

ADA03748

12  
B.S.

AFRPL-TR-76-99

No. 9006-085-1

RELIABILITY ESTIMATING PROCEDURES FOR ELECTRIC AND  
THERMOCHEMICAL PROPULSION SYSTEMS

FINAL REPORT

VOL II

BOOZ ALLEN APPLIED RESEARCH  
4733 BETHESDA AVENUE  
BETHESDA, MARYLAND 20014

FEBRUARY 1977

DDC  
RECEIVED  
APR 1 1977  
A

APPROVED FOR PUBLIC RELEASE

DISTRIBUTION UNLIMITED

**COPY AVAILABLE TO DDC DOES NOT  
PERMIT FULLY LEGIBLE PRODUCTION**

AD No. \_\_\_\_\_  
DDC FILE COPY

Prepared for:

AIR FORCE ROCKET PROPULSION LABORATORY  
DIRECTOR OF SCIENCE AND TECHNOLOGY  
AIR FORCE SYSTEMS COMMAND  
EDWARDS AFB, CALIFORNIA 93523

ACCESSION BY	<input type="checkbox"/>	White Section	<input type="checkbox"/>
NTIS	<input type="checkbox"/>	Dist. Section	<input type="checkbox"/>
DDC			
UNANNOUNCED			
JUSTIFICATION			
BY	DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL.	Dist. or SPECIAL	


NOTICES


When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related government procurement operation, the government thereby incurs no responsibility nor any obligation whatsoever and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

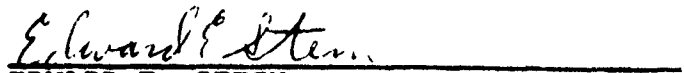
This final report was submitted by Booz, Allen Applied Research, 4733 Bethesda Avenue, Bethesda, Maryland 20014, under contract F04611-75-C-0039, job order number 305811TG, with the Air Force Rocket Propulsion Laboratory, Edwards AFB, California.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

  
 MELVIN V. ROGERS  
 Project Engineer

  
 THOMAS W. WADDELL  
 Chief, Satellite Propulsion  
 Section

  
 EDWARD E. STEIN  
 Deputy Chief, Liquid Rocket Division

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFRPL TR-76-99- <del>Vol-1</del> -2	2. GOVT ACCESSION NO.	3. REPORT'S CATALOG NUMBER
4. TITLE (and Subtitle) RELIABILITY ESTIMATING PROCEDURES FOR ELECTRIC AND THERMOCHEMICAL PROPULSION SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Final Report Mar 1975 - Dec 1976
6. AUTHOR(s) <del>Vol-1</del> Vol-1		7. PERFORMING ORG. REPORT NUMBER 3006-07T-8
8. PERFORMING ORGANIZATION NAME AND ADDRESS Booz Allen Applied Research 4733 Bethesda Avenue Bethesda, Maryland 20014		9. CONTRACT OR GRANT NUMBER(s) F04611-75-C-0039
10. CONTROLLING OFFICE NAME AND ADDRESS Air Force Rocket Propulsion Laboratory/LKDA Edwards AFB, California 93523		11. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 305811 TG
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. REPORT DATE February 1977
14. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED  (14) BAAR-9026-2-1-1-Vol-2		15. NUMBER OF PAGES 282
16. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		17. SECURITY CLASS. (of this report) UNCLASSIFIED
17. SUPPLEMENTARY NOTES		18. DECLASSIFICATION DOWNGRADING SCHEDULE
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Fault tree analysis                      Bi propellant systems Pulse plasma systems                    Reliability estimation ion systems Hydrazine Monopropellant systems		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The primary objective of this study was to develop a sound standardized basis for reliability comparisons of thermochemical and electric propulsion concepts applicable to Air Force satellite, spacecraft, and upper-stage mission requirements. A corollary objective was the identification of those propulsion system components which are currently the major contributors to propulsion system failures.  Nearly one hundred component level and failure mode level models were developed		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

in the course of the study. Constant and increasing failure rates were included to address erosion, wear, and fatigue failure, as well as random failures. Principal variables in these expressions included mission duration, operating time, and the number of operating cycles. For special cases (such as engine valves, injectors, thrust chambers) where design approaches were varied, the design life goals for the specific application were included as independent variables.

Inherent in the reliability modeling was a quantitative assessment of the uncertainty associated with each estimate. The log normal distribution was used as the uncertainty model for each component. The parameters characterizing the log normal distribution for each application were determined where possible from the scatter or statistical variance of reported failure rates for each component.

System level assessments were performed using functionally oriented fault trees. The functional approach was used to yield fault trees that are least affected by changes and revisions at the component level. System assessments were performed by aggregating the component reliability and uncertainty results through the fault tree logic using computer programs and approximation techniques which were modified or developed for this purpose.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)



# TABLE OF CONTENTS

Page  
Number

## VOLUME I

PREFACE	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
TECHNICAL APPROACH	I-1
Data Base Definition	I-3
Electronic Component Reliability and Uncertainty Derivation	I-14
Non-Electronic Component Reliability and Uncertainty Derivation	I-27
Systems Reliability Estimation	I-49
RESULTS	I-51
Electric Propulsion Components Reliability Models	I-52
Thermochemical Propulsion Components Reliability Models	I-124
System Level Fault Trees	I-183
Cesium Ion Electron Bombardment System	I-183
Mercury Ion Electron Bombardment System	I-196
Pulsed Plasma System	I-207
Colloid System	I-212

	<u>Page Number</u>
System Level Fault Trees (Continued)	
Catalytic Monopropellant System	I-223
Electrothermal Monopropellant System	I-240
Hypergolic Bipropellant System	I-257

## VOLUME II

### COMPUTER PROGRAMS

General	II-1
Program Descriptions	II-3
COMP1 Program Listing	II-13
BETSB1 Program Listing	II-38
BETSB2 Program Listing	II-42
BETSB3 Program Listing	II-49
BETFTA Program Listing	II-53
BETAL1 Program Listing	II-56
APPLICATION OF RESULTS	II-63
Systems Applications	II-63
Component and Limited Subsystems Analyses	II-66
SUMMARY AND CONCLUSIONS	II-68
GLOSSARY OR TERMS	II-70
REFERENCES	II-72

	<u>Page Number</u>
APPENDIX A - Examples	A-1
Examples of MIL-HDBK-217-B Procedures	A-1
Examples of Methodology Application	A-15
APPENDIX B - Aggregates of Beta Distribution Variates	B-1
APPENDIX C - BIBLIOGRAPHY	C-1

L I S T O F T A B L E S

<u>Table</u>		<u>Page Number</u>
1.	Literature Search Summary	I-11
2.	Technical Survey Summary	I-12
3.	Crystal Failure Rates	I-17
4.	Circuit Breaker Failure Rates	I-17
5.	Failure Rate Uncertainties	I-29
6.	Examples Distribution with Common R(40,000)	I-33
7.	Two-Point Fitted Distributions	I-35
8.	Fault Tree Analysis Symbology	I-184
9.	Alpha Numeric Component Code Listing	II-33

## L I S T O F F I G U R E S

<u>Figure</u>	<u>Page Number</u>
1. Reliability Estimation Procedures Study Plan	I-2
2. Cesium Ion Electron Bombardment Generic System Layout	I-4
3. Mercury Ion Electron Bombardment Generic System Layout	I-5
4. Pulsed Plasma Generic System Layout	I-6
5. Colloid System Generic System Layout	I-7
6. Catalytic Monopropellant Generic System Layout	I-8
7. Electrothermal Monopropellant Generic System Layout	I-9
8. Hypergolic Bipropellant Generic System Layout	I-10
9. Crystal Failure Rate (Ground life test)	I-18
10. Circuit Breaker Failure Rates (Ground)	I-19
11. Cesium Ion System Schematic	I-185
12. Cesium Ion System Fault Tree Analysis	I-187
13. Mercury Ion System Schematic	I-197
14. Mercury Ion System Fault Tree Analysis	I-199
15. Pulsed Plasma System Schematic	I-208
16. Pulsed Plasma System Fault Tree Analysis	I-210
17. Colloid System Schematic	I-213

<u>Figure</u>		<u>Page Number</u>
18.	Colloid System Fault Tree Analysis	I-215
19.	Catalytic Monopropellant System Schematic	I-224
20.	Catalytic Monopropellant System Fault Tree Analysis	I-226
21.	Catalytic Electrothermal Monopropellant System Schematic	I-241
22.	Electrothermal Monopropellant System Fault Tree Analysis	I-243
23.	Hypergolic Bipropellant System Fault Tree Schematic	I-258
24.	Hypergolic Bipropellant System Fault Tree Analysis	I-260

## COMPUTER PROGRAMS

### GENERAL

A family of computer programs provide the capability to examine life and uncertainty distributions at levels ranging from a specific failure mode of an individual device to a complete system of substantial complexity. All of the programs were written in the BASIC language (as implemented on the CDC Cybernet/Kronos time sharing system) in order to provide interactive-mode capabilities.

The family includes the following:

- . COMPl -- A program specifically tailored to 97 device types and/or failure modes included in the systems analyzed. For each device or failure mode, the program yields the median and 5 percent lower bound on reliability and the parameters of a beta distribution sharing those fractiles, for any desired point(s) in a mission.
- . BETSB1 -- A program that accepts reliability/uncertainty descriptions (in beta-distribution form) for a group of components that are either identical or independent and have either a strictly series or a strictly parallel-redundant relationship. The output is a reliability/uncertainty description of the group in the form of moments of the distribution and the parameters of a beta distribution possessing those moment values.\*

---

\* This program was developed under Contract No. N00123-74-C-1799 with the Naval Weapons Center, China Lake, California, and is described in NWC TP 5748, "Rocket-Ramjet Cost and Reliability Prediction Methodologies", July, 1975, the final technical report under that contract. Further discussion of the use of the Beta distribution is provided in Appendix B.

- . BETSB2 -- Analogous to BETSB1, but designed for independent components in m-of-n redundant configuration.
- . BETSB3 -- Also analogous to BETSB1, but designed for identical components in m-of-n redundant configuration.
- . BETFTA -- This program provides the capabilities of BETSB1, expanded to allow concurrent analysis of groups of the four kinds (series-independent, series-identical, parallel-independent, parallel-identical). The input is in fault-tree terms; up to 20 levels and 100 events per level are allowed. Inhibit gates (with conditioning probabilities) also are accommodated. Lowest-level (component, failure mode) inputs are required to be in the form of beta-distribution parameters. M-of-n redundant configurations must be preprocessed (via BETSB2 or BETSB3, as appropriate); the result then may be treated as a basic event.
- . BETAL1 -- This program is intended primarily for use at high levels (systems and major subsystems), although it may be used for any configuration whose elements are independent and in series. In addition to inputs as required for BETSB1, this program requires the cost of the next test for each element. The output, in addition to moments and parameters of a fitted beta distribution, includes identification of the element which, if tested next, would yield the maximum information gain (in terms of reduction in expected variance) per unit test cost; the corresponding amount of information gain, and that expected if the entire aggregate were tested next; and, via numerical integration of the fitted beta distribution, the 5, 10, and 20 percent lower bounds on the reliability of the aggregate. This program thus can be used for test planning/test resource allocation in advance of testing and, with minor manual intervention, as a real-time test planning tool.

Listings and short descriptions of each program follow.



## PROGRAM DESCRIPTIONS

### COMPl

This program will be described in somewhat greater detail than the others in view of its specificity, which will make it necessary to modify the program if components or failure rate estimates other than those provided are to be accommodated.

As noted above, program COMPl is designed to calculate reliability descriptors for each of a fixed list of components/failure modes. Each component may be evaluated for any desired point during a mission with exposure measured in terms of mission time, operating time, number of pulses, or other measure, as appropriate for that component. The required measure(s) are identified by the program as the computation proceeds.

For most components, the required parameters are stored in final form. For some components, the parameters are calculated from design factors (e.g., design life) that must be input when requested. Each component/failure mode must be identified using the 2-4 character alphanumeric code indicated in Table 9 immediately following the COMPl program listing.

Program output consists of the median and 5 percent lower bound of the reliability uncertainty distribution and of the parameters (alpha, beta) of an approximating beta distribution to those fractiles. Caveats also are displayed, as necessary, in the course of the interactive routine.

In some cases, the component life and uncertainty models are such that the 5 percent lower bound (R0 in the program) coincides with or exceeds the median (R5) at extremely early and/or extremely late points in a mission. Coincidence also can occur due to computation resolution limitation when the reliability is very near 1 or 0. Most such occurrences have been anticipated and caveats as well as provisions to avoid program termination incorporated. Occasionally, error messages (e.g., "attempt to divide by zero" or "negative argument in log function") and program termination may be encountered.

The following description is keyed to the program listing in terms of blocks of statements:

- 30-127 The dual-subscript variables,  $W(I,J)$ , are assigned values for subsequent use in decoding component labels and invoking the appropriate sequence of parameter assignment and exercise of life and uncertainty models.
- 201-209 The component label, a 2-4 character alphanumeric string, is requested, input, and translated into a unique I, J subscript pair. I is the display value of the first string character; J, the sum of the display values of the remaining characters.
- 210-252  $C=W(I,J)$  is used to select the appropriate "ON...GOTO..." statement and thus the statement to which control is transferred. If "ZZ" has been input deliberately, or a string without valid interpretation has been input accidentally, the program terminates via a "No such component" message at 99998.
- 300-1234 Each group of statements begins with a statement number that is a multiple of 10. Each such group contains distribution parameters, requests for design information and special comments as needed, and "GOTO..." statements leading directly or indirectly to the appropriate life/uncertainty model.
- 2000-2876 Blocks of statements within this range deal with specific models as indicated below.
- 2000-2026 Exponential life distribution involving operating time.
- 2030-2056 Exponential life distribution involving "pressurized" time.
- 2060-2098 Exponential life distribution involving number of cycles.
- 2130-2154 Weibull life distribution (3-parameter) involving operating time.
- 2160-2190 Weibull life distribution (3-parameter) involving operating time and exponential life distribution involving operating time.

- 2200-2226 Exponential life distribution involving mission time.
- 2230-2268 Exponential life distribution involving mission time and exponential distribution involving number of cycles.
- 2270-2308 Exponential life distribution involving operating time and exponential distribution involving dormant time (obtained by subtracting operating time from mission time) and exponential distribution involving number of cycles.
- 2310-2366 Weibull life distribution (2-parameter) involving mission time and Weibull distribution (2-parameter) involving operating time and Weibull distribution (2-parameter) involving number of cycles.
- 2370-2384 Exponential life distribution involving operating time and exponential life distribution involving mission time.
- 2400-2430 Weibull life distribution (3-parameter) involving mission time and exponential distribution involving mission time.
- 2440-2480 Weibull life distribution (3-parameter) involving operating time and exponential distribution involving number of cycles and fixed fraction capable of success.
- 2500-2542 Weibull life distribution (3-parameter) involving operating time and Weibull distribution (2-parameter) involving number of cycles.
- 2550-2568 Weibull life distribution (2-parameter) involving operating time and Weibull distribution (2-parameter, shape parameter same) involving number of cycles and Weibull distribution (2-parameter, shape parameter fixed at 3.0) involving number of cold starts.
- 2580-2624 Weibull life distribution (2-parameter) involving operating time and Weibull distribution (2-parameter, shape parameter same) involving number of cycles and exponential distribution involving dormant time (obtained by subtracting operating time from mission time).

- 2640-2704 Exponential life distribution involving operating time and normal distribution (coefficient of variation fixed at 1/3) involving operating time and normal distribution (coefficient of variation fixed at 1/3) involving number of cycles.
- 2710-2746 Exponential life distribution involving mission time and normal distribution (coefficient of variation fixed at 0.15) involving mission time; failure by normal-distribution mechanism restricted to pre-defined subpopulation; special preset flags for apportionment among failure modes.
- 2750-2774 Lognormal life distribution (log standard deviation fixed at 0.3991) involving mission time to firing (mission time elapsed before actuation).
- 2810-2834 Exponential life distribution involving number of operating pulses and normal distribution involving number of operating pulses.
- 2860-2876 Exponential life distribution involving dormant time (obtained by subtracting operating time from mission time).
- 3000-3310 This series of statements provides approximations for fitting a beta distribution to the  $R_0$ ,  $R_5$  values. The following blocks of statements deal with matters of special interest as indicated.
- 3001-3003 In the approximations used, the dividing line between positive and negative values of beta corresponds to  $S_0=0.89146$ , and computations are split accordingly.
- 3004-3009 If  $R_0$  equals or exceeds  $R_5$ , there are degeneracy (tail-crossing) problems as discussed previously. Appropriate messages are provided, and calculations are bypassed.
- 3010-3094 For negative values of beta, a piecewise-linear approximation is used. For beta less than  $-0.91$ , the approximation yields questionable alpha values as indicated by the programmed message.

- 3100-3310 For positive values of beta, the approximation used requires iterative calculations. The range for iteration is bounded, and a variable-increment procedure is used to limit the number of iterations required.
- 4000-4050 This block of statements embodies the infinite-series equivalent of the cumulative normal distribution. The series is truncated when the absolute value of the next term is on the order of 0.000001 or when 40 terms have been included; the series converges rapidly except at large distances from the mean. When the distance from the mean exceeds five standard deviations, the result is forced to 0.9999999 or 0.0000001 as appropriate.

The program also may be used, with minor modifications, to obtain the parameters of the fitted beta distribution for inputs consisting of R.05 (R0) and R.5 (R5). It is necessary only to overlay the following statements:

```
7 GOTO 5000
5000 PRINT "INPUT R.05, R.5 (0,0=END)"
5002 INPUT R0, R5
5004 IF R0=0 THEN 99999
5006 GOSUB 3000
5008 PRINT
5010 PRINT USING 2, R0, R5, A0, B0
5012 PRINT
5014 GOTO 5002
```

This modification will be referred to as BETAP 1.

BETSBI

This program, and those that follow, should be run in double precision mode if that feature is available (e.g., in IBM CALL-OS, where the corresponding command is "BASICL"). A reminder to that effect is printed following the "RUN" command. The feature is not available and not needed on CDC Cybernet/Kronos.

While this program is largely self-explanatory in execution, a description in terms of the inputs requested by the program may be helpful.

- . TYPE OF INPUT (1-PARAM, 2=MEAN&VAR)  
As indicated, there is an option of input in terms of beta distribution parameters (alpha and beta, e.g., from COMPl) or in terms of the mean and variance of the beta distribution.
- . HOW MANY COMPONENTS?  
The actual number of components (or failure modes) contained in the aggregate being examined. (For more than 10 components, it is necessary to add the statement 6 DIM A(\*\*), B(\*\*) where \*\* is a number exceeding the number of components by 1.)
- . INDEPENDENT=1, IDENTICAL=2  
The response should be "2" only if all components not only have identical failure rate expectations and variances, but are of the same type (e.g., composition resistors of the same rating and resistance value and hence likely to come from the same manufacturing lot).
- . SERIES=1, REDUNDANT=2  
Respond in accordance with the configuration being evaluated.
- . VALUES  
Respond \*\*\*, \*\* using alpha and beta or mean and variance, as previously indicated.

#### BETSB2

From the user's standpoint, this program is similar to BETSB1; however, it handles only the case of independent components in m-of-n redundant configuration. The salient differences are:

- . HOW MANY REQUIRED?  
Is an additional prompting statement; the response is the numerical value of m.
- . Neither the series/redundant nor the independent/identical question will appear, the answer being implicit in the choice of this program.

- . Twenty components are allowed by DIM statements at 140 and 142. A large number of good/bad state permutations are implicit; if that number is exceeded, a statement indicating the need for modification of the DIM statement at 142 will appear, as well as an indication of the numerical value required to be substituted.

### BETSB3

This program handles identical components in m-of-n redundant configuration. The prompting statements are identical to those of BETSB2, except that no statement indicating need to extend array dimensions is provided; such extension usually will be unnecessary here.

### BETFTA

This program is related to BETSB1, but allows combinations of identical/independent and series/redundant configurations and requires input in the form of a fault tree description. Input must be in parametric (alpha, beta) form and provided as a series of DATA statements. Immediately under any logic "gate" events must be either all identical or all independent; the fault tree always can be restructured to meet this condition. Multiple input DATA sets may be provided; the program will continue until all DATA sets have been used. (This feature permits evaluation of the aggregate at a succession of points in a mission.) Key features of the program are described by a series of REM statements that may be displayed by commanding a listing starting with statement 80000 (in CDC Cybernet/Kronos BASIC, the command is LIST, 80000). An expanded discussion follows:

- . HOW MANY LEVELS?  
The number of levels is equal to the number of events in the longest branch of the fault tree. (All logic gates within a branch, except inhibit gates, must be separated by events, which may be arbitrary if necessary.)
- . EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
A series of inputs, consisting of the number of events at each level except the (single-event) top level, is required. Each input should be the total number of events at the appropriate level,

beginning with the lowest. (Note that not all branches need have events at all lower levels, and that there must be no gaps between the top level and the level at which each branch terminates.)

#### DESTINATION

Each event is implicitly defined by dual subscripts I, J, where I is the level and J is the number of the event under consideration at that level -- e.g., counting left-to-right. Thus, the first (e.g., leftmost) event at the third level is defined by the subscripts 3,1. The program will cause I,J to be printed; the correct response (DESTINATION) is the index J' of the connected event at level I+1.

#### CONDITIONALS? (0.0=SKIP)

A response should be provided for each inhibit gate in the form of the I,J subscripts of the event immediately below the inhibit gate. The next response should be the value of the probability associated with the inhibit gate. The sequence will continue until a 0,0 response (or any 0,J response) is given.

#### GATE TYPES

Each gate (other than inhibit gates) is identified by the I,J subscripts of the event immediately above it. The program will indicate each gate by printing the subscripts; the response should be 1 for an OR gate connecting independent events, 2 for an AND gate connecting independent events, 3 for an OR gate connecting identical events, 4 for an AND gate connecting identical events.

Following completion of gate identification, the program automatically will read alpha and beta values for each input event from the DATA statements, which must be provided. Reading of data is in ascending order of levels and ascending value of the J subscript within each level, with automatic skipping of any event that is a "destination" (and thus has reliability values determined by lower-level events); the sequence of entries in DATA statements must correspond. For example, assume a three-level tree with two events at the lowest level and two at the second level, the first of which is the destination of the two



lowest-level events. In this program, the alpha value of the I,J event is represented by T(I,J) and the beta value by U(I,J). Support T(1,1)=3, U(1,1)=0, T(1,2)=9, U(1,2)=1.3, T(2,2)=11.5, U(2,2)=-.6. Then an appropriate set of DATA statements would be:

```
900 DATA 3,0,9,1.3
902 DATA 11.5,-.6
```

#### BETAL1

This program resembles BETSB1, but is intended for use in test planning and/or when calculation of lower bounds (5, 10, and 20 percent) is desired. Only series configurations of independent elements are accommodated; this restriction generally is met at high levels of aggregation (system, subsystems).

Most prompting statements are similar to those used in the BETSB series of programs or are self-explanatory. However, some statements are in the form of questions requiring yes/no answers. The response to such questions must be numeric (1 = yes, 0 = no). Some selected prompting statements and program features are discussed below.

- PERMIT NEGATIVE BETA?

The beta distribution becomes J-shaped when either parameter is negative and U-shaped when both are negative. Negative parameter values arise when the uncertainty (variance) is relatively large, especially if the expected value is near 0 or 1, and are legitimate. However, the user may elect to allow only non-negative values of beta by responding "0"; if a negative value of beta then is encountered during computation, the program will automatically set beta equal to zero while retaining the expected value of the distribution, thus obtaining the largest variance admissible without negative values of beta.

- VALUES? (THIRD VALUE IS COST OF FIRST TEST)

The required response is as in the BETSB programs, except that the cost of the first (next) test of each component also must be entered. This entry may be arbitrary when the program is used only to obtain lower bounds.

- DISPLAY COMPONENT VALUES?  
 A positive response ("1") will cause parameters, moments, and assigned test costs to be displayed for all components. The displayed moments include expected value,  $E(P)$ ; second moment about the origin,  $E(P^2P)$ ; and variance,  $V(P)$ .
- CLOSURE  
 The number displayed below this message is the total integral of the distribution over the interval 0,1. Numerical integration is used; if the displayed number differs substantially from 1.0, the validity of the displayed bounds is questionable.
- NO. DELV COST TOT COST NO. TESTS  
 Under these headings there are displayed the identity of the component just "tested", the change in variance resulting from the "test", the cost of the "test", the accumulated cost of all component "tests", and the number of "tests", and the number of "tests" of the identified component. The change in variance (DELV) may be compared to the expected change,  $E(\text{DELVAR})$ , displayed under "FOR SYSTEM"; taking costs into account, one may elect not to CONTINUE. (Use of BETALL may be resumed subsequently, after one or more system "tests", using updated input values.) If one elects to CONTINUE, and opportunity is provided to adjust the cost of the next test of the same component (CHANGE NEXT COST?); if not, a display of the end-of-run status of all components is available.

As a before-the-fact test planning tool, the program uses "test" results on an expected-value basis; that is, a "test" increments the corresponding alpha by  $E(P)$  and beta by  $1-E(P)$ . When used in a real-time mode, one would increment alpha by 1 for a successful test and beta by 1 for a failing test; this incrementation would take place off-line, and the program exercised with the new values to identify the next component to be tested.

COMPl Program Listing

```

2: #####          #####          #####          #####
4 PRINT "OUTPUT FORMAT IS"
6 PRINT "K.O5      K.O      ALPHA      HETA"
8 DIM W(32,7)
30 W(12,19)=1
31 W(21,19)=2
32 W(1,1)=3
33 W(13,7)=4
34 W(2,2)=5
35 W(6,50)=6
36 W(20,20)=7
37 W(16,18)=8
38 W(16,20)=9
39 W(22,3)=10
40 W(22,12)=11
41 W(19,1)=12
42 W(19,16)=13
43 W(6,12)=14
44 W(8,3)=15
45 W(9,9)=16
46 W(14,9)=17
47 W(14,22)=18
48 W(14,3)=19
49 W(4,3)=18
50 W(22,8)=19
51 W(13,19)=20
52 W(8,54)=21
53 W(21,59)=22
54 W(13,27)=23
55 W(14,16)=24
56 W(3,19)=25
57 W(22,38)=26
58 W(22,37)=27
59 W(22,25)=28
60 W(20,7)=29
61 W(16,35)=30
62 W(22,30)=31
63 W(16,21)=32
64 W(6,21)=30
65 W(6,51)=33
66 W(6,6)=34

```

67  $w(6,15)=35$   
 68  $w(2,34)=36$   
 69  $w(2,25)=37$   
 70  $w(2,37)=38$   
 71  $w(26,3)=39$   
 72  $w(19,13)=40$   
 73  $w(3,2)=41$   
 74  $w(3,22)=42$   
 75  $w(3,33)=43$   
 76  $w(3,26)=44$   
 77  $w(5,31)=45$   
 78  $w(6,31)=46$   
 79  $w(6,11)=47$   
 80  $w(13,47)=48$   
 81  $w(13,5)=49$   
 82  $w(3,12)=50$   
 83  $w(12,25)=51$   
 84  $w(8,25)=52$   
 85  $w(19,19)=53$   
 86  $w(19,3)=54$   
 87  $w(9,16)=55$   
 88  $w(16,2)=56$   
 89  $w(9,49)=57$   
 90  $w(9,37)=58$   
 91  $w(9,46)=59$   
 92  $w(18,14)=60$   
 93  $w(18,23)=61$   
 94  $w(3,37)=62$   
 95  $w(3,25)=63$   
 96  $w(3,38)=64$   
 97  $w(7,37)=65$   
 98  $w(5,25)=66$   
 99  $w(5,38)=67$   
 100  $w(5,53)=68$   
 101  $w(2,39)=69$   
 102  $w(2,40)=70$   
 103  $w(2,48)=71$   
 104  $w(2,49)=72$   
 105  $w(2,41)=73$   
 106  $w(2,42)=74$   
 107  $w(6,32)=75$   
 108  $w(6,73)=76$   
 109  $w(5,28)=77$   
 110  $w(9,29)=78$   
 111  $w(9,19)=79$   
 112  $w(9,31)=80$   
 113  $w(9,8)=81$   
 114  $w(3,18)=82$   
 115  $w(3,21)=83$   
 116  $w(3,6)=84$   
 117  $w(20,16)=85$   
 118  $w(20,5)=86$   
 119  $w(18,22)=87$   
 120  $w(8,29)=88$   
 121  $w(20,37)=89$

```

122 W(5,60)=90
123 W(2,4)=91
124 W(19,41)=92
125 W(26,26)=0
126 W(14,19)=93
127 W(9,50)=94
200 PRINT
201 PRINT "COMPONENT CODE?(Z7=END)"
202 INPUT A$
203 CHANGE A$ TO 0
204 J=0
205 FOR I=2 TO U(0)+.1
206 J=J+U(I)
207 NEXT I
208 I=U(1)
209 C=W(I,J)
210 IF C<1 THEN 99998
211 IF C>10 GOTO 214
212 ON C GOTO 300,310,320,330,340,350,360,370,380,390
214 IF C>20 GOTO 218
216 ON (C-10) GOTO 400,410,420,430,440,450,460,470,480,490
218 IF C>30 GOTO 222
220 ON (C-20) GOTO 500,510,520,530,540,550,560,570,580,590
222 IF C>40 GOTO 226
224 ON (C-30) GOTO 600,610,620,630,640,650,660,670,680,690
226 IF C>50 GOTO 230
228 ON (C-40) GOTO 700,710,720,730,740,750,760,770,780,790
230 IF C>60 GOTO 234
232 ON (C-50) GOTO 800,810,820,830,840,850,860,870,880,890
234 IF C>70 GOTO 238
236 ON (C-60) GOTO 900,910,920,930,940,950,960,970,980,990
238 IF C>80 GOTO 242
240 ON (C-70) GOTO 1000,1010,1020,1030,1040,1050,1060,1070,
1080,1090
242 IF C>90 GOTO 246
244 ON (C-80) GOTO 1100,1110,1120,1130,1140,1150,1160,1170,
1180,1190
246 IF C>100 THEN 250
248 ON (C-90) GOTO 1200,1210,1220,1230
250 PRINT "NO SUCH COMPONENT"
252 GOTO 99999
300 F(1,1)=5.3E-7
301 F(1,2)=8.03E-6
309 GOTO 2000
310 F(1,1)=2.71E-7
311 F(1,2)=5.3E-6
312 GOTO 2000
320 F(1,1)=1.78E-6
321 F(1,2)=1.79E-5
322 GOTO 2000
330 F(1,1)=1.86E-6
331 F(1,2)=1.85E-5
332 GOTO 2000
340 F(5,1)=1.04E-7

```

```

341 F(5,2)=3.12E-7
342 G010 2030
350 F(5,1)=9.1E-9
351 F(5,2)=3.23E-7
352 G010 2030
360 F(5,1)=8.6E-8
361 F(5,2)=8.7E-7
362 G010 2030
370 F(5,1)=4.3E-8
371 F(5,2)=4.35E-7
372 G010 2030
380 PRINT "SAME AS PK"
381 G010 370
390 F(1,1)=2.59E-7
391 F(1,2)=3.185E-6
392 G010 2000
400 F(1,1)=1.25E-6
401 F(1,2)=9.96E-6
402 F(2,1)=1.87E-6
403 F(2,2)=1.27E-5
404 G010 2060
410 F(3,1)=2.36E-9
411 F(3,2)=2.23E-8
412 G010 2100
420 PRINT "SAME AS SA"
421 G010 410
430 F(1,1)=7.55E-8
431 F(1,2)=.2E-6
432 G010 2000
440 F(1,1)=4.67E-6
441 F(1,2)=67.7E-6
442 G010 2000
450 F(6,1)=4.4E9
451 F(6,2)=3.4E8
452 F6=2
453 A6=0
454 G010 2130
460 PRINT "CLOG & LEAK COMBINED"
461 PRINT "(C LOG SEPARATE, USE VC AND VL )"
462 F(1,1)=3.84E-6
463 F(1,2)=1.2735E-5
464 F(2,1)=2.59E-7
465 F(2,2)=1.27E-5
466 G010 2060
470 F(1,1)=0.3E-6
471 F(1,2)=5.8E-6
472 F(6,1)=1.7E7E12
473 F(6,2)=1.146E11
474 F6=3
475 A6=5000
476 G010 2160
480 F(1,1)=4E-7
481 F(1,2)=2.73E-6
482 G010 2000
490 F(4,1)=1.66E-7
491 F(4,2)=1.57E-6
492 G010 2200

```

```

500 F(4,1)=2.09E-8
501 F(4,2)=1.69E-7
502 GOTO 2200
510 B9=0
511 F(4,1)=9.4E-7
512 F(4,2)=4.63E-6
513 F(7,1)=1E4
514 F(9,1)=.038
515 F(9,2)=.09
516 GOTO 2110
520 F(6,1)=1.3E9
521 F(6,2)=7.306E7
522 B6=2
523 A6=6000
524 F(1,1)=2.7E-6
525 F(1,2)=56.8E-6
526 GOTO 2160
530 F(1,1)=3.7E-5
531 F(1,2)=5.41E-5
532 GOTO 2000
540 F(4,1)=1.885E-6
541 F(4,2)=6.788E-6
542 GOTO 2200
550 F(1,1)=7.154E-7
551 F(1,2)=8.557E-6
552 GOTO 2000
560 PRINT "SAME AS VVP"
561 GOTO 550
570 PRINT "SAME AS VVP"
571 GOTO 550
580 B9=1
581 F(2,1)=9.7E-9
582 F(2,2)=7E-8
583 GOTO 511
590 PRINT "PCIL & FU ALIKE"
591 B9=2
592 GOTO 511
600 F(1,1)=4E-7
601 F(1,2)=2.73E-6
602 GOTO 2000
610 F(4,1)=4.85E-8
611 F(4,2)=1.877E-7
612 GOTO 2200
620 F(4,1)=1.94E-8
621 F(4,2)=1.4E-7
622 GOTO 2200
630 F(6,1)=2.95E9
631 F(6,2)=1.9E8
632 B6=2
633 A6=0
634 GOTO 2130
640 F(4,1)=1.08E-8
641 F(4,2)=1.66E-7
642 GOTO 2200
650 F(4,1)=1.8E-9
651 F(4,2)=5.2E-8

```

```

652 G010 2200
660 F(4,1)=6.5E-8
661 F(4,2)=7.66E-1
662 G010 2200
670 PRINT "SAME AS EVC"
671 G010 660
680 F(4,1)=5E-9
681 F(4,2)=5.8E-8
682 G010 2200
690 F(1,1)=7.55E-8
691 F(1,2)=2E-1
692 G010 2000
700 F(1,1)=4.85E-8
701 F(1,2)=1.877E-7
702 G010 2000
710 F(4,1)=1.302E-6
711 F(4,2)=4.658E-6
712 G010 2200
720 F(1,1)=2.3E-7
721 F(1,2)=6.14E-6
722 G010 2000
730 F(1,1)=6.5E-7
731 F(1,2)=9.47E-6
732 G010 2000
740 F(6,1)=4.9E9
741 F(6,2)=3.4E8
742 A6=0
743 R6=2
744 G010 2130
750 F(2,1)=3.5E-8
751 F(2,2)=1.1E-6
752 F(4,1)=3.7E-8
753 F(4,2)=1.01E-6
754 G010 2230
760 F(1,1)=3.8E-7
761 F(1,2)=5.8E-6
762 F(2,1)=2E4
763 F(2,2)=1E4
764 F(7,1)=1.85E4
765 F(7,2)=9.25E3
766 G010 2640
770 PRINT "APPLIED VOLTS/RATED VOLTS=?"
771 INPUT R4
772 F(2,1)=R4*5E-12*.224
773 F(2,2)=R4*5E-12*3.855
774 F(7,1)=(R4*(-1.5))*6.07E3
775 F(7,2)=(R4*(-1.5))*1.17E3
776 R1=.165
777 G010 2810
780 F(3,2)=2E-9
781 F(3,1)=2E-9
782 G010 2100
790 F(1,2)=2E-6
791 F(1,1)=1.42E-6
792 G010 2000

```



800 F(1,2)=3.01E-6  
 801 F(1,1)=1.241E-6  
 802 G010 2000  
 810 F(1,2)=2.62E-6  
 811 F(1,1)=1.56E-6  
 812 G010 2000  
 820 F(1,2)=2.85E-6  
 821 F(1,1)=1.15E-6  
 822 G010 2000  
 830 F(1,2)=2.5E-6  
 831 F(1,1)=0.198E-6  
 832 G010 2000  
 840 H7=.2  
 841 F(2,1)=2E-10  
 842 F(2,2)=2E-9  
 843 F(7,1)=2.4E7  
 844 F(7,2)=1.2E7  
 845 G010 2810  
 850 F(1,2)=1.48E-6  
 851 F(1,1)=0.826E-6  
 852 G010 2000  
 860 F(2,1)=3.03E-9  
 861 F(2,2)=1.08E-7  
 862 F(4,1)=3.6E-9  
 863 F(4,2)=1.04E-7  
 864 G010 2230  
 870 F(2,1)=9.1E-9  
 871 F(2,2)=3.24E-7  
 872 F(4,1)=1.08E-8  
 873 F(4,2)=3.12E-7  
 874 G010 2230  
 880 F(4,1)=1.8E-9  
 881 F(4,2)=5.2E-8  
 882 G010 2200  
 890 F(5,1)=1.143E-6  
 891 F(5,2)=6.6E-6  
 892 F(1,1)=2.42E-4  
 893 F(1,2)=2.04E-3  
 894 F(2,1)=2.24E-6  
 895 F(2,2)=1.2E-5  
 896 G010 2270  
 900 F(5,1)=1.7E-6  
 901 F(5,2)=9.9E-6  
 902 F(1,1)=3.63E-4  
 903 F(1,2)=3.06E-3  
 904 F(2,1)=3.36E-6  
 905 F(2,2)=1.8E-5  
 906 G010 2270  
 910 F(2,1)=6.6E-6  
 911 F(2,2)=2.6E-4  
 912 F(4,1)=3.8E-7  
 913 F(4,2)=2.93E-6  
 914 G010 2230  
 920 PRINT "SAME AS CV0"  
 921 G010 910

```

930 F(2,1)=1.32E-5
931 F(2,2)=5.15E-4
932 F(4,1)=1.6E-1
933 F(4,2)=5.85E-6
934 GOTO 2230
940 PRINT "DESIGN CYCLE LIFE, WP. LIFE, MISSION DURATION"
941 INPUT R2, B1, B4
942 B6=1.5
943 F(2,1)=((R2/2)1.5)/2.5E-8
944 F(2,2)=((R2/2)1.5)/R2-R
945 F(1,1)=((R1/2)1.5)/5.5E-6
946 F(1,2)=((R1/2)1.5)/3.32E-5
947 F(4,1)=((R4/2)1.5)/4.48E-8
948 F(4,2)=((R4/2)1.5)/3.63E-1
949 GOTO 2310
950 PRINT "DESIGN CYCLE LIFE, WP. LIFE, MISSION DURATION"
951 INPUT R2, F1, B4
952 H6=1.5
953 F(2,1)=((R2/2)1.5)/7.5E-8
954 F(2,2)=((R2/2)1.5)/2.4E-1
955 F(1,1)=((R1/2)1.5)/1.65E-5
956 F(1,2)=((R1/2)1.5)/9.96E-5
957 F(4,1)=((R4/2)1.5)/1.34E-1
958 F(4,2)=((R4/2)1.5)/1.09E-6
959 GOTO 2310
960 PRINT "DESIGN CYCLE LIFE, WP. LIFE, MISSION DURATION"
961 INPUT R2, F1, B4
962 H6=1.5
963 F(2,1)=((R2/2)1.5)/1.5E-1
964 F(2,2)=((R2/2)1.5)/4.8E-1
965 F(1,1)=((R1/2)1.5)/3.03E-5
966 F(1,2)=((R1/2)1.5)/1.83E-4
967 F(4,1)=((R4/2)1.5)/2.48E-1
968 F(4,2)=((R4/2)1.5)/2E-6
969 GOTO 2310
970 F(1,1)=2.15E-6
971 F(1,2)=1.66E-5
972 F(4,1)=2.24E-8
973 F(4,2)=1.8E-1
974 GOTO 2370
980 A6=2.2E4
981 H6=1.2
982 F(6,1)=1.54E6
983 F(6,2)=5E5
984 F(4,1)=4.14E-1
985 F(4,2)=1.48E-6
986 GOTO 2400
990 PRINT "SAME AS REF1"
991 GOTO 980
1000 A6=1.3E4
1001 B6=2
1002 GOTO 982

```

```

1010 PRINT "SAME AS BE01"
1011 GOTO 1000
1020 A6=4.3E4
1021 B6=1.2
1022 F(6,1)=4E7
1023 F(6,2)=2.42E6
1024 F(4,1)=2.84E-8
1025 F(4,2)=4.7E-7
1026 GOTO 2400
1030 PRINT "SAME AS BM1"
1031 GOTO 1020
1040 F(4,1)=1.07E-8
1041 F(4,2)=1.66E-7
1042 GOTO 2200
1050 F(6,1)=2.95E8
1051 F(6,2)=1.9E7
1052 A6=0
1053 B6=1.5
1054 GOTO 2130
1060 PRINT "INRUSTER CYCLES & OP.TIME"
1061 F(2,1)=3.57E-8
1062 F(2,2)=4.46E-7
1063 F(6,1)=6.3E12
1064 F(6,2)=1.64E12
1065 A6=0
1066 B6=3
1067 F(9,1)=0.99
1068 F(9,2)=.977
1069 GOTO 2440
1070 A6=0
1071 B6=1.5
1072 PRINT "DESIGN OP. LIFE=?"
1073 INPUT R1
1074 F(6,1)=(.2*R1)*.5/4.77E-7
1075 F(6,2)=(.2*R1)*.5/1.1E-6
1076 GOTO 2130
1080 A6=0
1081 B6=1.5
1082 PRINT "DESIGN CYCLE LIFE, OP.LIFE?"
1083 INPUT R2,R1
1084 F(6,1)=(.2*R1)*.5/4.77E-7
1085 F(6,2)=(.2*R1)*.5/1.1E-6
1086 F(2,1)=(.2*R2)*.5/1.67E-8
1087 F(2,2)=(.2*R2)*.5/7E-7
1088 GOTO 2500
1090 F(4,1)=2.77E-9
1091 F(4,2)=1.65E-8
1092 GOTO 2200
1100 PRINT "SAME AS I11"
1101 GOTO 1090
1102 PRINT "DESIGN CYC LIFE, DESIGN COLD STARTS, OP.LIFE?"
1104 INPUT R2,R3,R1
1106 B6=1.5

```

```

1108 F(1,1)=(.2*R1)*.5/1.53E-6
1110 F(1,2)=(.2*R1)*.5/9.2E-6
1112 F(2,1)=(.2*B2)*.5/4.9E-8
1114 F(2,2)=(.2*R2)*.5/3.5E-7
1116 IF R3=0 THEN 2550
1117 F(3,1)=(.2*B3)*2/6.2E-6
1118 F(3,2)=(.2*R3)*2/3.72E-5
1119 GOTO 2550
1120 PRINT "DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?"
1121 INPUT R2,R3,R1
1122 B6=2
1123 F(2,1)=.5*B2/2.8E-6
1124 F(2,2)=.5*B2/1.7E-5
1125 F(1,1)=.5*R1/7.6E-5
1126 F(1,2)=.5*R1/4.6E-4
1127 IF R3=0 THEN 2550
1128 F(3,1)=(.2*R3)*2/6.2E-6
1129 F(3,2)=(.2*R3)*2/3.72E-5
1130 GOTO 2550
1131 F(1,2)=3.5E-8
1132 F(1,1)=4.9E-9
1134 GOTO 2860
1140 PRINT "DESIGN CYCLE LIFE,OP.LIFE?"
1141 INPUT R2,R1
1142 F(2,1)=(.5*B2)*.5/9.7E-9
1143 F(2,2)=(.5*B2)*.5/7E-8
1144 F(1,1)=(.5*R1)*.5/1.02E-1
1145 F(1,2)=(.5*R1)*.5/6.1E-1
1148 B6=1.5
1149 GOTO 2580
1150 PRINT "DESIGN CYCLE LIFE,OP.LIFE?"
1151 PRINT "(CYCLES=PULSES)"
1152 INPUT R2,B1
1153 F(2,1)=(.5*B2)*.5/2.7E-9
1154 F(2,2)=(.5*B2)*.5/7E-9
1155 F(1,1)=(.5*R1)*.5/3E-5
1156 F(1,2)=(.5*R1)*.5/6.35E-5
1157 B6=1.5
1158 GOTO 2580
1160 F(2,1)=1.9E-6
1161 F(2,2)=8.34E-6
1162 F(4,1)=3E-1
1163 F(4,2)=1.23E-5
1164 GOTO 2230
1170 F(2,1)=3.45E-8
1171 F(2,2)=9.26E-1
1172 F(6,1)=1.9E15
1173 F(6,2)=7.07E13
1174 F(9,1)=0.96
1175 F(9,2)=.91

```

```

1176 A6=0
1177 R6=3.5
1178 G0T0 2440
1180 PRINT "DESIGN WP. LIFE=?"
1181 INPUT R1
1182 F(6,1)=(.1*R1)*1.5/1.11E-7
1183 F(6,2)=(.1*R1)*1.5/6.62E-7
1184 A6=0
1185 R6=2.5
1186 G0T0 2130
1190 PRINT "REL=1.0 UNTIL FIRING REQUIRED"
1191 F(1,1)=1
1192 F(1,2)=5
1193 G0T0 2750
1199 PRINT "ASSESSED AS BACK-UP TO RELIEF VALVE ONLY"
1200 PRINT "NEGLECTIBLE IMPACT AT SYSTEM LEVEL"
1201 PRINT "(USE REL=1.0 IF NO OTHER DATA)"
1202 G0T0 200
1210 F(4,1)=9.75E-9
1211 F(4,2)=1.66E-7
1212 G0T0 2200
1220 F(4,1)=3.89E-10
1221 F(4,2)=2.8E-9
1222 G0T0 2200
1230 F(2,1)=1.82E-8
1231 F(2,2)=6.48E-7
1232 F(4,1)=1.98E-8
1233 F(4,2)=6.24E-7
1234 G0T0 2230
2000 PRINT "WP TIME=? (0=END)"
2002 INPUT I(1)
2004 IF I(1)<=0 THEN 200
2006 K0=EXP(-F(1,2)*I(1))
2008 K5=EXP(-F(1,1)*I(1))
2020 G0SUB 3000
2022 PRINT USING 2,K0,K5,A0,R0
2024 PRINT "WP TIME=?"
2026 G0T0 2002
2030 PRINT "PRESS. TIME=? (0=END)"
2032 INPUT I(5)
2034 IF I(5)<=0 THEN 200
2036 K0=EXP(-F(5,2)*I(5))
2038 K5=EXP(-F(5,1)*I(5))
2050 G0SUB 3000
2052 PRINT USING 2,K0,K5,A0,R0
2054 PRINT "PRESS. TIME=?"
2056 G0T0 2032
2060 PRINT " INPUT OPTION"
2062 PRINT "1= FIXED CYCLES/WP.HR., 2=SEPARATE"
2064 INPUT F(9,9)
2066 IF F(9,9)=2 THEN 2074

```

```

2068 PRINT "CYCLES/OP.HR.=?"
2070 INPUT F(9,8)
2072 GOTO 2080
2074 PRINT "CYCLES =? (0=END)"
2076 INPUT I(2)
2078 IF I(2)<=0 THEN 200
2080 PRINT "OPTIME=? (0=END)"
2082 INPUT I(1)
2083 IF I(1)<=0 THEN 200
2084 IF F(9,9)=2 THEN 2088
2086 I(2)=F(9,8)*I(1)
2088 R0=EXP((-F(1,2)*I(1))-(F(2,2)*I(2)))
2090 R5=EXP((-F(1,1)*I(1))-(F(2,1)*I(2)))
2092 GOSUB 3000
2094 PRINT USING 2,R0,R5,A0,B0
2096 IF F(9,9)=2 THEN 2074
2098 GOTO 2080
2100 PRINT "NO. CYCLES =? (0=END)"
2102 INPUT I(3)
2104 IF I(3)<=0 THEN 200
2106 R0=EXP(-F(3,2)*I(3))
2108 R5=EXP(-F(3,1)*I(3))
2120 GOSUB 3000
2122 PRINT USING 2,R0,R5,A0,B0
2124 PRINT "NO. CYCLES=?"
2126 GOTO 2102
2130 PRINT "OPTIME=? (0=END)"
2132 INPUT I(6)
2134 IF I(6)<=0 THEN 200
2136 IF I(6)<=A6 THEN 2152
2138 I(6)=(I(6)-A6)*B6
2140 R0=EXP(-I(6)/F(6,2))
2142 R5=EXP(-I(6)/F(6,1))
2144 GOSUB 3000
2146 PRINT USING 2,R0,R5,A0,B0
2148 PRINT "OPTIME=?"
2150 GOTO 2132
2152 PRINT "RELIABILITY=1 (OP.TIME<=GUARANTEE)"
2154 GOTO 2130
2160 PRINT "OPTIME=? (0=END)"
2162 INPUT I(1)
2164 IF I(1)<=0 THEN 200
2166 I(6)=I(1)
2168 R0=1
2170 R5=1
2172 IF I(6)<=A6 THEN 2180
2174 I(6)=(I(6)-A6)*B6
2176 R0=EXP(-I(6)/F(6,2))
2178 R5=EXP(-I(6)/F(6,1))

```

```

2180 R0=R0*EXP(-F(1,2)*T(1))
2182 R5=R5*EXP(-F(1,1)*I(1))
2184 GOSUB 3000
2186 PRINT USING 2,R0,R5,A0,R0
2188 PRINT"OPTIME=?"
2190 GOTO 2162
2200 PRINT "MISSION TIME=? (0=END)"
2202 INPUT I(4)
2204 IF I(4)<=0 THEN 200
2206 R0=EXP(-F(4,2)*T(4))
2208 R5=EXP(-F(4,1)*I(4))
2220 GOSUB 3000
2222 PRINT USING 2,R0,R5,A0,R0
2224 PRINT "MISSION TIME=?"
2226 GOTO 2202
2230 PRINT "INPUT OPTION"
2232 PRINT "1=FIXED CYCLES/MISSION HR., 2=SEPARATE"
2234 INPUT F(9,9)
2236 IF F(9,9)=2 THEN 2244
2238 PRINT "CYCLES/MISSION HR.=?"
2240 INPUT F(9,8)
2242 GOTO 2250
2244 PRINT "CYCLES=? (0=END)"
2246 INPUT I(2)
2248 IF I(2)<=0 THEN 200
2250 PRINT "MISSION TIME =? (0=END)"
2252 INPUT I(4)
2253 IF I(4)<=0 THEN 200
2254 IF F(9,9)=2 THEN 2258
2256 I(2)=F(9,8)*I(4)
2258 R0=EXP((-F(4,2)*I(4))-(F(2,2)*I(2)))
2260 R5=EXP((-F(4,1)*I(4))-(F(2,1)*I(2)))
2262 GOSUB 3000
2264 PRINT USING 2,R0,R5,A0,R0
2266 IF F(9,9)=2 THEN 2244
2268 GOTO 2250
2270 PRINT"INPUT OPTION"
2272 PRINT "1=FIXED CYCLES/OP.HR., 2=SEPARATE"
2274 INPUT F(9,9)
2276 IF F(9,9)=2 THEN 2284
2278 PRINT "CYCLES/OP.HR.=?"
2280 INPUT F(9,8)
2282 GOTO 2290
2284 PRINT "CYCLES=? (0=END)"
2286 INPUT I(2)
2288 IF I(2)<=0 THEN 200
2290 PRINT "MISSION TIME,OP. TIME (0=END)"
2292 INPUT I(4),T(1)
2293 IF I(4)<=0 THEN 200

