliability is indicated as a function of the number of penetrations with supplementary scales showing total elapsed time for lunar day-night and day-only operation. The assumptions made establishing the reliability characteristics in this case are identical to those for the LVDT discussed in the preceding section, and the reliability characteristics are again shown for 8-hour and 24-hour on-time duty cycles during each earth day.

Considering the general performance of the electronic parts in the LVDT and switching circuit, the trends in the curves in Figures 2. 3-1 and 2. 3-3 indicate that, in the operation of the electronics, high temperatures (particularly above 100°C) should be avoided for maximum reliable performance. The thermal studies in the program indicate that adequate temperature control can quite easily be employed to maintain temperatures below this level. In addition, Figures 2. 3-2 and 2. 3-4 indicate the advantage of supplying power to the electronic units in the penetrometer only while the SLRV is in operation (8 hours per earth day for the case of only one earth tracking station). Under such an operational profile, the electronics are assumed to be in a stored condition in which no deterioration occurs (failure rate = 0).

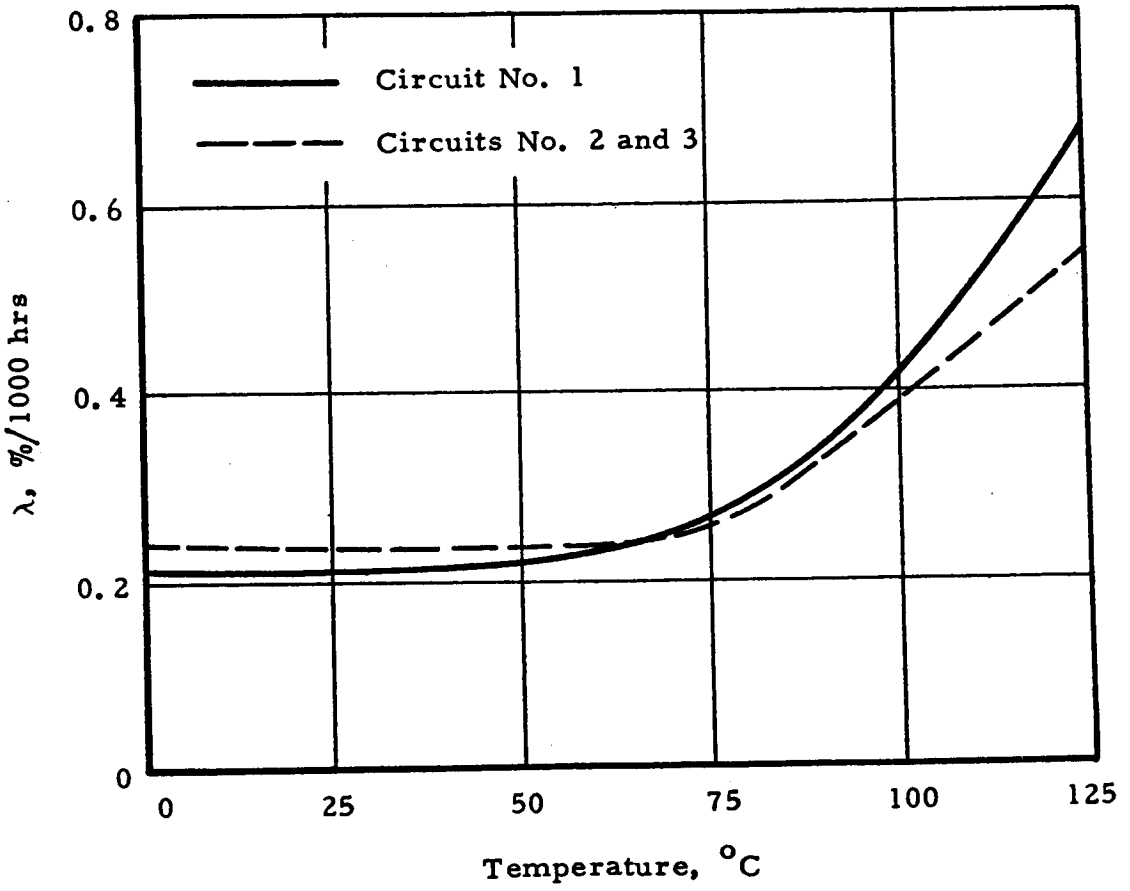


Figure 2.3-3 Switching Circuit Failure Rates vs Temperature

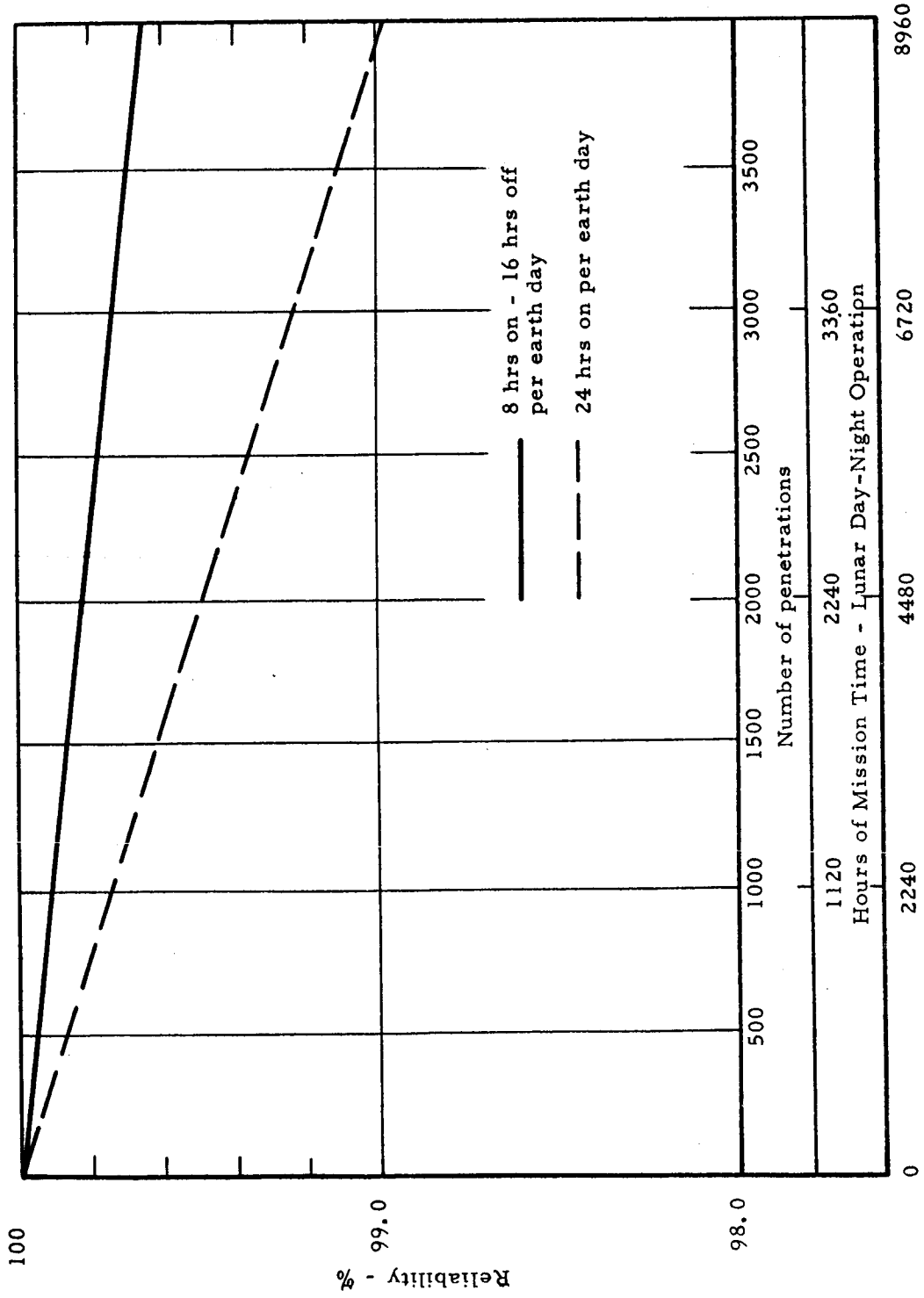


Figure 2.3-4 Reliability Characteristics Switching Circuit Operating Temperature: 60°C

TABLE 2.3-2

SWITCHING CIRCUIT FAILURE RATES—CIRCUIT NO. 1

Part Type	Number of Parts	Failure Rates - %/1000 hours					
		Part F.R. 0°C	Total F.R. 0°C	Part F.R. 100°C	Total F.R. 100°C	Part F.R. 125°C	Total F.R. 125°C
Relay	2	0.04	0.08	0.06	0.12	0.085	0.170
Limit Switch	3	0.04	0.12	0.07	0.21	0.095	0.285
Capacitor	2	0.006	0.012	0.036	0.072	0.067	0.134
Resistor	2	0.001	0.002	0.008	0.016	0.045	0.090
Total Switching Circuit Failure Rate			0.214		0.418		0.679

Penetrometer Drive Motor

The drive motor presents a particular problem in the penetrometer design, since from a reliability viewpoint, it is vital to the operation of the penetrometer. On the other hand, it is known that DC motor operation in a hard vacuum such as is expected at the lunar surface presents great problems because of brush wear. Several firms have been contacted concerning this problem, and some information has been obtained on possible motor performance under a lunar type environment.

Some information has been obtained from Inland Motor Corporation and Ball Brothers Research Corporation on the hard vacuum operation of low-speed torque motors. Some experience has been obtained with satellite operation of such motors. For instance, 18 months of operation have been obtained with such motors in the OSO satellite. These motors operate at 30 rpm in an estimated vacuum of 10^{-10} torr. Some limited tests have also been performed up to 2500 hours with such motors at approximately 10^{-9} torr. Available information on these motors indicates, however, that despite the long life characteristics of this type of motor, an excessive power penalty may result from their use under the low-speed operation for which they are recommended.

The Globe SD type motor has been utilized in the ETM. The motor originally considered as a possibility for use in the penetrometer was the Globe SS model, an adaptation of the SD giving longer brush life under vacuum conditions. Globe Industries has indicated experience with supplying such motors for X-ray equipment and has performed some very limited tests of motor performance under vacuum conditions. Applications and tests have included motors running in the vicinity of 8000 rpm and vacuum conditions of 10^{-9} torr, which at least approaches the possible lunar operating conditions. For such environments, a preliminary estimate of expected motor life of 90 to 200 hours was obtained from the manufacturer. The majority of the motors would fail within that time period. The life distribution under the conditions of wear that exist is most likely normal. Such a motor was regarded to have a very high criticality factor as indicated in the Interim Reliability Report, particularly for the motor operating times required for a tube extension speed of 0. 25 in. /sec. A motor which appears to give much more suitable operating characteristics is the Globe MM type. Here, for a small power and weight increase, the expected life range is increased to an estimated 190 to 250 hours. Coupled with the 0. 5 in./sec tube speed, consideration of the MM motor has allowed a reduction in the motor criticality

level. The use of AC brushless motors was also considered; however, the power and weight penalties (largely in the conversion circuitry) were considered to over-shadow the possible increase in expected life. Table 2. 3-3 presents a brief comparison of motor performance.

TABLE 2. 3-3

COMPARISON OF POSSIBLE PENETROMETER DRIVE MOTORS

Globe Motor (Type)	Power (Watts)	Weight (oz)	Expected Life Range (hours)
SS	5	7	90-160
MM	6	8	190-250
AC Brushless	12	12	300-500

The possible reliability characteristics of the MM motor are indicated in Figure 2. 3-5. Three curves are shown in this figure. One curve indicates the general wearout characteristics of the motor based on the life range of 190-250 hours suggested by the manufacturer. It was assumed in this case that the life distribution follows a normal distribution with a mean value of 220 hours. Taking 190 hours to be the point of 95% probability of survival, the resulting standard deviation of the distribution becomes 18. 2 hours. It should be noted that the above figures include the life characteristics of the brushes, bearings, and speed reducing gear assembly, although the brush life is probably the dominant factor in the distribution. Because this curve was to reflect primarily the wearout characteristic, it appeared desirable to superimpose a random failure characteristic for evaluating the motor performance. The second curve indicates this possible random failure characteristic, the data for which was obtained from the "RADC Reliability Notebook". The DC motor failure rate for a speed of 8000 rpm (approximately the motor speed for the present penetrometer design) is 5 percent per 1000 hours. The winding failure rate is obtained by taking the failure rate for class H at 60°C (0. 050% per 1000 hours) multiplied by a 1. 5 motor application factor. The sum of these two failure rates gives 5. 075% per 1000 hours. For use in the graph in Figure 2. 3-5, a more conservative figure of 6% per 1000 hours was selected as the random failure rate. The

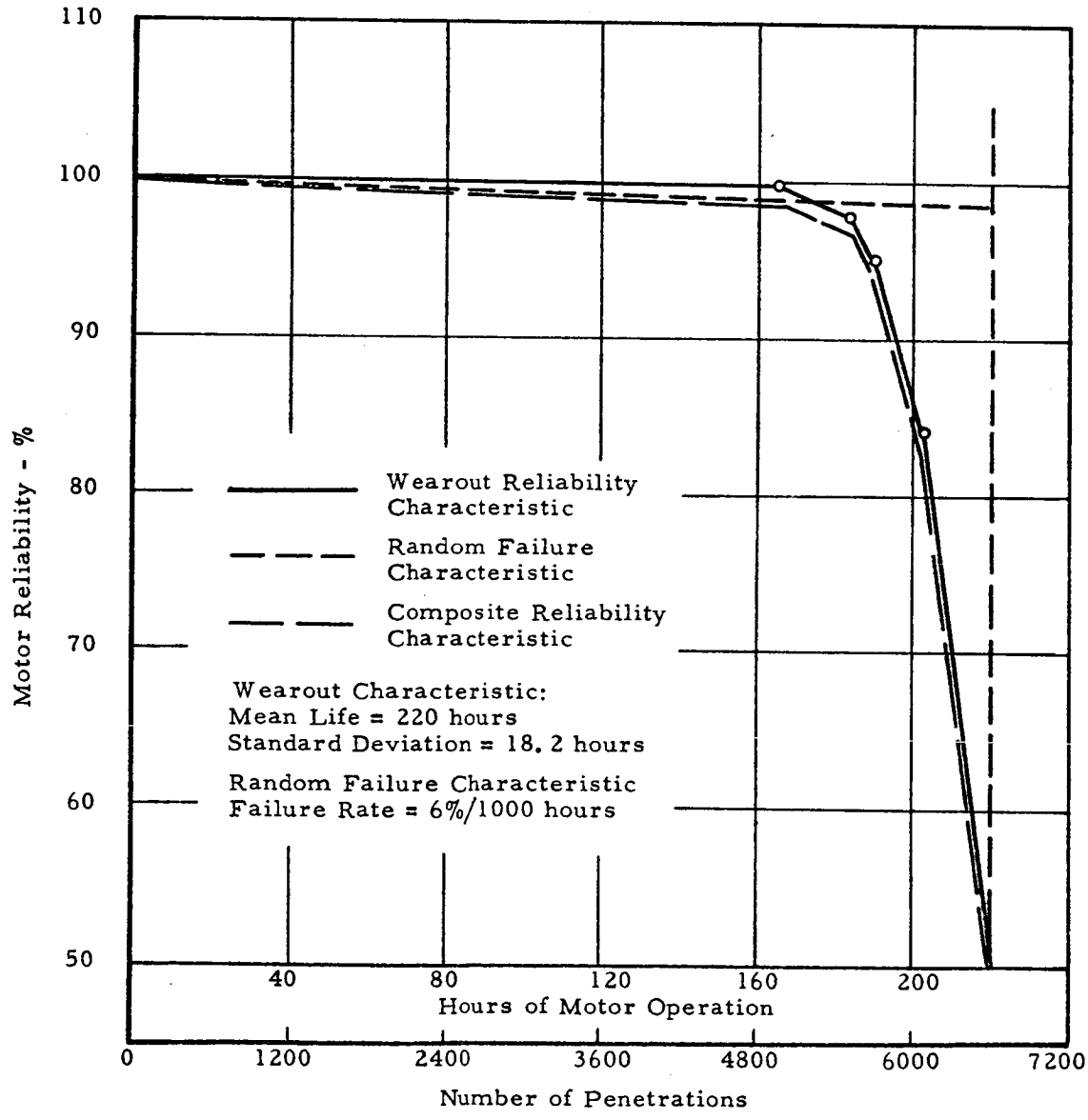


Figure 2.3-5 Estimated Reliability Characteristics Globe MM Type DC Motor

composite reliability characteristic is indicated in Figure 2. 3-5 as the product of the wearout and random failure reliability characteristics. The motor reliability is indicated as both a function of the motor operating time and the equivalent number of penetrations. Up to about 180 hours of operation (5400 penetrations), the random characteristic dominates, while beyond this point the wearout characteristic becomes dominant in rapidly decreasing the expected reliability. The figure indicates that satisfactory motor operation is possible, on the basis of available information up to about 160 hours of operating time, giving about 4800 penetrations, and a reliability figure of approximately 0. 99.

Penetration Depth Sensing

In the ETM design of the penetrometer subsystem, penetration depth is indicated by the setting of a potentiometer which is coupled to the tube storage drum assembly. The only electrical part of the position sensor is the potentiometer. The estimate presently being used for a potentiometer failure rate is derived from data for variable composition resistors in RD-101, "Reliability Assessment Handbook," Astro Reliability Corporation. The failure rate determined from this source is 0. 0194% per 1000 hours at 60°C and will represent the failure rate to be used in further analysis in this report.

2. 3. 1. 2 Mechanical Components

The following paragraphs discuss the reliability considerations for the various mechanical components in the penetrometer. Where possible at present, quantitative analysis is presented. Otherwise, the discussions of the reliability and design factors in mechanical component operation represent a qualitative parametric analysis.

Bearings

The problems associated with the design and/or selection of bearings for use in a space environment are sufficiently complex as to cause much concern to designers. This applies to bushings as well as rolling contact bearings.

In addition to the usual space problems of temperature, lubrication, high vacuum, radiation, and vibration, bearings used in the penetrometer should exhibit low coefficients of friction and "quiet" operating characteristics. It may well be necessary to trade off parameters in order to achieve a well balanced design.

In the current problem, those attributes which must take precedence are:

1. Operation in hard vacuum
2. Low coefficient of friction
3. Quiet operation
4. Good resistance to damage under high dynamic loading
5. High accuracy and low positional tolerance in mountings.

From a preliminary review of the field, three bearing types are indicated for possible use in the penetrometer: (1) rolling contact, high precision, miniature ball bearings, (2) rolling contact, miniature, roller and/or needle-roller bearings, and (3) bushings or miniature journal bearings.

The following section will briefly discuss the relative merits of each of the bearing types in terms of the five principal characteristics which these bearings must exhibit.

Perhaps the single most important attribute which these bearings must exhibit is a low coefficient of friction. The high precision ball bearings in an unshielded, unsealed configuration exhibit the following coefficients of friction[1] (these values are approximate):

1. Radial ball bearings	0.0015	- 0.0021
2. Self-Aligning ball bearings	0.0010	
3. Angular contact bearings	0.0013	- 0.0030.

All of these values are of course quite low, in general lower than any other type of bearing; however, as will be seen later, there are other mitigating factors. The need for quiet operation, as evidenced herein, has become a major selection criteria during the past 10 years for miniature bearings. The need for quiet operation has resulted from an attempt to reduce both airborne and structure-borne machinery noise. In general,

[1] Wilcox, D. F., and Booser, R. E. Bearing Design and Application, McGraw-Hill Book Company, Inc., New York, 1957.

low-noise characteristics are obtained by improved bearing metrology. In addition, maximum silencing can be achieved by exercising the same or comparable metrology control on bearing mating parts. Low-noise bearings are primarily available in the deep groove, and angular-contact, radial ball types. To achieve the required precision along with low noise characteristics, preloading of the bearings is used in many applications.

The mounting of miniature ball bearings is most commonly achieved by light press fitting or cementing the outer races in place. While this achieves the desired rigidity, positional accuracy may suffer, and subsequent loosening often occurs. A better method of handling this problem is to use a flange mount. With this technique, the bearing is pressed in place (with a somewhat heavier press) external to the actual unit. The flange is then attached to the unit proper, positioned to the desired tolerance, and locked in place. This procedure has an advantage from a load-resistance viewpoint which will subsequently be discussed.

Much of what has been said about miniature ball bearings applies to roller and needle-roller bearings. The corresponding coefficients of friction are:

1. Cylindrical roller bearings 0.0011 - 0.0015
2. Spherical roller bearings 0.0018
3. Needle-roller bearings 0.002.

Cylindrical roller bearings are generally employed where the loads are high, since this type of bearing is well suited for such heavy radial loads. A special advantage of this type of bearing over the ball bearing is its ability to sustain a much larger shock load without plastically indenting or brinelling the races. The load carrying capacity of a bearing is principally dependent upon its hertzian contact area. The larger the contact area, the greater is the indentation resistance. An additional advantage enjoyed by these bearings is the absolute minimum outer diameter for a given bore size of any of the rolling contact bearings. This is a very important consideration when over-all minimum size is important.

Mounting considerations for roller bearings are similar to those for ball bearings. It should be mentioned that if a separate flange (as previously discussed) is used, whether the bearings are ball or roller, additional shock and vibration resistance can be achieved by introducing some flexibility into the mounting. The flange can be so designed that some elastic deformation will occur under dynamic loading and, hence, decrease the stress in the races.

One additional bearing type that remains to be considered is the bushing or miniature journal bearing. Initial considerations indicated that several types might lend themselves to the subject application. These types are the sintered bronze bushings with solid film lubrication, the compacted graphite-carbon bushings with or without solid film lubrication, and the Teflon or epoxy filled bushings with solid film lubrication.

Subsequent investigation proved that the compacted carbon-graphite type of bushings is nonfeasible because of the hard vacuum associated with a lunar environment. The possibility of excessive outgassing and loss of compaction due to deterioration of the binder dictate against the use of this material. The use of powdered bronze (sintered, porous) bushings carry a weight penalty, over both the graphite and plastic, as well as a lubrication problem. The nature of sintered bronze is such that the surface geometry is not the optimum for adherence of solid film lubricants. Thus, of the three journal (bushing) types of bearings considered initially, the most promising for use in the flight model penetrometer subsystem is the plastic bushing.

The use of plastics as bearing materials in applications involving a lunar environment (space environment) is dependent upon the behavior of plastics in space environment. Those factors in the space environment which affect the behavior of plastics are:[1]

1. Vacuum and thermal vacuum
2. Ultraviolet radiation
3. Particle radiation.

The principal factor of the space environment which is of concern here is vacuum (and thermal vacuum). In some cases, vacuum degrades plastics

[1] Ringwood, A. F. Behavior of Plastics in Space Environments, Modern Plastics Magazine, January 1964, p. 173.

by volatilizing components essential to the optimum properties of the part. In others, it improves the properties by the same volatilization mechanism whereby impurities are outgassed.

Hard vacuum in the range of 10^{-6} to 10^{-10} torr has virtually no effect on thermoset materials.[1] This classification includes silicone resins, polyurethane resins, epoxies, polyesters, and phenolics. The latter three plastics require fairly high temperatures before measurable outgassing products can be detected. In general, for these materials the loss of weight due to any outgassing (vacuum-thermal environment) results in a decrease in elongation and an increase in tensile strength and the modulus of elasticity.

Among the thermoplastic materials, the two most feasible materials for space use are nylon and Teflon. Nylon, in general, is a stable polymer, essentially unaffected by vacuum at ambient and satellite orbit temperatures. Though some outgassing of the impurities in nylon does occur, their removal may actually improve the physical and mechanical properties of the plastic. Consequently nylon, in general, is a good selection for space applications.

Recent experiments have investigated the behavior of various filled and reinforced Teflons under hard vacuum and thermal-vacuum conditions. In no case was there any sign of degradation of a Teflon resin due to the effects of hard vacuum exposure alone. In a thermal-vacuum environment, a temperature of 710°F is required to effect a 10-percent weight loss in one year. Teflon, like nylon, should withstand space vacuum with no loss of physical or mechanical properties.

We are vitally concerned with the expected behavior of both nylon and Teflon under space environments, the former in terms of a possible gear material and the latter as a possible bearing material. In addition, the behavior of epoxies is of importance in terms of a coating for the pressure rolls to prevent possible cold welding to the tube. Many of the desired properties of a "good" bearing material are similar to those required for a "good" nonmetallic gear material. Nylon, for example, is quiet in operation, resists abrasion, and wears at a low rate. Improvement in the mechanical properties, rigidity, and wear resistance is obtained for some applications by adding fillers such as fiberglass and MoS_2.

[1] Ringwood, A. F. Behavior of Plastics in Space Environments, Modern Plastics Magazine, January 1964, p. 173.

Teflon has an exceptionally low coefficient of friction, and inertness to corrosion and chemical deterioration. In terms of bearings, unmodified Teflon can be used to a PV value of approximately 1000, while Teflon filled with a glass fiber can be used for PV values in excess of 30,000. Correspondingly, for comparison, a maximum value of PV equal to 50,000 is given for porus metal bearings. In this index, P equals the pressure (psi), and V equals the surface velocity (fpm); hence, the PV value gives an index of the energy dissipated on a unit area of the bearing surface. It is a common relative measure of bearing capabilities.

Specific factors for consideration in the use of Teflon for bearings are given in Figures 2.3-6 through 2.3-8 and Table 2.3-4. It is interesting to note that lower temperatures tend to increase the compressive yield stress of Teflon as shown in Figure 2.3-8. Tables 2.3-5 and 2.3-6 generally summarize the requirements and capabilities for plastics used as gears, and bearings, respectively. Before any recommendations can be made, however, some consideration of the required lubrication must be made. This is discussed in the following pages.

TABLE 2.3-4

EFFECT OF SHAFT MATERIAL ON
WEAR OF BEARINGS OF TFE

Shaft Material*	Relative Wear
Carbon steel	1
Cast iron	1 to 2
Stainless steel	1.5 to 3
Hard chrome plate**	10 to 20
Bronze **	1 to 2
Aluminum alloy **	20 to 50

* All materials have 16-mu in. finish.
** High rate of shaft wear.

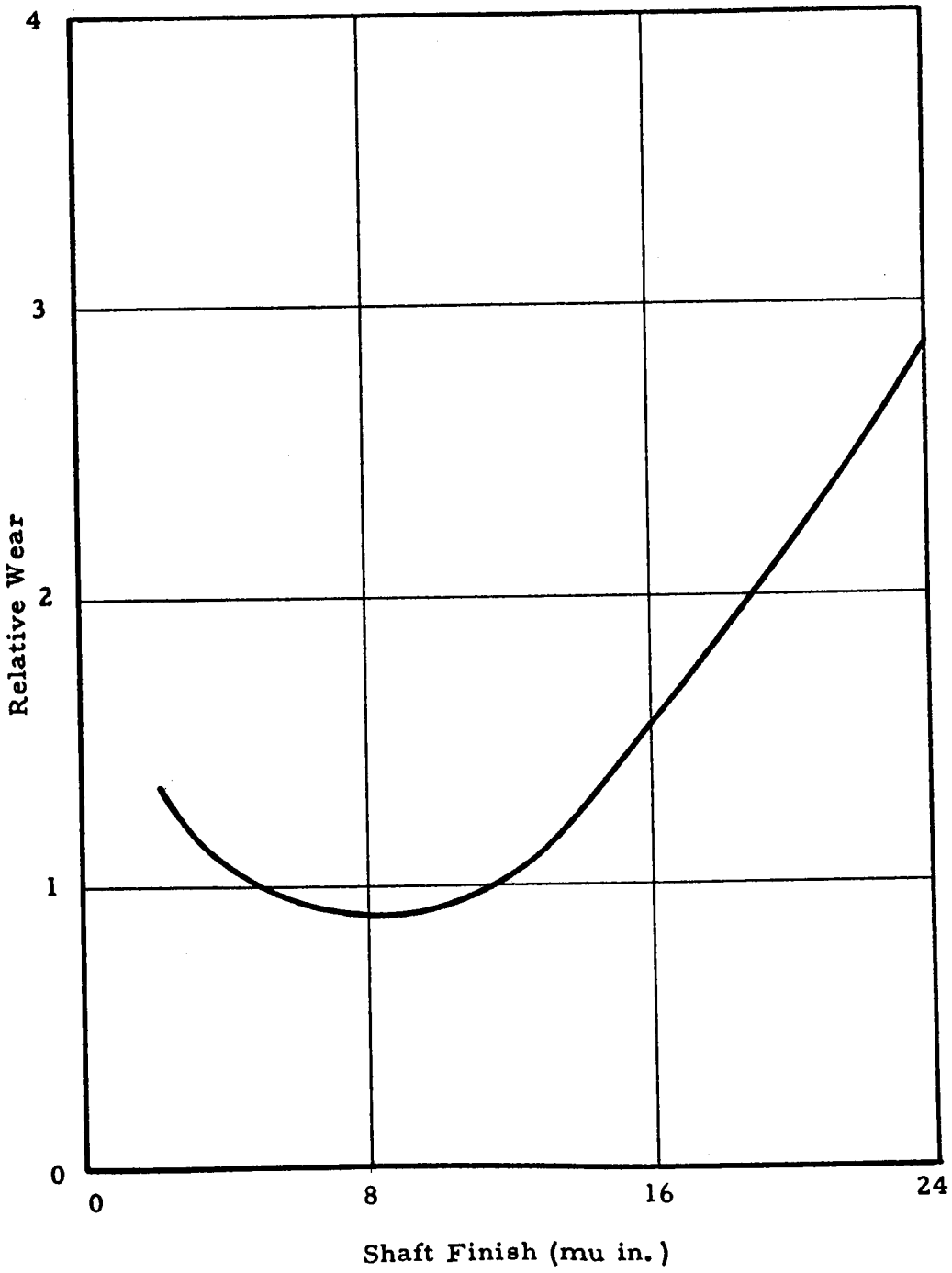


Figure 2.3-6 Effect of Shaft Finish on Wear of TFE Bearings

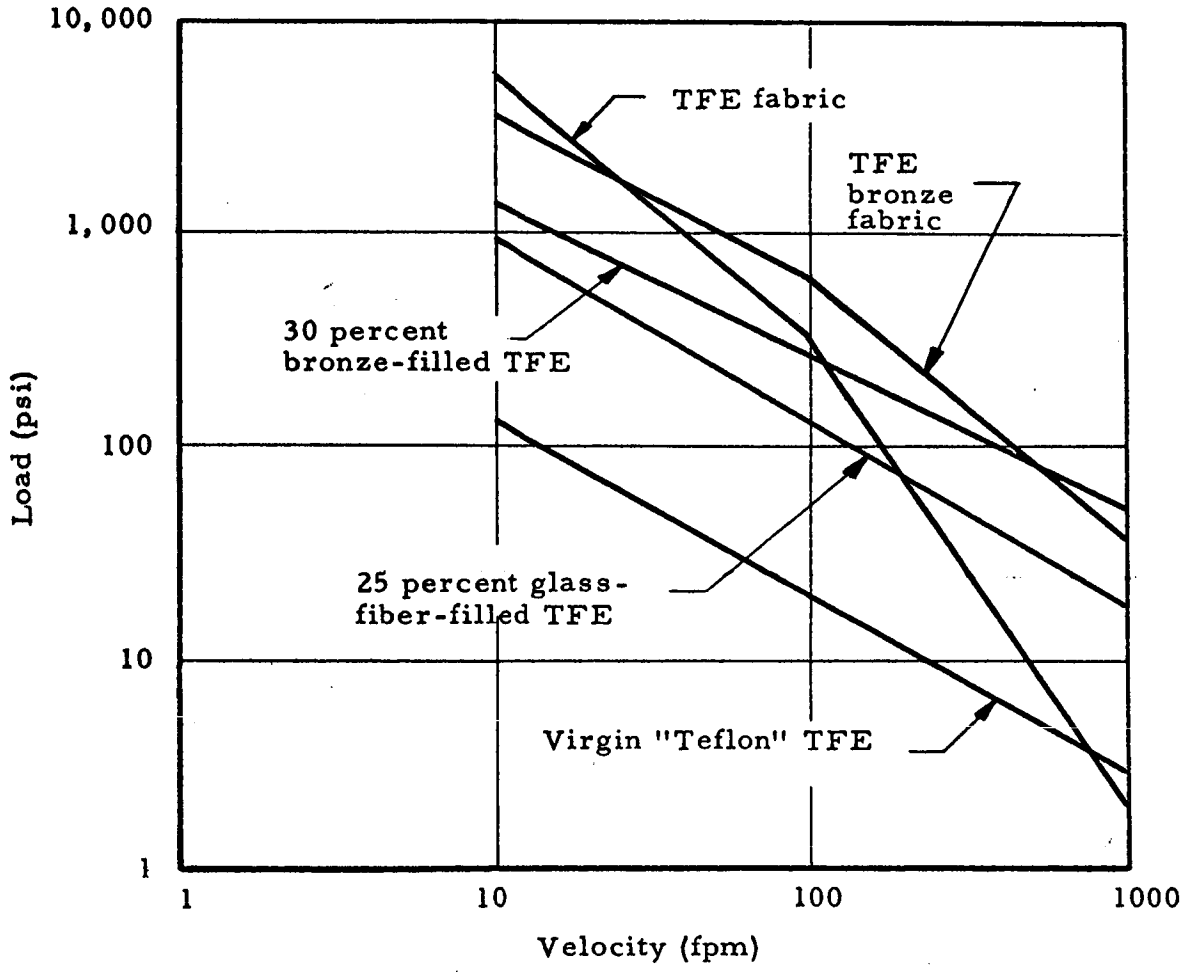


Figure 2.3-7 Typical PV Limits for Bearings of TFE

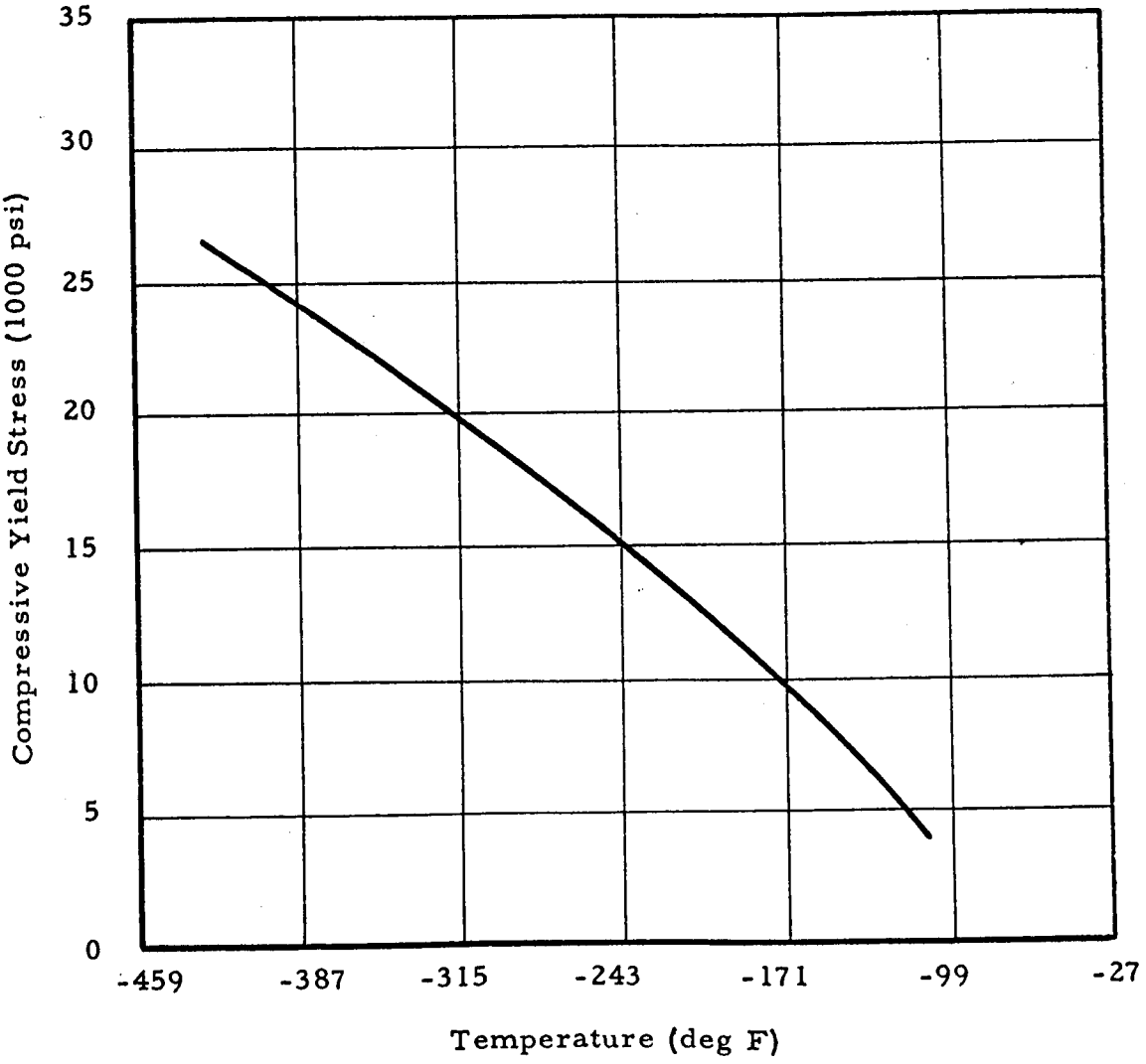


Figure 2.3-8 Effect of Temperature on Compressive Yield Stress of TFE

TABLE 2.3-5

PLASTICS SELECTION CHART

	Cost ($c/in.^3$)	Coefficient of Friction		Slip-Stick	Thermal Expansion ($10^{-5}/^{\circ}F$)	Thermal Conductivity ($Btu/^{\circ}F/hr/ft^2/in.$)	Heat Distortion Temperature ($^{\circ}F$)	Water Absorption (%/24 hr)	Abrasion Resistance Taber Rating (mg loss/ 1000 cycles)	Others
		Dry	Lubricated							
Fluorocarbons, TFE and FEP	25 to 52	0.4 to 0.8	0.4 to 0.8	No	10.5	0.11 to 0.14	250	Nil	7 to 26	Usable temperature range 430 to 500 F, will not adhere to tacky materials, harmlessly absorbs abrasive particles and is nongalling.
Filled TFE Fluorocarbon	26 to 58	0.16 to 0.28	0.06	No	7 to 9.7	1.7 to 20	250	Nil	8 to 26	High load capacities; some compounds to 30,000 PV
Nylons	4 to 9	0.15 to 0.40	0.06	Yes	4.6 to 7.1	0.10 to 14	260 to 360	0.4 to 3.3	6 to 8	Harmlessly absorbs or engulfs abrasive particles, nongalling, and available in massive shapes.
Acetals	3.3	0.15 to 0.35	0.1	No	4.5 to 6	0.13	316 to 338	0.12 to 0.41	6 to 20	Stiffest unfilled thermoplastic.
High-density Polyethylenes	0.9 to 1.2	0.21	0.1	Yes	6.5 to 16.7	0.19	140 to 180	0.01	6	Nongalling.
Polypropylenes	1.3 to 1.9	0.34	0.16	Yes	4 to 6.2	0.04 to 0.08	180 to 230	0.01 to 0.03	18 to 32	Lightest of plastics.

Note: Tables 7-4, 7-5 and 7-6 are taken from Machine Design Magazine, Sept. 20, 1962, Plastics Book Issue Published by the Penton Publishing Co.

Bearings, bushings, slides, guides, valve liners, wear surfaces

Properties Required

Low coefficient of friction, even when nonlubricated. High resistance to abrasion. Fair or better from stability, heat resistance, and corrosion resistance.

Suitable Plastics

Fluorocarbons (TFE and FEP), filled fluorocarbons (TFE), nylons, acetals, high-density polyethylenes and polypropylenes.

Other Suitable Materials

Babbitts, bronzes, cast irons, prelubricated woods, graphite, cermets, diamonds and sapphires.

Property Summary

Nylon recommended for general-purpose bearings and wear surfaces. Fluorocarbons (especially TFE) for sliding or low-speed-rotating dry bearings, for highly corrosive service or service in extreme temperatures (-430 to 500 F). Acetals for submerged or humid service, and when resistance to creep is important. Acetals and fluorocarbons for slides or valve liners to eliminate jerky starts and slip-stick. Filled fluorocarbons for heavier loadings and high creep resistance. Polypropylene and high-density polyethylene for lowest cost at very low speeds and loads. Fluorocarbons for non-stick surfaces.

TABLE 2. 3-6

PLASTICS SELECTION CHART

	Cost ($c/in.^3$)	Tensile Strength (1000 psi)	Impact Strength (ft-lb/in.)	Abrasion Resistance Taber Rating (mg loss/ 1000 cycles)	Fatigue Endurance Limit (1000 psi)	Heat Distortion Temperature (°F)		Flexure Modulus Stiffness (10^5 psi)	Machinability	Chemical Resistance		Others
						66 psi	264 psi			Acids / Solvents	Alkalies / Oils	
Nylons	4 to 9	7.1 to 12.6	0.6 to 4	3 to 8	3	340 to 360	140 to 165	1.5 to 4	E	F to E	E to E	Vibration damping, nongalling, available in massive shapes, low friction, and high dimensional stability.
Acetals	3.3	8.8 to 10	1.1 to 4	6 to 20	5	316 to 338	185 to 250	3.7 to 4.1	E	P to E	P to E	Creep resistant, excellent low temperature strength, low friction, and low moisture absorption.
Polycarbonates	4.5 to 5.2	9 to 10.5	12 to 16	7 to 24	2	283 to 293	270 to 280	3.8	E	E to G	G to F	Extremely creep resistant, transparent, excellent low-temperature strength, low moisture absorption, and high dimensional stability.
Phenolics, fabric-filled	1.5 to 3	9 to 16	1 to 2.5	...	...	320	7320	8 to 14	F to E	F to E	F to E	Hard thermoset, and extremely creep resistant.

