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VOLUME 4

APPLICATION OF REDUNDANCY STUDY

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Under Contract No. 951112

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SECTION 1

GENERAL

1.1 INTRODUCTION

This volume contains the final report for the Application of Redundancy Study, one of four studies comprising the Voyager Phase IA, Task C activity performed by the General Electric Company for the Jet Propulsion Laboratory under JPL Contract Number 951112.

This report covers the activity of the entire study, encompassing the period from 1 April 1966 through 31 July 1967.

Readers who are interested in an overview of the Application of Redundancy final report are referred to Section 4 of Volume 1 of this series, in which the redundancy final report is summarized in approximately 5% of the length of this volume. By intent, however, the abridgement is lacking in supporting depth and detail.

1.2 STUDY OBJECTIVES

The broad objective of the Application of Redundancy Study was to investigate the manner in which redundancy could be applied to Voyager at the mission and spacecraft system level, and the practical extent of such redundancy.

Redundancy at the mission level is interpreted to imply and involve the number and types of systems which should be employed at a given launch opportunity, with particular reference to the number and types of launch vehicles, spacecraft, and capsules. During the course of this study, the capsule system was redefined as two systems: the capsule bus system and the surface laboratory system. It was felt, however, that recognizing the subdivision at that point would not appreciably aid the study, and accordingly, the capsule system as defined in this volume includes both the bus and the surface laboratory.

Redundancy at the system level involves the number and types of hardware elements (i.e., black boxes or components) which should comprise the spacecraft system. All types of redundancy were considered to be within the scope of the study, including block, multi-channel, standby and functional redundancy. Redundancy below the black box level (i.e., the piece-part level) was not considered, except as required to determine the performance characteristics of the black box under consideration.

1.3 STUDY ORGANIZATION

To accomplish the objectives of the Application of Redundancy Study, activity was divided into three major areas of endeavor, as suggested in Figure 1-1:

a. Mission and System Definition

Definition of the Voyager mission profile and the systems comprising potential mission configurations. Detailed definition of the Voyager spacecraft system.

b. Selection of Spacecraft System Redundancy

The development of techniques for the selection of redundancy within the Voyager spacecraft system. Recommendation of a typical allocation of such redundancy.

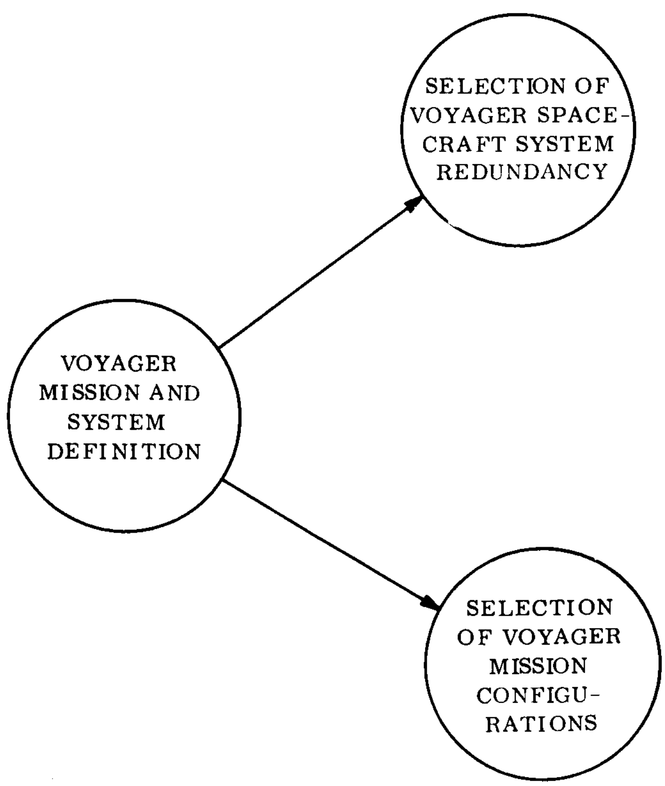


Figure 1-1. Application of Redundancy Study Organization

c. Selection of Voyager Mission Configurations

The development of techniques for the selection of the initial Voyager mission configuration and the probable sequence of configurations to follow the initial choice. Recommendation of a typical project sequence of mission configurations.