```

```

2294 IF F(9,9)=2 THEN 2298
2296 I(2)=F(9,8)*I(1)
2298 R0=EXP((-F(1,2)*I(1))-(F(5,2)*(I(4)-I(1)))-(F(2,2)*I(2)))
2300 R5=EXP((-F(1,1)*I(1))-(F(5,1)*(I(4)-I(1)))-(F(2,1)*I(2)))
2302 GOSUB 3000
2304 PRINT USING 2,R0,R5,A0,R0
2306 IF F(9,9)=2 THEN 2284
2308 GOTO 2290
2310 PRINT "INPUT OPTION"
2312 PRINT "1=FIXED CYCLES/OP.HR., 2=SEPARATE"
2314 INPUT F(9,9)
2328 IF F(9,9)=2 THEN 2336
2330 PRINT "CYCLES/OP.HR.=?"
2332 INPUT F(9,8)
2334 GOTO 2312
2336 PRINT "CYCLES=? (0=END)"
2338 INPUT I(2)
2340 IF I(2)<=0 THEN 200
2342 PRINT "MISSION TIME, OP.TIME(0,0=END)"
2344 INPUT I(4),I(1)
2346 IF I(4)<=0 THEN 200
2348 IF F(9,9)=2 THEN 2352
2350 I(2)=F(9,8)*I(1)
2352 R0=I(2)+B6/F(2,2)+I(1)+B6/F(1,2)+I(4)+B6/F(4,2)
2354 R0=EXP(-R0)
2356 R5=I(2)+B6/F(2,1)+I(1)+B6/F(1,1)+I(4)+B6/F(4,1)
2358 R5=EXP(-R5)
2360 GOSUB 3000
2362 PRINT USING 2,R0,R5,A0,R0
2364 IF F(9,9)=2 THEN 2336
2366 GOTO 2342
2370 PRINT "MISSION TIME, OP.TIME=? (0,0=END)"
2372 INPUT I(4),I(1)
2374 IF I(4)<=0 THEN 200
2376 R0=EXP(-(F(1,2)*I(1))-F(4,2)*I(4))
2378 R5=EXP(-(F(1,1)*I(1))-F(4,1)*I(4))
2380 GOSUB 3000
2382 PRINT 2,R0,R5,A0,R0
2384 GOTO 2370
2400 PRINT "MISSION TIME=? (0=END)"
2402 INPUT I(4)
2404 IF I(4)<=0 THEN 200
2406 I(6)=I(4)
2408 R0=1
2410 R5=1
2412 IF I(6)=-A6 THEN 2420
2414 I(6)=(I(6)-A6)+R6
2416 R0=EXP(-I(6)/F(6,2))
2418 R5=EXP(-I(6)/F(6,1))

```



```

2420 R0=R0*EXP(-F(4,2)*T(4))
2422 R5=R5*EXP(-F(4,1)*T(4))
2424 GOSUB 3000
2426 PRINT USING 2,R0,R5,A0,R0
2428 PRINT "MISSION TIME=?"
2430 GOTO 2402
2440 PRINT " INPUT OPTION"
2442 PRINT "1=FIXED CYCLES/OP.HR., 2=SEPARATE"
2444 INPUT F(9,9)
2446 IF F(9,9)=2 THEN 2454
2448 PRINT "CYCLES/OP.HR.=?"
2450 INPUT F(9,8)
2452 GOTO 2460
2454 PRINT "CYCLES=? (0=END)"
2456 INPUT I(2)
2458 IF I(2)<=0 THEN 200
2460 PRINT "OPTIME=? (0=END)"
2462 INPUT I(1)
2463 IF I(1)<=0 THEN 200
2464 IF F(9,9)=2 THEN 2468
2466 I(2)=F(9,8)*I(1)
2468 I(6)=(I(1)-A6)*B6
2470 R0=F(9,2)*EXP(-(F(2,2)*I(2))-I(6)/F(6,2))
2472 R5=F(9,1)*EXP(-(F(2,1)*I(2))-I(6)/F(6,1))
2474 GOSUB 3000
2476 PRINT USING 2,R0,R5,A0,R0
2478 IF F(9,9)=2 THEN 2454
2480 GOTO 2460
2500 PRINT "INPUT OPTION"
2502 PRINT "1=FIXED CYCLES/OP.HR., 2=SEPARATE"
2504 INPUT F(9,9)
2506 IF F(9,9)=2 THEN 2514
2508 PRINT "CYCLES/OP.HR.=?"
2510 INPUT F(9,8)
2512 GOTO 2520
2514 PRINT "CYCLES=? (0=END)"
2516 INPUT I(2)
2518 IF I(2)<=0 THEN 200
2520 PRINT "OPTIME=? (0=END)"
2522 INPUT I(1)
2523 IF I(1)<=0 THEN 200
2524 IF F(9,9)=2 THEN 2528
2526 I(2)=F(9,8)*I(1)
2528 I(6)=(I(1)-A6)*B6
2530 I(2)=I(2)*B6
2532 R0=EXP(-(I(6)/F(6,2))-I(2)/F(2,2))
2534 R5=EXP(-(I(6)/F(6,1))-I(2)/F(2,1))
2536 GOSUB 3000
2538 PRINT USING 2,R0,R5,A0,F0

```

```

2540 IF F(9,9)=2 THEN 2514
2542 GOTO 2520
2550 PRINT "CYCLES,COLD STARTS,WP. TIME, (I=0=END)"
2552 INPUT I(2),I(3),I(1)
2553 IF I(1)<=0 THEN 200
2554 T(2)=I(2)*B6
2556 T(1)=T(1)*B6
2558 IF B3=0 THEN 2562
2560 R0=EXP(-(I(2)/F(2,2))-I(3)/F(3,2)-I(1)/F(1,2))
2561 R5=EXP(-(I(2)/F(2,1))-I(3)/F(3,1)-I(1)/F(1,1))
2562 R0=EXP(-(I(2)/F(2,2))-I(1)/F(1,2))
2563 R5=EXP(-(I(2)/F(2,1))-I(1)/F(1,1))
2564 GOSUB 3000
2566 PRINT USING 2,R0,R5,A0,B0
2568 GOTO 2550
2580 PRINT "INPUT OPTION"
2582 PRINT "1=FIXED CYCLES/OP.HR., 2=SEPARATE"
2584 INPUT F(9,9)
2586 IF F(9,9)=2 THEN 2594
2588 PRINT "CYCLES/OP.HR.=?"
2590 INPUT F(9,8)
2592 GOTO 2600
2594 PRINT "CYCLES=? (0=END)"
2596 INPUT I(2)
2598 IF I(2)<=0 THEN 200
2600 PRINT "MISSION TIME,WP. TIME (0,0=END)"
2602 INPUT I(4),I(1)
2603 IF I(4)<=0 THEN 200
2604 IF F(9,9)=2 THEN 2608
2606 I(2)=F(9,8)*I(1)
2608 I(2)=I(2)*B6
2612 T(1)=I(1)*B6
2614 R0=EXP(-I(1)/F(1,2)-I(2)/F(2,2))
2616 R5=EXP(-I(1)/F(1,1)-I(2)/F(2,1))
2618 GOSUB 3000
2620 PRINT USING 2,R0,R5,A0,B0
2622 IF F(9,9)=2 THEN 2594
2624 GOTO 2600
2640 PRINT "INPUT OPTION"
2642 PRINT "1=FIXED CYCLES/OP.HR.,2=SEPARATE"
2644 INPUT F(9,9)
2646 IF F(9,9)=2 THEN 2654
2648 PRINT "CYCLES/OP.HR.=?"
2650 INPUT F(9,8)
2652 GOTO 2660
2654 PRINT "CYCLES=? (0=END)"
2656 INPUT I(2)
2658 IF I(2)<=0 THEN 200
2660 PRINT "OPTIME=? (0=END)"

```

```

2662 INPUT T(1)
2664 IF T(1)<=0 THEN 200
2666 IF F(9,9)=2 THEN 2670
2668 I(2)=F(9,8)*I(1)
2670 K0=EXP(-(F(1,2)*I(1)))
2672 K5=EXP(-(F(1,1)*I(1)))
2674 Y1=(I(2)-F(1,2))*3/F(1,2)
2676 GOSUB 4000
2678 R0=K0*Y9
2680 Y1=(I(2)-F(1,1))*3/F(1,1)
2682 GOSUB 4000
2684 K5=K5*Y9
2686 Y1=(I(1)-F(2,2))*3/F(2,2)
2688 GOSUB 4000
2690 R0=K0*Y9
2692 Y1=(I(1)-F(2,1))*3/F(2,1)
2694 GOSUB 4000
2696 K5=K5*Y9
2698 GOSUB 3000
2700 PRINT USING 2,R0,K5,A0,R0
2702 IF F(9,9)=2 THEN 2654
2704 GOTO 2660
2710 PRINT "MISSION TIME=? (0 TO END)"
2712 INPUT T(4)
2714 IF T(4)<=0 THEN 200
2716 R0=EXP(-(F(4,2)*T(4)))
2718 K5=EXP(-(F(4,1)*T(4)))
2720 Y1=(T(4)-F(7,1))/(.15*F(1,1))
2722 GOSUB 4000
2724 R0=R0*(1-(1-Y9)*F(9,2))
2726 K5=K5*(1-(1-Y9)*F(9,1))
2728 IF B9=0 THEN 2742
2730 IF B9=2 THEN 2738
2732 R0=R0*.2*EXP(-(F(2,2)*T(4)))
2734 K5=K5*.2*EXP(-(F(2,1)*T(4)))
2736 GOTO 2742
2738 R0=R0*.4
2740 K5=K5*.4
2742 GOSUB 3000
2744 PRINT USING 2,R0,K5,A0,R0
2746 GOTO 2710
2750 PRINT "MISSION TIME TO FIRING=? (YRS TO END)"
2752 INPUT T(1)
2754 IF T(1)<=0 THEN 200
2756 Y1=(LOG(T(1))-LOG(F(1,2)))/.3991
2758 GOSUB 4000
2760 R0=Y9
2762 Y1=(LOG(T(1))-LOG(F(7,1)))/.3991
2764 GOSUB 4000

```

```

2766 K5=Y9
2768 GOSUB 3000
2770 PRINT USING 2,R0,K5,A0,R0
2772 PRINT "MISS. TIME=?"
2774 GOTO 2752
2810 PRINT "WP.PULSES=? (0=END)"
2812 INPUT I(2)
2813 IF I(2)<=0 THEN 200
2814 Y1=(I(2)-F(7,2))/(B1*F(7,2))
2816 GOSUB 4000
2818 K0=Y9
2820 Y1=(I(2)-F(7,1))/(B1*F(7,1))
2822 GOSUB 4000
2824 K5=Y9
2826 R0=R0*EXP(-(F(2,2)*I(2)))
2828 K5=K5*EXP(-(F(2,1)*I(2)))
2830 GOSUB 3000
2832 PRINT USING 2,R0,K5,A0,R0
2834 GOTO 2810
2860 PRINT "MISSION TIME, WP. TIME (IMISS=0=END)"
2862 INPUT I(4),I(1)
2864 IF I(4)<=0 THEN 200
2866 R0=EXP(F(1,2)*(I(1)-I(4)))
2868 K5=EXP(F(1,1)*(I(1)-I(4)))
2870 GOSUB 3000
2872 PRINT USING 2,R0,K5,A0,R0
2874 PRINT "MISS.TIME, WP.TIME"
2876 GOTO 2862
3000 IF (LOG(R0)/LOG(K5))<=1 THEN 3004
3001 S0=LOG(LOG(R0)/LOG(K5))/1.644K5
3002 IF S0<.89146 THEN 3100
3003 GOTO 3010
3004 IF R0>K5 THEN 3007
3005 PRINT "R05=K5, DISREGARD ALPHA,BETA"
3006 GOTO 3210
3007 PRINT "PROGRAM ERROR OR TAIL REVERSAL:R0>K5"
3008 PRINT "TRY VALUE CLOSER TO MEAN LIFE"
3009 GOTO 3210
3010 R0=.646/(LOG(S0)+.646)-1.21634
3012 IF R0<-.91 THEN 3068
3014 IF R0<-.2 THEN 3020
3016 M0=.45*(-R0)
3018 GOTO 3090
3020 IF R0<-.3 THEN 3030
3022 M0=.09-.5*(R0+.2)
3024 GOTO 3090
3030 IF R0<-.4 THEN 3040
3032 M0=.14-.575*(R0+.3)
3034 GOTO 3090

```

```

3040 IF B0<-.5 THEN 3050
3042 M0=.1975-.675*(R0+.4)
3044 GOTO 3090
3050 IF B0<-.6 THEN 3060
3052 M0=.265-.7*(B0+.5)
3054 GOTO 3090
3060 IF B0<-.7 THEN 3070
3062 M0=.335-.9*(B0+.6)
3064 GOTO 3090
3068 PRINT "ALPHA APPROX. QUESTIONABLE"
3070 M0=.425-1.05*(B0+.7)
3074 GOTO 3090
3090 A0= LOG(1-.5*(1/(R0+1)))/LOG(R5)
3092 A0=(A0-1)/(M0+1)
3094 GOTO 3210
3100 Z0=(S0/.8899)*(-1/.4682)
3101 IF Z0<1 THEN 3104
3102 D=.1*Z0
3103 GOTO 3105
3104 D=.1
3105 Z1=Z0
3106 IF Z1<=D THEN 3102
3110 GOSUB 3300
3112 IF ABS(S3-S0)<=.00005 THEN 3200
3114 S3=S0
3116 Z1=Z0-D
3118 IF .8899*(Z1*(-.4682))*(1/(2*Z1-1))*(.0273/(Z1+.5))>S0
THEN 3130

3120 GOSUB 3300
3122 IF ABS(S3-S0)<=.00005 THEN 3200
3124 IF S3>S0 THEN 3130
3126 Z0=Z1
3128 GOTO 3116
3130 D=.1*D
3132 IF D<.0002 THEN 3200
3134 GOTO 3116
3200 A0=Z9
3202 R0=Z1
3210 RETURN
3300 Z9=(2*R5*(Z1-.6)+.6)/(2*(1-R5))
3302 S3=(Z9+Z1-1)/((2*Z1-1)*(Z9-Z1+1))
3303 IF S3<=0 THEN 3320
3304 S3=S3*(.0273/(Z1+.5))
3306 S3=S3*.8899*(Z1*(-.4682))
3310 RETURN
3320 PRINT "OUT OF RANGE; TRY SMALLER OR LARGER TIME/PULSES"
3322 GOTO 9999
4000 Y8=SGN(Y1)
4001 IF ABS(Y1)<5 THEN 4010

```

```

4002 Y9=.5-Y8*.49999999
4003 PRINT "I,APPROX. NORM PROF."
4004 PRINT Y1,Y9
4005 GOTO 4050
4010 Y9=1
4012 I=1
4014 Y7=1
4020 Y6=(((-1)I)*Y1(2*I))/((2I)*Y7(2*I+1))
4022 Y9=Y9+Y6
4024 IF ABS(Y6)<.000001 THEN 4040
4026 I=I+1
4028 IF I>40 THEN 4040
4029 Y7=Y7*I
4030 GOTO 4020
4040 Y9=.5-Y8*Y9*ABS(Y1)*((2/3.141592)I.5)I/2
4050 RETURN
99998 PRINT "NO SUCH COMPONENT"
99999 END

```

Table 9

## Alpha Numeric Component Code Listing

COMPONENT	COMP 1 EQUATION
1. Gimbal Thrust Vectoring	
1.1 Lower Support	LS
1.2 Upper Support	US
1.3 Linear Actuator	LA
1.4 Motor and Gearing	MG
2. Bladder, Mercury	BB
3. Fill Valve, Pressurized System	FV1
5. Pressurized Tank	
5.1 Whole Tank	TT
5.2 Propellant Reservoir	PR
5.3 Pressurant Tank	PT
6. Vaporizer	
6.1 Vaporizer Clogged	VC
6.2 Vaporizer Leakage	VL
7. PCC Switch	
7.1 Fails Active	SA
7.2 Fails Passive	SP
8. Propellant Feed Lines	FL
9. Cathode, hollow	HC
10. Isolator	II
11. Neutralizer Isolator	NI
12. Neutralizer Vaporizer	NV
13. Neutralizer Cathode	NC
14. Discharge Chamber, Kaufman	DC
15. Vaporizer Heater	VH
16. PCC Failure, Mercury Ion	MPC

	COMPONENT	COMP 1 EQUATION
17.	Line, Tank or Valve Heater	HLTV
18.	Unpressurized Surface Tension. Tank Cesium	USTT
19.	Discharge Chamber, MESC type, including TVC	MESC
20.	Neutralizer Probe Cesium Ion System	NP
21.	PCC, Cesium Ion, MESC Type	CPC
22.	Vapor Valve Cesium	
	22.1 Fails Part Open	VVP
	22.2 Fails Open	VVO
	22.3 Fails Closed	VVC
23.	Trapped Gas in Cesium Tank	TG
24.	Propellant (Cesium) Tank Leakage	PCTL
25.	Vapor Valve Heater, (also Vaporizer Heater)	VVH
26.	Fins Unwetted	FU
27.	Propellant Storage Bellows (Colloid)	PSB
28.	Fill Valve, Colloid	FV2
29.	Filter, Colloid	
	29.1 Clogging	FCC
	29.2 Leaking	FCL



COMPONENT	COMP 1 EQUATION
30. Propellant Flow Control Valve, (Ball Valve) Colloid (Ball Valve)	
30.1 Leak to Space	BVL
30.2 Ball Valve Closed	BVC
30.3 Ball Valve Fails Open	BVO
31. Zeolite Cannister Failure	ZC
32. System Manifold, Colloid	SM
33. Control Bellows, Colloid	CB
34. Colloid PCC	CPCC
35. Colloid Thruster Module	CTM
36. Colloid Thruster Frame	CTF
37. Electrofluidic Isolation Valve	
37.1 Electrical Failure	EIV
37.2 Fluid Failure	FIV
38. Filament Neutralizer Colloid	FNC
39. Main Capacitor, Pulsed Plasma	MCPl
40. Negator Spring, Pulsed Plasma	NS
41. Main Electrode Failure, Pulsed Plasma	ME
42. Control Logic, Pulsed Plasma	CL
43. Low Voltage Converter, Pulsed Plasma	LVC
44. High Voltage Converter, Pulsed Plasma	HVC
45. System Power Converter, Pulsed Plasma	SPC

COMPONENT		COMP 1 EQUATION
46.	Sense Circuit Pulsed Plasma	SC
47.	Initiator Plug Pulsed Plasma	IP
48.	Pulse Buffer Failure	PB
49.	Isolation Valve Solenoid Type, Normally Closed or Latch Valve	
49.1	Fail Open	ILVO
49.2	Fail Closed	ILVC
49.3	Fail Partial	ILVP
49.4	Fail Leak to Space	ILVL
50.	Regulator	
50.1	Fails or Biased Low	RBL
50.2	Fails High or Oscillatory	RHO
51.	Check Valve	
51.1	Fails Open	CVO
51.2	Fails Closed	CVC
51.3	Fail Partially Open/Closed	CVP
52.	Engine Valve	
52.1	Fail Open	EVO
52.2	Fail Closed	EVC
52.3	Fail Partial	EVP
52.4	Fail Leak to Space	EVLS
53.	Bladder/Diaphragm	
53.1	Elastomerics	
53.1.1	Fuel	
53.1.1.1	0 ≤ Mission Time ≤ 2.5 yrs	BEF1
53.1.1.2	Mission time > 2.5 yrs	BEF2
53.1.2	Oxidizer	
53.1.3.1	0 ≤ Mission Time ≤ 1.5 yrs	BE01
53.1.2.2	Mission > 1.5 yrs	BE02

COMPONENT	COMP 1 EQUATION
53.2 Metallics	
53.2.1 $0 \leq \text{Mission Time} \leq 5 \text{ yrs.}$	BM1
53.2.2 $5 \text{ yrs} \leq \text{Mission Time} < 10+ \text{ yrs.}$	BM2
54. Filter, Thermochemical System	
54.1 Leaking	FTL
54.2 Clogging	FTC
55. Heaters, External Thruster	HET
56. Injector (including Trim Orifice)	
56.1 Plugging	IMP
56.2 Fracture	IMF
56.3 Injector Seal Leak	ISL
56.4 Injector Braze Failure	IBF
57. Catalyst Bed	
57.1 Pulse Mode	CBP
57.2 Steady State	CBS
57.3 Dormant	CBD
58. Thrust Chamber, Mono-prop	TCM
59. Thrust Chamber Bipropellant	TCB
60. Relief Valve	RV
61. Heater, Thruster Internal	HTI
62. Thruster Screens and Retainer Electrothermal	TSR
63. Explosive Isolation Valve	EIV2
64. Burst Diaphragm	BD
65. Surface Tension Fins Unwetting	STFU

BETSBl Program Listing

```
1: SUBSYSTEM EVALUATION
2 PRINT "RUN IN DOUBLE PRECISION"
4 S8=0
5 S9=0
10 PRINT "TYPE OF INPUT(1=PARAM,2=MEAN&VAR)"
12 INPUT S1
14 PRINT "HOW MANY COMPONENTS?"
16 INPUT N
18 PRINT "INDEPENDENT=1,IDENTICAL=2"
20 INPUT S2
22 PRINT "SERIES=1,REDUNDANT=2"
24 INPUT S3
26 PRINT "VALUES"
28 IF S1=2 GOTO 44
30 IF S2=2 GOTO 40
32 FOR I=1 TO N
34 INPUT A(I),B(I)
36 NEXT I
38 GOTO 70
40 INPUT A(I),B(I)
42 GOTO 70
44 IF S2=2 GOTO 64
46 FOR I=1 TO N
48 INPUT E1,E2
50 GOSUB 300
60 NEXT I
62 GOTO 70
64 I=1
66 INPUT E1,E2
68 GOSUB 300
70 IF S1=2 GOTO 76
71 IF S2=2 GOTO 90
72 IF N=1 GOTO 90
74:00      00.000  00.000
76 PRINT
78 PRINT "COMP. ALPHA   BETA"
80 PRINT
81 FOR I=1 TO N
82 IF I=1 GOTO 84
83 IF S2=2 GOTO 87
84 PRINT USING 74,I,A(I),B(I)
85 IF A(I)<100 GOTO 87
```

```

86 PRINT A(I)
87 NEXT I
88 PRINT
90 IF S2=2 GOTO 92
91 IF S3=1 GOTO 100
92 IF S2=1 GOTO 94
93 IF S3=1 GOTO 104
94 IF S2=2 GOTO 96
95 IF S3=2 GOTO 108
96 GOSUB 400
98 GOTO 110
100 GOSUB 500
102 GOTO 110
104 GOSUB 600
106 GOTO 110
108 GOSUB 700
110 I=N+1
112 GOSUB 302
114:###.## ##.### .##### .##### .#####
116 PRINT "SUBSYSTEM"
118 PRINT "ALPHA   BETA           E(P)           E(P*P)       V(P)"
120 PRINT
122 PRINT USING 114,A(N+1),B(N+1),E1,E2,E2-E1*2
123 IF A(N+1)<1000 GOTO 125
124 PRINT A(N+1)
125 PRINT
126 PRINT
130 IF S9=0 GOTO 150
132 E1=(A(N+1)+1)/(A(N+1)+B(N+1)+2)
134 A(N+1)=(2+E1-1)/(1-E1)
136 E2=E1*(A(N+1)+2)/(A(N+1)+3)
138 B(N+1)=0
140 S9=0
142 PRINT
144 PRINT "IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED"
146 GOTO 116
150 IF S8=0 GOTO 990
152 FOR I=1 TO N
154 IF B(I)>=0 GOTO 164
156 E1=(A(I)+1)/(A(I)+B(I)+2)
158 A(I)=(2+E1-1)/(1-E1)
162 B(I)=0
164 NEXT I
166 PRINT "IF NEGATIVE BETA NOT ALLOWED"
168 PRINT "NEW COMPONENT VALUES"
170 S8=0
172 PRINT
174 PRINT "COMP.  ALPHA  BETA"
176 PRINT
178 FOR I=1 TO N

```

```

180 PRINT USING 74,I,A(I),B(I)
182 IF A(I)<100 GOTO 186
184 PRINT A(I)
186 NEXT I
188 PRINT
190 GOTO 90
300 E2=E2+E1*2
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B1<=(-1) GOTO 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF B(I)>=0 GOTO 314
309 IF I>N GOTO 312
310 S8=1
311 GOTO 314
312 S9=1
314 RETURN
330: BETA(###) ILLEGAL
332 PRINT USING 330,I
400 G1=1
402 G2=1
404 FOR I=1 TO N
406 G1=G1*(B(I)+1)/(A(I)+B(I)+1+1)
408 G2=G2*(B(I)+2*I-1)/(A(I)+B(I)+2*I)*(B(I)+2*I)/(A(I)+
B(I)+2*I+1)

410 NEXT I
412 E1=1-G1
414 E2=1-2*G1+G2
420 RETURN
500 G1=1
502 G2=1
504 FOR I=1 TO N
506 G1=G1*(A(I)+1)/(A(I)+B(I)+2)
508 G2=G2*(A(I)+2)/(A(I)+B(I)+3)
510 NEXT I
512 E1=G1
514 E2=G1*G2
520 RETURN
600 G1=1
602 G2=1
604 FOR I=1 TO N
606 G1=G1*(A(I)+1)/(A(I)+B(I)+I+1)
608 G2=G2*(A(I)+2*I)/(A(I)+B(I)+2*I)*(A(I)+2*I-1)/(A(I)+
B(I)+2*I+1)

610 NEXT I
612 E1=G1
614 E2=G2

```

```
620 RETURN
700 G1=1
702 G2=1
704 FOR I=1 TO N
706 G1=G1*(B(I)+1)/(A(I)+B(I)+2)
708 G2=G2*(B(I)+2)/(A(I)+B(I)+3)
710 NEXT I
712 E1=1-G1
714 E2=1-2*G1+G1*G2
720 RETURN
990 END
```

BETSB2 Program Listing

```
100 PRINT "M-OF-N, INDEPENDENT"
110 PRINT "RUN IN DOUBLE PRECISION"
120 S8=0
130 S9=0
140 DIM A(21),B(21),U(21),Z(21)
142 DIM H(150,21)
150 PRINT "TYPE OF INPUT(1=PARAM,2=MEAN&VAR)"
160 INPUT S1
170 PRINT "HOW MANY COMPONENTS?"
180 INPUT N
190 PRINT "HOW MANY REQ'D?"
200 INPUT S3
202 PRINT "SAME PARAMS?(1=YES,0=NO)"
204 INPUT S4
210 IF S4=1 THEN 4000
222 GOSUB 1610
224 IF L1<150 THEN 230
226 PRINT "RESET DIM AT 142"
227: USING ### TO REPLACE 150
228 PRINT USING 227,L1
229 GOTO 9999
230 PRINT "VALUES"
240 IF S1=2 GOTO 330
260 FOR I=1 TO N
270 INPUT A(I),B(I)
290 NEXT I
312 PRINT
320 GOTO 470
330 PRINT "COMP. ALPHA BETA"
332 FOR I=1 TO N
334 INPUT E1,E2
350 GOSUB 1200
356 PRINT USING 390,I,A(I),B(I)
358 NEXT I
360 PRINT
390:## ##.#### ##.####
470 E1=0
480 E2=0
490 GOSUB 1820
500 GOTO 900
510 I=N+1
520 GOSUB 1200
```



```

530:##.#### 50.#### .##### .##### .#####
540 PRINT "SUBSYSTEM"
550 PRINT "ALPHA BETA E(P) E(P*P) V(P)"
560 PRINT
570 PRINT USING 530,A(N+1),B(N+1),E1,E2,E2-E1*2
580 IF A(N+1)<100 GOTO 600
590 PRINT A(N+1)
600 PRINT
610 PRINT
612 IF B(N+1)>=0 THEN 9999
620 IF S9=0 GOTO 710
630 E1=(A(N+1)+1)/(A(N+1)+B(N+1)+2)
640 A(N+1)=(2+E1-1)/(1-E1)
650 E2=E1*(A(N+1)+2)/(A(N+1)+3)
660 B(N+1)=0
670 S9=0
680 PRINT
690 PRINT "IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED"
700 GOTO 540
710 IF S8=0 THEN 9999
720 FOR I=1 TO N
730 IF B(I)>=0 GOTO 770
740 E1=(A(I)+1)/(A(I)+B(I)+2)
750 A(I)=(2+E1-1)/(1-E1)
760 B(I)=0
770 NEXT I
772 PRINT
780 PRINT "IF NEGATIVE BETA NOT ALLOWED"
790 PRINT "NEW COMPONENT VALUES"
800 S8=0
810 PRINT
820 PRINT "COMP. ALPHA BETA"
830 PRINT
840 FOR I=1 TO N
850 PRINT USING 390,A(I),B(I)
860 IF A(I)<100 THEN 880
870 PRINT A(I)
878 NEXT I
880 PRINT
890 GOTO 470
900 FOR I=1 TO LI
910 D3=1
920 D4=1
930 FOR K2=1 TO N
940 IF H(I,K2)<.5 THEN 980
950 D3=D3*(A(K2)+1)
960 D4=D4*(A(K2)+1)*(A(K2)+2)
970 GOTO 992
980 D3=D3*(B(K2)+1)
990 D4=D4*(B(K2)+1)*(B(K2)+2)

```

```

992 D3=D3/(A(K2)+B(K2)+2)
994 D4=D4/((A(K2)+B(K2)+2)*(A(K2)+B(K2)+3))
1000 NEXT K2
1010 E1=E1+D3
1020 E2=E2+D4-D3*2
1030 NEXT I
1050 FOR I=1 TO L1-.99
1052 FOR J=I+1 TO L1+.01
1054 D2=1
1056 D3=1
1058 D4=1
1060 FOR K2=1 TO N
1070 F9=H(I,K2)+H(J,K2)
1071 GOSUB 1400
1072 NEXT K2
1080 E2=E2+2*(D2-D3+D4)
1082 NEXT J
1090 NEXT I
1100 GOTO 510
1200 E2=E2+E1*2
1210 C=E2/E1
1220 C(I)=(1-C)*(E1-1)/(E1-C)-1
1230 IF B(I)<=(-1) GOTO 1310
1240 A(I)=(B(I)+1)*E1/(1-E1)-1
1250 IF B(I)>=0 GOTO 1300
1260 IF I>N GOTO 1290
1270 S8=1
1280 GOTO 1300
1290 S9=1
1300 RETURN
1310: BETA(###) ILLEGAL
1320 PRINT USING 1310,I
1322 GOTO 9999
1400 IF F9<.5 THEN 1450
1410 D2=D2*(A(K2)+1)
1420 IF F9<1.5 THEN 1450
1430 D2=D2*(A(K2)+2)
1440 GOTO 1480
1450 D2=D2*(B(K2)+1)
1460 IF F9>.5 THEN 1480
1470 D2=D2*(B(K2)+2)
1480 D2=D2/((A(K2)+B(K2)+2)*(A(K2)+B(K2)+3))
1490 IF H(I,K2)<.5 THEN 1520
1500 D3=D3*(A(K2)+1)/(A(K2)+B(K2)+2)
1510 GOTO 1530
1520 D3=D3*(B(K2)+1)/(A(K2)+B(K2)+2)
1530 IF H(J,K2)<.5 THEN 1560
1540 D4=D4*(A(K2)+1)/(A(K2)+B(K2)+2)
1550 GOTO 1570
1560 D4=D4*(B(K2)+1)/(A(K2)+B(K2)+2)

```

```

1570 RETURN
1610 D1=1
1611 L1=1
1612 IF N-S3<.99 THEN 1740
1613 Z(1)=1
1614 L1=N+1
1615 Z(2)=N+1
1616 IF N-S3<1.99 THEN 1740
1618 FOR X=2 TO N-S3+.01
1620 D1=1
1640 FOR D2=X+1 TO N+.01
1650 D1=D1*D2
1660 NEXT D2
1662 IF N-X<2 THEN 1720
1670 FOR D2=2 TO N-X+.01
1680 D1=D1/D2
1690 NEXT D2
1720 L1=L1+D1
1726 Z(X+1)=Z(X)+D1
1730 NEXT X
1740 RETURN
1820 FOR I=2*N-1 TO 0.99 STEP -1
1822 S7=I
1824 FOR J=N TO 1.99 STEP -1
1825 U(J)=0
1826 IF S7<2*(J-1)+.1 THEN 1832
1828 U(J)=1
1830 S7=S7-2*(J-1)
1832 NEXT J
1833 U(1)=0
1834 IF S7<.99 THEN 1840
1836 U(1)=1
1840 K1=0
1842 FOR J=1 TO N
1844 K1=K1+U(J)
1846 NEXT J
1847 IF K1<S3 THEN 1858
1848 IF N-K1<1 THEN 1858
1850 Z(N-K1)=Z(N-K1)+1
1852 FOR J=1 TO N
1854 H(Z(N-K1),J)=U(J)
1856 NEXT J
1858 NEXT I
1860 FOR J=1 TO N
1862 H(1,J)=1
1864 NEXT J
1880 RETURN
1900 H(K1,K2)=0
1910 IF K2>K1+.01 THEN 2020

```

```

1912 IF K1<.99 THEN 2020
1920 H(K1,K2)=1
1930 IF ABS(K1-K2 )<.01 THEN 2020
1940 IF K1<2.99 THEN 2020
1950 FOR K3=(K1-K2+1) TO K1-.99
1960 H(K1,K2)=H(K1,K2)*K3
1970 NEXT K3
1980 IF K2<2.99 THEN 2020
1990 FOR K3=2 TO K2-.99
2000 H(K1,K2)=H(K1,K2)/K3
2010 NEXT K3
2020 RETURN
3000 E1=((A(1)+1)/(A(1)+B(1)+2))N
3010 E2=((A(1)+1)*(A(1)+2)/(A(1)+B(1)+2)/(A(1)+B(1)+3))N
3020 E2=E2-E12
3030 IF L1<1.99 THEN 510
3040 FOR X=1 TO N-S3+.01
3050 D3=((A(1)+1)(N-X)*(B(1)+1)X/(A(1)+B(1)+2)N
3060 D4=((A(1)+1)*(A(1)+2))(N-X)
3070 D4=D4*((B(1)+1)*(B(1)+2))X
3080 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))N
3090 D4=D4-D32
3100 E1=E1+D3*(Z(X+1)-Z(X))
3110 E2=E2+D4*(Z(X+1)-Z(X))
3120 NEXT X
3130 FOR I=0 TO N-S3-.99
3140 K1=N+1
3150 K2=I+1
3160 GOSUB 1900
3170 F1=H(K1,K2)
3200 FOR J=I+1 TO N-S3+.01
3202 K1=N+1
3210 K2=J+1
3220 GOSUB 1900
3230 F2=H(K1,K2)
3240 D4=(A(1)+1)(N-J)*(B(1)+1)J
3250 D4=D4/(A(1)+B(1)+2)(2*N)
3260 D4=D4*(A(1)+1)(N-I)*(B(1)+1)I
3270 E2=E2-2*F1*F2*D4
3280 FOR F3=0 TO I+.01
3290 K1=I+1
3300 K2=F3+1
3310 GOSUB 1900
3320 F4=H(K1,K2)*F1*F2
3330 IF F3<.99 THEN 3370
3340 FOR K1=1 TO F3+.01
3350 F4=F4*(J-K1+1)
3360 NEXT K1
3370 IF I-F3<.99 THEN 3410

```

```

3380 FOR K1=1 TO (I-F3+.01)
3390 F4=F4*(N-J-K1+1)
3400 NEXT K1
3410 IF I<.99 THEN 3450
3420 FOR K1=1 TO I+.01
3430 F4=F4/(N-K1+1)
3440 NEXT K1
3450 D4=1
3460 IF F3<.99 THEN 3480
3470 D4=D4*((B(1)+1)*(B(1)+2))*F3
3480 IF (I+J-2*F3)<.99 THEN 3500
3490 D4=D4*((A(1)+1)*(B(1)+1))*(I+J-2*F3)
3500 IF (N-I-J+F3)<.99 THEN 3520
3510 D4=D4*((A(1)+1)*(A(1)+2))*(N-I-J+F3)
3520 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))*N
3530 E2=E2+2*F4*D4
3540 NEXT F3
3550 NEXT J
3560 NEXT I
3570 FOR I=1 TO N-S3+.01
3580 K1=N+1
3590 K2=I+1
3600 GOSUB 1900
3610 F5=H(K1,K2)
3615 FOR F3=0 TO I-.99
3620 K1=I+1
3630 K2=F3+1
3640 GOSUB 1900
3650 F4=F5*H(K1,K2)
3660 K1=N-I+1
3670 K2=I-F3+1
3672 IF K2>K1 THEN 3800
3675 GOSUB 1900
3680 F4=F4*H(K1,K2)/2
3690 D3=(A(1)+1)*(N-I)*(B(1)+1)*I
3700 D3=(D3/(A(1)+B(1)+2)*N)*2
3710 E2=E2-2*F4*D3
3720 D4=((B(1)+1)*(B(1)+2))*F3
3730 D4=D4*((A(1)+1)*(B(1)+1))*(2*(I-F3))
3740 D4=D4*((A(1)+1)*(A(1)+2))*(N-2*I+F3)
3750 D4=D4/((A(1)+B(1)+2)*(A(1)+B(1)+3))*N
3760 E2=E2+2*F4*D4
3800 NEXT F3
3810 NEXT I
3820 GOTO 510
4000 PRINT "VALUES?"
4002 IF S1=2 THEN 4030
4010 INPUT A(1),B(1)
4020 GOTO 4110

```

```
4030 INPUT E1,E2
4040 I=1
4050 GOSUB 1200
4060 PRINT "ALPHA    BETA"
4070:###.###.###.###
4080 PRINT USING 4070,A(1),B(1)
4090 IF A(1)<1000 THEN 4110
4100 PRINT A(1)
4110 GOSUB 1610
4120 GOTO 3000
9999 END
READY.
```

BETSB 3 Program Listing

```

1 PRINT "M-OF-N IDENTICAL"
2 PRINT "RUN IN DOUBLE PRECISION"
4 S8=0
5 S9=0
7 DIM A(21),B(21)
8 DIM H(200,10)
10 PRINT "TYPE OF INPUT(1=PARAM,2=MEAN&VAR)"
12 INPUT S1
14 PRINT "HOW MANY COMPONENTS?"
16 INPUT N
22 PRINT "HOW MANY REQ'D?"
24 INPUT S3
26 PRINT "VALUES"
28 IF S1=2 THEN 64
32 INPUT A(1),B(1)
38 GOTO 76
64 I=1
66 INPUT E1,E2
68 GOSUB 300
70 PRINT "ALPHA  BETA"
72 PRINT USING 74,A(1),B(1)
74:###.###  ##.###
76 PRINT
100 E1=0
102 E2=0
104 GOTO 204
110 I=N+1
112 GOSUB 300
114:###.### ##.### .##### .##### .#####
116 PRINT "SUBSYSTEM"
118 PRINT "ALPHA  BETA      E(P)      E(P*P)      V(P)"
120 PRINT
122 PRINT USING 114,A(N+1),B(N+1),E1,E2,E2-E1*2
123 IF A(N+1)<1000 GOTO 125
124 PRINT A(N+1)
125 PRINT
126 PRINT
130 IF S9=0 THEN 150
132 E1=(A(N+1)+1)/(A(N+1)+B(N+1)+2)
134 A(N+1)=(2+E1-1)/(1-E1)
136 E2=E1*(A(N+1)+2)/(A(N+1)+3)
138 B(N+1)=0
140 S9=0

```

```

142 PRINT
144 PRINT "IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED"
146 GOTO 116
150 IF S8=0 THEN 9999
152 FOR I=1 TO N
154 IF B(I)>=0 GOTO 164
156 E1=(A(I)+1)/(A(I)+B(I)+2)
158 A(I)=(2+E1-1)/(1-E1)
162 B(I)=0
164 NEXT I
166 PRINT "IF NEGATIVE BETA NOT ALLOWED"
168 PRINT "NEW COMPONENT VALUES"
170 S8=0
172 PRINT
174 PRINT "COMP. ALPHA BETA"
176 PRINT
178 I=1
180 PRINT USING 74,I,A(I),B(I)
182 IF A(I)<1000 THEN 188
184 PRINT A(I)
188 PRINT
190 GOTO 100
193:9
198:99
204 FOR I=C TO N-S3+.01
206 K1=N+1
208 K2=I+1
210 GOSUB 1900
212 F4=H(K1,K2)
214 GOSUB 1000
216 E1=E1+F4*D1
218 GOSUB 1200
220 E2=E2+F4*(D2-D1*2)
222 IF I<.99 THEN 236
224 K1=F4+1
226 K2=3
230 GOSUB 1900
232 F4=H(K1,K2)
234 E2=E2+2*F4*(D2-D1*2)
236 NEXT I
238 FOR I1=0 TO N-S3-.99
240 K1=N+1
242 K2=I1+1
244 GOSUB 1900
246 F5=H(K1,K2)
248 I=I1
250 GOSUB 1000
252 D3=D1
254 FOR I2=I1+1 TO N-S3+.01

```



```

256 K1=N+1
258 K2=I2+1
260 GOSUB 1900
262 F4=H(K1,K2)
264 I=I2
266 GOSUB 1000
268 D4=D3*D1
270 D2=D1
272 FOR K1=1 TO N-I1+.01
274 D2=D2*(A(1)+N-I2+K1)
276 NEXT K1
278 IF I1<.99 THEN 286
280 FOR K1=1 TO I1+.01
282 D2=D2*(B(1)+I2+K1)
284 NEXT K1
286 FOR K1=1 TO N
288 D2=D2/(A(1)+B(1)+N+K1+1)
290 NEXT K1
292 E2=E2+2*F4+F5*(D2-D4)
294 NEXT I2
296 NEXT I1
298 GOTO 110
300 E2=E2+E1*2
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B(I)<=(-1) GOTO 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF B(I)>=0 GOTO 314
309 IF I>N GOTO 312
310 S8=1
311 GOTO 314
312 S9=i
314 RETURN
330: BETA(###) ILLEGAL
332 PRINT USING 330,I
334 GOTO 9999
1000 D1=1
1010 IF I<.99 THEN 1050
1020 FOR K1=1 TO I+.01
1030 D1=D1*(B(1)+K1)
1040 NEXT K1
1050 FOR K1=1 TO N-I+.01
1060 D1=D1*(A(1)+K1)
1070 NEXT K1
1080 FOR K1=1 TO N
1090 D1=D1/(A(1)+B(1)+K1+1)
1100 NEXT K1

```

```

1110 RETURN
1200 D2=1
1210 IF I<.99 THEN 1250
1220 FOR K1=1 TO I+.01
1230 D2=D2*(B(1)+2*K1)*(B(1)+2*K1-1)
1240 NEXT K1
1250 FOR K1=1 TO N-I+.01
1260 D2=D2*(A(1)+2*K1)*(A(1)+2*K1-1)
1270 NEXT K1
1280 FOR K1=1 TO 2*N+.01
1290 D2=D2/(A(1)+B(1)+K1+1)
1300 NEXT K1
1310 RETURN
1900 H(K1,K2)=0
1910 IF K2>K1 THEN 2000
1912 IF K1<.99 THEN 2020
1920 H(K1,K2)=1
1930 IF ABS(K1-K2)<.01 THEN 2020
1940 IF K1 <2.99 THEN 2020
1950 FOR K3=(K1-K2+1) TO K1-.99
1960 H(K1,K2)=H(K1,K2)*K3
1970 NEXT K3
1980 IF K2<2.99 THEN 2020
1990 FOR K3=2 TO K2-.99
2000 H(K1,K2)=H(K1,K2)/K3
2010 NEXT K3
2020 RETURN
9999 END
READY.

```

BETFTA Program Listing

```
1 PRINT "FOR EXPLANATION LIST 80000"
2 DIM M(20),G(20,100),D(20,100),C(20,100),T(20,100),U(20,100)
4 DIM A(20),B(20)
6 PRINT "HOW MANY LEVELS?"
8 INPUT L
12 PRINT "EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)"
13 FOR I=1 TO L-.99
14 INPUT M(I)
15 NEXT I
16 M(L)=1
18 K2=1
20 PRINT "DESTINATION?"
22 FOR I=1 TO L-.99
24 FOR J=1 TO M(I)
25 C(I,J)=1
26 PRINT I;J;
28 INPUT D(I,J)
29 G(I+1,D(I,J))=-1
30 NEXT J
32 NEXT I
34 PRINT "CONDITIONALS?(0,0=SKIP)"
35 INPUT I,J
36 IF I=0 THEN 41
37 PRINT "PCONDITIONAL"
38 INPUT C(I,J)
39 PRINT "NEXT?"
40 GOTO 35
41 PRINT "GATE TYPES"
42 FOR I=2 TO L
43 FOR J=1 TO M(I)
44 IF G(I,J)>-.5 THEN 48
45 PRINT I;J;
46 INPUT K3
47 G(I,J)=K3
48 NEXT J
49 NEXT I
50 FOR I=1 TO L-.99
52 FOR J=1 TO M(I)
54 IF G(I,J)>0 THEN 60
58 READ T(I,J),U(I,J)
60 NEXT J
62 NEXT I
```

```

64 PRINT
70 FOR I1=1 TO L-.99
72 FOR J1=1 TO M(I1)
74 IF N>0 THEN 78
76 K1=D(I1,J1)
78 N=N+1
80 A(N)=T(I1,J1)
82 B(N)=U(I1,J1)
84 IF C(I1,J1)=1 THEN 90
86 A(N)=(A(N)+B(N)+2)/C(I1,J1)-B(N)-2
90 IF J1>=M(I1) THEN 200
92 IF D(I1,J1+1)<>K1 THEN 200
94 NEXT J1
96 NEXT I1
100 PRINT
102 PRINT
106:SYSTEM (ITERATION ##)
108 PRINT USING 106,K2
110 PRINT "ALPHA   BETA   E(P)   E(P*P)   V(P)"
112 PRINT
114:##.#### ##.#### .##### .##### .#####
116 E1=(T(L,1)+1)/(T(L,1)+U(L,1)+2)
118 E2=E1*(T(L,1)+2)/(T(L,1)+U(L,1)+3)
120 PRINT USING 114,T(L,1),U(L,1),E1,E2,E2-E1^2
122 PRINT
124 PRINT
130 K2=K2+1
136 GOTO 50
200 ON G(I1+1,K1)+.1 GOTO 500,700,600,400
202 T(I1+1,K1)=A(N+1)
204 U(I1+1,K1)=B(N+1)
205 PRINT I1+1,K1,A(N+1),B(N+1)
206 N=0
210 GOTO 94
300 I=N+1
302 C=E2/E1
304 B(I)=(1-C)*(E1-1)/(E1-C)-1
305 IF B(I)<=(-1) THEN 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
314 GOTO 202
330:BETA(##,###) ILLEGAL
332 PRINT USING 330,I1+1,K1
334 GOTO 99999
400 G1=1
402 G2=1
404 FOR I=1 TO N
406 G1=G1*(B(I)+I)/(A(I)+B(I)+I+1)
408 G2=G2*(B(I)+2*I-1)/(A(I)+B(I)+2*I)*(B(I)+2*I)/(A(I)+
B(I)+2*I+1)

```

```

410 NEXT I
412 E1=1-G1
414 E2=1-2*G1+G2
420 GOTO 300
500 G1=1
502 G2=1
504 FOR I=1 TO N
506 G1=G1*(A(I)+1)/(A(I)+B(I)+2)
508 G2=G2*(A(I)+2)/(A(I)+B(I)+3)
510 NEXT I
512 E1=G1
514 E2=G1*G2
520 GOTO 300
600 G1=1
602 G2=1
604 FOR I=1 TO N
606 G1=G1*(A(I)+I)/(A(I)+B(I)+I+1)
608 G2=G2*(A(I)+2*I)/(A(I)+B(I)+2*I)*(A(I)+2*I-1)/(A(I)+
B(I)+2*I+1)

610 NEXT I
612 E1=G1
614 E2=G2
620 GOTO 300
700 G1=1
702 G2=1
704 FOR I=1 TO N
706 G1=G1*(B(I)+1)/(A(I)+B(I)+2)
708 G2=G2*(B(I)+2)/(A(I)+B(I)+3)
710 NEXT I
712 E1=1-G1
714 E2=1-2*G1+G1*G2
720 GOTO 300
80000 REM GATE TYPE 1 OR,INDEP; 2 AND,INDEP; 3 OR,ID;
4 AND,ID

80002 REM GATE BELOW LEVEL I, JTH EVENT
80004 REM ALL GATES EXCEPT INHIBIT MUST BE SEPARATED BY EVENTS
80006 REM DESTINATION IS INDEX J OF I+1TH LEVEL EVENT
80008 REM PCONDITIONAL IS INHIBIT (FAIL) PROB. (DEFAULT=1)
80010 REM WRITE ALPHA,BETA IN DATA STATEMENTS 90000 UP
80012 REM STARTING WITH ALL LEVEL 1 (LOWEST), ETC
80014 REM IF MULTIPLE SETS PROVIDED, PROGRAM WILL ITERATE
80016 REM UNTIL DATA EXHAUSTED
80018 REM FOR TYPE 3&4 GATES, FIRST EVENT A,B ARE USED
99999 END

```

BETAL1 Program Listing

```

1 PRINT "RUN IN DOUBLE PRECISION"
2 DIM A(100),B(100),C(100),D(100),E(100),F(100),X(100)
3 PRINT "PERMIT NEGATIVE BETA?"
4 INPUT S9
6 F2=1
7 PRINT "TYPE OF INPUT?"
8 PRINT "1=PARAMETERS,2=MOMENTS (MEAN & VA)"
10 INPUT S1
12 PRINT "HOW MANY COMPONENTS?"
14 INPUT N
15 PRINT "VALUES? (THIRD VALUE IS COST OF FIRST TEST)"
17 FOR I=1 TO N
18 IF S1=1 THEN GOTO 22
19 INPUT E1,E2,C(I)
20 GOSUB 300
21 GOTO 24
22 INPUT A(I),B(I),C(I)
23 GOSUB 100
24 NEXT I
25 PRINT "DISPLAY COMPONENT VALUES?"
26 INPUT S2
27 IF S2=0 THEN GOTO 48
28 PRINT
30 PRINT "NO. ALPHA    BETA    E(P)    E(P+P)    V(P)    COST"
31 PRINT
32:000 0000.00 00.00 .000000 .000000 .00000000 000000.00
34 FOR I=1 TO N
36 GOSUB 100
38 PRINT USING 32,I,A(I),B(I),E1,E2,V,C(I)
39 IF A(I) <10000 THEN GOTO 41
40 PRINT A(I)
41 NEXT I
42 PRINT
44 PRINT
48 K1=0
50 GOSUB 200
52 PRINT "FIRST COMPONENT TESTED"
58 GOTO 400
100 E1=(A(I)+1)/(A(I)+B(I)+2)
102 E2=E1*(A(I)+2)/(A(I)+B(I)+3)
103 V=E2-(E1*E1)
104 IF I>1 THEN GOTO 107

```

```

105 F1=1
106 F2=1
107 F1=F1+E1
108 F2=F2+E2
120 RETURN
200 PRINT
202 PRINT
204 PRINT "FOR SYSTEM"
206 PRINT
208 C=F2/F1
210 B1=(1-C)*(F1-1)/(F1-C)-1
212 A1=(B1+1)*F1/(1-F1)-1
214 V=F2-(F1*F1)
216 PRINT
218 PRINT "E(R)      E(R*R)      V(R)"
220 PRINT
222: .##### .##### .#####
224 PRINT USING 222,F1,F2,V
226 PRINT
228 PRINT
229 IF B1<0 THEN 360
230 R2=B1+1
231 IF ABS(B1+1-INT(B1+1))<.0000001 THEN 900
232 GOSUB 800
234 R4=-R
236 R2=A1+B1+2
237 IF (A1+1)>100 THEN 350
238 GOSUB 800
240 R4=R4+R
242 R2=A1+1
243 GOSUB 800
244 R4=EXP(R4-R)
245 U3=0
246 U4=0
247 U8=0
248 U5=0
249 U6=0
250 GOSUB 930
252 GOSUB 700
255 PRINT "CLOSURE"
256 PRINT U8*.00000001
257 PRINT "LOWER CONF. BOUNDS"
258:80 .#### 90 .#### 95 .####
260 PRINT USING 258,U3,U4,U5
262 PRINT
264 PRINT
270 RETURN
300 E2=E2+E1+E1
301 C=E2/E1

```

```

302 B(I)=(1-C)*(E1-1)/(E1-C)-1
303 IF S9=1 THEN 305
304 IF B(I)<0 THEN 336
305 IF B(I)<(-1) THEN 330
306 A(I)=(B(I)+1)*E1/(1-E1)-1
308 IF I>1 THEN 314
310 F1=1
312 F2=1
314 F1=F1+E1
316 F2=F2+E2
320 RETURN
330 PRINT "ILLEGAL BETA"
332 GOTO 990
334 B(###) CHANGED FROM #.###
336 PRINT USING 334,I,B(I)
338 B(I)=0
340 A(I)=(2*E1-1)/(1-E1)
342 E2=E1*(A(I)+2)/(A(I)+3)
344 GOTO 308
350 R1=(R2-.5)*LOG(R2)-(A1+.5)*LOG(A1+1)
352 R4=EXP(R4+R1-B1-1)
354 GOTO 245
360 R2=B1+1
362 GOSUB 822
364 R=LOG(R3)-LOG(B1+1)
366 GOTO 234
400 FOR I=1 TO N
402 E1=(A(I)+1)/(A(I)+B(I)+2)
404 G1=(A(I)+1+E1)/(A(I)+B(I)+3)
406 E2=E1*(A(I)+2)/(A(I)+B(I)+3)
408 G2=G1*(A(I)+2+E1)/(A(I)+B(I)+4)
410 G3=F1*G1/E1
412 G4=F2*G2/E2
414 D(I)=F2-F1*2-G4+G3*2
416 X(I)=D(I)/C(I)
420 NEXT I
430 M=0
432 FOR I=1 TO N
434 IF X(I)<M THEN 440
435 IF X(I)=M THEN 440
436 M=X(I)
438 S3=I
440 NEXT I
441 E(S3)=E(S3)+1
442 PRINT "NO.      DELV      COST      TOT COST      NO. TESTS"
443 F(S3)=F(S3)+C(S3)
444:### .##### ####.## #####.## ###
446 PRINT
447 K1=K1+C(S3)

```



```

448 PRINT USING 444,S3,X(S3),C(S3),K1,E(S3)
449 PRINT
450 I=S3
451 GOSUB 100
452 A(S3)=A(S3)+E1
453 B(S3)=B(S3)+1-E1
454 FOR I=1 TO N
455 GOSUB 100
456 NEXT I
457 GOSUB 200
458 GOSUB 600
459 PRINT "CONTINUE?"
460 INPUT K
461 IF K<.99 THEN 500
462 PRINT "CHANGE NEXT COST?"
463 INPUT K
464 IF K<.99 THEN 487
465: NEW C(###)=?
466 PRINT USING 465,S3
468 INPUT C(S3)
487 PRINT
488 PRINT "NEW VALUES FOR LAST COMPONENT TESTED"
489 GOSUB 100
490 PRINT "NO. ALPHA BETA E(P) E(P+P) V(P) COST"
491 PRINT USING 32,I,A(I),B(I),E1,E2,V,C(I)
492 PRINT
495 FOR I=1 TO N
496 GOSUB 100
497 NEXT I
498 PRINT "NEXT COMPONENT TESTED"
499 GOTO 400
500 PRINT "DISPLAY STATUS FOR ALL COMPONENTS?"
502 INPUT K4
504 IF K4<.99 THEN 990
506 PRINT
508 PRINT "NO. ALPHA BETA E(P) TESTS COST"
510 PRINT
512:### ####.## ##.## .##### ### #####.##
513 FOR I=1 TO N
514 GOSUB 100
515 PRINT USING 512,I,A(I),B(I),E1,E(I),F(I)
516 IF A(I)<10000 THEN 519
517 PRINT A(I)
519 NEXT I
520 PRINT
522 PRINT
530 GOTO 990
600 PRINT
602 V8=F2-(F1+F1)

```

```

604 F5=1
606 F6=1
608 FOR I=1 TO N
610 E1=(A(I)+1)/(A(I)+B(I)+2)
612 F3=(A(I)+E1+1)/(A(I)+B(I)+3)
614 F4=F3*(A(I)+E1+2)/(A(I)+B(I)+4)
616 F5=F5*F3
618 F6=F6*F4
620 NEXT I
622 V9=F6-(F5*F5)
624: E(DELVAR)=.#####
626 PRINT USING 624,V8-V9
628 PRINT
630 PRINT
638 I=53
640 RETURN
700 IF S4<.975 THEN 706
702 S5=.95
704 GOTO 727
706 S6=.001*INT(1000*S4)+.025
708 FOR X=.999 TO (S6-.0001) STEP -.001
710 GOSUB 840
712 NEXT X
714 S5=S6-.05
716 R4=R4/10
717 U6=.1*U6
718 FOR X=S6-.0001 TO S5 STEP -.0001
720 GOSUB 840
722 NEXT X
724 R4=10*R4
725 IF S5<0 THEN 736
726 IF S5=0 THEN 736
727 U6=10*U6
728 FOR X=S5-.001 TO 0 STEP -.001
730 GOSUB 840
732 NEXT X
734 GOTO 740
736 PRINT "MODE <=.025"
738 PRINT "INTEGRATION TRUNCATED"
740 RETURN
800 R1=0
804 IF R2<2 THEN 820
805 IF R2=2 THEN 820
806 R1=R1+LOG(R2-1)
808 R2=R2-1
810 GOTO 804
820 R2=R2-1
822 R3=1-.5748646*R2+.9512363*R2^2
824 R3=R3-.6998588*R2^3+.4245549*R2^4

```

```

826 R3=R3-.1010678*R2+5
828 R=R1+LOG(R3)
830 RETURN
840 IF X>0 THEN 843
841 U7=0
842 GOTO 844
843 U7=EXP(A1*LOG(X)+B1*LOG(1-X) +L. (R4)+LOG(50000))
844 U8=U8+U7+U6
845 IF U3>0 THEN 850
846 IF U8<80000000 THEN 864
848 U3=X
850 IF U4>0 THEN 856
852 IF U8<90000000 THEN 864
854 U4=X
856 IF U5>0 THEN 864
858 IF U8<95000000 THEN 864
860 U5=X
864 U6=U7
870 RETURN
880 R4=10*R4
882 RETURN
900 R=1
902 FOR J=1 TO B1+1
904 R=R*(A1+J)
906 NEXT J
908 FOR J=2 TO B1
910 R=R/J
912 NEXT J
914 R4=R
920 GOTO 245
930 S4=A1/(A1+B1)
932 IF S4<.975 THEN 960
933 IF S4<.99 THEN 936
934 IF S4=.99 THEN 936
935 GOTO 962
936 S4=.975
944 R4=R4/10
946 FOR X=.9999 TO .94999 STEP -.0001
948 GOSUB 840
950 NEXT X
952 R4=10*R4
960 RETURN
962 U6=EXP(A1*LOG(.9999)+B1*LOG(.0001)+LOG(R4)+LOG(5000))
963 U9=U6
964 R4=R4/10
965 FOR X=.9998 TO .94999 STEP -.0001
966 GOSUB 840
968 NEXT X
970 U6=10*U6

```

```
972 R4=10*R4
974 FOR X=.949 TO 0 STEP -.001
976 GOSUB 840
977 NEXT X
978: "INT .9999 TO I="###
979 U8=100000000-U8
980 PRINT USING 978,U8*.00000001
981 U6=U9
982 U3=0
983 U4=0
984 U5=0
985 R4=R4/10
986 FOR X=.9998 TO .94999 STEP -.0001
987 GOSUB 840
988 NEXT X
989 GOTO 880
990 END
READY.
```

## APPLICATION OF RESULTS

The results obtained from this study provide a means of assessing overall system reliability and subsystem and component reliability as well. The systems application will be outlined first; the simplified techniques to be used for the reliability analysis at lower levels will follow. The overall applications procedure is outlined in figure 25.