Gears, cams, racks, couplings, rollers, heavily stressed mechanical components

Properties Required

High-tensile plus high-impact strength. Good fatigue resistance and stability at elevated temperatures. Machinable or moldable to close tolerance.

Suitable Plastics

Nylons, acetals, polycarbonates, and phenolics (fabric filled).

Other Suitable Materials

Cast iron, brasses, and steels.

Property Summary

Nylons are recommended for general purpose gears, and other mechanical components. Acetals for maximum fatigue life, for highly accurate parts or exposure to extremely humid conditions. Phenolic-fabric laminates for low-cost, thin-stamped gears or parts. Polycarbonates for intermittent, very high impacts (not recommended for applications involving repeated cyclical stress).

The selection of bushings or sleeve-type bearings for use on the SLRV penetrometer subsystem requires a rather extensive investigation of the most applicable type of lubrication. Because of the nature of the bearing, some type of lubrication is definitely required. An unlubricated shaft, riding in an unlubricated journal (as opposed to rolling contact bearings), could result in cold welding or excessive wear. The environment to which the penetrometer will be subjected is definitely hostile to mechanical devices and to the more common lubricants. Thus, the dictates of the environment are such that consideration of solid or bonded film lubricants must be part of any parametric study.

The nature of the penetrometer operation and its operational environment dictate the use of boundary lubrication. The basic requirements of any boundary lubricant are:

1. Resistance to penetration by surface asperities under relatively high loads

2. The ability to shear more easily than the base materials

3. The ability to encourage relative motion between the sliding surfaces to occur in the lubricant layer.

Table 2.3-7 lists the degree to which certain solid lubricants possess these requirements.

When the lubricant is applied as a dry powder or grease or in oil suspension, it is generally referred to as a solid lubricant. When it is applied in conjunction with binders in a uniformly thin layer, confining a high concentration of lubricant to a given area, it is referred to as a bonded dry film. These latter coatings are especially important in the aerospace technology. The extremely low atmospheric pressures encountered in aerospace environments, generally far below the vapor pressures of greases and oils, have made bonded coatings essential for lubrication under these environments. Bonded coatings have often been used in the past when a component may not be used for extended periods, but when called upon, must function reliably. Consideration of Tables 2.3-7 through 2.3-9 indicates that the most likely lubricant for use in the penetrometer subsystem is molybdenum disulfide (MoS_2) in a bonded dry-film form.

TABLE 2.3-7

COEFFICIENTS OF FRICTION* FOR SELECTED MATERIALS

Material	Kinetic Coefficient of Friction	Material	Kinetic Coefficient of Friction
Molybdenum disulfide (MoS_2)	0.035	Rottenstone	0.189
Tungsten disulfice (WS_2)	0.035	Lead chloride	0.191
Natural MoS_2 (steel on bronze)	0.075	Borax	0.210
		Silver iodide	0.231
Commercial oil-silver paste	0.095	Boron nitride	0.25+
Cu-Pb powder mixture (50/50 percent composition)	0.183	Kaolin	0.25+
Zinc	0.186	Leaded zinc oxide	0.25+
Copper-zinc alloy (85/15 percent composition)	0.226	Talc	0.25+
Copper	0.25+		
Cu-Zn-Al alloy (70/29.75/0.25 percent composition)	0.25+	Spermaceti wax	0.048
		Beeswax	0.050
Graphite, lubricating grade	0.045	Bayberry wax	0.054
Teflon, modified	0.060	Polyethylene glycol	0.077
Colloidal graphite dipped in water	0.100	Nylon	0.100
Barium hydroxide	0.151	Paraffin	0.104
Vermiculite	0.160	Carnauba wax, 83 to 86 C	0.143

Note: This table is taken from Machine Design Magazine, June 13, 1963, Bearings Book Issue, published by the Penton Publishing Co.

* Coefficients of friction are measured with solids rubbed into bearing surfaces of hardened steel on hardened steel in pressure-fit tests. Relative velocity is 0.6 in. per min. Bearing pressure is 15,000 psi. Exceptions are noted.

TABLE 2.3-8

USEFUL RANGE OF SOLIDS FOR DRY LUBRICATION

Lubricant	Load* (psi)	Temperature (F)
Molybdenum disulfide, commercially available, particle-size grades	2000 to yield point of metal	-300 to +750**
Graphite powder, lubricating grade	2000 to 100,000	-300 to +1200
Tungsten disulfide powder, commercially available	2000 to yield point of metal	Low not investigated Maximum 850**
Teflon powder and sintered shapes	150 to 3000	-300 to +500
Teflon and other plastics containing fillers	50 to 4000	Maximum 500
Organic binder coatings, graphite-MoS_2 type	2000 to yield point of metal	-100 to 500
Inorganic binder coatings, graphite-MoS_2 type	2000 to yield point of metal	-300 to 1000
Teflon	Minimum 50 Maximum not investigated	Maximum 500

* Speed affects the load capacity to a marked degree, but solid lubricants should only be considered at low speeds. As speed increases, load carrying capacity decreases.

** In inert and reducing atmospheres these solids are used at temperatures above 2000 F.

TABLE 2.3-9

OPERATING CHARACTERISTICS FOR APPLICATIONS OF POWDERED SOLID LUBRICANTS AND BONDED DRY FILMS

Lubricant	Application			
	Vacuum	Radiation	Sleeve Bearings	Anti-Friction Bearings
Molybdenum disulfide	E	E	E	L
Graphite	L	E	G	L
Tungsten disulfide	E	E	No data	No data
Teflon	G	G	E	As retainers
Bonded coatings				
Organic binders	L	L	E	L
Inorganic binders	E	E	G	L

Note: E = excellent
G = good
L = limited use.

Table 2.3-10 presents representative characteristics and applicabilities of this type of lubricant. Bonded dry-film coatings are similar to paints in their constructional makeup. These coatings have three basic components:

1. A pigment to provide lubrication
2. A binder to cause the pigment to adhere
3. A vehicle or solvent system for controlled application.

Binder-pigment combinations may be organic/inorganic, organic/organic, inorganic/organic, and inorganic/inorganic. Organic/organic systems are used for light load applications. Organic/inorganic, and vice versa, systems are general purpose lubrications, while inorganic/inorganic systems provide better high temperature lubrication.

The best binder for a particular application depends upon service conditions. In addition, the service life of the lubricant depends upon the lubricant-to-binder ratio. Typical curves are illustrated in Figure 2.3-9. Optimum service is obtained from a lubricant-to-binder ratio of 4:1. Above this ratio, the film tends to crumble, since there is insufficient binder to hold the lubricant particles together. In addition, the film adherence characteristics are poor.

Optimum wear life of a dry film is achieved with an initial coating thickness of 7×10^{-4} in. as shown in Figure 2.3-10. Thicker films seem to have little adverse effect, but thinner films may severely reduce the life of the coating. For optimum operating conditions, the substrate should be relatively hard. In general, the harder the substrate, the lower the frictional forces and the longer the surface life. From extensive experimental investigation, it appears that the optimum wear life is obtained when the substrate hardness is approximately 60 R_C and its surface finish is 20 μ in. rms. This is illustrated in Figure 2.3-11.

The use of graphite as a portion of the pigment (in mixture with MoS_2) is not feasible for a lunar environment. Graphite requires an absorbed layer of moisture to function as a lubricant. This requirement precludes its use as a lubricant in hard vacuums. MoS_2 does not require moisture and will perform successfully under hard vacuum conditions. As mentioned previously, the most efficient form for the lubricant under hard vacuum is an inorganic bonded dry film.

TABLE 2.3-10

REPRESENTATIVE BONDED LUBRICANT COATINGS

Type of Coating	Pigment System	Binder	Major Constituents	Characteristics	Limitations	Recommended Application
General purpose, air cure	Inorganic	Organic	MoS_2 in vinyl-butyral resin	Cures at room temperature. Applicable to all metals and most nonmetals. Excellent for large parts already installed.	Somewhat lower wear life than oven-cured coatings.	Spray, dip or tumble.
General purpose, oven cure	Inorganic	Organic	MoS_2-graphite anine modified epoxy	Excellent wear life, corrosion protection and resistance to chemical attack. High peel strength	Requires surface pretreatment for best performance. Limited to base materials that can withstand 300 F for 1 hr or 400 F for 15 min.	Spray, dip or tumble.
High-temperature service, oven cure	Inorganic	Inorganic	MoS_2-graphite in sodium silicate binder	For service to 1000 F. Maintains moderately low friction coefficient through temperature range.	Requires two step oven cure. Somewhat reduced wear life at room temperature.	Spray
Low-load service, air cure	Organic	Inorganic	Modified teflon system	Extended wear life at low loads. Cures in less than 1 min.	No apparent limitations for specified service.	Spray

Bonded films may be used on ferrous and nonferrous metals, metal compositions, plastics, glass and elastomers. Solubility effects and curing temperatures should be reconciled with the properties of a particular plastic or elastomer.

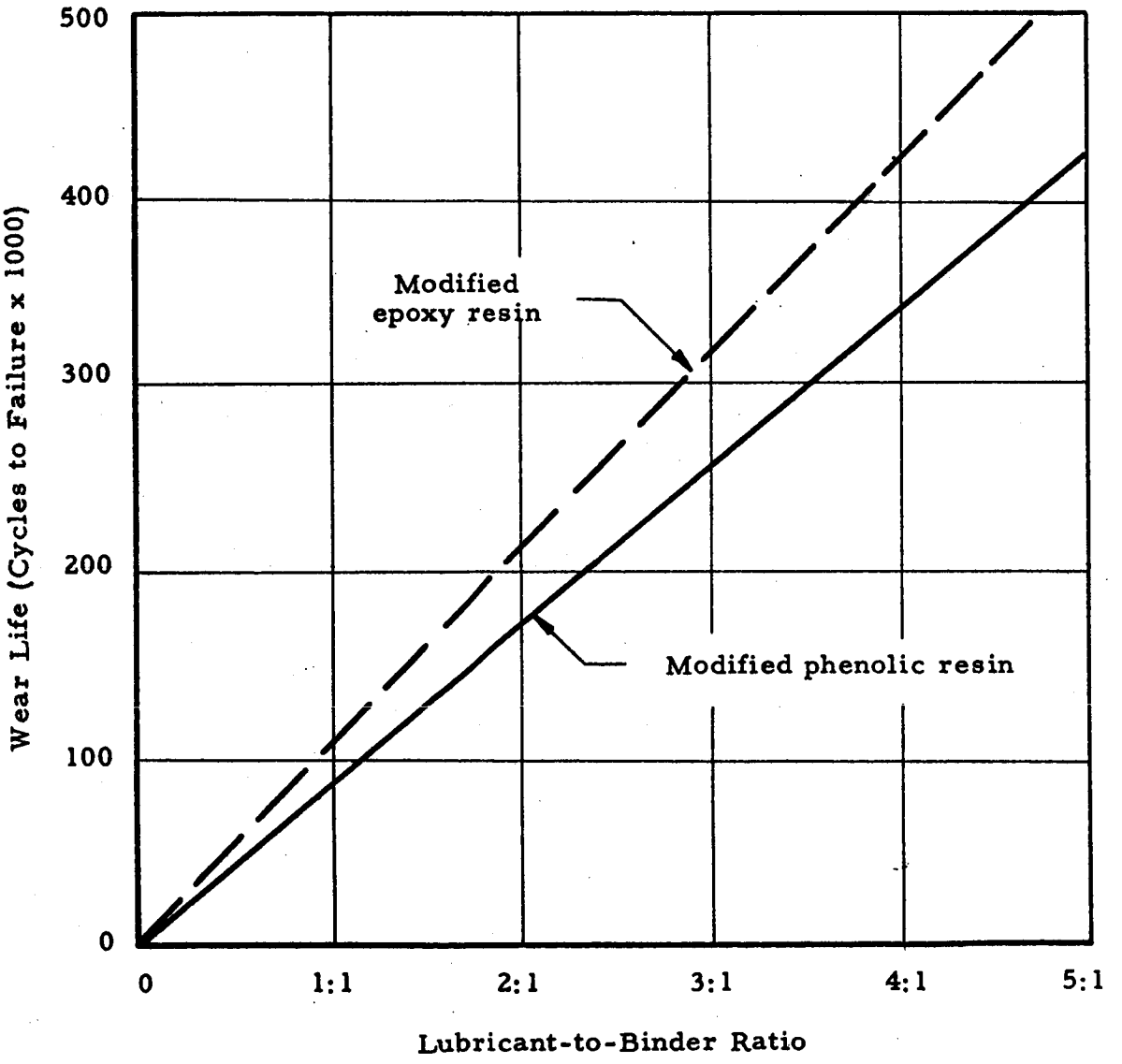


Figure 2. 3-9 Effect of Varying Lubricant-to-Binder Ratio on Wear Life Under Humidity and Temperature Controlled Conditions (Specimens Finished to 22 mu in. rms)

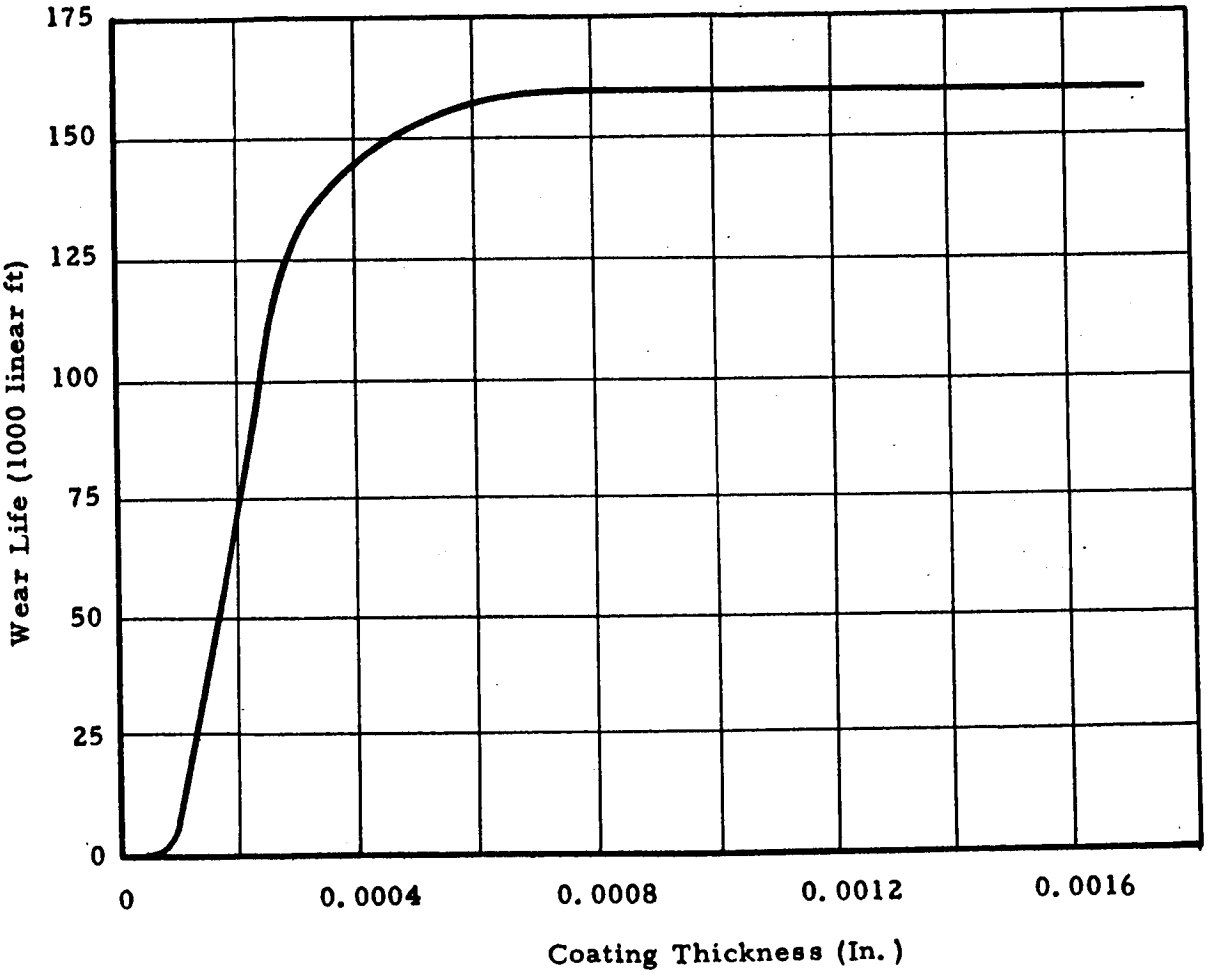


Figure 2.3-10 Wear Life vs Coating Thickness for a Typical Bonded Coating

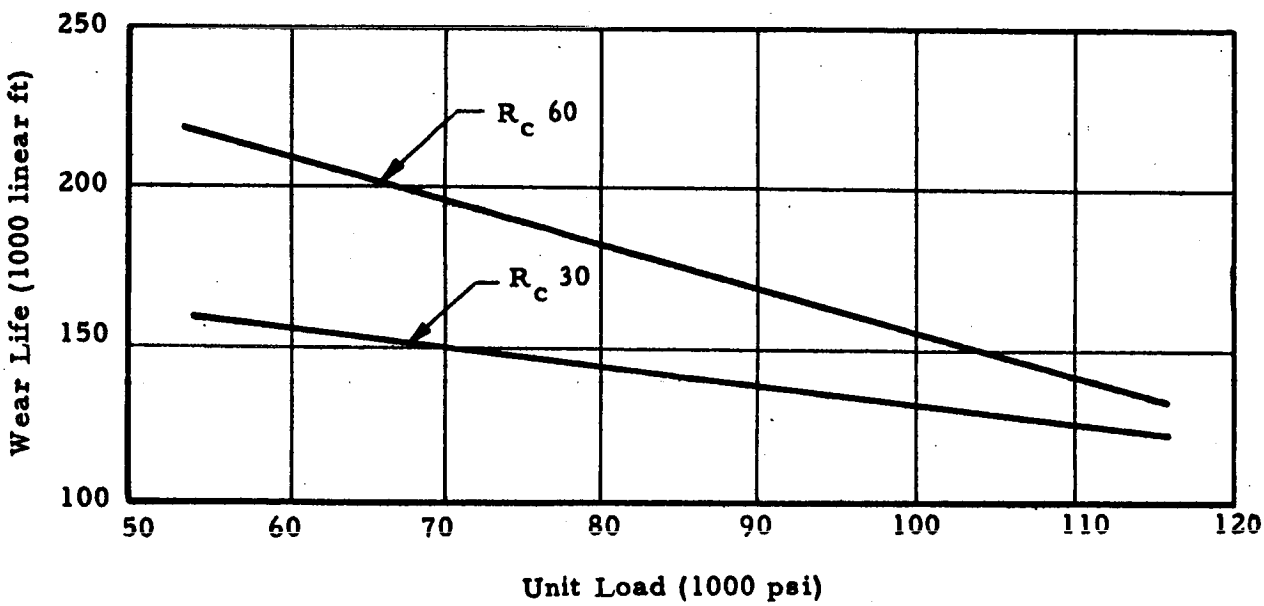


Figure 2.3-11 Variation of Wear Life With Load

Dry films may be applied manually, by brush, spray, or dip, or these latter operations may be performed automatically. For large batches, tumbling is generally the cheapest and most efficient method. For optimum service life, dry films should be deposited on surfaces which have been vapor blasted to 20-30μ-in. rms.

Thus, it can be concluded that for lubrication of bearings and gears for the penetrometer subsystem, based upon the preceding discussion, the most applicable method would be to use a bonded dry-film lubricant. This lubricant would most probably have MoS_2 as a vehicle in an epoxy or vinyl butyral binder. Figure 2.3-12 illustrates the coefficient of friction properties of MoS_2 as a function of the load.

Returning to bearings and their selection, the bearing applications in the penetrometer subsystem can be grouped into two general areas: (1) those bearings contained internally within the motor and which run at relatively high speeds, and (2) those bearings which are external to the motor. This latter grouping can also be split into two divisions. The first contains the four bearings in the storage module subjected to low speeds and low loads (quite low PV value). These bearings will most probably be of the flanged bushing type, manufactured from fiberglass filled Teflon, lubricated with MoS_2.

The second division contains the four bearings in the tube drive module. These bearings are subjected to low speeds, but relatively high loads (100-lb radial load) indicating a moderately high PV value. In the current preliminary design for the flight model penetrometer subsystem, these bearings are shown as radial ball (rolling-contact) bearings and were selected because of the PV value. However, current indications are that the aforementioned plastic bushings can also operate successfully in this area. The use of plastic bearings would, of course, effect a weight savings and, in general, provide at least as reliable a unit. The determination of the bearing type which will ultimately be used is a portion of the work planned for Phase II.

The bearings contained within the motor will most probably be rolling contact (radial-ball) bearings. Discussions with motor manufacturers indicate that one type of bearing that has been used in space environments is a steel or steel-Teflon ball bearing lubricated with MoS_2. Typical of such bearings is the "Bar-Temp" bearing manufactured by the Borden

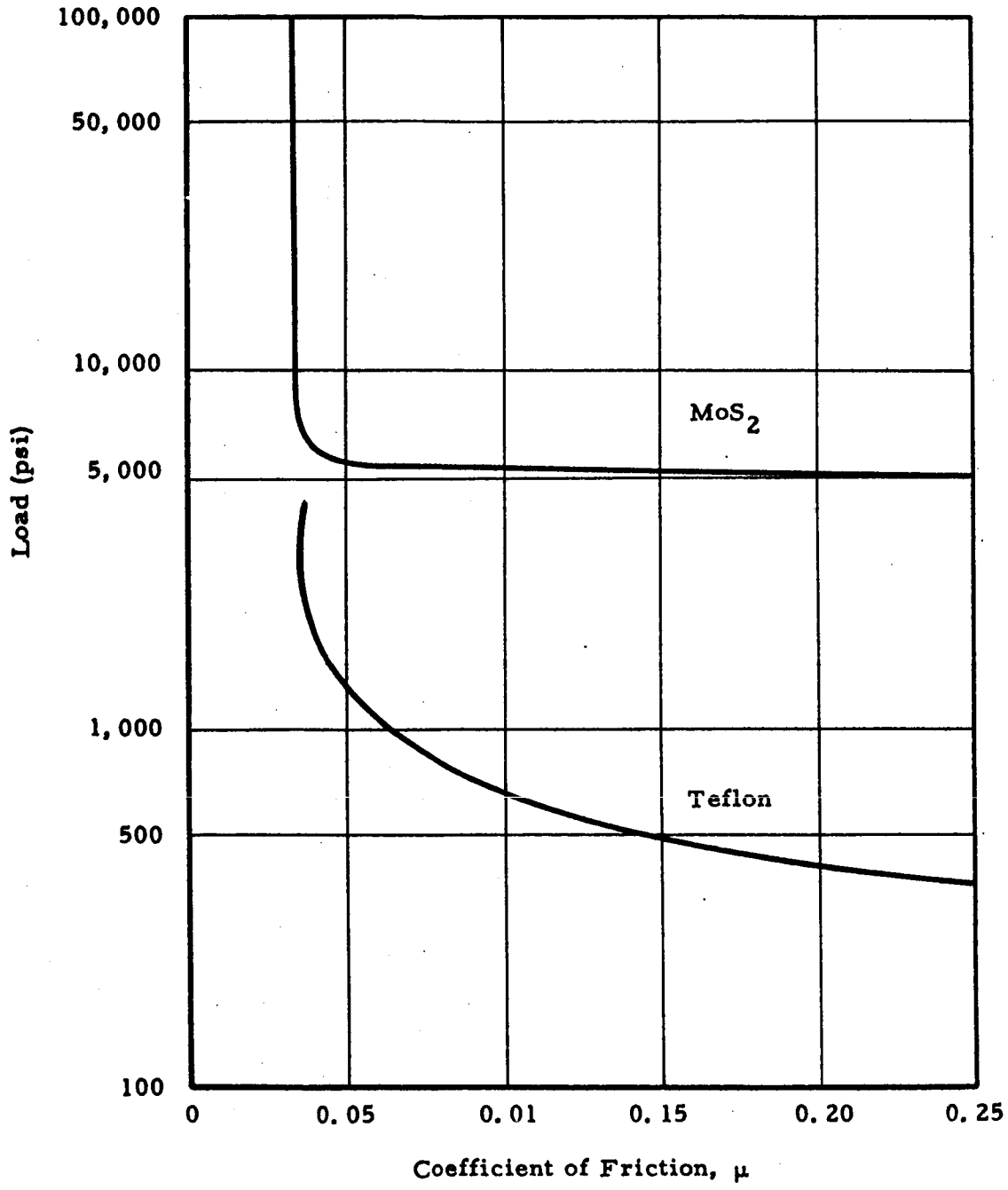


Figure 2.3-12 Comparison of Coefficients of Friction for MoS_2 and Teflon for Various Loads

Bearing Company. This radial ball bearing type is the one shown in the design drawings and mentioned above.

Gears - Reliability - Design Factors

The gears in the penetrometer can be grouped within three specific areas: (1) planetary gear reduction unit associated with the motor, (2) the larger gearing which couples the motor to the drive wheel, and (3) worm and wheel gearing employed in the position sensing circuit. All of the gearing in the first two areas is of the involute, spur type. For the purpose of discussing preliminary reliability design cirteria, this gearing can be further grouped into two classes:

1. High speed - low torque gearing

2. Lower speed - higher torque gearing.

The first category of gearing is used in the first stages of the motor gear reduction unit, while the second category is representative of the drive wheel gears.

To understand the various problems associated with gear reliability in a space environment, one must first understand the various ways in which gears may become unreliable. Since gear performance will primarily be evaluated by using design techniques and information, a knowledge of the gear design problem is necessary. The gear must essentially fulfill three requirements.

First, the gears must operate together without interference, with a proper length of contact, and without undue noise. The solution of this problem requires a knowledge of gear geometry. Secondly, the gear must have the ability to transmit the applied loads without failure and with a certain margin of safety. This involves the ability of the teeth to resist not only the load resulting from the power transmitted but also the increases in the load due to impact and shock caused by inaccuracy of tooth contour, tooth deflection and acceleration, stress concentrations at the root of the tooth, and finally cyclic loading, or tooth fatique. The total resulting load is commonly referred to as the dynamic load. Third, the wearing qualities of the tooth must be considered. The surface material along the tooth profile must be able to withstand the stresses imposed by the contact load, this load is known as the wear load.

Thus, the problem of designing and/or selecting reliable gears resolves to one involving considerations of:

1. Geometrical design consideration

2. Geometry, material, manufacture, and operational loading considerations

3. Environmental and operational "stress" considerations.

For the high-speed, low torque gears, the major problem appears to be one of excessive adhesive wear. The load-carrying capacity does not appear to present a problem. The most likely choice for this area is non-metallic gears. For many of the same reasons as were given in the section on bearings, fiberglass filled, nylon spur gears lubricated with MoS_2 present attractive qualities. Information on their most probable behavior in a hard vacuum and on their wear qualities was given in the preceding section.

The operational requirements for the lower speed, higher torque gears seem to indicate metallic spur gears. These gears should be made from surface hardenable steels,to allow for a hard wear surface and a tough inner case. In addition, the hard surface adapts well to the possible use of MoS_2 as a lubricant. Detailed parametric studies, including experimental investigations, to evaluate the reliability of alternate gear designs are planned for Phase II. However, it currently appears that the two classes of gears discussed here will both be employed in the penetrometer.

The problems associated with the third gear group, the worm and wheel, are minor. The speeds and the loads are both small. The current design calls for a bronze worm gear and a steel worm; however, indications are that fiberglass reinforced plastics can also be used here. In either case, a bonded film lubricant (MoS_2) is required.

Mechanical Reliability of Penetrometer Tubes - Fatigue as a Failure Mode

Having discussed the requirements for gears, bearings, and lubricants for the SLRV penetrometer subsystem and having made recommendations in these areas, it remains to discuss the penetrometer tube

and the storage drum drive springs. A material suitable for the penetrometer tube will be evaluated quantitatively. The results of this evaluation will be assumed to apply to the storage roll springs as well as to the tube itself.

The penetrometer tube is the heart of the SLRV penetrometer. This component alone dictates requirements for relatively high reliability. In addition, however, this device is a relatively new concept in comparison with the other elements in the system, and the degree of confidence which can be associated with a specific reliability number is correspondingly less. Thus, in order to obtain the highest possible confidence level on the tube reliability, an exhaustive analysis must be made. The major failure mode for the tube itself is fatigue fracture. The study of this failure mode constitutes the subject of the following discussion.

The preliminary analysis of tube fatigue life has already been discussed in Volume III, Book 2, Section 6. However, part of that discussion will be included herein to provide continuity. In addition, the present discussion is concerned with the flight model hardware in a lunar environment, while the previous discussion centered about the ETM. The techniques discussed are similar, but the numbers will differ. The aforementioned analysis was principally concerned with the 50-percent reliability level for mean life. The current discussion will associate probability of failure at the value stated for a given stress level in the penetrometer tube.

The geometry of the tube remains unchanged (0.004-in. thick, 3/4-in. diameter); however, the material and the hardness of the material are different. Reliability parameter studies and material behavior characteristics in a lunar environment have dictated that the tube hardness be lowered to a value of 40 → 45 points on a Rockwell C scale, and the tube material for the present analysis be changed from AISI 1095 steel to either a Chrome-Vanadium Alloy Steel (SAE 6150) or a Chrome Silicon Alloy Steel (SAE 9254). For the present discussion, and in consequence of fabrication requirements, consider the use of the former steel.

A typical stress-number of cycles (S-N) diagram for the SAE 6150 steel is given in Figure 2.3-13.[1] The stress cycle through which any particular point on the tube must pass is different for the ETM than that

[1] The S-N curves used were constructed from data contained in The Mechanical Properties of Four Heat-Treated Spring Steels, Hankins G. A. and Ford G. W.

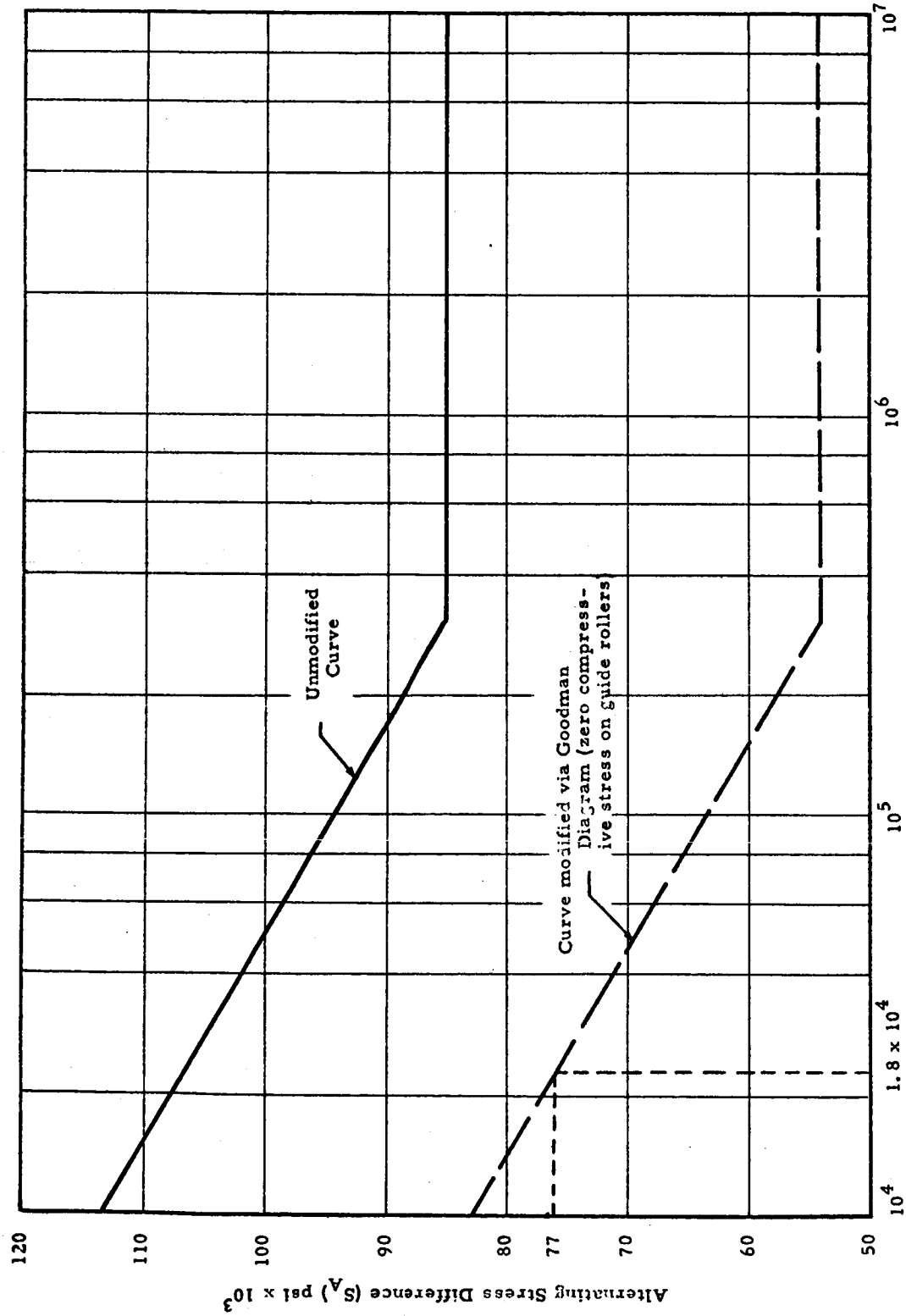


Figure 2.3-13 Chrome-Vanadium Steel S-N Curve

considered for the SLRV penetrometer. The addition of roller guides, constraining the edges of the tube, causes that portion of the tube to experience relatively high compressive stresses. From Volume III, Book 2, Section 6, they are assumed equal to the yield point stress of the material (apparently a conservative figure) which is

$$S_{yp} = 162,000 \text{ lb/in.}^2$$

The stress cycle is illustrated in Figure 2.3-14. It should again be mentioned that, when dealing with tensile stresses, the concept of stress intensity (S.I. = $|\sigma_i - \sigma_j|$, $i \neq j$) may be useful. When compressive stresses are present, the sign value of the stresses becomes quite important, and the stress difference (S.D. = $(\sigma_i - \sigma_j)_{max}$, $i \neq j$) is commonly used. Thus, the S.D. vs stress state diagram above is the result. The values for σ_i are as previously given except for $(\sigma_i)_B$ which is equal to the yield point stress of the material.

From a calculation of the stresses in the tube, the following values are obtained for Figure 2.3-14:

$$S_R = \text{S.D.}_C - (-\text{S.D.}_B) = 140,000 + 142,000 = 292,000 \text{ lb/in.}^2$$

$$S_A = \frac{SR}{2} = \frac{292,000}{2} = 146,000 \text{ lb/in.}^2$$

$$S_M = \frac{\text{S.D.}_C + (-\text{S.D.}_B)}{2} = \frac{140,000 - 142,000}{2} = -6000 \text{ lb/in.}^2$$

The preliminary fatigue evaluation employed the Goodman Diagram to compensate for the existence of a tensile mean stress (stress intensity). This effectively lowered the S-N curve from its initial position. It can be shown, however, that a mean stress (stress difference) which is compressive will not similarly affect the S-N curve. For engineering calculations, the existence of a compressive mean stress will not affect the S-N curve to any appreciable degree. Thus, the unmodified S-N curve for the tube material (as shown in Figure 2.3-13) will be used with an Alternating Stress Difference (S_A) of 146,000 psi. An extension of this curve to lower values of N is given in Figure 2.3-15. Thus, by intersecting the curve as

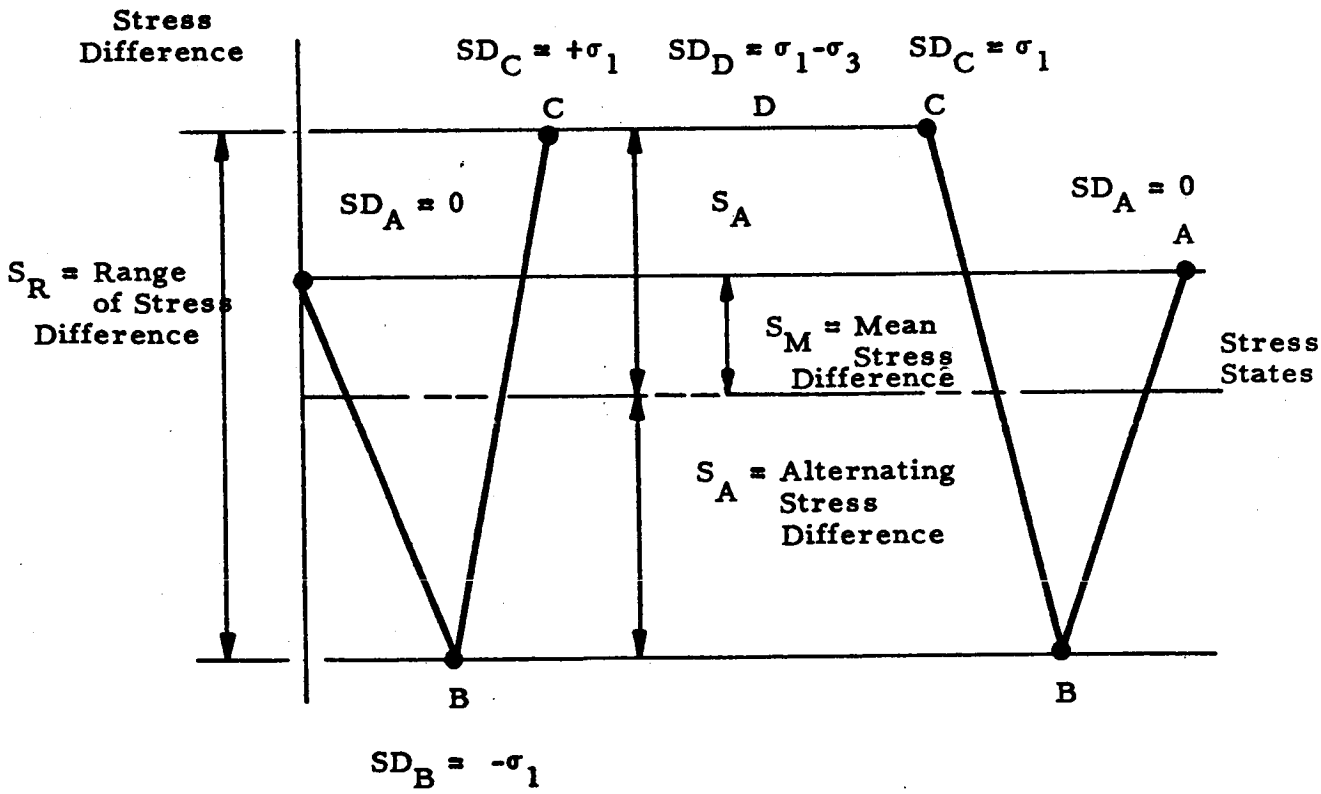


Figure 2.3-14 Typical Stress Cycle

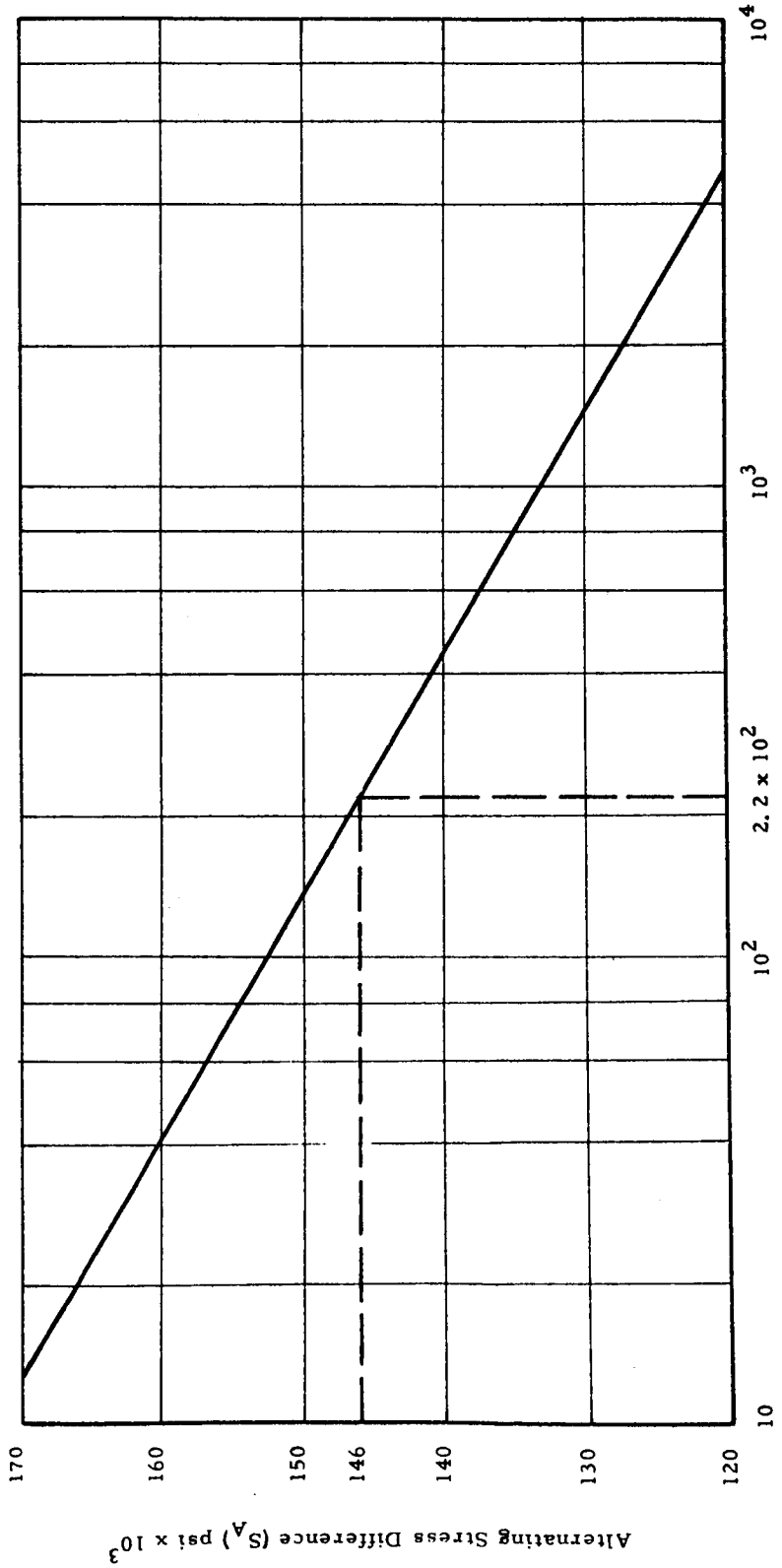


Figure 2.3-15 Chrome Vanadium Steel Low Cycle S-N Curve

shown at S_A = 146,000 psi the 50-percent fatigue life, N_{50}, for the tube can be obtained. This value is

$$N_{50} = 220 \text{ cycles.}$$

From a reliability standpoint, a reliability of 50% is relatively poor. A more desirable approach would be to express the fatigue life N over the entire probability range, using alternating stress (stress difference) as a parameter.