For detailed management of the Application of Redundancy Task, these three major areas of endeavor were further divided into a total of nine subtasks, as follows:

1.3.1 MISSION AND SYSTEM DEFINITION

a. Mission and System Definition - Definition of the Voyager mission profile and the role of the Voyager spacecraft system therein via the medium of functional flow diagrams. Definition of nominal and alternate mission and system configurations.

b. Trade Studies - Principally at the mission and system level, to assist in the identification and definition of the nominal Voyager mission profile and spacecraft system configuration, and to identify candidates for redundancy, especially functional redundancy.

1.3.2 SELECTION OF VOYAGER MISSION CONFIGURATIONS

a. Project Models - The development of analytical models of the costs of potential mission configurations, the values of specified project levels of accomplishment, and the probabilities of achieving project accomplishments with potential mission configurations.

b. Project Decision Model - The application of decision analysis in the development of techniques for the selection of the initial Voyager mission configuration and the configuration selection strategy to follow the initial choice. Exercise of the technique to select a typical sequence of mission configurations.

1.3.3 SELECTION OF SPACECRAFT SYSTEM REDUNDANCY

a. Mission Value Model - Definition of an exhaustive and mutually exclusive set of possible outcomes of the Voyager mission and assignment of relative worth to these outcomes.

b. Failure Effects Analysis - Correlation of the effects of failure of hardware elements within the spacecraft system with the resulting outcomes of the mission.

c. Definition of Reliability Characteristics - The assignment of reliability characteristics to the modes of operation of spacecraft system hardware.

d. Mission Optimization Program Development - The application of dynamic programming in the development of a technique for selecting redundancy within the spacecraft system to maximize the expected worth of the mission.

e. Mission Optimization - Exercise of the above technique to select typical optimum system configurations within preselected system constraints.

Figure 1-2 illustrates the detailed flow of work that was followed within each of the foregoing nine subtasks during the period of the study, and the interrelationships among the subtasks. The progress of the Application of Redundancy Study in the six Voyager Phase IA Task C Bi-Monthly Progress Reports (General Electric Documents VOY-CO-PR1 through PR6) published during the course of the study followed the outline of the nine subtasks. This subtask structure is not to be employed in this final report and is presented only for the purpose of cross referencing this report with previous bi-monthly progress reports.

1.4 FINAL REPORT ORGANIZATION

Following Section 1, the remainder of this volume is divided into three sections in concert with the study organization shown in Figure 1-1.

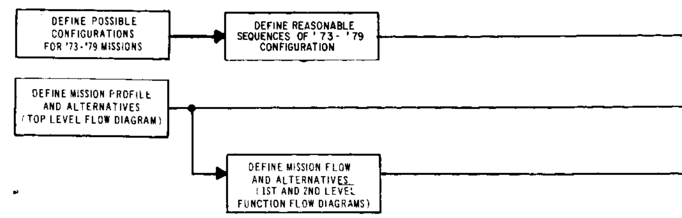
1.4.1 MISSION AND SYSTEM DEFINITION (SECTION 2)

Section 2 describes the identification of a nominal Voyager mission profile and configuration, and the detailed definition of the mission flight sequence and the role of the Voyager spacecraft system therein. Functional flow diagrams, i.e., the Air Force 375-5 systems engineering approach, were employed as the medium for definition.