### SYSTEMS APPLICATION

The assessment of systems level reliability using this methodology requires that a reasonable description of the system and the mission be available. The following five step procedure requires that system configuration and component identity be known and that mission profile parameters including number of cycles, cumulative operating time and elapsed mission time be available for every mission time point analyzed.

Fault tree development. At the system level the initial step requires the development of a fault tree for the system being analyzed. This study included the development of seven typical system fault trees that should be applicable (with minor modifications) to a broad range of propulsion systems. This analysis process need only continue down to those levels of the system for which models have been developed.

Model Quantification. The second step involves model identification and the determination of parameter values. Using the developed fault tree determine which expression contained in Volume I will be required. Assign the values to the identified input parameters corresponding to the mission times being analyzed. Note that component operating parameters (such as operating time and cycles) are independent of mission time. This allows the structuring of duty cycles that vary with the mission being assessed. Model identification and the appropriate parameter values for the time points being analyzed are then provided to the COMPl computer program as requested (COMPl is an interactive program).

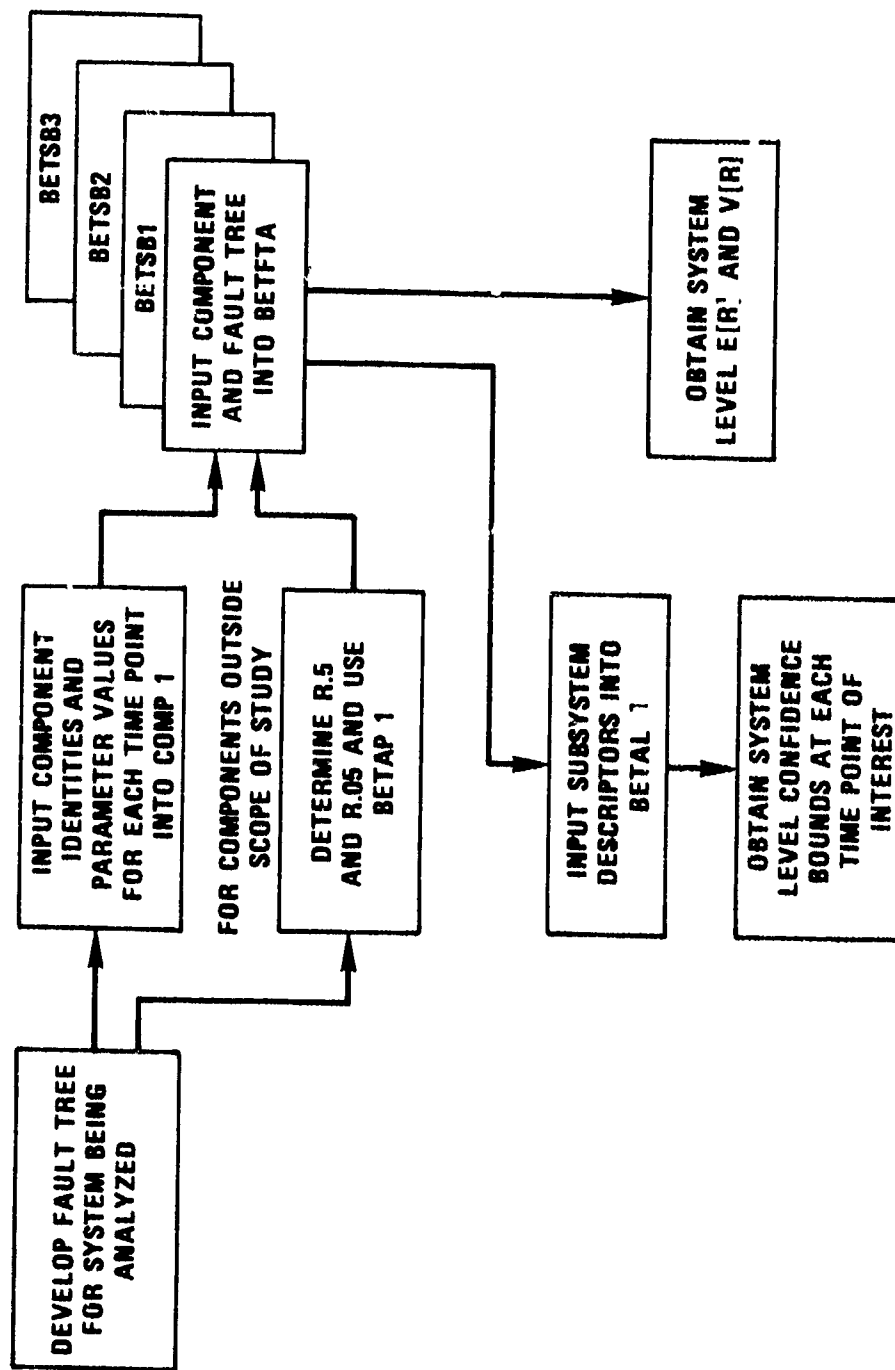


Figure 25. Methodology Application Procedure

If it is desired to consider components beyond the scope of the study in the system, the following procedure is used:

- Determine the median and 5% lower bound values of reliability of the component. While no model will be directly applicable from this study, the compendium of models provided and the approaches outlined should serve as a useful guide.
- Use the BETAP1 approximation technique to obtain  $\alpha$  and  $\beta$  parameters of the Beta distribution used to aggregate to the subsystem and system levels.

System Level Analysis. From COMPl and for BETAP1, the  $\alpha$  and  $\beta$  parameters for the Beta distribution will be available. These parameters and the complete description of the fault tree (as described in the NUMERICAL PROCEDURES section) are provided to BETFTA if M out of N redundancies are not used in the system. For the special cases using M out of N redundancies, BETSB2 or BETSB3 are used as directed in the NUMERICAL PROCEDURES section. From COMPl (or the iterative use of BESB2 or BETSB3) system level assessments of expected reliability  $E \{R_{SYSTEM}\}$  and associated variance  $V \{R_{SYSTEM}\}$  are obtained.

Reliability Estimate Bounds Computation. The results of COMPl (or BETSB1, BETSB3) provide input for the BETAL1 program which computes the system level confidence bounds. It should be noted that BETAL1 can be used as soon as a level is reached in the fault tree where the remaining elements are connected by OR gates ( $\cup$ ) only.

As discussed in the CONCLUSIONS section a closed form systems level solution was not possible. To obtain a description of the system reliability variation with mission time, the last three steps in the above procedure must be repeated for each time point of interest.

Identification of Reliability and Uncertainty Drivers. If the results of the preceding calculations are entered on the system fault tree the reliability and uncertainty hierarchy will be readily observable. Those components most critical to system reliability and system uncertainty will be identified by tracing through the fault tree top to bottom.

In general it should be noted that the above procedures do not discriminate between systems and subsystems. The process is equally applicable to major subsystem. For complex systems it may prove desirable to treat major subsystems as systems to keep the process from becoming unwieldy, leaving the aggregation to the systems level as a final step.

#### COMPONENT AND LIMITED SUBSYSTEM ANALYSIS

To assess subsystems of a simple nature (four components) or isolated components when aggregation to the system level is not desired. The following simplified procedure should be employed.

Determine and Quantify Component Models. Select the appropriate models from the RESULTS section. Identify the values of the required parameters for each time point being analyzed. For subsystem analysis, compute the reliability values at the median ( $R_{.5}$ ) the 5% Lower Bound and the 95% ( $R_{.95}$ ) Upper Bound. (This involves the use of  $\lambda$ 's and  $\alpha$ 's subscripted with .5 for the median case. However, for the 5% lower bound case the  $\lambda$ 's subscripted with .95 must be used along with  $\alpha$ 's subscripted by .05. Input these results into BETSBI to obtain the expected subsystem reliability and variance  $E\{R\}$  and  $V\{R\}$ , respectively. BETAL1 is not required since the bounds were already computed. It must be noted that while fractiles hold in transformation that is:

$$R_{.05} = f(\lambda_{.95}, \alpha_{.05})$$

$$R_{.5} = f(\lambda_{.5}, \alpha_{.5})$$

$$R_{.95} = f(\lambda_{.05}, \alpha_{.95})$$

the expected value does not

$$E\{R\} \neq f[E\{\lambda\}, \alpha \text{ E ONLY}]$$

For analysis of individual components the mean ( $R_{.5}$ ) the lower bound ( $R_{.05}$ ) and the upper bound ( $R_{.95}$ ) are computed using the models obtained from the results section. Then the following calculation will yield the expected value of reliability.



. Determine the standard deviation. From

$$R_{.05} = \exp[ \mu_R - 1.645 \sigma ] \quad (1)$$

and

$$R_{.5} = \exp( \mu_R ) \quad (2)$$

where  $\mu_R$  = mean of the reliability distribution  
 $\sigma$  = standard deviation of the reliability distribution,

obtain

$$\sigma = \frac{\mu_R - \ln(R_{.05})}{1.645} \quad (3)$$

and

$$\ln(R_{.5}) = \mu_R \quad (4)$$

From (3) and (4) obtain  $\sigma$

$$\sigma = \frac{\ln(R_{.5}) - \ln R_{.05}}{1.645}$$

. Determine the expected reliability  $E \{ R \}$

$$E \{ R \} = \exp[ \mu + \frac{\sigma^2}{2} ]$$

## SUMMARY AND CONCLUSIONS

A credible, standardized basis for reliability comparison of thermochemical and electric propulsion concepts has been developed. The method employs detailed assessment of reliability at the component level and aggregates these estimates to provide a system level assessment using fault tree analysis as the system framework. Inherent in this approach is the capability of providing reliability estimates at all intermediate levels. Methodology credibility is assured through the quantification of estimate uncertainty at the component level and the systematic aggregation of this uncertainty to all higher levels.

It was not possible to develop a closed form analytical expression for the variation of system reliability as a function of time with the diverse set of component reliability models that resulted. To determine the time-wise system behavior, the methodology must be exercised at several time points and a curve must be fitted to the results. The principal obstacle to a straight forward system expression was fundamental: the inclusion of non-constant failure rates. It was concluded however that certain failure mechanisms (such as wear, fatigue, erosion) significant to the long duration missions of interest could not be realistically modeled with the constant failure rate approach. The imposition of this artificial restraint would not have to be justifiable merely on the grounds of mathematical tractability.

The results include the capability of identifying those components that are the greatest contributors to system failures. The determination of these "reliability drivers" cannot realistically be accomplished without reference to their position in the system configuration, their expected operating lives and duty cycles, and assessment of the uncertainty surrounding the reliability estimates themselves. With this information the methodology can also provide identification of those components that are the greatest contributors to system estimate uncertainty. Furthermore, a technique to develop test planning strategy to optimally reduce system uncertainty at minimum test costs has been generated and adapted for application to the system included in this study.

Finally, the developed methodology is modular throughout to facilitate revision and updating as additional reliability information becomes available. The component failure mode partitioning can be revised without requiring development of new component models. Changes at the component level can be made with minimum impact on the structure of the system fault trees. The functional approach taken in developing the system fault trees provides the flexibility of fault tree modification without the need to redevelop the entire fault tree structure. An example of this flexibility is provided by the thermochemical systems assessed. This category included three propulsion system concepts. For the purpose of fault tree development each system employed a different pressurization scheme (blowdown on the catalytic monoprop, pressurized surface tension on the electrothermal monoprop and regulated constant pressure on the biprop). In reality, any combination of pressurization scheme and propulsion concept is feasible. In an analagous manner the fault trees for these systems can be readily modified to reflect this interchangeability. Therefore nine system variations can be synthesized from the three baseline configurations used in this study.

## GLOSSARY OF TERMS

E {R} or E {P}	Expected value of reliability
E {R*R} or E {P*P}	Expected value of the square of the reliability (the second moment about the origin).
V {R}	<p>Variance associated with the expected value of reliability and is given by</p> $V \{R\} = E \{R^2\} - E^2 \{R\}$
ALPHA	Label used in computer programs developed in this study to identify the $\alpha$ parameter of the $\beta$ -distribution
BETA	Label used in developed computer programs to identify the $\beta$ parameter of the $\beta$ -distribution
DELV and DELVAR	Used in program BETAL1 to represent "delta variance", the expected change in variance of the uncertainty distribution DELVAR is used at the system level, DELVAR at lower levels of aggregation
E(DELVAR)	Expected value of DELVAR
Independent Components	Components are regarded as being statistically independent if there is no reason to believe their (unknown) failure rates are alike. It is therefore possible for components to be independent even if the corresponding distribution parameters are alike.

Identical Components	Components are regarded as statistically identical if they are drawn from the same production lot because the initial and subsequent uncertainty descriptors remain alike (except for known differences in application stresses). See Appendix B for a discussion of independent/identical distinction.
Mission time =	Elapsed time from start of mission to the time at which reliability is being assessed. The units used are hours
Operating time =	Accumulated hours of actual operation at the time reliability is being assessed. The units used are hours.
Pressurized time =	Elapsed time from final charging and pressurization of component or subsystem to the time at which reliability is being assessed. For all the systems analyzed, pressurized time will be equal to or greater than mission time. The units are hours
Design cycle life =	Nominal number of operating cycle for which component was designed.
Design mission life =	Nominal mission length for which component was designed
Design operating life =	Nominal accumulative operative time for which component was designed.

## R E F E R E N C E S

1. Military Standardization Handbook, Reliability Prediction of Electronic Equipment, MIL-HDBK-217B, 20 September 1974
2. R. L. Madison, P. Gottfried and GR. Herd, Reliability Variation Analysis for Space Systems Development. Final report under contract NASW-63, available as NASA CR-60315, November 1963.
3. GIDEP, Volume 1, Summaries of Failure Rate Data, Fleet Missiles Systems Analysis and Evaluation Group, Naval Weapons Station Seal Beach, Calif. August 1975
4. GIDEP, Volume 1, Summaries of Replacement Rate Data, Fleet Missile Systems Analysis and Evaluation Group, Naval Weapons Station Seal Beach, Calif. August 1975
5. D.J. Palumbo, W.J. Guman and M. Begun, Pulsed Plasma Propulsion Technology, AFRPL-TR-74-50, Interim Report, July 1974
6. Catalog Data, Maxwell Laboratories, San Diego, California
7. G E. Unruh, Final Reliability Estimate for the Pulsed Plasma Thruster. Fairchild Republic Company Report MS 173N0005, July 1974
8. Final Report, Extended Life Test, Paper Mylar Capacitors, Contracts DA36-030-SC-85271, Inland Testing Laboratories, August 1960
9. P. Gottfried and H.R. Roberts, "Some Pitfalls of the Weibull Distribution," Proceedings of the Ninth National Symposium on Reliability and Quality Control, January 1963
10. W.J. Guman and T.E. Williams, "Pulsed Plasma Microthruster for Synchronous Meteorological Satellites (SMS), AIAP Paper No. 73-1066
11. P. Gottfried et al, Reliability Prediction Techniques for Flight Systems, Technical Report AFFDC TR-67-20, April, 1967

12. P. Gottfried et al, Evaluation of Reliability Prediction Techniques for Entire Flight Control Systems, Technical Report AFFDL-TR-67-183, March 1968
13. ATS-F Ion Engine Experiment Electronic Component Status, Rev F Electro Optical Systems, Inc., September 1971
14. Colloid Advanced Development Program, Interim Final Report NO. 1, TRW Systems Group, Redondo Beach California February 1972, AFRPL-TR-72-10
15. Colloid Advanced Development Program, Project Approved Parts List No. 14292.74.4761.001, Rev A, TRW Systems Group Redondo Beach California, April, 1974
16. Failure Modes, Effects and Criticality Analysis, Summary Report, Hughes Research Laboratories, Malibu California July 1976. (Worked performed under contract to Lewis Research Center, contract no. NAS 3-18917
17. E. James, et al, A One Millipound Cesium Ion Thruster System, Electro-Optical Systems, Pasadena California, AIAA paper no. 70-1149, AIAA 8th Electric Propulsion Conference, August, 1970.
18. R. Worlock, et al, A North-South Stationkeeping Ion Thruster System for ATS-F, Electro Optical Systems, Pasadena. California, AIAA paper No. 72-439, AIAA 9th Electric Propulsion Conference, April 1972
19. E. James et al, A North-South Stationkeeping Ion Thruster System for ATS-F, AIAA paper No 73-1133, AIAA 10th Electric Propulsion Conference, October 1973
20. W. E. Ramsey and E. L. James, A Prototype North-South Stationkeeping Thruster, Electro-Optical Systems, AIAA paper No. 74-1119, AIAA/SAE 10th Propulsion Conference October, 1974
21. R. Worlock, et al, The Cesium Bombardment Engine North-South Stationkeeping Experiment in ATS-G, AIAA Paper 75-363, AIAA 11th Electric Propulsion Conference, March 1975
22. Feed Assembly, IMLB MESC THRUSTER, DWG No. 1132272, Rev F Electro Optical Systems, Pasadena California August 1972

23. J.H. Molitor, Ion Propulsion Flight Experience Life Tests and Reliability Estimates, AIAA paper 73-1256, AIAA/SAE Propulsion Conference, 1973
24. M. A. Mantenieks, Investigation of Mercury Thruster Isolators, NASA Lewis Research Center, Cleveland Ohio, AIAA Paper No. 73-1088, AIAA 10th Electric Propulsion Conference, October 1973
25. S. Nakanishi and R.C. Finke, A 9700 Hour Durability Test of a Five Centimeter Diameter Ion Thruster, NASA Lewis Research Center, AIAA Paper No. 73-1111, AIAA 10th Electric Propulsion Conference October, 1973
26. J. Hyman, et al, One-Millipound Mercury Ion Thruster, Hughes Research Laboratories, Malibu, California, AIAA Paper No. 75-386, AIAA 11th Electric Propulsion Conference, March 1975
27. D. Zuccaro, Mercury Vapor Hollow Cathode Component Studies, Hughes Research Laboratories, Malibu California, AIAA Paper No. 73-1141, AIAA 10th Electric Propulsion Conference, October 1973
28. W.R. Hudson and Albert J. Weigand, Hollow Cathodes with BaO Impregnated, Porous Tungsten Inserts and Tips, NASA Lewis Research Center, Cleveland Ohio, AIAA Paper No. 73-1142, AIAA 10th Electric Propulsion Conference, October 1973
29. W.R. Kerlake, Design and Test of Porous-Tungsten Mercury Vaporizers, NASA Lewis Research Center, Cleveland, Ohio, AIAA Paper No. 72-484, AIAA 9th Electric Propulsion Conference April, 1972
30. J.L. Power, Sputter Erosion and Deposition in the Discharge of a Small Mercury Ion Thruster, NASA Lewis Research Center Cleveland, Ohio, AIAA Paper No. 73-1109, AIAA 10th Electric Propulsion Conference, October 1973
31. R.F. Kemp, et al, Life Limiting Processes in Mercury Electron Bombardment Ion Engines as Determined from Erosion Tests, TRW Systems, Redondo Beach, California, AIAA Paper No. 73-1110, AIAA 10th Electric Propulsion Conference, October 1973



32. J.L. Power and Donna J. Hiznay, Solutions for Discharge Chamber Sputtering and Anode Deposit Spalling in Small Mercury Ion Thrusters, Lewis Research Center, Cleveland Ohio, NASA Technical Memorandum, NASA-TMS-71675, March 1975
33. Thruster Subsystem, 1Mlb MESC Thruster, Dwg No. 1132299, Rev D, Electro-Optical Systems Pasadena California, July 1973
34. Electrode Assembly, 1Mlb MESC Thruster, Dwg No. 1132248, Rev F, Electro-Optical Systems, Pasadena, California, December, 1973
35. Feed Tube Weld Assy-Anode, 1Mlb MESC Thruster, Dwg No. 1133719, Rev J, Electro-Optical Systems, Pasadena, California, April, 1975
36. Boundary Anode and Magnet Assembly, 1Mlb MESC Thruster, Dwg No. 1132234 Rev F, Electro-Optical Systems, Pasadena, California, October, 1972
37. Discharge Chamber Assembly, 1Mlb MESC Thruster, Dwg No. 1132249, Rev E, Electro-Optical Systems, Pasadena, California, July 1973
38. Concept Definition and System Analysis Study for a Solar Electric Propulsion Stage, Final Report, Vols. I, II, III, IV, V, VI, The Boeing Co., Seattle Wash. Contract No. NAS 8-30921, January 1975
39. Concept Definition and Systems Analysis Study for a Solar Electric Propulsion Stage; Vol. I, II, III, IV, V, VI, Final Report, Rockwell International Downey, California Contract No. NAS 8-30920, February 1975
40. N. Milly and V. Gillespie, Retention and Application of Skylab Experiment Experiences to Future Programs, NASA Technical Memorandum TM X-64839, May 1974
41. N. Milly and D. Brown, Retention and Application of Saturn Experiences to Future Programs, NASA Technical Memorandum TM X-64574, September 1971
42. Long-Life Assurance Study for Manned Spacecraft Long-Life Hardware, Final Report, Vols I, II, III, IV, V, VI, Martin Marietta, Denver, Colorado, Contract No. NAS9-12359, December 1972

54. Preliminary Studies and Recommendations on a Midcourse Propulsion System for TOPS, Inter-office Memo, Jet Propulsion Laboratory, September 1969
55. Throttleable Monopropellant Hydrazine Propulsion System, Bipropellant Liquid Propulsion System Reliability Analysis, (Rough Draft) JPL Contract No. 952545, September 1969
56. Reliability Analysis Report, Walter Kidde & Co., Belleville, New Jersey Report No. 4999RAR-5, March 1975 Contract No. F04701-73-C-0038
57. Y. Brill, Investigation of Assigned Failure Rates, Hydrazine RCS Components, Letter Progress Report, Subsystem Committee of Monopropellant Working Group, May 1975
58. P. Martin, Cost and Reliability Estimates for Chemical Propulsion Systems, Final Report, Stanford Research Institute, Menlo Park, California, January 1969
59. C. Murch and C.R. Hunter, Electrothermal Hydrazine Thruster Development, TRW Systems Group, Redondo Beach California, AIAA Paper No. 72-451, AIAA 9th Electric Propulsion Conference, April, 1972
60. R.A. Callens and C. Murch, Electrothermal Hydrazine Thruster Analyses and Performance Evaluation, AIAA Paper No. 72-1152, AIAA/SAE 8th Propulsion Specialist Conference, November, 1972
61. Monopropellant Hydrazine Resistojet, Analysis Task Summary Report, TRW Systems Group, Redondo Beach California, November 1971
62. J.D. Kuenzly, Study of Monopropellants for Electrothermal Thrusters, TRW Systems Group, Redondo Beach, California, June 1974
63. Model R-4D, 100lb Thrust Liquid Bipropellant Rocket Engine, The Marquardt Co., Van Nuys, California
64. Technical Description, Marquardt Model R-1E, 22 lb Thrust Rocket Engine, The Marquardt Co., Van Nuys, California, October 1972

43. M.J. Russi, A Survey of Monopropellant Hydrazine Thruster Technology, Aerospace Corp., El Segundo, California, AIAA Paper No. 73-1263, AIAA/SAE 9th Propulsion Conference, November 1973
44. C.D. Coulbert and G. Yankura, Survey of Materials for Hydrazine Propulsion Systems in Multicycle Extended Life Applications, Jet Propulsion Laboratory, Pasadena, California, NASA Technical Memorandum 33-561, September 1972
45. V.A. Moseley, et al, Long Life Monopropellant Design Criteria, Interim Report, Bell Aerospace Co., Buffalo, New York, July 1975
46. Hydrazine Propulsion System Reliability Description, Rocket Research Corporation, Redmond Washington, July 1975
47. B.W. Schmitz and W.W. Wilson, Long-Life Monopropellant Hydrazine Engine Development Program, Rocket Research Corp., Redmond Washington Final Report AFRPL-TR-71-103, September, 1971
48. Reaction Engine Module-Monopropellant (Block III) Failure Mode, Effect and Criticality Analysis, Rocket Research Corp., Redmond Washington, June 1973
49. P.J. Marteney and A.S. Kesten, "Catalyst Particle Welting and Breakup in Hydrazine Systems", Journal of Spacecraft and Rockets, Vol. 13, No. 7 pp. 430-442
50. Lt. J. A. Quirk, Performance Mapping of Hydrazine Attitude Control Thrusters, Interim Report, Air Force Rocket Propulsion Laboratory, Edwards A.F.B.
51. Minuteman III Propulsion System Rocket Engine Reliability and Failure Status Report, Bell Aerospace Co., Buffalo, New York, Contract No. F04701-73-C-0214, August 1975
52. V.A. Moseley and H.D. Fricke, Operational Effects on the Life of Monopropellant Hydrazine Devices, Bell Aerospace, Buffalo, New York October 1975
53. Failure Rate Estimates, Internal Correspondence, Hamilton Standard, Hartford Connecticut, May 1972

65. L. Schoeman and R.C. Schindler, Fire Pound Bipropellant Engine, Aerojet Liquid Rocket Co., Sacramento, California, AFRPL-TR-74-51, September 1974
66. TRW Hardware Flight Experience Data Mechanical/Electro-Mechanical Components, TRW Systems Group, Redondo Beach California, Document No. 70-2246.0-76, December 1970
67. Failure Rate Data for Low Thrust Liquid Propulsion Systems Components, Internal Letter Report, Aerojet Liquid Rocket Co., Sacramento, California, November 1970
68. GLM Christopher and C.T. Brown, Hydrazine Impurity Survey, Phase I Special Report, United Aircraft Research Laboratories, Hartford Connecticut, June 1973
69. W. Yurkowsky, Data Collection for Nonelectronic Reliability Handbook (NEDCO I & NEDCO II) Vol. I, II, III, IV, V Hughes Aircraft Co., RADC-TR-68-114, June 1968
70. D. Cuttrell, et al, Revision of RADC-TR-69-458, Section 2 Martin Marietta Aerospace, Orlando Florida, RADC-TR-74-268 October 1974
71. C. Ryerson, et al, RADC Reliability Notebook Vol. II, Hughes Aircraft Co., RADC-TR-67-108
72. Non Electronic Reliability Handbook, Hughes Aircraft Co., RADC-TR-75 -22, January 1975

APPENDIX A

EXAMPLES

Electronic Components Reliability  
Estimation Procedures

Example 1: Diode, General Purpose, Silicon	A-1
Example 2: Capacitor, Tantalum Solid	A-5
Example 3: Transformer, Power	A-7

Methodology Application Examples

Example I Mercury Ion System	A-15
Example II Catalytic Monopropellant System	A-41
Example III M-out-of-N Redundance	A-94

ELECTRONIC COMPONENTS RELIABILITY  
ESTIMATION PROCEDURES EXAMPLES

EXAMPLE 1

Diode, General Purpose, Silicon

Device Characteristics:

$T_{MAX}$	maximum junction temperature	175°C
$T_S$	temperature derating point	25°C
$I_{MAX}$	maximum rated average forward current	500 ma
	Rated voltage	200 v

Application Characteristics:

Heat sink temperature	25°C
Operating average forward current	200 ma
Applied voltage	140 v

Calculation of Expected Failure Rate

Part Failure Rate Model:

$$\lambda_p = \lambda_b (\pi_E \pi_Q \pi_A \pi_{S2} \pi_C) \text{ failures}/10^6 \text{ hr}$$

$\lambda_b$  is found by table look-up (Table 2.2.4-6), \* requiring temperature

( $T=T_C$ ) and electrical stress ratio (S)

---

\* All references to tables and figures in Examples 1, 2, and 3 can be found in MIL-HDBK-217B.

S is given by

$$S = \frac{I_{OP}}{I_{MAX}} \text{ (C.F.)}$$

and C.F. = 1 for  $T_{MAX} = 175^{\circ}\text{C}$   $T_S = 25^{\circ}\text{C}$

So that

$$S = \frac{200}{500} = .4$$

The table yields

$$b = 0.0023$$

The  $\pi$ -factors are obtained from Tables 2.2.4-1 through 2.2.4-5:

<u>Factor</u>		<u>Value</u>
$\pi_E$	Space, flight	1
$\pi_Q$	JANTXV quality	0.5
$\pi_A$	Small signal	1.0
$\pi_{S2}$	Voltage stress $\frac{140}{200} \times 100 = 70\%$	0.75
$\pi_C$	Metallurgically bonded	1

thus

$$\lambda_p = 0.0023 \cdot 1 \cdot 0.5 \cdot 1 \cdot 0.75 \cdot 1 = 0.0008625 \text{ failures}/10^6 \text{ hr}$$

### Uncertainty Expression

As noted earlier, the lognormal distribution model with square of coefficient of variation

$$\eta^2 = 2.74$$

will be used to estimate and describe uncertainties surrounding estimates of constant failure rates for electronic devices.

For the diode, we have

$$E\{\lambda\} = 0.0008625 \text{ failures}/10^6 \text{ hr}$$

since

$$\eta^2 = e^{\sigma^2} - 1 = 2.74$$

We have

$$\sigma^2 = \ln 3.74 = 1.3191$$

$$\sigma = 1.149$$

but

$$E\{\lambda\} = e^{\mu + \frac{1}{2}\sigma^2}$$

$$\mu = \ln E\{\lambda\} - \frac{1}{2}\sigma^2 = -7.715$$



The uncertainty distribution for the diode thus is lognormal with  $\mu = -7.715$ ,  $\sigma = 1.149$ . This in turn yields

$$\text{Lower bound, } F_{.05} = e^{\mu - 1.645\sigma} = 0.00007 \text{ failures}/10^6 \text{ hr}$$

$$\text{Median, } M = e^{\mu} = 0.00045$$

$$\text{Upper bound, } F_{.95} = e^{\mu + 1.645\sigma} = 0.00295.$$

Alternatively, but less comprehensively, the diode failure rate could be said to be  $0.0086 \begin{matrix} +243\% \\ -92\% \end{matrix} \times 10^{-6}$ .

For nonelectronic devices, the uncertainty estimates (coefficient of variation) are adjusted to reflect information gained (e. g., by detailed stress analysis) and additional uncertainties introduced (e. g., by extrapolation to different device types or use of large and arguable environmental correction factors) during analysis. This is unnecessary for electronic devices because gains and losses in MIL-HDBK-217B analyses are considered to be balanced.

## EXAMPLE 2

### Capacitor, Tantalum, Solid

#### Device Characteristics

MIL-C-39003, level P

20v, 10 F

#### Application Characteristics:

T	Ambient Temperature	25°C
S	Applied voltage	10v
SR	Circuit series resistance	5 ohms

### Calculation of Expected Failure Rate

#### Part Failure Rate Model:

$$\lambda_p = \lambda_b (\pi_E \cdot \pi_{SR} \cdot \pi_Q) \text{ failures}/10^6 \text{ hr}$$

$\lambda_b$ ,  $\pi_E$ , and  $\pi_Q$  are found from Tables 2.6.5-4, 2.6.5-1, and 2.6.5-3, respectively:

$$\lambda_b = 0.010$$

$$\pi_E = 1$$

$$\pi_Q = 0.3$$

The relative circuit resistance is 5/10 ohms/volt. Interpolating in Table 2.6.5-2 yields  $\pi_{SR} = 0.5$ . Thus

$$\begin{aligned}\lambda_p &= 0.010 \cdot 1 \cdot 0.5 \cdot 0.3 \text{ failures}/10^6 \text{ hr.} \\ &= 0.0015 \text{ failures}/10^6 \text{ hr.}\end{aligned}$$

### Uncertainty Expression

Proceeding as in Example 1, we obtain:

$$E\{\lambda\} = e^{\mu + 1/2\sigma^2} = 0.0015$$

since  $\sigma$  is fixed for constant  $\eta^2$ ,

$$\mu = \ln E\{\lambda\} - .6595 = -7.162$$

and the uncertainty distribution for the capacitor is lognormal with  $\mu = -7.162$ ,  $\sigma = 1.149$ . This in turn yields

$$F_{.05} = 0.00012 \text{ failures}/10^6 \text{ hr.}$$

$$M = 0.00078$$

$$F_{.95} = 0.00513$$

In tolerance form, the capacitor failure rate could be said to be  $0.0015 \begin{matrix} +242\% \\ -92\% \end{matrix} \times 10^{-6}$ ; for fixed  $\eta^2$ , percentage tolerances referenced to the expected value also are fixed in the lognormal distribution.

EXAMPLE 3

Transformer, Power

Device Characteristics:

MIL-T-27 Grade 4, Class R, Family 1

Hermetically Sealed

28/240v, 20va

Weight 1.5 lbs.

Application Characteristics:

$T_A$	ambient (radiation sink) temperature	25°C
	weighted average load	16va

## CALCULATION OF EXPECTED FAILURE RATE

Part Failure Rate Model:

$$\lambda_p = \lambda_b (\pi_E \cdot \pi_f) \text{ failures}/1.0^6 \text{ hr}$$

$\lambda_b$  is found from

$$\lambda_b = Ae^x$$

where

$$x = \left( \frac{T_{HS} + 273}{N_T} \right)^G$$

$T_{HS}$  = Hot spot temperature ( $^{\circ}\text{C}.$ )

From Table 2.7-1:

$$A = 7.2 \cdot 10^{-4}$$

$$N_T = 352$$

$$G = 14$$

With the available data, it is necessary to enter Figure 2.7-4 for weight 1.5 lbs, input 20 watts (16 VA output, unity power factor, 80 percent efficiency). This yields an average temperature rise

$$\Delta T = 32^{\circ} \text{ C.}$$

From paragraph 2.7.1.2

$$T_{HS} \approx T_A + 1.1 (\Delta T) = 60^\circ \text{C}$$

then

$$x = \frac{60 + 273}{352}^{14} = 0.46$$

$$\lambda_b = 7.2 \cdot 10^{-4} \cdot 0.46 = 3.3 \times 10^{-4}$$

From Tables 2.7-3 and 2.7-4, we obtain

$$\pi_f = 8$$

$$\pi_E = 1$$

so that

$$\begin{aligned} \lambda_p &= 3.3 \times 10^{-4} \cdot 8 \cdot 1 \text{ failures}/10^6 \text{ hours} \\ &= .0026 \qquad \qquad \qquad \text{failures}/10^6 \text{ hours} \end{aligned}$$

### Uncertainty Expression

Proceeding as before, we would obtain:

$$\mu = -6.612$$

$$F_{.05} = 0.0002 \text{ failures}/10^6 \text{ hr.}$$

$$M = 0.0013$$

$$F_{.95} = 0.0089$$

However, transformers are among the least standardized electronic devices and are sensitive to the relatively frequent assembly and processing variations and errors reflected in Table 2.7-3. In addition, the failure rate is rather sensitive to the hot spot temperature,  $T_{HS}$ , which was crudely approximated. In view of this, an exception to the stated procedure for electronic part uncertainties is in order.

Table 2.7-3 indicates a 5:1 ratio between upper and lower values of  $\pi_f$  taking these values to define a 95 percent interval (lognormal) and setting 4 standard deviations equal to the natural logarithm of 5 yields

$$\sigma_E = 0.4$$

A similar contribution by  $T_{HS}$  uncertainties leads to a new overall estimate for the aggregate standard deviation of the uncertainty distribution:

$$\begin{aligned}\sigma^1 &= \sqrt{\sigma^2 + \sigma_E^2 + \sigma_{HS}^2} \\ &= \sqrt{1.3191 + 0.16 + 0.16} = 1.28\end{aligned}$$

The nature of these changes is such that  $\lambda_p$  remains the best estimate of  $E(\lambda)$ . The modified uncertainty distribution descriptors thus become

$$\mu^1 = -6.771$$

$$F_{.05} = 0.0001 \text{ failures}/10^6 \text{ hours}$$

$$M = 0.0011$$

$$F_{.95} = 0.0094$$

#### Wear-Out Effects

The preceding estimates considered only constant-failure-rate effects. Transformers are subject to thermal aging of insulation and hence to a well-defined "wear-out" pattern. To determine whether it is necessary to take into account, it is desirable to start with conservative estimates of the wear-out distribution.

At maximum rated hot-spot temperature, transformer wear-out life can be described by a normal distribution with  $\mu_{105} = 10,000$  hours,  $\sigma_{105} \leq 2,000$  hours.



For class R insulation, the maximum temperature is 105° C. Previously,  $T_{HS}$  was estimated to be 60° C. Since we are scaling down from 105° C, it is conservative to use 10° C rather than 7° C in the "rule of thumb" (or Arrhenius equation) for a factor of 2 in life expectancy. Thus, the 60° C life expectancy is

$$\mu_{60} = 2^{\frac{105-60}{10}} \cdot \mu_{105} \approx 225,000 \text{ hours}$$

The coefficient of variation ( $\frac{\sigma}{\mu}$ ) is unaffected by scaling, so that

$$\sigma_{60} \approx 45,000 \text{ hours}$$

The longest mission under consideration is 10 years = 87,600 hours =  $\mu_{60} - 4 \sigma_{60}$ . Pessimistically, the probability of failure due to wear-out is  $\sim 0.000032$ .\*

---

\*From tables of integrals of the normal distribution; for such large multiples of  $\sigma$ , it is desirable to use a detailed table such as the National Bureau of Standards' AMS23. It should be emphasized, however, that results from the extreme tails of a distribution are always subject to question. It is rare that physical reality can be represented credibly by theoretical models at the extremes.

For comparison, the 87,600-hour failure probabilities (exponential) due to  $F_{.05}$ ,  $\lambda_p$ , and  $F_{.95}$ , respectively, are

$$Q_{.05} \approx 0.000009$$

$$\hat{Q} \approx 0.00023$$

$$Q_{.95} \approx 0.0008$$

(In all cases, a 100 percent duty cycle has been assumed.)

In this example, the wear-out contribution is dominant compared to the constant-failure-rate contribution at  $F_{.05}$ , small compared to the best estimate of the latter, and negligible compared to the  $F_{.95}$  contribution.

The wear-out contribution becomes smaller (both absolutely and relatively) under any of the following:

- . A less conservative estimate of wear-out
- . A reduced duty cycle
- . A shorter mission
- . Any earlier time in a 10-year mission

In view of these considerations, and in light of the fact that system-level use of device failure rates concentrates on the expected

and  $F_{.95}$  values, wear-out effects should be disregarded here. However, wear-out life may be the limiting factor for other components and should not be disregarded without analytical justification. As noted earlier, physical demonstration of adequate life expectancy sometimes will be necessary. Reliability prediction using MIL-HDBK-217B data is not an adequate tool when there is reason to expect clustered failures within desired mission durations.

## METHODOLOGY APPLICATIONS

### EXAMPLE I MERCURY ION SYSTEM

1. Mission: Duration = 5 yrs = 43,800 hrs  
Cumulative Operating Time =  $22.876 \times 10^6$  sec =  
6354 hrs  
Number of Cycles = 1826
2. Evaluation Point  $t_m$  = 5 yrs (End of Mission) = 43800 hrs  
 $t_{op}$  = 6354 hrs  
 $N$  = 1826
3. Component/Failure Mode Identity - Obtain From Fault Tree  
Component/Failure Mode Code Identity - Obtain From  
Table 9, Vol II

Component/Failure Mode	Code
Bladder Leak/Rupture	BB
Propellant Line Leak/Rupture	FL
Propellant Fill Valve Leak/ Rupture	FV1
Propellant Tank Half, Leak/ Rupture	PR
Pressurant Fill Valve Leak/ Rupture	FV1
Pressurant Tank Leak/Rupture	PT
Tank Heater Failure	HLTV
Line Heater Failure	HLTV
FCC Switch Fails Active	SA
PCC Switch Fails Passive	SP
PCC Failure Mercury Ion	MPC
Liquid Mercury to Cathode -Use Vaporizer Leakage	VL
Vaporizer Heater Failure	VH
Vaporizer Clogged	VC
Feed Line Leak/Rupture	FL
Loss of Electrical Isolation	II
Discharge Chamber Malfunction	DC
Cathode Assembly out of Tolerance Use Cathode, Hollow	HC
Neutralizer Cathode out of Tolerance	NC
Neutralizer Vaporizer	NV
Neutralizer Isolator	NI

Gimbal Thrust Vectoring

Lower Support	LS
Upper Support	US
Linear Actuator	LA
Motor and Gearing	MG

4. Enter Program COMPl with the preceding codes and appropriate cycles, mission times and operating times. For this case as stated in 2. above

N = 1826 cycles  
top = 6354 hrs  
tm = 43800 hrs

COMPl output is shown on the following pages. Note each computation result is followed by request for second data entry for the component. This feature is exercised when multiple time points in system life are being analyzed.

76/12/14. 10.36.07.  
PROGRAM COMP1

OUTPUT FORMAT IS  
R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)  
? BB  
PRESS. TIME=? (O=END)  
? 43800  
.978552 .998945 67.9354 -.7013  
PRESS. TIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? FL  
OPTIME=? (O=END)  
? 6354  
.998730 .999520 \*4110.8949 2.2724  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? FV1  
PRESS. TIME=? (O=END)  
? 43800  
.985952 .999601 93.8530 -.7616  
PRESS. TIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? PR  
PRESS. TIME=? (O=END)  
? 43800  
.981127 .998118 92.5260 -.5621  
PRESS. TIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? PT  
SAME AS PR  
PRESS. TIME=? (O=END)  
? 43800  
.981127 .998118 92.5260 -.5621  
PRESS. TIME=?  
? 0

COMPONENT CODE?(ZZ=END)

? HLTV

MISSION TIME=? (O=END)

? 43800

.992625 .999085 259.9071 -.4869

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? SA

NO. CYCLES =? (O=END)

? 200

.999996 1.00000 \*407623.0801 -.5416

NO. CYCLES=?

? 0

COMPONENT CODE?(ZZ=END)

? SP

SAME AS SA

NO. CYCLES =? (O=END)

? 200

.999996 1.00000 \*407623.0801 -.5416

NO. CYCLES=?

? 0

COMPONENT CODE?(ZZ=END)

? MPC

MISSION TIME=? (O=END)

? 43800

.940275 .989938 35.4690 -.3431

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? VL

INPUT OPTION

1= FIXED CYCLES/OP.HR., 2=SEPARATE

? 2

CYCLES =? (O=END)

? 1826

OPTIME=? (O=END)

? 4354

.919492 .991620 20.5070 -.5580

CYCLES =? (O=END)

? 0

COMPONENT CODE?(ZZ=END)  
? VH  
OPTIME=? (O=END)  
? 6354  
    .982803      .997462      119.9300      -.4098  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? VC  
OPTIME=? (O=END)  
? 6354  
    .979966      .998356      82.2047      -.6117  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? FL  
OPTIME=? (O=END)  
? 6354  
    .998730      .999520      \*4110.8949      2.2724  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? II  
OPTIME=? (O=END)  
? 6354  
    .888034      .990866      13.1973      -.6229  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? DC  
OPTIME=? (O=END)  
? 6354  
    .943165      .996188      26.3681      -.6557  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? HC  
OPTIME=? (O=END)  
? 6354  
    .650401      .894764      7.6656      1.1666  
OPTIME=?  
? 0



COMPONENT CODE?(ZZ=END)  
 ? NC  
 OPTIME=? (O=END)  
 ? 6354  
 .650401 .894764 7.6686 1.1666  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? NV  
 CLOG & LEAK COMBINED  
 ( TO SEPARATE, USE VC AND VL )  
 INPUT OPTION  
 1= FIXED CYCLES/OP.HR., 2=SEPARATE  
 ? 2  
 CYCLES =? (O=END)  
 ? 1826  
 OPTIME=? (O=END)  
 ? 6354  
 .901128 .975434 29.8529 1.0432  
 CYCLES =? (O=END)  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? NI  
 OPTIME=? (O=END)  
 ? 6354  
 .888034 .990866 13.1973 -.6229  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? LZ  
 OPTIME=? (O=END)  
 ? 6354  
 .950257 .996638 30.4268 -.6538  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? US  
 OPTIME=? (O=END)  
 ? 6354  
 .966885 .998153 44.5823 -.6841  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)

? LA

OPTIME=? (O=END)

? 6354

.889097

.988251

14.4370

-.5572

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? MG

OPTIME=? (O=END)

? 6354

.889097

.988251

14.4370

-.5572

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.601 UNTS.

RUN COMPLETE.