It is indicated in the literature that the fatigue life distribution at a specific constant value of alternating stress follows the log-normal distribution, or that log N is normally distributed.[1] (See Figure 2.3-16.) Some authors indicate that at the extreme ends of the distribution, for probability of failure greater than 0.9 and less than 0.1, the extreme value distributions of Gumbel and/or Weibull are more representative. However, in this discussion the log-normal distribution will be applied throughout. This distribution is given by

$$F_{(N)} = \frac{M}{N\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(\log N - \log C)^2}$$

where

N is a particular number of cycles

log C is the mean value of log N

σ is the log standard deviation

M = log e = 0.4343

log = log to the base 10.

The establishment of a probability of survival or failure relationship using the log-normal distribution requires information on the two statistical parameters describing the distribution function; the measure of

[1] Dieter G.E., Mechanical Metallurgy, McGraw-Hill Book Co., Inc, New York, New York, 1961.

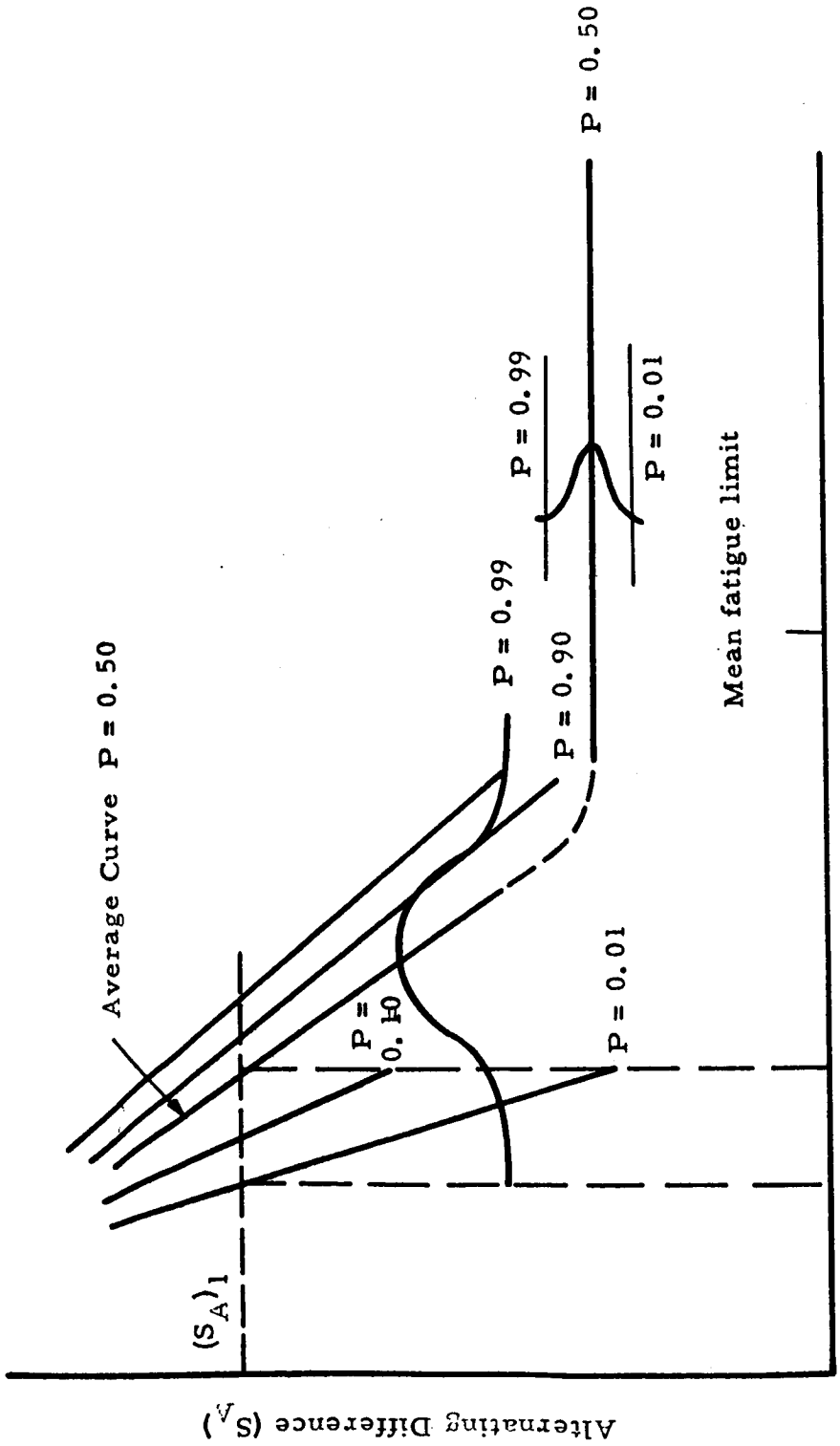


Figure 2.3-16 Representation of Fatigue Data on a Probability Basis

central tendency (log C), and the measure of the dispersion about the mean (σ). It is at this latter point that difficulty is encountered, for data is generally not obtained in sufficient quantity to allow an estimation of this parameter. Thus, data for S-N curves generally contain no information on the variance about the mean value.

To proceed to the desired ends, use must be made of whatever variability data on fatigue life of steel are available. From the literature,[1] variability data for Bofors FR86 steel are available. This steel is a high class alloy steel, exhibiting good metallurgical control in its manufacture. It is assumed (with considerable justification) that these variability data are applicable to SAE 6150.

The variance data for the FR86 steel are given for stress values which are in general different than those for which we wish to plot probability of survival. To allow extrapolation of the data, the curve shown in Figure 2.3-17 was drawn. This curve relates σ for FR86 steel to the level of Alternating Stress Difference. This curve indicates, as would be expected, a decrease in σ as $(SD)_A$ increases. In addition, it is assumed that the mean values of the distribution are contained in the conventional S-N diagram.

The application of the variance data in estimating failure probabilities involves selecting the value of σ for the appropriate stress value and applying it, together with the mean value data, to the log normal distribution. The resulting probability of survival (or failure) curve for the particular stress level can then be plotted on log normal probability paper as a cumulative distribution. Such a curve for the tube fabricated from SAE 6150 is shown in Figure 2.3-18. Here the probability of survival (failure) is plotted as a function of the number of stress cycles for an alternating stress difference of 146,000 psi.

The reliability vs cyclic life is strongly influenced by the alternating stress difference which in turn is controlled by the contact pressure between the tube edges and the roller guides. A bounded solution for the 50-percent values of N for the two extremes of contact stress, yield point and zero, are 220 cycles and 17,000 cycles, respectively. The curves shown in Figures 2.3-18 and 2.3-19 respectively represent a parametric representation of reliability with S_A (a function of contact pressure) as a parameter.

[1] Fatigue and Fracture of Metals, Proceedings of the Symposium held at MIT in June of 1950; edited by W. M. Murray, John Wiley and Sons, Inc, New York.

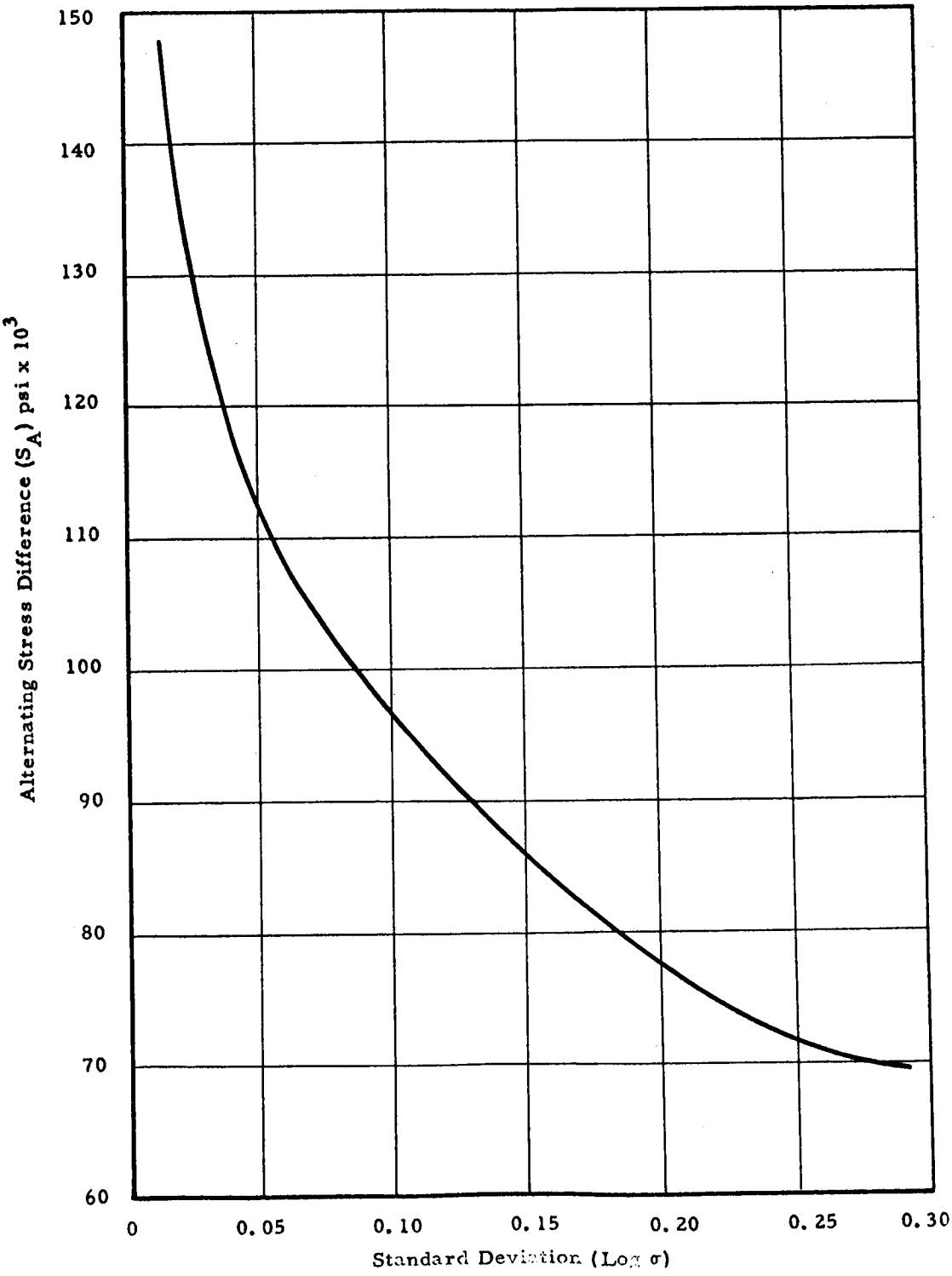


Figure 2.3-17 Approximate Relationship Between Alternating Stress Difference and Standard Deviation for BOFARS FR86 Steel (Extended Curve)

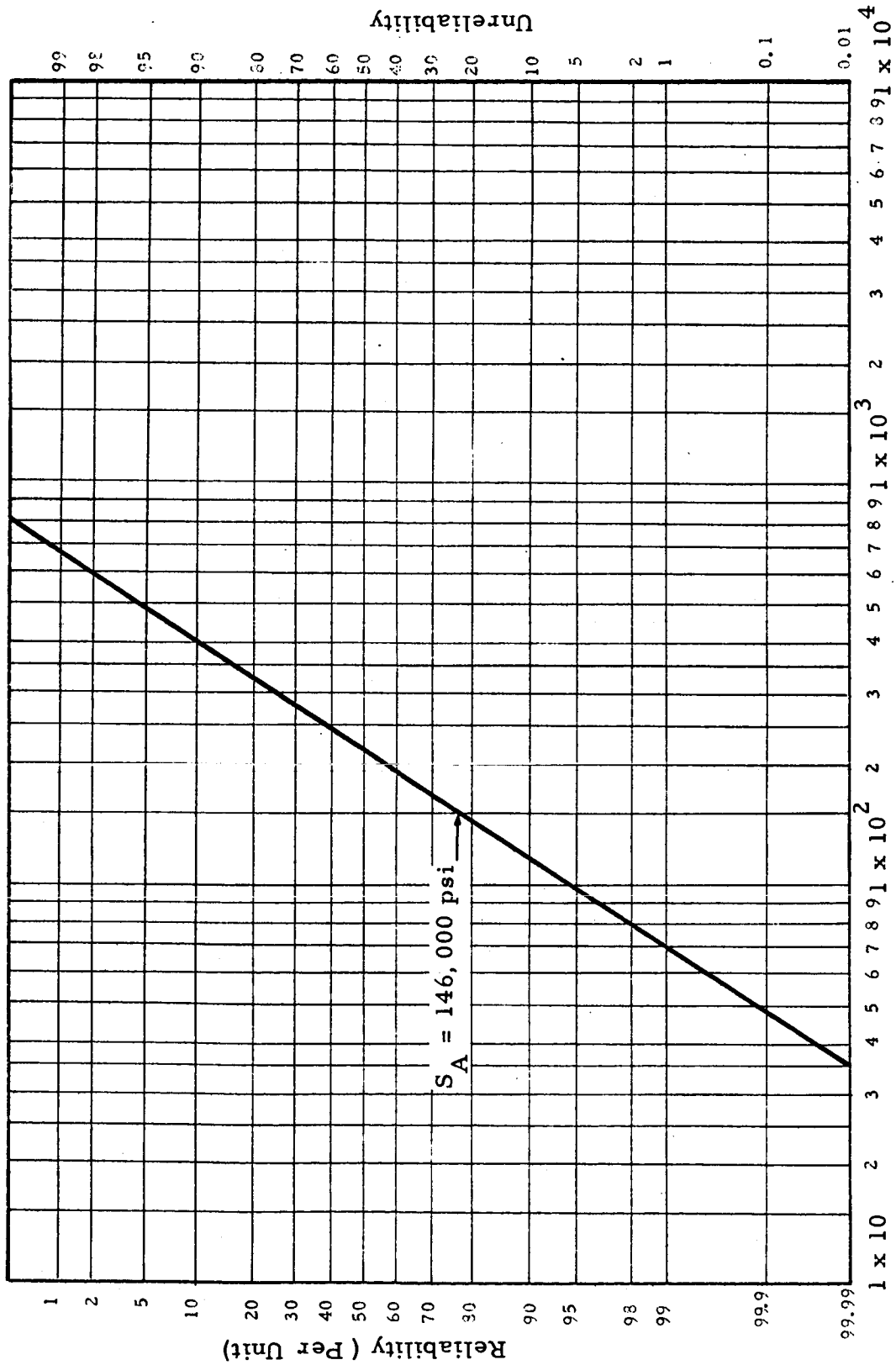


Figure 2.3-18 Chrome Vanadium Steel Failure Probability Curve (S_A = 146, 000 psi)

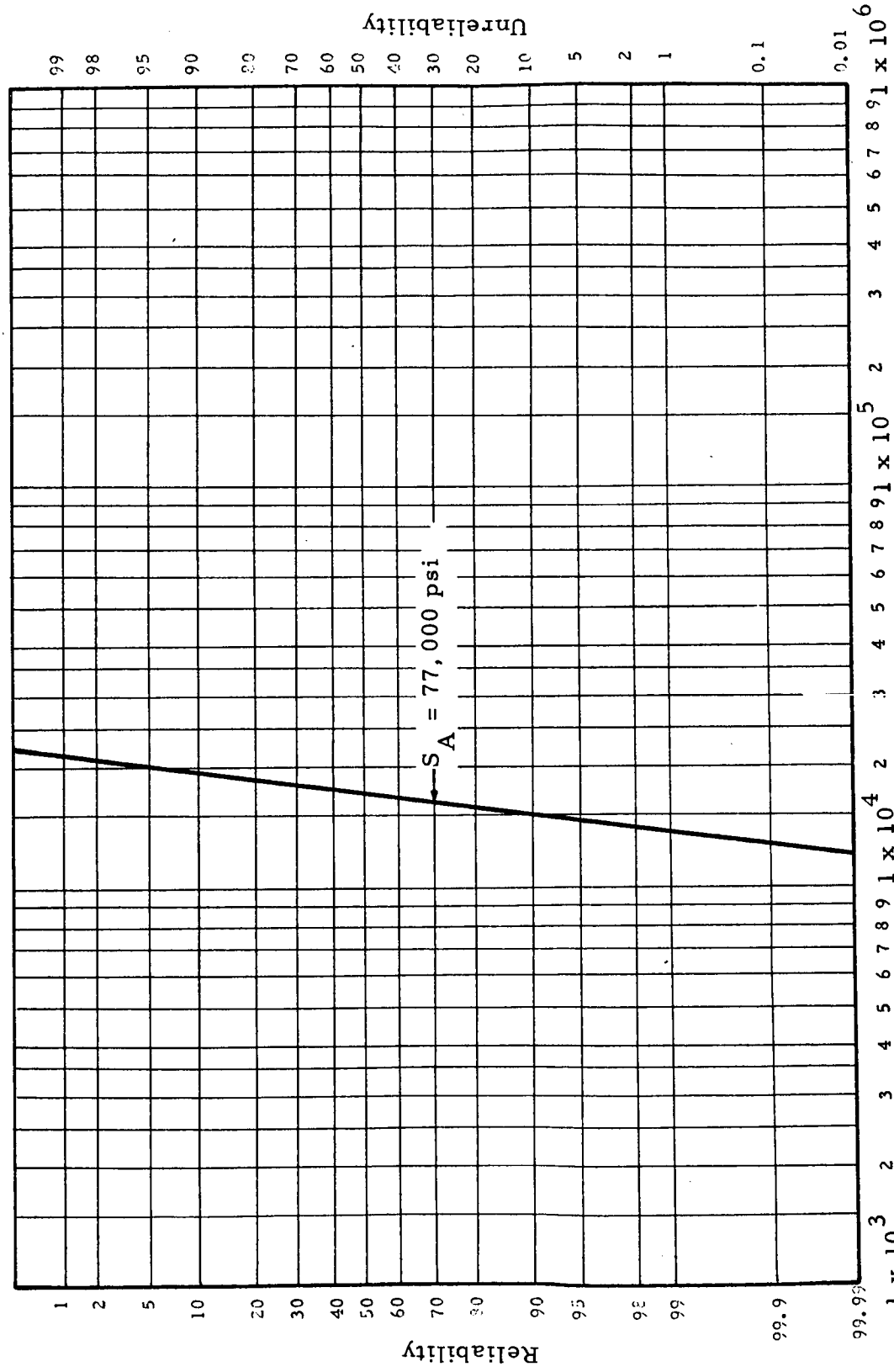


Figure 2.3-19 Chrome Vanadium Steel Failure Probability Curve (S_A = 77,000 psi)

The curves can be plotted easily on the basis that when log N= log C the probability of survival is 0.50, and when log N = log C + log σ the probability of survival is 0.1517, giving two points which identify the probability of survival line for a particular value of alternating stress.

Thus, through the use of fatigue life information as given in the S-N curve and the application of available data on the fatigue life standard deviations for a particular material to a class of similar materials, the probability of survival of a device under fatigue can be estimated, given that either the stress or expected life is known.

Parametric studies on the tube indicate that under lunar environment another applicable tube material might be one of the 18-8 class of stainless steels. These steels exhibit moderate fatigue resistance (not as good as say chrome vanadium or silicon manganese) but exhibit better behaviorial characteristics under hard vacuum and low temperatures near the cryogenic region.

In accordance with the above discussion and in keeping with the preceding analysis for SAE 6150 steel, the following analysis for a typical AISI, 18-8 class stainless steel is presented.

A typical stress-number of cycles (S-N) diagram for an 18-8 stainless steel is given in Figure 2.3-20 (see the unmodified curve). The applicable stress cycle for any particular point on the tube is as presented in the preceding analysis. The compressive stress level which the tube sees as a result of contacting the roller guides is a function of the contact pressure. The exact amount of contact pressure depends upon several factors. For the purposes of this analysis, the level of compressive stress was permitted to vary between the material's yield point and zero.

A typical 18-8 stainless steel exhibits a range of values for the ultimate stress S_u and the yield point stress S_{yp}, depending upon the amount of work hardening done on the material. Figure 2.3-21 illustrates this relationship (assumed linear). Since the computed value for the maximum tensile stress in the tube is 140,000 psi, it is assumed that the yield point stress of the 18-8 steel is 150,000 psi. The corresponding value for S_u is 237,000 psi. For these stresses, the material must be work hardened to approximately $R_c = 40$.

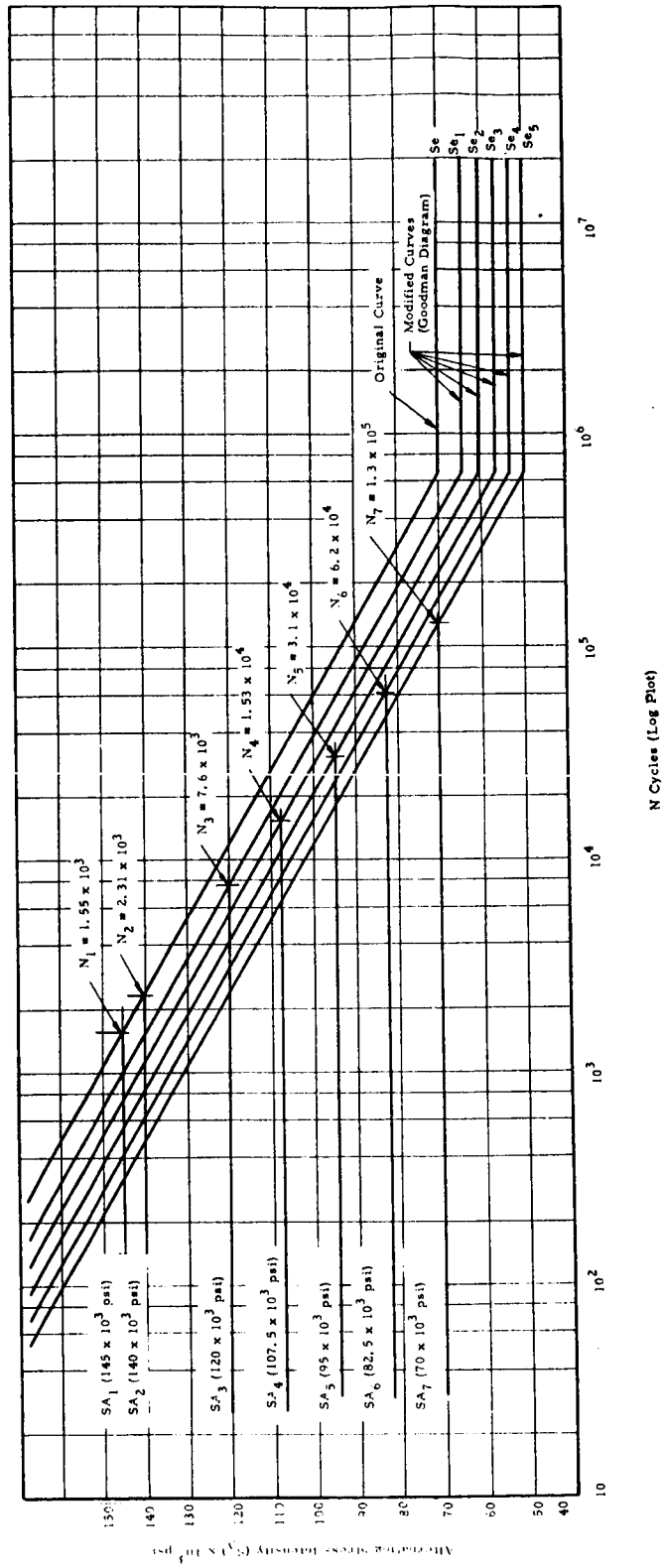


Figure 2.3-20 Original and Modified S-N Curves for 18-8 Stainless Steel

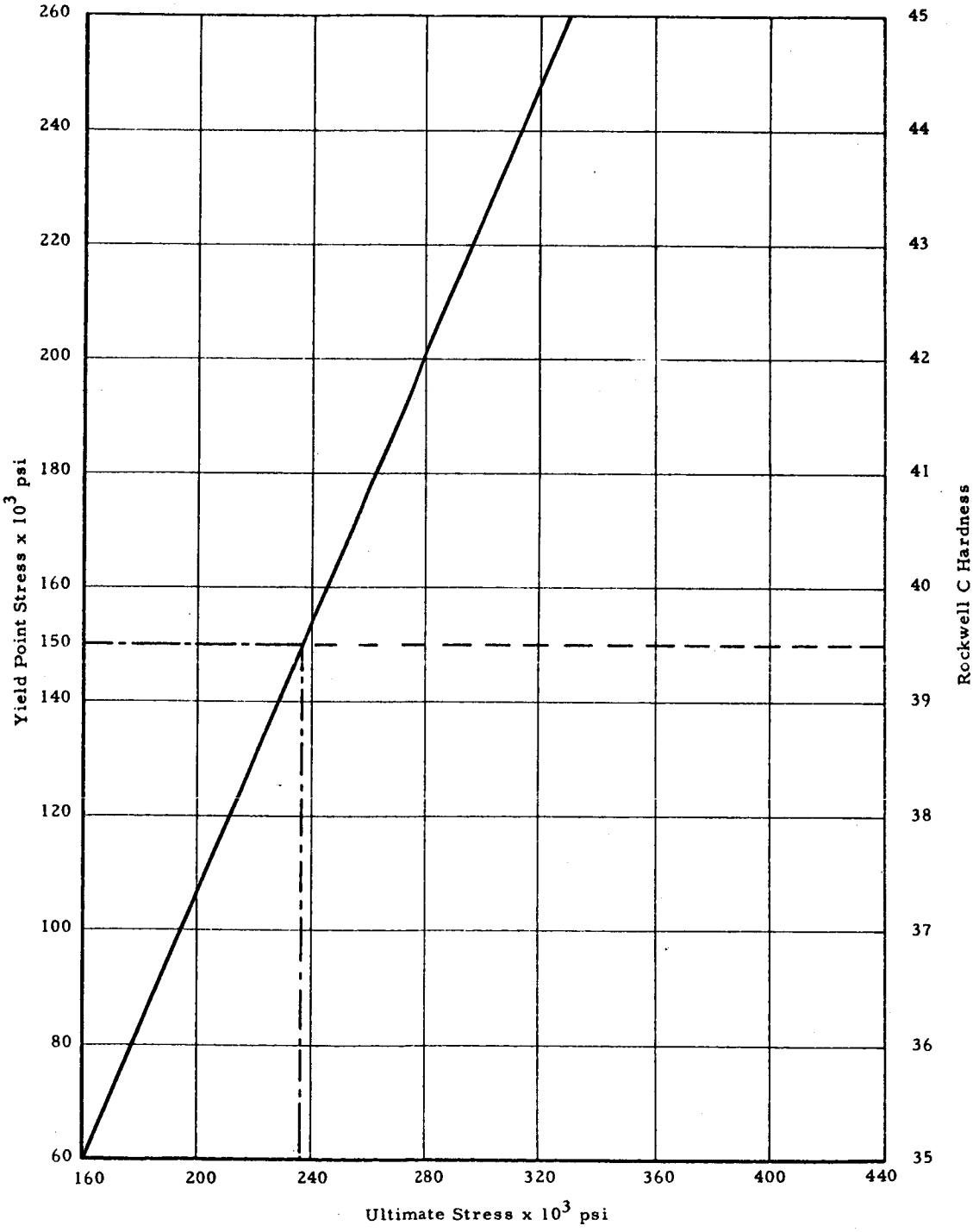


Figure 2.3-21 Linear Approximation for Ultimate Stress vs Yield Point Stress and Rockwell C Hardness for Work Hardened 18-8 Stainless Steel

The values of the mean stress intensity S_M and the alternating stress intensity S_A vary, as the level of compressive stress varies. The relationship between S_M and the compressive stress is illustrated in Figure 2.3-22. As the level of compressive stress decreases, the value of S_M goes from compression to tension. When S_M is compressive, the unmodified S-N curve can be used; however, when S_M is tensile, the S-N curve must be modified through the use of a Goodman diagram. This fact was discussed in the preceding analysis.

To ultimately provide a range of reliability data, several values of S_M are considered. The corresponding values of S_A are shown in Figure 2.3-20. To plot these modified values of the S-N curve, the aforementioned Goodman diagram was used. Figure 2.3-23 illustrates this diagram. For values of S_M equal to -5000 psi and 0 psi, the unmodified S-N curve can be used. For values of S_M equal to +20,000 psi, the Goodman diagram must be used to modify the S-N curves. These points are shown in Figure 2.3-23. The resulting lowering of the endurance limit values (S_e^{-1}) due to the use of the Goodman diagram is shown as a function of the mean stress difference S_M in Figure 2.3-24.

The S-N curves contained in Figure 2.3-20 are converted to corresponding P-S-N curves (probability of failure) using the same techniques discussed in the preceding analysis of chrome existing steel. To achieve the desired results, use must be made of any exciting variability data on the fatigue life of stainless steel. A quite limited amount of such data is available, with the variability given as a function of the alternating stress intensity. To encompass a sufficiently wide range of values for S_A, the existing data must be extended.

Such an extension of variability data is shown in Figure 2.3-25. Also on the same curves are indicated the values of σ_i and S_{A_i} associated with the aforementioned point of analysis. Using these data and the assumed log-normal distribution, the reliability curves for the seven specific values of S_{A_i} previously mentioned are plotted in Figures 2.3-26 and 2.3-27.

Thus, as before, through the use of the S-N curve and variability data, the probability of survival of a device under fatigue can be estimated, given that either the stress or expected life is known.

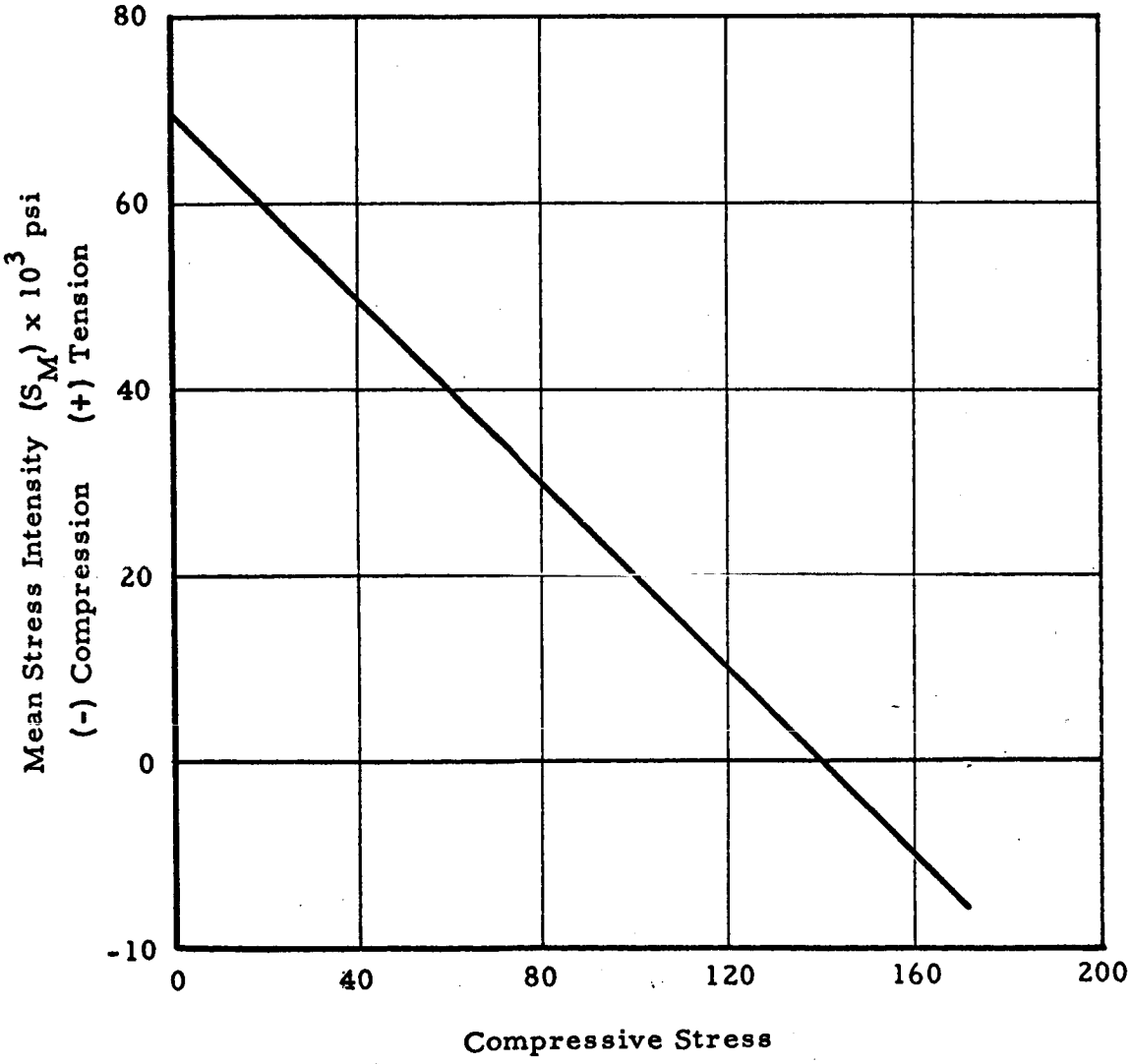


Figure 2.3-22 Mean Stress Intensity vs Level of Compressive Stress for Penetrometer Tube

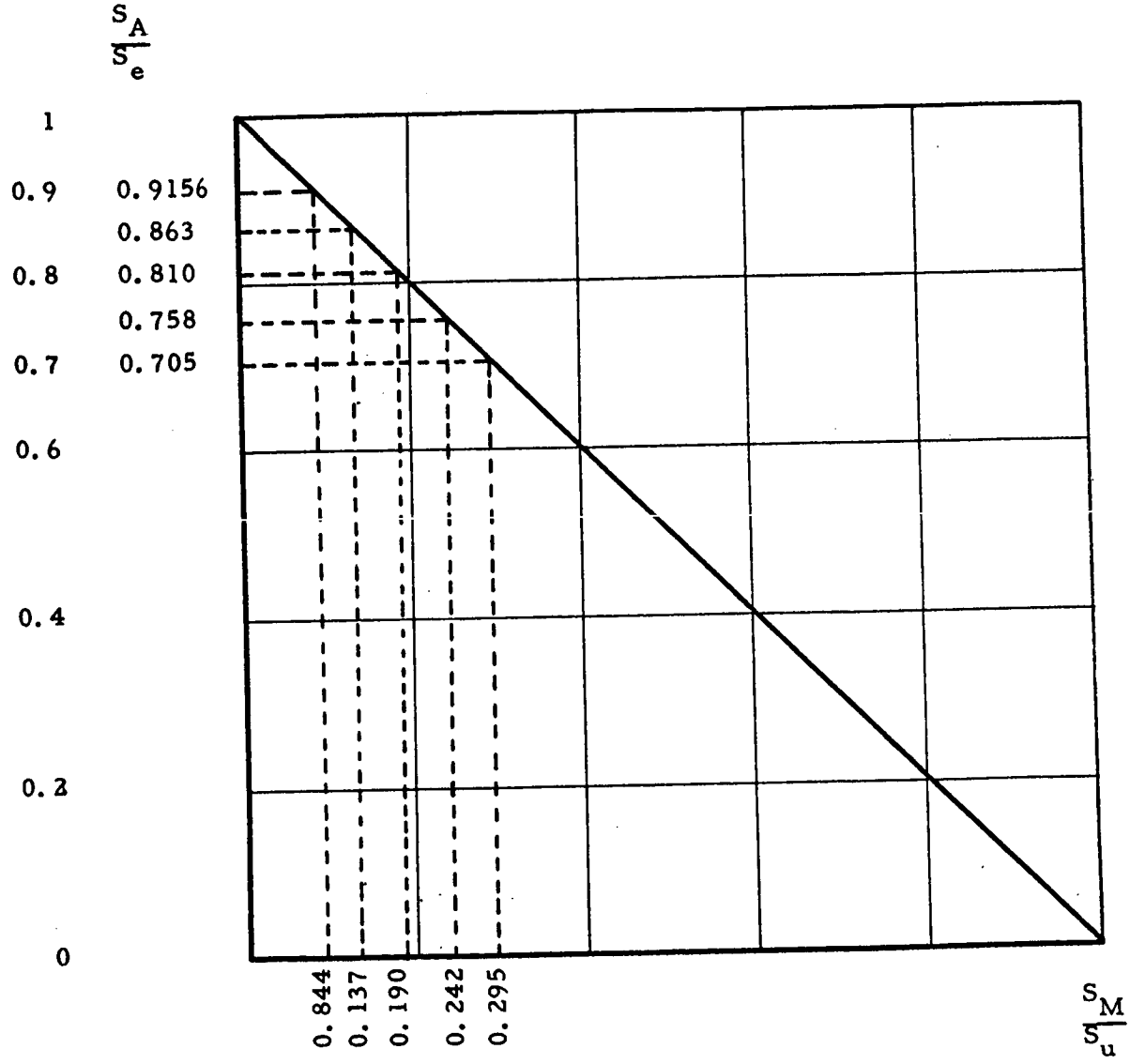


Figure 2.3-23 Modified Goodman Diagram for a Typical 18-8 Stainless Steel

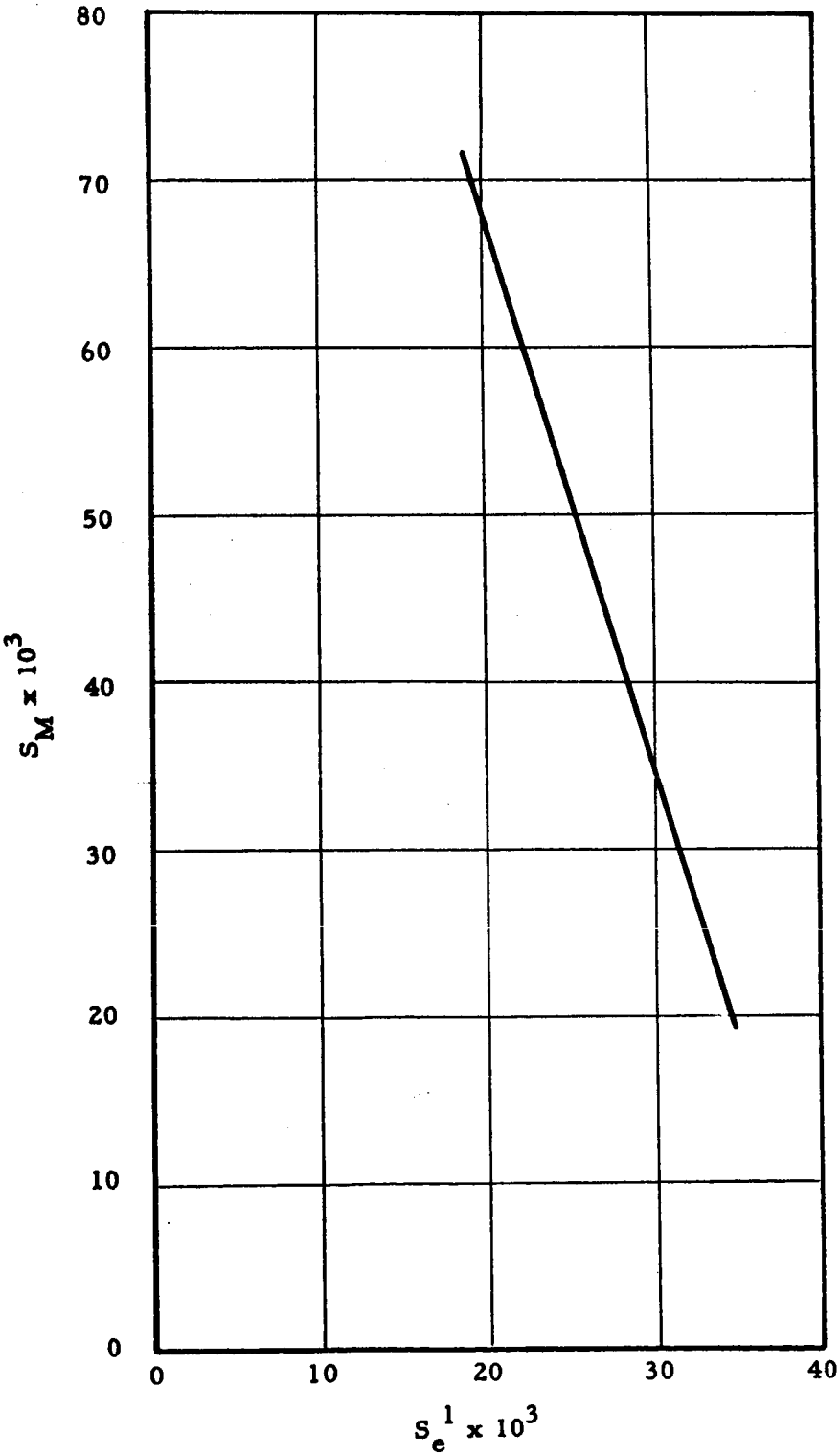


Figure 2.3-24 Modified Values of Endurance Limit (S_e^1) Due to the Use of the Goodman Diagram vs Mean Stress Difference (S_M)