Summarized in Section 2 is the development of the functional flow diagrams to that level of detail where the detailed functions to be performed could be correlated with discrete elements of spacecraft hardware. The spacecraft hardware is categorized as either single-string hardware; i.e., comprising the single-string spacecraft system (the baseline system

JULY | AUGUST

1. MISSION AND SYSTEM DEFINITION



2. TRADE STUDIES

3. PROJECT MODELS

4. PROJECT DECISION MODEL

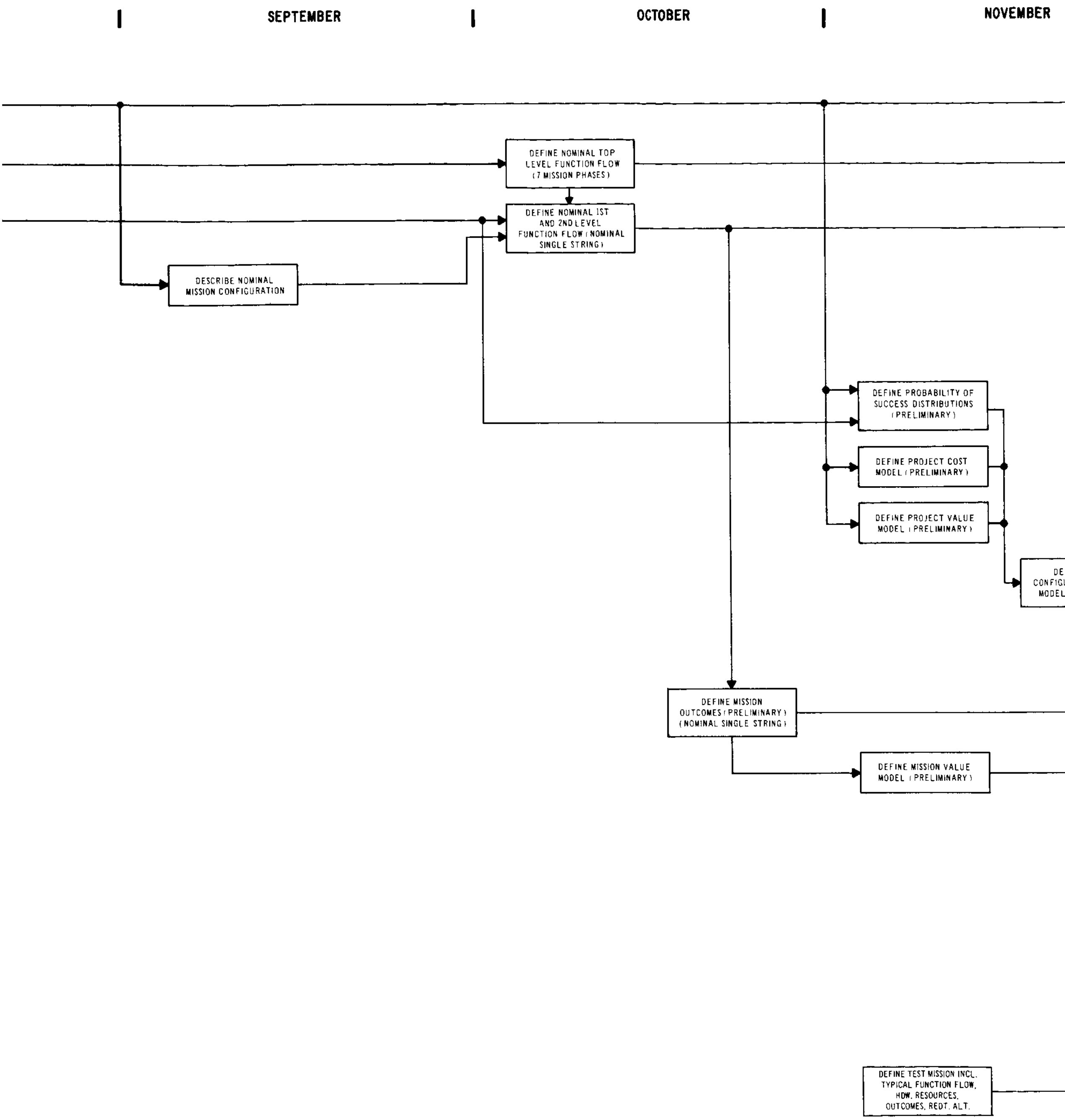
5. MISSION VALUE MODEL

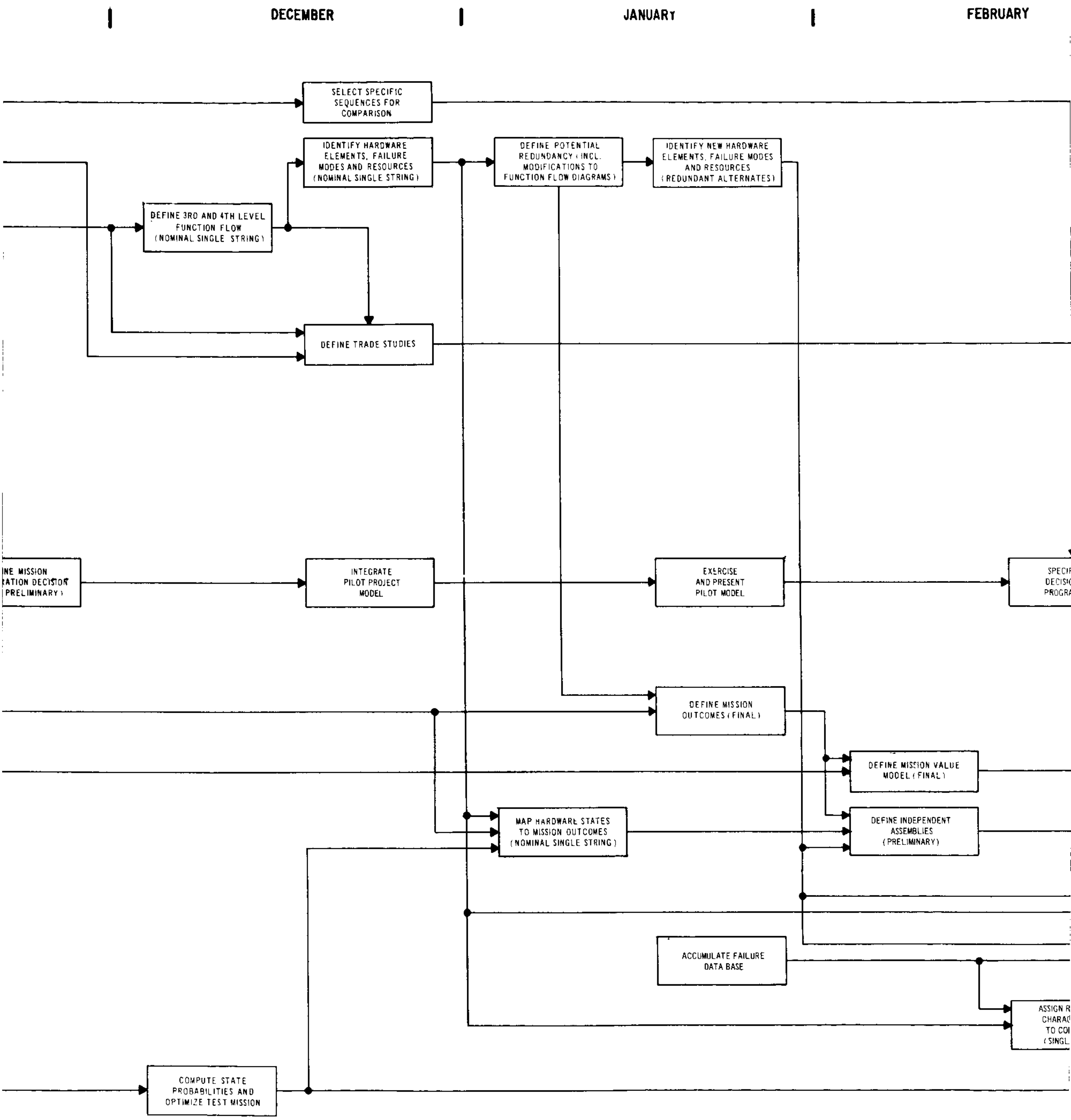
6. FAILURE EFFECTS ANALYSIS

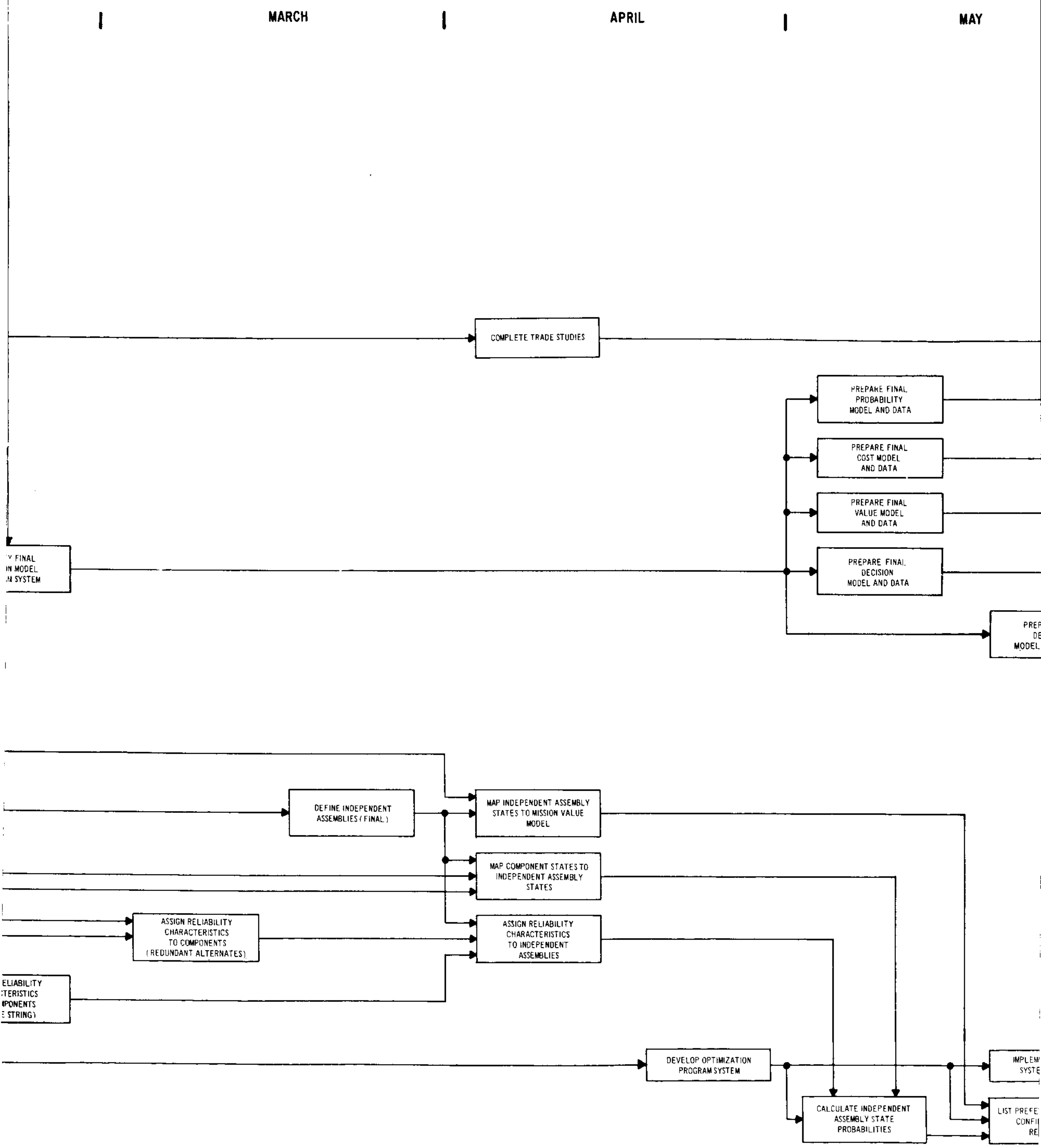
7. DEFINITION OF RELIABILITY CHARACTERISTICS