BYE

3229333 LOG OFF 10.55.01.

SBU 12.201

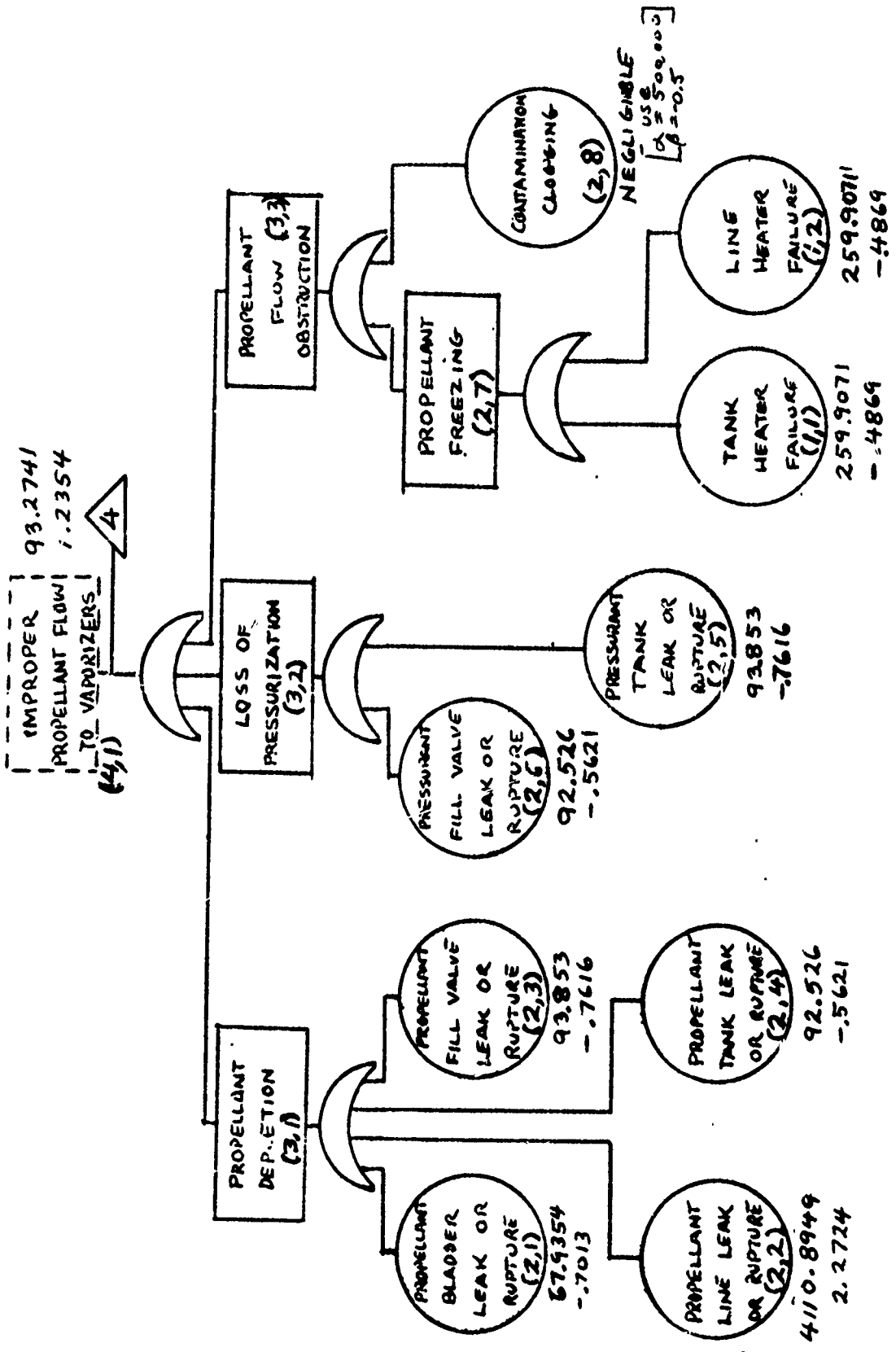
TIO = 3485

P

5. Enter BETFTA with COMPl results and fault tree logic. In this example the fault tree will be traced from the component/failure mode level up to the overall systems level. While BETFTA has the capacity to compute the entire fault tree in one sequence of operations, for the sake of clarity each major portion of the fault tree was analyzed as an independent entity.

The first portion shown "Improper Propellant Flow to Vaporizers" will be used to identify the numerical entries identifying fault tree events and magnitudes of the  $\alpha$  and  $\beta$  parameters of the beta distribution. These values ( $\alpha, \beta$ ) were taken directly from the output of COMPl. They appear with their associated event;  $\alpha$  is given first with  $\beta$  following immediately below. The numbers contained in parenthesis are the event code for use in BETFTA. As described in the BETFTA outline, the first number identifies the fault tree level (counted from the bottom up) to which the event belongs. The second entry identifies the location (counting left to right) of the event in the level. Therefore, the set (2,3) uniquely identifies "Propellant Fill Valve Leak or Rupture" as the third event on the second level in the fault tree "improper propellant flow to vaporizers". Note that "Contamination Clogging" was not given an identifying code. It was assessed as being negligible and can be disregarded in the remainder of the analysis (the degenerate one-on-one tree that results from the elimination of this event can be accepted by the BETFTA program.

The level 1 and 2 events obtain their values from COMPl output; the level 4 event obtains its value from BETFTA. Although not shown on the fault tree, BETFTA also computes the  $\alpha$  and  $\beta$  values of intermediate level events, in this case level 3 events. These appear immediately after the "Gate Type" response, preceded by the appropriate event code, in the BETFTA output following the fault tree. The remainder of the Mercury Ion System Computation follows in the same format.



PROGRAM BETFTA

90000 DATA 259.9071, -.4869, 259.9071, -.4869  
90004 DATA 67.9354, -.7013, 4110.8949, 2.2724, 93.853, -.7616, 92.526, -.5621  
90006 DATA 92.853, -.7615, 92.526, -.5621  
90008 DATA 500000, -.5  
99999 END  
READY.

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 4

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 2

? 8

? 3

DESTINATION?

1 1 7 7

1 2 7 7

2 1 7 1

2 2 7 1

2 3 7 1

2 4 7 1

2 5 7 2

2 6 7 2

2 7 7 3

3 1 7 1

3 2 7 1

3 3 7 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

2 7 7 3

3 1 7 1

3 2 7 1

3 3 7 1

4 1 7 1

2	7	129.575	-.486901
3	1	87.0179	8.93594E-2
3	2	92.4872	-.323599
3	3	129.608	-.486639
4	1	93.2741	1.23518
I	J	$\alpha$	$\beta$

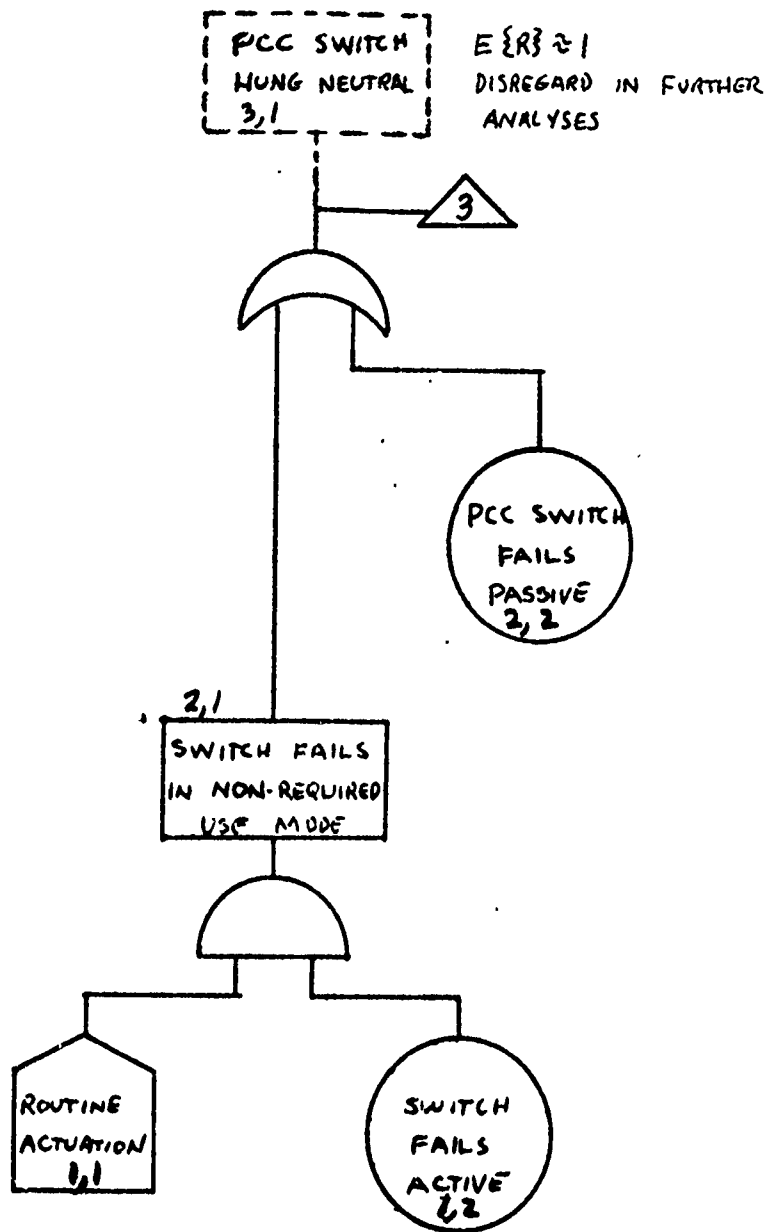
INTERMEDIATE (LEVEL 3) RESULTS  
IDENTIFIED BY (I,J) CODE

SYSTEM (ITERATION 1)

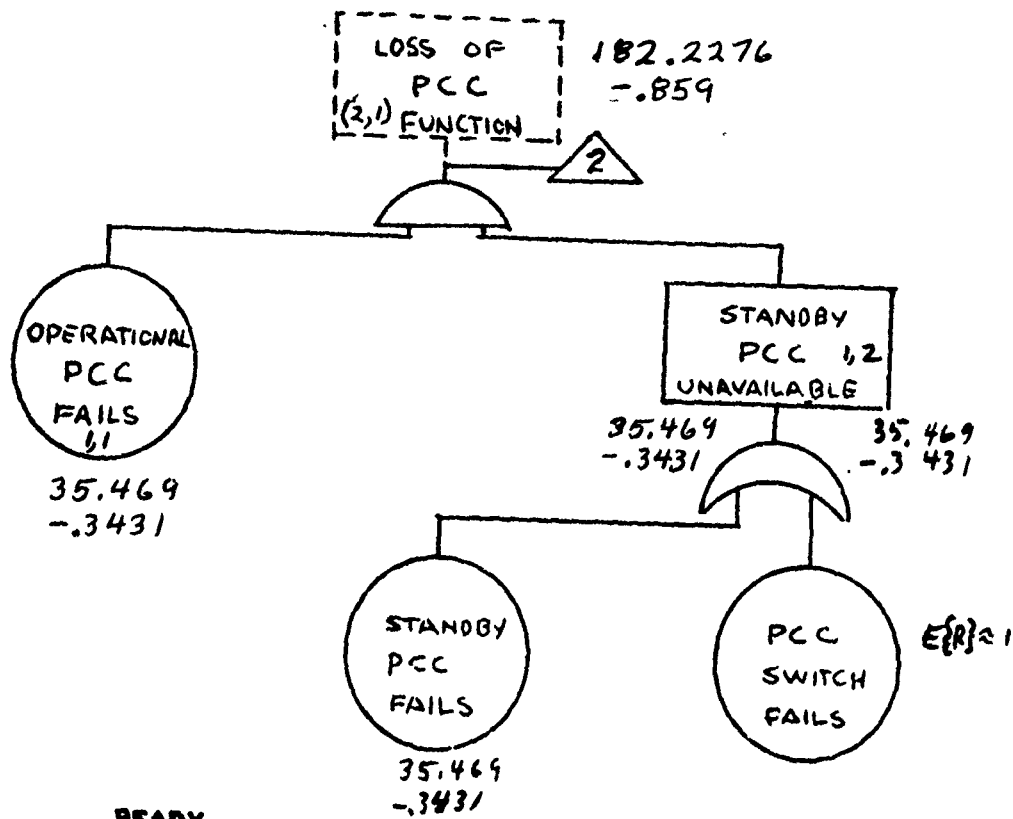
ALPHA BETA E(P) E(P\*P) V(P)

93.2741 1.2352 .976840 .954448 .00023202

RUN COMPLETE.



NOTE THE RESULTS FROM THE COMP 1 MODELS (SA AND SP) FOR THE PCC SWITCH INDICATE A RELIABILITY APPROACHING 1.0. IT WILL NOT BE CONSIDERED FURTHER DUE TO ITS NEGLIGIBLE IMPACT RELATIVE TO THE REMAINING COMPONENTS IN THE SYSTEM



READY.

90000 DATA 35.469, -.3431, 35.469, -.3431  
RUN

76/12/14. 15.14.59.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 2

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

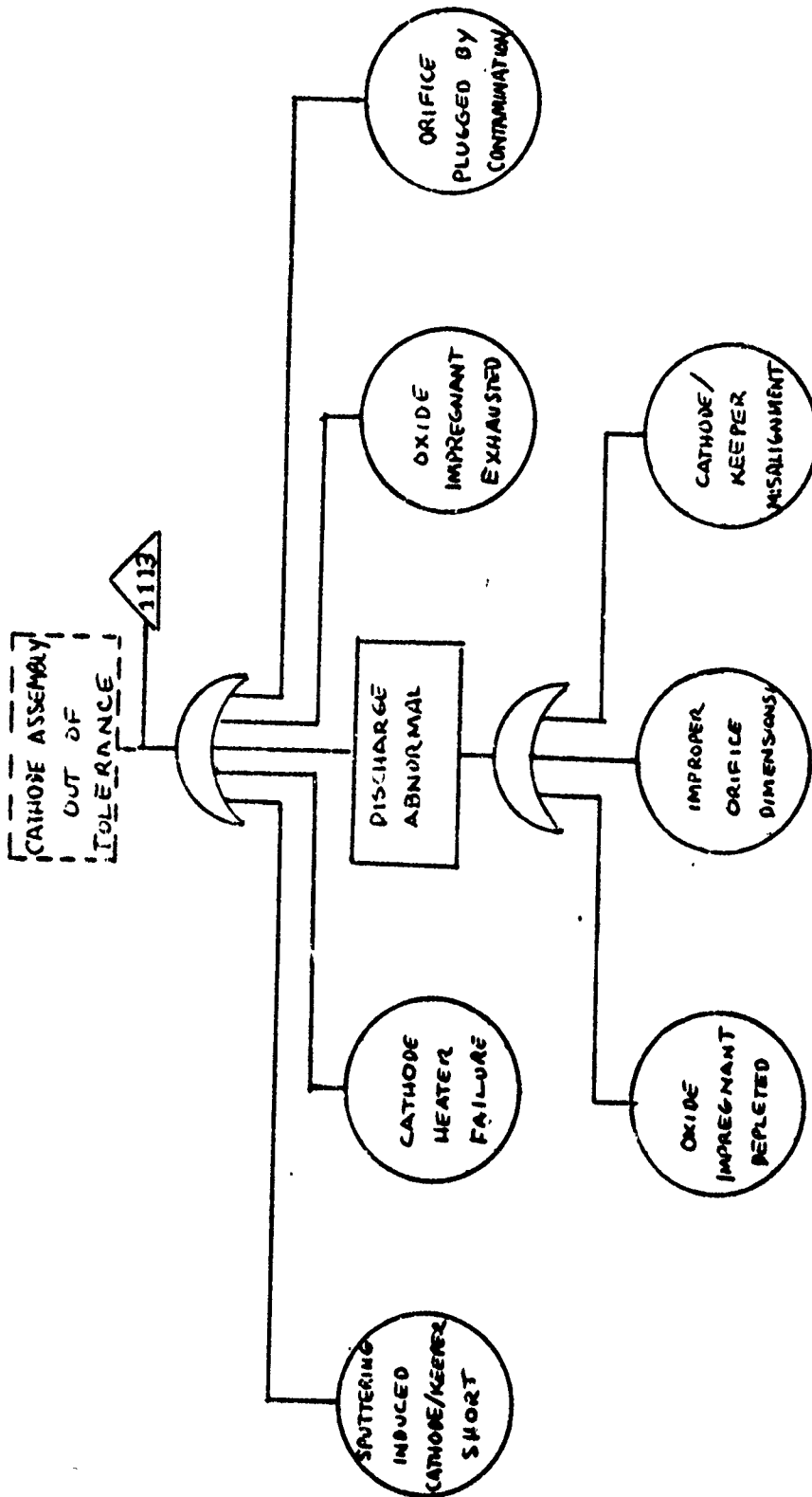
2 1 ? 4

2 1 182.228 -.858999

SYSTEM (ITERATION 1)

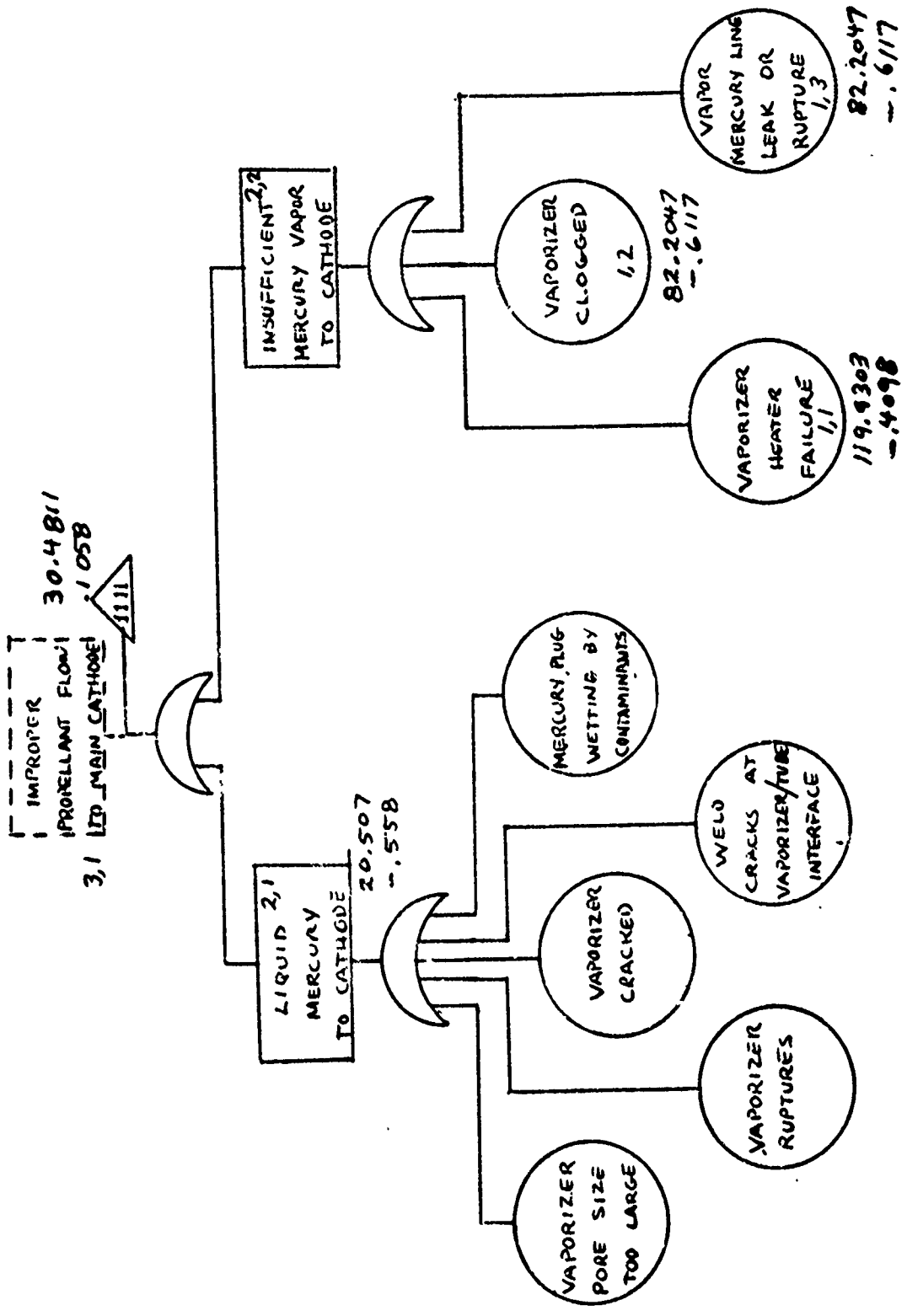
ALPHA BETA E(P) E(P\*P) V(P)

\*182.2276 -.8590 .999231 .998467 .00000417



NOTE THERE WERE NO MODELS DEVELOPED AT THESE LEVELS DUE TO DATA LIMITATIONS, THIS BREAKDOWN OF THE CATHODE IS PROVIDED FOR POSSIBLE FUTURE USE AS ADDITIONAL DATA BECOMES AVAILABLE





PROGRAM BETFTA

90000 DATA 119.9303, -.4098, 82.2047, -.6117, 82.2047, -.611

90002 DATA 20.507, -.558

99999 END

READY.

PROGRAM BETFTA

FOR EXPLANATION LIST 80000

HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 3

? 2

DESTINATION?

1 1 7 2

1 2 7 2

1 3 7 2

2 1 7 1

2 2 7 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

2 2 7 1

3 1 7 1

2 2 91.7731 .324943

3 1 30.4811 .105821

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P+P) V(P)

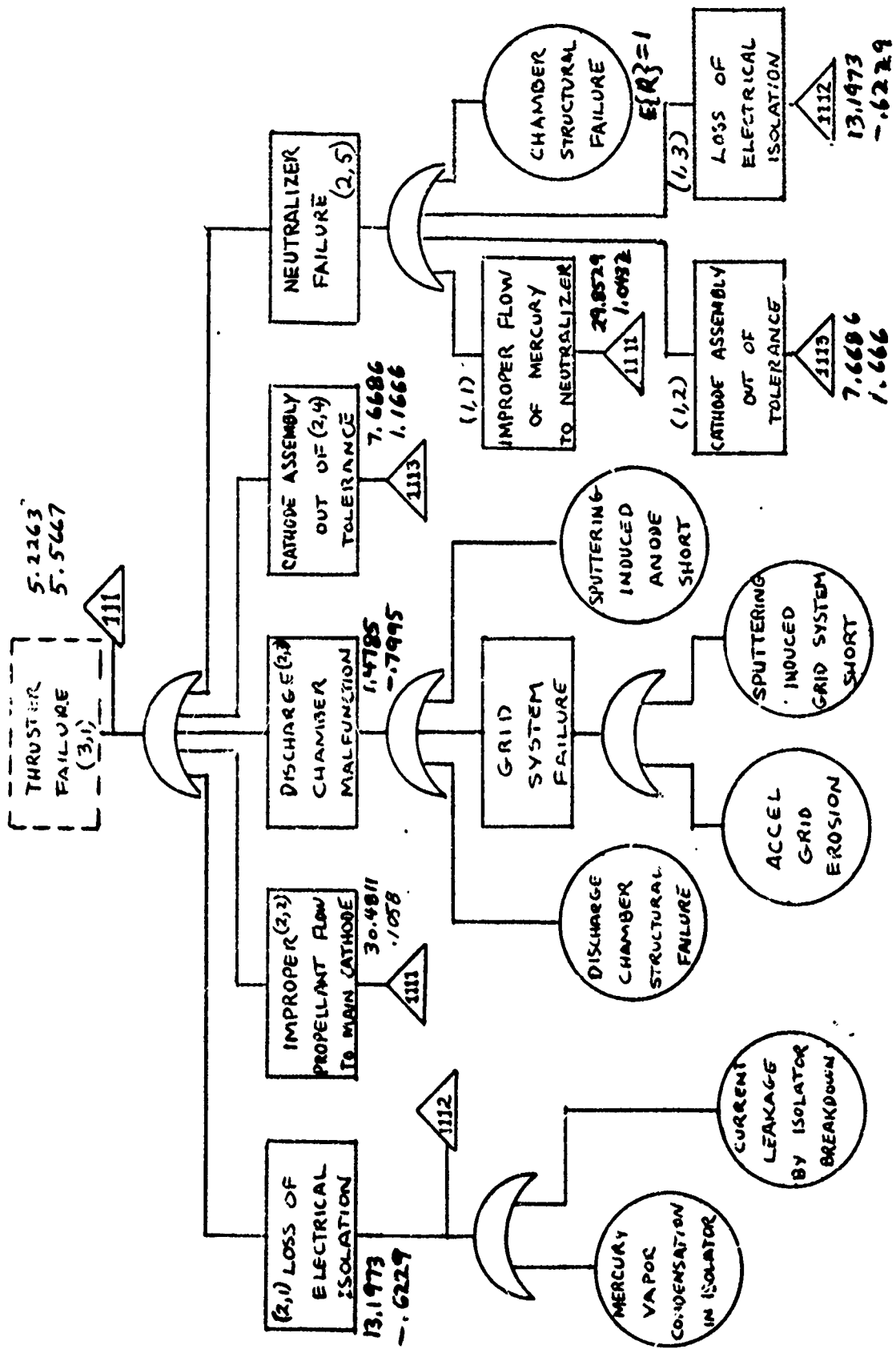
30.4811 .1058 .966066 .934259 .00097606

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.719 UNITS.

RUN COMPLETE.  
LIST,90000

76/12/14. 15.36.00.



90000 DATA 29.8529,1.0432,7.6686,1.666,13.1973,-.6229  
90002 DATA 13.1973,-.6229,30.4811,.1058,1.4785,-.7995  
90004 DATA 7.6686,1.1666

RUN  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 3  
? 5  
DESTINATION?

1 1 ? 5  
1 2 ? 5  
1 3 ? 5  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1  
2 4 ? 1  
2 5 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0  
GATE TYPES

2 5 ? 1  
3 1 ? 1

2 5 3.34509 -.3544  
3 1 5.22631 5.56665

SYSTEM (ITERATION 1)

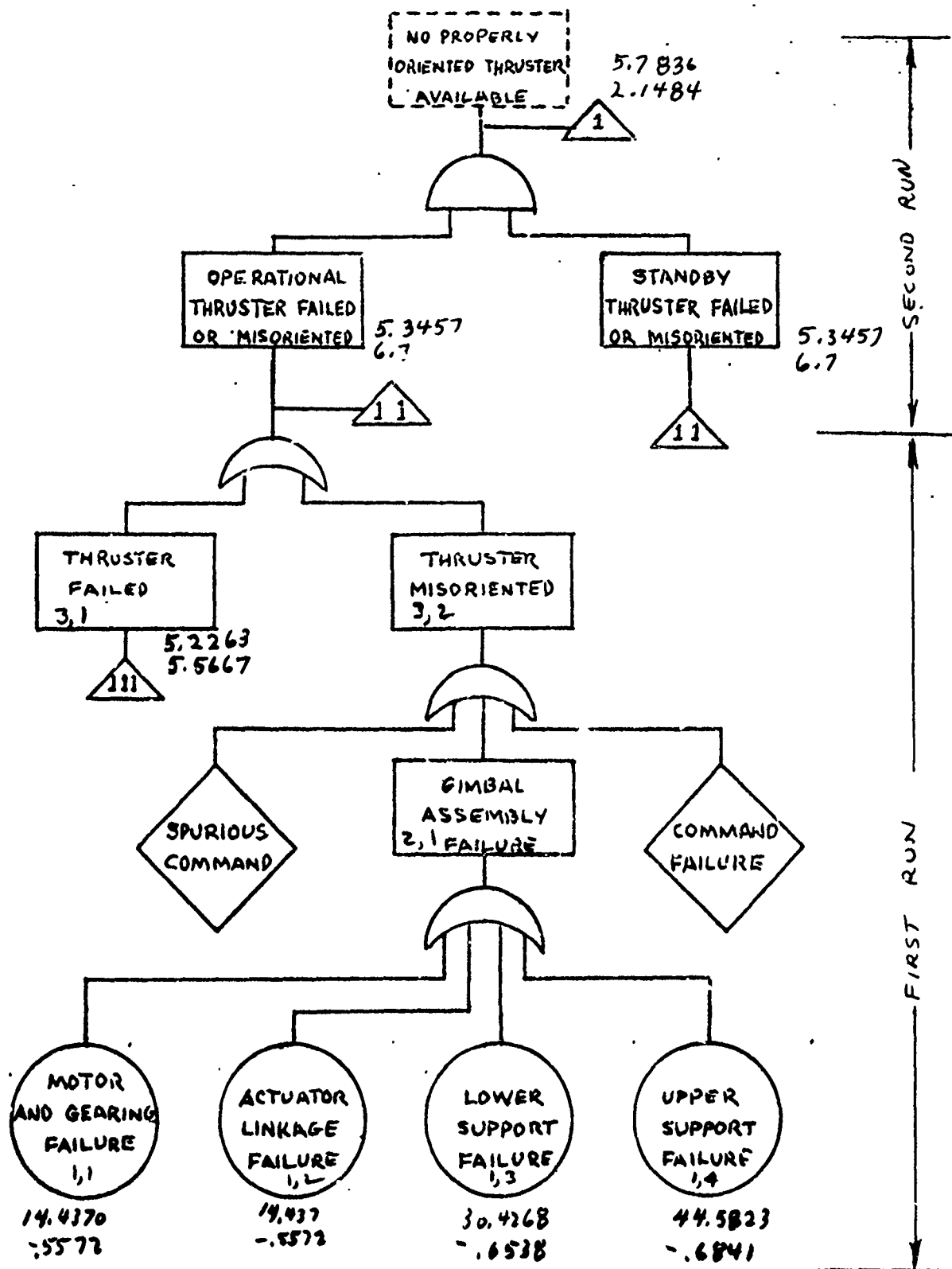
ALPHA BETA E(P) E(P\*P) V(P)

5.2263 5.5667 .486698 .254987 .01811236

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.678 UNTS.

RUN COMPLETE.



READY.  
 90000 DATA 14.437,-.5572,14.437,-.5572,30.4268,-.6538  
 90002 DT  
 90008 DATA 44.5823,-.6841,5.2263,5.5667  
 90004  
 RUN  
 PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
 HOW MANY LEVELS?

? 4  
 EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
 ? 4  
 ? 1  
 ? 2

DESTINATION?

1 1 ? 1  
 1 2 ? 1  
 1 3 ? 1  
 1 4 ? 1  
 2 1 ? 2  
 3 1 ? 1  
 3 2 ? 1

FIRST RUN
--------------

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1  
 3 2 ? 1  
 4 1 ? 1

1 1 16.5227 .353853  
 3 2 16.5227 .353853  
 4 1 5.34573 6.70005

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P+P) V(P)

5.3457 6.7000 .451789 .220575 .01646148

END OF DATA AT 58  
 BASIC EXECUTION ERROR

SBU 0.717 UNTS.

RUN COMPLETE.

90000 DATA 5.3457,6.7,5.3457,6.7  
90002  
90004  
RUN

76/12/14. 15.59.50.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?  
? 2  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 2  
DESTINATION?  
! 1 ? 1  
1 2 ? 1  
CONDITIONALS?(0,0=SKIP)  
? 0,0  
GATE TYPES  
2 1 ? 4

2 1 5.78357 2.1484

SYSTEM (ITERATION 1)  
ALPHA BETA E(P) E(P\*P) V(P)  
5.7836 2.1484 .683004 .486299 .01980519

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.681 UNTS.

RUN COMPLETE.

6. At this point only series (or gate) relationships remain in the system. Therefore BETALL is used to obtain Principal Subsystem Parameter values as well as the system level value of expected reliability and the associated 80%, 90% and 95% Lower Confidence Bounds. (LCB)

In order to illustrate the before-the-fact test planning capability of BETALL, arbitrary and significantly different test costs have been assigned as shown

1. Redundant Thruster Subsystem (No Properly Oriented Thruster available)

$$\alpha = 5.7836$$

$$\beta = 2.1484$$

Test Cost = \$50,000 per test

2. Redundant PCC Subsystem (Loss of PCC Function)

$$\alpha = 182.2226$$

$$\beta = -0.859$$

Test Cost = \$1,000 per test

3. Propellant Containment/Delivery Subsystem (Improper Propellant Flow to Vaporizer)

$$\alpha = 93.2741$$

$$\beta = 1.2352$$

Test Cost = \$10,000 per test

The program will first display component values if requested (1 = Yes, 0 = No), and then compute the system level expected reliability  $E(R)$  and variance  $V(R)$  values. A numerical integration follows and the result "Closure" is printed. Since analytic integration would yield a result of 1.0, the closure statement can be used to assess the quality of the numerical approximation and the accuracy of the following results. The 80, 90, 95% lower confidence bounds are then provided.



FILE NAME: BETAL1  
READY.  
RUN

77/01/27. 19.23.30.  
PROGRAM BETAL1

RUN IN DOUBLE PRECISION  
PERMIT NEGATIVE BETA?  
? 1  
TYPE OF INPUT?  
1=PARAMETERS,2=MOMENTS (MEAN & VAR)  
? 1  
HOW MANY COMPONENTS?  
? 3  
VALUES? (THIRD VALUE IS COST OF FIRST TEST)  
? 5.7836,2.1484,50000  
? 182.2276,-.859,1000  
? 93.2741,1.2352,10000  
DISPLAY COMPONENT VALUES?  
? 1

NO.	ALPHA	BETA	E(P)	E(P*P)	V(P)	COST
1	5.78	2.15	.683004	.486300	.01980510	50000.00
2	182.23	-.86	.999231	.998467	.00000417	1000.00
3	93.27	1.24	.976840	.954448	.00023202	10000.00

FOR SYSTEM

E(R)	E(R*R)	V(R)
.666673	.463436	.01898387

CLOSURE

.999672  
LOWER CONF. BOUNDS  
80 .5480 90 .4780 95 .4210

The program then enters the test planning routines using the greatest reduction in uncertainty (variance) per test dollar as the principal criteria in selecting components for testing. As output the identity of the component tested, the change in variance (DELV), and test cost are provided. In addition a running count of total test cost per component and total number of tests per component are also presented. The system level values of expected reliability and variance are then recomputed. Note that as expected the expected reliability is the same, but the variance  $V(R)$  has decreased. Numerical integration quality is again provided by "Closure" and is followed by the 80, 90, 95 lower confidence bands. These lower bands also reflect the decrease in variance in the increased values of reliability at each bound level. The expected value of variance reduction  $E(\text{DELVAR})$  is then provided.

FIRST COMPONENT TESTED				
NO.	DELV	COST	TOT COST	NO. TESTS
1	.00000003	*50000.00	50000.00	1

FOR SYSTEM

$E(R)$	$E(R^2)$	$V(R)$
.666673	.461855	.01740208

CLOSURE

.99963

LOWER CONF. BOUNDS

80	.5530	90	.4870	95	.4320
----	-------	----	-------	----	-------

$E(\text{DELVAR}) = .00133831$

The program next asks if a subsequent test is desired (Continue, Yes = 1, No = 0). For this example, two further test sequences were requested. At the end of the second additional sequence, a summary display was requested. In addition to the  $\alpha$ ,  $\beta$ , and expected reliability  $E(R)$  values for each component, the total number of tests and total test dollars per component are provided.

CONTINUE?

? 1

CHANGE NEXT COST?

? 0

NEW VALUES FOR LAST COMPONENT TESTED

NO.	ALPHA	BETA	E(P)	E(P*P)	V(P)	COST
1	6.47	2.47	.683004	.484640	.01814527	50000.00

NEXT COMPONENT TESTED

NO.	DELV	COST	TOT COST	NO. TESTS
1	.00000003	*50000.00	100000.00	2

FOR SYSTEM

E(R)	E(R*R)	V(R)
.666673	.460517	.01606492

CLOSURE

.999693
LOWER CONF. BOUNDS
80 .5580 90 .4940 95 .4420

$E(\text{DELVAR}) = .00114635$

CONTINUE?

? 1

CHANGE NEXT COST?

? 0

NEW VALUES FOR LAST COMPONENT TESTED

NO.	ALPHA	BETA	E(P)	E(P*P)	V(P)	COST
1	7.15	2.78	.683004	.483237	.01674214	50000.00

NEXT COMPONENT TESTED				
NØ.	DELV	CØST	TØT CØST	NØ. TESTS
1	.00000002	*50000.00	150000.00	3

FØR SYSTEM

E(R)	E(R*R)	V(R)
.666673	.459372	.01491972

CLØSURE  
 .999775  
 LØWER CØNF. BØUNDS  
 80 .5620 90 .5010 95 .4510

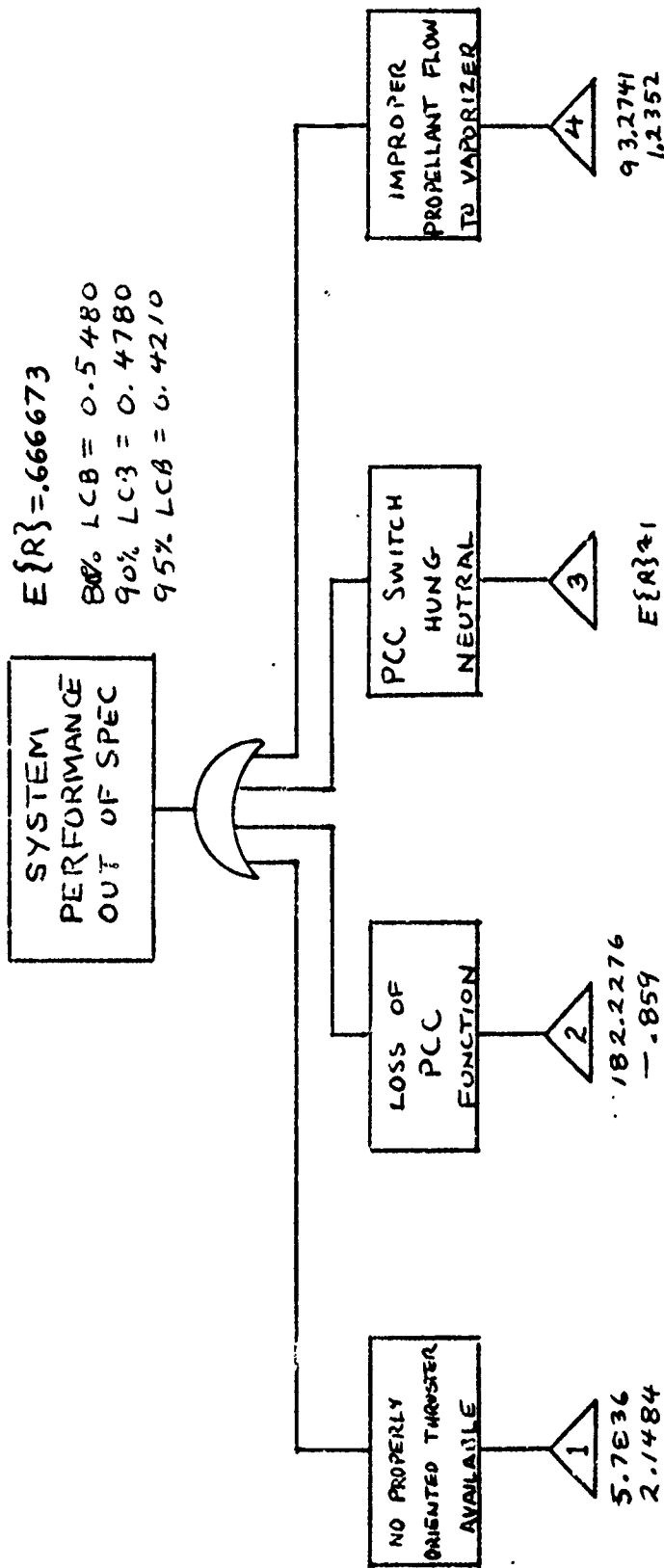
E(DELVAR)=.00099296

CØNTINUE?  
 ? 0  
 DISPLAY STATUS FØR ALL CØMPONENTS?  
 ? 1

NØ.	ALPHA	BETA	E(P)	TESTS	CØST
1	7.83	3.10	.683004	3	150000.00
2	182.23	-.86	.999231	0	.00
3	93.27	1.24	.976840	0	.00

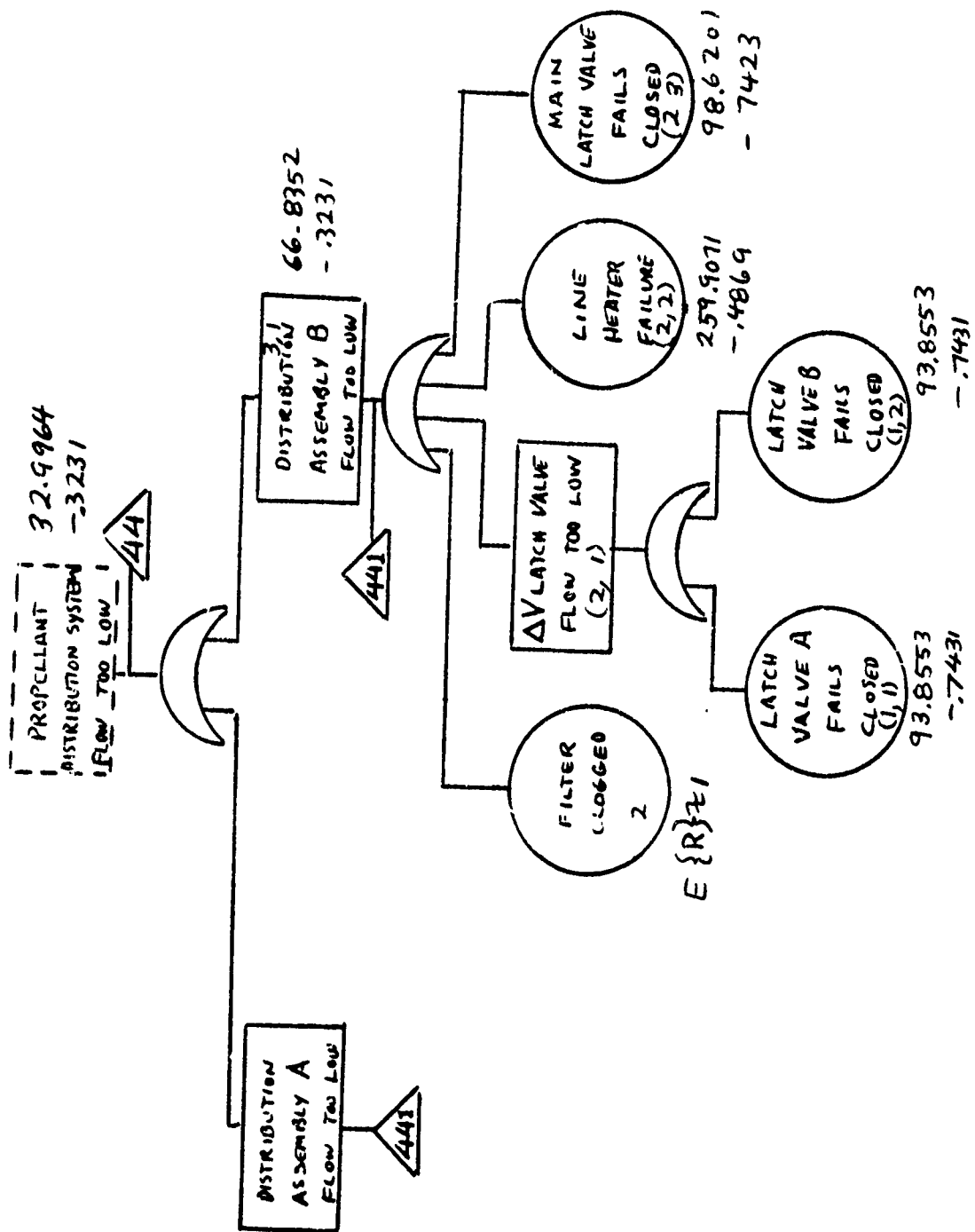
SRU 6.183 UNTS.

RUN CØMPLETE.



EXAMPLE II CATALYTIC MONOPROPELLANT SYSTEM

1. Mission 5 years or 43,800 hrs
  - a. 0.1 lbs Thrusters (Position Control)
    1. Pulse
      - a. Cycles = 6348
      - b. CUM Firing Time = 1.75 hrs
    2. Steady State
      - a. Cycles = 11
      - b. CUM Firing Time = 14.55 hrs
  - b. 5.0 lbs Thrusters ( $\Delta V$ )
    1. Pulse
      - a. Cycles = 3100
      - b. CUM Firing Time = 0.1 hr
    2. Steady State
      - a. Cycles = 2
      - b. CUM Firing Time = 0.4 hr
2. Evaluation Point, t mission = 5 years; End of Mission
3. Procedure: Because of the more complex tree developed for this system each tree section (still to be treated as entities) will be evaluated completely (using BETFTA and COMPl) before moving to the next section.



PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? FTC

OPTIME=? (0=END)

? 16.3

.999997 1.00000 \*456219.2871 -.6581

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ILVC

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 3102

MISSION TIME =? (0=END)

? 43800

.985436 .999499 93.8553 -.7431

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? HLTV

MISSION TIME=? (0=END)

? 43800

.992625 .999085 259.9071 -.4869

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ILVC

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 1000

MISSION TIME =? (0=END)

? 43800

.986108 .999518 98.6201 -.7423

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.589 UNTS.

RUN COMPLETE.



BASIC,OLD,BETFTA  
READY.  
90000 DATA 93.8553,-.7431,93.8553,-.7431  
90002 DATA 259.9071,-.4869,98.6201,-.7423  
RU N  
ILLEGAL COMMAND.  
RUN

76/12/14. 19.22.06.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?  
? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 2  
? 3  
DESTINATION?  
1 1 ? 1  
1 2 ? 1  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1  
CONDITIONALS?(0,0=SKIP)  
? 0,0  
GATE TYPES  
2 1 ? 3  
3 1 ? 1  
  
2 1 46.611 -.743106  
3 1 66.8352 -.323087

SYSTEM (ITERATION 1)  
ALPHA BETA E(P) E(P\*P) V(P)  
66.8352 -.3231 .990120 .980478 .00014073

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.699 UNTS.  
RUN COMPLETE.

90000 DATA 66.8352,-.3231  
90002 DATA 66.8352,-.3231  
RUN

76/12/14. 19.26.16.  
PROGRAM BETPTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 2

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 3

2 1 32.9964 -.323119

SYSTEM (ITERATION 1)

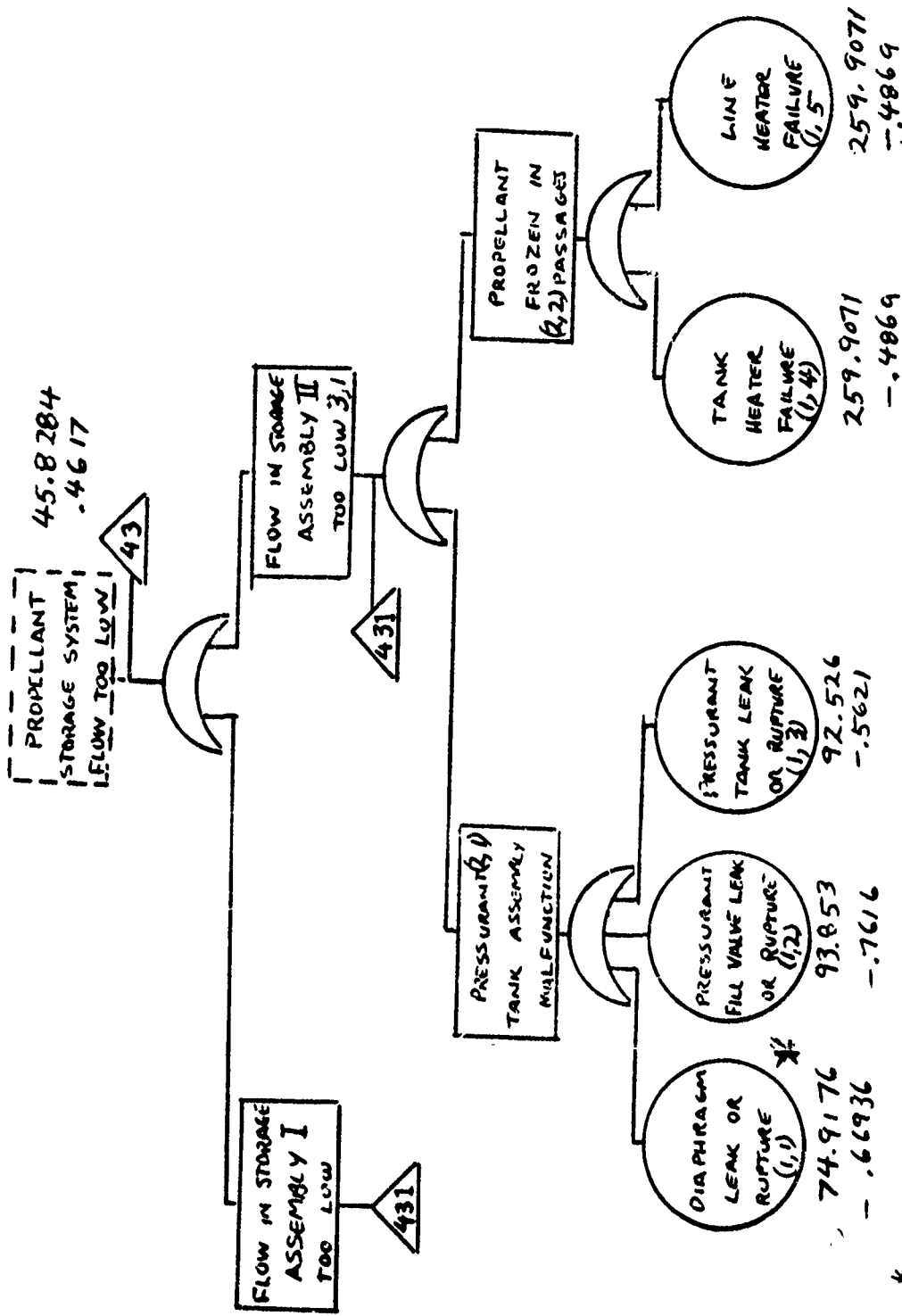
ALPHA BETA E(P) E(P+P) V(P)

32.9964 -.3231 .980478 .961874 .00053655

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.668 UNTS.

RUN COMPLETE.



\* INITIAL CALCULATIONS EMPLOYED THE ELASTOMERIC BLENDER/DIAPHRAGM MODEL. BECAUSE OF THE LOW RESULTING RELIABILITY ESTIMATES, THE METALLIC DIAPHRAGM MODEL WAS SUBSTITUTED

90000 DATA 74.9176,-.66936,93.853,-.7616,92.526,-.5621  
 90002 DATA 259.9071,-.4869,259.9071,-.4869  
 90004 DATA 74.9176,-.66936  
 90006 DATA 93.853,-.7616,92.526,-.5621  
 90008 DATA 259.9071,-.4869,259.9071,-.4869  
 99999 END  
 READY.  
 RUN

76/12/15. 10.21.26.  
 PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
 HOW MANY LEVELS?