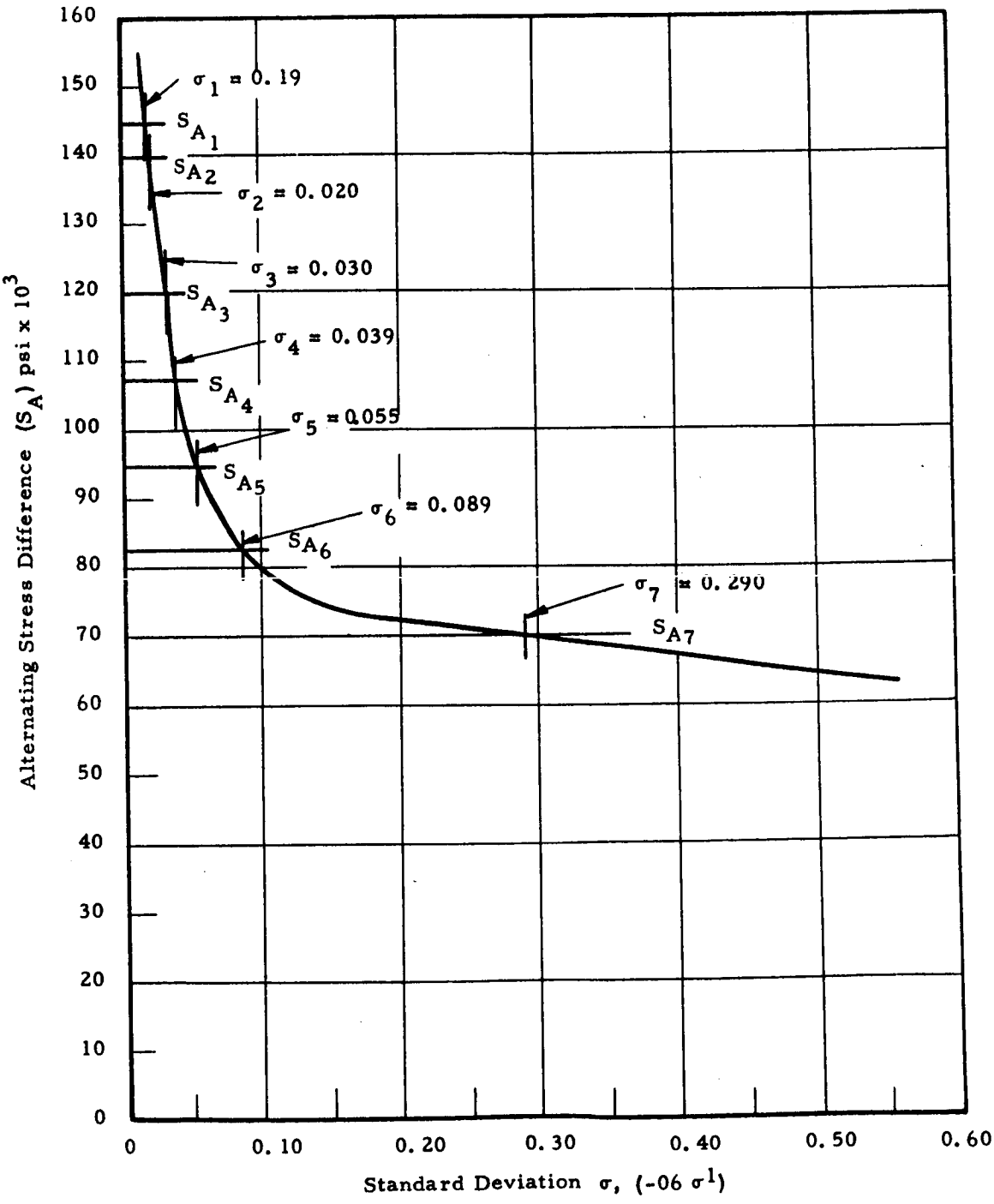


Figure 2.3-25 Approximate Relationship Between Alternating Stress Difference and Standard Deviation for a Chrome-Nickel (18-8) Steel (Extended Curve)

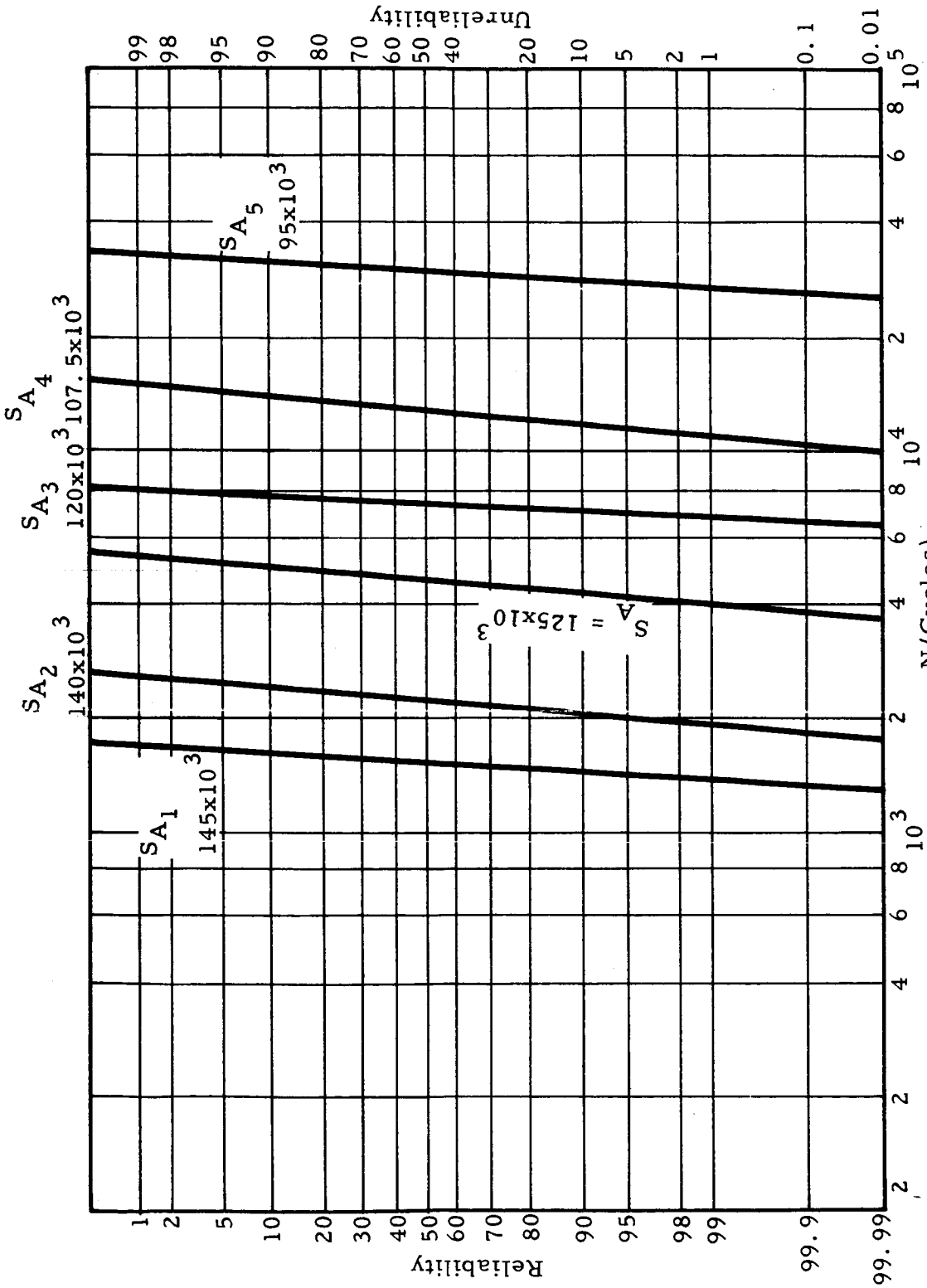


Figure 2.3-26 Typical 18-8 Stainless Steel Failure Probability Curve (Sheet 1 of 2)

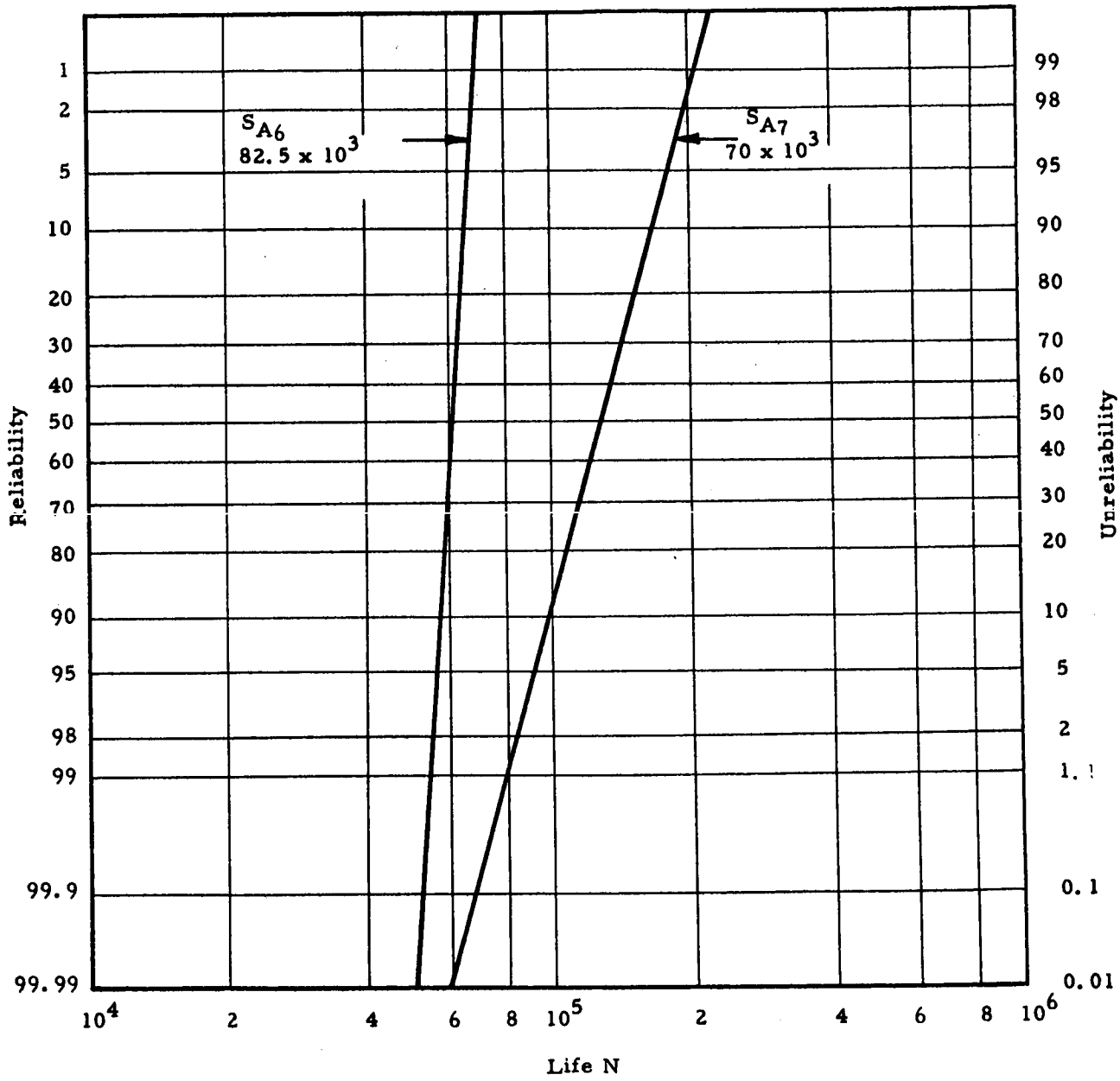


Figure 2.3-27 Typical 18-8 Stainless Steel Failure Probability Curve (Sheet 2 of 2)

One additional specific problem associated with the use of 18-8 stainless is the fact that it cannot be heat treated, but must be work hardened. This requires a change in the procedure for manufacturing the tube, indications based upon discussions with spring manufacturers are that the fabrication of springs (penetrometer tube) from stainless steel can successfully be accomplished.

Considerations similar to the above also apply to the Negator springs used to load the tube storage and wire storage drum. For these springs, the manufacturer states that a life of 5000 cycles should be obtained from any of their stock springs and that springs manufactured from 18-8 stainless steel are available. The balancing springs (coiled, helical) in the LVDT unit can likewise be manufactured from the same material.

Pressure Drive Rollers

The pressure drive rollers will most probably fail to operate properly in either of two modes. The rolls can slip and hence fail to extend or retract the penetrometer tube; conversely, they could cold weld to the tube and thus impede or prevent tube motion. The obvious solution to each of these problems in turn represents no solution to the other and, in fact, may tend to worsen it. Thus, the problem of slippage could be greatly reduced by increasing the normal contact force between the rollers and the tube; however, this increases the possibility of cold welding. On the other hand, the problem of cold welding can be eliminated by lubicating the tube (or the rollers) with MoS_2, which would increase the tendency for the rollers to slip. The solution to this problem must be in the form of a trade-off between the requirements for preventing the two failure modes.

The most likely solution fulfilling these requirements is to coat the contacting surfaces of the pressure rollers with a 1-3 mil thick coating of an epoxy resin. The epoxy coating will effectively eliminate the possibility of cold-welding. In addition, the coefficient of friction between steel and epoxy is relatively high. In fact, if alumina (Al_2O_3) powder is mixed with the epoxy prior to its application to the rollers, this coefficient of friction can be increased. Concentrations of alumina up to 20% will not seriously affect the strength of the epoxy. The resin exhibits a good strength characteristic in terms of Hertizian loading. Thus, the use of reinforced resin may represent a suitable solution to pressure roller failure.

Thus, from the preceding discussions of operational feasibility, design integrity, and the various parameter studies, the materials and/or configurations for the critical mechanical component parts for the SLRV penetrometer subsystem can now be selected. Table 2.3-11 indicates IIT Research Institute's preliminary recommendations for the critical mechanical components for the SLRV penetrometer subsystem. It should be pointed out that, while the conclusions and recommendations made herein reflect good engineering approaches to preliminary design, the actual feasibility of these items must be evaluated experimentally. Similarly, to make an intelligent reliability assessment of the penetrometer, extensive experimental evaluation of materials and configurations under simulated space environments must be made. These are, of course, a large part of the scope of work for Phase II.

Penetrometer Electrical Wiring Considerations

Although the electrical wiring in the penetrometer subsystem has not been considered as a separate component for reliability study, operation of the penetrometer does depend upon the reliable performance of the interconnecting wiring. In the penetrometer subsystem, the electrical stresses should not present any great problem in view of the low voltage and current levels which are expected. The principal problems which must be considered are the mechanical stresses and the interaction of the insulation material with the lunar environment. The most severe stresses to be expected on the wiring would probably be under conditions of lunar night operation, where a portion of the connecting wiring to the penetrometer probe tip would be exposed to extremely low temperature state, the actual temperature of the wiring depending upon the heat transfer characteristics of the wiring configuration, the length of time of exposure, and the internal penetrometer and external lunar temperatures.

From information available on the general properties of insulation materials available for space applications, TFE and FEP fluorocarbons presently appear to offer the most suitable characteristics.[1] The high and

[1] Survivability of Wire on Moon Tested," Aviation Week and Space Technology, Vol. 78, No. 21, May 27, 1963, p. 77, McGraw Hill Publishing Co.

Adams, H. S. "Problems in Insulated Wire and Cable in Space Vehicle Systems," Electro-Tech., Vol. 72, No. 3, Sept. 1963, p. 133, Conover-Mast Publ. Co.

TABLE 2.3-11

SUMMARY OF MECHANICAL COMPONENTS BASED UPON PARAMETRIC STUDIES - PENETROMETER SUBSYSTEM

Part	Configuration	Material	Remarks
Penetrometer Tube	Flat sheet stock prestressed to form a tube upon unrolling.	18-8 stainless steel work hardened to approximately $R_c = 40$ with a $S_{yp} = 150,000$ psi	The use of 18-8 requires a change in the tube fabrication specifications. Will require extensive-hard vacuum-fatigue tests. Test with S_A as parameter, results plot as P-S-N diagrams.
Tube storage Drum and Wire Storage Drum, Drive Springs	Negator springs in a "B" motor configuration	18-8 stainless steel as per the penetrometer tube.	Stock items - Hunter spring
LVDT Balancing Springs	Standard helical coiled springs	18-8 stainless steel as per above	Stock items - commercial spring manufacturer.
Bearings	Flange type journals or bushings	Fiberglass filled teflon	Lubricate with MoS_2 bonded dry film lubricant.
	Rolling contact, radial ball bearings	Teflon-steel balls - races	Lubricate as above - "Bar-Temp" bearings typical subsequent evaluation may eliminate this type of bearing from penetrometer system.
Gears	Involute spur	Fiberglass filled nylon	In general, gears to be lubricated with MoS_2 bonded dry film lubricant. The use of non-metallic gears in the motor gear reducer is also intended.
	Worm and wheel	Fiberglass filled teflon worm gear - fiberglass filled nylon worm	
Pressure Drive Rolls	Right circular cylinders	Aluminum cylinders coated with alumina (20%) filled epoxy resin	Thin coating to minimize stress cracking care taken in epoxy formula used to minimize creep.

low operating temperature limits are beyond the expected lunar surface temperatures of -173°C to +127°C. Particularly important is the low temperature flexibility characteristic. Both materials perform suitably at ± 180°C. The outgassing and radiation resistance characteristics under vacuum conditions appear to present no significant problems. The flexure life required (up to 4000 cycles) also appears to be well within the flexure life limits of stranded insulated wire, particularly if smaller size wires in the area of No. 24 are used.

2.3.2 Failure Mode and Criticality Analysis

A failure mode and criticality analysis has been carried out to determine the primary modes of failure, the estimated likelihood of each failure, and the effect of the failure upon penetrometer subsystem operation. The analysis has been conducted essentially along the lines suggested in the system assurance program document. The initial results of this study were discussed in the Interim Reliability Report, with the work presented herein representing an updating of this portion of that particular study. In rating the severity of failure, a rating designation has been adopted which reflects the penetrometer subsystem operation and capabilities. This preliminary lising is indicated as:

0.75 - 1.00	-	Failures of penetrometer subsystem affecting entire vehicle (including catastrophic failures)
0.60 - 0.75	-	Failure mcdes resulting in penetrometer subsystem failure only
0.40 - 0.60	-	Failure of force sensor
0.25 - 0.40	-	Failure of position indicating sensor only
0 - 0.25	-	No effect.

The various failures are then rated for criticalness by obtaining the product of the probability of failure occurence times the effect. Criticality ranking levels range from 1 to 13, with a one-rating being the most serious failure, and a 13-rating being the least serious.

Table 2.3-12 indicates such a failure mode analysis as was carried out for the electrical portion of the penetrometer subsystem, with particular attention given to the switching system failure modes (switching circuit No. 1). Details of the switching circuit are shown in Figure 2.3-28.

A further updating of this criticality analysis has been carried out with the aim of numerically rating the criticality level of the failure modes, and, in particular, simplifying the failure mode designations for the switching circuit, based on the rather detailed failure mode analysis indicated in Table 2.3-12. This revised criticality estimate for the electrical portion of the penetrometer subsystem is indicated in Table 2.3-13. The probability of failure estimates are based upon a 4000-cycle (penetration) mission. In this case, the use of standard electronic parts is conservatively assumed. Consideration of higher reliability parts, as was done in Section 2.3.1.1 under the headings "LVDT Unit" and "Switching Circuit", could further reduce the criticality level. The degradation index shown for each failure mode is based upon estimates of the effect of the particular failure upon the operation of the entire SLRV, and upon the degradation in data gathering capability.

A similar criticality analysis was also performed on the mechanical portion of the penetrometer. The following list categorizes the possible mechanical failures of the penetrometer subsystem:

1. Failure of the penetrometer tube under one of the following modes:

   a. Column buckling due to axial load

   b. Local buckling and fracture due to transverse bending load

   c. Fracture due to fatigue

   d. Static fracture due to environmental effects

   e. Jamming in the extended position due to soil accumulation

2. Failure of the penetrometer drive mechanism under the following modes:

   a. Slippage of the drive and pressure rolls

TABLE 2.3-12

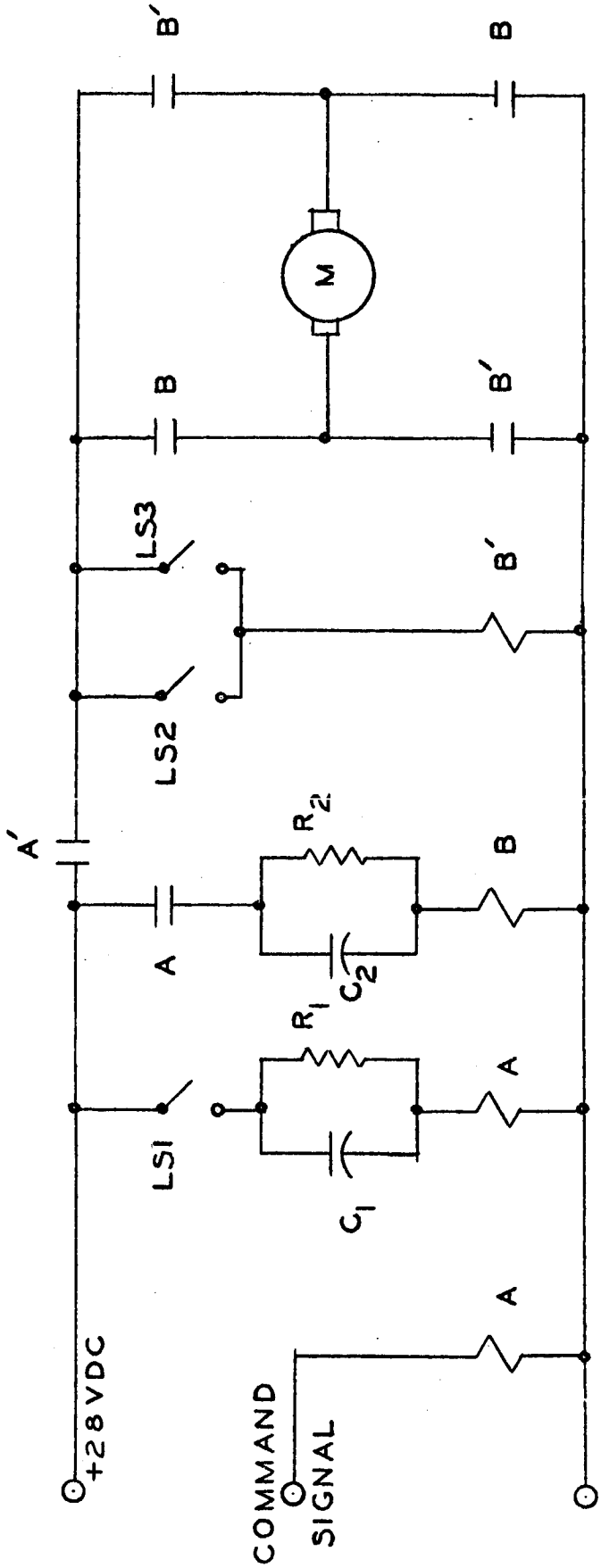
CONTROL CIRCUIT AND ELECTRICAL SYSTEM FAILURE ANALYSIS

Malfunction Switching Circuit	Result
1) A^1 will not close	No operation
2) LS1 will not open	C_1 cannot discharge, prevents later actuation of A and keeps motor running reverse
3) LS2 will not close	Motor keeps running forward
4) LS3 will not close	Motor won't reverse, may damage tube; motor keeps going forward (drive slips?)
5) B^1 will not close	Motor keeps running forward
6) LS2, LS3 will not open	Motor remains in reverse position, starts following cycle backwards
7) LS1 will not close	A^1 not switched off, motor keeps running in reverse
8) A will not close	B is not actuated, motor starts reverse next cycle, keeps running reverse
9) B will not close	No operation
10) R_1 open	C_1 cannot discharge A won't actuate later, motor keeps running reverse
11) C_1 short	Coil A keeps drawing power, A^1 cannot switch unit on
12) R_2 open	C_2 cannot discharge, prevents B from actuating, motor keeps running in reverse
13) C_2 short	Coil B keeps drawing power
14) Leads for LS3 short	Same as LS3 won't open
15) Leads for LS3 open	Same as LS3 won't close
LVDT Sensor Position Indicating Potentiometer Drive Motor	

TABLE 2.3-13

ELECTRICAL SYSTEM FAILURE MODE AND CRITICALITY ANALYSIS

Component	Failure Mode and Result	Failure Probability	Degradation Index	Combined Product	Criticality Level
Switching Circuit	I. Penetrometer will not operate (see Failure Modes 1, 9, and 11 Table 2.3-12)	0.0012	0.9	1.1×10^{-3}	9
	II. Motor tries to keep driving tube in forward direction (tube payout) (see Failure Modes 3, 4, 5, 14, and 14 Table 2.3-12)	0.0022	1.0	2.2×10^{-3}	5
	III. Motor tries to keep driving tube in reverse direction (tube retraction) (see Failure Modes 2, 6, 7, 8, 10, and 12 Table 2.3-12)	0.0027	0.9	2.4×10^{-3}	4
LVDT Sensor	Catastrophic failure - no force data obtainable	0.005	0.75	3.8×10^{-3}	3
Drive Motor	Catastrophic failure - penetrometer unoperable	0.01	0.9	9×10^{-3}	2
Position Indicator	Catastrophic failure - no direct penetration depth data	0.001	0.25	25×10^{-3}	12



A&B - DUAL COIL MAGNETIC LATCHING RELAYS
LS1, LS2 & LS3 LIMIT SWITCHES

Figure 2.3-28 Penetrometer Switching Circuit

b. Improper guiding of the tube resulting in ultimate jamming

c. Failure of the wiping mechanism producing ultimate jamming of the drive mechanism due to contamination

d. Failure of the drive mechanisms due to failure of the drive gears

e. Failure of the drive mechanism due to failure of the bearings

3. Failure of the penetrometer storage assembly under the following modes:

a. Failure of the probe by buckling of the flattened tube due to failure of the Negator drive to tension the storage roll

b. Failure of the penetrometer due to poor tube tracking and ultimate jamming due to improper operation of the storage drum and drive system

c. Failure of the penetrometer due to slippage and jamming of of the tube, due to failure of the tube and constraint on the storage drum

4. Failure of the sensor assembly under the following modes:

a. Failure of the sensor due to mechanical failure of the LVDT

b. Failure of the sensor due to the fracture and jamming of the penetrometer tip

c. Failure of the sensor due to contamination

d. Failure of the sensor due to faulty readings because of failure of balancing mechanism

e. Failure of the sensor due to jamming of bearings and guides because of friction.

While the above is not a complete list on the parts level, it is representative of the failure mode analysis on a subsystem level. Included in each of the latter three categories must be the following general failure modes:

1. Failure of the static support structure either due to fracture or excessive deflection

2. Failure of the operational mechanical structural elements such as shaft bearings, bearing mounts, brackets; guides and/or guide rollers.

In this analysis, item 1 shall be considered as a unit under structural failures (with an assumed reliability of 1.00), while item 2 shall be similarly considered as mechanical element failures.

The preceding listing represents a preliminary listing of the most logical and most probable mechanical failures which could affect the penetrometer subsystem. Criticality levels for these various failure modes were analyzed in the Interim Reliability Report. However, parametric analyses and design studies have eliminated or reduced the likelihood of occurrence of many of these failure modes. The most critical failure modes, as reflected by the subsequent reliability mathematical models and reliability prediction, are presented in the following listing. For the purposes of generality and continuity, the criticality listing will include only the abbreviated list of the failure modes. The numbers associated with the listings will indicate the relative significance of the mode:

1. Failure of the penetrometer tube due to:

   a. Fracture due to fatigue - major failure

   b. Local buckling and fracture due to transverse bending load - secondary failure

2. Failure of the penetrometer drive mechanism due to:

   a. Slippage of the drive and pressure rolls - major failure

   b. Failure of the bearings - secondary failure

   c. Failure of the drive gears - secondary failure

3. Failure of the penetrometer storage mechanism due to failure of the Negator drive springs - major failure

4. Failure of the sensor assembly due to failure of the penetrometer tip - major failure.

Table 2.3-14 summarizes the preceding discussion and assigns appropriate probability ranges for failure modes, as well as degradation indices and levels of criticalness for the failure modes. Designations for failure probability and effect and resulting criticality levels are identical to those used in the preceding electrical analysis.

It should be noted that in Table 2.3-14 the assignment of the various indices, while being as objective as possible, still is subjective to a certain extent. The manner of index assignment precludes complete objectivity. However, the use of a technique such as this greatly enhances the design reviews. The figures in the failure mode column refer to the identification of the failure mode column refer to the identification of the failure modes contained in text.

The highest level of criticalness is (as indicated by the large difference is associated numerics) assumed to be the governing failure mode. This mode is the basis for the reliability mathematical model and associated reliability prediction. The criticality analsis is predicated upon operation over a 4000-cycle (penetration) total mission.

TABLE 2.3-14

MECHANICAL FAILURE CRITICALITY ANALYSIS

Sub-Assembly	Failure Modes	Failure Mode Probability	Degradation Index	Combined Product	Critical Level
Penetrometer Tube	1a	1.5×10^{-2}	0.90	13.5×10^{-3}	1
Drive Mechanism	2a	1.5×10^{-3}	0.77	1.5×10^{-3}	6
Drive Mechanism	2c	1.5×10^{-3}	0.90	1.35×10^{-3}	7
Drive Mechanism	2b	1.5×10^{-3}	0.90	1.35×10^{-3}	8
Storage Module	3a	1.5×10^{-3}	0.50	0.75×10^{-3}	10
Sensing Mechanism	4a	1.5×10^{-3}	0.25	0.38×10^{-3}	11
Penetrometer Tube	1b	1.5×10^{-4}	0.85	0.128×10^{-3}	13

2.3.3 Mathematical Models and System Reliability Block Diagram

This section describes the reliability mathematical model and associated reliability block diagrams for the SLRV penetrometer subsystem. The reliability mathematical model with which we shall be concerned must exhibit two characteristics:

1. The model must reflect the effects of variation of at least the most significant parameters affecting system operation

2. The model must indicate the reliability relationship between the components of a system and their effect on the performance of that system (as shown in a reliability block diagram).

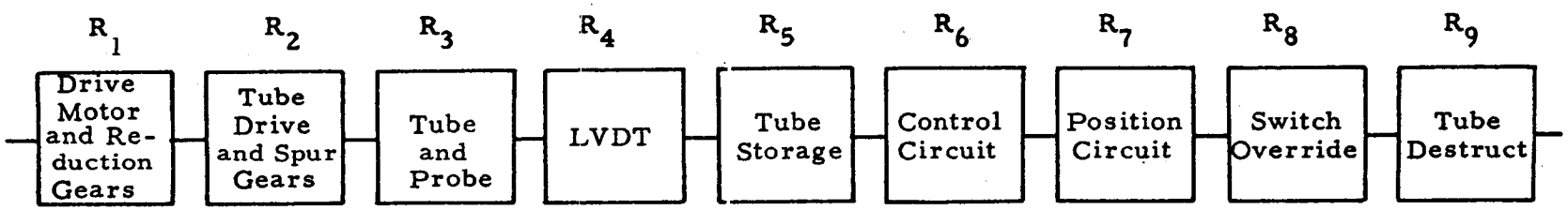
Thus, a representative model must be concerned with: (1) the output or performance of an individual component (or module), and (2) the functional relationships between the totality of components or modules which together form the system's structure. One representative model for a system such as the penetrometer is that of a nonmaintained system which is typical of aerospace and satellite systems.

2.3.3.1 Reliability Mathematical Model

This section discusses the formulation of a reliability mathematical model of the SLRV penetrometer subsystem. The model formulation in terms of the constituent modules and the various reliability expressions for these modules is included herein.

Over-all System Block Diagram

The over-all penetrometer subsystem reliability block diagram is illustrated in Figure 2.3-29. This diagram forms the basis for subsequent reliability mathematical model development. The determination of this diagram is based in part upon the mechanical functional block diagrams shown in Figure 2.3-30, 2.3-31, and 2.3-32. These figures illustrate the sensor unit subassembly including the tube, probe, pressure sensing unit, the tube drive subassembly, and the tube storage subassembly. The constituent reliability block diagrams shown in Figure 2.3-33, 2.3-34, and 2.3-35 are a direct extension of the functional module figures.



R_i = Reliability for individual block in terms of mission profile.

$R_T = \prod_{i=1}^{9} R_i$ = system reliability

Figure 2.3-29 System Reliability Block Diagram

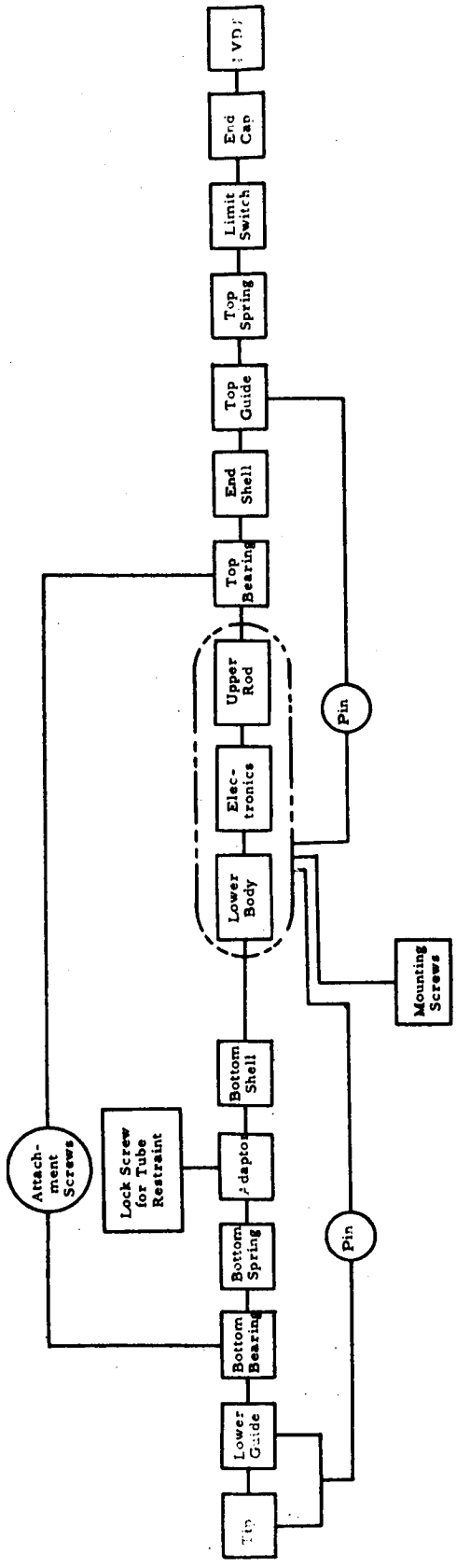


Figure 2.3-30 Sensor Circuit Subassembly Functional Block Diagram

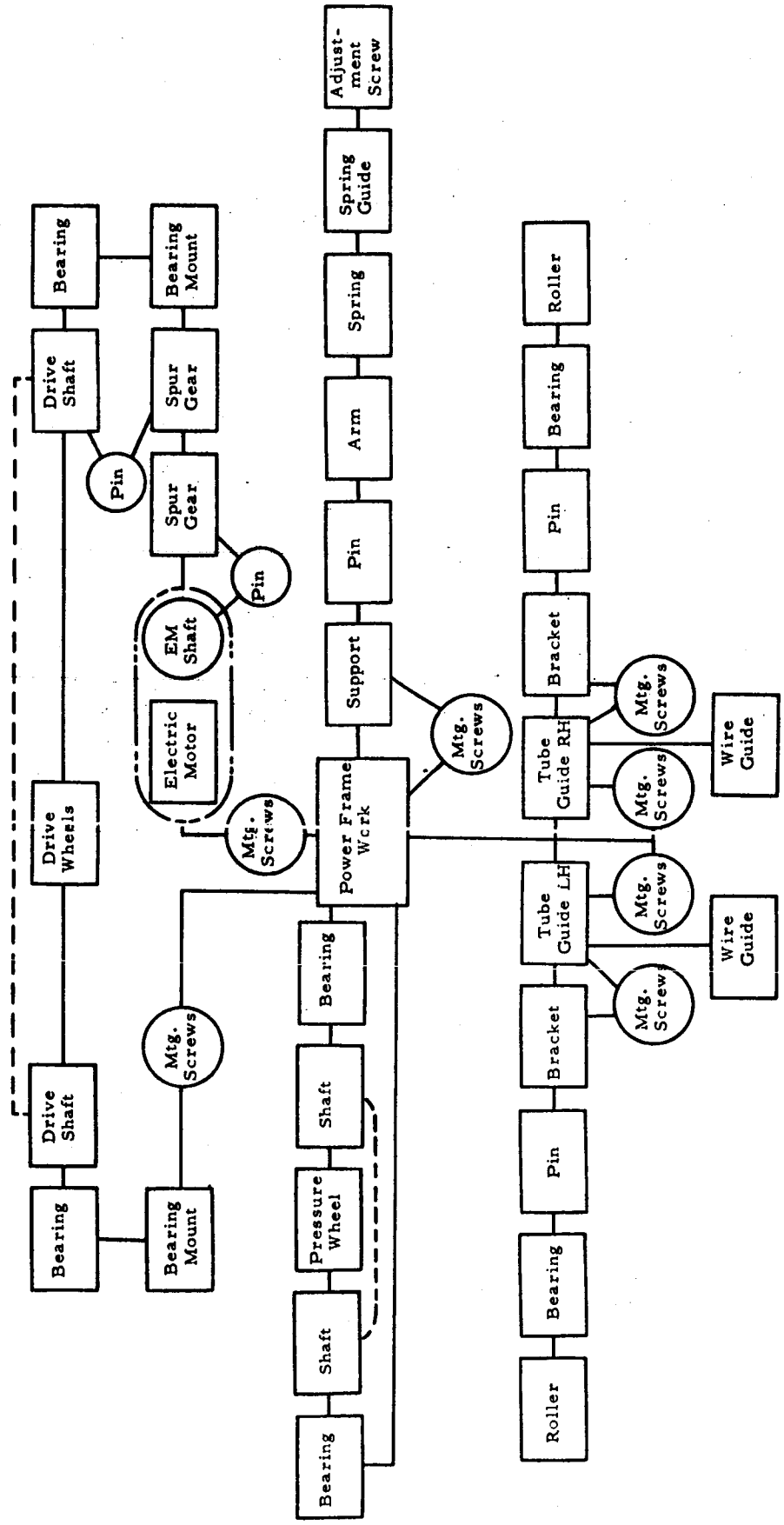


Figure 2.3-31 Drive Mechanism Subassembly Functional Block Diagram

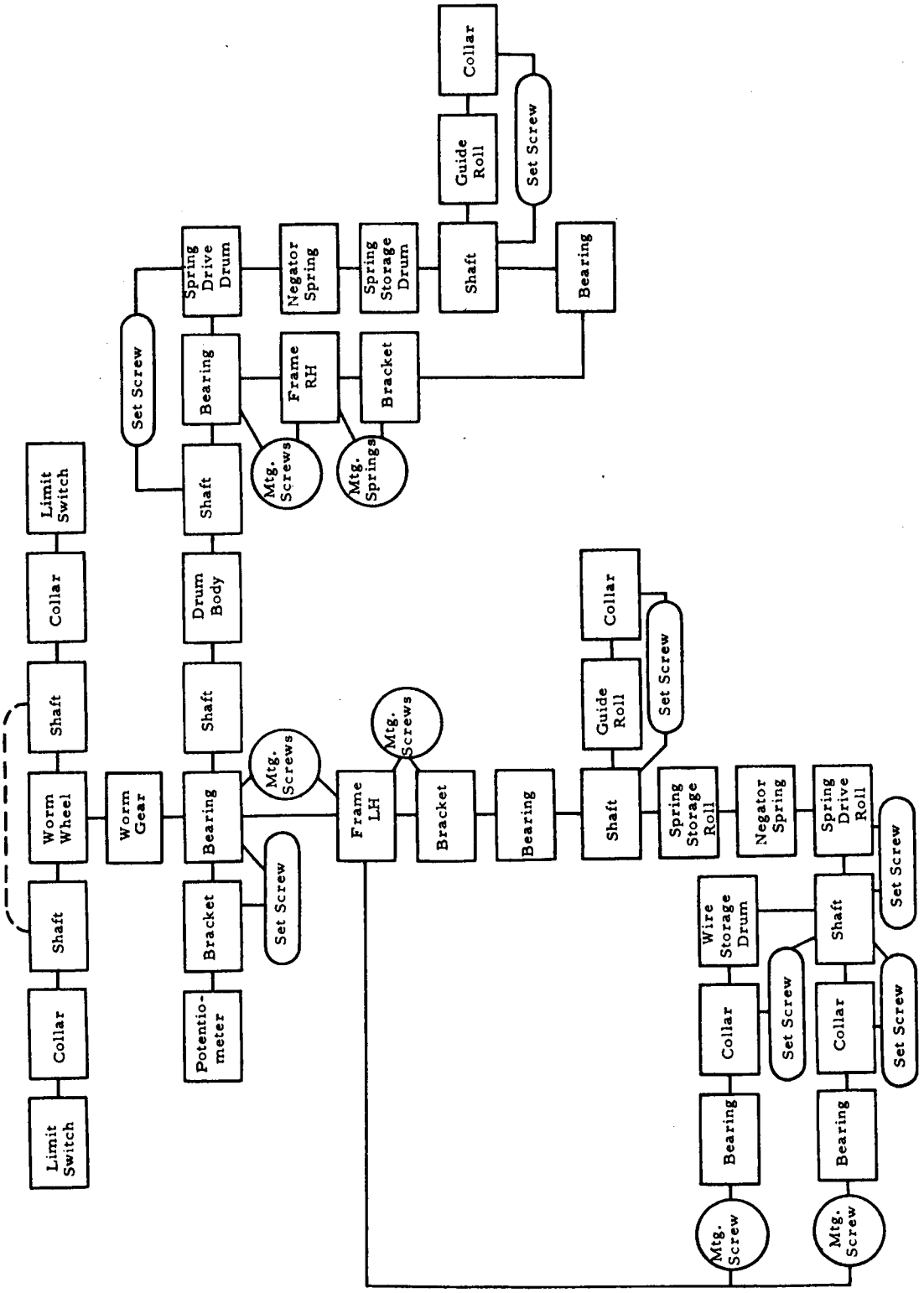
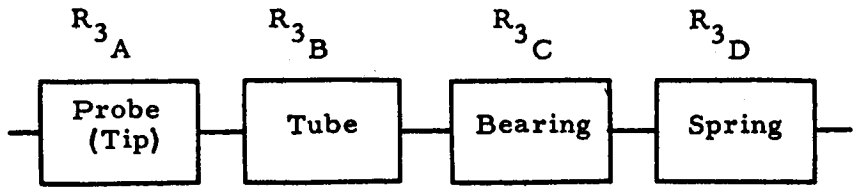
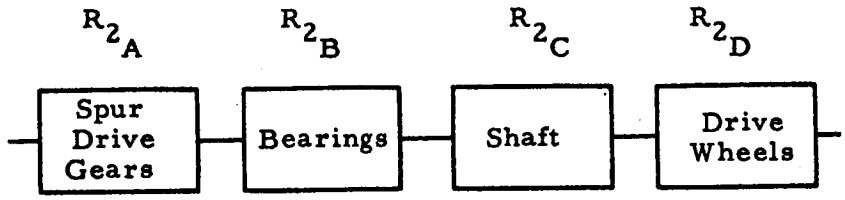


Figure 2.3-32 Storage Mechanism Subassembly Functional Block Diagram



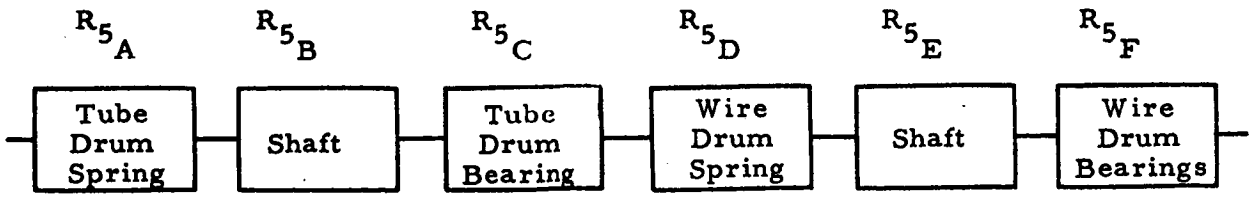
$$R_3 = \prod_{i=A}^{D} R_{3_i}$$

Figure 2.3-33 Constituent Reliability Block Diagram for Probe and Tip Module



$$R_2 = \prod_{i=A}^{D} R_{2_i}$$

Figure 2.3-34 Constituent Reliability Block Diagram for Tube Drive Module



$$R_5 = \prod_{i=A}^{F} R_{5_i}$$

Figure 2.3-35 Constituent Reliability Block Diagram for Tube Storage Module

The mechanical components in the penetrometer subsystem can essentially be placed into one of two categories – static items or dynamic items. Parts which fall into the static classification include such items as fasteners, framework, all structural elements, shafts (in general), mounting brackets, and similar items. These parts are characterized by a high inherent reliability. The second class includes the dynamic elements such as bearings, gears, certain shafts, and the tube. These latter items are in general more sensitive to environmental and operational stressing, and generally exhibit a lower reliability.