8. MISSION OPTIMIZATION PROGRAM DEVELOPMENT

9. MISSION OPTIMIZATION


SEPTEMBER
OCTOBER
NOVEMBER
DEFINE NOMINAL TOP LEVEL FUNCTION FLOW (7 MISSION PHASES)
DEFINE NOMINAL 1ST AND 2ND LEVEL FUNCTION FLOW (NOMINAL SINGLE STRING)
DESCRIBE NOMINAL MISSION CONFIGURATION
DEFINE PROBABILITY OF SUCCESS DISTRIBUTIONS (PRELIMINARY)
DEFINE PROJECT COST MODEL (PRELIMINARY)
DEFINE PROJECT VALUE MODEL (PRELIMINARY)
DEFINE MISSION OUTCOMES (PRELIMINARY) (NOMINAL SINGLE STRING)
DEFINE MISSION VALUE MODEL (PRELIMINARY)
DEFINE TEST MISSION INCL. TYPICAL FUNCTION FLOW, HDW. RESOURCES, OUTCOMES, REDT. ALT.


DECEMBER
JANUARY
FEBRUARY
SELECT SPECIFIC SEQUENCES FOR COMPARISON
IDENTIFY HARDWARE ELEMENTS, FAILURE MODES AND RESOURCES (NOMINAL SINGLE STRING)
DEFINE POTENTIAL REDUNDANCY (INCL. MODIFICATIONS TO FUNCTION FLOW DIAGRAMS)
IDENTIFY NEW HARDWARE ELEMENTS, FAILURE MODES AND RESOURCES (REDUNDANT ALTERNATES)
DEFINE 3RD AND 4TH LEVEL FUNCTION FLOW (NOMINAL SINGLE STRING)
DEFINE TRADE STUDIES
INE MISSION ATION DECISION (PRELIMINARY)
INTEGRATE PILOT PROJECT MODEL
EXERCISE AND PRESENT PILOT MODEL
SPECI DECISI PROGRA
DEFINE MISSION OUTCOMES (FINAL)
DEFINE MISSION VALUE MODEL (FINAL)
MAP HARDWARE STATES TO MISSION OUTCOMES (NOMINAL SINGLE STRING)
DEFINE INDEPENDENT ASSEMBLIES (PRELIMINARY)
ACCUMULATE FAILURE DATA BASE
ASSIGN R CHARAC TO CO (SINGL
COMPUTE STATE PROBABILITIES AND OPTIMIZE TEST MISSION


MARCH
APRIL
MAY
COMPLETE TRADE STUDIES
PREPARE FINAL PROBABILITY MODEL AND DATA
PREPARE FINAL COST MODEL AND DATA
PREPARE FINAL VALUE MODEL AND DATA
PREPARE FINAL DECISION MODEL AND DATA
DEFINE INDEPENDENT ASSEMBLIES (FINAL)
MAP INDEPENDENT ASSEMBLY STATES TO MISSION VALUE MODEL
MAP COMPONENT STATES TO INDEPENDENT ASSEMBLY STATES
ASSIGN RELIABILITY CHARACTERISTICS TO COMPONENTS (REDUNDANT ALTERNATES)
ASSIGN RELIABILITY CHARACTERISTICS TO INDEPENDENT ASSEMBLIES
DEVELOP OPTIMIZATION PROGRAM SYSTEM
CALCULATE INDEPENDENT ASSEMBLY STATE PROBABILITIES