? 4

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 10

? 4

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 1

1 4 ? 2

1 5 ? 2

1 6 ? 3

1 7 ? 3

1 8 ? 3

1 9 ? 4

1 10 ? 4

2 1 ? 1

2 2 ? 1

2 3 ? 2

2 4 ? 2

3 1 ? 1

3 2 ? 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

2 2 ? 3

2 3 ? 1

2 4 ? 3

3 1 ? 1

3 2 ? 1

4 1 ? 3

2 1 84.939 -3.63317E-3

2 2 129.575 -.486901

2 3 84.939 -3.63317E-3

2 4 129.575 -.486901

3 1 92.8817 .461643

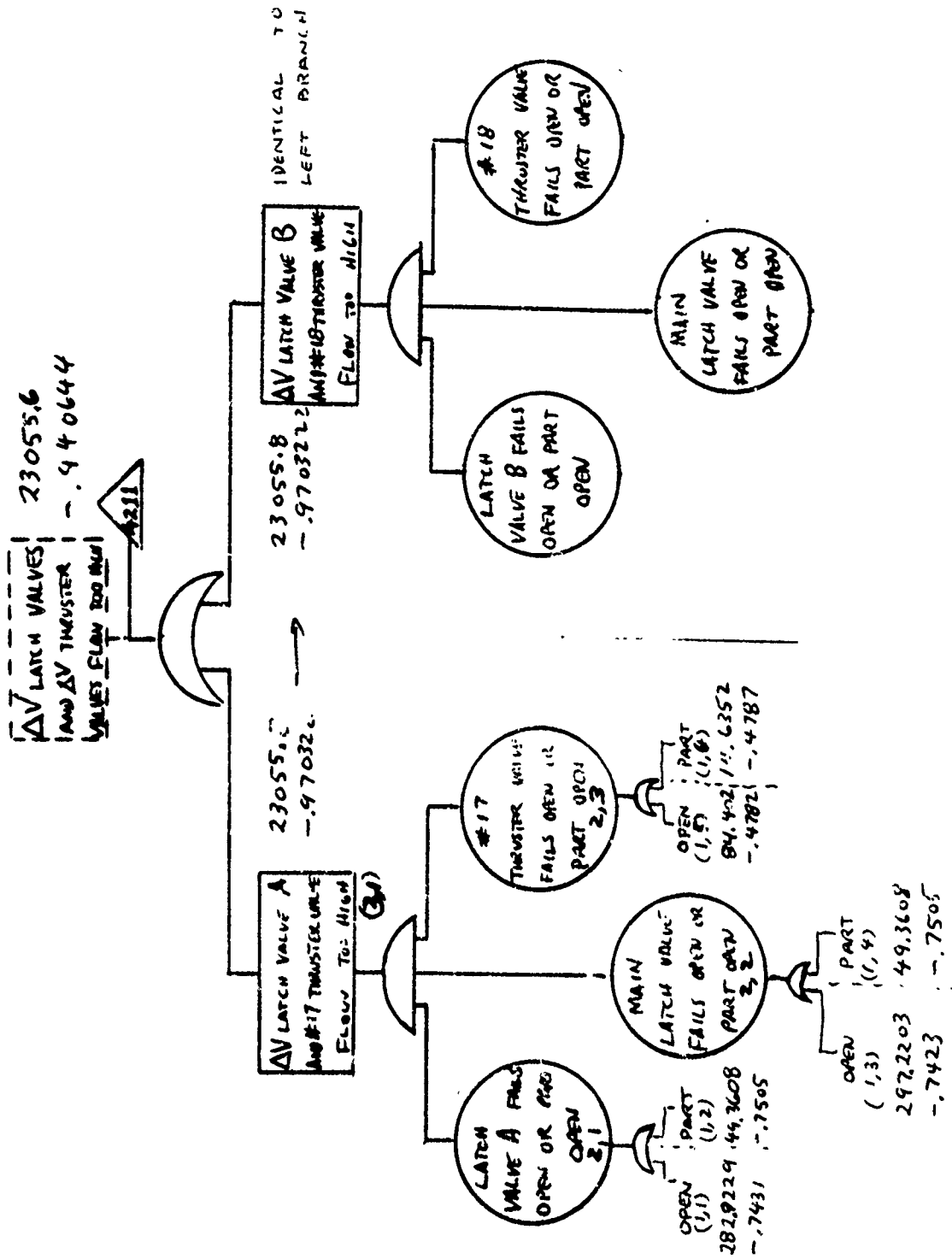
3 2 9.817 .461643

4 1 45.8284 .461688

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

45.8284 .4617 .969731 .940974 .00059551



PROGRAM COMPI

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? ILV8

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 3102

MISSION TIME =? (0=END)

? 43800

.995122 .999833 282.9229 -.7431

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? ILVP

MISSION TIME=? (0=END)

? 43800

.973039 .999133 49.3608 -.7505

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? EV8

DESIGN CYCLE LIFE,OP. LIFE,MISSION DURATION

? 3102,.5,43800

INPUT OPTION

1=FIXED CYCLES/OP.HR.,2=SEPARATE

? 2

CYCLES=? (0=END)

? 3102

MISSION TIME,OP. TIME (0,0=END)

? 43800,.5

.977400 .997116 84.4020 -.4782

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)  
 ? EVP  
 DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION  
 ? 3102,.5,43800  
 INPUT OPTION  
 1=FIXED CYCLES/OP.HR.,2=SEPARATE  
 ? 2  
 CYCLES=? (0=END)  
 ? 3102  
 MISSION TIME,OP. TIME (0,0=END)  
 ? 43800,.5  
    .881509           .984209           14.6352           -.4787  
 CYCLES=? (0=END)  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? ILV8  
 INPUT OPTION  
 1=FIXED CYCLES/MISSION HR., 2=SEPARATE  
 ? 2  
 CYCLES=? (0=END)  
 ? 1000  
 MISSION TIME =? (0=END)  
 ? 43800  
    .995348           .999839           297.2203           -.7423  
 CYCLES=? (0=END)  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? ILVP  
 MISSION TIME=? (0=END)  
 ? 43800  
    .973039           .999133           49.3608           -.7505  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? ZZ  
 NO SUCH COMPONENT

SBU       5.717 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 282.9229,-.7431,49.36,-.7505  
90002 DATA 297.2203,-.7423,49.3608,-.7505  
90004 DATA 84.402,-.4782,14.6352,-.4787  
99999 END  
READY.  
RUN

76/12/14. 19.58.13.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6  
? 3

DESTINATION?

1 1 ? 1  
1 2 ? 1  
1 3 ? 2  
1 4 ? 2  
1 5 ? 3  
1 6 ? 3  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

( 1 ? 1  
2 2 ? 1  
2 3 ? 1  
3 1 ? 2

2 1 56.7885 -.661149  
2 2 56.5515 -.664897  
2 3 16.9787 -.287052  
3 1 23055.8 -.970322

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

\*23055.7676 -.9703 .999999 .999997 .00000000

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.740 UNTS.

RUN COMPLETE.



90000 DATA 23055.8,-.970322,23055.8,-.970322  
90002  
90004  
90006  
LIST,90000

76/12/14. 20.02.03.  
PROGRAM BETFTA

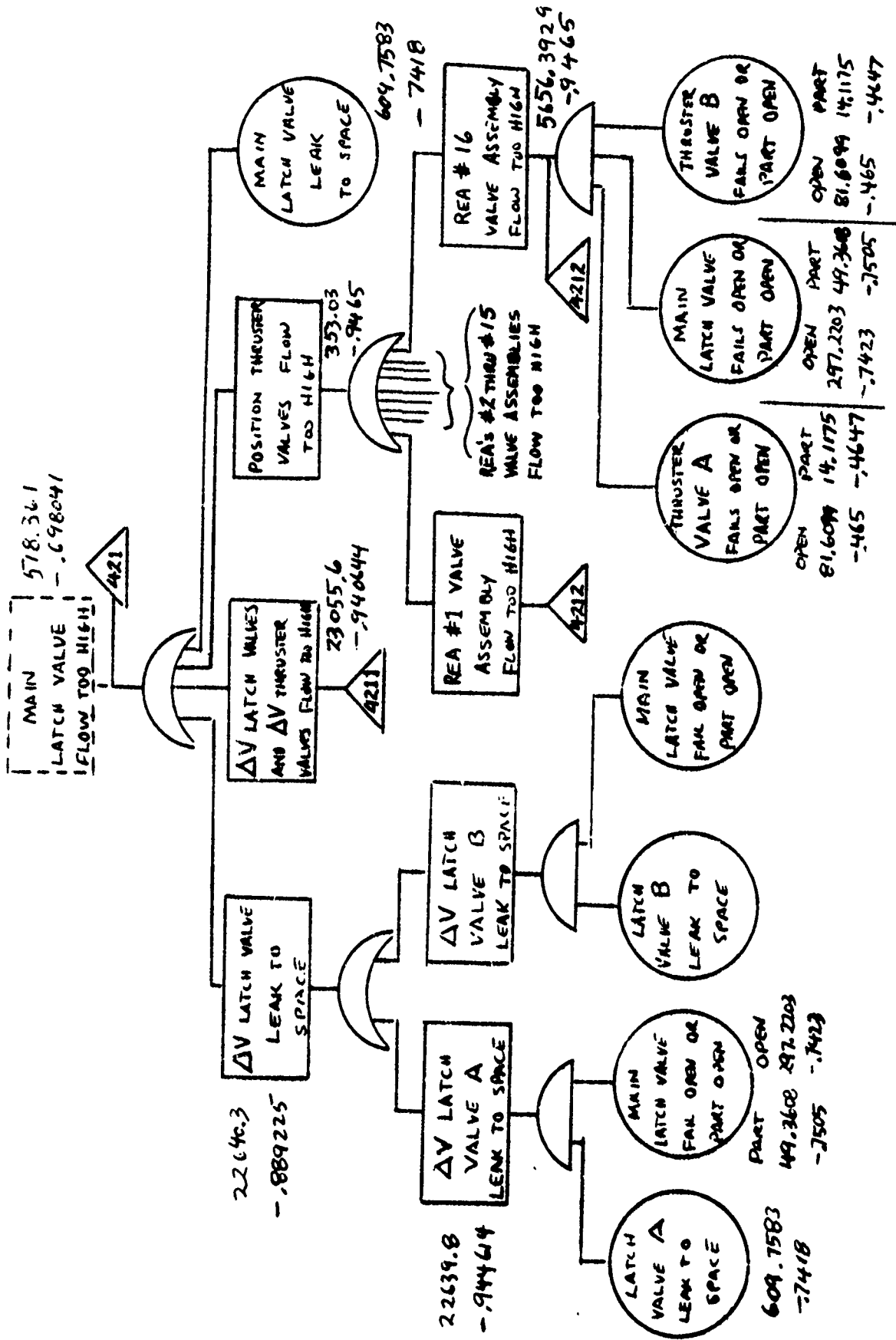
90000 DATA 23055.8,-.970322,23055.8,-.970322  
99999 END  
READY.  
RUN

76/12/14. 20.02.19.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?  
? 2  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 2  
DESTINATION?  
1 1 ? 1  
1 2 ? 1  
CONDITIONALS?(0,0=SKIP)  
? 0,0  
GATE TYPES  
2 1 ? 1  
  
2 1 23055.6 -.940644

SYSTEM (ITERATION 1)  
ALPHA BETA E(P) E(P\*P) V(P)  
\*23055.6117 -.9406 .999997 .999995 .00000000

END OF DATA AT 58  
BASIC EXECUTION ERROR  
SBU 0.681 UNTS.  
RUN COMPLETE.



PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? ILVL

MISSION TIME=? (0=END)

? 43800

.997725 .999921 609.7583 -.7418

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ILV8

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 1000

MISSION TIME =? (0=END)

? 43800

.995348 .999839 297.2203 -.7423

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? ILVP

MISSION TIME=? (0=END)

? 43800

.973039 .999133 49.3608 -.7505

OPTIME=?

? .05

1.00000 1.00000 \*43832710.7167 -.7505

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.504 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 49.3608,-.7505  
90002 DATA 251.2203,-.7423  
90004 DATA 609.7583,-.7418  
99999 END  
READY.  
RUN

76/12/14. 20.11.57.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 2

? 2

DESTINATION?

1 1 ? 2

1 2 ? 2

2 1 ? 1

2 2 ? 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

2 2 ? 1

3 1 ? 2

2 2 56.5515 -.664897

3 1 22639.8 -.944614

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P+P) V(P)

\*22639.8109 -.9446 .999998 .999995 .00000000

END OF DATA AT 38  
BASIC EXECUTION ERROR

SBU 0.684 UNTS.

RUN COMPLETE.

90000 DATA 22639.8,-.944614,22639.8,-.944614  
99999 END  
READY.  
RUN

76/12/14. 20.15.01.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?  
? 2  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 2  
DESTINATION?  
1 1 ? 1  
1 2 ? 1  
CONDITIONALS?(0,0=SKIP)  
? 0,0  
GATE TYPES  
2 1 ? 1

2 1 22640.3 -.889225

SYSTEM (ITERATION 1)  
ALPHA BETA E(P) E(P\*P) V(P)  
\*22640.3107 -.8892 .999995 .999990 .00000000

END OF DATA AT 56  
BASIC EXECUTION ERROR

SBU 0.665 UNTS.

RUN COMPLETE.

PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? EV0

DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION

? 6359, 16.3, 43800

INPUT OPTION

1=FIXED CYCLES/OP.HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 6359

MISSION TIME, OP. TIME (0,0=END)

? 43800, 16.3

.976315

.996878

81.6099

-.4650

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? EVP

DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION

? 6359, 16.3, 43800

INPUT OPTION

1=FIXED CYCLES/OP.HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 6359

MISSION TIME, OP. TIME (0,0=END)

? 43800, 16.3

.875973

.982863

14.1175

-.4647

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? ILV0

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 1000

MISSION TIME=? (0=END)

? 43800

.995348

.999839

297.2203

-.7423

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? ILVP

MISSION TIME=? (0=END)

? 43800

.973039

.999133

49.3608

-.7505

OPTIME=?

? 0

PROGRAM BETFTA

90000 DATA 81.6099,-.465,14.1175,-.4647  
90002 DATA 297.2203,-.7423,49.3608,-.7505  
90004 DATA 81.6099,-.465,14.1175,-.4647  
99999 END  
READY.  
RUN

76/12/14. 20.27.10.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6  
? 3  
DESTINATION?

1 1 ? 1  
1 2 ? 1  
1 3 ? 2  
1 4 ? 2  
1 5 ? 3  
1 6 ? 3  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1

CONDITIONALS?(0,0=SKIP)  
? 0,0

GATE TYPES  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1  
3 1 ? 2

2 1 16.3811 -.267999  
2 2 56.5515 -.664897  
2 3 16.3811 -.267999  
3 1 5656.39 -.946512

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P+P) V(P)

5656.3929 -.9465 .999991 .999981 .00000000

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.744 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 5656.3929,-.9465  
90002 DATA 5656.3929,-.9465  
90004 DATA 5656.3929,-.9465  
90006 DATA 5656.3929,-.9465  
90008 DATA 5656.3929,-.9465  
90010 DATA 5656.3929,-.9465  
90012 DATA 5656.3929,-.9465  
90014 DATA 5656.3929,-.9465  
90016 DATA 5656.3929,-.9465  
90018 DATA 5656.3929,-.9465  
90020 DATA 5656.3929,-.9465  
90022 DATA 5656.3929,-.9465  
90024 DATA 5656.3929,-.9465  
90026 DATA 5656.3929,-.9465  
90028 DATA 5656.3929,-.9465  
90030 DATA 5656.3929,-.9465  
90032LIW  
99999 END  
READY.  
90032  
RUN

76/12/14. 20.36.15.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 2

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 16

DESTINATION?

1 1 ? 1  
1 2 ? 1  
1 3 ? 1  
1 4 ? 1  
1 5 ? 1  
1 6 ? 1  
1 7 ? 1  
1 8 ? 1  
1 9 ? 1  
1 10 ? 1  
1 11 ? 1  
1 12 ? 1  
1 13 ? 1  
1 14 ? 1  
1 15 ? 1  
1 16 ? 1



CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 3

2 1 353.03 -.9465

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

353.0303 -.9465 .997 .999698 .00000043

PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? IL VL

SUBSCRIPT ERROR AT 209

BASIC EXECUTION ERROR

SBU 5.498 UNTS.

RUN COMPLETE.

RUN

76/12/14. 20.42.40.

PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? ILVL

MISSION TIME=? (0=END)

? 43800

.997725 .999921 609.7583 -.7418

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.594 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 22640.3, -.889225  
90002 DATA 23055.6, -.940644  
90004 DATA 353.03, -.9465  
90006 DATA 609.7583, -.7418  
99999 END  
READY.  
RUN

76/12/14. 20.47.22.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 2

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 4

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 1

1 4 ? 1

CONDITIONALS? (0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

2 1 518.361 -.698041

SYSTEM (ITERATION 1)

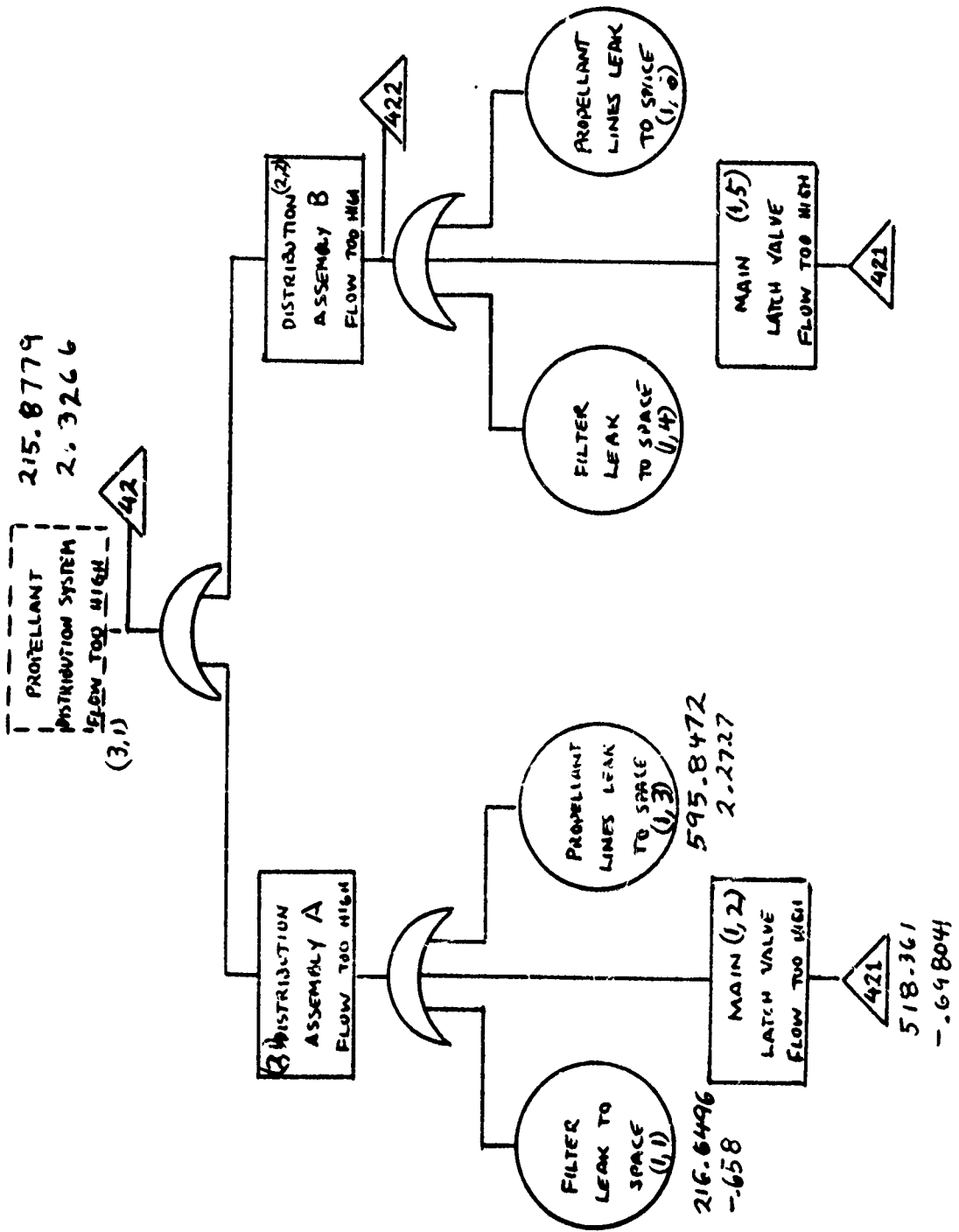
ALPHA BETA E(P) E(7\*P) V(P)

518.3606 -.6980 .999419 .998839 .00000112

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.684 UNTS.

RUN COMPLETE.



PROGRAM COMP1

OUTPUT FORMAT IS

R-05 R-5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? FTL

MISSION TIME=? (0=END)

? 43800

.992756 .999531 216.6496 -.6380

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? FL

OPTIME=? (0=END)

? 17

.999997 .999999 \*1536763.1884 2.2724

OPTIME=?

? 43800

.991278 .996699 595.8472 2.2727

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.592 UNTS.

PROGRAM BETFTA

90000 DATA 216.6496,-.658  
90002 DATA 518.361,-.698041  
90004 DATA 595.8472,2.2727  
90006 DATA 216.6496,-.658  
90008 DATA 518.361,-.698041  
90010 DATA 595.8472,2.2727  
99999 END  
READY.  
RUN

76/12/14. 21.44.06.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 1

1 4 ? 2

1 5 ? 2

1 6 ? 2

2 1 ? 1

2 2 ? 1

CONDITIONALS?(U,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

2 2 ? 1

3 1 ? 3

2 1 433.908 2.32651

2 2 433.908 2.32651

3 1 215.878 2.32655

SYSTEM (ITERATION 1)

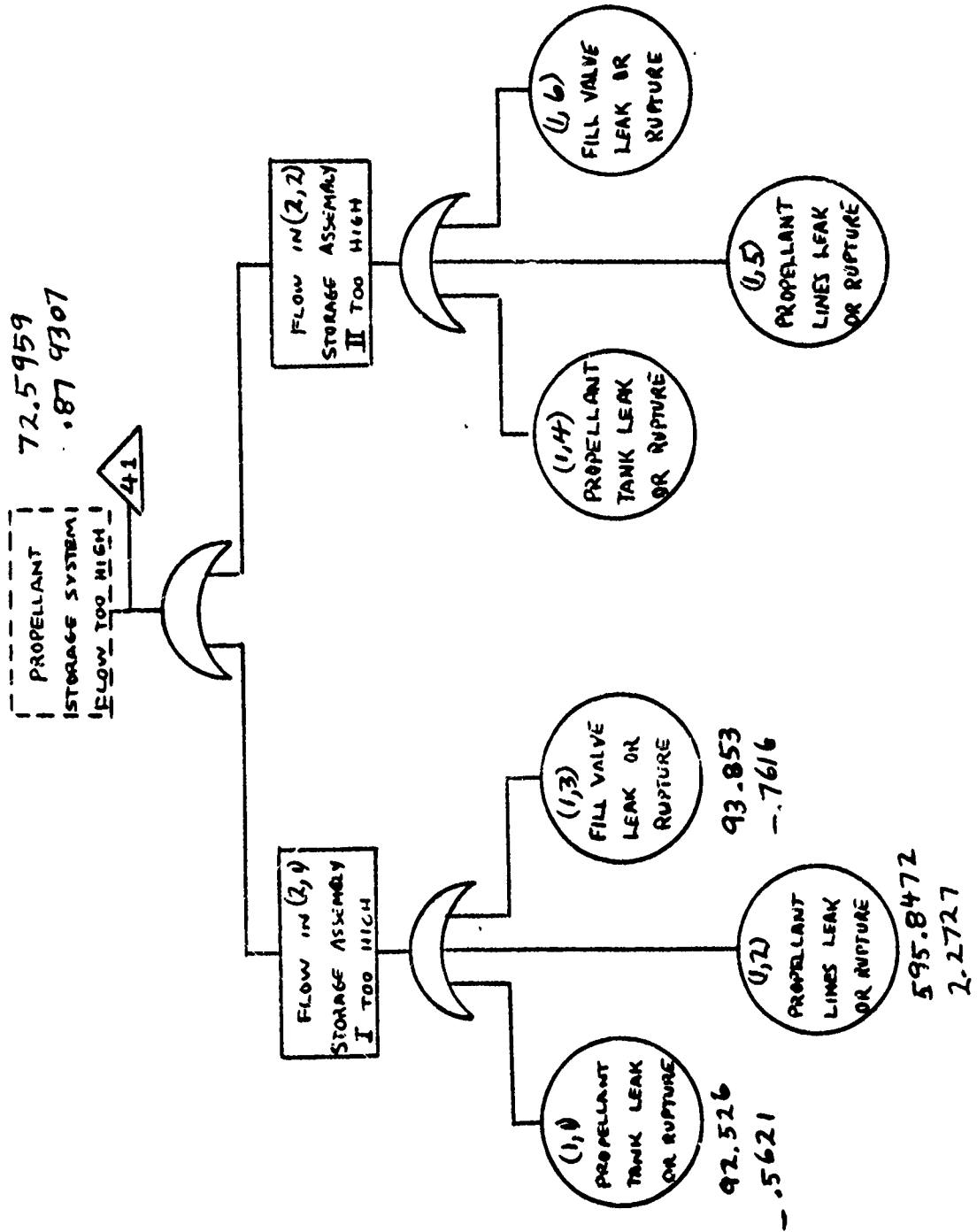
ALPHA BETA E(P) E(P\*P) V(P)

215.8779 2.3266 .984893 .970082 .00006726

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.710 UNTS.

RUN COMPLETE.



PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? PR

PRESS. TIME=? (0=END)

? 43800

.981127 .998118 92.5260 -.5621

PRESS. TIME=?

? 0

COMPONENT CODE?(ZZ=END)

? FL

OPTIME=? (0=END)

? 438000GHJ

TOO MUCH DATA, RETYPE INPUT AT 2002

? 43800

.991278 .996699 595.8472 2.2727

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? FV1

PRESS. TIME=? (0=END)

? 43800

.985952 .999601 93.8530 -.7616

PRESS. TIME=?

? 0

COMPONENT CODE?(ZZ=END)

? ZZ

NO SUCH COMPONENT

SBU 5.540 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 92.526,-.5621  
90002 DATA 595.8472,2.2727  
90004 DATA 93.853,-.7616  
90006 DATA 92.526,-.5621  
90008 DATA 595.8472,2.2727  
90010 DATA 93.853,-.7616  
99999 END  
READY.  
RUN

76/12/14. 21.52.01.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 1

1 4 ? 2

1 5 ? 2

1 6 ? 2

2 1 ? 1

2 2 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

2 2 ? 1

3 1 ? 3

2 1 146.623 .879254

2 2 146.623 .879254

3 1 72.5959 .879307

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

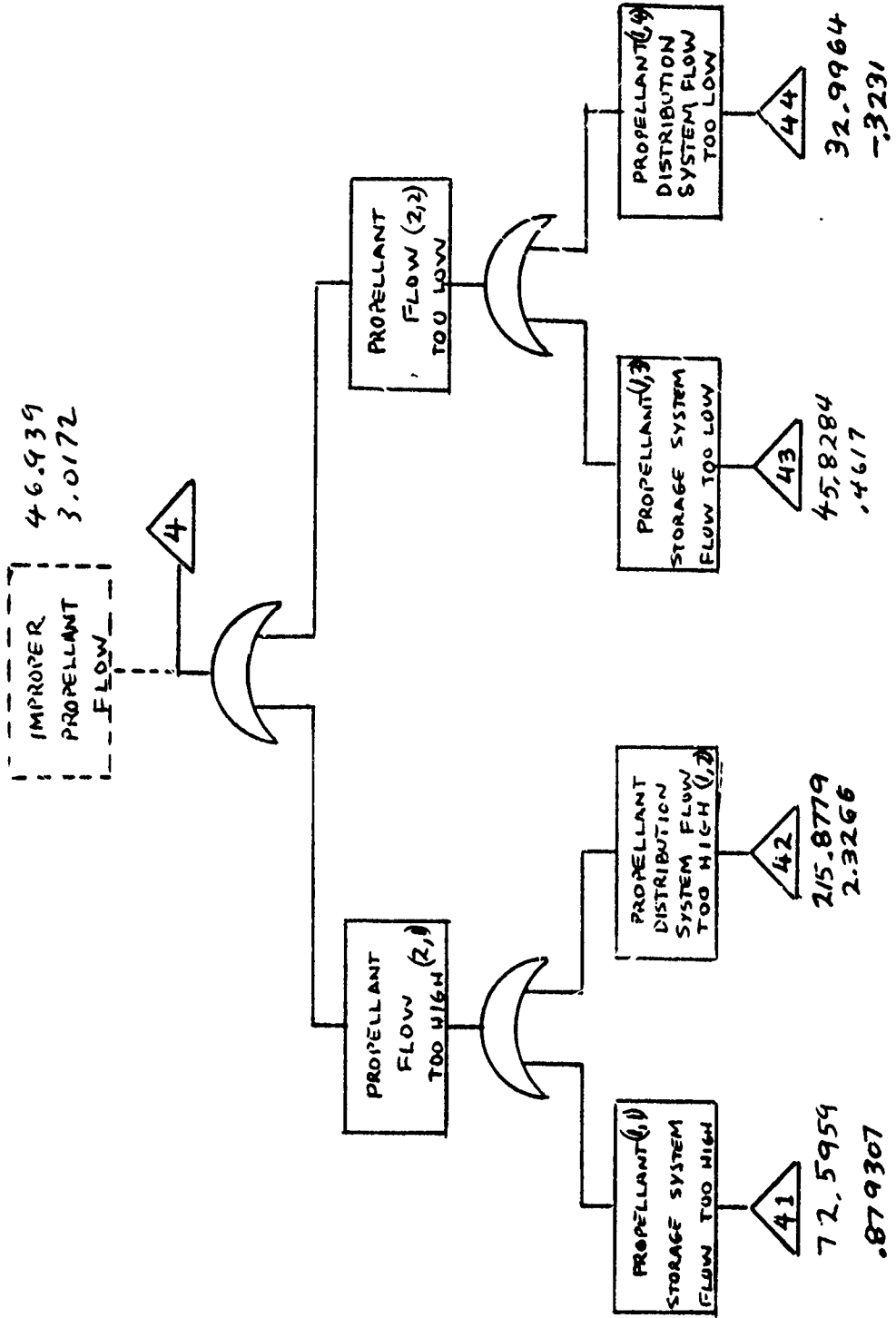
72.5959 .8793 .975100 .951138 .00031748

END OF DATA AT 56  
BASIC EXECUTION ERROR

SBU 0.715 UNTS.

RUN COMPLETE.





PROGRAM BETFTA

90000 DATA 72.5959,.879307,215.8779,2.3266,45.8284,.4617  
90002 DATA 32.9964,-.3231  
99999 END  
READY.  
RUN

76/12/15. 10.40.17.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 4

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 2

1 4 ? 2

2 1 ? 1

2 2 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

2 2 ? 1

3 1 ? 3

2 1 96.3122 3.01566

2 2 39.3327 1.08707

3 1 46.939 3.01716

SYSTEM (ITERATION 1)

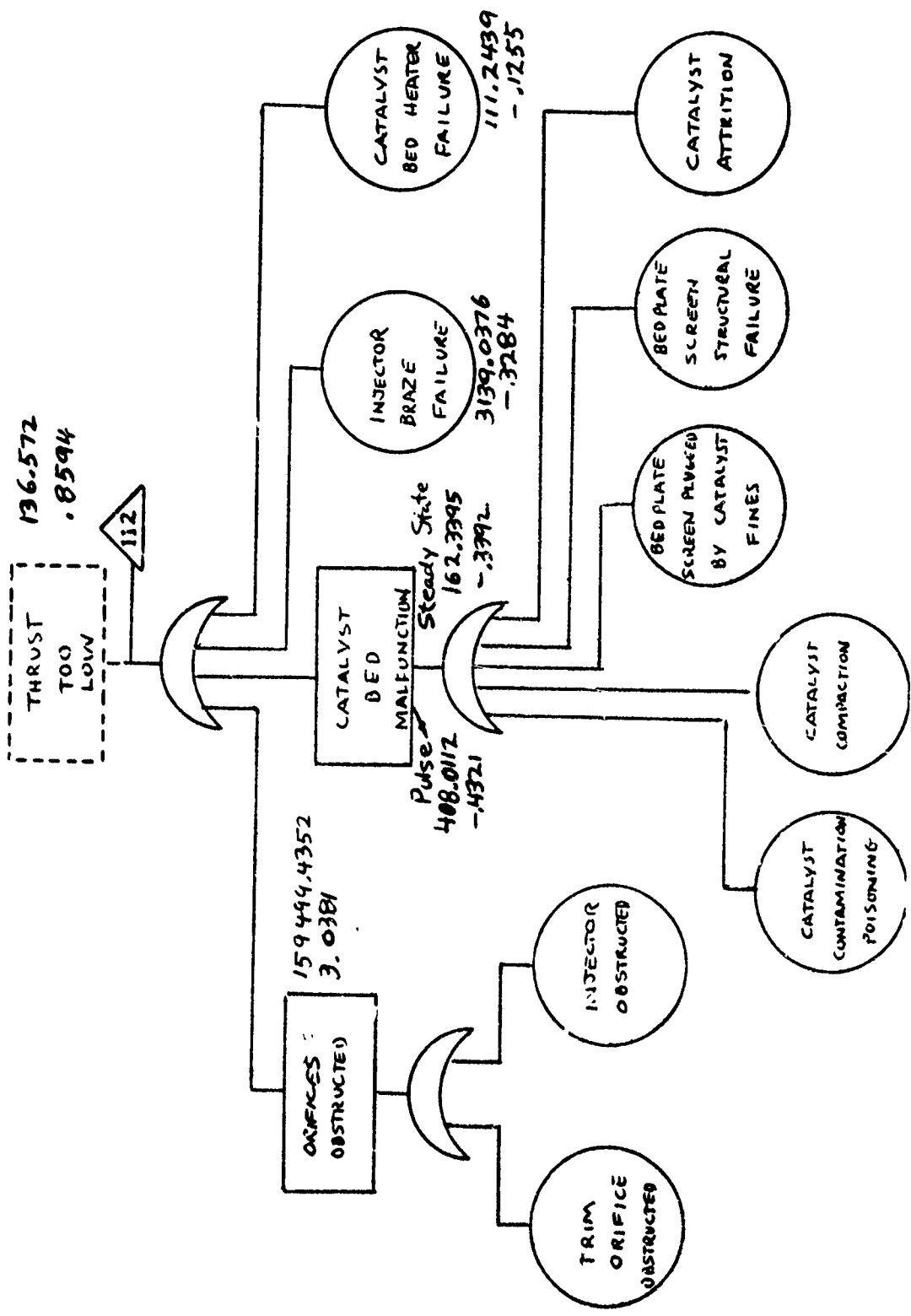
ALPHA BETA E(P) E(P\*P) V(P)

46.9390 3.0172 .922682 .852689 .00134716

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.709 UNITS.

RUN COMPLETE.



PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? IMP

DESIGN OP. LIFE=?

? 16.3

OPTIME=? (0=END)

? 16.3

.999960 .999983 \*159499.4352 3.0381

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? IBF

SAME AS ISL

MISSION TIME=? (0=END)

? 43800

.999278 .999879 3139.0376 -.3284

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? HET

THRUSTER CYCLES & OP.TIME

INPUT OPTION

1=FIXED CYCLES/OP.HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 6359

OPTIME=? (0=END)

? 16.3

.976124 .994929 111.2439 -.1255

CYCLES=? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? CBP

DESIGN CYCLE LIFE,COLD START LIFE,OP.LIFE?

? 6348,1E-6,1.75

CYCLES,COLD STARTS,OP. TIME, (T=0=END)

? 6348,1E-6,1.75

.995008 .999299 408.0112 -.4321

CYCLES,COLD STARTS,OP. TIME, (T=0=END)

? 0,0,0

COMPONENT CODE?(ZZ=END)  
? CBS  
DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?  
? 11,1E-6,14.55  
CYCLES,COLD STARTS,OP. TIME, (T=0=END)  
? 11,1E-6,14.55  
    .986334    .997729    162.3395    -.3392  
CYCLES,COLD STARTS,OP. TIME, (T=0=END)  
? 0,0,0

PROGRAM BETFTA

90000 DATA 159499.4352,3.0381  
90002 DATA 408.0112,-.4321  
90004 DATA 162.3395,-.3392  
90006 DATA 3139.0376,-.3284  
90008 DATA 111.2439,-.1255  
99999 END  
READY.  
RUN

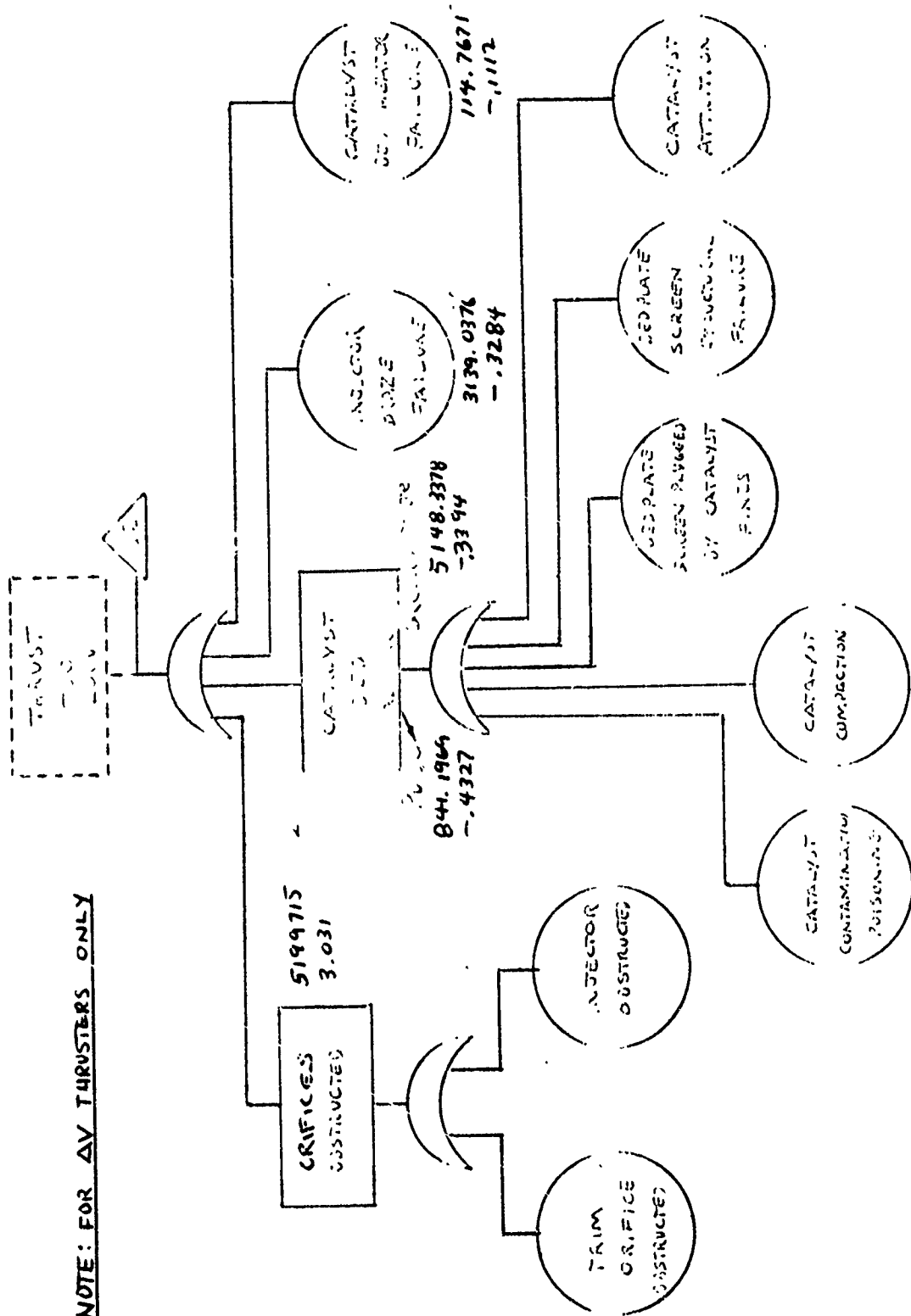
76/12/14. 21.33.44.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?  
? 2  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 5  
DESTINATION?  
1 1 ? 1  
1 2 ? 1  
1 3 ? 1  
1 4 ? 1  
1 5 ? 1  
CONDITIONALS?(0,0=SKIP)  
? 0,0  
GATE TYPES  
2 1 ? 1  
  
2 1 136.572 .859358

SYSTEM (ITERATION 1)  
ALPHA BETA E(P) E(P+P) V(P)  
136.5725 .8594 .986665 .973601 .00009369

RUN COMPLETE.

NOTE: FOR AV THRUSTERS ONLY



PROGRAM COMP1

OUTPUT FORMAT IS  
R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? IMP

DESIGN OP. LIFE=?

? .5

OPTIME=? (O=END)

? .5

.999999 .999999 \*5199715.3910 3.0381

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? CBP

DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?

? 3100,1E-6,.1

CYCLES,COLD STARTS,OP. TIME, (T=O=END)

? 3100,1E-6,.1

.997575 .999660 841.1969 -.4327

CYCLES,COLD STARTS,OP. TIME, (T=O=END)

? 0,0,0

COMPONENT CODE?(ZZ=END)

? CBS

DESIGN CYCLE LIFE,COLD START LIFE,OP. LIFE?

? 2,1E-6,.4

CYCLES,COLD STARTS,OP. TIME, (T=O=END)

? 2,1E-6,.4

.999564 .999928 5148.3378 -.3394

CYCLES,COLD STARTS,OP. TIME, (T=O=END)

? 0,0,0

COMPONENT CODE?(ZZ=END)

? IBF

SAME AS ISL

MISSION TIME=? (O=END)

? 43800

.999278 .999879 3139.0376 -.3284

OPTIME=?

? 0

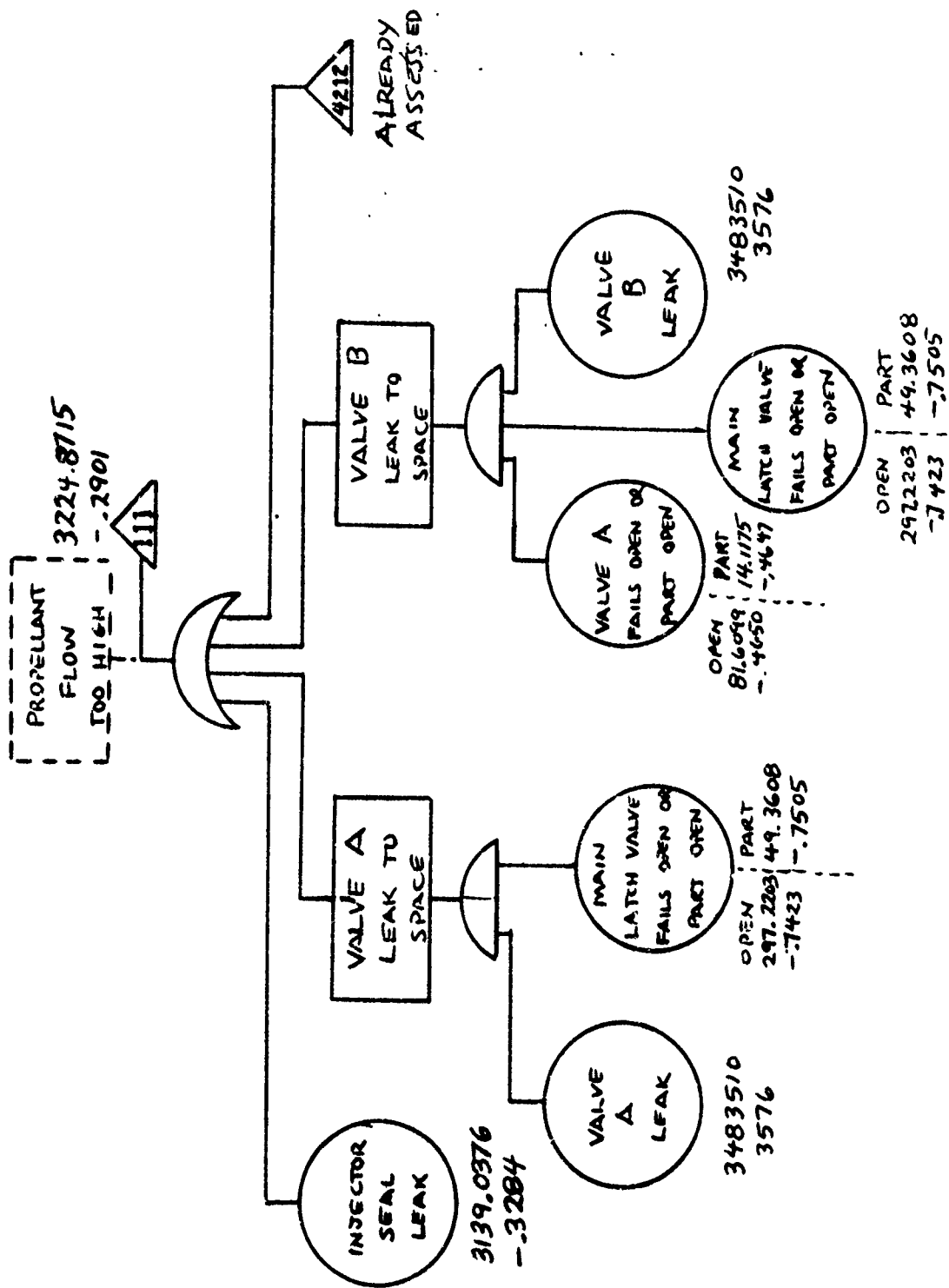
COMPONENT CODE?(ZZ=END)  
 ? HET  
 THRUSTER CYCLES & OP.TIME  
 INPUT OPTION  
 1=FIXED CYCLES/OP.HR., 2=SEPARATE  
 ? 2  
 CYCLES=? (0=END)  
 ? 3102  
 OPTIME=? (0=END)  
 ? .5  
 .976573 .994965 114.7671 -.1112  
 CYCLES=? (0=END)  
 ? 0  
 90000 DATA 5199715.39,3.0381  
 90002 DATA 841.1969,-.4327,5148.0376,.3394  
 90004 DATA 3139.0376,-.3284,114.7671,-.1112  
 99999 END  
 READY.  
 RN  
 ILLEGAL COMMAND.  
 RUN

76/12/15. 11.34.25.  
 PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
 HOW MANY LEVELS?  
 ? 2  
 EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
 ? 5  
 DESTINATION?  
 1 1 ? 1  
 1 2 ? 1  
 1 3 ? 1  
 1 4 ? 1  
 1 5 ? 1  
 CONDITIONALS?(0,0=SKIP)  
 ? 0,0  
 GATE TYPES  
 2 1 ? 1  
 2 1 130.359 .160562

SYSTEM (ITERATION 1)  
 ALPHA BETA E(P) E(P\*P) V(P)  
 130.3587 .1606 .991242 .982626 .00006502





PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? ISL

MISSION TIME=? (O=END)

? 43800

.999278 .999879 3139.0376 -.3284

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? EVLS

MISSION TIME, OPTIME=? (O,O=END)

? 43800,16.3

.998942 .998975 3.48351E+6 3576.03

MISSION TIME, OPTIME=? (O,O=END)

? 0,0

COMPONENT CODE?(ZZ=END)

? ILVS

INPUT OPTION

1=FIXED CYCLES/MISSION HR., 2=SEPARATE

? 2

CYCLES=? (O=END)

? 1000

MISSION TIME =? (O=END)

? 43800

.995348 .999839 297.2203 -.7423

CYCLES=? (O=END)

? 0

COMPONENT CODE?(ZZ=END)

? EVS

DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION

? 6359,16.3,43800

INPUT OPTION

1=FIXED CYCLES/OP.HR., 2=SEPARATE

? 2

CYCLES=? (O=END)

? 6359

MISSION TIME, OP. TIME (O,O=END)

? 43800,16.3

.976315 .996878 81.6099 -.4650

CYCLES=? (O=END)

? 0

COMPONENT CODE?(ZZ=END)  
 ? EVP  
 DESIGN CYCLE LIFE, OP. LIFE, MISSION DURATION  
 ? 6359  
 NOT ENOUGH DATA, TYPE IN MORE AT 961  
 ? 16.3,43800  
 INPUT OPTION  
 1=FIXED CYCLES/OP.HR.,2=SEPARATE  
 ? 2  
 CYCLES=? (0=END)  
 ? 6359  
 MISSION TIME,OP. TIME (0,0=END)  
 ? 43800  
 NOT ENOUGH DATA, TYPE IN MORE AT 2344  
 ? 16.3  
 .875973 .982863 14.1175 -.4647  
 CYCLES=? (0=END)  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? ILVP  
 MISSION TIME=? (0=END)  
 ? 43800  
 .973039 .999133 49.3608 -.7505  
 OPTIME=?  
 ? 0

COMPONENT CODE?(ZZ=END)  
 ? ZZ  
 NO SUCH COMPONENT

SBU 5.594 UNTS.

RUN COMPLETE.

PROGRAM BETFTA

90000 DATA 297.2203,-.7423,49.3608,-.7505  
90002 DATA 81.6099,-.465,14.1175,-.4647  
90004 DATA 297.2203,-.7423,49.3608,-.7505  
90006 DATA 3483510,3576,3483510,3576  
99999 END  
READY.  
RUN

76/12/14. 21.12.42.

PROGRAM BETFTA

FOR EXPLANATION LIST 80000

HOW MANY LEVELS?

? 4

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6

? 5

? 3

DESTINATION?

1 1 ? 2

1 2 ? 2

1 3 ? 3

1 4 ? 3

1 5 ? 4

1 6 ? 4

2 1 ? 2

2 2 ? 2

2 3 ? 3

2 4 ? 3

2 5 ? 3

3 1 ? 1

3 2 ? 1

3 3 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 2 ? 1

2 3 ? 1

2 4 ? 1

3 2 ? 2

3 3 ? 2

4 1 ? 1

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.729 UNTS.

RUN COMPLETE.

90000 DATA 297.2203,-.7423,49.3608,-.7505  
 90002 DATA 81.6099,-.465,14.1175,-.4647  
 90004 DATA 297.2203,-.7423,49.3608,-.7505  
 90006 DATA 3483510,3576,3483510,3576  
 99999 END  
 READY.  
 90008 DATA 3139.0376,-.3284  
 RUN

76/12/14. 21.17.00.  
 PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
 HOW MANY LEVELS?

? 4  
 EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 6  
 ? 5  
 ? 3

DESTINATION?

1 1 ? 2  
 1 2 ? 2  
 1 3 ? 3  
 1 4 ? 3  
 1 5 ? 4  
 1 6 ? 4  
 2 1 ? 2  
 2 2 ? 2  
 2 3 ? 3  
 2 4 ? 3  
 2 5 ? 3  
 3 1 ? 1  
 3 2 ? 1  
 3 3 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

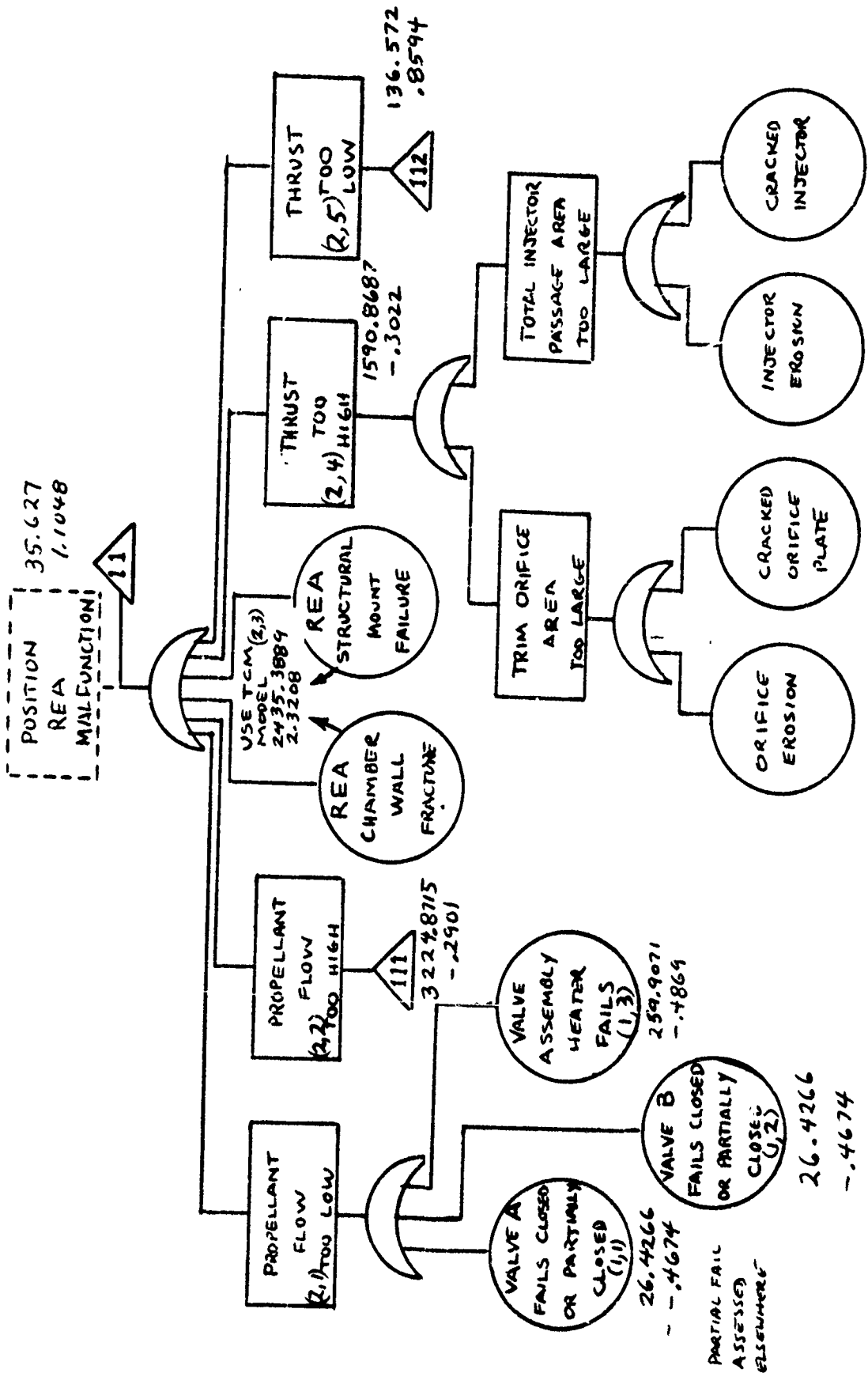
2 2 ? 1  
 2 3 ? 1  
 2 4 ? 1  
 3 2 ? 2  
 3 3 ? 2  
 4 1 ? 1

2 2 56.5515 -.664897  
 2 3 16.3811 -.267999  
 2 4 56.5515 -.664897  
 3 2 57713.8 -.657275  
 3 3 540385. -.870318  
 4 1 3224.87 -.290107

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

3224.8715 -.2901 .999780 .999560 .0000007



PROGRAM COMP1

OUTPUT FORMAT IS

R.05 R.5 ALPHA BETA

COMPONENT CODE?(ZZ=END)

? HLTV

MISSION TIME=? (0=END)

? 43800

.992625 .999085 259.9071 -.4869

OPTIME=?