Figure 2.3-30 represents the sensor unit subassembly (tube and probe). Here the basic element is the LVDT, and the other components form functional series relationships from the LVDT. Figure 2.3-31 represents the drive mechanism subassembly. The basic element is the structural framework; grouped around it in serial relationships are the drive wheel subsystem, the pressure wheel subsystem, and the tube guide subsystem. Figure 2.3-32 represents the storage mechanism. Here, the basic element is taken to be the tube storage drum and its supporting shaft, and the other subsystems are arranged in serial and parallel fashion. In fact, for all of the subassemblies, the various fasteners would appear in parallel in a fully detailed reliability diagram. This in effect introduces some redundancy into that portion of the system.

Referring again to Figure 2.3-29, it should be noted, that, in addition to the elemental blocks contained therein, the switching circuit override and tube destruct elements have been added to fully represent the reliability characteristics of the system. The system as illustrated exhibits a serial relationship. This is a realistic approximation of the actual system as well as a mathematically tractable model. The total system reliability is given by

$$R_T(t) = \prod_{i=1}^{9} R_i(t)$$

where

$R_T(t)$ = system reliability at time t

$R_i(t)$ = individual block reliability at time t.

The most meaningful common parameter in which to express the various reliabilities is elapsed time. This time is that reflected by the mission profile. For the electronic components, this is the time during which the various circuits are energized. For the mechanical components, however, the significant parameter is cycles of operation, since they are operated only intermittently. To have a common parameter in these cases, the following relationship is employed:

$$t = kN$$

where

N = number of cycles of operation or penetrations

t = elapsed operating time

k = transformation constant.

It should be noted that k has the units of elapsed time per penetration cycle. Assuming an average penetration speed of 1/2 in. per second and a total extension of 32 in., the approximate operating time per cycle is 2 minutes. Using this value of time, the numerical value for the transformation constant is

$$k = 0.0034 \text{ hr/cycle.}$$

It should be noted that in some instances an additional modification factor is required for relating the number of cycles (penetrations) to total mission time. Thus

$$N = (t)\, K\, t$$

where

K = (0.894 average penetration)/(hour of mission time) if no shutdown for lunar night occurs

K = (0.447 average penetration)/(hour of mission time) if lunar night shutdown is included.

The use of this factor is subsequently discussed.

Mechanical Subsystems

The individual reliabilities of the various parts of the penetrometer depend upon the elements which make up each of the "blocks". Mechanically speaking there are three "blocks" which are combinations of several items:

1. Tube Drive Block

2. Tube and Probe Block

3. Tube and Storage Block.

The constituent reliability block diagram for item 1 above is shown in Figure 2.3-33. In establishing this diagram and those shown in Figures 2.3-34 and 2.3-35, it has been assumed that the reliability of all static components such as supports, flanges, screws, etc., can be taken as unity. Thus, they need not be considered in the diagram. This leaves only the critical dynamic elements shown. As a consequence of this assumption, the reliability of block 3 in Figure 2.3-29 is given by

$$R_3(t) = \prod_{i=A}^{D} R_{3_i}(t)$$

where R_{3_i} is the specific subblock reliability. From considerations of the failure mode analysis for the various items, the following preliminary reliability expressions have been generated:

1. The probe (tip) probably exhibits a normally distributed probability of failure. Its reliability function is accordingly

$$R_{3_A}(N) = \int_t^{\infty} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(N-\theta)^2}{2\sigma^2}} dt \qquad (2.3.3\text{-}1)$$

where

σ = standard deviation

θ = mean value.

To assess the reliability in terms of various values of elapsed operating times, the two characteristic parameters must be evaluated. From a combination of engineering evaluation, conservative estimates, and failure data on functionally similar equipment the following values have been assigned to the parameters as a preliminary estimate:

σ = 40 cycles

θ = 4103 cycles.

Two values of reliability will be computed, the first for a 4000-cycle mission and the second for a 2000-cycle mission. The reliabilities will be assessed using the standardized normal variate tables. This involves making the substitution in Equation (2.3.3-1) of

$$Z = \frac{N - \theta}{\sigma}$$

and

$$R_{3_A}(N) = \int_{Z_N}^{\infty} \frac{1}{2\pi} e^{\frac{-Z^2}{2}} dZ = a$$

for N = 4000 cycles, $Z_N = -2.575$, a = 0.995

thus $R_{3_A}(4000) = 0.995$

for N = 2000 cycles, $Z_N = 52.6$

$R_{3_A}(2000) \cong 1.000$

2. The principal failure mode for the tube is fatigue, and correspondingly the applicable distribution is the log-normal.

Thus

$$R_{3_B}(N) = \int_{t}^{\infty} \frac{M}{N\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}\log N - \log \theta^2} dt \qquad (2.3.3\text{-}2)$$

where

N = number of cycles

$\log \theta$ = mean of log (t/k)

M = log e = 0.4343

σ = variance of the log N

log = $\log_{10}$.

This particular reliability function has been evaluated in the preceding paragraphs. The value of reliability depends upon the level of the alternating stress difference (S_A), which in turn depends upon the value of the compressive stress in the tube. For the purposes of this discussion, assume a value of $S_A = 125 \times 10^3$ psi. From Figure 2.3-26, this yields

$$R_{3_B}(4000) = 0.990$$

$$R_{3_B}(2000) \cong 1.000.$$

It should be noted that a firm value for a tube reliability estimate is dependent upon the level of compressive stress in the tube. Experimental determination of this value in Phase II is imperative.

3. The principal failure modes for bearings (as expressed in the literature) are wear and surface fatigue. The most representative failure probability distribution for these failure mechanisms is reflected by a form of the Weibull distribution[1].

$$R_{3_C}(t) = e - \left[\frac{N}{e}\right]^b \qquad (2.3.3\text{-}3)$$

[1] Schube, E., "Ball Bearing Survival," Machine Design Magazine, July 19, 1962, The Penton Publishing Co., Cleveland, Ohio.

where

(t/k) = N = number of cycles

θ = decrease of central tendency

b = a measure of the variance.

It should be noted that this reliability mathematical model was developed for rolling contact bearings. However, for the purposes of this discussion, it is assumed that the model is equally applicable to the linear bushings within the probe tip as well as the bushings (journals) elsewhere. Indications are that the bushings are at least as reliable as the rolling contact bearings in the penetrometer subsystem. Using the techniques described in the referenced article, the following values for the reliability parameter can be assigned:

$$\theta = 0.30\ L_o = 50.4 \times 10^{+4}$$

where

L_o = B_{10} life of bearing

b = 1.01

From these data

$$R_{3_C}(4000) = 0.993$$

$$R_{3_C}(2000) \tilde{=} 1.000.$$

Since there are two linear bushings, the reliability $R_{3_C}(t)$ must be entered twice into a serial reliability relationship.

4. On the basis of general experience with springs, a representative failure distribution for helical springs (and

assumed to apply to Negator springs as well) is also given by

$$R_{3_D}(t) = e - \left[\frac{N}{\theta}\right]^b \qquad (2.3.3\text{-}4)$$

where

θ = a measure of central tendency

b = a measure of variance.

Using the techniques described in the cited reference, the following values for the reliability parameters can be assigned:

$$\theta = 2.44\ L_o = 2.48 \times 10^4$$

where

P = 90% design point of the springs

b = 2.539.

From these data

$$R_{3_D}(4000) = 0.990$$

$$R_{3_D}(2000) = 0.999.$$

Again, there are two helical springs, so that $R_{3_D}(t)$ must also be entered twice in serial reliability relationships.

The constituent reliability block diagram for item 2, the Tube Drive Module, is shown in Figure 2.3-34. In this figure, a block has been included for the shaft. This was done to reflect the ultimate possible need for considering the design of this component in reliability assessment. However, for the purposes of the present mathematical model, its reliability (R_{2_C}) may be considered to be equal to unity. Thus, only three blocks need to be considered.

Block A represents a single pair of spur gears. Gear reliability must be evaluated in terms of gear pairs. The most probable mode of failure for a gear is surface fatigue and wear. From considerations of fatigue failure, a log normal failure distribution is used for preliminary considerations. The reliability relationship for such a distribution is given by Equation (2.3.3-2). Employing techniques discussed in the evaluation of Equation (2.3.3-1) the parameters are

$$\log(\theta) = 3.960$$

$$\theta = 9500 \text{ cycles}$$

$$\sigma = 0.15.$$

Evaluating the reliability function:

$$R_{2_A}(4000) = 0.993$$

$$R_{2_A}(2000) \tilde{=} 1.000.$$

The representative reliability relationship for bearing failure is given by Equation (2.3.3-3). In this case there are four bearings and R_{2_B} must be eneterd four times in a serial reliability relationship. The remaining block in Figure 2.3-34 represents the pair of drive rollers. The most probable mode of failure for these components is slippage. Arguments can be offered giving reasonable justification for assuming an increasing failure rate with time as well as a decreasing failure rate with time. For the purpose of the present model, it will be assumed that a sufficiently high preload is placed upon the wheels so that the failure rate remains constant.

Thus

$$R_{2_D}(t) = e^{-\lambda N} \qquad (2.3.3\text{-}5)$$

where

λ = constant failure rate.

In this case, the following value has been assigned as a preliminary estimate

$$\lambda = 0.5 \times 10^{-6} \text{ failure/cycle.}$$

Evaluating the expression for reliability:

$$R_{2_D}(4000) = 0.998$$

$$R_{2_D}(2000) = 0.999.$$

The constituent reliability block diagram for item 3, the tube drive module, is shown in Figure 2.3-35. In accordance with the discussion in the preceding paragraphs, reliabilities R_{5_B} and R_{5_E} will be assumed to be unity. The tube drum spring and the wire drum spring are in fact Negator springs. For the purposes of the preliminary model, the reliability function given by Equation (2.3.3-4) can be used. Similarly, R_{5_F} and R_{5_C} are given by Equation (2.3.3-3). Each of the bearing blocks indicated in Figure 2.3-35 are representative of two bearings. Thus, both R_{5_C} and R_{5_F} must be entered twice in a serial reliability relationship. The associated numerical reliability values also apply here.

Table 2.3-15 presents a summary of the mathematical models used for the reliability characteristics for the various mechanical elements, along with the assumed values of the parameters, and reliability estimations for 2000 and 4000 penetrations which will be used in the penetrometer subsystem reliability predictions in Section 2.3.4.

Electrical-Electronic Reliability Model

The electrical-electronic portions of the penetrometer subsystem are represented in Figure 2.3-29 by five separate units. These units are represented by the following reliability designations:

Drive Motor	R_1
LVDT Transducer	R_4
Switching Circuit	R_6
Position Indicating Potentiometer	R_7
Switching System Override	R_8.

TABLE 2.3-15

SUMMARY TABLE OF MECHANICAL RELIABILITY FUNCTIONS

Block No.	Major Block Reliability Function	Constituent Block Reliability Function	Parameter Values	R(4000)	R(2000)	Equation Reference
3	$R_3 = \prod_{i=A}^{D} R_{3_i}$	$R_{3_A} = \int_N^\infty \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(N-\theta)^2}{2\sigma^2}} dN$	$\sigma = 40$ $\theta = 4103$	0.995	~1.000	(7.1)
		$R_{3_B} = \int_N^\infty \frac{M}{(N)\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}\left[\text{Log}(N)-\text{Log}\theta\right]^2} dN$	See Fatigue Analysis	0.990	~1.000	(7.2)
		$R_{3_C} = e^{-(\frac{N}{\theta})^b}$	$\theta = 50.4 \times 10^4$ $b = 1.01$	0.993	~1.000	(7.3)
		$R_{3_D} = e^{-(\frac{N}{\theta})^b}$	$\theta = 2.48 \times 10^4$ $b = 2.539$	0.990	0.999	(7.4)
2	$R_2 = \prod_{i=A}^{D} R_{2_i}$	R_{2_A} ....See R_{3_B} above	$\text{Log}(\theta) = 3.968$ $\sigma = 0.15$	0.993	~1.000	(7.2)
		R_{2_B} ....Unity				
		R_{2_C} ....Unity				
		R_{2_D} .... $e^{-\lambda N}$	$\lambda = 0.5 \times 10^{-6}$	0.998	0.999	(7.5)
5	$R_5 = \prod_{i=A}^{F} R_{5_i}$	R_{5_A} .... See R_{3_D} above	See above	0.990	0.999	(7.4)
		R_{5_B} .... Unity				
		R_{5_C} .... See R_{3_C} above	See Above	0.993	~1.000	(7.3)
		R_{5_D} .... See R_{3_D} above	See Above	0.990	0.999	(7.4)
		R_{5_E} .... Unity				
		R_{5_F} .... See R_{3_C} above	See Above	0.993	~1.000	(7.3)
9	R_9 = C(constant)		C = 0.999	0.999	0.999	(7.9)

For the present, the motor reliability R_1 is considered to have three separate components which take into consideration winding and wiring reliability (random failure characteristic) R_{1A}, motor bearing and brush reliability (random failure characteristic) R_{1B}, and a total wearout reliability characteristic R_{1C}, which for the present motor application is expected to be largely determined by the brush and commutator wear under vacuum conditions. Because operation of the motor is vitally dependent upon proper functioning of all three segments, the reliability terms are considered to have a serial relationship:

$$R_1 = R_{1A} R_{1B} R_{1C}.$$

For the present, the winding reliability factor is represented by

$$R_{1A} = e^{-\lambda_{1A} t} \qquad (2.3.3\text{-}6)$$

where t is the motor operating time, given by t = kN, N being the number of penetrations. The determination of this factor follows the conventional procedure presented in the "RADC Reliability Notebook," where modified transformer failure data are used for representation of motor winding reliability characteristics.

In considering the bearing and brush factors, deterioration is assumed to occur only while the motor is in actual operation; hence, the elapsed operating time t is again given by t = kN where operating time is again related to the number of penetrations. In this way, the brush and bearing random failure characteristic is represented by

$$R_{1B} = e^{-\lambda_{1B} t}. \qquad (2.3.3\text{-}7)$$

It should be noted that the above procedure for estimating R_{1B} also follows the procedures presented in the "RADC Reliability Notebook" for predicting motor reliability. In addition to the above reliability factors, information has been obtained from the motor manufacturer (Globe Industries) regarding the general reliability characteristics of the motor presently being considered as suitable for lunar application. This motor life information, which has been regarded as representing the general wearout characteristics of the motor and gear reduction unit, has been fitted to a normal failure distribution. Details on the motor life characteristics have been discussed in Section 2.3.1.

The motor brush and commutator reliability, on the basis of these data, is then represented by the normal distribution as follows:

$$R_{1C} = \int_{t}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\theta}{\sigma}\right)^2} dt \qquad (2.3.3\text{-}8)$$

where

θ is the mean brush life

σ is the standard deviation.

Because deterioration is considered to occur only during motor operation, the k factor is again used to transform the number of penetrations into actual operating time.

The remainder of the electronic-electrical portions of the penetrometer subsystem have failure rates which are determined by the particular operating environment. Considerations in the determination of these failure rates have been discussed previously. The reliability functions for the remainder of the electronics package are given as follows:

$R_4 = e^{-\lambda_4 t}$ for the LVDT unit (see Section 2.3.1.1)

$R_6 = e^{-\lambda_6 t}$ for the switching circuitry (see Section 2.3.1.1)

$R_7 = e^{-\lambda_7 t}$ for the position indicating potentiometer (see Section 2.3.1.1).

In addition, the operation of the switching circuit override must be considered, and its reliability characteristic is given by

$$R_8 = e^{-\lambda_8 t}.$$

Considerations for the estimation of particular values for the failure rate λ_8 will be discussed in Section 2.3.4.

The last block in Figure 2.3-29, the tube destruct mechanism, is a pyrotechnic blow-off device. Such a typical device, exhibiting good reliability under hard vacuum, is an Exploding Bridge Wire detonator. Experience has shown that the reliability for this element is essentially independent of time. In this case, the assumed value for the reliability is given by

$$R_9(t) = C = \text{constant} = 0.999. \qquad (2.3.3\text{-}9)$$

It should be noted that, for R_8 and R_9, these values actually represent in this case the probabilities that these elements do not abort or impede normal penetrometer operation. For instance, R_9 in this case represents an estimation of the probability that the tube destruct mechanism does not fire during normal penetrometer operation.

Modes of Operation

Figure 2.3-29, the System Reliability Block Diagram, indicates a series relationship between the various units of the penetrometer subsystem, with the resulting reliability estimation representing the probability of the entire subsystem operating satisfactorily. However, modes of partial operation and the corresponding probabilities of partial success may also be considered. Referring to Figure 2.3-29, units 1, 2, 3, 5, and 6 represent those portions of the subsystem which must operate without failure. Because these particular portions of the penetrometer (the drive motor, tube drive configuration, the tube and probe, tube storage configuration, and the switching circuit) are concerned with the actual operation of the penetrometer tube, the operation of these portions of the penetrometer can be considered to represent the minimal operational mode of the subsystem. Catastrophic failure in any of these units will result in total disablement of the penetrometer. Reliability factors for units 8 (switching circuit override) and 9 (tube destruct) must also be considered in this case from the viewpoint of their probability of nonoperation, while the switching circuit and tube drive units are operating properly. Operation of either of these two emergency units during normal penetrometer operation could constitute a failure, particularly in the case of the tube destruct unit which is only utilized to free the SLRV in the event that the penetrometer ceases to function while the tube is in an extended position.

The next mode of operation includes operation of the LVDT unit to give force measurement data. A third mode of operation can be described, wherein the LVDT unit fails, and the depth indication unit operates. A fourth mode of partial penetrometer operation is possible if the penetrometer operating time can be monitored. Some elementary information could still be obtained on depth of penetration and whether or not an over-force condition was encountered. These modes of penetrometer operation are summarized in Table 2.3-16. The product of the reliability terms for the units in a particular mode of operation is then the probability of at least those units operating in that particular mode throughout the selected mission. The various units in the penetrometer subsystem are identified as follows:

1. Drive motor and reduction gears
2. Tube drive module
3. Tube and probe
4. LVDT force transducer
5. Tube storage
6. Control circuit
7. Position circuit
8. Switch override
9. Tube destruct.

TABLE 2.3-16

PENETROMETER SUBSYSTEM MODES OF OPERATION

Operational Mode	Description	Identification of Operational Units and Reliability
I	Complete operation	$R_1R_2R_3R_4R_5R_6R_7R_8R_9$
II	Operation of force sensor only	$R_1R_2R_3R_4R_5R_6 \quad R_8R_9$
III	Operation of position sensor only	$R_1R_2R_3 \quad R_5R_6R_7R_8R_9$
IV	Operation of tube only	$R_1R_2R_3 \quad R_5R_6 \quad R_8R_9$

2.3.4 Penetrometer Subsystem Reliability Predictions

This section presents a summary of the reliability characteristics of the SLRV penetrometer subsystem in the form of a total subsystem reliability prediction. Two predictions are considered, one for a medium length mission of 2000 penetrations, and a longer length mission of 4000 penetrations. The predictions are for successful operation of the entire penetrometer subsystem. The major conditions considered for the prediction are an operating temperature of 60°C for the penetrometer electronics (standard MIL parts application), with the electronics being in operation (in a powered state) only during the 8-hour operating time per earth day. Table 2.3-17 then summarizes the reliability estimates for each portion of the penetrometer subsystem, and gives a total subsystem reliability estimate. The considerations in the derivation and estimation of the various constituent reliability predictions has been covered for each part of the penetrometer subsystem in previous sections of this reliability report.

The end of Table 2.3-17 thus gives the present reliability predictions for 2000 and 4000 penetration missions as 0.983 and 0.860, respectively. It should be noted that the major portion of the reliability decrease for the longer mission is accounted for by the mechanical portion of the penetrometer. It is in this area that much of the specialized design work and investigation is required if the longer mission would be anticipated. The present reliability estimates indicate that redundancy in the electronic portions of the penetrometer is not a necessity, particularly in view of the relatively small number of electronic parts and the high part reliabilities which may be obtainable. In general, it should be noted that the reliability figures are indeed estimates which are based on the ETM design, with consideration for extension of application to the lunar environment and mission profile and using the design and reliability information presently available.

TABLE 2.3-17

SLRV PENETROMETER SUBSYSTEM RELIABILITY PREDICTIONS

Unit Identification	No. Units Used	Unit Reliability Designation	Unit Reliability 2000 Cycles	Reliability 2000 Cycles	Unit Reliability 4000 Cycles	Reliability 4000 Cycles
1 - Drive Motor	1	R_1	0.995	0.995	0.990	0.990
2A - Spur Drive Gear Set	1	R_{2A}	~1.000	~1.000	0.993	0.993
2B - Bearings	4	R_{2B}	~1.000	~1.000	0.993	0.972
2C - Shaft	1	R_{2C}	1.000	1.000	1.000	1.000
2D - Drive Roller Set	1	R_{2D}	0.999	0.999	0.998	0.998
3A - Probe Tip	1	R_{3A}	~1.000	~1.000	0.995	0.995
3B - Tube	1	R_{3B}	~1.000	~1.000	0.990	0.990
3C - Bearings	2	R_{3C}	~1.000	~1.000	0.993	0.986
3D - Springs	2	R_{3D}	0.999	0.998	0.990	0.980
4 - LVDT Unit	1	R_4	0.998	0.998	0.997	0.997
5A - Tube Drum Spring	1	R_{5A}	0.999	0.999	0.990	0.990
5B - Shaft	1	R_{5B}	1.000	1.000	1.000	1.000
5C - Tube Drum Bearings	2	R_{5C}	~1.000	~1.000	0.993	0.986
5D - Wire Drum Spring	1	R_{5D}	0.999	0.999	0.990	0.990
5E - Shaft	1	R_{5E}	1.000	1.000	1.000	1.000
5F - Wire Drum Bearings	2	R_{5F}	~1.000	~1.000	0.993	0.986
6 - Switching Circuit	1	R_6	0.998	0.998	0.996	0.996
7 - Depth Measurement	1	R_7	0.999	0.999	0.999	0.999
8 - Switch Override	1	R_8	0.999	0.999	0.999	0.999
9 - Tube Destruct	1	R_9	0.999	0.999	0.999	0.999
Total Penetrometer Subsystem Reliability				0.983		0.860

2.3.5 Parts Selection Program

2.3.5.1 Basic Elements of a Parts Program

A parts selection program may be considered as involving basically two aspects of project control. The first is the internal procedure for determining part application, required part design specifications, reliability evaluation, part selection, and vendor selection. The second aspect involves the relationship with the parts vendors where the basic reliability task involves the assurance that the parts supplied by the vendor meet the required specifications.

The various tasks and procedures which might make up a general parts and materials selection program are outlined below. The elements of such a program include:

1. Part and material selection for a specific application
    a. On the basis of operational characteristics
    b. On the basis of reliability characteristics
2. Selection of vendors or manufacturers
3. Assurance of proper part application
    a. During design phase
    b. During assembly
4. Establishment of specifications for procurement
    a. Electrical, mechanical, and environmental requirements
    b. Material and process control requirements
    c. Handling requirements
    d. Reliability assurance requirements
        (1) Qualification tests
        (2) Acceptance tests
        (3) Reassurance tests
    e. Requirements for inspection of vendors facilities and processes

5. Liaison with parts vendors

    a. For improved component design
    b. For improved processes

6. Specification for part use

    a. Handling
    b. Storage
    c. Testing
    d. Assembly.

The degree to which any of the above items may be specified or developed will depend upon several factors, including the complexity of the device, the over-all project reliability requirements and procedures as may be set by the prime contracting body, the number of production devices to be built thus determining the number of component parts required, and the funds which may be allocated to the reliability assurance task.

In concept, the above considerations are applicable to both the mechanical and electrical areas. However, the particular application of such general concepts to mechanical parts, because of specific problems in that area, will be discussed in the following section.

With regard to the penetrometer subsystem in general, and the electronic/electrical area in particular, two of the significant factors will probably be a high reliability requirement with a relatively small number of production units. Thus, the availability of materials, parts, and completed units for testing must be considered closely in the development of the penetrometer flight model in order that attainment of realibility goals will be established. Specific areas to which consideration must be given, are listed in document BSR751. These areas include:

1. Selection and application of parts and materials
2. Reduction of parts (if feasible)
3. Specification of parts and materials
4. Qualification of parts (if necessary)
5. Screening and aging tests.

Particular considerations regarding the application of effort in these areas to the development of the penetrometer flight model will now be discussed.

Selection and Application of Parts and Materials

Selection of parts and materials for the flight model by the design engineers shall be reviewed by the reliability activity. Criteria for evaluation will include: derating factors, environmental compatibility, performance capability, application considerations, documented reliability (long-life) levels, etc.

Reduction in Number of Types

Summary listings of each type of part will be made, along with the principal required operating characteristics. These will be reviewed by type, along with the application of the part to determine those cases where it would be possible and desirable to replace specific selections with alternates -- the objective being to mainimize the number of different types of parts used in the penetrometer subassembly of the flight model.

Specifications

Parts purchased for assembly into the flight model of the penetrometer subassembly will be purchased to applicable military and/or NASA specifications, where such procedures are possible and where such parts will meet the reliability requirements of the penetrometer subsystem. As part of the activities under "Reduction in Number of Types", above, every effort consistent with the over-all objectives of the flight model will be made to minimize the number of special parts used.

Qualifications

Parts will be purchased whenever possible from suppliers who are on a qualified parts list for the particular selected part and capable of meeting the reliability requirements. Inspection procedures will be instituted on such parts to assure that the parts qualify within the framework of the flight model program.

Screening/Aging Tests

The extent to which such tests would be used in the development of the flight model will most certainly depend upon the reliability requirements of a particular part and the effort which can be devoted to such tests within the scope of the total program. On the other hand, where reliability requirements and lack of data dictate, testing will most definitely have to be considered. For instance, one area where a need for thorough testing is expected is in the motor operation. Because little data are generally available in this area, performance and reliability characteristics under the anticipated operational and environmental conditions must be established in a suitable test program. Tests and procedures will also be considered for the process of screening suitable parts or groups of parts for actual application in flight model penetrometers.

2.3.5.2 Mechanical Considerations in a Parts Program

The detailed preparation of a parts selection program for high reliability parts, such as may be used in the electronics industry, has little applicability or signigicance in terms of the mechanical parts for the SLRV penetrometer subsystem. In the first place, the classical parts program is usually associated with large numbers of parts. In addition, these parts are capable of being subjected to rather simple life tests. Finally, the industry itself has been established in the disciplines of part reliability.

In constrast to this situation, the mechanical parts or components for the penetrometer are few in number, and only a very small quantity of any specific component will probably be used throughout the entire program (it is noted, again, that this situation also exists to some degree even in the penetrometer subsystem electronics). Furthermore, many, if not most, of the components are unique designs and as such are not available commerically. All of this leads up to the fact that most careful consideration must be given to the procedures for selection and specification of mechanical components for the SLRV penetrometer subsystem. The following paragraphs outline a comprehensive and realistic mechanical parts selection program applicable to the penetrometer flight model development in Phase II.

Material Selection

The materials which will be used for the aforementioned components will be subjected to a rigorous analytical investigation (in terms of applicable parameters). The material/materials indicated most applicable will be life tested under simulated environmental and operational stresses to the greatest extent possible in the laboratory.

Configuration Evaluation

Once the material has been evaluated and selected, the components will be fabricated and tested, again under simulated operational and environmental stress conditions. Obviously, redesign and reevaluation will occur if any of the components fail to meet requirements.

Interaction Evaluation

Having completed the first two steps in the parts selection program, the components will be assembled into a unit experimentally evaluated again under simulated operational and environmental stresses. This test will be planned to evaluate the interaction problem between the various components and between the components (as a whole) and their over-all environment.

As an example of this approach, consider the single most critical mechanical component in ths system, the penetrometer tube. The techniques and results of a preliminary parametric study on the tube material from a fatigue standpoint (the most probable failure mode) were discussed in Section 2.3.1.2. The results of that study indicated that there were three possible material choices, silicon manganese steel, chrome-vanadium steel, and an 18-8 series stainless steel. The latter material appeared to have a slight advantage over the first two for use in the penetrometer system. However, for the sake of completeness, all three of these materials must be further investigated under items "Material Selection," "Configuration Evaluation," and "Interaction Evaluation" of the aforementioned parts selection program. Such an investigation would entail:

1. Preparation of a number of fatigue test specimens from each of the three materials. Several groups of specimens from each type of material would be tested, each group at a specific level of hardness. The tests would be standard

fatigue tests to failure at various stress levels under simulated lunar environments. These test data will provide P-S-N data for reliability computations as well as comparative fatigue life data.

2. Penetrometer tubes would be fabricated from these groups of materials at different hardnesses and cyclicly tested to failure in a fixture which simulates the operational cycle of the actual penetrometer. As before, this testing will be carried out under simulated lunar conditions.

3. Finally, the most promising material, in terms of the results of the first two evaluations, will be fabricated into a penetrometer tube, assembled on an actual penetrometer, and tested under simulated lunar conditions.

Thus, by using the outlined procedure, a comprehensive evaluation of the component can be achieved.

It should be noted extreme care will be employed in the selection of commercial components. IIT Research Institute personnel will work closely with the engineering personnel of the vendor to ensure that the component ultimately purchased will be of high quality and exhibit the required capabilities. In addition, all purchased components will be subjected to steps 2 and 3 of the aforementioned parts selection program.

The unit resulting from this type of part selection and evaluation should exhibit optimum performance for the specific design in terms of intended use and operational and environmental stresses.

2.4 NAVIGATION

The reliability block diagram for the navigation subsystem is shown in Figure 2.4-1. The reliability of this subsystem for a 4.5-month mission is 0.9675 and somewhat higher for missions of lesser duration as shown in Table 2.4-1.

TABLE 2.4-1

NAVIGATION SUBSYSTEM

Item	Reliability 1 Mo.	2 Mo.	3 Mo.	4.5 Mo.	Remarks
RF Ranging Unit	.9944	.9889	.9834	.9752	
Sun Sensor	.9989	.9979	.9969	.9953	Energized during DSIF control hours.
Inclinometer	.9993	.9986	.9979	.9969	
Odometer	.9999	.9999	.9999	.9999	
Navigation Subsystem	.9925	.9855	.9782	.9675	

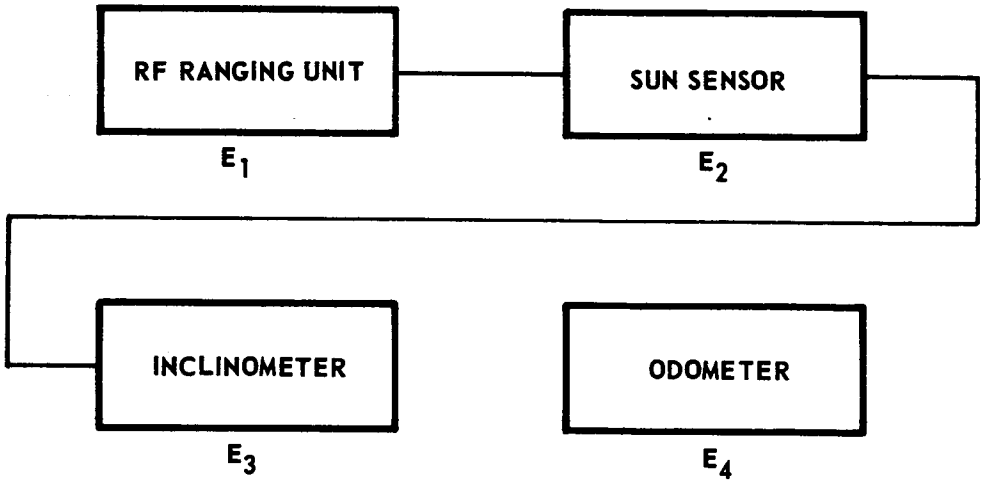
2.4.1 RF Ranging Unit

The first part of this section develops a reliability model for the CW ranging system. This model is then applied to a subunit reliability and criticality analysis as described in the following section.

2.4.1.1 Reliability Model

The reliability model used for this preliminary analysis assumes that all failures are random and catastrophic. The failure rate for each subunit of the system was obtained by summing up the failure rates for all of its constituent parts.

$$\lambda_i = \sum_{k=1}^{k=n} \lambda_{ik}$$



$$R = E_1 \times E_2 \times E_3 \times E_4$$

where

λ_i = total failure rate for i^{th} subunit of the system

λ_{ik} = failure rate of kth component in i^{th} subunit

n = number of components in the ith subunit

The reliability of the ith subunit as a function of time is:

$$R_i(t) = e^{-\lambda_i t}$$

$R_i(t)$ = probability that the ith subunit will be operational at the end of a time period t.

The reliability of the total system was taken to be the product of the reliabilities of all subunits in the system, since all subunits are essentially in series with each other. Thus,

$$R_T(t) = \prod_{i=1}^{i=n} R_i(t)$$

where

$R_T(t)$ = reliability at time t of the total system

N = number of subunits in the total system

Since the reliability of each subunit is of the form $e^{-\lambda_i t}$, the overall reliability of the system may be calculated as follows:

$$R_T(t) = e^{-\lambda_T t}$$

where

$$\lambda_T = \sum_{i=1}^{i=N} \lambda_i$$

2.4.1.2 Reliability and Criticality Analysis

A preliminary reliability analysis of the CW ranging system was made using the reliability model discussed above. Since the final designs of the circuits for each subunit have not yet been made, it was necessary to estimate the number and types of components in each subunit. The estimates are based mainly on standard circuit designs of the type which might finally be used in the system. The failure rates for all components were derived from Mil-Handbook 217, "Reliability Stress and Failure Rate Data for Electronic Equipment" dated August 1962.

The component failure rates from this source are presented as functions of ambient temperature and the main stress ratio. For transistors, diodes, and resistors the main stress ratio is the ratio of operating power to rated power. The main stress ratio for capacitors is the ratio of operating voltage to rated voltage. The stress ratios used in this analysis are given in Table 2.4-2 under the column designated as part derating. These stress ratios were selected as an initial compromise between weight and size, and reliability. The ambient temperature was assumed to be 50°C. This corresponds to the maximum internal compartment temperature expected during lunar day operation. On the basis of these two factors, a single part failure rate was obtained for each type of component used in the system. These part failure rates are given in Table 2.4-2.

The number of components of each type and the subtotal failure rate for each type of component are also given in the last two columns of Table 2.4-2. This component failure analysis indicates that silicone transistors are the most critical type of component in the system. A first step in improving the reliability of the system could be to use Minuteman reliability transistors. The total failure rate for the system is 3.875 percent/1000 hours. This corresponds to a mean-time-to-failure of 25,800 hours. Figure 2.4-2 shows a plot of reliability as a function of the number of hours of operation for the complete ranging system.

The CW ranging system block diagram used for the reliability and criticality analysis is shown in Figures 2.4-3 and 2.4-4. A reliability prediction worksheet has been filled out for each distinctive type of subunit in the system. The component failure rates used on these worksheets are the same as those given in Table 2.4-2. The subunit failure rates derived on the following 14 worksheets[1] are used for the subunit reliability and criticality analysis presented in Table 2.4-3. The probability of failure for each

[1] The worksheets begin on page 2-299.