? 0

COMPONENT CODE?(ZZ=END)

? TCM

DESIGN CYCLE LIFE, OP. LIFE?

? 6359, 16, KL

TOO MUCH DATA, RETYPE INPUT AT 1141

? 6359, 16.3

INPUT OPTION

1=FIXED CYCLES/OP. HR., 2=SEPARATE

? 2

CYCLES =? (0=END)

? 6359

MISSION TIME, OP. TIME (0,0=END)

? 43800, 16.3

.997826 .999171 2435.3889 2.3208

CYCLES =? (0=END)

? 0

COMPONENT CODE?(ZZ=END)

? IMF

DESIGN CYCLE LIFE, OP. LIFE?

? 6359, 16.3

INPUT OPTION

1=FIXED CYCLES/OP. HR., 2=SEPARATE

? 2

CYCLES=? (0=END)

? 6359

OPTIME=? (0=END)

? 16.3

.998539 .999745 1590.3687 -.3022

CYCLES=? (0=END)

? 0

90000 DATA 26.4266,-.4674,26.4266,-.4674,259.9071,-.4865  
90002 DATA 3224.8715,-.2901,2435.3889,2.3208  
90004 DATA 1590.8687,-.3022,136.572,.8594  
99999 END  
READY.  
RUN

76/12/15. 11.01.14.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 3

? 5

DESTINATION?

1 1 ? 1

1 2 ? 1

1 3 ? 1

2 1 ? 1

2 2 ? 1

2 3 ? 1

2 4 ? 1

2 5 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1

3 1 ? 1

2 1 27.4107 .172197

3 1 35.627 1.10484

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

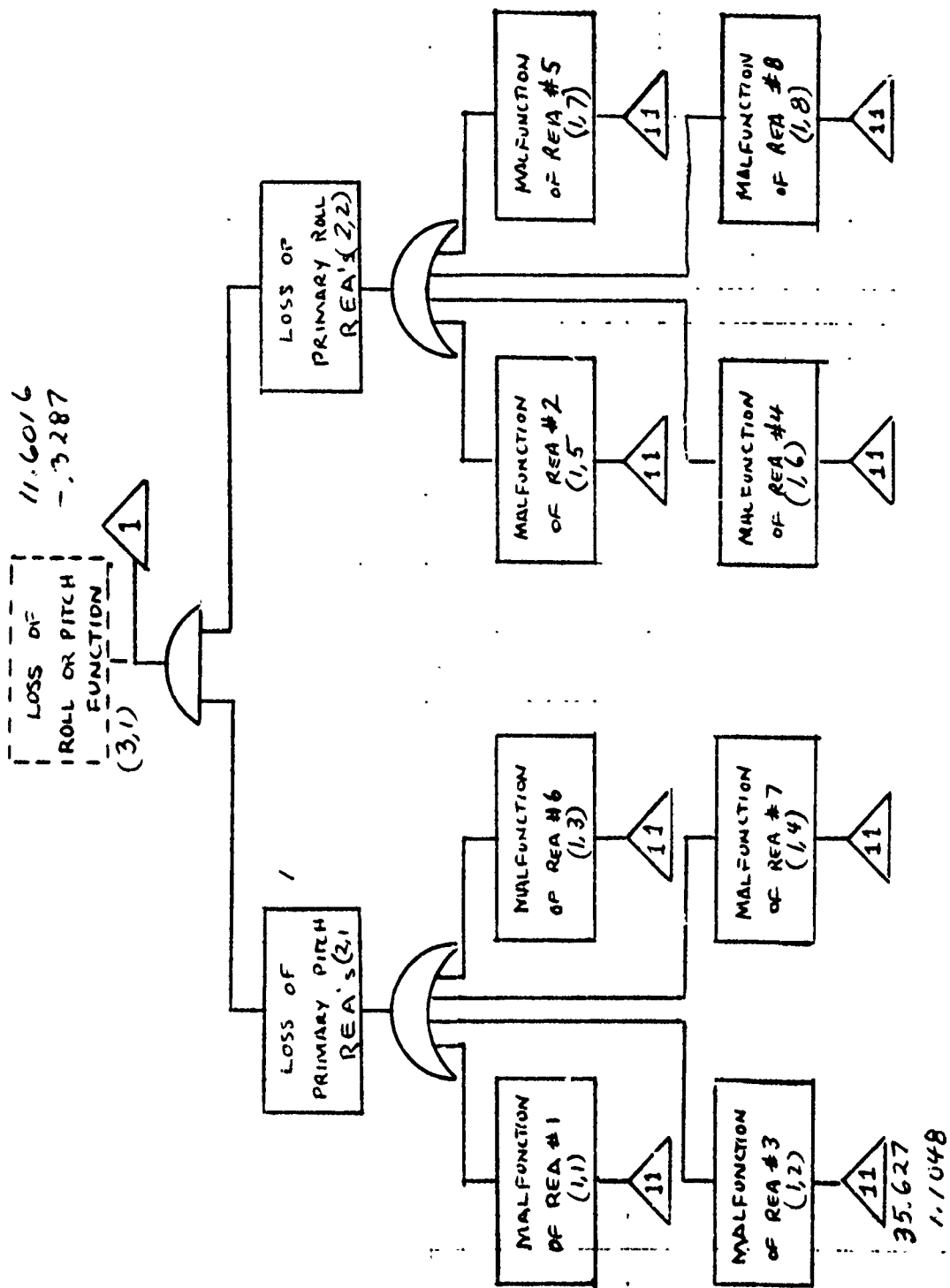
35.6270 1.1048 .945656 .895559 .00129344

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.752 UNITS.

RUN COMPLETE.





90000 DATA 35.627,1.1048,35.6270,1.1048  
90002 DATA 35.6270,1.1048,35.6270,1.1048  
90004 DATA 35.6270,1.1048,35.6270,1.1048  
90006 DATA 35.6270,1.1048,35.6270,1.1048  
99999 END  
READY.  
RUN

76/12/15. 11.07.19.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 8  
? 2

DESTINATION?

1 1 ? 1  
1 2 ? 1  
1 3 ? 1  
1 4 ? 1  
1 5 ? 2  
1 6 ? 2  
1 7 ? 2  
1 8 ? 2  
2 1 ? 1  
2 2 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 3  
2 2 ? 3  
3 1 ? 4

2 1 7.79209 1.11015  
2 2 7.79209 1.11015  
3 1 11.6016 -.3287

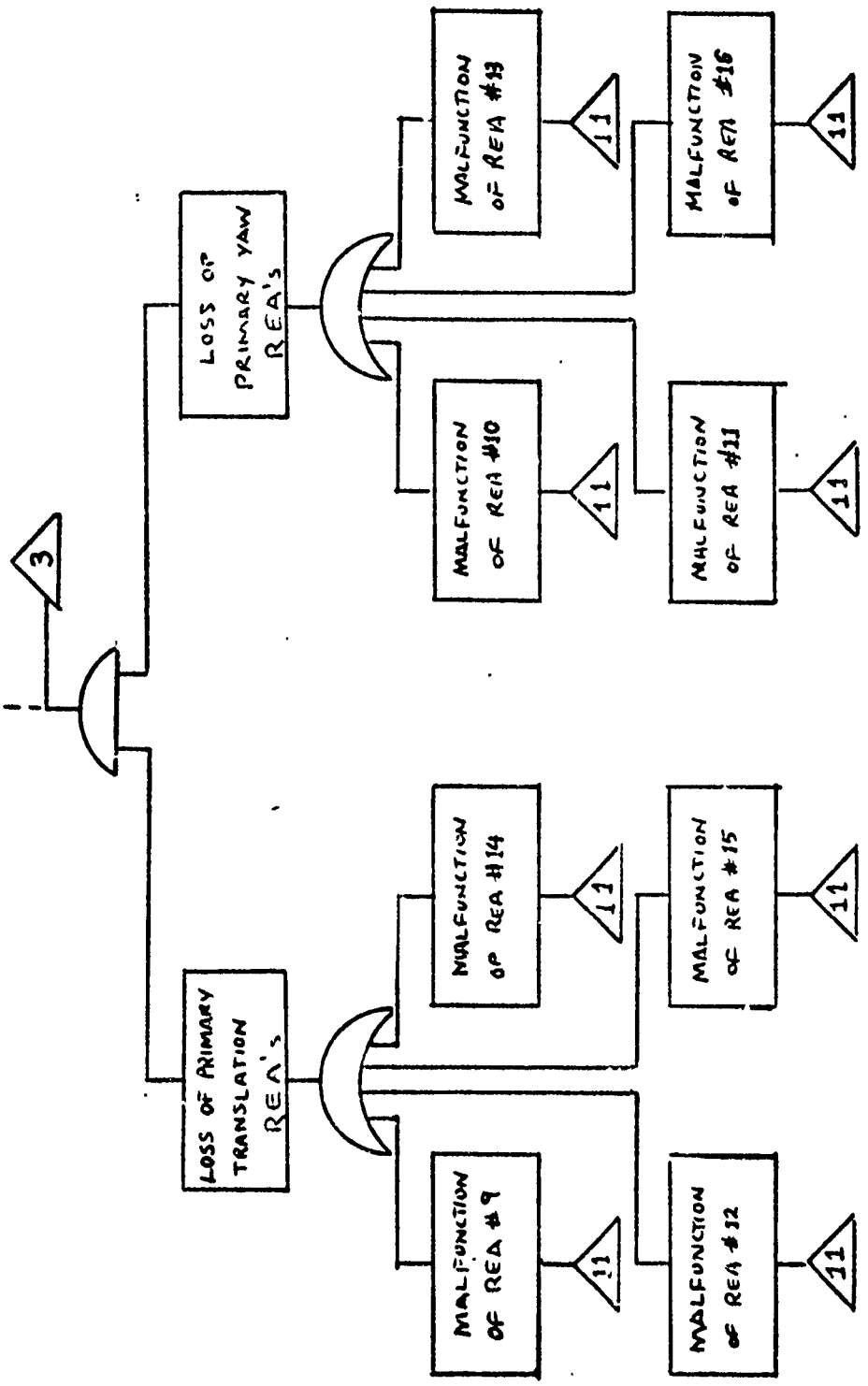
SYSTEM (ITERATION 1)

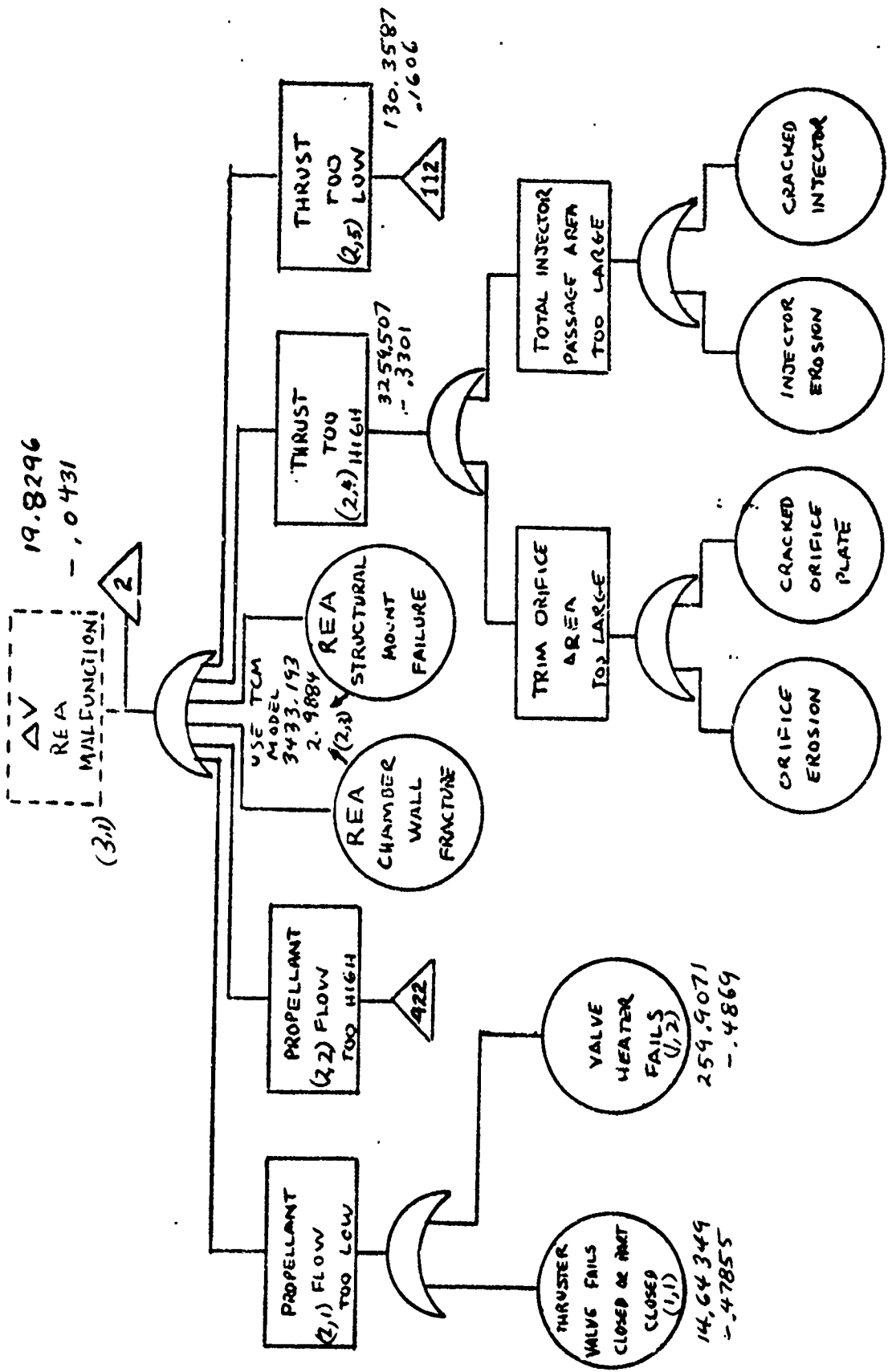
ALPHA BETA E(P) E(P\*P) V(P)

11.6016 -.3287 .949423 .904769 .00336431

LOSS OF YAW OR TRANSLATION FUNCTION

11.60/6 (IDENTICAL TO  $\Delta$ )  
-.3287





PROGRAM COMPI

OUTPUT FORMAT IS  
R.05 R=5 ALPHA BETA

COMPONENT CODE?(ZZ=END)  
? HLTV  
MISSION TIME=? (0=END)  
? 43800  
.992625 .999085 259.9071 -.4869  
OPTIME=?  
? 0

COMPONENT CODE?(ZZ=END)  
? TCM  
DESIGN CYCLE LIFE, OP. LIFE?  
? 3102, .5  
INPUT OPTION  
1=FIXED CYCLES/OP. HR., 2=SEPARATE  
? 2  
CYCLES =? (0=END)  
? 3102  
MISSION TIME, OP. TIME (0,0=END)  
? 43800, .5  
.998161 .999217 3433.1930 2.9884  
CYCLES =? (0=END)  
? 0

COMPONENT CODE?(ZZ=END)  
? IMF  
DESIGN CYCLE LIFE, OP. LIFE?  
? 3102, .5  
INPUT OPTION  
1=FIXED CYCLES/OP. HR., 2=SEPARATE  
? 2  
CYCLES=? (0=END)  
? 3102  
OPTIME=? (0=END)  
? .5  
.999305 .999884 3259.5070 -.3301  
CYCLES=? (0=END)  
? 0

90000 DATA 14.64349, -.47855, 259.9071, -.4869  
90002 DATA 3433.193, 2.9884, 3259.507, -.3301, 130.3587, .1606  
99999 END  
READY.  
RUN

76/12/15. 12.37.25.  
PROGRAM BETFTA

FOR EXPLANATION LIST 80000  
HOW MANY LEVELS?

? 3  
EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)  
? 2  
? 4

DESTINATION?

1 1 ? 1  
1 2 ? 1  
2 1 ? 1  
2 2 ? 1  
2 3 ? 1  
2 4 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 1  
3 1 ? 1

2 1 15.5557 -.414498  
3 1 19.8296 -4.30613E-2

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

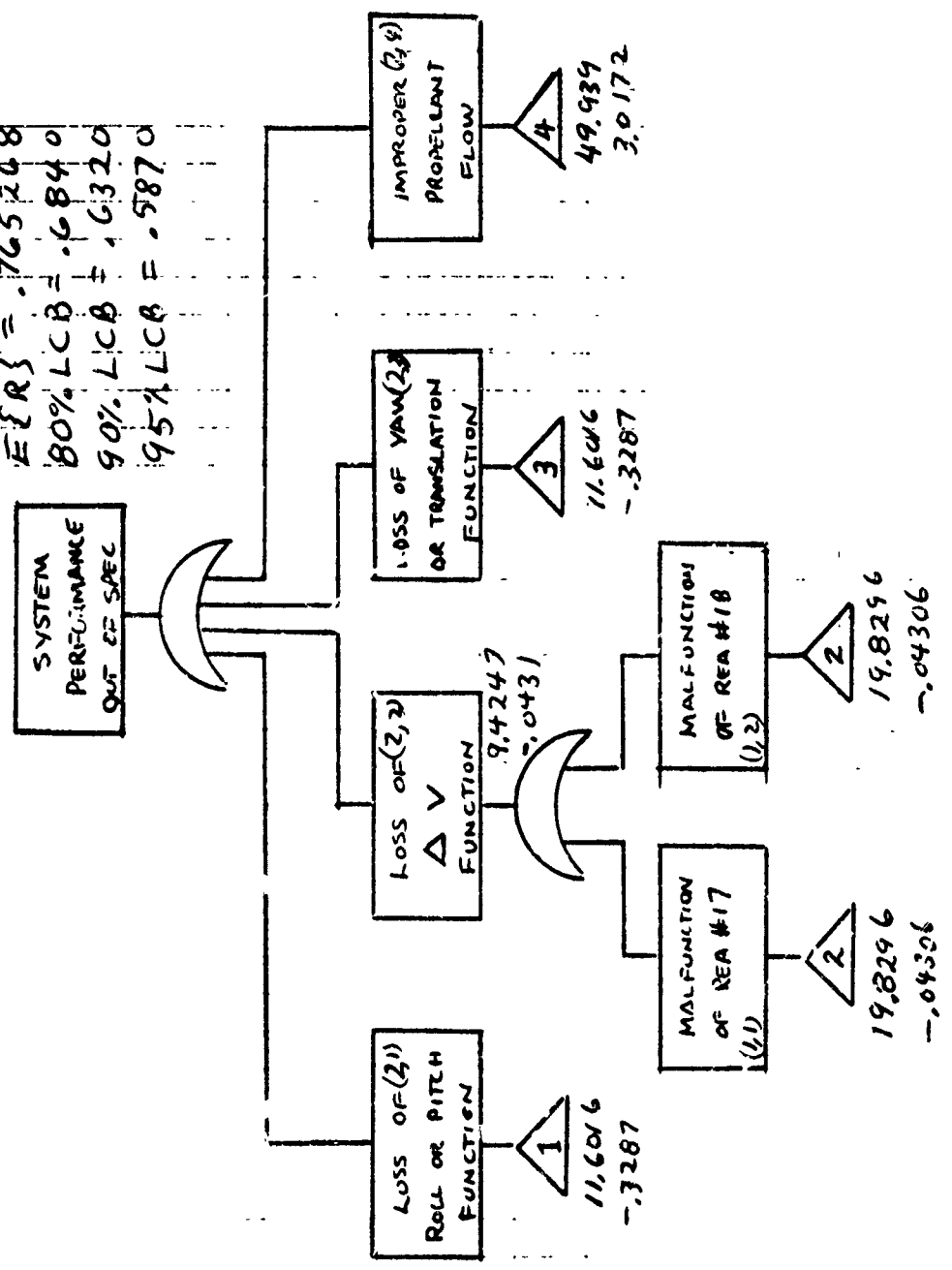
19.8296 -.0431 .956077 .915925 .00184293

END OF DATA AT 58  
BASIC EXECUTION ERROR

SBU 0.701 UNTS.

RUN COMPLETE.

$ER\} = .765248$   
 $80\% LCB = .6840$   
 $90\% LCB = .6320$   
 $95\% LCB = .5870$



90000 DATA 19.8296,-.04306,19.8296,-.04306  
RUN

76/12/15. 14.30.49.  
PROGRAM BETFTA

FOR EXPLANATION LIST 8000  
HOW MANY LEVELS?

? 2

EVENTS? (LOWEST FIRST) (SINGLE ASSUMED AT TOP)

? 2

DESTINATION?

1 1 ? 1

1 2 ? 1

CONDITIONALS?(0,0=SKIP)

? 0,0

GATE TYPES

2 1 ? 3

2 1 9.42466 -4.30988E-2

SYSTEM (ITERATION 1)

ALPHA BETA E(P) E(P\*P) V(P)

9.4247 -.0431 .915925 .845139 .00621942



PROGRAM BETAL1

RUN IN DOUBLE PRECISION  
PERMIT NEGATIVE BETA?

? 1

TYPE OF INPUT?

1=PARAMETERS, 2=MOMENTS (MEAN & VAR)

? 1

HOW MANY COMPONENTS?

? 4

VALUES? (THIRD VALUE IS COST OF FIRST TEST)

? 11.6016, -.3287, 10

? 9.4247, -.0431, 10

? 11.6016, -.3287, 10

? 49.939, 3.0172, 10

DISPLAY COMPONENT VALUES?

? 1

NO.	ALPHA	BETA	E(P)	E(P*P)	V(P)	COST
1	11.60	-.33	.949423	.904769	.00336433	10.00
2	9.42	-.04	.915926	.845139	.00621937	10.00
3	11.60	-.33	.949423	.904769	.00336433	10.00
4	49.94	3.02	.926902	.860358	.00121086	10.00

FOR SYSTEM

E(R)	E(R*R)	V(R)
.765268	.595227	.00959154

CLOSURE

.999564

LOWER CONF. BOUNDS

80 .6840 90 .6320 95 .5870

### EXAMPLE III M-out-of-N Redundance

In addition to standby redundancy (exemplified by the dual PCC's and Thrusters of the Mercury ion system of Example I) a system can employ m-out-of-n redundancy where n units are all in operation but only m are required for successful mission completion. There are two types of m-out-of-n dedundancy, identical and independent. The identical case is that in which all (n) components not only have identical failure rate expectations and variances, but are of the same type (e.g. compositor resistor of the same rating and resistance value and hence likely to come from the same manufacturing lot). The independent case includes (1) similar components with identical failure rate expectation and variances, coming from different manufacturing lots and (2) dissimilar components, regardless of their failure rate and variance values, meeting the m-out-of-n criterion.

#### A. Identical M-out-of-N Redundancy

The colloid thruster system presents a good example of identical m-out-of-n redundancy. Twelve identical thrust modules make up the thrust unit of the system. However the system can successfully complete a mission with less than all twelve modules operating. First the lower bound and median reliability, and  $\alpha$  and  $\beta$  values for the Colloid Thruster Module (CTM) component are determined using COMPI. The reliability at the 8000 operating hour will be computed.

```
PROGRAM  COMPI

OUTPUT FORM: IS
R.05      K.5      ALPHA      BETA

COMPONENT CODE?(ZZ=END)
? CTM
OPTIME=? (O=END)
? 8000
  .952067      .998162      28.0522      -.7334
OPTIME=?
? 0
```

Program BETSB3 has been developed for the Identical M-out-of-N case and is next used. For the purpose of this example ten modules of the total twelve will

be assumed to be required. Further the component input data will use the parameter option, that is, the  $\alpha$  and  $\beta$  output of COMPl will be used. (BETSB3 can also accept input information in the form of the mean value of reliability and the variance). BETSB3 output provides  $\alpha$ ,  $\beta$ ,  $E\{R\}$ ,  $E\{R^2\}$  and  $V\{R\}$  for the subsystem of the twelve modules.

PROGRAM BETSB3

M-OF-N IDENTICAL  
 RUN IN DOUBLE PRECISION  
 TYPE OF INPUT(1=PARAM,2=MEAN&VAR)  
 ? 1  
 HOW MANY COMPONENTS?  
 ? 12  
 HOW MANY REQ'D?  
 ? 10  
 VALUES  
 ? 28.0522,-.7334

SUBSYSTEM				
ALPHA	BETA	E(R)	E(R*R)	V(R)
8.3306	-.9700	.99679445	.99390757	.00030841

IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED

SUBSYSTEM				
ALPHA	BETA	E(R)	E(R*R)	V(R)
309.9585	.0000	.99679445	.99360938	.00001021

Note the first value of BETA in the output is negative. This implies a lognormal uncertainty distribution that has degenerated to a J shape. If for some application the degenerated lognormal is not permissible, the program in this situation sets  $\beta$  equal to zero (the lowest possible value for  $\beta$  without curve shape degeneration) and recomputes the other parameters. The principal differences are in the value of  $\alpha$  and the variance  $V\{R\}$ . The latter parameter will always be understated if the constraint of  $\beta \geq 0$  (non degenerate log normal uncertainty distribution) is applied. The degree of understatement will vary from

case to case.

B. Independent M-out-of-N Redundancy

Program BETSB2 was developed to address the independent M-out-of-N case. It was developed to present the complete M-out-of-N situation, even though the systems included in this study do not employ such a configuration. For the purpose of presenting a comparative example the colloid thruster module (CTM) used in example IIIA will be used here AS IF the independent m-out-of-n criteria had been met.

```
PROGRAM   BETSB2

M-OF-N, INDEPENDENT
RUN IN DOUBLE PRECISION
TYPE OF INPUT(1=PARAM,2=MEAN&VAR)
? 1
HOW MANY COMPONENTS?
? 12
HOW MANY REQ'D?
? 10
SAME PARAMS?(1=YES,0=NO)
? 1
VALUES?
? 28.0522,-.7334
SUBSYSTEM
ALPHA    BETA      E(R)      E(R*R)     V(R)

*1498.6459  -.7667  .99984445  .999689031  .00000010
 1498.65

IF NEGATIVE SUBSYSTEM BETA NOT ALLOWED
SUBSYSTEM
ALPHA    BETA      E(R)      E(R*R)     V(R)

*6426.8587  .0000  .99984445  .999688951  .00000002
 6426.86
```

Again a negative value for BETA resulted, and as in BETSB3, the  $\beta \geq 0$  alternative was computed and presented.

APPENDIX B  
AGGREGATES OF BETA - DISTRIBUTED VARIATES

APPENDIX B

AGGREGATES OF BETA - DISTRIBUTED VARIATES

Consider a set of N stochastically independent events whose probabilities of occurrence (nonoccurrence) are represented by  $P_i$  ( $1-P_i = q_i$ ),  $i = 1, 2, \dots, N$ . Suppose that the  $P_i$  ( $q_i$ ) are themselves Beta - distributed random variables, so that the probability density function for  $P_i$  may be written

$$f(P_i) = \frac{\Gamma(\alpha_i + \beta_i + 2)}{\Gamma(\alpha_i + 1)\Gamma(\beta_i + 1)} P_i^{\alpha_i} (1-P_i)^{\beta_i}, \begin{cases} \alpha_i > -1 \\ \beta_i > -1 \end{cases} \quad (1)$$

where the  $\alpha_i, \beta_i$  may, but need not, be alike for some or all  $i$ . It is well known that

$$E \{P_i\} = \frac{\alpha_i + 1}{\alpha_i + \beta_i + 2} \quad (2)$$

$$E \{P_i^2\} = \frac{(\alpha_i + 1)(\alpha_i + 2)}{(\alpha_i + \beta_i + 2)(\alpha_i + \beta_i + 3)} \quad (3)$$

where  $E \{ \}$  denotes the expected value of the variable in braces.

We shall be interested in the probabilities of occurrence of higher-level events bearing known relationships to the event sets under consideration. Specifically, we shall consider three relationships of special interest in reliability. Letting  $P_i$  represent the probability of occurrence of "Success" of the  $i$ th component and  $R$  the probability of occurrence of a higher-level event (the "success" of an aggregate of components corresponding to the N events), we have

$$R = \prod_{i=1}^N P_i \quad (4)$$

corresponding to a "series" (N - of - N) system,

$$R = 1 - \prod_{i=1}^N q_i \quad (5)$$

corresponding to a "redundant" (1 - of - N) system, and

$$R = \sum_{x=M}^N \binom{N}{x} p_i^x q_i^{N-x}, \quad p_1 = p_2 = \dots = p_i = \dots = p_N \quad (6)$$

corresponding to an "M - of - N redundant" system (of N like components).

In each case, we shall desire a distributional description of R in addition to  $E\{R\}$  and the variance  $V\{R\}$

The relationship between the  $P_i$  and R involves further independence considerations. If the  $P_i$  are distributed differently or identically and independently (i.i.d.) the series case is

$$E\{R\} = \prod_{i=1}^N E\{P_i\} = \prod_{i=1}^N \frac{\alpha_i + 1}{\alpha_i + \beta_i + 2} \quad (7)$$

$$E\{R^2\} = \prod_{i=1}^N E\{P_i^2\} = \prod_{i=1}^N \frac{(\alpha_i + 1)(\alpha_i + 2)}{(\alpha_i + \beta_i + 2)(\alpha_i + \beta_i + 3)} \quad (8)$$

and, as in all cases, the variance is

$$V\{R\} = E\{R^2\} - [E\{R\}]^2 \quad (9)$$

It is known that Beta-distributed  $P_i$  do not lead to a Beta-distributed R, and exact description and evaluation of the distribution of R are cumbersome at best. For integer  $\alpha_i$  and  $\beta_i$ , exact evaluation is possible through a Mellin integral transform described by Springer and Thompson. The results for a number of cases have been compared to those obtained by fitting a Beta-distributed to  $E\{R\}$ ,  $V\{R\}$  and performing numerical integration; the cumulants generally agree to three decimal places or better.

We regard the fitting of a Beta distribution as satisfactory and appropriate. The fitting process is straightforward; writing

$$f(R) = \frac{\Gamma(A+B+2)}{\Gamma(A+1)\Gamma(B+1)} R^A (1-R)^B$$

we have \*

$$B = 1 - \frac{E\{R^2\}}{E\{R\}} \cdot \frac{E\{R\}-1}{E\{R\} - \frac{E\{R^2\}}{E\{R\}}} \quad (10)$$

$$A = [B+1] \cdot \frac{E\{R\}}{[1-E\{R\}]} - 1 \quad (11)$$

For the redundant (1 - of - N) case with the  $P_i$  independent

$$E\{R\} = 1 - \prod_{i=1}^N [1 - E\{p_i\}] = 1 - \prod_{i=1}^N E\{q_i\} = \prod_{i=1}^N \frac{\beta_i + 1}{\alpha_i + \beta_i + 2} \quad (12)$$

$$\begin{aligned} E\{R^2\} &= 1 - 2 \left[ 1 - E\{R\} \right] + E\{(1-R)^2\} = 1 - 2 E\{q_i\} \prod_{i=1}^N E\{q_i\} + \prod_{i=1}^N E\{q_i^2\} \\ &= 1 - 2 \prod_{i=1}^N \frac{\beta_i + 1}{\alpha_i + \beta_i + 2} + \prod_{i=1}^N \frac{(\beta_i + 1)(\beta_i + 2)}{(\alpha_i + \beta_i + 2)(\alpha_i + \beta_i + 3)} \end{aligned} \quad (13)$$

Since the distributions of  $R$  and  $(1 - R)$  are perfectly symmetrical, with  $E\{R\} = 1 - E\{1 - R\}$  and  $V\{R\} = V\{1 - R\}$ , the validity of the approximation for the series case is not impaired in the redundant case.

\* Under some conditions, this procedure leads to  $B < 0$  (or  $A < 0$ ), implying that the behavior of  $f(R)$  near  $R = 1$  ( $R = 0$ ) is inconsistent with the component p.d.f.'s if all  $B_i > 0$  (all  $\alpha_i > 0$ ). If this is unacceptable, set  $B = 0$  ( $A = 0$ ); this also results in an arbitrary reduction in  $V_R$ .



Of interest also are the relationships involving independence of occurrence, but not of prior probabilities of occurrence. By this is meant that for any two events, say the success events J and K among the N events,

$$P_K | J = P_K$$

but

$$P_K = P_j$$

where  $P_K$  and  $P_j$  remain Beta-distributed random variables (i.e.,  $\alpha_K, \alpha_j, \beta_K = \beta_j$ ). A physical example of such a situation would arise if a subsystem involved two pyrotechnic devices drawn from the same production lot, the reliability of devices from that lot being unknown but constituting a random sample from a Beta distribution describing the lot-to-lot variation in reliability. The corresponding models are not restricted to two such devices, for the series case,

$$E \{R\} = E P_i^N = \prod_{i=1}^N \frac{\alpha + i}{\alpha + \beta + i + 1} \quad (12)$$

$$E \{R^2\} = E \{P_i^{2N}\} = \prod_{i=1}^{2N} \frac{\alpha + i}{\alpha + \beta + i + 1} \quad (13)$$

where  $\alpha = \alpha_1 = \alpha_2 = \dots = \alpha_N = \beta_1 = \beta_2 = \dots = \beta_N$ .

Similarly, for the redundant (1-of N) case

$$E \{R\} = 1 - E \{9_i^N\} = 1 - \prod_{i=1}^N \frac{\beta + 1}{\alpha + \beta + i + 1} \quad (14)$$

$$\begin{aligned} E \{R^2\} &= 1 - 2[1 - E \{R\}] + E \{(1-R)^2\} = 1 - 2E \{9_i^N\} + E \{9^{2N}\} \\ &= 1 - 2 \prod_{i=1}^N \frac{\beta + 1}{\alpha + \beta + i + 1} \end{aligned} \quad (15)$$

Among the interesting consequences is that the series-case  $E\{R\}$  is greater for identical than for i.i.d. components, while the converse is true in the redundant case.

It should be noted that combinations of identical with different or i.i.d. components can be handled by applying the procedure in two stages.

The M-of-N redundant case with different or i.i.d. components is more complex due to nonzero covariance terms associated with the various "success" outcomes, even though the components as such are independent. To illustrate this, consider a three-component aggregate with 2-of-3 redundancy. Let the component non-failure events be denoted by J,K,L with  $P(J) = P_j$ ,  $P(K) = P_k$ ,  $P(L) = P_l$ , and the system success event S with  $P(S) = R$ . Then

$$S = (J \cap K \cap L) \cup (\bar{J} \cap K \cap L) \cup (J \cap \bar{K} \cap L) \cup (J \cap K \cap \bar{L})$$

$$R = P_j \cdot P_k \cdot P_l + P_j \cdot P_k \cdot \bar{P}_l + P_j \cdot \bar{P}_k \cdot P_l + P_j \cdot P_k \cdot \bar{P}_l$$

Since J, K and L are independent,

$$E\{R\} = E\{P_j\} \cdot E\{P_k\} \cdot E\{P_l\} + E\{P_j\} \cdot E\{P_k\} \cdot E\{\bar{P}_l\} \\ + E\{P_j\} \cdot E\{\bar{P}_k\} \cdot E\{P_l\} + E\{P_j\} \cdot E\{P_k\} \cdot E\{\bar{P}_l\}$$

but

$$V\{R\} = V\{1-R\} = V\{P_j P_k P_l + P_j P_k \bar{P}_l \\ + P_j \bar{P}_k P_l + P_j P_k \bar{P}_l\}$$

rather,

$$V\{R\} = V\{1-R\} = V\{P_j P_k P_l\} + V\{P_j P_k \bar{P}_l\} \\ + V\{P_j \bar{P}_k P_l\} + V\{P_j P_k \bar{P}_l\} \\ + 2 \text{COV}\{P_j P_k P_l, P_j P_k \bar{P}_l\}$$

$$\begin{aligned}
& +2 \text{ COV } \left\{ P_j P_k P_l, P_j^9 P_k P_l \right\} \\
& +2 \text{ COV } \left\{ P_j P_k P_l, P_j P_k^9 P_l \right\} \\
& +2 \text{ COV } \left\{ P_j P_k P_l, P_j P_k P_l^9 \right\} \\
& +2 \text{ COV } \left\{ P_j P_k P_l, P_j P_k^9 P_l^9 \right\} \\
& +2 \text{ COV } \left\{ P_j P_k P_l, P_j^9 P_k P_l^9 \right\}
\end{aligned} \tag{16}$$

Additional notation is useful in generalizing this. Denoting by  $Y$  the number of distinct success states in  $M$ -of- $N$  redundancy,

$$Y = \sum_{X=M}^N \binom{N}{X} \tag{17}$$

Let  $s, t$  be the indices of any two of the  $Y$  distinct success states, and  $R_s$  ( $R_t$ ) the probability of occurrence of the  $s$ 'th ( $t$ 'th) such state. Then

$$V \{R\} = V \left\{ \sum_{s=1}^N R_s \right\} = \sum_{s=1}^Y V \{R_s\} + 2 \sum_{s=1}^Y \sum_{t=s+1}^Y \text{COV}(R_s, R_t) \tag{18}$$

where

$$\text{COV} \{R_s R_t\} = E \{R_s R_t\} - E \{R_s\} E \{R_t\} \tag{19}$$

now define

$$h(i, r) = 1 \quad \text{if the } r\text{'th success state implies component success } I \tag{20a}$$

$$h(i, r) = 0 \quad \text{if the } r\text{'th success state implies component failure } I \tag{20b}$$

For example, if the  $r$ 'th success state is defined by  $J_n K_n L$ ,

$$h(j,r) = 1$$

$$h(k,r) = 1$$

$$h(l,r) = 0$$

then

$$E \{R_s R_t\} = \prod_{i=1}^N \left[ \prod_{x=1}^{h(i,s)} (\alpha_i + x) \cdot \prod_{x=1}^{2-h(i,s)-h(i,t)} (\beta_i + x) \right] \quad (21)$$

where

$$\prod_{x=1}^0 (\alpha_i + x) = \prod_{x=1}^0 (\beta_i + x) = 1$$

$$E \{R_r\} = \prod_{i=1}^N \frac{(\alpha_i + 1)^{h(i,r)} (\beta_i + 1)^{[1-h(i,r)]}}{\alpha_i + \beta_i + 2} \quad (22)$$

$$V \{R_r\} = \prod_{i=1}^N \frac{[(\alpha_i + 1)(\alpha_i + 2)]^{h(i,r)} [(\beta_i + 1)(\beta_i + 2)]^{[1-h(i,r)]}}{(\alpha_i + \beta_i + 2)(\alpha_i + \beta_i + 3)} - [E \{R_r\}]^2 \quad (23)$$

allowing evaluation of (19) and (18). Of course,

$$E \{R\} = \sum_{r=1}^N E \{R_r\} \quad (24)$$

Obvious computational simplifications are available when the components are i.i.d., but care must be exercised because  $E R_s R_t$  depends on identity/nonidentity of the failed/unfailed components in the s'th and t'th states. For example, if the 2nd state is defined by J K L, the 5th by J K L, and the 7th by J K L, usually

$$E \{R_2 R_5\} \quad E \{R_2 R_7\}$$

(This example is chosen for simplicity; normally 1-of-3 redundancy would be evaluated as an ordinary redundant case.)

There remains the M-of-N redundant case for identical components. Expressions (18), (19), and (24) remain valid, but (21) - (23) are replaced by different (and simpler) forms.

Count the number of component successes in the s'th and t'th case and denote these by  $H_s$  and  $H_t$ , respectively; i.e.

$$H_s = \sum_{i=1}^N h(i,s)$$

$$H_t = \sum_{i=1}^N h(i,t)$$

then

$$E\{R_s R_t\} = \prod_{i=1}^{H_s+H_t} (\alpha+i) \prod_{i=1}^{2N-H_s H_t} (\beta+i) \cdot \prod_{i=1}^{2N} \frac{1}{(\alpha+\beta+i+1)} \quad (25)$$

where again

$$E\{R_r\} = \prod_{i=1}^{H_r} (\alpha+i) \cdot \prod_{i=1}^{N-H_r} (\beta+i) \cdot \prod_{i=1}^N \frac{1}{(\alpha+\beta+i+1)} \quad (26)$$

$$V\{R_r\} = \prod_{i=1}^{2H_r} (\alpha+i) \cdot \prod_{i=1}^{2(N-H_r)} (\beta+i) \cdot \prod_{i=1}^{2N} \frac{1}{(\alpha+\beta+i+1)} \quad (27)$$

**APPENDIX C**  
**BIBLIOGRAPHY**

This bibliography is designed to enlighten the reader as to documents that are available in the field of reliability estimation procedures for electric and thermochemical propulsion systems. The bibliography is divided into eight separate sections:

- . Electric (Ion)
- . Electric (Colloid)
- . Electric (Pulsed Plasma)
- . Electric (General)
- . Thermo-Chemical (Electro-Thermal Monopropellant)
- . Thermo-Chemical (Catalytic Monopropellant)
- . Thermo-Chemical (Bipropellant)
- . Thermo-Chemical (General).

Within each section, the documents are subcategorized by the source (company, agency, or organization) which authored them. This subcategorization was selected in order to help the reader obtain any documents he may wish, directly from the source responsible for them. This is especially helpful in the cases of papers authorized by an organization for either publication separately, as part of a conference, or within a journal. All documents in these subcategories are then arranged alphabetically by title.

Note: All bibliographic citations that are followed by an asterisk (\*) refer to documents that were obtained in performance of this contract.

## BIBLIOGRAPHY

### 1. ELECTRIC (ION)

#### (1) American Institute of Aeronautics and Astronautics (AIAA)

##### 1. Conferences

"Auxiliary Propulsion Thruster Performance with Ion Machined Accelerator Grids," W. R. Hudson, Lewis Research Center, NASA TM X-71653, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 19-21, 1975. \*

"Measurement of Ion Thruster Exhaust Characteristics and Interaction with Simulated ATS-F Spacecraft," R. Worlock et al, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, November 1973. \*

"A Prototype North-South Stationkeeping Thruster," W. D. Ramsey and E. L. James, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 1974.

"Spacecraft Integration of an Ion Propulsion System," R. Worlock, Presented at the AIAA/SAE 9th Propulsion Conference, Las Vegas, Nevada, November 1973. \*

"Status of 30 cm Mercury Ion Thruster Development," J. S. Sovey and H. J. King, Presented at the AIAA 10th Propulsion Conference, San Diego, California, October 21-24, 1974. \*



## 2. Journals

"Cesium Election-Bombardment Ion Microthrusters," G. Sohl, et al., AIAA Journal of Spacecraft and Rockets, Volume 4, Number 9, pages 1180-1183, September 1967.

"Experimental Mercury Bombardment Thruster at Submillipound Thrust," W. R. Kerlake, J. R. Wasserbauer and P. M. Morgosian, AIAA Journal, Number 4, pages 683-691, April 1967.

"Experimental Results in High-Specific-Impulse Thermo-Ionic Acceleration," A. C. Ducati, G. M. Giannini and E. Muchlberger, AIAA Journal, Volume 2, Number 8, pages 1452-1454, August 1964.

"Ion Propulsion," A. T. Forrester and G. Kuskevics, AIAA Selected Reprints Series, Volume III by R. A. Gross, Published by AIAA, New York, New York.

"Performance of Ion Engines and Systems for Satellite Control," J. R. Anderson, AIAA Journal of Spacecraft and Rockets, Volume 3, Number 7, pages 1086-1092, July 1966.

"SERT II: Durability of the Hollow Cathode and Future Applications of Hollow Cathodes," V. K. Rawlin and W. R. Kerlake, AIAA Journal of Spacecraft and Rockets, Volume 7, Number 1, pages 14-20, January 1970.

## 3. Papers

"An Advanced Contact Ion Microthruster System," R. M. Worlock, et al., AIAA Paper 68-552, Presented at the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 1968.

"Bombardment Thruster Investigation at the Lewis Research Center, F. A. Richley and W. R. Kerlake, AIAA Paper 68-542, Presented at the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 1968.

3. Papers (Continued)

"The Cesium Bombardment Engine North-South Stationkeeping Experiment on ATS-6," R. M. Worlock, E. L. James, R. E. Hunter, R. D. Bartlett, AIAA Paper 75-363, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 19-21, 1975.\*

"Cesium Contact Ion Microthruster Experiment Aboard Applications Technology Satellite (ATS) IV," R. E. Hunter, R. O. Bartlett, R. M. Worlock, and E. L. James, AIAA Paper 69-297, Presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"A Cesium Electron-Bombardment Microthruster System," V. V. Forsnight, G. Stohl, E. Caplinger, E. H. Schrouf, and T. R. Dillion, Air Force Contract F 33615-67-C-1268, AIAA Paper 69-293, Presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"Cesium Electron-Bombardment Ion Microthrusters," G. Stohl, et al., AIAA Paper 67-81, Presented at the AIAA 5th Aerospace Sciences Meeting, New York, New York, January 1967.

"Cesium Microthruster System," C. R. Collett, C. R. Dulgeroff and J. M. Simpkins, AIAA Paper 69-292, Presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"Characteristics of Micropound Range Ion Thrusters," R. M. Worlock, et al., AIAA Paper 66-212, Presented at the AIAA 5th Electric Propulsion Conference, San Diego, California, March 1966.

"A Contact Ion Microthruster System," R. M. Worlock, et al., AIAA Paper 67-80, Presented at the AIAA 5th Aerospace Sciences Meeting, New York, New York, January 1967.

3. Papers (Continued)

"Current Technology in Ion and Electrothermal Propulsion," R. C. Finke and C. K. Murch, AIAA Paper 73-1253, 1973.

"Design, Fabrication and Operation of Dished Accelerator Grids on 30 cm Thrusters," V. K. Rawlin, B. A. Banks and D. C. Byers, AIAA Paper 72-486, April 1972.

"Design of a Mercury Propellant Storage and Distribution Assembly," L. B. Holcomb and J. R. Womack, AIAA Paper 73-1119, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

"Design and Test of Porous Tungsten Mercury Vaporizers," W. R. Kerlake, AIAA Paper 73-484, April 1972. \*

"Development, Integration and Testing of a 30-cm Thruster/Power Conditioning and Control System," B. G. Herron, C. R. Collett and D. R. Garth, AIAA Paper 72-509, 1972.

"Development and Long Life Performance of Ion Engines for Satellite Control," J. R. Anderson and S. A. Thompson, Contract Number 3-7927, Paper 66-234, Presented at the AIAA 5th Electric Propulsion Conference, San Diego, California, March 1966.

"The Development of Microthrusters in France Under the C. N. E. S. Authority," J. P. Pujes, AIAA Paper 70-617, Presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

"Durability of a Five-Centimeter Diameter Ion Thruster System," S. Nakanishi, AIAA Paper 72-1151, Presented at the AIAA/SAE 8th Joint Propulsion Specialist Conference, New Orleans, Louisiana, November 29-December 1, 1972. \*

3. Papers (Continued)

"Effect of Facility Backspattered Material On Performance of Glass-Coated Accelerator Grids for Kaufman Thrusters," R. T. Bechtel, et al, AIAA Paper 71-156, Presented at the AIAA 9th Aerospace Sciences Meeting, New York, New York, January 1971.

"Endurance Testing of a 30 cm Kaufman Thruster," C. R. Collett, AIAA Paper 73-1085, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. "

"An Engineering Model 30 cm Thruster," R. L. Poeschel, H. J. King and D. E. Schnelker, AIAA Paper 73-1084, November 1973. \*

"Experimental Mercury Bombardment Thruster at ~ 1 $\mu$  Millipound Thrust," W. R. Kerlake, J. F. Wasserbauer and P. Margosian, AIAA Paper 4, Volume 5, pages 683-691, April 1967.

"Experimental Performance of a Low-Thrust, Divergent Flow, Contact-Ionization Electrostatic Thruster," J. F. Staggs and W. C. Lathern, Paper 66-569, Presented at the AIAA 2nd Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 1966.

"A Hollow Cathode Neutralizer for a 30 cm Diameter Bombardment Thruster," R. J. Bechtel, AIAA Paper 73-1052, November 1973.

"Hollow Cathodes with BaO Impregnated, Porous Tungsten Inserts and Tips," W. R. Hudson, A. J. Weigand, Lewis Research Center, AIAA Paper 73-1142, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

"Investigation of Hollow Cathode Performance for 30 cm Thrusters," AIAA Paper 73-1138, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

3. Papers (Continued)

"Investigation of Mercury Thruster Isolators," M. A. Mantienicks, AIAA Paper 73-1088, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"Ion Propulsion Flight Experience, Life Tests and Reliability Estimates," J. H. Molitor, AIAA Paper 73-1256, Invited Paper Presented at AIAA/SAE Propulsion Conference, Las Vegas, Nevada, November 5-7, 1973.\*

"Ion Thruster ESKA 8 for North-South Stationkeeping of Synchronous Satellites," G. F. Au, S. F. J. Baumgarth, Germany, AIAA Paper 73-1129, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"Life-Limiting Processes in Mercury Electron-Bombardment Ion Engines as Determined from Erosion Tests," R. F. Kemp, D. S. Goldin, W. P. Goldstein, AIAA Paper 73-1110, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"Magneto-Electrostatically Contained Plasma Ion Thruster," R. D. Moore, AIAA Paper 69-760, Presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"Measurement of Beam Divergence of 30 cm Dished Grids," R. L. Danilowicz, et al., AIAA Paper 73-1051, November 1973.

"Measurement of Double Charged Ions in the Beams of a 30 cm Mercury Bombardment Thruster," R. P. Vahrenkamp, AIAA Paper 73-1057, November 1973.

"Measurement of the Ion Thruster Exhaust Characteristics and Interaction with Simulated ATS-F Spacecraft," R. Worlock, G. Trump, J. M. Sellen, Jr.,

3. Papers (Continued)

R. F. Kemp, AIAA Paper 73-1101, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"Mercury Vapor Hollow Cathode Component Studies," D. Zucarro, AIAA Paper 73-1141, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"A 9700-Hour Durability Test of a Five Centimeter Diameter Ion Thruster," S. Nakanishi and R. C. Finke, AIAA Paper 73-1111, November 1973.\*

"A Noble Gas Ion Propulsion System, W. L. Owens, Jr., AIAA Paper 73-1114, 1973.\*

"A North-South Stationkeeping Ion Thruster System for ATS-F, E. L. James, et al., AIAA Paper 73-1133, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"A One Millipound Cesium Ion Thruster System, E. L. James, et al., AIAA Paper 70-1149, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, August 31-September 2, 1970.\*

"One-Millipound Mercury Ion Thruster," J. Hyman, Jr., C. R. Dulgeroff, S. Kami, W. S. Williamson, AIAA Paper 73-386, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 19-21, 1975.\*

"Optimization of Ion Propulsion for North-South Stationkeeping of Communications Satellites," W. L. Owens, AIAA Paper 72-1150, November 1972.

"Performance of 30 cm Ion Thrusters with Dished Accelerator Grids," V. K. Rawlin, AIAA Paper 73-1053, November 1973.

3. Papers (Continued)

"Power Processing Systems for Ion Thrusters," B. G. Herron, et al., AIAA Paper 72-518, April 1972. \*

"The RAE/Culham T4 10 cm Electron-Bombardment Mercury Ion Thruster," D. G. Fearn, R. Hastings, C. M. Philip, P. J. Harbour, H. H. H. Watson, England, AIAA Paper 73-1130, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

"Recent Experimental Results in RIT-Engines Development," German Paper, AIAA Paper 73-1083, November 1973. \*

"A Reliability Tradeoff Study of Interconnection of Interconnecting Power Processors to Mercury Ion Thrusters," E. N. Costogue, P. O. Chelson, AIAA Paper 75-435, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 1975. \*

"Satellite Control Mercury Ion Thruster," J. Hyman, Jr. and R. L. Poeschel, AIAA Paper 73-1132, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

"Segmented Anode, CO<sub>2</sub>-H<sub>2</sub> Performance and Hollow Cathode Erosion Tests on A Low Power MPD Arc Thruster," J. Burkhardt, AIAA Paper 69-242, Presented at the AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"Solar-Electric Propulsion System Evaluation," T. W. Macie, E. V. Pawlik, J. D. Ferrera, E. N. Costogue, AIAA Paper 69-498, Presented at the AIAA 5th Propulsion Joint Specialist Conference, U.S. Air Force Academy, Colorado, June 9-13, 1969. \*

3. Papers (Continued)

"Solutions for Discharge Chamber Sputtering and Anode Deposit Spalling in Small Mercury Ion Thrusters," J. L. Power, D. J. Hiznay, NASA TM X71675. Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 19-21, 1975. \*

"Sputter Erosion and Deposition in the Discharge of a Small Mercury Ion Thruster," J. L. Power, Lewis Research Center, AIAA Paper 73-1109, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973. \*

"Studies of Dished Accelerator Grids for 30 cm Ion Thrusters," V. K. Rawlin, AIAA Paper 73-1086, November 1973.

"A Sub-Millipound Mercury Electron-Bombardment Thruster," P. E. Reader, et al., Paper 70-616, Presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

"A 30-cm Thruster Power Processor Test Console," B. G. Herron, et al., AIAA Paper 73-1104, 1973.

"The Variable Magnetic Baffle as a Control Device for Kaufman Thrusters," R. L. Poeschel, AIAA Paper 73-488, April 1972.

(2) United States Air Force

Applicability of Electric Propulsion for Future Military Satellites, C. W. Thomas, W. M. Adams, OAS, Kirtland Air Force Base, Project 63101F, Report Number OAS-TR-73-4, September 1973. \*

Arc-Over and Rapid Pumpdown Tests on the Cesium Contact Ionization Engine Flight Test Payload, E. T. Mahefkey, R. H. Johnson, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, May 1964. \*



(2) United States Air Force (Continued)

Cesium Bombardment Ion Engine System Development,  
R. M. Worlock, et al., Air Force Technical Report  
AFAPL-TR-69-87, October 1969.

Ion Engine Systems Testing, E. L. James and S. J.  
Goldner, Air Force Report AFAPL-TR-69-112,  
February 1970.

(3) Aeronautic Research Laboratory (ARL)

"Theoretical Consideration of Nonuniformly Charged Ex-  
pellant Beams," R. E. Hunter, Air Force Research Di-  
vision, Aeronautic Research Laboratory, ARL Technical  
Note 60-138, October 1960.

(4) ARS

"Design and Performance of Small Ion Engines," G. R.  
Brewer, J. E. Etter and J. R. Anderson, ARS Preprint  
1125-60, May 1960.

"Experimental Studies of Cesium Ion Rocket Performance,"  
R. N. Edwards, et al., ARS Paper 5, Presented at the  
ARS Semi-Annual Meeting, Los Angeles, California, May  
1960.

"Experimental Studies with Small Scale Ion Motors,"  
R. C. Speiser, C. R. Dulgeroff and A. T. Forrester,  
ARS Preprint 926, Presented at the 14th ARS Annual  
Meeting, Washington, D. C., November 1959.

"Ion Propulsion Systems: Experimental Studies,"  
S. Naiditch, et al., ARS Preprint 928-59, Presented at  
the 14th ARS Annual Meeting, Washington, D. C.,  
November 1959.

"Space Charge Measurements in Expanding Ion Beams,"  
J. M. Sellen and H. Shelton, ARS Preprint 1160-60,  
May 1960.

(5) Battelle Memorial Institute

"Thermal Radiative Properties of Selected Materials,"  
W. D. Wood, H. W. Deem and C. F. Lucks, Report to  
Office of Director of Defense Research and Engineering,  
Defense Metals Information Center, Battelle Memorial  
Institute, Columbus, Ohio, Report 177, Volume 1,  
page 65, November 1962.

(6) Bell Aerosystems Company

Study of Spacecraft Attitude Control Propulsion Devices,  
Bell Aerosystems Company, Report Number 8214-933001,  
December 1962. (Confidential)\*

(7) Colorado State University

Performance of a 15-cm Ion Thruster with Reliable  
Restart Capability, Colorado State University, November  
1973. \*

Technology of Electron-Bombardment Ion Thruster,  
Colorado State University, 1974. \*

(8) Electro-Optical Systems, Incorporated

Part I—"Electric Thrusters Survey," From Auxiliary  
Propulsion Survey, R. Shattuck, Electro-Optical Systems  
For the U. S. Air Force, Technical Report AFAPL-TR-68-67,  
September 1968. \*

Election Bombardment Cesium Ion Engine System, G.  
Sohl, V. V. Fosnight and S. J. Goldner, Electro-Optical  
Systems, Incorporated, EOS Report 6954 CR-54711,  
December 1966.

Reliability of the Flight Test Ion Thruster, M. P. Ernstene,  
Electro-Optical Systems, Incorporated for the U. S. Air  
Force, Contract Number AF33-657-10150, Report Number  
3450F, May 1964.

(8) Electro-Optical Systems, Incorporated (Continued)

Survey of U. S. Programs Related to Satellite Propulsion, Orientation and Station Keeping Devices, Electro-Optical Systems, Incorporated, Contract F 33615-67-C-1854, May 1967.

(9) Energy Research and Development Administration (ERDA)

Small Nuclear (Isotope) Powered Thrusters for Satellite Maneuvers, I. Helms, SNS Division, Energy Research and Development Administration, undated.\*

(10) Hittman Associates

A Study of Cesium Exhaust from An Ion Engine and Its Effect Upon Several Spacecraft Components, W. Lyon, Hittman Associates, Report HIT-399, June 1969.\*

A Study of the Effects of a Cesium Ion Thruster Upon a Polaris Star Tracker for ATS-F and ATS-G, W. Lyon, Hittman Associates, for the National Aeronautics and Space Administration, Contract NAS5-9479, May 1970.\*

A Study of Environmental Effects Caused by Cesium from Ion Thrusters, W. Lyon, Hittman Associates, for the National Aeronautics and Space Administration, Contract NAS5-11826, March 1971.\*

(11) Hughes Aircraft Company

"A Configurational Analysis of the Effects of Electrode Geometry On the Mass Utilization Efficiency of Ion Thrusters," D. Zucarro, Hughes Aircraft Company Interdepartmental Correspondence, Malibu, California, December 17, 1973.

Ion Engine Reliability as Affected by Corrosion of Materials, P. M. Winslow, Hughes Aircraft Company, Report No. HAC-63032, NTIS AD-406-675, 1963.\*

(11) Hughes Aircraft Company (Continued)

Ion Propulsion - A Key to Space Exploration, Hughes Aircraft Company, January 1968.\*

(12) Hughes Research Laboratories

Ion Microthruster System Design Report, Hughes Research Laboratories, Contract Number NAS5-12513, Malibu, California, October 1969.

Mercury Bombardment Ion Thrusters: Development Status, Performance Levels, and Test History, J. H. Molitor, Hughes Research Laboratories, Malibu, California, 1975.\*

(13) Jet Propulsion Laboratory (JPL)

Actuator Endurance Testing for a Clustered Ion Engine Array, J. D. Ferrera, E. V. Pawlik, Jet Propulsion Laboratory, SPS 37-58, Volume III, August 1969.\*

Development of a Mercury Propellant Storage and Distribution Assembly, Jet Propulsion Laboratory, March 1975.\*

Operation of a 20-cm-diam. Electron-Bombardment Ion Thruster with a Hollow Cathode, E. V. Pawlik, T. D. Masek, Jet Propulsion Laboratory, SPS 37-49, Volume III, February 29, 1968.\*

Suitability of a Hollow Cathode for a 20-cm-diam. Ion Engine, E. V. Pawlik, D. J. Fitzgerald, Jet Propulsion Laboratory, SPS 37-48, Volume III, pages 119-125, December 31, 1967.\*

Thruster Failure Modes, Jet Propulsion Laboratory, undated.\*

(14) National Aeronautics and Space Administration (NASA)

Design and Development of a Small Structurally Integrated Ion Thruster System, J. Hyman, Jr., et al., Final Report, NASA, Contract NAS 3-14129, NASA Report CR-120821.

8-cm Mercury Ion Thruster System Technology, Lewis Research Center, NASA, October 1974.\*

5000-Hour Test of a Grid-Translation Beam Deflection System for a 5-cm Diameter Kaufman Thruster, W. C. Latham, Lewis Research Center, NASA TM X-68185, January 15, 1973.\*

Low Voltage 30 cm Ion Thruster, H. J. King, et al., Final Report, NASA, Contract NAS3-14140, NASA CR-120919.

Low Voltage 30 cm Ion Thruster, H. J. King, et al., Final Report, NASA, Contract NAS3-16528.

1000-Hour Endurance Test of A Glass-Coated Accelerator Grid On A 15-Centimeter-Diameter Kaufman Thruster, B. A. Banks and R. T. Bechtel, NASA, NASA TN D-5891, July 1970.

Performance Optimized Small Structurally Integrated Ion Thruster System, J. Hyman, Jr., Final Report, NASA, Contract NAS 3-15483.

Plasma Fluctuations in a Kaufman Thruster, Lewis Research Center, NASA, November 1973.\*

Results from SERT I Ion Rocket Flight Test, R. J. Cybulski, D. M. Shellhammer, R. R. Lovell, E. J. Domino and J. T. Kotnik, NASA, NASA-TN-D-2718, Washington, D. C., March 1965.

"Review of Kaufman Thruster Development at the Lewis Research Center - 1973," W. R. Kerslake, NASA TM-X-6820, Presented at the "Electric Propulsion Conference," Culham, England, April 10-12, 1973.

(14) NASA (Continued)

Thrust Vectoring System, H. J. King, et al., Final Report, NASA, Contract NAS 3-15385, NASA CR-121142.

A 20,000-Hour Endurance Test of a Structurally and Thermally Integrated 5-cm Diameter Ion Thruster Main Cathode, Lewis Research Center, NASA, March 1975.\*

2-1/2 kW Advanced Technology Ion Thruster, R. L. Poeschel, et al., Final Report, NASA, Contract NAS 3-16949.

(15) Princeton University

Energy Management Technology Forecast Space Operations and Propulsion, R. G. John, K. E. Clark, School of Engineering and Applied Science, Princeton University, January 2, 1975.\*

(16) Rockwell International and North American Rockwell

Concept Definition and Systems Analysis Study for a Solar Electric Propulsion Stage, Space Division, Rockwell International for NASA, Contract Number NAS 8-30920, Report Number MA-04 DPD 436, February 3, 1975.\*

(17) Space Technology Laboratories, Incorporated

Cesium Ion Beam Neutralization in Vehicular Simulation, J. M. Sellen and R. F. Kemp, Space Technology Laboratories, Incorporated, 1961.

(18) TRW Systems, Incorporated

Electrostatic Propulsion Beam Divergence Effects on Spacecraft Surfaces, Volume III, TRW Systems, Incorporated, for the Jet Propulsion Laboratory, September 1973.

(18) TRW Systems, Incorporated (Continued)

Propulsion Beam Divergence Effects, D. Hall, TRW Systems, Incorporated, Final Report, JPL Contract 952350.

(19) Other Publications

1. Books

Ion Propulsion, G. R. Brewer, Gordon and Breach Science Publishers, New York, London, Paris, 1970.

Ion Propulsion for Space Flight, E. Stuhlinger, Chapter 1, McGraw-Hill Book Company, New York, 1964.

Ionenraketen, H. W. Loeb and J. Freisinger, Vieweg, Braunschweig, Germany, 1967.

2. Magazines

"Cesium-Ion Propulsion," A. T. Forrester and R. C. Speiser, Astronautics, Volume 4, Number 10, page 34, October 1959.

"Development of a 5-cm Flight-Qualified Mercury Ion Thruster," J. Hyman, Jr., Journal of Spacecraft and Rockets, Volume 10, Number 8, pages 503-509, August 1973.

"Experimental Performance of Ion Rockets Employing Electron-Bombardment Ion Sources," H. R. Kaufman and P. D. Reader, from Progress in Astronautics and Rocketry: Electrostatic Propulsion: Volume V. Edited by D. B. Langmuir, E. Stuhlinger and J. M. Sellen, Jr., Academic Press, New York, 1961.

2. Magazines (Continued)

"Exploratory Tests on a Downstream Cathode MPD Thruster," J. A. Burkhart, Journal of Spacecraft and Rockets, Volume 8, Number 3, pages 240-244, March 1971.

"Performance of a Modified Downstream Cathode MPD Thruster," J. A. Burkhart, Journal of Spacecraft and Rockets, Volume 10, Number 1, pages 86-88, January 1973.

"12-cm Magneto-Electrostatic Containment Mercury Ion Thruster Development," W. D. Ramsey, Journal of Spacecraft and Rockets, Volume 9, Number 5, pages 318-321, May 1972.

3. Papers/Reports

Configuration and Operating Mode of an Electric Propulsion System for Stationkeeping in the View of Reliability, German Report, November 1973.\*

Perspectives Actuelles de Developpement et D'Applications de la Propulsion Ionique (Present Status and Prospects for Applications of Ion Thrusters), E. LeGrives, Office National D'Etudes et de Recherches Aerospatiales Chatillon-Sous-Bagneux, France, Report Number Onera-Note Technique-149, September 1969.\*

Physical Behavior of Some Biowaste Gases in an Ion Engine, English Report, November 1973.\*

Physical Processes Affecting the Design and Performance of Ion Thrusters with Particular Reference to the 10-cm, RAE/CULHAM TY Thruster, English Report, November 1973.\*

Recent Hollow Cathode Investigations at the Royal Aircraft Establishment, English Report, November 1973.\*



2. ELECTRIC (COLLOID)

(1) Aerojet General Corporation

Some Technical Problems Associated With A Charged Colloid Propulsion System, R. D. Schultz, Aerojet General Corporations, Technical Memorandum 808, September 1958.

(2) AGARD

"Electric Propulsion with Colloidal Materials," R. D. Schultz and R. E. Weich, Jr., Presented at the AGARD Combustion and Propulsion Panel-Technical Meeting on Advanced Propulsion Techniques, Pasadena, California, pages 24-26, August 1960.

(3) American Institute of Aeronautics and Astronautics (AIAA) Papers

"Advanced High Thrust Colloid Sources," M. N. Huberman and S. G. Rosen, AIAA Paper 73-1075, 1975.

"Analytical Study of Colloid Annular Thrusters," J. Perel, J. F. Mahoney and A. Y. Yahiku, AIAA Paper 70-1113, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, August-September 1970.

"Colloid Annular Array Thruster Development," H. L. Daley et al., AIAA Paper 73-1077, 1973. \*

"Colloid Microthruster Life Test," S. Zafran and J. C. Beynon, AIAA Paper 70-1110, Presented at AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

"Colloid Microthruster System Development," S. Zafran, J. C. Beynon and E. Cohen, AIAA Paper 68-84, Presented at the AIAA Sixth Aerospace Sciences Meeting, New York, New York, January 1968.

(3) AIAA Papers (Continued)

"Colloid Propulsion Using Chemically-Formed Particles," W. G. Courtney and C. Budnik, AIAA Paper 66-254, Presented at the AIAA 5th Electric Propulsion Conference, San Diego, California, March 1966.

"Colloid And Pulsed Plasma Thrusters For Spacecraft Propulsion," AIAA Paper 73-1254, 1973.

"Duration Test of an Annular Colloid Thruster," J. Perel, J. F. Mahoney and H. L. Daley, AIAA Paper 72-483, 1972.

"Experimental Analysis of the Exhaust From A Colloid Thruster," C. T. Norgren and D. S. Goldin, AIAA Paper 64-674, Presented at the AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August-September 1964.

"Life Test (4350 hour) of an Advanced Colloid Thruster Module," P. W. Kidd and H. Shelton, AIAA Paper 73-1078 1973.

"Negatively Charged Colloid Generation Research," S. H. Wineland and R. E. Hunter, AIAA Paper 66-251, Presented at the AIAA Fifth Electric Propulsion Conference, San Diego, California, March 1966.

"Parametric Studies of Electrohydrodynamic Spraying," C. D. Hendricks and R. J. Pfeifer, AIAA Paper 66-252, Presented at the AIAA 5th Electric Propulsion Conference, San Diego, California, March 1966.

"Parametric Studies With a Single Needle Colloid Thruster," P. W. Kidd, AIAA Paper 67-530, Presented at the AIAA Electric Propulsion and Plasmadynamics Conference, Colorado Springs, Colorado, September 1967.

"Performance of Colloid Annular Emitters," J. F. Mahoney et al., AIAA Paper 73-1076, 1973.

(3) AIAA Papers (Continued)

"Research on a Charged Particle Bipolar Thruster,"  
J. Perel et al., AIAA Paper 57-728, Presented at the  
AIAA Electric Propulsion and Plasmadynamics Conference,  
September 1967.

"Research on a Charged Particle Bipolar Thruster,"  
J. Perel et al, AIAA Paper 67-728, September 1967.

"Thrust Measurements of Colloidal Particles as an Indi-  
cation of Particle Size and Thruster Operation," D. S.  
Goldin and C. T. Norgren, AIAA Paper 63-050, Presented  
at the AIAA Electric Propulsion Conference, Colorado  
Springs, Colorado, March 1963.

(4) United States Air Force

Charged Droplet Electrostatic Thruster Systems,  
H. Shelton et al., Air Force Technical Report AFAPL-  
TR-70-31, June 1970.

Charged Particle Electrostatic Thrusters, M. N. Huberman  
and P. W. Kidd, Air Force Technical Report AFAPL-TR-  
69-14, March 1969.

Colloid Microthruster Experiment, S. Zafran et al., Air  
Force Technical Report AFAPL-TR-70-55, August 1970.

Life Testing of A Colloid Thruster Source, W. C. Burson,  
Air Force Technical Report AFAPL-TR-69-8, May 1969.

Research on the Bipolar Thruster, P. W. Kidd, Air Force  
Technical Report AFAPL-TR-67-110, September 1967.

(5) Aeronautic Research Laboratory (ARL)

Research on the Electrostatic Generation and Acceleration  
of Submicron Size Particles, E. Cohen, Aeronautic Re-  
search Laboratory ARL 32-88-WPAFB, May 1963.

(6) American Society of Mechanical Engineers (ASME)

"Earth Orbital Mission Requirements for Secondary Propulsion Systems and Their Impact on Colloid Systems," R. A. Benson, ASME Paper 70-Av/SpT-31, Presented at the ASME Space Technology and Heat Transfer Conference, Los Angeles, California, June 1970.

(7) Electro-Optical Systems

Auxiliary Propulsion Survey, Part I--"Electric Thrusters Survey," R. Shattuck, Electro-Optical Systems For The U.S. Air Force, \* Technical Report AFAPL-TR-68-67, September 1968.

(8) Thiokol Chemical Corporation

Heavy Particle Propulsion Research, R. E. Weich, Jr., Thiokol Chemical Corporation Report Number RMD-1155-S2, December 1959.

(9) TRW Systems, Incorporated

Colloid Advanced Development Program, TRW Systems Group for the Air Force Rocket Propulsion Laboratory, Reports 1 and 2, \* Technical Report AFRPL-TR-72-10, February 1972.

Continued Development of High Performance Colloid Systems, P. W. Kidd, TRW Systems Group for the U.S. Air Force, Contract Number F04611-74-C-0014, October 1974.

Prototype One-Millipound Colloid Thruster System, TRW Systems, Incorporated, March 1975. \*

Research and Development in Colloid Thruster Technology, TRW Systems, Incorporated, TRW Proposal Number 11882.000, January 1969.

(10) Other Publications

1. Conferences

"Colloid Thruster Technology '69," E. Cohen, W. C. Burson and P. C. Herren, Jr., Presented at the 8th International Symposium on Space Technology and Science, Tokyo, 1969.

"Exploration of the Feasibility of an Electrodeless Colloid Thruster Concept," R. E. Hunter and S. H. Wineland, Presented at the Sixth International Symposium on Space Technology and Science, Tokyo, Japan, 1965.

"Progress in the Development of a One-Millipound-Thrust Colloid Propulsion System," F. A. Jackson, Presented at IEE and UKAEA Conference on Electric Propulsion of Space Vehicles, Culham, England, April 1973.

2. Magazines

"Charged Droplet Experiments," C. D. Hendricks, Journal of Colloid Science, Volume 17, pages 249-259, 1962.

"One-Millipound Colloid Thruster System Development," S. Zafran et al, AIAA Paper 72-1153 (1972), Journal of Spacecraft and Rockets, Volume 10, Number 8, pages 531-533, August 1973.

3. ELECTRIC (PULSED PLASMA)

(1) American Institute of Aeronautics and Astronautics (AIAA)

1. Journals

"Analysis of Solid Teflon Pulsed Plasma Thruster," R. J. Vondra, K. Thomassen and A. Solbes, AIAA Journal of Spacecraft and Rockets, Volume 7, Number 12, pages 1402-1406, December 1970.

"Energy Efficiency Trends in a Coaxial Gun Plasma Engine System," P. Gloersen, B. Gorowitz and J. T. Kenney, AIAA Journal, Volume 4, Number 3, pages 436-441, March 1966.

"Flight Qualified Pulsed Electric Thruster for Satellite Control," R. J. Vondra and K. I. Thomassen, AIAA Journal of Spacecraft and Rockets, Volume 11, Number 9, pages 613-617, September 1974.

"Hall Current Plasma Accelerator," G. L. Cann and G. L. Marlotte, AIAA Journal, Volume 2, Number 7, pages 1234-1241, July 1964.

"Performance of an Electrically Triggered Repetitively Pulsed Coaxial Plasma Engine," B. Gorowitz, T. W. Karras and P. Gloersen, AIAA Journal, Volume 4, Number 6, pages 1027-1031, June 1966.

"RFI Measurements on a LES-7 Prototype Pulsed Plasma Thruster," R. E. Dolbec, AIAA Journal of Spacecraft and Rockets, Volume 7, Number 7, Engineering Note, pages 889-890, July 1970.

"RFI Measurements of UHF on a Pulsed Plasma Thruster," R. L. Sicotte, AIAA Journal of Spacecraft and Rockets, Volume 7, Number 3, pages 337-338, March 1970.

(1) AIAA (Continued)

2. Papers

"Colloid and Pulsed Plasma Thrusters for Spacecraft Propulsion," S. G. Rosen, AIAA Paper 73-1254, 1973.

"Concerning the Feasibility of a Vacuum Arc Thruster," A. S. Gilmour, AIAA Paper 66-202, Presented at the AIAA 5th Electric Propulsion Conference, San Diego, California, March 1966.

"Continuing Development of the Short-Pulsed Ablative Space Propulsion System," D. J. Palumbo and W. J. Guman, AIAA Paper 72-1154, 1972.

"Current Status of Plasma Propulsion," R. R. John, S. Bennett and R. Jahn, AIAA Paper 66-565, Presented at the AIAA 2nd Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 1966.

"Current Status of Pulsed Plasma Engine Development," P. Gloersen, AIAA Paper 66-566, Presented at the AIAA 2nd Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 1966.

"Development of Solid Propellant Electric Thruster Systems for Attitude Control and Station Keeping of Spacecraft," A. V. LaRocca and G. S. Perkins, AIAA Paper 67-661, Presented at the AIAA Electric Propulsion and Plasmadynamics Conference, Colorado Springs, Colorado, September 1967.

"A Flight Qualified Electric Thruster for Satellite Control," R. J. Vondra and K. I. Thomassen, AIAA Paper 73-1067, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.

"Investigation of Plasma Rotation In A Pulsed Inductive Accelerator," C. L. Dailey, AIAA Paper 68-86, Presented at the AIAA 6th Aerospace Sciences Meeting, New York, January 1968.

"Plasma Separator Thruster," B. A. Free and W. R. Mickelsen, AIAA Paper 66-598, June 1966.

2. Papers (Continued)

"Pulsed Plasma and Low-Pressure Detonator Thrusters," A. V. LaRocca, AIAA Paper 70-1147, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

"Pulsed Plasma Microthruster Applications and Techniques," A. V. LaRocca and G. S. Perkins, AIAA Paper 68-554, Presented at the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 1968.

"Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite," W. J. Guman and D. M. Nathanson, AIAA Paper 69-298, AIAA 7th Electric Propulsion Conference, Williamsburg, Virginia, March 1969.

"Pulsed Plasma Microthruster for Synchronous Meteorological Satellite (SMS)," W. J. Guman and T. E. Williams, AIAA Paper 73-1066, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.

"Pulsed Plasma Propulsion System Studies," W. J. Guman et al., AIAA Paper 70-1141, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

"Pulsed Vacuum-Arc Microthrusters," A. S. Gilmour, R. J. Clark and H. Vernon, AIAA Paper 67-737, Presented at the AIAA Electric Propulsion and Plasmadynamics Conference, Colorado Springs, Colorado, September 1967.

"A Pulsed Vacuum-Arc System Incorporating Throttle and Thrust Vector Controls," D. L. Lockwood and L. R. Burdette, AIAA Paper 70-180, Presented at the AIAA 8th Aerospace Sciences Meeting, New York, January 1970.



2. Papers (Continued)

"Recent Progress in Pulsed Vacuum-Arc Micro-thruster Research," A. S. Gilmour, et al., AIAA Paper 68-555, Presented at the AIAA 4th Propulsion Specialist Conference, Cleveland, Ohio, June 1968.

"Solid Propellant Electric Thrusters for Attitude Control and Drift Correction of Space Vehicles," A. V. LaRocca, AIAA Paper 66-229, Presented at the AIAA Fifth Electric Propulsion Conference, San Diego, California, March 1966.

"Solid Propellant Pulsed Plasma Microthruster Studies," W. J. Guman and P. E. Peko, AIAA Paper 68-85, Presented at the AIAA 6th Aerospace Sciences Meeting, New York, January 1968.

"Thrust Measurements on a Pulsed Vacuum-Arc Thruster," O. Jarrett, et al., AIAA Paper 70-1146, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

(2) United States Air Force

Pulsed Plasma Propulsion Technology, D. J. Palumbo and W. J. Guman, AFRPL-TR-73-79, September 1973.

Pulsed Plasma Propulsion Technology, C. L. Dailey, H. A. Davis and B. R. Hayworth, AFRPL-TR-73-81, July 1973.

Pulsed Plasma Technology in Microthruster, W. Guman, Air Force Aero Propulsion Laboratory, AFSC, Wright-Patterson AFB, Ohio, AFAPL-TR-68-132, November 1968.

(3) ARS

"The Confined Parallel Rail Pulsed Plasma Accelerator," M. E. Maes, ARS Paper 2397-62, Presented at the ARS Electric Propulsion Conference, Berkeley, California, March 1962.

"Pulsed Plasma Accelerators," P. Gloersen, ARS Paper 2129-61, Presented at the ARS Space Flight Report to the Nation Meeting, New York, October 1961.

(4) AVCO Corporation

Study of Magnetic Annular Plasma Accelerator, R. M. Patrick and A. M. Schneiderman, Summary Report, Avco-Everett Research Laboratory, Contract NAS 3-5748, Report Number NASA CR-54686, April 15, 1964-January 14, 1966.

(5) Bell Aerosystems Company

Study of Spacecraft Attitude Control Propulsion Devices, Bell Aerosystems Company, Report Number 8214-933001, December 1962. (Confidential)

(6) Fairchild Hiller Corporation

Pulsed Plasma Microthruster Propulsion System Application Notes, Fairchild Hiller, Report PCD-TR-694, January 1967.

Pulsed Plasma Microthruster Propulsion System Application Notes, W. Guman, Fairchild-Hiller, Report Number PCD-TR-69-1, January 1969.

(7) Fairchild Republic Company

Development of a Short Pulsed Solid Propellant Plasma Thruster, W. J. Guman, Fairchild Republic Company, Final Report MS 172R0001, March 1974.

(7) Fairchild Republic Company (Continued)

Electromagnetic Interference Testing Conducted Interference, M. Begun, W. J. Guman and D. J. Palumbo, Fairchild Republic Company for the Air Force Rocket Propulsion Laboratories, Contract F04611-72-C-0053, Report MS 147N0001, June 26, 1975.

Failure Mode and Effect Analysis, G. E. Uhruh, Fairchild Republic Company for Applied Physics Laboratory, Contract Number 600064, Report Number MS 173N0002, February 7, 1974.

Final Reliability Estimate for the Pulsed Plasma Thruster, G. E. Uhruh, Fairchild Republic Company for the APL, Contract Number 600064, Report Number MS 173N0005, July 10, 1974.

Pulsed Plasma Propulsion Technology, Interim Report for Period 10 May 1973-10 July 1974, D. J. Palumbo, M. Begun and W. J. Guman, Fairchild Republic Company for the Air Force Rocket Propulsion Laboratory, Report Number AFRPL-TR-74-50, 1974.

Solid Propellant Pulsed Plasma Propulsion System, Fairchild Republic Company, undated.\*

Worst Case Analysis TIP II Power Conditioner, 1 July 1974, G. Uhruh, Fairchild Republic Company, Report Number MS 173N0004, September 16, 1974.

(8) General Electric Company

Life Tests on Capacitors for Pulsed Plasma Engine Applications, B. Gorowitz and T. W. Karras, Missile and Space Division, General Electric Company, Report Number R655D26, June 1965.

(9) Giannini Scientific Corporation

High Specific Impulse Thermo-Ionic Acceleration,  
Giannini Scientific Corporation, PRE-114-a, December  
1963.

The Plasma Jet and Its Application, G. M. Giannini,  
Office Scientific Research, Giannina Scientific Corpora-  
tion, Technical Note 57-520, 1957.

(10) Jet Propulsion Laboratory (JPL)

"A Pulsed Plasma Jet Attitude Controller for an ATS-H  
Synchronous Satellite," G. E. Fleischer, Jet Propulsion  
Laboratory, Internal Document, Engineering Memo 344-  
365ATS, December 1971.

(11) Massachusetts Institute of Technology (MIT)

Electronic Parts List for the "LES. 9" Pulsed Plasma  
Thruster, MIT, August 1975.

(12) National Aeronautics and Space Administration (NASA)

Axisymmetric Expansion of a Plasma in a Magnetic  
Nozzle Including Thermal Conduction, E. L. Walker and  
G. R. Seikel, NASA, NASA TN D-6154, February 1971.

Development of a Coaxial Plasma Gun for Space Propul-  
sion, A. V. Larson et al., NASA, Semiannual Report,  
Contract NAS3-7111, November 1965.

(13) Plasmadyne Corporation

Investigation of a Low-Thrust Plasma Propulsion Device,  
W. A. Stoner, Plasmadyne Corporation, Report Number  
1FR-021-1806, February 1961.

(14) Talley Industries

A Solid-State Pulse Motor System for Spacecraft Attitude Control, D. Suddreth and D. Blackwood, Talley Industries.

(15) TRW Systems, Incorporated

Development of a Pulsed Inductive Plasma Thruster, C. R. Dailey, TRW Systems, October 1968.

Thrust Measurement For A Pulsed Inductive Thruster, C. L. Dailey, TRW Systems for the U.S. Air Force, Report AFOSR 70-0757TR, Air Force OSR Contract AF 44620-68-C-0042, March 1970.

(16) University of California Radiation Laboratory (UCRL)

A Button Source of Plasma, V. G. McIntosh and W. H. Bostick, University of California Lawrence Radiation Laboratories, Report UCRL-4688, April 1956.

(17) Other Publications

1. Magazines

"Characteristics of the Pinch Discharge in a Pulsed Plasma Accelerator," L. Aronowitz and D. P. Duclos, Progress in Astronautics and Aeronautics: Volume IX, Electric Propulsion Development, page 513, Edited by E. Stuhlinger, Academic Press Inc., New York, 1963.

"Performance of a Hydromagnetic Plasma Gun," J. Marshall, Physics of Fluids, Volume 3, page 134, 1960.

1. Magazines (Continued)

"Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite," W. J. Guman and D. M. Nathanson, Journal of Spacecraft and Rockets, Volume 7, Number 4, pages 409-415, April 1970.

2. Papers/Reports

Pulsed Plasma Microthruster Applications and Techniques, A. V. LaRocca and G. S. Perkins.

4. ELECTRIC (GENERAL)

(1) Aerospace Corporation

Candidate Low Thrust Devices for the Space Station Reaction Control System, G. Nunz, Aerospace Corporation, Contract F 04701-69-C-0066, Report Number TOR-0066 (5759-03-1), May 1970. \*

(2) American Institute of Aeronautics and Astronautics (AIAA)

1. Conferences

"Mission Design for a 1980 Encke Slow Flyby Using Solar Electric Propulsion," D. Bender, K. Atkins and C. Sauer, Presented at the AIAA/AAS Astrodynamics Conference, Vail, Colorado, 1973.

"An Optimal Transfer to Out-of-the-Ecliptic Using a Solar Electric Spacecraft," C. L. Yen, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 1975.

"Trajectory Design of a Solar Electric Propulsion Slow Flyby Mission," C. G. Sauer, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 1975.

2. Papers

"All-Electric Thruster Control of a Geostationary Communications Satellite Which Employs Narrow-Beam Antennas," M. H. Kaplan, AIAA Paper 72-436, Presented at the AIAA 9th Electric Propulsion Conference, Bethesda, Maryland, April 1972.

"Anode Power Deposition in Quasi-Steady MPD Arcs," A. J. Saber and R. G. Jahn, AIAA Paper 73-1091, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.

2. Papers (Continued)

"Application of Magnetic-Expansion Plasma Thrusters to Satellite Station Keeping and Attitude Control Missions," G. R. Seikel, D. N. Bowditch and S. Domitz, AIAA Paper 64-677, Presented at the AIAA Fourth Electric Propulsion Conference, Philadelphia, Pennsylvania, August 1964.

"A Common Solar Electric Upper Stage for Multi-Mission Applications," H. F. Meissinger and D. S. Goldin, TRW Systems, A. C. Masey, NASA/OART, AIAA Paper 72-464, Presented at the AIAA 9th Electric Propulsion Conference, Washington, D. C., April 17-19, 1972.\*

"Development of an Assembly for the Distribution and Isolation of Mercury Propellant Flow to Electric Thrusters," R. H. Smith, J. R. Womack, AIAA Paper 75-407, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 1975.\*

"Early Application of Solar Electric Propulsion to a 1-AU Out-of-Ecliptic Mission, W. Strack, F. Hrach, AIAA Paper 70-1118, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, 1970.

"Effects of Electrostatic Rocket Material Deposited on Solar Cells," R. F. Kemp, et al., AIAA Paper 72-447, April 1972.

"Electric Propulsion--Past History and Future Prospects," E. Stuhlinger, AIAA Paper 74-1081, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974.\*

"Electric Propulsion Status and Development Plans," J. Lazar, AIAA Paper 73-1143, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, 1973.



2. Papers (Continued)

"Electric Propulsion Technology Status and Development Plans - European Programs," H. W. Loeb, AIAA Paper 73-1146, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31-November 2, 1973.\*

"Electrostatic Thrusters," H. R. Kaufman and P. D. Reader, AIAA Paper 72-1123, 1972.

"Factors in the Design of Spacecraft Utilizing Multiple Electric Thrusters," D. J. Fitzgerald, AIAA Paper 75-404, Presented at the AIAA 11th Electric Propulsion Conference, New Orleans, Louisiana, March 1975.\*

"Failure Recovery and Failsafe Encke Rendezvous and Flyby Missions Using Solar Electric Propulsion," J. M. Driver, AIAA Paper 74-804, Presented at the AIAA Mechanics and Control of Flight Conference, Anaheim, California, August 1974.\*

"Initial Performance Data On A Low-Power MPD Arc Thruster With A Downstream Cathode," J. Burkhart, AIAA Paper 70-1084, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, August 1970.

"Interplanetary Spacecraft Design Using Solar Electric Propulsion," J. H. Duxbury and G. M. Paul, AIAA Paper 74-1084, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, 1974.\*

"Low Thrust Mission Risk Analysis," C. L. Yen, D. B. Smith, AIAA Paper 73-208, Presented at the AIAA 11th Aerospace Sciences Meeting, Washington, D. C., January 1973.\*

"Measurements of Mass, Momentum and Energy Discharge," K. E. Clark, R. G. Jahn and W. F. von Jaskowsky, AIAA Paper 72-497, Presented at the AIAA 9th Electric Propulsion Conference, Bethesda, Maryland, April 17-19, 1972.

2. Papers (Continued)

"Mission Applications of Electric Propulsion," K. L. Atkins, AIAA Paper 74-1085, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974.\*

"Multiple Gimbaling of Thrusters for Thrust Vector Control and Thrust Vector Reorienting of Solar Electric Spacecraft," E. L. Marsh, AIAA Paper 73-1116, October-November 1973.\*

"NASA Overview of Electric Propulsion," J. Lazar and J. P. Mullin, AIAA Paper 72-1127, 1972.

"SEP Stage for Earth Orbital Missions," S. P. Horio and C. H. Guttman, AIAA Paper 73-1123, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, 1973.

"Spacecraft Capillary Propellant Retention and Control for Long-Life Missions," AIAA Paper 68-465, April 1968.

"Structural Evaluation and Dynamic Testing of Solar Electric Propulsion Components," J. R. Womack, Jay-Chung Chen, AIAA Paper 72-442, Presented at the AIAA 9th Electric Propulsion Conference, Bethesda, Maryland, April 17-19, 1972.\*

"Survey of Electric Propulsion Capability," K. E. Clark, AIAA Paper 74-1082, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974.\*

"A Survey of Solar Array Technology for Electric Propulsion," R. W. Given, AIAA Paper 74-1083, Presented at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974.\*

"System Study of Electric Propulsion for Military Space Vehicles," C. Hawk, et al., AIAA Paper 72-493, 1972.

2. Papers (Continued)

"Thrust System Technology For Solar Electric Propulsion," T. D. Masek and E. V. Pawlik, AIAA Paper 68-541, Presented at the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 1968.

"Thrust Vectoring Systems," H. J. King and D. E. Schnelker, AIAA Paper 70-1150, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

"Thruster Array Approaches for a Solar Electric Propulsion Encke Flyby Mission," R. G. Ross, AIAA Paper 73-1115, October-November 1973.

"Trajectory Analysis and Performance for SEP Comet Encke Missions," C. Sauer, AIAA Paper 73-1059, Presented at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, 1973.

"Trajectory Design for a Solar-Electric Propulsion Mars High Data Rate Orbiter," C. G. Sauer, AIAA Paper 70-1119, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, 1970.

(3) United States Air Force

Advanced Electric Thruster (A Space Electric Ramjet), G. L. Cann, AFRPL-TR-73-12, April 1973.

Applicability of Electric Propulsion for Future Military Satellites, C. W. Thomas, W. M. Adamson, Office of the Assistant for Study Support (OAS), Kirtland Air Force Base, New Mexico, September 1973.\*

Areas of Applicability for Electric Propulsion Systems, J. W. Geis, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Report Number AFAPL-TR-67-80, September 1967.\*

(3) United States Air Force (Continued)

Magnetic Field Annihilation of Impulsive Current Sheets,  
C. L. Dailey, AFOSR-TR-73-0564, March 1973.

Millipound Thrust Electric Propulsion, J. W. Geis, Air  
Force Aero Propulsion Laboratory, Wright-Patterson Air  
Force Base, Report Number AFAPL-TR-66-65,  
September 1966. \*

Research on Charged Particle Electrostatic Thrusters,  
E. Cohen and M. N. Huberman, Air Force Technical  
Report AFAPL-TR-66-94, September 1966.

(4) Battelle Memorial Institute

Compatibility of Rocket Propellants With Materials of  
Construction, Defense Metals Information Center, Battelle  
Memorial Institute, OTS PB-161215, DMIC Memorandum  
65, September 15, 1960. \*

(5) Boeing Aircraft Company

"Small Engines," Volume I of Rocket Engines, H. R.  
Bader, Jr., Boeing Company, Report Number D2-114118-  
2-Vol-1, October 1968. \*

(6) COMSAT Corporation

A User Assessment of Servicing in Geostationary Orbit,  
COMSAT Corporation, undated. \*

(7) Energy Research and Development Administration (ERDA)

Operational Risk and Reliability of Space Transportation  
Systems, ERDA, undated. \*

(8) General Electric Company

"Failure Modes and Effects Criticality Analysis," Volume V of Superconducting Propulsion System, B. D. Hatch and D. L. Kerr, General Electric Company, Power Generation and Propulsion Laboratory for the U. S. Navy, Contract Number N00024-73-C-5488, Report Number SRD-74-106-5, November 1974.

Feasibility Study of a 110 Watt Per Kilogram Lightweight Solar Array System, N. F. Shepard, et al., Final Report, General Electric for the Jet Propulsion Laboratory, JPL Contract 953387, May 1973.

Final Report Feasibility Assessment of a Solid Propellant Electric Thruster (SPET), General Electric Spacecraft Department, General Electric Report 66 SD 4255, March 15, 1966.

(9) Hughes Aircraft Company

Electric Propulsion Reliability Analysis, Research and Development Division, Hughes Aircraft Company for NASA, NASA Contract NAS7-559.

Nonelectric Reliability Notebook, Hughes Aircraft Company for Rome Air Development Center, NTIS AD/A-005-657, January 1975.

Part 1 - "Technical and Management Proposal," Volume IV - Reliability and Quality Assurance, Hughes Aircraft Company, April 1968. \*

(10) Illinois Institute of Technology (IIT)

Aerospace Tanks, Volumes I and II, Illinois Institute of Technology of Research Institute for the Jet Propulsion Laboratory, IITRI Project C6309, JPL Contract 953830, July 1974. \*

(10) Illinois Institute of Technology (IIT) (Continued)

Microcircuit Device Environmental Data, Reliability Analysis Center, Illinois Institute of Technology Research Institute for the U. S. Air Force, Rome Air Development Center, MDED0474, NTIS AD-785-920K, April 1974.\*

Microcircuit Device Failure Rates, Illinois Institute of Technology Research Institute, RAC-MDFR-0674, June 1974.\*

Microcircuit Reliability Bibliography, Volume I, "Cumulative Index," Volume II, "Cumulative References," Illinois Institute of Technology Research Institute, Reliability Analysis Center, RAC-MRB-0474, April 1974.\*

(11) Jet Propulsion Laboratory (JPL)

"Development of Electronic Parts Failure Rates for Long Duration Space Missions," P. O. Chelson, Sigol, Jet Propulsion Laboratory, Presented at the Proceedings of the Twenty-Second Electronics Component Conference, 1972.

Low Thrust Mission Risk Analysis With Application to a 1980 Rendezvous With the Comet Encke, C. L. Yen, D. B. Smith, Jet Propulsion Laboratory, NASA TM 33-593, March 15, 1973.\*

Nuclear Electric Propulsion Stage, J. F. Mondt, M. L. Peelgren, A. M. Nakashima, T. M. Hsieh, W. M. Phillips, and G. M. Kitkin, Jet Propulsion Laboratory, California Institute of Technology, Report Number TM-33-647, August 1, 1974.

Optimized Silicon Solar Cells For Space Exploration Power Systems, Peter A. Iles, Final Report, Centralab Semiconductor Division, Jet Propulsion Laboratory, JPL Contract 952865, November 1971.

(11) JPL (Continued)

Preliminary Studies and Recommendation on a Midcourse Propulsion System for TOPS, Jet Propulsion Laboratory, September 1969. \*

Reliability Compiler (A Reliability Network Processor), Jet Propulsion Laboratory, October 1972. \*

Reliability Computation From Reliability Block Diagrams, P. O. Chelson, R. E. Eckstein, Jet Propulsion Laboratory For NASA, Contract NAS 7-100, JPL Technical Report 32-1543, December 1, 1971. \*

Reliability Computation Using Fault Tree Analysis, P. O. Chelson, Jet Propulsion Laboratory for NASA, Contract NAS 7-100, JPL Technical Report 32-1542, December 1, 1971. \*

Reliability Data for Electronic and Electromechanical Components, Jet Propulsion Laboratory, April 1975. \*

A Rendezvous with Comet Encke Using Solar Electric Propulsion, R. L. Newburn, Jet Propulsion Laboratory, JPL Internal Document 701-201.

Satellite Auxiliary-Propulsion Selection Techniques, L. B. Holcomb, Jet Propulsion Laboratory, Technical Report 32-1505, November 1, 1970. \*

Ibid, "Addendum Survey of Auxiliary Electric Propulsion Systems," July 15, 1971. \*

Ibid, "Supplement 1 - Application of Selection Techniques to the ATS-H Satellite," October 1, 1972. \*

Solar Electric Multimission Spacecraft, Phase A Final Report, Spacecraft Subsystem Analysis, JPL, March 1972.

Solar Electric Propulsion Encke Slow-Flyby 1979 Mission and Spacecraft Description, J. Gerpheide and J. Duxbury, Jet Propulsion Laboratory, JPL Internal Document 701-200, June 28, 1974.

(11) JPL (Continued)

Solar Electric Propulsion System Test, E. V. Pawlik, E. N. Costogue, J. D. Ferrera, Jet Propulsion Laboratory, JPL Technical Report 32-1480, August 15, 1970.\*

Solar Electric Propulsion Thrust Subsystem Development, T. D. Masek, Jet Propulsion Laboratory, California Institute of Technology, Report Number TR 32-1579, March 15, 1973.

Technical Support Package on Reliability Data for Electronic and Electromechanical Components: A Report, Jet Propulsion Laboratory, for NASA, Tech Brief 74-10280. JPL Invention Report 30-2864/NPO-13153, April 1975.

User's Guide for Prep/Kitt on 1108 Computer, Jet Propulsion Laboratory, January 25, 1974.\*

(12) Lockheed Missile and Space Company, Incorporated

Fault Tree Graphics - Application to System Safety, Lockheed Missiles and Space Company, Incorporated, July 1975.\*

Low Thrust Solid and Hybrid Propulsion Systems (Phase II), Final Report, Lockheed Missiles and Space Company for NASA, Contract NAS 7-573, Report Number LMSC-685070, February 1968.

Solar Array Technology Evaluation Program for SEPS, Midterm Report, NAS8-30315, Lockheed Missiles and Space Company, Incorporated, April 1974.

SSD Electronic Parts Orbital Failure Rates (Active and Dormant Operations) and Associated Failure Modes, Lockheed Missiles and Space Company, Incorporated, July 1972.\*



(13) Martin-Marietta Corporation

Long-Life Assurance Study for Manned Spacecraft Long-Life Hardware, R. W. Burrows, Martin-Marietta Corporation for NASA, Contract NAS 9-12359, Volumes 1-5, Report Number MCR-72-169, December 1972. \*

Revision of RADC Nonelectronic Reliability Notebook (RADC-TR-69-458), Section 2, D. F. Cottrell et al, Martin-Marietta Corporation for the Rome Air Development Center, NTIS AD/A-002-152, October 1974. \*

Ibid, Index and Revision to Section 2, NTIS AD/A-002-899. \*

(14) Massachusetts Institute of Technology (MIT)

Wear Particle Formation Mechanisms, H. Koba, N. H. Cook, Cambridge Materials Processing Laboratory, MIT, May 1974. \*

(15) McDonnell Aircraft Company

Bibliography on Engines (General), McDonnell Aircraft Company, April 1973. \*

(16) McDonnell Douglas Astronautics Company

"Attitude Control and Translation System/Propulsion Subsystem," Sequence Number B242, Volume V of Laboratory Module/Effectiveness Model Report, Western Division, McDonnell Douglas Astronautics Company, April 1968. \*

(17) National Aeronautics and Space Administration (NASA)

Advanced Propulsion Comparison Study - Definition, Technical Status, Operation, and Cost of Advanced Propulsion Systems, NASA, April 1973. \*

(17) NASA (Continued)

Design Criteria for Spacecraft Propulsion Systems, C. N. Jennings, Space General for NASA/OART, Contract NAS 7-519, Final Report, October 1967.\*

"Generation of Thrust-Electromagnet Thrusters," in Electric Propulsion for Spacecraft, G. R. Seikel, National Aeronautics and Space Administration, Washington, D. C., NASA SP-22, pages 19-24, 1962.

Liquid Rocket Engine Combustion Stabilization Devices, Design Criteria Office, Lewis Research Center, NASA, Report Number NASA SP-8113, November 1974.\*

Reliability Testing and Demonstration--Aerospace Problems, U. R. Lalli, Lewis Research Center, NASA, Report Number NASA TM X-67877, November 1971.

Reports and Papers Pertaining to Electrostatic Propulsion, NASA-Lewis Research Center, 1972.

Retention and Application of Saturn Experiences to Future Programs, W. D. Brown, N. Milly, Quality and Reliability Assurance Laboratory, Marshall Space Flight Center, NASA, NASA Technical Memorandum NASA TM X-64574, September 14, 1971.\*

Retention and Application of Skylab Experiment Experiences to Future Programs, N. Milly, V. G. Gillespie, Quality and Reliability Assurance Laboratory, Marshall Space Flight Center, NASA, NASA Technical Memorandum NASA TM X-64839, May 1, 1974.\*

A Study of Programs for Evaluation of Component Life, Marshall Space Flight Center, NASA, Contract NAS 8-21296, Report Number MCR-69-366, 1969.

A Study of Storage Technology for Various Launch Vehicle Systems, NASA, Contract NAS 8-21296, Report Number MCR-68-329, 1968.

(17) NASA (Continued)

A Study of Total Space Life Performance of GSFC Spacecraft, A. R. Timmins, Goddard Space Flight Center, NASA, Report Number NASA TN D-8017, July 1975.

(18) United States Navy

An Evaluation of Electric and Hydrazine Propulsion Systems for Orbit Maintenance, R. U. Silverman, Naval Space Systems Activity, Final Report NSSA R40-70-3, May 1971.\*

(19) Planning Research Corporation (PRC)

Reliability Data From In-Flight Spacecraft, 1958-1970, E. E. Bean, C. E. Bloomquist, PRC for the U. S. Navy Space Systems Activity, Report Number PRC R-1453, November 30, 1971.\*

Ibid ADDENDUM, November 1972.

A Standardized Approach for the Evaluation of Spacecraft Reliability, E. E. Bean, C. E. Bloomquist, PRC for the U. S. Navy Space Systems Activity, Report Number PRC R-1453, November 30, 1971.\*

(20) Princeton University

Methodology for Reliability - Cost-Risk Analysis of Satellite Networks, Princeton University, March 1974.\*

Multiple Payload Risk Considerations, Princeton University, undated.\*

Operational Risk and Reliability of Space Transportation Systems, Princeton University, undated.\*

Reliability Compiler (A Reliability Network Processor), Princeton University, October 1972.\*

(20) Princeton University (Continued)

Risk Analysis: Flying by the Seat of the Pants Will Not Serve the Aerospace Manager Nearly So Well as the Quantitative Gauges of this Modern Treatment of Decision Making, Princeton University, undated.\*

(21) Rockwell International and North American Rockwell

Extended Definition Feasibility Study for a Solar Electric Propulsion Stage, J. Gilbert, et al, Final Report, Volume II - "Concept and Feasibility Analysis," Part 1 - "Planetary Missions," Rockwell International for NASA, Contract NAS 8-27360, December 1973.

Feasibility Study for a Solar Electric Propulsion Stage, Space Division, North American Rockwell for NASA, Contract NAS 8-27360, Report SD 72-SA-0177-1.\*

(22) Space Technology Laboratories, Incorporated

Research on the Generation and Acceleration of Submicron-Size Particles, V. E. Krohn, Space Technology Laboratories, Incorporated, Summary Report covering August 1959-February 1962, STL Report 8937-6005-cu-000, 1962.

(23) TRW Systems, Incorporated

Advanced Spacecraft Valve Technology Compilation, TRW Systems, Incorporated, July 1970.\*

Comparative Reliability Study--Monopropellant - Bi-propellant Jupiter Mission Systems, R. A. Paulson, TRW Systems for the Jet Propulsion Laboratory, JPL Contract 952545, November 1969.

Feasibility Study for a Multi-Mission Electric Propulsion Spacecraft, TRW Systems, Incorporated, Contract No. NAS-2-6287, Report 18305-6001-R000, June 1971.\*

(23) TRW (Continued)

Study of Advanced Techniques for Determining the Long Term Performance of Components, TRW Systems, Incorporated, March 1972.\*

(24) University of Southern California

Investigation of the Feasibility of the Delphi Technique for Estimating Risk Analysis Parameters, University of Southern California, April 1974.\*

(25) Other Publications

1. Books

"The Electromagnetic Pinch Effect for Space Propulsion," in Dynamics of Conducting Gases, A. E. Kunen and W. McIlroy, pages 179-189. Edited by A. B. Cambel and J. B. Fenn, Northwestern University Press, Evanston, Illinois, 1960.

Electric Contacts Handbook, R. Holm and E. Holme, Springer-Verlag, Berlin, Third Edition, 1958.