TABLE 2.4-2

COMPONENT FAILURE ANALYSIS OF CW RANGING SYSTEM

Component	Mil-Spec.	Part Ambient Temp. °C	Part Derating	*Part Failure Rate %/1000 hr	Number of Parts in System	Sub-Total Failure Rate %/1000 hr
Silicon Transistor	Mil-T-19500A	50°	0.4	0.042	43	1.806
Silicon Diode	Mil-E-1D	50°	0.3	0.017	30	0.510
Composition Resistor	Mil-R-11C	50°	0.4	0.001	263	0.263
Ceramic Capacitor	Mil-C-11015B	50°	0.4	0.001	209	0.209
Var Ceramic Capacitor	Mil-C-81A	50°	0.3	0.003	49	0.147
RF Inductor	Mil-C-15305A	50°	---	0.005	126	0.630
RF Transformer	Mil-C-15305A	50°	---	0.010	23	0.230
Quartz Crystal	Mil-C-3098C	50°	---	0.020	4	0.080

Total System Failure Rate 3.875%/1000 hr

Mean Time to Failure 25,800 hr

*Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

TABLE 2.4-3

SUBUNIT RELIABILITY AND CRITICALITY ANALYSIS CW RANGING SYSTEM

Sub-Unit			Failure Rate %/1000 hrs.	Probability of Failure 1,250 hrs. Operation	Criticality Factor	Criticality Product x 10^{-3}	Order of Criticality
SIRV Ranging Sub-System	1	36.25 MC Crystal Oscillator	0.076	0.00095	1.0	0.95	7
	2	Varactor Phase Modulator	0.075	0.00094	1.0	0.94	12
	3	X2 Transistor Multiplier	0.076	0.00095	1.0	0.95	8
	4	X2 Transistor Multiplier	0.076	0.00095	1.0	0.95	9
	5	145 MC Class C Power Amp.	0.062	0.00078	1.0	0.78	13
	6	80 KC Crystal Oscillator	0.076	0.00095	1.0	0.95	10
	7	Signal Summer	0.074	0.00093	0.7	0.65	18
	8	Range Signal Separation Filter	0.048	0.00060	0.7	0.42	21
	9	Discriminator	0.052	0.00065	1.0	0.65	19
	10	125 MC High Gain Limiting Amp.	0.825	0.01031	1.0	10.31	1
	11	Diplexer	0.060	0.00075	1.0	0.75	15
	12	2 MC Crystal Oscillator	0.076	0.00095	0.5	0.48	20
	13	2 MC Phase Comparator	0.357	0.00446	0.3	1.34	5
	14	80 KC Phase Comparator	0.357	0.00446	1.0	4.46	3
	15	Antenna Coupler	0.013	0.00016	1.0	0.16	22
	16	2 MC Phase Comparator (Quad)	0.357	0.00446	0.3	1.34	6
	17	Phase Shifter	0.004	0.00006	0.3	0.02	24
Surveyor Ranging Sub-System	18	20 MC Crystal Oscillator	0.076	0.00095	1.0	0.95	11
	19	Mixer	0.119	0.00149	1.0	1.49	4
	20	145 MC High Gain Limiting Amp.	0.825	0.01031	1.0	10.31	2
	21	Diplexer	0.060	0.00075	1.0	0.75	16
	22	Antenna Coupler	0.013	0.00016	1.0	0.16	23
	23	125 MC Bandpass Filter	0.056	0.00070	1.0	0.70	17
	24	125 MC Class C Power Amp.	0.062	0.00078	1.0	0.78	14

Total Failure Rate 3.875%/1000 hrs.

Mean Time to Failure 25,800 hr

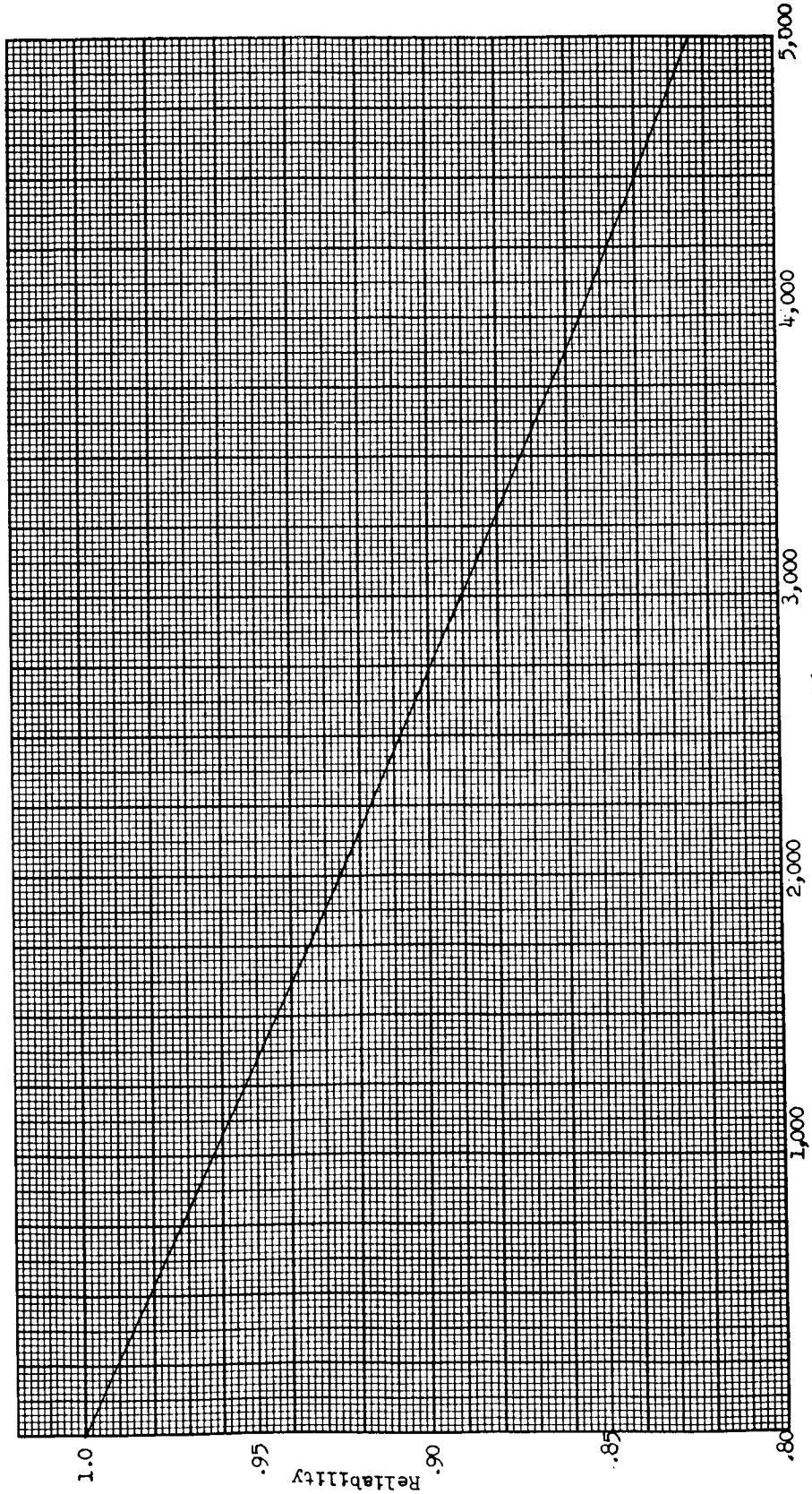


Figure IV-2.4-2 Reliability Vs. Hours of Operation CW Ranging System

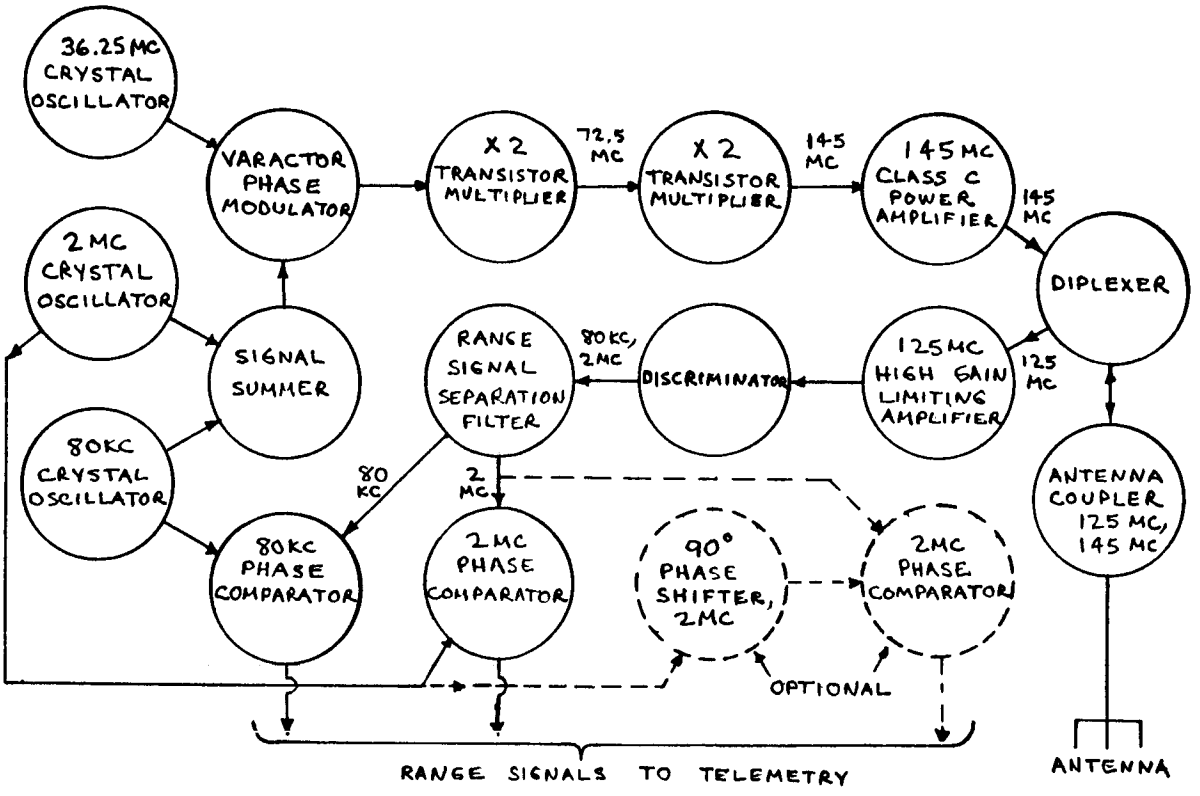


Figure IV-2.4-3 SLRV Mounted Ranging Circuitry

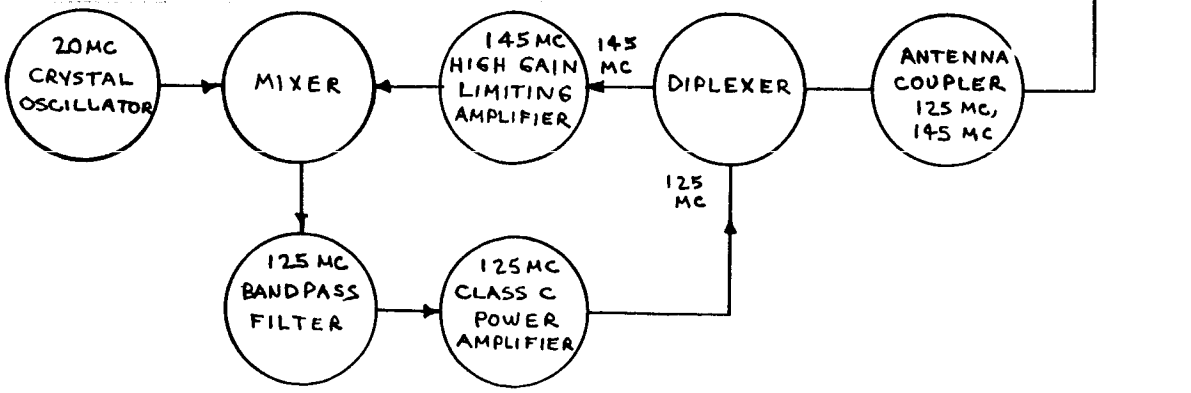


Figure IV-2.4-4 Surveyor Mounted Repeater Translator

subunit was calculated for 1,250 hours. This is the time required to travel the maximum mission distance of 60 kilometers at the slowest speed, and therefore, represents approximately the maximum number of hours the SLRV will be moving on the lunar surface. It has been assumed that the ranging system is operated only when the drive mechanism is operated, and that none of the subunits are activated during the lunar night.

The subunit criticality factors used in the analysis are defined below.

Criticality	Effect
1.0	Complete failure of the system
0.7	Failure of a portion of a subunit that causes loss of fine ranging
0.5	Failure of a subunit that causes complete loss of fine ranging
0.3	Failure of a subunit that causes degradation of fine ranging

The 0.3 criticality is applied to the two 2-Mc phase comparators and the phase shifter. One of these units can fail with only a slight effect in ranging accuracy. The 0.5 criticality is applied to the 2-Mc crystal oscillator. If this unit fails, fine ranging will be completely lost. The 0.7 criticality is applied to the signal summer and the range separation filter. Both of these subunits have some components that effect only the 2-Mc fine ranging signal. All other subunits are assigned a criticality of 1.0, since the failure of any of these subunits will result in a catastrophic failure of the ranging system.

The product of the criticality factor and the probability of failure for each subunit is formed in column four of Table 2.4-3. The highest products represent the most critical subunits in the system.

There are six subunits with criticality products greater than 1.0×10^{-3}. They are listed below in order of a decreasing product:

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Crystal Oscillator SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * est	PART DERATING * est	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50°	0.4	3	.042	1	0.042		
	Resistor	Comp.	MIL-R-11C			50°	0.4	2	.001	5	0.005		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	4	0.004		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	1	0.005		
	Crystal	Quartz	MIL-C-3098C			50°	—	2	.020	1	0.020		

SUB-UNIT TOTAL FAILURE RATE 0.076

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment.

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Transistor Multiplier SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50° est	0.4 est	3	.042	1	0.042		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	2	0.002		
	Capacitor	Var Cer.	MIL-C-81A			50°	0.3	2	.003	4	0.012		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	4	0.020		

SUB-UNIT TOTAL FAILURE RATE 0.076

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Class C Power Amp. SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50° est	0.4 est	3	.042	1	0.042		
	Resistor	Comp.	MIL-R-11C			50°	0.4	2	.001	1	0.001		
	Capacitor	Var Cer.	MIL-C-81A			50°	0.3	2	.003	3	0.009		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	2	0.010		

SUB-UNIT TOTAL FAILURE RATE 0.062

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

1 Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION 120 Mc High Gain Amp. SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans	Si	MIL-T-19500A			50° est.	0.4 est.	3	.042	10	0.420		
	Diode	Si	MIL-E-1D			50°	0.3	2	.017	5	0.085		
	Resistor	Comp	MIL-R-11C			50°	0.4	2	.001	70	0.070		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	40	0.040		
	Inductor	RF	MIL-C-15305A			50°	–	2	.005	20	0.100		
	Transformer	IF	MIL-C-15305A			50°	–	4	.010	11	0.710		

SUB-UNIT TOTAL FAILURE RATE 0.825

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

1 Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Discriminator SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Diode	Si	MIL-E-1D			50° est	0.3 est.	2	.017	2	0.034		
	Resistor	Comp	MIL-R-11C			50°	0.4	2	.001	4	0.004		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	4	0.004		
	Transformer	IF	MIL-C-15305A			50°	-	4	.010	1	0.010		

SUB-UNIT TOTAL FAILURE RATE 0.052

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION: CW Ranging System — SCHEMATIC No.: ____ REV.: ____ DATE: ____

SUB-UNIT DESIGNATION: Diplexer — SCHEMATIC No.: ____ REV.: ____ DATE: ____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * est.	PART DERATING * est.	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE [1]	COMMENTS
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	5	0.005		
	Capacitor	Var Cer	MIL-C-81A			50°	0.3	2	.003	5	0.015		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	8	0.040		

SUB-UNIT TOTAL FAILURE RATE: 0.060

SUB-UNIT MTBF (HOURS): ____

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Antenna Coupler SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Capacitor	Ceramic	MIL-C-11015B			50° est	0.4 est.	2	.001	3	0.003		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	2	0.010		

SUB-UNIT TOTAL FAILURE RATE 0.013

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION C (U) Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Range Signal Seperation Filter SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
						est.	est.						
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	8	0.008		
	Inductor	RF	MIL-C-15305A			50°	–	2	.005	8	0.040		

SUB-UNIT TOTAL FAILURE RATE 0.048

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION C(L) Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Signal Summer SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50° est.	0.4 est.	3	.042	1	0.042		
	Resistor	Comp	MIL-R-11C			50°	0.4	2	.001	6	0.006		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	6	0.006		
	Inductor	RF	MIL-C-15305A			50°	-	2	.005	4	0.020		

SUB-UNIT TOTAL FAILURE RATE 0.074

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Mixer SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50° est.	0.4 est.	3	.042	2	0.084		
	Resistor	Comp.	MIL-R-11C			50°	0.4	2	.001	10	0.010		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	10	0.010		
	Inductor	RF	MIL-C-15305A			50°	–	2	.005	3	0.015		

SUB-UNIT TOTAL FAILURE RATE 0.119

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Phase Comparator SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Trans.	Si	MIL-T-19500A			50° est.	0.4 est.	3	.042	4	0.168		
	Diode	Si	MIL-E-1D			50°	0.3	2	.017	5	0.085		
	Resistor	Comp	MIL-R-11C			50°	0.4	2	.001	25	0.025		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	18	0.018		
	Capacitor	Var Cer.	MIL-C-81A			50°	0.3	2	.003	7	0.021		
	Inductor	RF	MIL-C-15305A			50°	–	2	.005	8	0.040		

SUB-UNIT TOTAL FAILURE RATE 0.357

* INDICATE ESTIMATED OR ACTUAL

SUB-UNIT MTBF (HOURS)

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION CW Ranging System SCHEMATIC No.____ REV.____ DATE____

SUB-UNIT DESIGNATION Varactor Phase Modulator SCHEMATIC No.____ REV.____ DATE____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C * est	PART DERATING * est.	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
	Varactor	Diode	—			50°	0.3	2	.017	3	0.051		
	Resistor	Comp.	MIL-R-11C			50°	0.4	2	.001	4	0.004		
	Capacitor	Ceramic	MIL-C-11015A			50°	0.4	2	.001	5	0.005		
	Inductor	RF	MIL-C-15305A			50°	—	2	.005	3	0.015		

SUB-UNIT TOTAL FAILURE RATE 0.075

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION: CW Ranging System — SCHEMATIC No. ______ REV. ______ DATE ______

SUB-UNIT DESIGNATION: Band Pass Filter — SCHEMATIC No. ______ REV. ______ DATE ______

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
						est.	est.						
	Capacitor	Ceramic	MIL-C-11015A			50°	0.4	2	.001	4	0.004		
	Capacitor	Var Cer.	MIL-C-81A			50°	0.3	2	.003	4	0.012		
	Inductor	RF	MIL-C-15305A			50°	–	2	.005	8	0.040		

SUB-UNIT TOTAL FAILURE RATE: 0.056

SUB-UNIT MTBF (HOURS): ______

* INDICATE ESTIMATED OR ACTUAL

[1] Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION C W Ranging System SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Phase Shifter SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE 1	COMMENTS
						est.	est.						
	Resistor	Comp	MIL-R-11C			50°	0.4	2	.001	2	0.002		
	Capacitor	Ceramic	MIL-C-11015B			50°	0.4	2	.001	2	0.002		

SUB-UNIT TOTAL FAILURE RATE 0.004

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

1 Mil-Handbook 217, Reliability Stress and Failure Rate Data for Electronic Equipment

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125 Mc	high gain limiting amplifier
145 Mc	high gain limiting amplifier
80 kc	phase comparator
	mixer
2 Mc	phase comparator
2 Mc	phase comparator (quadrature)

The major contributors to the failure rate of each of these subunits are silicon transistors. A transistor failure in any of the first four subunits listed above will cause a complete system failure, while a failure in the last two will result in loss of accuracy in the fine ranging. The reliability of the transistor used in these units can be increased by selecting transistors which can be operated at a stress ratio of 0.1 or less. This would reduce the transistor failure rate from 0.042 per cent/1000 hours to 0.020 percent/1000 hours. A second alternative would be to use Minuteman reliability transistors, which have failure rates between 0.003 percent/1000 hours and 0.001 percent/1000 hours for a stress ratio of 0.2 at 40°C. If this does not provide enough reliability, Minuteman components could be used throughout the system. If this is done, it appears possible to decrease the failure rate derived in this analysis by a factor of ten.

2.4.2 Sun Sensor

The sun sensor essentially consists of four eyes and electronics; each eye has 16 solar cells. Although the system can continue to function with the loss of one eye (operate in a degraded mode) the reliability of the sun sensor has been calculated on the basis that all parts operate successfully.

The reliability of the sun sensor, based upon DSIF control hours of 648 for a 4.5-month mission is 0.995. Table 2.4-1 shows the reliability of this unit for various mission months. The prediction work sheet on the following page shows the failure rates and sources of failure rate data for each part.

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Navigation SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Sun Sensor SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	~~XXRT~~ ~~XXXX~~ ~~XXX~~ Stress %	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Transistors						.001		.002	120	.240	Mil Hdbk 217 modified	
												by order of magnitude	
												because of low stress	
	Diodes		Pacific Semi	IN643			.10		.0001	110	.0110	Minuteman	
	Cap.	Glass	Corning	CYFM			.024		.000006	94	.0005	Minuteman	
	Cap.	Tant	Sprague	350D			.3		.001	30	.0300	Sprague	
	Resistor			RN60			.01		.0065	35	.2280	Sprague	
	Resistor	Comp.					.01		.001	190	.1900	Mil HDBK 217	
	Transformer								.05	1	.0500	Mil HDBK 217	
	Solar Cells								.0001	64	.0064		

SUB-UNIT TOTAL FAILURE RATE .7559

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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2.4.3 Inclinometer

Since 1959 the average improvement for Honeywell failure rates has been approximately 20% per year. This has been due mainly to a combination of increased emphasis on design and piece part application reviews, tighter process controls, and better parts. The following component parts and their associated high reliability failure rates were used in determining the overall inclinometer reliability.

The reliability of the inclinometer for a 4.5-month mission is 0.9969 as shown in Table 2.4-1. The failure rate for each of the parts in this unit is shown in Table 2.4-4.

TABLE 2.4-4

PARTS FAILURE RATE

Carbon Resistors	9 @ .0006%/1000 hours	.0054%/1000 hours
Diodes	9 @ .0022%/1000 hours	.0198%/1000 hours
Zener Diode	1 @ .03%/1000 hours	.03%/1000 hours
Accelerometer Microsyn	1 @ .1%/1000 hours	.3%/1000 hours
Transformer	1 @ .3%/1000 hours	.3%/1000 hours
Capacitors (Mica)	1 @ .002%/1000 hours	.01%/1000 hours
Capacitors (Tantalum)	1 @ .01%/1000 hours	.01%/1000 hours
Switching Transistors	2 @ .003%/1000 hours	.006%/1000 hours
Ball Bearings	2 @ .01%/1000 hours	.02%/1000 hours
	Total Failure Rate	.493%/1000 hours

2.5 MOBILITY SUBSYSTEM RELIABILITY

The mobility subsystem consists of four-traction-drive assemblies, a steering lock assembly, and the support structure. The traction drive assemblies and steering lock assembly are controlled by the command subsystem which is not included in this analysis.

2.5.1 Block Diagram

The reliability block diagram (Figure 2.5-1) requires a series arrangement of the support structure, traction drive assemblies, and steering lock assembly for mission success. Though the LRV can operate with three of the drive motions functioning, such an arrangement would result in a degraded mode of operation because of the decrease in climbing ability and increase in mission time. The analysis will be limited to that required for total mission success; i.e., four drive motors functioning.

2.5.2 Mathematical Model

The reliability mathematical mode is as follows:

$$R_M = M_1 \times M_2 \times M_3 \times M_4 \times M_5 \times M_6 \qquad (2.5\text{-}1)$$

where:

R_M = Mobility Subsystem Reliability

M_1 = Reliability of Support Structure

M_2 = Reliability of TDA-1

M_3 = Reliability of TDA-2

M_4 = Reliability of TDA-3

M_5 = Reliability of TDA-4

M_6 = Reliability of Steering Lock Assembly.

Since the four traction drive assemblies are identical and assuming equal operating periods for each, Equation (2.5-1) can be reduced to:

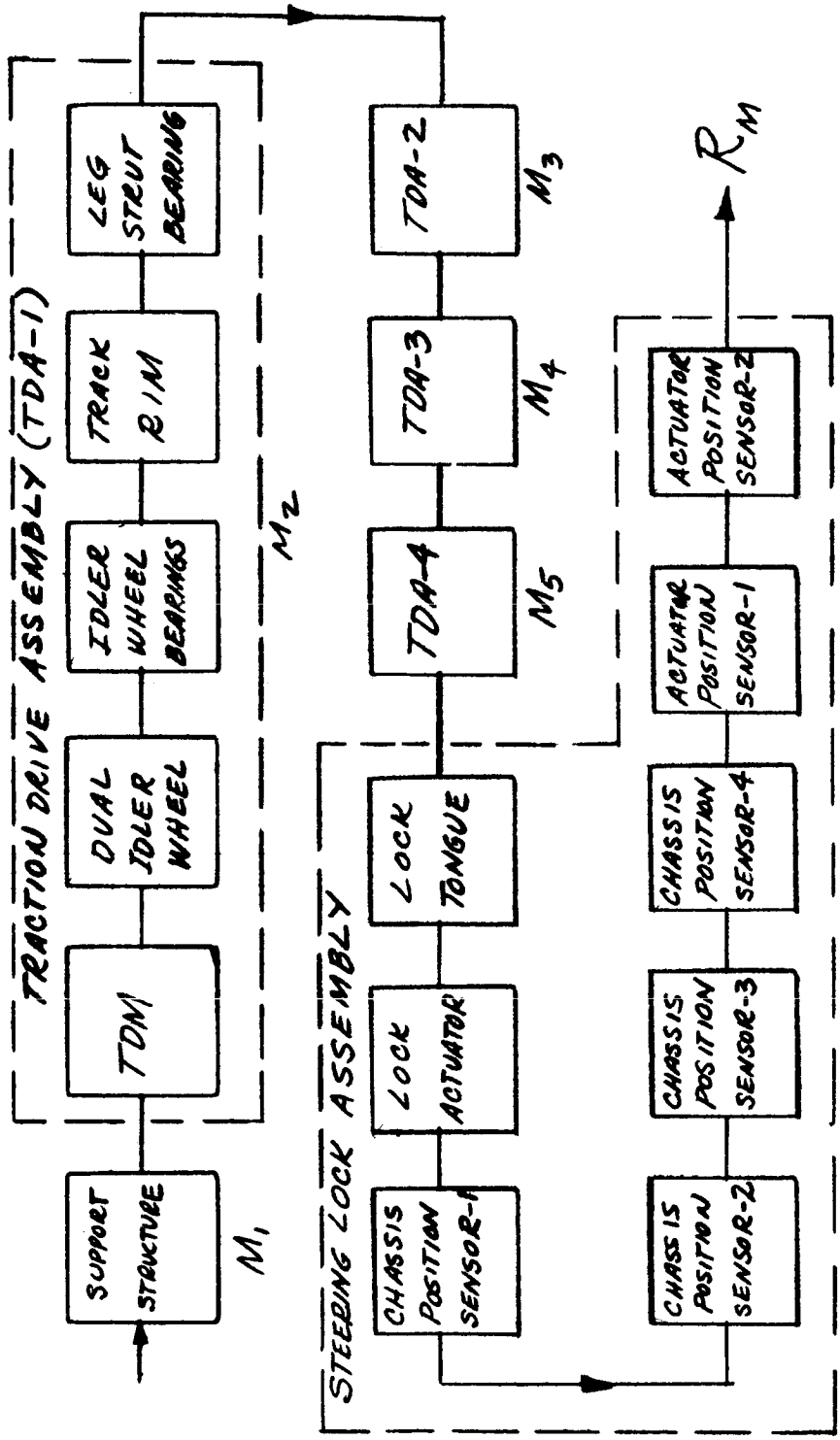

Figure 2.5-1 Mobility Subsystem Reliability Block Diagram

$$R_M = M_1 \times M_2^4 \times M_6 \quad (2.5\text{-}2)$$

The reliabilities for each of the subunits are expressed by the following equations:

$$M_1 = e^{-\lambda t} \quad (2.5\text{-}3)$$

$$M_2 = Rel_{TDM} \times e^{-\lambda_1 t_1} \times e^{-\lambda_2 t_1} \times e^{-\lambda_3 C_1} \times e^{-\lambda_4 t_1} \quad (2.5\text{-}4)$$

$$M_6 = e^{-\lambda_5 C_2} \times e^{-\lambda_6 t_2} \times e^{-\lambda_7 C_3} \times e^{-\lambda_7 C_4} \times e^{-\lambda_7 C_5} \times e^{-\lambda_7 C_6} \times e^{-\lambda_8 C_7} \times e^{-\lambda_8 C_8} \quad (2.5\text{-}5)$$

where:

Rel_{TDM} = Reliability of Traction Drive Mechanism (Refer to Section 2.5.5.2 for equation).

λ_1 = Failure rate of dual idler wheel

λ_2 = Failure rate of idler wheel bearings

λ_3 = Failure rate of track rim

λ_4 = Failure rate of leg strut bearing

λ_5 = Failure Rate of lock tongue

λ_6 = Failure rate of lock actuator

λ_7 = Failure rate of chassis position sensor 1 to 4

λ_8 = Failure rate of actuator position sensor 1 and 2

t = operating time

C = cycles of operation.

Substituting Equations (2.5-3), (2, 5-4), and (2.5-5) into Equation (2.5-2) yields the following mathematical model for the mobility subsystem:

$$R_M = e^{-\lambda t} \times (Rel_{TDM}) \times e^{-4\left[(\lambda_1 + \lambda_2 + \lambda_4) t_1 + \lambda_3 C_1\right]} \times$$

$$e^{-\lambda_5 C_2} \times e^{-\lambda_6 t_2} \times e^{-\lambda_7 (C_3 + C_4 + C_5 + C_6)} \times \qquad (2.5\text{-}6)$$

$$e^{-\lambda_8 (C_7 + C_8)}.$$

2.5.3 Prediction

Assuming a mission distance of 25 km, a vehicle speed of 0.16 mph, and the number of turns the vehicle makes to cover 19 landing point surveys and traverses as 1000, the mission reliability can be obtained using the prediction worksheets (Table 2.5-1), the data shown in Table 2.5-2, and Equation (2.5-6). Thus:

$$R_M + e^{-0.0004} \times (0.995)^4 \times e^{-4\,(0.0504)} \times e^{-0.001} \times$$

$$e^{-0.00198 \times 10^{-6}} \times e^{-0.01 \times 10^{-5}} \times e^{-0.01 \times 10^{-5}}$$

and

$$R_M + 0.8009.$$

This low figure for the reliability is essentially the product of the high failure rate of the track rim. The failure is caused when the track is torn as a function of tensile forces rather than wearout of track tread.

2.5.4 Criticality of Track Rim

It is seen from λt values of Table 2.5-2 that the failure of the track rim has the highest failure compared to the other units of the subsystem. Therefore it can be stated that the other units will have a low probability of failure and consequently lower criticality.

TABLE 2.5-1

MOBILITY SUBSYSTEM PREDICTION WORKSHEETS (Sheet 1 of 3)

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Mobility Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Traction Drive Assemblies SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs OR %/1000	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs OR %/1000	REF. FAILURE RATE SOURCE	COMMENTS
									M		M		
	TDM									4		See TDM Section	
	Dual Idler Wheel								0.99hr	4	3.96	A-Priori	
	Idler Wheel Bearing								4.7 hr	4	18.8	"	
	Leg Strut Bearing								4.7 hr	4	18.8	"	
	Track Rim								.16M	4	.64	"	

SUB-UNIT TOTAL FAILURE RATE _____

SUB-UNIT MTBF (HOURS) _____

* INDICATE ESTIMATED OR ACTUAL

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TABLE 2.5-1

MOBILITY SUBSYSTEM PREDICTION WORKSHEETS (Sheet 2 of 3)

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Mobility Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Steering Lock Assembly SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs OR %/1000 cy	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs OR %/1000 cy	REF. FAILURE RATE SOURCE	COMMENTS
	Lock Tongue								.025cy	1	.025cy	A-Prioni	
	Lock Actuator								7.1 hr	1	7.1 hr	AVCO	
	Reed Switch				Chassis Position				.0001cy	4	.0004cy	"	
	Reed Switch				Actuator Position				.0001cy	2	.0002cy	"	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

B.S. 260 PROJECT SLRV DATE 4/16/64 PAGE 2 OF 3

TABLE 2.5-1

MOBILITY SUBSYSTEM PREDICTION WORKSHEETS (Sheet 3 of 3)

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Mobility Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Support Structure SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Structure								.39	--	.39	A-Priori	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

B.S. 260 PROJECT SLRV DATE 4/16/64 PAGE 3 OF 3

TABLE 2.5-2

MOBILITY SUBSYSTEM RELIABILITY DATA FOR 25-KM MISSION DISTANCE

UNIT	$\lambda \times 10^{-5}$	t or C	λ (t or C)	Remarks
Traction Wheel Drive Assembly				
TDM			0.005	(7)
Dual Idler Wheel	0.99/hr.	100.9hr	0.0010	(1)
Dual Idler Wheel Bearings	4.7/hr	100.9hr	0.0047	(1)
Track Rim	0.16/meter	25000meters	0.0400	
Leg Strut Bearing	4.7/hr	100.9hr	0.0027	(1)
Steering Lock Assembly				
Lock Tongue	0.025/cy	4000cy	0.0010	(2)
Lock Actuator	7.1/hr	0.11hr	0.781×10^{-5}	(3)
Chassis Pos. Sensor 1	0.0001/cy	1000cy	0.100×10^{-5}	(4)
" " " 2	"	1000cy	0.100×10^{-5}	(4)
" " " 3	"	1000cy	0.100×10^{-5}	(4)
" " " 4	"	1000 cy	0.100×10^{-5}	(4)
Actuator Pos. Sensor 1	"	2000cy	0.200×10^{-5}	(5)
" " " 2	"	2000cy	0.200×10^{-5}	(5)
Support Structure			0.0004	(6)

NOTES: (1) For LRV speed of 0.16 mph.

(2) For 1000 turns at 4 cycles per turn.

(3) Assuming actuator operating time of 0.100 sec and 4000 operations.

(4) Assumes each position sensor switch operates once for each of the 1000 turns.

(5) Assumes each position sensor switch operates 2000 times.

(6) Based on reliability of 0.9996.

(7) Based on TDM reliability of 0.995 from Section 2.5.5.1.

The probability of failure for the track rims is obtained from the equation:

$$P = P_F = 1 - e^{-\lambda C} \qquad (2.5\text{-}7)$$

where:

P_F = probability of failure

λ = failure rate of 4 track rims

C = number of cycles.

Therefore, using the λC value for the track rim in Table 2.5-2, the probability of track failure during the mission becomes:

$$P_F = 1 - e^{0.16}$$

and

$$P_F = .1479.$$

The criticality of the track rim, which is the product of the probability of failure and the subsystem degradation caused by failure, can next be determined. Since failure of the track rim would be catastrophic, the subsystem degradation would be 100% and therefore the criticality level for the track rim becomes:

$$\text{Criticality} = P_F \times \% \text{ Deg.}$$

$$= 0.1479 \times 1 = 147.9 \times 10^{-3}.$$

The above criticality level is based on a postulated value for the failure rate of the track rim, since the track was of a unique design and no previous data were available. However, during Phase II of the LRV Program, extensive study and life testing will be made to determine the actual failure rate of the track rim and also ways to reduce the failure rate to give a lower criticality. Some possible ways to decrease the failure would be: (1) to increase the thickness of the stainless steel rim giving greater tensile strength and, (2) improve the manufacturing methods. A 30% increase in the track rim thickness of the four tracks would probably add about 1 lb to the total LRV weight. The reliability of the mobility subsystem would increase from 80% to 87%.

The following sections discuss in detail the reliability and failure mode analysis of the traction drive mechanism (TDM).

2.5.5 Traction Drive Mechanism

2.5.5.1 Introduction and Summary

The traction drive mechanism reliability as a function of vehicle travel in the drive mode is plotted in Figure 2.5-2. These curves are plotted from the data presented in Table 2.5-3. The cross-hatched area represents the region of probability for equal time at high and low speed. Whether the high or low value is more exact depends upon the manner in which the speeds are distributed.

The reliability for the free wheeling mode of operation is shown in Figure 2.5-3. This, of course, is not applied until some prior failure has made the free wheeling mode necessary.

Failure Mode Summary

The failure mode analysis as presented in detail in Section 2.5.5.4 indicates that the most critical assembly is the drive motor. The motor winding and brush failures are the major contributions to this reliability problem. The second most critical assembly is the drive wheel. From the mission standpoint this is probably the most critical since it applied to both the drive and free wheeling modes. The explosive coupling is next most critical with the transmission being last in order of criticality.

Conclusions and Recommendations

On the basis of this analysis, the reliability of the traction drive mechanism for 20 km of vehicle travel lies between 0.993 and 0.996. The present configuration should be evaluated to determine whether any redesign is advisable and whether some preliminary testing should be undertaken prior to redesign. As a task in Phase II, it is recommended that:

1. The drive wheel (or drum) assembly be carefully analyzed and that at least a minimum reliability demonstration be provided.

2. A reliability demonstration program for the explosive

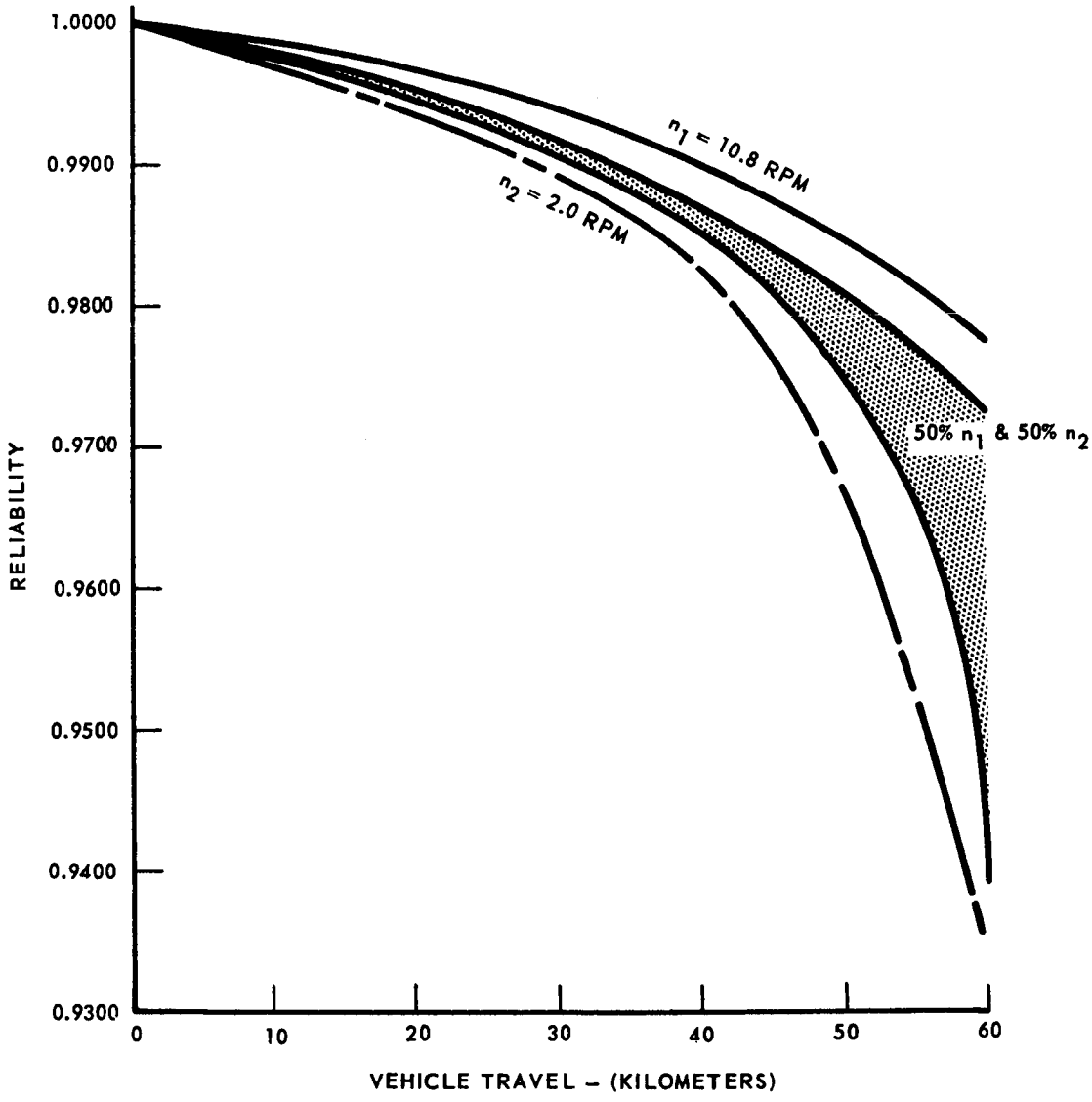


Figure 2.5-2 TDM Reliability, Drive Mode (D_o)

TABLE 2.5-3

TIME DISTANCE RELATIONSHIP

Distance (Km)	Time (hr)	
	n + 10.8 rpm	n + 2 rpm
10	38.6	208
20	77.2	416
40	154	830
60	232	1250

TABLE 2.5-4

RELIABILITY OF MOTOR
WINDING AS A FUNCTION OF DISTANCE

Distance	Motor Winding Reliability (D_1)	
	n + 10.8 rpm	n + 2.0 rpm
10 Km	.99970	.99846
20 Km	.99940	.99688
30 Km	.99880	.99389
40 Km	.99830	.99067

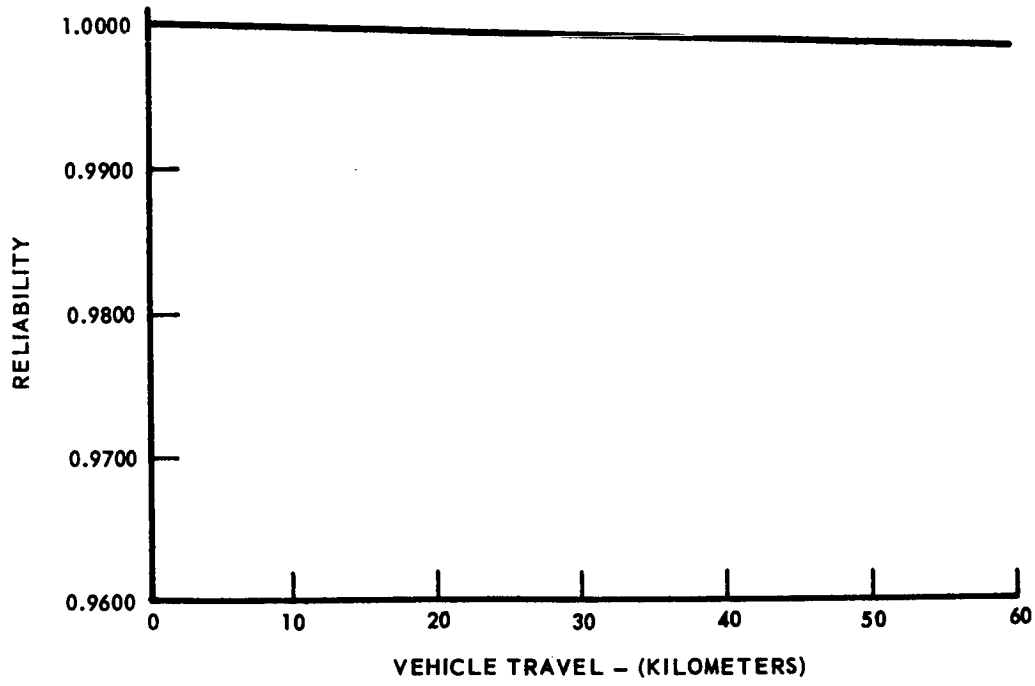


Figure 2. 5-3 TDM Reliability, Free-Wheeling Mode (D_w)

decoupling mechanism be pursued to establish its performance characteristics.

3. Efforts be made to secure adequate motor reliability, either by verification of available information or by a suitable test program.

4. That a suitable qualification test program be devised and performed for the complete traction drive mechanism.

2.5.5.2 Reliability Model

Block Diagram

Figure 2.5-4 portrays the critical elements in the power flow path as the electrical energy is converted to mechanical energy and delivered to the output of the drive wheel.

It can be seen from Figure 2.5-4 that the critical elements are those affecting the continuity of the electrical circuit and the mechanical parts which either provide a power transmitting function or are stressed by operation.

Mathematical Model and Definitions

The reliability of the traction drive mechanism represented in the block diagram can be expressed with two equations,

$$D_o = D_1 \cdot D_2 \cdot D_3 \cdot D_4 \cdot D_5 \cdot D_6 \cdot D_7 \cdot D_8 \qquad (2.5\text{-}8)$$

where D_o is the probability (reliability) of unqualified success in the drive mode, and,

$$D_m = D_6' \cdot D_7' \cdot D_8 \qquad (2.5\text{-}9)$$

where D_m is the probability of a minimum performance as represented by the free wheeling mode of operation.

The terms shown in the block diagram are defined as follows:

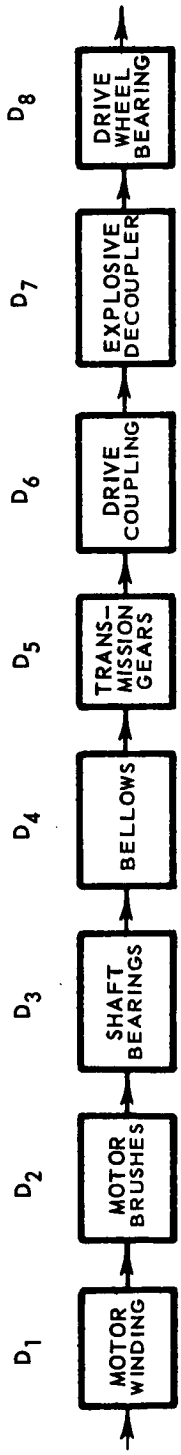


Figure 2.5-4 Traction Drive Reliability Block Diagram

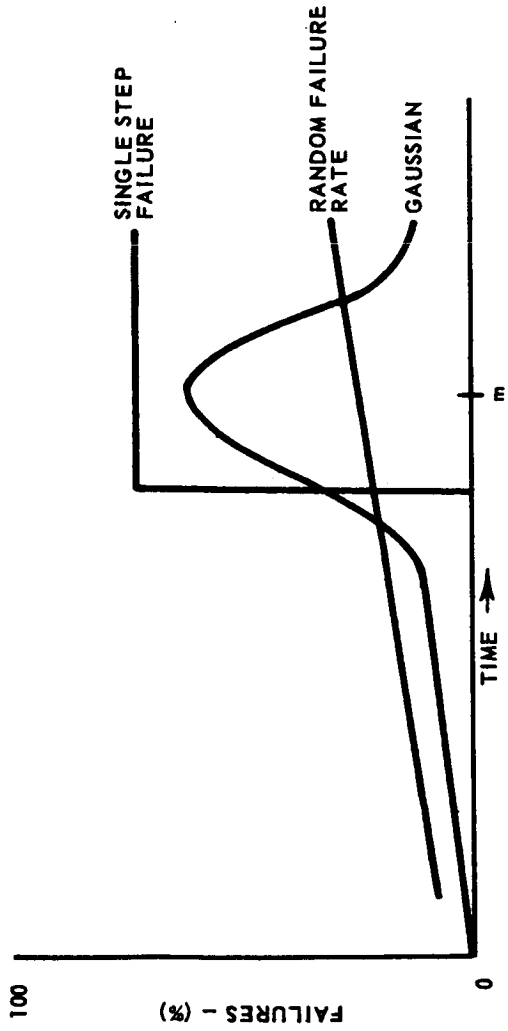


Figure 2.5-5 Failure Distribution Curves

D_1 = Reliability, DC Motor Winding

D_2 = Reliability, DC Motor Brushes

D_3 = Reliability, Shaft Bearings (for DC motor and nutator transmission)

D_4 = Reliability, Bellows

D_5 = Reliability, Transmission Gears

D_6 = Reliability, Drive Coupling functioning as a coupling

D_6' = Probability that the coupling will disengage if explosive device operates

D_7 = Probability that the explosive device does not inadvertently activate.

D_7' = Probability that the explosive device will operate if and when required

D_8 = Reliability, Drive Wheel Bearing.

Derivation and Significant Factors

This section describes the derivation of the defining equations for the reliability terms itemized above and the philosophy and background upon which the derivation is based.

Motor Winding

Motor considerations are based upon the use of the 5-ounce motor which was determined to be the optimum selection in the parametric tradeoff studies.

The reliability of the motor winding is expressed as follows:

$$D_1 = R_{(t)} = e^{-\lambda t} C e^{-\lambda \frac{k d}{\pi D n}} \qquad (2.5\text{-}10)$$

where

λ = failure rate

t = time required to travel a distance d as shown in Table 2.5-3.

and

$$= \frac{d}{v} = k \frac{d}{\pi D n} \qquad (2.5\text{-}11)$$

k = conversion constant

d = distance traveled

D = diameter of the drive hub

n = rotational speed of the hub

V = linear velocity of the vehicle.

Mathematically this may be represented as,

$$D_2 = R_{(t)} = e^{-\lambda_t} = e^{-(\lambda_r + \lambda_w)t} \qquad (2.5\text{-}12)$$

where

λ_r = failure rate due to random failures

λ_w = failure rate contribution due to wearout.

The brush characteristic then will be a combination of a step distribution on a failure distribution which is predictable in the time domain. Graphically this might be represented as shown in Figure 2.5-5.

Experience with transformers and electric motors has led to the estimated failure rates, as a function of temperature, given in the RADC Reliability Notebook. On page 137, the rate for a transformer with class HT insulation is given as 0.5% per 1000 hours, at a hot-spot temperature of 180°C. This temperature is conservatively high for the power input and motor size. On page 139, RADC, a factor of 1.5 is applied to the transformer failure rate to cover the increased hazards of general-purpose motor operation. Thus the insulation failure rate is 0.75% per 1000 hours.

A variation in motor speed affects the time required to travel a specific distance and will affect the motor winding reliability. Since low speeds are associated with motor loading it is logical to assume that stresses producted by hot spot temperatures will occur at low speeds at a time when friction generated heat is minimum. For this reason it is assumed that time is the critical variable and the data calculated on this basis are presented in Table 2.5-4.

Motor Brushes

The motor brush reliability is a more complex function involving the contributions of random failure and brush wearout.

Over a large number of tests not all brushes will fail at the same time so the failure distribution can be closely approximated by the Gaussian distribution about the mean life of the sampling as shown above.

The random failure rate contribution to the reliability D_2 can be obtained from the summary Table 2.5-5. The accuracy to which one can determine the wear out contribution is dependent upon the information one has about the failure distribution curve. The latest data provided to Bendix Research Laboratories Division by Inland Motors Corporation indicates the brushes have a minimum life of 10×10^6 cycles and the mean life is 20×10^6 cycles. If one assumes a Gaussian distribution of failures around this mean life a calculation of failure rates can be made by assuming some interpretation of minimum life. Assuming that this value of 10 million cycles is near the 5-sigma limit (essentially all brushes exceed

TABLE 2.5-5

RELIABILITY PREDICTION WORK SHEET

UNIT DESIGNATION: SLRV - Traction Drive Mechanism

Drawing Number D-215444-26
Date March 24, 1964

Reference Designation	Part Name and Type	MIL-SPEC or Vendor	Vendor Part Number	Application	Part Amb. Temp °C *(E)	Part Derating *	Part Failure Rate %/1000 hrs.	No. of Parts in Sub-Total	Sub-Total Failure Rate %/1000 hrs	Ref. Failure Rate Source	Comments
D_1	Permanent Magnet, D.C. Motor	INLAND	T-1321-A	Vehicle Drive Motor	180	1E	0.75	1	0.75	#2	
D_2	Motor Brushes	INLAND	T-1321-A	Drive Motor	180	1E	0.10	1	0.10	#2	Prior to wear-out
D_3^+	S.S. Ball Bearing #1	New Departure	R-2	Power Shaft	130	.7A	0.07	1	0.07	#1	
	Bearing #2	New Departure	R-3	Power Shaft	130	.25A	0.025	1	0.025	#1	
	Bearing #3	New Departure	R-4	Power Shaft	130	.7A	0.07	1	0.07	#1	
	Bearing #4	New Departure	R-4	Power Shaft	130	.4A	0.04	1	0.04	#1	
D_4	Flexible Bellows	Robertshaw	M-790	Nutator Seal	130	1A	0.1	1	0.1	#1	
D_5	Face years	BRLD	-	Transmission	130	.25E	0.025	2	0.05	#1	
D_6	Mechanical coupling	BRLD	-	Drive Coupling	130	.1E	0.05	1	0.05	#1	
D_6'	Mechanical coupling	BRLD	-	-	130	-	-	-	-	-	Reliability - 1.0
D_7	E.B.W. Explosive Decoupler	Conax	-	Decoupler	130	1E	N A	1	N A	#3	Inadvertent firing, reliability 1.0
D_7'	E.B.W. Explosive Decoupler	Conax	-	-	130	-	-	1	n	#3	Reliability -.9995
D_8^+	Split Ring Bearing	Messinger	A-230	Hub Bearing	130	17A	0.07	1	0.07	#1	

* Indicate Estimated (E) or Actual (A)

Source #1 - Eclipse-Pioneer Reliability Handbook

#2 - RADC Reliability Notebook

#3 - Aerojet-General Ordinance Technical Bulletin #9, 6-17-60, Exploding Wire Intiation Systems

+ Reliability calculations as reported in the report were based on actual cycles rather than the failure rates as given in Table

this value on the basis of wear-out), the effect of the "tail-out" becomes almost negligible so far as brush reliability is concerned. The more conservative approach is the former and this has been used for calculating the values shown in Tables 2.5-6 and 2.5-7. The failure rates were converted to the time base by:

$$\lambda_w = \frac{\text{percent failure}}{\text{time to travel the distance}} \times 1000 \text{ hrs} \qquad (2.5\text{-}13)$$

TABLE 2.5-6

BRUSH FAILURE RATES

Distance	Motor Rev.	Sigma Region	Failure* Rate	$n_1 \lambda_w$ Percent/ 1000 hrs.	$n_2 \lambda_w$ Percent/ 1000 hrs.
10 KM	2.13×10^6	Over 5 sigma	.00006%	.00155	.000288
20 KM	4.26×10^6	Bet. 4&5 sigma	..006%	.0778	.0144
40 KM	8.52×10^6	Bet. 3&4 sigma	.27%	1.75	.326
60 KM	12.78×10^6	Bet. 2&3 sigma	4.55%	19.6	3.64

*From normal distribution tables

The reliability of the motor brushes is presented in Table 2.5-7.

TABLE 2.5-7

MOTOR BRUSH RELIABILITY

Distance Km	Reliability D_2 10.8 rpm	2.0 rpm
10	.99996	.99972
20	.99986	.99952
40	.99715	.99646
60	.98925	.95437

Shaft Bearings

The life of ball bearings has been the subject of very extensive and continuing tests by bearing manufacturers. Under apparently identical conditions of loading, the life has been found to conform to a Weibull distribution, with the form

$$F_\theta = 1 - e^{-\left(\frac{\theta}{\bar{\theta}}\right)^b}, \qquad (2.5\text{-}14)$$

where F_θ is the fraction of the original population which have failed after $\theta\theta$ revolutions, θ is the "characteristic life" under the given loading conditions and b is the "Weibull slope". (See Weibull, W. - "A statistical distribution function of wide applicability" - Journal of Applied Mechanics, September 1951, pp. 293-297.) Typical values of b range from 1.2 to 1.4 for bearings mounted with ordinary care, and much higher when extreme care is exercised. The characteristic life for ordinary care is given by New Departure's general catalog, page 35, as

$$\text{LIFE} = 3800 \left(\frac{\text{capacity}}{\text{load}}\right)^4 \qquad (2.5\text{-}15)$$

where life is in hours, and the capacity is the rated load at operating speed. This relation can be reduced to

$$\bar{\theta} = 228 \times 10^6 \left(\frac{C}{P}\right)^4 \qquad (2.5\text{-}16)$$

where $\bar{\theta}$ is characteristic life in revolutions, C is rated capacity at 1000 rpm, and P is the effective radial load. The following table gives the rated capacity of the bearings for 3800 hrs. average life at 1000 rpm, their maximum effective radial loads, and the average life in revolutions for the maximum effective loads, per New Departure Catalog, 1961.

Bearing Number	a	b	c	d
Size	R-2	R-3	R-4	R-4
Rated capacity, lb	17	40	43	43
Effective radial load	11.8	8.4	28.0	16.0
Life in revolutions ($\bar{\theta}$)	9.8×10^8	1170×10^8	12.8×10^8	118×10^8

The individual shaft bearing reliability for θ motor revolutions is

$$D = e^{-\left(\frac{\theta}{\bar{\theta}}\right)^{b}} \qquad (2.5\text{-}17)$$

and total shaft bearing reliability is

$$D_3 = D_{3a} \cdot D_{3b} \cdot D_{3c} \cdot D_{3d} \qquad (2.5\text{-}18)$$

The resulting shaft bearing reliabilities are shown in Table 2.5-8.

TABLE 2.5-8

SHAFT BEARING RELIABILITY

D_3 - Shaft Bearings:

Bearing a	.99933	.99865	.99690	.99495
b	.99999	.99999	.99998	.99997
c	.99950	.99900	.99770	.99626
d	.99996	.99993	.99984	.99974
$D_3 = D_{3a} \cdot D_{3b} \cdot D_{3c} \cdot D_{3d}$	.99878	.99757	.99443	.99094

Bellows

This flexible part provides a positive sealing mechanism to make it possible to maintain an atmosphere within the motor and transmission. This prevents evaporation of lubricants and plasticizers, minimizes wear rates on motor brushes and eliminates metal welding associated with high vacuum environment.

Any failure of this part, whether it occurs in the flexible member or the joining regions will result in a loss of this pressure and to some subsequent failure. How soon the subsequent failure will occur depends upon the severity of the bellows failure. For this analysis it has been assumed that any bellows failure is a critical one.

The failures which can be anticipated in the flexible member as well as the joining regions are associated with manufacturing methods, process controls and environment. As such they can logically be assumed to be random with time, therefore

$$D_4 = e^{-\lambda t}. \qquad (2.5\text{-}19)$$

Table 2.5-9 is based on the failure rate of 0.1 percent/1000 hours listed on Table 2.5-5 and the time shown in Table 2.5-3.

TABLE 2.5-9

BELLOWS RELIABILITY

Distance Km	Bellow Reliability D_4	
	10.8 rpm	2 rpm
10	0.99996	0.99980
20	0.99992	0.99960
40	0.99990	0.99920
60	0.99977	0.99870

Transmission Gears

Because of the low stress levels in all modes of operation and the relatively low life requirement, wearout and fatigue failures of the gears are considered to be negligible. However, there is a lubricated sliding contact at the gear teeth and when this condition exists random failures associated with the processing of parts and lubricants and the assembly of the component can occur. Generally such failures are caused by contamination even though the most careful techniques and white room equipment is used.

The reliability evaluation for the transmission gears is based upon a 25 percent derated gear pass as shown in Table 2.5-10.

TABLE 2.5-10

TRANSMISSION GEAR RELIABILITY

Distance Km	Transmission Gear Reliability (D_5)	
	10.8 rpm	2 rpm
10	0.99998	0.99990
20	0.99996	0.99979
40	0.99992	0.99958
60	0.99990	0.99937

Drive Coupling

The drive coupling reliability must be evaluated in the two modes of operation related to its function. As a coupling it must transmit the power from the motor shaft to the transmission and, secondly, it must permanently decouple the drive when some malfunction in the drive unit prevents it from operating satisfactorily.

In the drive mode, the reliability (D_6) of the device is dependent upon its design. In this application, it is estimated that it has been derated to 10 percent, providing a margin of safety over the maximum torque capability of the motor more than adequate for the anticipated mission. On this basis the failure rate indicated in Table 2.5-5 was used to calculate the values shown in Table 2.5-11.

TABLE 2.5-11

COUPLER RELIABILITY

Distance Km	Coupler Reliability (D_6)	
	10.8 rpm	2 rpm
10	0.99998	0.99990
20	0.99996	0.99979
40	0.99992	0.99958
60	0.99990	0.99937

The reliability of the device as a decoupler (D'_6) is also a function of the design of the device. Considerable experience has been accumulated in the design of explosively actuated mechanisms such as safety and arming devices, explosive bolts for stage separation, explosive actuators, thrust termination devices, et. cetera. On the basis of information provided in Aerojet-General Ordnance technical bulletin no. 13, (reporting on laboratory qualified devices and space flight results on explosive bolts used in the Able-type rockets; Able 0. . .Able 1. . .Able 3. . .Able 4. . .Able Bravo . . .Transit. . .Tiros. . .Echo. . .Able Star.--no reported or suspected failures)one can conclude that a properly designed decoupler could have a mechanical failure rate which is neglible. This particular application, on the other hand, has problems peculiar to its design which have not been fully evaluated. These problems are associated with the need to mechanically decouple the drive and to assure that the device does not re-engage. This involves a more complex mechanical design and one in which prior explosive bolt and actuator experience may not be entirely applicable. In lieu of information to the contrary, a high reliability has been assigned to this function.

Explosive Decoupler

In considering the explosive decoupling device, again two effects must be evaluated. Firstly, the effect on the drive mode, inadvertent firing of the device. Since an E. B. W. uses thermally stable chemicals and the device cannot readily be initiated with radio frequency radiation, static electricity, or even with direct application of voltages up to 500 volts, it is reasonable to assume that inadvertent firing during the mission operation is negligible.

Secondly, effect on the ability to go into the free wheeling mode, the probability that the device will fire when called upon.

Reliabilities of Exploding Bridge Wire initiators (D'_7) are reported to be .9995 over environmental extremes which include those estimated for this mission.

Drive Wheel Bearing

For the calculation of the drive wheel bearing reliability (D_8) the Weibull distribution was used. In this case, however, the mean life of the bearing, taken from data supplied by the manufacturer (Messinger), was used as the characteristic life. The values for D_8 are shown in Table 2. 5-12.

TABLE 2.5-12

WHEEL BEARINGS RELIABILITY

Distance Km	Drive Wheel Bearing Reliability (D_8)
10	0.99986
20	0.99976
40	0.99945
60	0.99910

While these reliability estimates will serve for this evaluation, the situation here is not comparable to the shaft bearings which are hermetically protected from the environment. As it is now presented, the data makes no provision for the time element and relates the reliability only to the distance travelled. Whatever may be the initial conditions of dust protection and lubrication sealing, after some period of time there will be some deleterious effect. Admittedly, by proper design, sublimation and/or evaporation can become diffusion rate limited and performance can remain high over the mission duration involved. This has not been adequately proven.

Before terminating the discussion of the reliability data, one might question the validity of using constant failure rates in the time regime to evaluate reliability at slower speeds with the variable being the time required to travel a certain distance. While it is true that the number of stress cycles required to travel a certain distance are the same in all cases, the stress rates vary with speed as do localized temperatures. Since it is assumed that slower speeds are caused primarily by load requirements it can be expected that temperatures due to electrical power losses will rise. On the other hand, heat from friction and elastic deformations will decrease at lower speeds. These tend to be self compensating to a degree, and it has been assumed that the net effect is comparable to increased operating time at the original higher speed conditions.

The previous analysis was based upon daytime operation on the moon. In general it might be expected that this provides the most stringent

requirements because most of the expected degradation is anticipated from the higher temperatures. Before dismissing the effects of lunar night on operation and survival, however, some examination is in order.

The traction drive mechanism must be designed to withstand thermal shock even though night operation is not required. During a lunar day mission it is possible for the vehicle to run into a shadow which will create a much more severe thermal shock than the normal moon surface temperature gradient. This thermal shock can occur when the vehicle path carries it into a region which has been shaded for an extended period of time, for example, early in the lunar day when the shadowed region has not been exposed to the sun. Under these conditions, the lunar surface will not have been warmed sufficiently by conduction to provide heat to the traction drive mechanism.

As it is presently designed, the traction drive mechanism would not operate during the lunar night. Even though enough heat were generated in the motor to keep the motor and transmission functioning, it is unlikely that enough would be transferred into the drive wheel outer bearing race to prevent interference in the bearing. To what extent this problem can be relieved by supplying additional heating power is not readily determined. In any case, lunar night operation would require a redesign requiring additional weight and power.

2.5.5.3 TDM Reliability Predictions

Mission Operation

As indicated above, the value for the operational reliability of the traction drive mechanism is given by:

$D_0 = D_1 \cdot D_2 \cdot D_3 \cdot D_4 \cdot D_5 \cdot D_6 \cdot D_7 \cdot D_8$ for unqualified success in the drive mode (see Table 2.5-13) and;

$D_m = D'_6 \cdot D'_7 \cdot D_8$ in the minimum performance or free wheeling mode. D'_6 and D'_7 are tabulated in Table 2.5-14.

A tabulation of the numerical values of these reliabilities is shown in Table 2.5-15.

TABLE 2.5-13

TRACTION DRIVE RELIABILITY
DRIVE MODE (D_o)
FOR WHEEL SPEEDS n_1 = 10.8 rpm and n_2 = 2.0 rpm

Distance KM	D_1		D_2		D_3	D_4		D_5		D_6		D_7	D_8	D_o	
	n_1	n_2	n_1	n_2		n_1	n_2	n_1	n_2	n_1	n_2			n_1	n_2
10	.99970	.99846	.99996	.99972	.99878	.99996	.99980	.99998	.99990	.99998	.99990	1	.99986	.99822	.99642
20	.99940	.99688	.99986	.99952	.99757	.99992	.99960	.99996	.99979	.99996	.99974	1	.99976	.99643	.99292
40	.99880	.99389	.99715	.99646	.99443	.99990	.99920	.99992	.99958	.99992	.99958	1	.99945	.98960	.98270
60	.99830	.99067	.98925	.95437	.99094	.99977	.99870	.99990	.99937	.99990	.99937	1	.99910	.97731	.93365

TABLE 2.5-14

TRACTION DRIVE RELIABILITY FREE WHEELING MODE (D_m)

Distance Km	D'_6	D'_7	D_8	D_m
10	1	.9995	.99986	.99936
20	1	.9995	.99976	.99926
40	1	.9995	.99945	.99895
60	1	.9995	.99910	.99860

TABLE 2.5-15

TRACTION DRIVE MECHANISM RELIABILITY

Distance Km	Drive Mode D_o		Free Wheeling Mode D_m
	10.8 rpm	2 rpm	
10	.99822	.99642	.99936
20	.99643	.99292	.99926
40	.98640	.98270	.99895
60	.97731	.93365	.99860

It must be remembered that D_o and D_m do not necessarily relate to the same time base. It is much more likely that the unit will have operated for some extended period before D_m is applied. In this case, D_8 will not be starting at 0 kilometers. From the mathematical standpoint this has no significance if the failure rate is constant. If, however, there is some factor of either time or distance which alters the failure rate of the wheel bearing (affecting D_8) over the regime under consideration, extreme care must be exercised in interpreting the results from this analysis. This only accentuates the need to know more about the wheel bearing behavior.

Checkout

The Traction Drive Mechanism is inoperative during the checkout period. Explosive actuator checks are standard procedure, any inadvertent firing could not go undetected. Continuity checks on electrical circuits are also routine. No reliability correction factor need be applied for the checkout.

Launch to Lunar Landing

The Traction Drive Mechanism is also inactive during this period. Remote monitoring of ground check points would provide condition information but could have no effect on the reliability. As a mechanical device designed for shock and vibration, the traction drive mechanism will not be degraded by extremes experienced during lunar landing.

2. 5. 5. 4 Failure Mode, Effect and Cirticality Analysis

Probability of Occurrence

One of the difficulties in extracting the probability of occurrence data from the values for reliability is that of proportioning to total failures among the several modes of failure. The quantity of test required to accomplish this accurately is not yet available. In lieu of more exact information the following assignments have been made.

1. Motor winding failures have been equally divided between open and insulation failure.

2. Motor and transmission bearings are 70 percent fatigue failures (seizure) and 30 percent wear (high friction).

3. Essentially all bellows failures are due to fatigue.

4. Gear failures are wear-out or lubrication breakdown type.

5. Drive sprocket bearing failures are 20 percent fatigue-type, 40 percent metal-to-metal welding and 40 percent seal failure.

In view of this arbitrary assignment, the element criticalness is likely to be less significant than the criticalness rating for the part.

Degrading Effect on Performance

The degrading effect of the failure on the performance of the unit is assigned in accordance with the definitions of the degradation categories presented below:

Category 1 - Failure causes abort	1
Category 2 - Failure requires transfer to free wheeling mode	0.7
Category 3 - Failure produces a degraded mode of drive operation	0.4
Category 4 - Failure has slight effect	0.1

On the basis of these definitions all of the failure modes presented in Table 2.5-16 fall in the first three categories.

Criticalness

The criticalness level of the failure as represented by the product of the probability of occurrence and the degradation rating are shown in column 3 of Table 2.5-16. For further definition, rankings for the specific failures are presented in the fourth column.

On the basis of this analysis one must conclude that the motor is the most critical component from the performance standpoint. From the mission viewpoint, however, there is always the chance to go to the free wheeling mode. If one combines the criticalness effect of the motor with that of the explosive actuator (value 4.2) the over-all result indicates the drive wheel to be most critical. This is most logical since a failure in the drive wheel affects the performance in either mode of operation.

2.5.5.5 Problem Areas and Improvement Analysis

As a result of the reliability analysis certain problem areas emerge as significant factors in the reliability. Some design improvements and

TABLE 2.5-16

FAILURE MODE ANALYSIS

FAILURE MODES	Probability of Occurrence (1)	Degrading Effect on Performance (2)	Criticalness Level	
			Product x 10^{-3} (1) x (2) = (3)	Ranking (4)
1. D.C. Motor	--	--	--	--
1.1 Open Winding	.0016	0.7	1.12	1
1.2 Breakdown of Electrical Insulation	.0016	0.4	.64	3
1.3 Spring - Fatigue Failure (Brush Spring)	.0004	0.7	.28	6
1.4 Brushes - Wear-out	.0001	0.7	.07	15
1.5 Bearing Failure:	--	--	--	--
1.5.1 Fatigue Failure (seizure)	.001	0.7	.7	2
1.5.2 Lubrication (wear-out; high friction)	.0004	0.4	.16	10
1.6 De-magnetization of Permanent Magnet	1×10^{-6}	0.7	.0007	18
2. Nutator Transmission	--	--	--	--
2.1 Bearing Failure	--	--	--	--
2.1.1 Fatigue Failure (seizure)	.0007	0.7	.49	5
2.1.2 Lube Failure (wear-out; high friction)	.0002	0.5	.10	13
2.2 Hermetic Seal Failure:	--	--	--	--
2.2.1 Mechanical Failure:	--	--	--	--
a) Welding	1×10^{-6}	0.4	.0004	20
b) Cracking	1×10^{-6}	0.4	.0004	21
2.2.2 Bellows Failure - Fatigue	.0004	0.4	.16	9
2.3 Gear Teeth Failure	--	--	--	--
2.3.1 Tooth Fracture	1×10^{-6}	0.4	.0004	19
2.3.2 Lube Failure (wear-out)	.0002	0.7	.14	11
3. Explosive Actuator	--	--	--	--
3.1 As a Coupled Drive	.0002	0.7	.14	12
3.2 Inadvertent Firing	1×10^{-6}	0.7	.0007	17
3.3 Fail to Fire	.0005	1.0	.5	4
3.4 Fail to Decouple	1×10^{-6}	1.0	.001	16
4. Drive Wheel	--	--	--	--
4.1 Bearing - Fatigue Failure	.0001	1.0	.1	14
4.2 Cold Welding - Metal-to-Metal	.0002	1.0	.2	7
4.3 Contamination (grease seal failure)	.0002	1.0	.2	8

component developments which are required to improve the reliability of the traction drive mechanism are suggested in the following paragraphs.

Design Improvements

The reliability analysis indicates that the electric motor is a key problem area in the traction drive mechanism. Much doubt exists over the meaning of life data supplied by the vendor and the method by which this should be intepreted. The analysis to date does not indicate that the motor is excessively stressed with respect to the power requirement; yet some of the part life expectancy data indicate that a more detailed examination of motor bearings and brushes is required. The state-of-the-art of bearings has been advancing rapidly, and this particular problem is one of selection rather than development. Advances in brush development are not obtained as readily; however, some effort has been directed at solving this problem. Bendix is already investigating some recently proposed motor designs which appear to offer advantages in both weight and reliability.

Because of the critical nature of the drive wheel assembly a complete design analysis and re-evaluation is in order. A re-examination of the grease retention and contaminant exclusion problems is already being undertaken. It is recommended that this have high priority in Phase II of this program.

A more rigorous study should be conducted of the lunar night environmental effects on the traction drive mechanism. This study should contain a re-evaluation of metallic material selections, lubrication, explosive components and all non-metallic materials.

Component Development

There is an apparent need to develop a small drive motor with adequate brush life. A motor properly sized to accomplish the mechanical functions within reasonable weight and size limitations is only marginal with respect to reliability.

At a very early date the drive wheel assembly should be built and tested in a simulated lunar environment (within the limits of available equipment). Effectiveness of the grease seal in a high vacuum environment is especially important. Because of the critical position this assembly has in the operation of the mobility system, time should be allowed for a reliability demonstration.

The explosive decoupling device is a new design upon which no substantiated reliability data are available. The mechanical portion of this device should have a reliability demonstration.

2.6 DEPLOYMENT

The deployment subsystem reliability block diagram is shown in Figure 2.6-1. A mission success for the subsystem is defined as the deployment of the LRV from the Surveyor and subsequent erection of the TV camera, steerable antenna, omni-antenna, and RF ranging antenna.

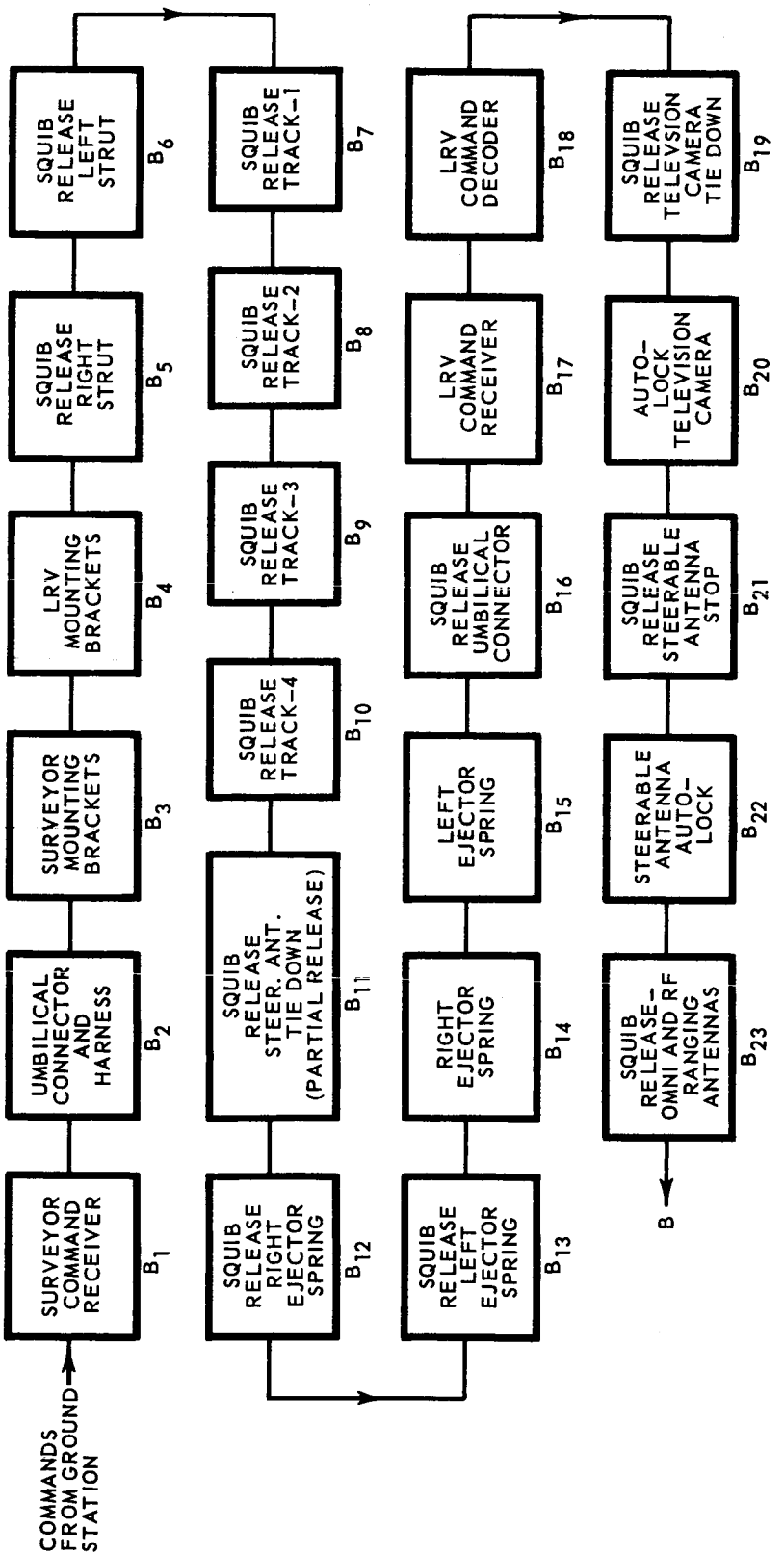
The presumed sequence of events would be as follows:

Upon landing of the Surveyor on the lunar surface, a ground command will be sent and received via the Surveyor command subsystem and will be transferred to the LRV through the umbilical connector and harness. This command will then fire the squibs associated with the release of the LRV right and left struts and release of the four LRV tracks. A second ground command will then be sent for firing the squibs associated with partial release of the steerable antenna, release of the right and left ejector springs, a delayed release of the omni and RF ranging antennas and release of the umbilical connector. The second command results in ejection of the LRV from the Surveyor. Upon landing on the lunar surface the omni and RF antennas erect. A ground command is then sent to the LRV through its command subsystem for firing of the squibs associated with the release and erection of the TV camera and steerable antenna. This completes the deployment function.

The reliability mathematical model for the deployment subsystem is obtained by using the reliability block diagram. Since this block diagram indicates a series arrangement of the sub-units, the total reliability is obtained by the product of the reliabilities of all of the sub-units. The total reliability is then given by the expression:

$$R_B = \prod_{i=1}^{i=23} B_i$$

The reliability equation for each sub-unit is shown in Table 2.6-1, which indicates the reliability of each sub-unit for the mission, together with the total reliability of the subsystem. As shown in Table 2.6-1 the



NOTE: SQUIBS WIRED WITH REDUNDANT FIRING CIRCUITS

Figure 2.6-1 Deployment Subsystem Reliability Block Diagram

TABLE 2.6-1

DEPLOYMENT SUBSYSTEM RELIABILITY

Sub-Unit Name	Designation	Reliability Equation	Failure Rate (λ) In Fail./Hr. or Cy. x 10^{-5}	Time (t) or (C) In Hrs. or Cy.	Reliability
Surveyor Command Receiver	B_1	$B_1 = e^{-\lambda t}$	0.35	.0019	.99999
Umbilical Connector and Harness	B_2	$B_2 = e^{-\lambda t}$	0.20	.0019	.99999
Surveyor Mounting Brackets	B_3	$B_3 = e^{-\lambda C}$	1.00	1	.99999
LRV Mounting Brackets	B_4	$B_4 = e^{-\lambda C}$	1.00	1	.99999
Squib Release Right Strut	B_5	$B_5 = e^{-\lambda C}$	10.00	1	.99990
Squib Release Left Strut	B_6	$B_6 = e^{-\lambda C}$	10.00	1	.99990
Squib Release Track - 1	B_7	$B_7 = e^{-\lambda C}$	10.00	1	.99990
Squib Release Track - 2	B_8	$B_8 = e^{-\lambda C}$	10.00	1	.99990
Squib Release Track - 3	B_9	$B_9 = e^{-\lambda C}$	10.00	1	.99990
Squib Release Track - 4	B_{10}	$B_{10} = e^{-\lambda C}$	10.00	1	.99990
Squib Release Steerable Antenna Tie Down	B_{11}	$B_{11} = e^{-\lambda C}$	10.00	1	.99990
Squib Release Right Ejector Spring	B_{12}	$B_{12} = e^{-\lambda C}$	10.00	1	.99990
Squib Release Left Ejector Spring	B_{13}	$B_{13} = e^{-\lambda C}$	10.00	1	.99990
Right Ejector Spring	B_{14}	$B_{14} = e^{-\lambda C}$	1.00	1	.99999
Left Ejector Spring	B_{15}	$B_{15} = e^{-\lambda C}$	1.00	1	.99999
Squib Release Umbilical Connector	B_{16}	$B_{16} = e^{-\lambda C}$	10.00	1	.99990
LRV Command Receiver	B_{17}	$B_{17} = e^{-\lambda t}$	0.917	.0019	.99999
LRV Command Decoder	B_{18}	$B_{18} = e^{-\lambda t}$	6.53	.0019	.99999
Squib Release TV Camera Tie Down	B_{19}	$B_{19} = e^{-\lambda C}$	10.00	1	.99990
Auto-Lock TV Camera	B_{20}	$B_{20} = e^{-\lambda C}$	1.00	1	.99999
Squib Release Steering Antenna Stop	B_{21}	$B_{21} = e^{-\lambda C}$	10.00	1	.99990
Steering Antenna Auto-Lock	B_{22}	$B_{22} = e^{-\lambda C}$	1.00	1	.99999
Squib Release-Omni and RF Ranging Antennas	B_{23}	$B_{23} = e^{-\lambda C}$	10.00	1	.99990

$$\text{TOTAL RELIABILITY} = \prod_{i=1}^{i=23} B_i = .99850$$

subunit reliabilities are high because some operate for a short period of time to accomplish the mission and others are one cycle operations such as squib firing, ejecting springs, etc. This then produces a high subsystem reliability of 0.99850 for the mission.

Because of the above high reliability and the provision for dual firing circuits for each squib, the probability of failure for the subsystem will be low.

2.7 STRUCTURE AND THERMAL CONTROL SUBSYSTEM RELIABILITY ANALYSIS

This section contains the reliability analysis for the SLRV structure and thermal control subsystem for determining the reliability block diagram and mathematical model.

The structure and thermal control subsystem provides the mounting and temperature control requirements for the SLRV subsystems. The structure consists of the two body elements (with steering straps) and the struts. The thermal control subsystem includes: (1) thermal coatings applied to the SLRV structure, (2) a thermal plate used to mount the electronic packages for heat sink with a thermal insulated cover enclosing the electronics to the thermal plate, (3) strip heaters installed in six units for maintaining temperatures during lunar nights, and (4) the on-off control relay and temperature limit switch for commanded operation of the heaters and to turn the heaters off automatically if a temperature limit is reached.

The reliability block diagram for the structure and thermal control subsystem is shown in Figure 2.7-1. A mission success is defined as that obtained from the proper function of the structure and thermal control elements. Thus the reliability block diagram indicates a series chain of the elements. It had been planned to use redundant elements for the control relay, temperature switch, and heaters, but an investigation of the probability of failure for these parts (based on a mission time of 4.5 months) indicated a very low probability of failure. In addition, the strip heaters are actually redundant in construction since the heater elements are wired in parallel and openings in the elements would not prevent the heater from operating. Consequently, the redundant parts were eliminated giving a series chain for the reliability block diagram.