Elektrische Antriebe von Raumfahrzeugen, G. F. Au, Verlag G. Braun, Karlsruhe, 1968.

Elements of Rocket Propulsion, G. P. Sutton, John Wiley & Sons, Incorporated, New York, First Edition, 1949.

Physics of Electric Propulsion, R. G. Jahn, McGraw-Hill Book Company, New York-St. Louis-San Francisco-Toronto-London-Sydney, 1968.

2. Conferences

"Position and Orientation Propulsion Systems for Unmanned Vehicles," A. Burnstein, H. Dicristina, Presented at the 19th Congress of the International Astronautical Federation, New York, Paper P37, October 1968.

"STL Heavy Particle Propulsion Program," E. Cohen, Presented at the Third Symposium on Advanced Propulsion Concepts, Cincinnati, Ohio, October 1962.

3. Dissertation

"On the Electric Propulsion/Mission System: Energy, Constraints, and Characteristic Surfaces," K. L. Atkins, PhD Dissertation, University of Illinois, Urbana, Illinois, 1974.

4. Magazines

"Electrical Propulsion Systems for Space Ships with Nuclear Power Source," E. Stuhlinger, Journal of Astronautics, Volume 2, page 149, 1955; Volume 3, pages 11, 33, 1956.

"Electrostatic Rocket Exhaust Effects on Solar-Electric Spacecraft Systems," D. F. Hall, et al, Journal of Spacecraft and Rockets, Volume 7, Number 3, pages 305-312, March 1970.

"Flight Path of an Electrically Propelled Space Ship," E. Stuhlinger, Jet Propulsion, Volume 27, Number 4, Page 410, April 1957.

"Introducing Magnetohydrodynamics," A. Kantrowitz, Astronautics, Volume 3, Number 10, October 1958.

4. Magazines (Continued)

"Low Thrust Flight: Constant Exhaust Velocity in Field-Free Space, D. B. Langmuir, Chapter 9, H. S. Seifert (Editor), Space Technology, John Wiley and Sons, Incorporated, New York, 1959. (Also see Chapter 18.)

"Magnetohydrodynamics," M. U. Clauser, in Space Technology, Chapter 18, H. S. Seifert (Editor), John Wiley and Sons, Incorporated, New York, 1959.

"Plasma Motors," W. Bostick, Advanced Astronauts Sciences, Volume 2, American Rocket Society, Plenum Press, Incorporated, New York, 1957.

"Spacecraft Mission Effectiveness," A. Leventhal and C. E. Bloomquist, Annals of Reliability and Maintainability, Spring Issue, 1968.

"Survey of Satellite Auxiliary Propulsion Systems," L. G. Holcomb, Journal Spacecraft and Rocket, Volume 9, Number 3, pages 133-147, March 1972.

5. Papers/Reports

"A Circular 1.0 AU Out-of-the-Ecliptic Mission Using Solar Electric Propulsion, J. H. Duxbury, III EEPC Paper 74-242, October 1974.

Cost Optimization of a Re-Supplied Communications Satellite System with Mixed-Thruster Electric Propulsion, R. C. Parkinson, Rocket Propulsion Establishment, Westcott, England, Report No. RPE-TR-20, March 1974.

"Ein Elektrostatisches Raketentriebwerk mit Hochfrequenzionenquelle," H. W. Loeb, Astronautica Acta VIII, Volume 1, Number 49, 1962.

"Flexible Solar Array Applications In Communications Satellites," W. J. Billerbeck and D. J. Curtin, IECEC Paper 749045, August 1974.

5. Papers/Reports (Continued)

Literature Searches on Chemical Propulsion Reliability, (Obtained through L. Holcomb), September 1969.

"NASA's Position in Electric Propulsion," R. C. Finke, Invited Paper Presented at the IIIrd European Electric Propulsion Conference, Hinterzarten, Germany, October 14-18, 1974.

Reliability Analysis and Prediction Standards, (Obtained through L. Holcomb), April 1965. \*

"U.S. Solar-Electric Propulsion Planetary Mission Candidates: Out-of-the-Ecliptic, Small Bodies, and Orbiters of Mercury and Saturn," K. Atkins, III EEPC Paper 74-243, October 1974.



5. THERMO-CHEMICAL ELECTRO-THERMAL MONOPROPELLANT

(1) American Institute of Aeronautics and Astronautics (AIAA)

1. Conferences

"NASA Research on Resistance-Heated Hydrogen Jet," J. R. Jack, Presented at the AIAA Electric Propulsion Conference, Colorado, March 1963.

"Resistojet Engine Performance. A Comparison of Experiment with Theory," R. J. Page and C. R. Halbach, Presented at the AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August 1964.

2. Journals

"Arcjet Engine Performance: Experiment and Theory," R. R. John, S. Bennett and J. F. Connors, AIAA Journal, Volume 1, Number 11, pages 2517-2525, November 1963.

"1-KW Arcjet-Engine System-Performance Test," A. C. Ducati et al., AIAA Journal of Spacecraft and Rockets, Volume 1, Number 3, pages 327-332, May-June 1964.

3. Papers

"Ammonia Resistojet Station Keeping Subsystem Aboard Applications Technology Satellite (ATS)-IV," T. K. Pugmire, R. Shaw and R. A. Collens, AIAA Paper 69-296, March 1969.

"Applied Resistojet Technology," T. K. Pugmire and R. Shaw, AIAA Paper 70-211, Presented at the AIAA 8th Aerospace Sciences Meeting, New York, New York, January 1970.

3. Papers (Continued)

"ATS-III Resistojet Thruster System Performance,"  
T. K. Pugmire and W. Lund, AIAA Paper 68-553,  
June 1968.

"Design and Demonstration of a Radioisojet,"  
R. Viventi and W. C. Isley, AIAA Paper 67-425,  
July 1967.

"Design and Performance of a Thermal Storage  
Resistojet," T. A. Cygnarowicz and R. N. Gibson,  
AIAA Paper 67-662, September 1967.

"Development of a Biowaste Resistojet," C. R.  
Halbach and R. Y. Yoshida, AIAA Paper 70-1133,  
Presented at the AIAA 8th Electric Propulsion Con-  
ference, Stanford, California, September 1970.

"The Development Of Microthrusters In France  
Under the C. N. E. S. Authority," AIAA Paper 70-617,  
Presented at the AIAA 6th Propulsion Joint Specialist  
Conference, San Diego, California, June 1970.

"Electrothermal Hydrazine Thruster Development,"  
C. K. Murch and C. R. Hunter, AIAA Paper 72-451,  
1972.

"Electrothermal Microthrust Systems," A. F. White,  
AIAA Paper 67-423, July 1967.

"Electrothermal Thruster Performance with Bio-  
waste Propellants," C. K. Murch, AIAA Paper 70-  
1161, Presented at the AIAA 8th Electric Propul-  
sion Conference, Stanford, California, September  
1970.

"An Experimental Study of Superheated Subliming  
Solid Thruster Performance," W. L. Owens, AIAA  
Paper 70-210, Presented at the AIAA 8th Aerospace  
Science Meeting, January 1970.

3. Papers (Continued)

"The Hybrid (Hydrazine) Resistojet," R. R. Schreib, T. K. Pugmire and S. G. Chapin, AIAA Paper 69-496, June 1969.

"Investigation of Electrical Systems of Plasma Arc Jet Engines," R. Richter, AIAA Paper 63-044, Presented at the AIAA Electric Propulsion Conference, Colorado Springs, Colorado, March 1963.

"Life Test of Six High Temperature Resistojets," R. J. Page, C. R. Halbach, R. A. Short and M. L. Ownby, AIAA Paper 69-299, March 1969.

"Low Thrust Propulsion for the MORL," M. Goodman, AIAA Paper 66-226, March 1966.

"An Operational Electrothermal Propulsion System for Spacecraft Reaction Control," F. A. Jackson, J. C. Stansel, D. Fortner and C. F. Hagelberg, AIAA Paper 66-213, March 1966.

"Propulsion Requirements for Communications Satellites," W. C. Isley and K. I. Duck, AIAA Paper 72-515, Proceedings of AIAA Fourth Communications Satellite Systems Conference, Washington, D.C., April 1972.

"Resistojet and Plasma Propulsion System Technology," R. V. Greco et al., AIAA Paper 72-1124, 1972.

"A Resistojet System for Attitude Control of Unmanned Earth Satellites," Ivan Tobias and R. L. Kasson, AIAA Paper 66-225, March 1966.

"Resistojet Systems Manned Spacecraft Applications," R. V. Greco and D. E. Charhut, AIAA Paper 69-255, March 1969.

"Subsystems Analyses for a MORL Resistojet Control System," A. Pisciotta and E. Eusanio, AIAA Paper 67-721, September 1967.

3. Papers (Continued)

"Ten-Millipound Resistojet Performance," R. J. Page and R. A. Short, AIAA Paper 67-664, October 1967.

"Thermal and Material Considerations Pertinent to the Biowaste Resistojet," T. K. Pugmire and R. R. John, AIAA Paper 70-1135, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

"3 KW Concentric Tubular Resistojet Performance Compared With Theory," R. J. Page, C. R. Halbach and R. A. Short, AIAA Paper 66-224, March 1966.

(2) United States Air Force

Auxiliary Propulsion Survey, Part III, I. Grossman, T. R. Jones and D. N. Lee, Air Force Aero Propulsion Laboratory, Technical Report AFAPL-TR-68-67, Part III, September 1968.

(3) Aeronautic Research Laboratory (ARS)

"The Resistojet, ARS Space Flight Report to the Nation," J. M. Howard, ARS Preprint 61-2126, October 1961; also ARS Journal 33, Number 6, pages 961-962, June 1962.

"Theoretical Performance of Propellants Suitable for Electrothermal Jet Engines," J. R. Jack, Presented at the ARS 15th Annual Meeting, Washington, D.C.; ARS Preprint Number 1506-60, December 1960; also ARS Journal 31, pages 1685-1689, 1961.

(4) ASDT

Investigation of Electric Resistance-Heated Rocket for Feasibility In Space Propulsion Applications, J. M. Howard, ASDT PR-62-487, June 1962.

(5) American Society of Mechanical Engineers (ASME)

"Advanced Resistojet Propulsion and Control Systems for Spacecraft," R. J. Page and R. A. Short, ASME Paper 70-Av/SpT-10, Space Technology and Heat Transfer Conference, Los Angeles, California, June 1970.

(6) AVCO Corporation

"Weapon System K107A-2," Volume 2 of The Arc-Jet-Propelled Space Vehicle Status Report, Research and Advanced Development Division, AVCO Corporation, for the U.S. Air Force, Contract Number AF04-647-305, Report Number SR61-27, March 1961.

"Appendices," Volume 2 of Weapon System 107A-2. The Arc-Jet-Propelled Space Vehicle, Research and Advanced Development Division, AVCO Corporation, for the U.S. Air Force, Contract Number AF04-647-305, Report Number SR61-61, Volume 2, April 1961.

Arc Jet Technology Research and Development, R. R. John and S. Bennett, Research and Advanced Development Division (now AVSSD), AVCO Corporation, AVCO/RAD SR 64-239, October 1954.

Design, Development, Fabrication, Test, and Delivery of Electrothermal Engine Systems, T. K. Pugmire, Final Report, AVCO Space Systems Division, Report AVSSD-0062-68-RR, NASA CR-72362, November 1967.

Flight Prototype Ammonia Storage and Feed System, T. K. Pugmire, AVCO Space Systems Division, Contract NAS5-10128, Report AVSSD-0100-67-RR, January 1967.

(6) AVCO Corporation (Continued)

Resistojet Research and Development, Phase II, R. R. John, Final Report, AVCO Corporation for NASA, NASA CR-54688, AVCO Report AVSSD-0356-66-CR, December 1966.

(7) Bell Aerosystems Company

Study of Spacecraft Attitude Control Propulsion Devices, Bell Aerosystems Company, Report No. 8214-933001, December 1962. (Confidential)

(8) Electro-Optical Systems

Auxiliary Propulsion Survey, R. Shattuck, Part I—"Electric Thrusters Survey," Electro-Optical Systems for the U.S. Air Force, Technical Report AFAPL-TR-68-67, Part I, September 1968.

(9) Fairchild Hiller Corporation

Final Report: ATS-4, Fairchild Hiller Space Systems Division for NASA-Goddard, NASA CR-81562, December 1966.

(10) General Dynamics/Convair

Utilization of Electric Propulsion for Interplanetary Spacecraft, J. E. Stumm, H. D. Girouard, K. W. Eckert, M. Nelson and R. K. Ruhe, General Dynamics/Convair, Report Number GDC-ERR-AN-1142, April 1968.

(11) General Electric Company

Analytical Methods for Resistance Jet Design, N. P. Jeffries, General Electric, Technical Information Series Report Number R 64SD3008.

NRL Ammonia Vapor Microthruster System, J. Kamin and M. L. Bromberg, General Electric, Space Power and Propulsion Section, Contract N00014-66-C0129, September 1966.

Simulated Radioisotope Thrust System and Component Development, Final Report, R. E. Viventi et al., General Electric Nuclear Systems Programs, Report GESP-87.

(12) Hamilton Standard, Division of United Aircraft Corporation

Hydrazine Impurity Survey, Phase I, G. L. M. Christopher and C. T. Brown, Hamilton Standard Division, United Aircraft Corporation for the U.S. Air Force, Technical Report January 1973-March 1973, AFRPL-TR-73-24, Contract F04611-73-C-0019, June 1973.\*

Monopropellant Hydrazine Tank Self-Pressurizer Demonstration Program, E. R. Bruun and J. E. Genovese, Hamilton Standard Division, United Aircraft Corporation, Final Report November 1971-December 1972, SVHSER-6049, AFRPL-TR-73-55, Contract F04611-72-C-0021, June 1973. †

(13) ITR

Resistance-Heated Thrustor Research, J. P. Todd, Plasmadyne, Report ITR 093-18628, September 1963.

(14) JANNAF

"An Experimental Evaluation of Metallic Diaphragms for Positive Fuel Expansion in the Atmosphere Explorer Hydrazine Propulsion Subsystem," in 1972 JANNAF Propulsion Meeting, W. L. Woodruff, Goddard Space Flight Center, NASA, Technical Report November 1972, CPIA Publication 228, Volume IV, Contract NAS 3-12026, December 1972.

(15) Jet Propulsion Laboratory (JPL)

"Survey of Materials for Hydrazine Propulsion Systems in Multicycle Extended Life Applications," C. D. Coulbert and G. Yankura, Jet Propulsion Laboratory, California Institute of Technology, Technical Memorandum TM-33-561, Contract NAS 7-100, September 1972.

(16) The Marquardt Corporation

Resistojet Thruster Life Test, R. J. Page, R. A. Short and M. L. Ownby, Rocket Systems Division, The Marquardt Corporation, First Quarterly Report for Contract Number NAS-1-8090, July 1968.

Survey of the Electric Propulsion Field, A. Belsley, The Marquardt Corporation, Report Number MIR 399, May 1971.

3-kw Concentric Tubular Resistojet Performance, The Marquardt Corporation, November 1966. \*

(17) National Aeronautics and Space Administration (NASA)

The Design and Performance of a 3-kw Concentric Tube Resistojet, R. J. Page and R. A. Short, NASA CR-54410, September 1965.

Electrothermal Engine Research and Development, S. Bennett, NASA Report CR-54104.



- (18) Princeton University  
Resistojet and Plasma Propulsion System Technology,  
Princeton University, December 1972. \*
- (19) Rocket Propulsion Establishment  
Cost Optimization of a Re-Supplied Communications Satel-  
lite System with Mixed-Thruster Electric Propulsion,  
Rocket Propulsion Establishment, March 1974. \*
- (20) TRW Systems, Incorporated  
Electrothermal and Radioisotope Heated Propulsion for  
Spacecraft Reaction Control, TRW Systems Group, Feb-  
ruary 1968.  
Monopropellant Spacecraft Maneuvering and Attitude  
Control System, TRW Systems Group, December 1968.  
Radioisotope Propulsion Technology Program (POODLE)  
Final Report, Volumes I, II, & III, TRW Systems, Con-  
tract Number AT (04-3)-517, Report STL-517-0049,  
April 1967.  
Study of Monopropellants for Electrothermal Thrusters,  
J. D. Kuenzly, TRW Systems Group, Report 22409-6014-  
RU-00, March 1974.
- (21) United Aircraft Corporation (See Hamilton Standard)

(22) Other Publications

1. Magazines

"Life Test Summary and High Vacuum Tests of 10-mlb Resistojets," R. Y. Yoshida, C. R. Halbach and C. S. Hill, Journal of Spacecraft and Rockets, Volume 8, Number 4, pages 414-416, April 1971.

"3-kw Concentric Tubular Resistojet Performance," R. J. Page, C. R. Halbach and R. A. Short, Journal of Spacecraft, Volume 3, Number 11, November 1966.\*

2. Papers/Reports

Reliability Electronics, Defense Documentation Center, DDC-TAS-74-35, October 1974.\*

6. THERMO-CHEMICAL (CATALYTIC MONOPROPELLANT)

(1) Aerojet General Corporation

Monopropellant Rocket Engines, Propulsion Division,  
Aerojet-General Corporation, June 1969.

(2) Aerojet Liquid Rocket Company

Final Report AJ 46-3 Monopropellant Thruster (5 lbj.),  
D. Lemke, Aerojet Liquid Rocket Company, Contract  
FO4611-72-C-0075, September 22, 1975.

(3) Aerospace Corporation

Propulsion Systems for Advanced Geosynchronous  
Satellites, G. Nunz and J. Oberstone, Aerospace Corpora-  
tion for the U.S. Air Force, Air Force Report No.  
SAMSO-TR-70-171, May 1970.

Qualification Test Program for the DSCP-2 Hydrazine  
Rocket Engine Assembly, R. L. Doebler, Aerospace C  
Corporation, Report Number TOR-0059 (6143)-26,  
January 22, 1971.

A Survey of Monopropellant Hydrazine Thruster Tech-  
nology, Aerospace Corporation, November 1973.\*

(4) American Institute of Aeronautics and Astronautics  
(AIAA) Paper

"Microthrust Monopropellant Hydrazine Propulsion  
System Technology," R. F. Eggers, AIAA Paper 68-556,  
Presented at the AIAA 4th Propulsion Joint Specialist  
Conference, Cleveland, Ohio, June 1968.

(5) United States Air Force

Performance Mapping of Hydrazine Attitude Control Thrusters: Interim Report, J. A. Quirk, Air Force Rocket Propulsion Laboratory, Edwards AFB, California, 1974.\*

Transtage ACS Valve Storage Tests, G. J. Gunderson, Air Force Rocket Propulsion Laboratory, Edwards AFB. Technical Report AFRPL-TR-70-150, January 1971.\*

Transtage ACS Valve Storage Tests, G. J. Gunderson, Air Force Rocket Propulsion Laboratory, Edwards AFB, Technical Report AFRPL-TR-72-14, March 1972.\*

(6) COMSAT Corporation

Success Criteria for Intelsat IV on a per Channel Basis, R. Strauss, COMSAT Corporation, COMSAT Task 211-4019, TCLP 112, September 11, 1968.

(7) Fairchild Hiller Corporation

Final Report: ATS-4, Fairchild Hiller Space Systems Division for NASA-Goddard, NASA CR-81562, December 1966.

(8) General Dynamics/Convair

Space Tug Attitude Control Systems, Monopropellant Versus Bipropellant, General Dynamics/Convair, 1974.\*

(9) Hamilton Standard, Division of United Aircraft Corporation

0.1 lb, 15-Hour Continuous Mode Firing Test Results, Proposal, Hamilton Standard.

Final Report on 0.1 lb, Valve/Thruster Evaluation Testing, W. Beauregard, Hamilton Standard, Report SVHSER 5447, Volume I, July 1969.

(9) Hamilton Standard, Division of United Aircraft Corporation (Continued)

Final Report, 0.1 lbf Valve/Thruster Evaluation Testing, Volume 1 Valve/Thruster Performance, Hamilton Standard, Report SVHSER 5447, July 1969.

Hydrazine Impurity Survey, Phase I, G. L. M. Christopher, C. T. Brown, Hamilton Standard Division, United Aircraft Corporation for the U.S. Air Force, Technical Report January 1973 - March 1973, AFRPL-TR-73-24, Contract F04611-73-C-0019, June 1973.\*

Long Life 5 lbf Hydrazine Engines for Endurance Requirements, Hamilton Standard, Report SP13R68, August 1968.

Monopropellant Hydrazine Rocket Engine, Hamilton Standard for the Jet Propulsion Laboratory, Report HSPC 69R02, May 1969.

Monopropellant Hydrazine Rocket Engine Technical Information, Hamilton Standard for the Jet Propulsion Laboratory, Report Number HSPC 691202, May 1969.

Monopropellant Hydrazine Tank Self-Pressurizer Demonstration Program, E. R. Bruun, J. E. Genovese, Hamilton Standard Division, United Aircraft Corporation, Final Report November 1971 - December 1972, SVHSER-6049, AFRPL-TR-73-55, Contract F04611-72-C-0021, June 1973.\*

(10) The Johns Hopkins University

Monopropellant Hydrazine Technology (Bibliography), The Johns Hopkins University, August 1975.\*

(11) Hughes Aircraft Company

Proposal for Intelsat IV Satellite and Associated Equipment, Hughes Aircraft Company, Document Number PFP 68-3, Volume IV, 1968.

(12) JANNAF

"An Experimental Evaluation of Metallic Diaphragms for Positive Fuel Expulsion in the Atmosphere Explorer Hydrazine Propulsion Subsystem," In 1972 JANNAF Propulsion Meeting, W. L. Woodruff, NASA Goddard Space Flight Center, Technical Report November 1972, CPIA Publication 223, Volume IV, Contract NAS 3-12026 December 1972.

"Flight Performance of Hydrazine Thrusters on Intelsat I and IV," In 1972 JANNAF Propulsion Meeting, G. Huson, W. Kinney, Communications Satellite Corporation, COM-SAT Laboratory, Technical Report November 1972, CPIA Publication 228, Volume IV, December 1972.

"Life Evaluation of Monopropellant Hydrazine Thruster," In 1972 JANNAF Propulsion Meeting, J. A. Quirk, Air Force Rocket Propulsion Laboratory, Edwards AFB, Technical Report November 1972, December 1972.

"Mariner Spacecraft Experience with Monopropellant Hydrazine Propulsion Systems," In 12th JANNAF Liquid Propulsion Meeting, R. W. Rowley, California Institute of Technology, Jet Propulsion Laboratory, Technical Report, Contract NAS 7-100, 1970.

"Mariner Spacecraft Experience with Monopropellant Hydrazine Propulsion Systems," In 12th JANNAF Liquid Propulsion Meeting, R. W. Rowley, Technical Report November 1970, CPIA Publication 201, Volume I, Contract NAS 7-100, October 1970.

(13) Jet Propulsion Laboratory (JPL)

Comparative Reliability Study: Monopropellant-Bipropellant Jupiter Mission Systems, Jet Propulsion Laboratory, November 1969.\*

Failure Rate Analysis of Mariner Venus 69 Spacecraft Data, F. H. Wright, Jet Propulsion Laboratory for NASA, Contract Number NAS 7-100, Jet Propulsion Laboratory Technical Report 32-1266, June 1, 1969.\*

(13) JPL (Continued)

Failure-Rate Computations Based on Mariner Mass 1969 Spacecraft Data, P. O. Chelson, JPL for NASA, Contract Number NAS 7-100, JPL Technical Report 32-1544, December 1, 1971.\*

Preliminary Studies and Recommendations on a Midcourse Propulsion System for TOPS, Jet Propulsion Laboratory, September 1969.\*

Selected Component List, Jet Propulsion Laboratory, August 1969.\*

The Status of Monopropellant Hydrazine Technology, T. W. Price and D. D. Evans, Jet Propulsion Laboratory, Technical Report 32-12271, February 1968.

A Survey of the Compatibility with Hydrazine and Mixtures of Hydrazine, Hydrazine Nitrate, and Water, D. H. Lee, JPL, LPIA-LPM-1 (Hydrazine, March 1961), Memorandum 20-152, December 22, 1957.\*

Survey of Materials for Hydrazine Propulsion Systems in Multicycle Extended Life Applications, C. D. Coulbert, G. Yankura, California Institute of Technology, Jet Propulsion Laboratory, Contract NAS 7-100, Technical Memorandum TM-33-561, September 1972.\*

(14) The Marquardt Corporation

Basic Data Package Flight Weight Hydrazine Monopropellant REA, Model R12D, 5-lb Thrust, Propulsion Division, The Marquardt Corporation, August 1969.

Basic Data Package Flight Weight Hydrazine Monopropellant REA, Model R25A, 0.1-lb. Thrust, Propulsion Division, The Marquardt Corporation, August 1969.

Investigation of Exhaust Nozzle Flow Phenomena In Arc Jet Engines, L. R. Oswalt, A. Widawsky, The Marquardt Corporation, Contract NAS 8-8951, Report Number MR-25,052, May 1962.

(14) The Marquardt Corporation (Continued)

"Optimization of Conical Nozzle Angle with Viscous Velocity Profile," E. Pitkin, The Marquardt Corporation Interoffice Memo, December 13, 1962.

User's Manual for the Marquardt Model R-13E 5 lb Throat Monopropellant Engine, R. C. Stechman, The Marquardt Corporation, May 1973.

Viscous Laminar Flow In Conical Nozzles, E. Pitkin, The Marquardt Corporation, Report Number MR-20, 187, July 1962.

(15) Princeton University

Nuclear Propulsion Systems and Mission Analysis Research: Reliability Model of a Monopropellant Auxiliary Propulsion System, Aerospace System Laboratory, Princeton University, June 1971.\*

Reliability Model of a Monopropellant Auxiliary Propulsion System, J. S. Greenberg, Princeton University for NASA Technical Report AMS-997, NASA CR-131400, Grant NSR-31-001-150, June 1971.

"Space System Comparison and Evaluation - Basic Concepts," J. Greensberg, Aerospace Systems Laboratory, Princeton University, ASAR Memo Number 71, May 28, 1971.\*

(16) RCA

A Mathematical Model for the Performance of a Spacecraft Auxiliary Propulsion System, R. Lake, RCA, Number RCA PRAE-71-TR-014, May 21, 1971.\*

(17) Rocket Research Corporation

Advanced Fleet Ballistic Missile Weapon Systems, Rocket Research Corporation, June 1972.\*



(17) Rocket Research Corporation (Continued)

Engine Life Consideration--In 1972 JANNAF Propulsion Meeting, F. McCullough, Jr., Rocket Research Corporation, Contract NAS 8-28950, Technical Report November 1972, CPIA Publication 228, Volume IV, December 1972.\*

Hydrazine Propulsion System Reliability Description, Rocket Research Corporation, Subcontract Number 9006-085-16043, July 1975.\*

Long-Life Monopropellant Hydrazine Engine Development Program, B. W. Schmitz, W. W. Wilson, Rocket Research Corporation for the U. S. Air Force, Final Report April 1970 - June 1971, RRC-71-R-257, AFRPL-TR-71-103, September 1971.\*

MR-50A Rocket Engine Assembly Design and Description, Rocket Research Corporation, Report 69-R-183, November 1969.

MR-74 Rocket Engine Test Report, B. Schmitz, Rocket Research Corporation, Report Number 69-R-194, August 1969.

Monopropellant Hydrazine Plenum System, Rocket Research Corporation, First Quarterly Report under Contract Number NAS 5-10389 (67-R-117), August 24, 1961.

Final Report for Monopropellant Hydrazine Plenum Study, Rocket Research Corporation, December 1969.

Planetary Explorer Liquid Propulsion Study, Rocket Research Corporation, June 1971.\*

Propulsion System Reliability Study, Rocket Research Corporation, September 1974.\*

Reaction Engine Module - Monopropellant (FMECA), Rocket Research Corporation, June 1973.\*

(18) Textron Bell Aerospace

Operational Effects on the Life Monopropellant Hydrazine Devices, Textron Bell Aerospace, October 1975.\*

(19) TRW Systems, Incorporated

Bi-Propellant, Mono-Propellant Reliability, R. A. Paulson, TRW Systems, Report Number 95254, August 1969.

Comparative Reliability Study--Monopropellant-Bipropellant Jupiter Mission Systems, R. A. Paulson, TRW Systems, Incorporated, for JPL, JPL Contract 952545, Final Report, November 1969.

Half-Pound Monopropellant Hydrazine Thruster, TRW Systems Group, December 1968.

Monopropellant Spacecraft Maneuvering and Attitude Control System, TRW Systems Group, August 1969.

(20) United Aircraft Corporation (See Hamilton Standard)

(21) United Technologies Research Center

Analysis of Gas Pressure Buildups Within a Porous Catalyst Particle Which Is Wet by a Liquid Reactant, A. S. Kesten, United Technologies Research Center, May 1970.\*

Analytical and Experimental Studies of the Startup Characteristics of Catalytic Reactors for Hydrazine Decomposition, A. S. Kesten, United Technologies Research Center, November 1968.\*

Analytical Study of Catalytic Reactors for Hydrazine Decomposition, A. S. Kesten, United Technologies Research Center, undated.\*

Ascent Phase Guidance and Orbital Correction Propulsion Module, A. S. Kesten, United Technologies Research Center, November 1973.\*

A Conceptual Model of Hydrazine Catalytic Reactor Washout Caused by Decomposition Product Poisoning and Pressure Buildup, A. S. Kesten, United Technologies Research Center, November 1972.\*

(21) United Technologies Research Center (Continued)

An Integral Equation for Evaluating the Effects of Film and Pore Diffusion of Heat and Mass on Reaction Rates in Porous Catalyst Particles, A. S. Kesten, United Technologies Research Center, January 1969. \*

Motion Picture Studies of the Startup Characteristics of Liquid Hydrazine Catalytic Reactors, A. S. Kesten, United Technologies Research Center, June 1971. \*

The Use of Axial Heat Conduction as a Mechanism for Promoting Exothermic Chemical Reactions in Packed-Bed Reactors, A. S. Kesten, United Technologies Research Center, September 1970. \*

(22) Walter Kidde and Company

300-LBF Monopropellant Hydrazine Thruster Life Evaluation, G. M. Hall, T. P. Layendecker, Aerospace Marketing Division, Walter Kidde and Company for the U.S. Air Force, Final Report November 1971 - April 1972, Report Number 4928-FTR-1, AFRPL-TR-73-23, Contract F04611-72-C-0027, March 1973.

(23) Other Publications

1. Magazines

"Hydrazine Monopropellant Provides 0.5-600 lb Thrust," T. W. Price, Space Aeronautics, page 70, October 1969.

2. Papers/Reports

Thrusters for ESRO "Symphonie" Satellite; 10-N Thruster is MON 0,3/MMH, 400-N Thruster MON 0,3/AZ 50, Messerschmitt-Bölkow-Blohm Unternehmenbereich Raumfahrt; Contact is Fortek Corporation. \*

7. THERMO-CHEMICAL (BIPROPELLANT)

(1) Aerojet Liquid Rocket Company

Five-Pound Bipropellant Engine, Aerojet Liquid Rocket Company, September 1974.\*

(2) United States Air Force

Minuteman III Propulsion System Rocket Engine Reliability and Failure Status Report, 5/10/75 through 6/20/75, Space and Missile Systems Organization, Air Force Systems Command, Norton Air Force Base, California, Contract F04701-73-C-0214, Report Number 8477-928946.\*

Ten-Year Surveillance Program Progress Report Bell Model 8477, 9/1/74 through 2/28/75, Ogden Air Logistics Center, Air Force Logistics Command, Hill Air Force Base, Utah, Contract F04701-73-C-0451, Report Number 8477-927789.

Thermodynamics of Rocket Propulsion and Theoretical Evaluation of Some Prototype Propellant Combustions, T. Dobbins, Wright Air Development Center, Report TR-59-757, December 1959.

(3) JANNAF

"Post-Boost Propulsion Experience," Major H. W. Galo, Captain N. Adams, SAMSO, Norton Air Force Base, Presented at JANNAF Meeting, undated.

(4) Jet Propulsion Laboratory (JPL)

Reliability Analysis (Rough Draft), Jet Propulsion Laboratory, Contract Number 952545, September 16, 1969.\*

Selected Component List, Jet Propulsion Laboratory, August 1969.\*

(5) The Marquardt Corporation

Electro-Chemical Propulsion Technology, The Marquardt Corporation, undated.\*

Investigation of Exhaust Nozzle Flow Phenomena in Arc Jet Engines, L. R. Oswalt and A. Widawsky, The Marquardt Corporation for NASA, MR 25,052, Contract NAS 8-8951, May 1962.

Model R-1E 22 Pound Thrust Liquid Rocket Engine, The Marquardt Corporation, undated.\*

Model R-4D 100 Pound Thrust Liquid Bipropellant Rocket Engine, The Marquardt Corporation, undated.\*

"Optimization of Conical Nozzle Angle with Viscous Velocity Profile," E. Pitkin, The Marquardt Corporation, Interoffice Memo, December 13, 1962.

Technical Description: Marquardt Model R-1E 22 Pound Thrust Rocket Engine, The Marquardt Corporation, October 1972.\*

Viscous Laminar Flow in Conical Nozzles, E. Pitkin, The Marquardt Corporation, MR-20,187, July 1962.

(6) TRW Systems, Incorporated

Bi-Propellant, Mono-Propellant Reliability Study, R. A. Paulson, TRW Systems, Incorporated, Contract Report Number 95254, August 1969.

Comparative Reliability Study--Monopropellant-Bipropellant Jupiter Mission Systems, Final Report, R. A. Paulson, TRW Systems for JPL, JPL Contract 952545, November 1969.

8. THERMO-CHEMICAL (GENERAL)

(1) Advanced Technology Center

Procedure for the Design and Optimization of Liquid Rocket Propulsion Systems, Advanced Technology Center, April 1966.\*

(2) Aerospace Corporation

Candidate Low Thrust Devices For the Space Station Reaction Control System, G. Nunz, Aerospace Corporation, Contract F04701-69-C-0066, Report Number TOR-0066 (5759-03-1), May 1970.

Experimental Performance of Anhydrous Ammonia, D. J. Griep, Contract Number AF 04 (696) 469, Aerospace Corporation Report Number TDR-469 (5230-33)-1, October 1964.

(3) Aerospace Industries

Dynamic Performance of Low Thrust Cold Gas Reaction Jets in a Vacuum, H. Greer and D. J. Griep, Aerospace Industries, Report Number TR-669(6230-33)-1, August 1966.

Dynamic Performance of a Subliming Solid Reaction Jet, H. Greer and D. J. Griep, Aerospace Industries, Report Number TR-1001 (2230-33)-1, December 1966.

(4) American Institute of Aeronautics and Astronautics (AIAA)

1. Conferences

"Design Criteria for Subliming Solid Applications," H. M. Kindevater, Presented at ICRPG/AIAA Solid Propulsion Conference, Anaheim, California, June 6-8, 1967.

1. Conferences (Continued)

"Microthrusters Employing Catalytically Reacted Gas Mixtures, Tridyne," H. E. Barber, et al, Presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

"Subliming Solid Propulsion System Technology," R. F. Eggers, Presented at ICRPG/AIAA Solid Propulsion Conference, Anaheim, California, June 6-8, 1967.

2. Journals

"Dynamic Performance of Low-Thrust, Cold Gas Reaction Jets in a Vacuum," H. Greer and D. J. Griep, AIAA Journal of Spacecraft, Volume 4, Number 8, page 983, August 1967.

"Thrust and Impulse Requirements for Jet Attitude-Control Systems," V. E. Haloulakos, AIAA Journal of Spacecraft, Volume 1, Number 1, page 84, January 1964.

3. Papers

"Attitude Control With Hydrogen Microthrusters," F. J. Hendel, AIAA Paper 70-613, Presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

"The Chemistry of Subliming Solids For Micro Thrust Engines," A. P. Hardt, W. M. Foley and R. L. Brandon, AIAA Paper 65-595, June 14-18, 1965.

"Design Aspects of Subliming Solid Reaction Control Systems," W. L. Owens, Jr., AIAA Paper 68-516, June 1968.

"The Development of Microthrusters in France under the C.N.E.S. Authority," J. P. Pujes, AIAA Paper

3. Papers (Continued)

70-617, Presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 1970.

"Low Thrust Mission Risk Analysis," C. L. Yen, D. B. Smith, AIAA Paper Number 73-208, Presented at the AIAA 11th Aerospace Sciences Meeting, Washington, D. C., January 1973.\*

"A Review of Micro-Rocket Technology:  $10^{-6}$  to 1 lb. Thrust," G. S. Sutherland and M. E. Maes, AIAA Paper 65-620, June 1965.

"Spacecraft Capillary Propellant Retention and Control for Long-Life Missions," S. C. DeBrock, AIAA Paper 68-465, April 1968.

"Synchronous Satellite Station-Keeping," M. J. Neufeld and B. M. Angel, AIAA Paper 66-304, May 1966.

"Zero Gravity Ammonia Propellant System," W. F. Krieve, F. L. Merritt and R. Grobbi, AIAA Paper 70-1151, Presented at the AIAA 8th Electric Propulsion Conference, Stanford, California, September 1970.

(5) United States Air Force

Bambi Phase II. Technical Investigations Single Interceptor Satellite, Volume III, Space Systems Division, Los Angeles Air Force Station, November 1962.\*

Methods for Control of Satellites And Space Vehicles, R. E. Roberson, Volume I, Wright Air Development Division, WADD Technical Report 60-643, July 1960.

Reaction Engine Module Test Evaluations, F. N. Fredrickson, Air Force Rocket Propulsion Laboratory, Edwards AFB, Final Report August 1971 - January 1972, Report Number AFRPL-TR-72-44, July 1972.



(6) Allis-Chalmers

A Study of the Feasibility of a Separated O<sub>2</sub>H<sub>2</sub> Electro-  
thochemical Propulsion System, E. Picciotti, K. Rouch,  
and C. Pox, Advanced Electrochemical Products Division,  
Allis Chalmers, September 1969.

(7) AVCO Corporation

Reliability Engineering Data Series Failure Rates,  
D. R. Earles and M. F. Eddins, AVCO Corporation,  
April 1962.

Solenoid Valve Qualification Test Report ATS-D/E  
Auxiliary Propulsion System, AVCO Corporation for  
NASA, Report Number AVSSD-0165-68-CR for  
Contract Number NAS 5-10394, August 1968.

(8) Ball Brothers Research Corporation

Final Report and Technical Manual S-16 Orbiting Solar  
Observatory, F. D. Dolder, Ball Brothers Research  
Corporation.

(9) Battelle Memorial Institute

Compatibility of Rocket Propellants with Materials of  
Construction, Defense Metals Information Center, Battelle  
Memorial Institute, OTS PB-161215, DMIC Memorandum  
65, September 15, 1960. \*

(10) Bird Engineering—Research Associates

Reliability of the Cold Gas Attitude Control System,  
R. H. Broadhurst, Bird Engineering—Research  
Associates, Incorporated, May 1967.

- (11) Boeing Aircraft Company  
Voyager '71 Program (Reliability Analysis), Boeing Aircraft Company, Report D2-23834-1, April 1965.
- (12) COMSAT Corporation  
A User Assessment of Servicing in Geostationary Orbit, COMSAT Corporation, undated.\*
- (13) Curtiss-Wright  
Encapsulated Solid Propellant Rockets, Curtiss-Wright, Report Number WAD R831, August 1966.
- (14) Dayton University  
Experimental Evaluation of a Reliability Assessment Model for Adhesively Bonded Joints, Dayton University, June 1974.\*
- (15) DRL  
Viking 75 Project VLC Reliability Prediction Analysis, RA-372-0059, DRL Line Item Number N3-R002, NAS 1-9000.
- (16) Energy Research and Development Administration (ERDA)  
Operational Risk and Reliability of Space Transportation Systems, ERDA, undated.\*
- (17) Fairchild Hiller Corporation  
Analysis of a Cold Gas Thruster Subsystem for the Anchored Interplanetary Monitoring Platform Attitude Control System, Space and Electronic Systems Division, Fairchild Hiller Corporation, SSD-165.0, December 1966.

(18) General Electric Company

Application of Cost Effectiveness Criteria as a Basis for Attitude Control System Selection, R. F. Wanger, General Electric Corporation, Spacecraft Department, Report PIR 9752-033, April 1, 1964.

"Failure Modes and Effects Criticality Analysis," Volume V of Superconducting Propulsion System, B.D. Hatch and D. L. Kerr, Power Generation and Propulsion Laboratory, General Electric Company, for the U. S. Navy, Contract Number N00024-73-C-5488, Report Number SRD-74-106-5, November 1974.

(19) Giannini Scientific Corporation

Study of the Factors Affecting the Efficiency in Thermal Acceleration of Propellants, A. C. Ducati, Giannini Scientific Corporation, Sixth Quarterly Technical Report 6QS-113-1161, October 1963.

(20) Hughes Aircraft Company

Hydrazine Electrolysis for Spacecraft Propulsion, W. W. Butcher, Space Systems Division, Hughes Aircraft Company for JPL, Report for JPL Contract Number 951720 ISS080316R, August 1968.

Nonelectric Reliability Notebook, Hughes Aircraft Company for Rome Air Development Center, NTIS AD/A-005-657, January 1975.

Spacecraft Attitude Control Gas System Analysis, W. W. Butcher, et al., Hughes Aircraft Company, Report SS07017212, April 1967.

(21) Illinois Institute of Technology (IIT)

Aerospace Tanks, Volumes I and II, Illinois Institute of Technology, Research Institute, IITRI Project C6309, JPL Contract 953830, July 1974. \*

Attitude Control Propulsion Components, Volumes I and II, Illinois Institute of Technology, Research Institute, IITF C6309, JPL Contract 953830, November 1974.\*

(22) Jet Propulsion Laboratory (JPL)

Design and Evaluation of Propellant Tankage for SEPST Program, J. R. Womack, Jet Propulsion Laboratory, SPS 37-58, Volume III, August 1969.\*

Failure Rate Computations Based on Mariner Mars 1964 Spacecraft Data, F. H. Wright, Jet Propulsion Laboratory, Technical Report 32-1036, January 15, 1967.

Low Thrust Mission Risk Analysis with Application to a 1980 Rendezvous with the Comet Encke, C. L. Yen, D. B. Smith, Jet Propulsion Laboratory, NASA TM 33-593, March 15, 1973.\*

Reliability Computation from Reliability Block Diagrams, P. O. Chelson, R. E. Eckstein, Jet Propulsion Laboratory for National Aeronautics and Space Administration, Contract NAS 7-100, JPL Technical Report 32-1543, December 1, 1971.\*

Reliability Computation Using Fault Tree Analysis, P. O. Chelson, JPL for NASA, Contract NAS 7-100, JPL Technical Report 32-1542, December 1, 1971.\*

Satellite Auxiliary-Propulsion Selection Techniques, L. B. Holcomb, Jet Propulsion Laboratory, Technical Report 32-1505, November 1, 1970.\*

Ibid, "Addendum Survey of Auxiliary Electric Propulsion Systems," July 15, 1971.\*

Ibid, "Supplement 1--Application of Selection Techniques to the ATS-II Satellite," October 1, 1972.\*

Spacecraft Attitude Control Gas Systems Analysis, Jet Propulsion Laboratory, JPL Contract 951720, Report Number SSD 70172R, April 1967.\*

(22) Jet Propulsion Laboratory (Continued)

Technical Support Package on Reliability Data for Electronic and Electromechanical Components: A Report, Jet Propulsion Laboratory, for NASA TECHBRIEF 74-10280, JPL Invention Report 30-2864/NPO-13153, April 1975.

"Viking Reaction Control Gas System Weight Reduction Analysis Phase I," J. D. Ferrera and F. G. Roselli-Lorenzini, Jet Propulsion Laboratory, Engineering Memorandum 344-222FGR-L, April 1969.

(23) Life Systems, Incorporated

In-Flight Bipropellant Generator for Attitude Control, Life Systems, Incorporated, June 1969.

(24) Lockheed Missile and Space Company, Incorporated

Low Thrust Solid and Hybrid Propulsion Systems (Phase II) Lockheed Missiles and Space Company, for NASA, Contract NAS 7-573, Final Report LMSC-685070, February 1968.

Subliming Solid Reaction Control System, Missile & Space Company, Lockheed Aircraft Corporation, Final Report Number LMSC-679102, October 1967.

Final Report, Subliming Solid Reaction Control System, Lockheed Missiles and Space Company, Report LMSC-5A102, Hughes Aircraft Company Purchase Order 44-810904, October 1967.

(25) Martin-Marietta Corporation

Handbook of Piece Part Failure Rates Long Life Spare Vehicle Investigation, Martin-Marietta Corporation, Task Authorization TOS 48891, Report Number T-70-48891-007.

(25) Martin-Marietta Corporation (Continued)

Long-Life Assurance Study for Manned Spacecraft Long-Life Hardware, R. W. Burrows, Martin-Marietta Corporation for NASA, Contract NAS 9-12359, Volumes 1-5, Report Number MCR-72-169, December 1972.\*

Revision of RADC Nonelectronic Reliability Notebook (RADC-TR-69-458), Section 2, D. F., Cottrell et. al., Martin-Marietta Corporation for the Rome Air Development Center, NTIS AD/A-002-152, October 1974.\*

Ibid, Index and Revision to Section 2, NTIS AD/A-002-898.

Voyager Studies, Martin-Marietta Corporation, Report FR-22-103, Volume II, Section I, 1967.

(26) Massachusetts Institute of Technology (MIT)

Wear Particle Formation Mechanisms, H. Koba, N. H. Cook, Cambridge Materials Processing Laboratory, Massachusetts Institute of Technology, May 1974.\*

(27) McDonnell Douglas Astronautics Company

"Attitude Control and Translation System/Propulsion Subsystem," Sequence Number B242, Volume V of Laboratory Module/Effectiveness Model Report, Western Division, McDonnell Douglas Astronautics Company, April 1968.\*

(28) National Aeronautics and Space Administration (NASA)

AIMP-E Attitude Control System, D. K. McCarthy and R. H. Corter, Goddard Space Flight Center, Report X-723-68-410, November 1968.

Design Criteria for Spacecraft Propulsion Systems, C. N. Jennings, Space General for NASA/OART, Contract NAS 7-519, Final Report, October 1967.\*

(28) NASA (Continued)

Evaluation and Demonstration of the Use of Cryogenic Propellants (O<sub>2</sub>/H<sub>2</sub>) for Reaction Control Systems, N. Rodewald, G. Falkenstein, P. Herr, and E. Provo, NASA, Report Number NASA CR-72244 (R-6838-2), June 1968.

Evaluation and Demonstration of the Use of Cryogenic Propellants (O<sub>2</sub>/H<sub>2</sub>) for Reaction Control Systems, N. Rodewald, G. Falkenstein, P. Herr, and E. Provo, for NASA, Volume II, NASA CR-72244 (R-6838-2), June 1968.

Experimental Performance of a Water-Electrolysis Rocket, J. R. Rollubler, for NASA, NASA TM X-1737, February 1969.

Liquid Rocket Engine Combustion Stabilization Devices, Design Criteria Office, Lewis Research Center, National Aeronautics and Space Administration, Report Number NASA SP-8113, November 1974.\*

Measured Steady-State Performance of Water Vapor Jets for Use in Space Vehicle Attitude Control Systems, B. E. Tinling, for NASA, NASA TND-1302, May 1962.

Reliability Testing and Demonstration—Aerospace Problems, Vincent R. Lalli, Lewis Research Center, NASA TM X-67877, November 1971.

A Study of Programs for Evaluation of Component Life, Marshall Space Flight Center, NASA, Contract NAS 8-21296, Report Number MCR-69-366.

A Study of Storage Technology for Various Launch Vehicle Systems, NASA Contract NAS 8-21296, Report Number MCR-68-329.

A Study of Total Space Life Performance of GSFC Spacecraft, A. R. Timmins, Goddard Space Flight Center, NASA, NASA Technical Note NASA TN D-8017, July 1975.

(29) United States Navy

An Evaluation of Electric and Hydrazine Propulsion Systems for Orbit Maintenance, R. V. Silverman, Naval Space Systems Activity, Final Report NSSA R40-70-3, May 1971.\*

(30) Planning Research Corporation (PRC)

Reliability Data From In-Flight Spacecraft, 1958-1970, E. E. Bean, C. E. Bloomquist, PRC for the U. S. Navy Space Systems Activity, Report Number PRC R-1453, November 30, 1971.\*

A Standardized Approach for the Evaluation of Spacecraft Reliability, E. E. Bean, C. E. Bloomquist, PRC for the U. S. Navy Space Systems Activity, Report Number PRC R-1453, November 30, 1971.\*

(31) Princeton University

Effects of Insulator Ablation on the Operation of a Quasi-Steady MPD Arc, Princeton University, November 1973.\*

Nuclear Propulsion Systems and Mission Analysis Research: Reliability, Uncertainty and Risk Analysis of Space Systems, Princeton University, December 1972.\*

(32) Rocketdyne

"Rocketdyne Internal Memorandum," A. T. Forrester and R. C. Speiser, Rocketdyne, RM 433191, to R. H. Boden, August 1958.

Tridyne Attitude Control Thruster Investigation, S. F. Iacobellis, Rocketdyne, Report Number R-7743P, January 1969.



(33) Rockwell International and North American Rockwell

Advanced Composites Design Guide, Rockwell International,  
Third Addition, Volumes I-V, AFML, 1973.

(34) Space General Corporation

Design Criteria for Spacecraft Propulsion Systems,  
C. N. Jennings, Space General Corporation, Report  
Number 1069 FR-1, October 1967.

Design Criteria for Spacecraft Propulsion Systems,  
C. N. Jennings, Space General Corporation, Volume V,  
Report 1069 FR-1, October 1967.

Procedure for the Design and Optimization of Liquid  
Rocket Propulsion Systems, C. N. Jennings, Space  
General Corporation, Volume II-B, Report SGC 837 FR-1,  
April 1966. \*

(35) Stanford Research Institute (SRI)

Cost and Reliability Estimates for Chemical Propulsion  
Systems, Stanford Research Institute, January 1969. †

Reliability Estimation for Chemical Propulsion Systems,  
Stanford Research Institute for NASA, Proposal Number  
MU-69-100, May 13, 1969. †

Ibid, Stanford Research Institute for NASA, May 1970. †

(36) TRW Systems, Incorporated

Elastomers for Liquid Rocket Propellant Containment,  
J. W. Martin, H. E. Green, Part II, TRW Systems Group,  
for the U. S. Air Force, Technical Report AFML-TR-71-59,  
October 1973. \*

(37) Other Publications

1. Book

Elements of Rocket Propulsion, G. P. Sutton,  
John Wiley & Sons Inc., New York, First Edition,  
1949.

2. Conferences

"Electro Chemical Propulsion System," L. R. Bell  
and E. F. Picciotti, Presented at the 12th Liquid  
Propulsion Meeting, New Technology Session, Las  
Vegas, Nevada, November 1970.

"Position and Orientation Propulsion Systems for  
Unmanned Vehicles," A. Burnstein and H. Dicristina,  
Paper P 37, Presented at the 19th Congress of the  
International Astronautical Federation, New York,  
October 1968.

"Spacecraft Attitude Control," V. S. Robertson and  
J. J. Weaver, British Interplanetary Society,  
1st Annual Meeting, University of Southampton,  
Released from Elliott Brothers (London) Limited,  
Space and Guided Weapons Division, Chobham Road,  
Frimley, Camberley, Surrey, England, April 1968.

3. Magazines

"The Choice of Propellant for a Cold Gas Propulsion  
System for a Satellite," H. M. Briscoe, Journal  
of the British Interplanetary Society, Volume 20,  
page 72, 1965-66.

"Spacecraft Mission Effectiveness," A. Leventhal  
and C. E. Bloomquist, Annals of Reliability and  
Maintainability, Spring Issue, 1968.

"Survey of Satellite Auxiliary Propulsion Systems,"  
L. G. Holcomb, Journal of Spacecraft and Rocket,  
Volume 9, Number 3, pages 133-147, March 1972.

(37) Other Publications (Continued)

4. Papers/Reports

Auxiliary Propulsion Survey Part III Survey of  
Secondary Propulsion and Passive Attitude Control  
Systems for Spacecraft, I. Grossman, I. R. Jones,  
and D. H. Lee, Technical Report APAPL-TR-68-67,  
September 1968.

Development Trends in Special-Purpose Nuclear  
Energy Installations, German Report, June 1972.\*