Figure 2.7-2 shows the reliability block diagram for the redundant configuration. The parallel combination of control relays, A3, provided to ensure a success if one relay did not operate. Series relay, A4, was provided to ensure success if either relay of A3 failed because of a shorted contact. A parallel combination of the temperature limit control switch was provided to ensure success in the event that the switch failed in an open condition. Finally, the strip heaters for each unit were parallelled to provide success if one heater failed due to an open condition.

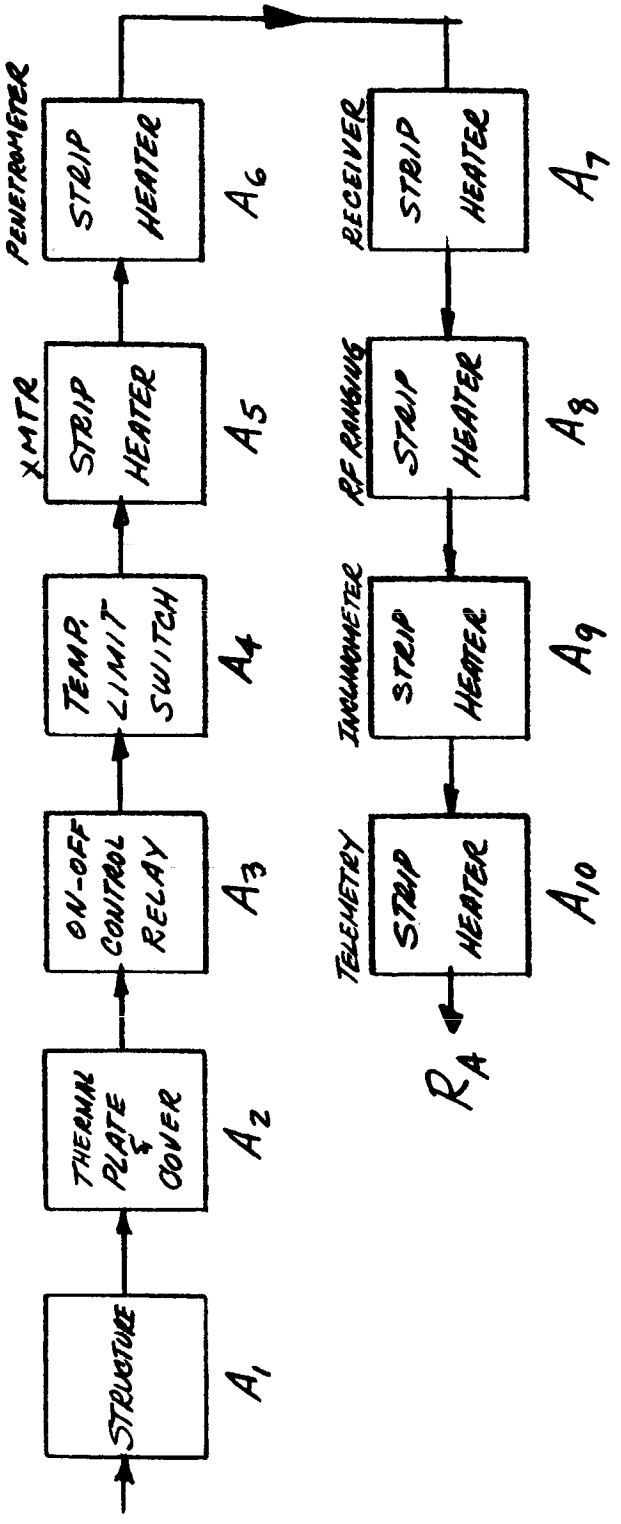


Figure 2.7-1 Structure and Thermal Control Subsystem Reliability Block Diagram (Nonredundant)

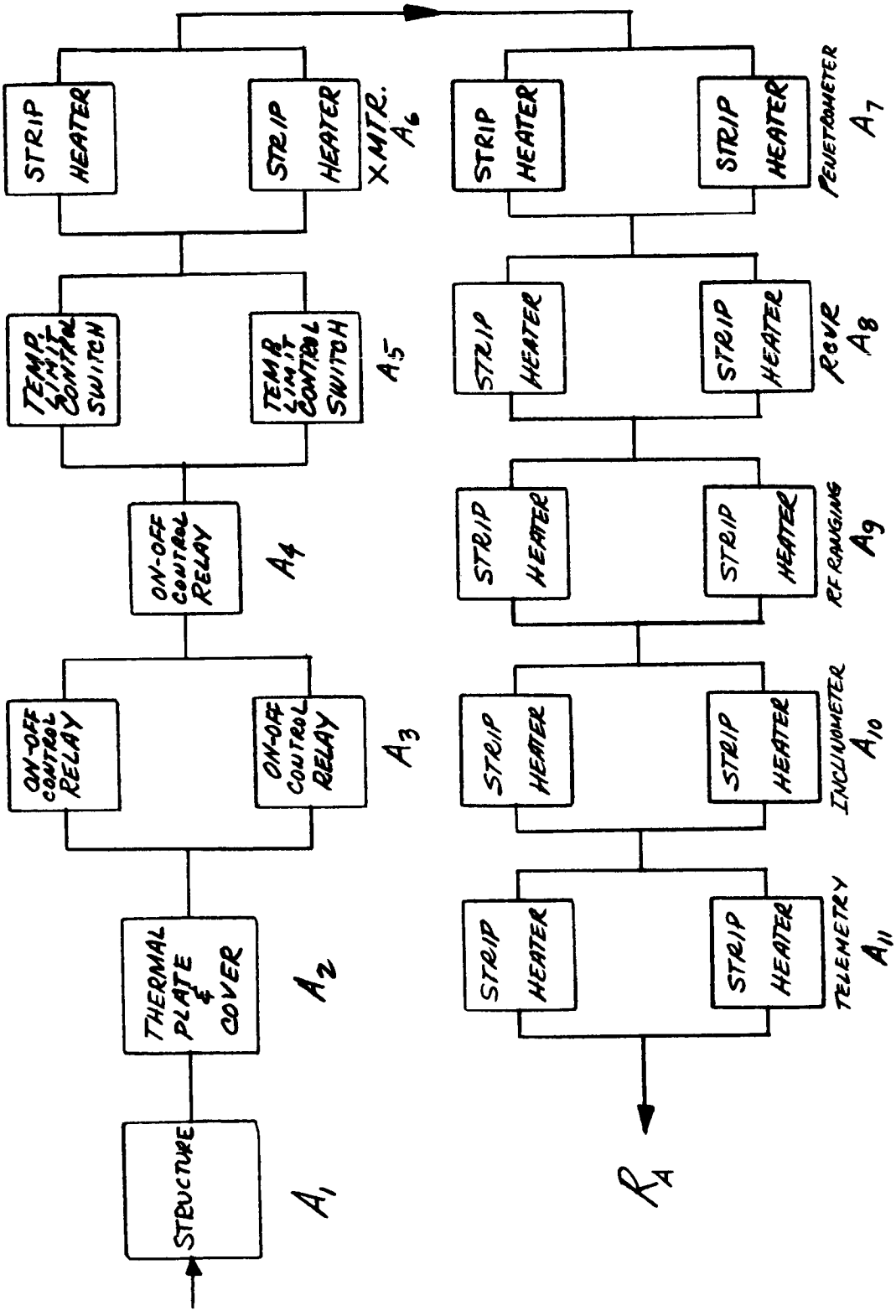


Figure 2.7-2 Structure and Thermal Control Subsystem Reliability Block Diagram (Redundant Configuration)

From Figure 2.7-1, the mathematical model for reliability becomes the product of the reliability A_1 through A_{10} or

$$R_A = \prod_{i=1}^{10} R_i . \qquad (2.7\text{-}1)$$

Since the strip heaters are identical and operate at the same time, Equation (2.7-1) can then be rewritten as

$$R_A = \prod_{i=1}^{4} R_i \times (A_5)^6 . \qquad (2.7\text{-}2)$$

The reliability equations for the subunits are as follows:

$$A_1 = e^{-\lambda_1 t_1} \qquad (2.7\text{-}3)$$

$$A_2 = e^{-\lambda_2 t_1} \qquad (2.7\text{-}4)$$

$$A_3 = e^{-\lambda_3 C_1} \qquad (2.7\text{-}5)$$

$$A_4 = e^{-\lambda_4 C_2} \qquad (2.7\text{-}6)$$

$$A_5 = e^{-\lambda_5 t_2} . \qquad (2.7\text{-}7)$$

where: λ_1 = failure rate of support structure

λ_2 = failure rate of thermal plate and cover

λ_3 = failure rate of on-off control relay

λ_4 = failure rate of temperature limit switch

λ_5 = failure rate of strip heater

t = operating time

C = cycles

Substituting the above equations into Equation 2.7-2 the mission reliability becomes:

$$R_A = e^{-\lambda_1 t_1} \times e^{-\lambda_2 t_1} \times e^{-\lambda_3 C_1} \times e^{-\lambda_4 C_2} \times e^{\left(-\lambda_5 t_2\right) 6} \qquad (2.7\text{-}8)$$

The reliability for a mission time of 4.5 months can then be obtained by solving Equation (2.7-8) using the failure rates shown on the reliability prediction sheets at the end of this section and the following:

1. Assume the reliability of the structure and thermal plate and cover to be 0.9999.

2. That heater operation is required only during lunar nights, giving eight cycles of the control relay (one at the beginning and end of each lunar night) and heater operation time of 1512 hours for four lunar night periods.

3. Assume the temperature limit switch operates only a short period of time during the lunar nights; therefore the reliability is approximately unity.

From the above assumptions the values for t and C become:

t_1 = 3294 hours

t_2 = 1344 hours

C_1 = 8 cycles

C_2 = 0

Therefore, the reliability for the 4.5-month mission is:

$$R_A = 0.9999 \times 0.9999 \times e^{-0.09 \times 10^{-5}} \times 1 \times e^{-0.001}$$

and

$$R_A = 0.9990.$$

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Structure & Thermal Control Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Structure SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIG-- NATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Structure								.003	--	.003	A-Priori	

SUB-UNIT TOTAL FAILURE RATE _____

SUB-UNIT MTBF (HOURS) _____

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Structure & Thermal Control Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Thermal Plate and Cover SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
	Thermal Plate and Cover								.003	--	.003	A-Priori	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Structure & Thermal Control Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION ON-OFF Temp. Control SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000 Cycles	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000 cycles	REF. FAILURE RATE SOURCE	COMMENTS
A_3	Relay				Heater ON-OFF Control				.010	1	.010	RADC	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION: Structure & Thermal Control Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION: Temperature Limit Control SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
A_4	Temp.	Switch							.007	1	.007	AVCO	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

* INDICATE ESTIMATED OR ACTUAL

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RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION Structure & Thermal Control Subsystem SCHEMATIC No. _____ REV. _____ DATE _____

SUB-UNIT DESIGNATION Strip Heaters SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
A_5-A_{10}	Strip Heater								.01	6	.06	A-Priori	

SUB-UNIT TOTAL FAILURE RATE

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

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2.8 PRIME POWER

2.8.1 Parametric Studies Summary

During the first bimonthly period, reliability parametric data were generated for a prime power subsystem consisting of an RTG and a DC-DC converter. During the second bimonthly period, the study was continued and provided parametric data for the reliability comparison of five prime power subsystem concepts: RTG, RTG-solar cells, RTG-battery, solar cells-battery, solar cells-battery-isotope heat source and their necessary associated electronics and electromechanical activators. The concepts rank from highest to lowest in the order named. An RTG was chosen for the SLRV (see Volume III, Book 2, Section 11).

2.8.2 Reliability Model and Prediction

The reliability model for the prime power subsystem is a simple series chain consisting of the RTG, DC-DC converter and the regulator. A lambda of 0.1%/1000 hours was assumed for the RTG. The reliability model of the DC-DC converter regulator is a simple series chain of all its piece parts which results in the equation

$$R = e^{-\sum_{i}^{n} \lambda_i t}$$

where

λ_i = failure rate in %/1000 hours for the ith part

n = total number of parts.

The resulting prime power subsystem reliability is 0.970 for 4000 hours of operation. Table 2.8-1 provides backup details for this prediction. The schematic for the converter upon which the prediction is based is shown in Figure 2.8-1.

2.8.3 Failure Mode, Effect, and Criticality Analysis

The methodology is the same as for other subsystems discussed in previous sections. The five most critical failure modes are listed in Table 2.8-2. Opening of the center taps on the power transformer and

Table 2, 8-1

RELIABILITY PREDICTION WORKSHEET

UNIT DESIGNATION PRIME POWER SUBSYSTEM SCHEMATIC No. BSD REV. A DATE 4-10-64

SUB-UNIT DESIGNATION _____ SCHEMATIC No. _____ REV. _____ DATE _____

REFERENCE DESIGNATION	PART NAME	PART TYPE	MIL-SPEC OR VENDOR	MIL TYPE DESIGNATION OR VENDOR PART No.	APPLICATION	PART AMB TEMP °C *	PART DERATING *	NUMBER OF TERMINALS	PART FAILURE RATE %/1000hrs	NUMBER OF PARTS IN SUB-TOTAL	SUB-TOTAL FAILURE RATE %/1000hrs	REF. FAILURE RATE SOURCE	COMMENTS
T-1	Transformer				Switching	55°C	50%	5	.0250	1	.0250	Tra-	
T-2	"				Power			39	.0250	1	.0250	873-74	
C	Capacitor				Filter			26	.0022	13	.0286		
CR	Diode				Rectifier			48	.0165	24	.3960		
TR	Transistor				Switching			4	.0365	2	.0730		
R	Resistor				Power			4	.0076	2	.0152		
ZR	Zener Diode				Regulator			28	.0066	14	.0942		
RTG	Radioisotope Thermal Generator				D. C. Source			2	.1000	1	.1000		

SUB-UNIT TOTAL FAILURE RATE .7570

SUB-UNIT MTBF (HOURS)

*INDICATE ESTIMATED OR ACTUAL

B.S. 260 PROJECT _____ DATE _____ PAGE _____ OF _____

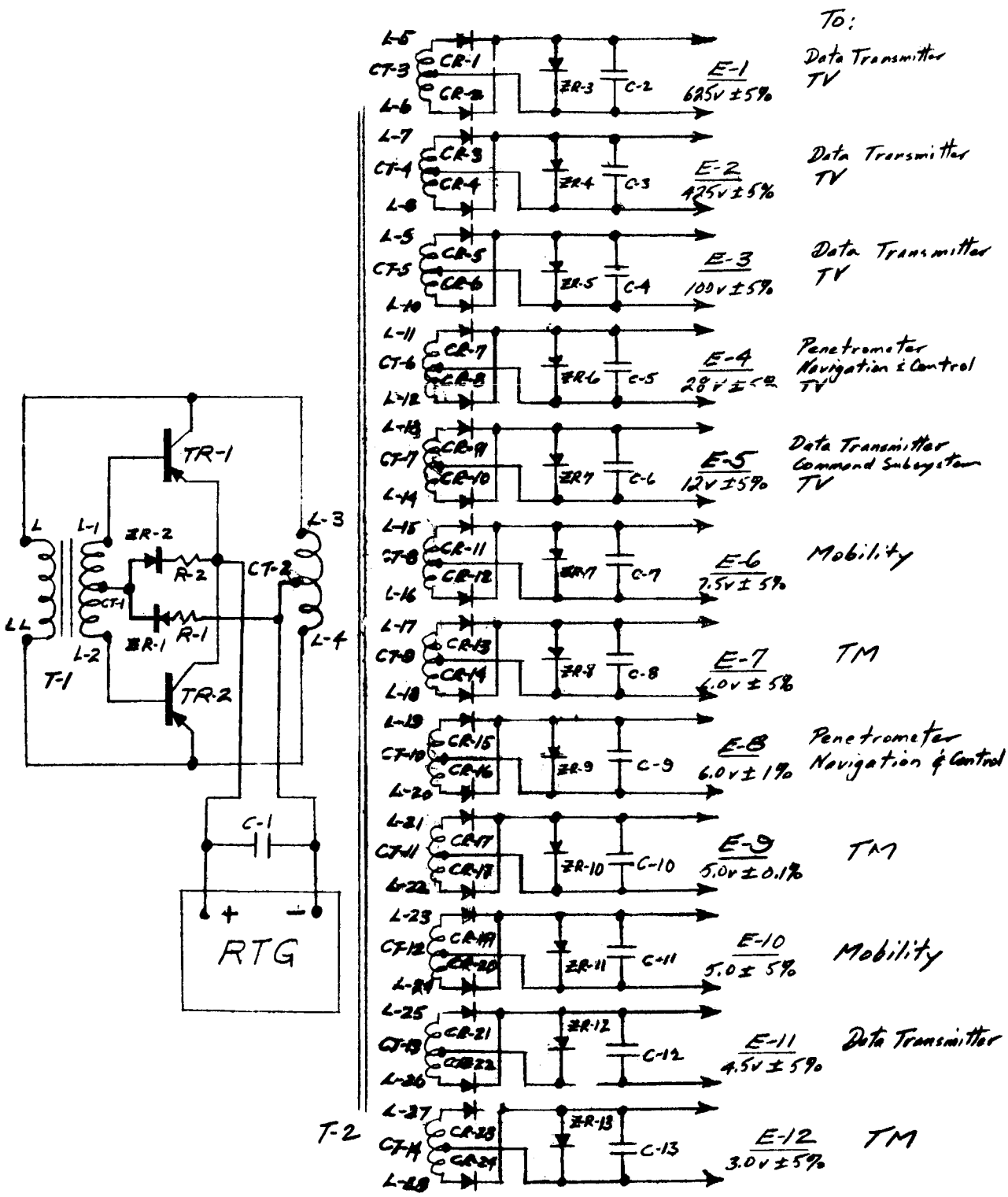

Figure 2.8-1 Prime Power Converter Schematic Diagram

TABLE 2.8-2

PRIME POWER SYSTEM CRITICALITY LEVELS

Part Mode	Fail Mode	Fail Mode Probability $\lambda t \times 10^{-3}$	System Degradation %	System Criticality Value ($\lambda t \times 10^{-3}$)	System Criticality Index	System Effects
CT-2/T-2	OPEN	.0500	100	5.00	1	Zero power from converter all subsystems inoperative
CT-1/T-1	OPEN	.0500	100	5.00	2	Zero power from converter subsystems inoperative
C-1	SHORT	.0400	100	4.40	3	Zero power from converter subsystems inoperative
TR-1/TR-2	SHORT	.0270	100	2.70	4	75% power loss from converter subsystems inoperative
R-1/R-2	OPEN	.0150	100	1.50	5	Zero power from converter subsystems inoperative

saturable core transformer (T-2 and T-1 respectively in Figure 2.8-1) in the oscillator circuit both result in complete loss of power from the converter. T-2 is rated more critical than T-1 since T-2 has the greater number of windings and terminals, hence greater susceptibility to the open failure mode. Shorting of C-1, filter capacitor on the output of the RTG, also results in complete loss of power output. Although shorting of either transistor in the oscillator circuit results in 75% compared to 100% loss for opening of either R-1 or R-2, the probability of occurrence of the transistors shorting is greater. Detail results of the analysis are included in Tables 2.8-3 through 2.8-5. Table 2.8-4 has been truncated with E-3 output because E-5 through E-12 are all similar.

2.8.4 Conclusions

The reliability of the prime power subsystem could be improved as follows:

1. Careful design, selection of materials and mounting terminals, exercising extreme care in electro-mechanical mounting, assembly, and potting procedures for transformer T-1 and T-2.

2. The C-1 shorting failure mode can be minimized by providing series redundant capacitors of appropriate value.

3. Parallel redundancy for the transistors in the oscillator would reduce the criticality of the short mode of those transistors.

Considering the relatively high reliability 0.970 of the prime power subsystem, any improvement in this subsystem would provide only a negligible improvement in overall system reliability. Therefore, major reliability effort will be concentrated on subsystems which will result in considerable improvement in the overall system reliability.

TABLE 2.8-3

PART FAIL MODE PROBABILITY

Component	Part Failure Rate for Failure Mode ($\times 10^{-3}$)			Failure Mode Probability (1) ($\times 10^{-3}$)		
	λ Short (λ_s)	λ Open (λ_o)	λ Drift (λ_d)	$1-e^{-\lambda_s t}$ Short	$1-e^{-\lambda_o t}$ Open	$1-e^{-\lambda_d t}$ Drift
T-1		.000025	.00022		.050	.440
T-2		.000025	.00022		.050	.440
L/CT		.000025	.00022		.050	.440
C	.000022	.0000012	.0000012	.044	.0024	.0024
CR	.000057	.000033	.000074	.114	.066	.148
TR	.000018	.000036	.000023	.036	.007	.046
R		.000076			.015	
ZR	.000019	.0000066	.000039	.038	.0012	.078

(1) Time t was assumed to be 2000 hours for failure mode effect and criticality analysis.

TABLE 2.8-4

FAILURE EFFECTS NOMENCLATURE

Effect Symbol	PART FAILURE SUBSYSTEM EFFECTS
A	Zero power from converter
B	Reduced power
C	Increased Ripple %
D	Reduced regulation
E	Minor decrease in power
F	Zero regulation
G	Power reduction greater than 50%
H	Effect is assumed minor to system
I	Zero power on associated "E" subsystem

TABLE 2.8-5

CRITICALITY ANALYSIS

Part Symbol	Part Failure Effects Table 7			Subsystem Degradation %			Subsystem Effected	Subsystem Criticality Value ($\times 10^{-3}$)	Subsystem Criticality Index
	Short	Open	Drift	Short	Open	Drift			
C-1	A			100			All	.0440	2
		B-C			20		All	.0005	20
			B-C			10	All	.0002	21
R-1		A			100		All	.0150	6
L		A			100		All	.0500	1
L			H			2	All	.0088	11
LL		A			100		All	.0500	1
LL			H			2	All	.0088	11
L-1		G			60		All	.0300	3
L-1			H			2	All	.0088	11
L-2		G			60		All	.0300	3
L-2			H				All	.0088	11
CT-1	A				100		All	.0500	1
CT-1			H			2	All	.0088	11
L-3		G			60		All	.0300	3
L-3			H			2	All	.0088	11
L-4		G			60		All	00300	3
L-4			H			2	All	.0088	11
CT-2		A			100		All	.0500	1
CT-2			H			2	All	.0088	11
R-2		A			100		All	.0150	6

TABLE 2.8-5 (continued)

Part Symbol	Part Failure Effects Table 7			Subsystem Degradation %			Subsystem Effected	Subsystem Criticality Value ($\times 10^{-3}$)	Subsystem Criticality Index
	Short	Open	Drift	Short	Open	Drift			
TR	G			75			All	.0270	4
		G-C			50		All	.0035	13
			E			20	All	.0092	9
TR-2	G			75			All	.0270	4
		G-C			50		All	.0035	13
			E			20	All	.0092	9
ZR-1	F			25			All	.0095	7
		A			100		All	.0012	17
			D			2	All	.0093	8
ZR-2	F			25			All	.0095	7
		A			100		All	.0012	17
			D			2	All	.0093	8
L-5		G-C			4.15		E-1	.0025	5
L-5			H			.166	E-1	.0088	11
L-6		G-C			4.15		E-1	.0025	5
L-6			H			.166	E-1	.0088	10
CT-2		G-C			100		E-1	.0500	1
CT-2			H			2	E-1	.0010	18
CR-1	I			8.3			E-1	.0091	10
		G-C			4.98		E-1	.0033	14
			E			1.66	E-1	.00005	24

TABLE 2.8-5 (continued)

Part Symbol	Part Failure Effects Table 7			Subsystem Degradation %			Subsystem Effected	Subsystem Criticality Value (x 10-3)	Subsystem Criticality Index
	Short	Open	Drift	Short	Open	Drift			
CR-2	I			8.3			E-1	.0092	9
		G-C			4.98		"	.0033	14
			E			.166	"	.00005	23
C-2	I			8.3			"	.0035	13
		B-C			4.15		"	.0001	23
			B-C			.830	"	.000001	25
ZR-3	I			8.3			"	.0030	15
		F			1.66		"	.00002	24
			D			.830	"	.0007	19
L-7		G-C			4.15		E-2	.0025	16
"			H			.166	"	.0088	11
L-8		G-C			4.15		"	.0025	16
"			H			.166	"	.0088	11
CT-4		G-C			4.15		"	.0025	16
"			H			.166	"	.0088	11
CR-3	I			8.3			"	.0092	9
		G-C			4.98		"	.0033	14
			E			.166	"	.00005	23
CR-4	I			8.3			"	.0092	9
		G-C			4.98		"	.0033	14
			E			.166	"	.00005	23

TABLE 2. 8-5 (continued)

Part Symbol	Part Failure Effects Table 7			Subsystem Degradation %			Subsystem Effected	Subsystem Criticality Valve (x 10-3)	Subsystem Criticality Index
	Short	Open	Drift	Short	Open	Drift			
ZR-4	F			8.3			E-2	.0030	15
"		A			1.66		"	.00002	24
			D			.830	"	.0007	19
L-9		G-C			4.15		E-3	.0025	16
"			H			.166	"	.0088	11
L-10		G-C			4.15		"	.0025	16
"			H			.166	"	.0088	11
CT-5		G-C			4.98		"	.0025	16
"			H			.166	"	.0088	11
CR-5	I			8.3			"	.0092	9
"		G-C			4.98		"	.0033	14
"			E			1.66	"	.00005	23
CR-6	I			8.3			"	.0092	9
"		G-C			4.98		"	.0033	14
"			E			1.66	"	.00005	23
C-4	I			8.3			"	.0035	13
"		B-C			4.98		"	.0001	22
"			B-C			1.66	"	.000001	25
ZR-5	I			8.3			"	.0030	15
"		F			1.66		"	.00002	24
"			D			.830	"	.0007	19

SECTION 3

MAINTAINABILITY

The Phase I SLRV design maintainability attributes are described to show how requirements are met for inspection, checkout, test, parts and components replacement, disassembly, reassembly, repair, and maintenance performance from fabrication through launch countdown. The design inherently eliminates potential human-induced failures, and gives assurance that preflight maintenance action and handling can be performed with minimum wear and stress on flight articles.

3.1 PHASE I DESIGN REQUIREMENTS

SLRV design feasibility is partially a function of the ability to survive prelaunch life and retain peak reliability. Thus a vehicle must be designed which can survive storage, shipment, handling, test, and required service with a minimum wear accumulation. The test and inspection program required for flight acceptance is designed to reveal defects requiring corrective action prior to flight. Therefore, Phase I development details which establish the feasibility of fault location and corrective actions are described in the following sections. However, detailed procedures are not developed during Phase I beyond the requirement to show feasibility.

3.2 MAINTENANCE REQUIREMENTS DURING LIFE OF SLRV

Inspection, adjustment, and repair procedures must be performed with minimum effects on remaining parts, and minimum delay in schedules or countdown. A design which satisfies these requirements will be amenable to relatively easy retrofitting; such retrofitting may be required when data from preceding Surveyor flights become available.

Following fairing installation, (see HAC 239503, Par. 3.6), only temperatures and selected test points will be monitored through telemetry channels provided by Surveyor (HAC 239503). Failures detected after this time require that the standby Surveyor be substituted for the mission. The effect on possible re-use of the RTG as a function of using the standby Surveyor will be further studied.

3.3 SUBSYSTEM REPAIRABILITY

Each of the following maintainability considerations is discussed for each subsystem where available design detail permits:

1. Repair and replacement disassembly sequence.
2. Subassemblies, throwaway units or modules, throwaway rationale.
3. Disassembly: techniques.
4. Reassembly: RFI shielding, thermal continuity, thermal reflective coatings, requirements for matched parts.
5. Servicing requirements: tuning, adjustment, lubrication, and checks.
6. Can performance decrement, wear, or total failure be detected and located for each assembly, subassembly, or throwaway unit?
7. Is special or automatic checking equipment required?
8. Are special tools, jigs, or fixtures required for any maintenance, repair, or transport?
9. Service Access: How does it relate to structural or functional requirements of the design and to frequency and criticality of service?
10. How does the unit withstand extended storage: restrictions in storage environment, position, condition, time to prevent oxidation, and other types of deterioration?
11. How does the unit withstand repeated handling, transport, manipulation, and their effects on surface and contents?
12. Hazards to personnel and equipment.
13. Special skills and critical operations.
14. Could any maintainability features adversely effect mission success probability?

3.4 STRUCTURE AND VEHICLE ASSEMBLY

Figure 3-1 shows behicle disassembly for major replaceable components or subsystems. The structure is primarily designed to permit service access, and flexibility in thermal design. No special disassembly or reassembly sequence is required, since replaceable subassemblies are readily accessible. The only exception to this maintainability scheme is the odometer which must be removed to replace the left rear traction drive assembly. One structural member with threaded attachment hardware must be removed to replace the RTG.

The temperature of the vehicle assembly will rise when the RTG is activated. The vehicle half containing the RTG will rise approximately 300°F; i.e., 200°F below the surface temperature of the RTG. At this temperature, special handling devices will facilitate handling and reduce risk of burns.

Vehicle surface treatment will conform to thermal design requirements. The full effect of changes to thermal control surface cannot be predicted at this time. Therefore, all necessary handling must minimize changes in the surface condition caused by abrasion and soiling.

Gages will be provided to check the structure for excessive elasticity or permanent deformation to assure proper geometric alignment of all subsystems. The shipping container will provide added support during shipping, handling, and storage to maintain proper alignment.

The deployment assembly is secured by two pins and their respective explosive pin extractors. The strut tiedown and pivot lock assembly is removed by two explosive bolts.

3.5 RTG

The supplier will perform any disassembly/reassembly procedures deemed necessary. However, such actions take the RTG out of service for several weeks. Servicing requirements will consist of voltage monitoring and surface temperature measurement. If fuel is delivered separately, heat capacity will be checked. Disassembly for repair and replacement of this unit is not presently foreseen.

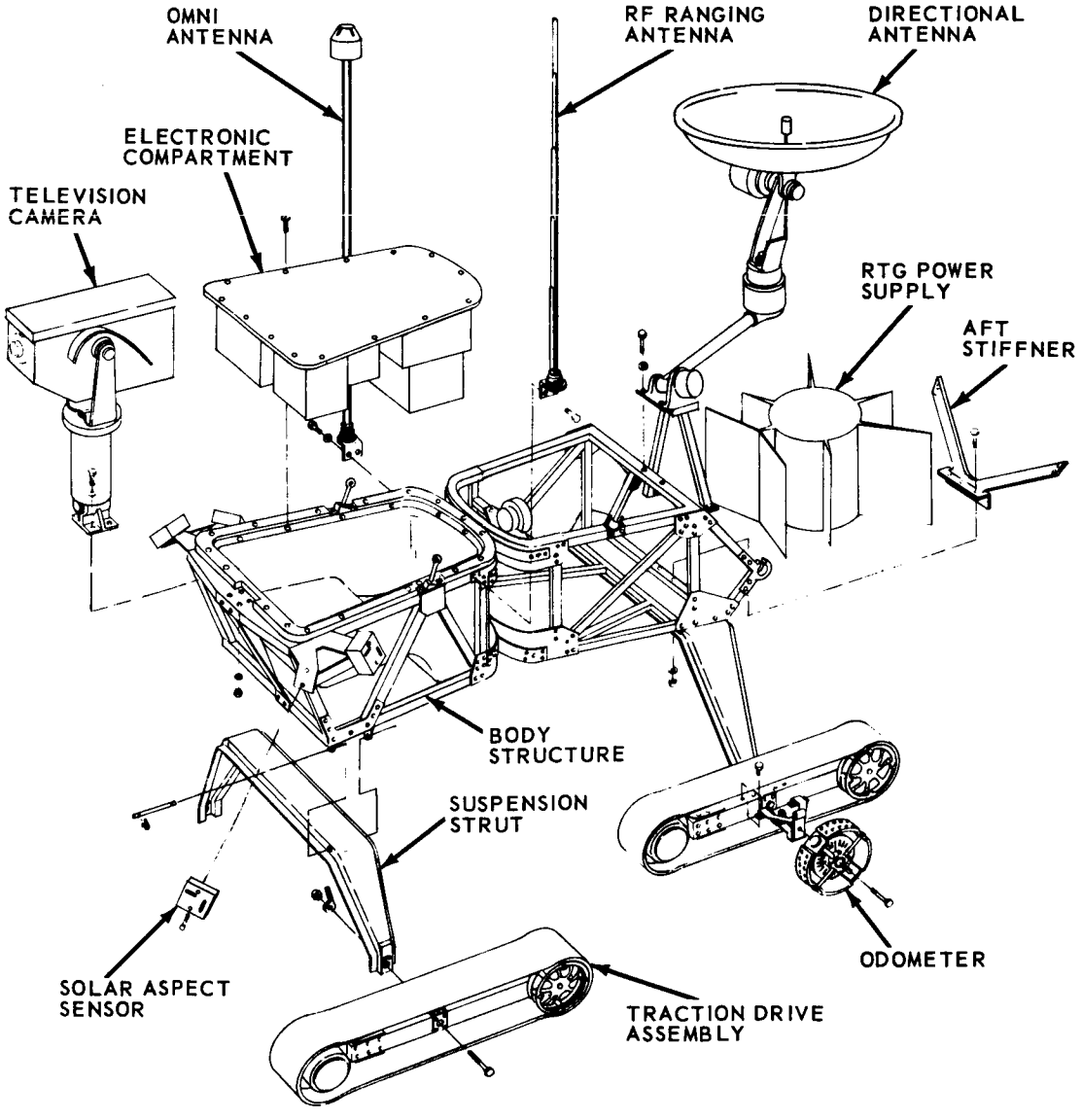

Figure 3-1 Vehicle Disassembly for Replacement of Major Components

If fuel is removed and reinstalled, RTG performance must be checked to assure adequate performance. The removal and reinstallation must anticipate replacement of the entire RTG. This is true for all procedures that permit the RTG to cool after it has been brought to operating temperature. The permissable number of these heat cycles is limited, and accurate records of heat cycles must be kept throughout the life of the RTG. Since knowledge of the full extent of deterioration resulting from alterations in heat and cold has not been precisely determined, it is anticipated that prelaunch procedures will prevent the cooling of the RTG.

Life of the system with radio isotope fuel installed is limited. Thus the fuel will be installed at the latest possible time, within 12 days of launch. If the heating compartment is opened, oxygen must be removed and an inert atmosphere substituted.

No special test equipment is required since voltage and surface temperature checkpoints are expected to be an integral part of the unit. However, special shipping and storage facilities will be required for temperature control.

Personnel and equipment hazards will result from the 500°F surface temperatures; however, radiation hazards are not anticipated. The supplier will furnish the personnel required to perform any operations on the RTG.

3.6 ELECTRICAL COMPARTMENT

The electrical compartment contains nine electronics and mechanical packages:

1. Penetrometer.
2. Inclinometer.
3. Command Receiver.
4. Transmitter.
5. Converter.
6. Command Decoder.
7. Telemetry Processor.
8. Odometer Processor.
9. Mobility Control.

The electronic packages are attached to one thermal plate in a manner which permits intact removal of the entire electronics package. Replacement with an intact unit permits relatively low down-time in the event of electronic failure.

Defective subsystems can be removed from this assembly without disturbing the remainder of the assembly. RF conductors and interconnections between packages by printed-circuit cables will permit individual detachment of units.

The packages divide into modular throwaway units and components, with digital circuits composed entirely of modules. The packaging scheme will be chosen partially on the basis of component reliability, cost, space, and effect of disassembly on circuit reliability.

The units are quickly disassembled by unfastening screws and unsoldering taper pin interconnections. The units are just as easily reassembled.

RFI shielding can be quickly restored by simply reapplying the conductive paint with a brush. The packaging materials which will be used ensure that thermal conduction between reassembled parts does not require precise fits or application of thermal conducting interface materials.

The reflecting surface on the thermal plate may be broken during disassembly and reassembly. The effects of such slight damage, and the possible correction actions have not yet been determined.

Requirements for selective fits and matched parts in reassembly are held to a minimum, and servicing requirements consist of programmed checking of digital circuits and retuning of some RF circuits following prolonged periods of test or storage. Performance decrement, wear, or total failure can easily be measured at the test points. Special checkout equipment and programs will be provided for this assembly and its subsystems to aid in performance analysis and fault isolation. The packaging concept provides service access without compromise to structural and functional integrity, and places no restrictions on frequency and criticality of service. Special jigs, fixtures, or shipping containers are not required. The unit is not unduly affected by extended storage, can withstand repeated handling, and creates no hazards to personnel and equipment. Special skills requirements can be met by Bendix personnel.

3.6.1 Penetrometer

From a functional and maintainability standpoint, the flight model of the penetrometer will be similar to the existing engineering prototype. Thus, the detail level of this discussion furnishes a reliable description of flight model maintainability.

The unit can be disassembled from the electronics package thermal plate by removing the cover, wiring, and finally the unit proper. Modular construction of this unit permits further disassembly into four modules. Replacement of any one of these modules, reassembly, and installation could thus be accomplished at field locations.

Calibration can be accomplished with a laboratory platform balance and a multi-range voltage measuring instrument which provides at least a 100,000-ohm input impedence. Calibration must be performed so that suspension deflection of the vehicle may be considered.

Special skills for critical operations are only required for disassembly beyond the module stage.

3.6.2 Inclinometer

The inclinometer is located in the electronics package and is fully interchangeable. It consists of two accelerometers packaged to permit appropriate alignment and calibration. It may be repaired by replacing the mechanical or electronic module on either accelerometer.

1. Inclinometer reassembly requires alignment. Recalibration with respect to the guide-pin locating holes is accomplished at the supplier's facility.

2. The inclinometer is replaced in the electronics package and installed in the SLRV by using the system of locating pins. Thus, replacement of this unit can be accomplished at AMR with alignment accuracies required by the navigational subsystem.

3.6.3 Sun Sensor

Each sun sensor is a replaceable part, and although they are not attached to the electronics package, they are critically aligned with the

inclinometer on the electronics package. Each is calibrated to guide pin holes, and aligned on the SLRV to the required accuracy by guide pins.

3.7 ANTENNAS

The three antennas can be disconnected at their bases without further disassembly of components other than connecting hardware. Each of the three antenna types is designed to be fully interchangeable if properly aligned at some stage prior to installation. This maintenance action is feasible for all projected alternatives of RF conducter development.

3.8 TRACTION DRIVE ASSEMBLY

Each traction drive assembly is detached from the vehicle by removal of one lock nut and associated assembly hardware. To ensure reliability and weight savings, this assembly is constructed for complete replacement, and further disassembly is not required. Certain components, however, may be salvaged. Replacement units for the left and right side of the SLRV will differ. Thus, future adjustment and monitoring is not required; however, continuity checks may be performed on the motors at any time. Operational checks may be performed in any environment and will have no effect on the equipment except for normal wear.

Wear indications may be checked on all visible surfaces including idler and drive unit rims and both sides of the track. Power input measurement may also be used to determine assembly performance. Special measuring equipment will be used to set track tension at the factory. No special containers, tools, jigs, or fixtures will be required for storage, shipment, and handling. There are no restrictions on storage time or environment. Exterior surfaces requiring special handling are not currently considered in the design.

Sharp edges on the track may pose a personnel hazard. Explosives are planned for two applications on each TDA, but time, method of installation, and testing requirements are not yet fixed. No special skills are required to maintain this unit.

3.8.1 Odometer

The odometer is attached by threaded fastening hardware to the left rear traction drive assembly. (Phase II design can eliminate special

sparing requirements for left rear traction drive assemblies necessitated by the odometer attachment.) The wheel-bearing/transducer-dish assembly can be replaced independent of the pickoff/suspension assembly. These two assemblies will be replaced as non-repairable modules (cost of repairing these modules will nearly equal their procurement cost).

3.9 TV SUBSYSTEM

If the SLRV TV subsystem fails, it will be removed, and a new TV will be installed. The faulty TV subsystem is then repaired in the shop. Detailed shop-repair time is excluded from the present maintainability analysis.

The requirements for reliability, weight, volume, and packaging will normally have precedence over maintainability because of the vehicle and mission requirements and constraints. The design of the TV subsystem reflects this order of precedence.

A preliminary maintainability analysis limited to the replacement of a complete TV subsystem shows SLRV mean downtime (MDT) of 0.5 hour. This estimate does not include time for the following repair elements, since these are either variable, unknown in part or in whole, or not entirely a function of Raytheon's design responsibility:

1. Detect failure.
2. Prepare for repair action.
3. Gain access to SLRV TV subsystem.
4. Checkout and verify proper operation of the replacement TV subsystem.

Presumably the tools, facilities, equipment, technicians, and the spare TV subsystem will be available when needed, thus precluding any waiting, supply, or administrative downtime.

Since maintenance will not be accomplished during the mission, the concept of availability (normally related to mean-time-between-failure and mean downtime) is not significant, particularly in consideration of the maintenance philosophy, the repair by engineering personnel, and the type of equipment represented by the TV subsystem.

The size, weight, volume, packaging requirements, and constraints of the TV subsystem prevent the inclusion of the usual types and extent of safety features and provisions which are normally designed into military equipment.

The TV subsystem requirements and constraints, the maintenance philosophy (maintenance by skilled engineering-type personnel rather than by technicians of limited skills), and the limited number of equipments to be built, all combine to indicate the adequacy of minimal and reasonable safety features to safeguard against equipment damage and personnel injury.

Safety provisions to prevent equipment damage during handling and transportation are:

1. Provide suitable protective outer case for the complete TV subsystem.

2. Provide reasonable protection for the Galilean telescope aperture.

3. Avoid fragile protuberances on the outer case.

4. Provide adequate design load margins for gearing, bearings, stops, and structures between the coupled assembly consisting of camera case, elevation drive, and azimuth drive, to prevent damage when torques are inadvertently applied in handling this coupled assembly.