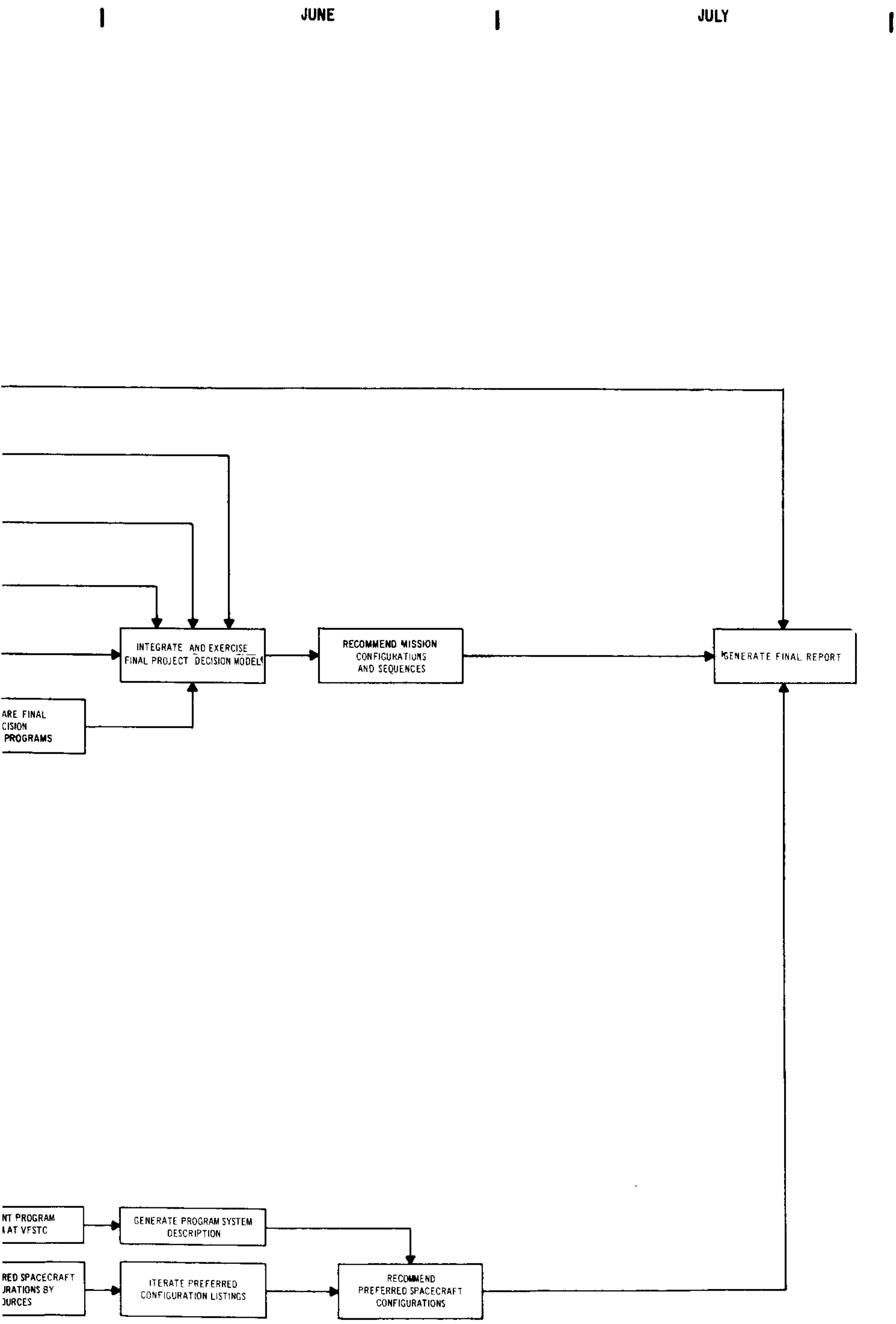


Figure 1-2. Application of Redundancy Work Flow Chart

void of any intentional redundancy), or potentially redundant hardware. Descriptions of the weight, power, failure modes, and design characteristics of the single-string and potentially redundant hardware are reviewed in Section 2.

Also covered are summaries of the 10 trade studies performed during the Application of Redundancy Study.

1.4.2 SELECTION OF SPACECRAFT REDUNDANCY (SECTION 3)

Section 3 of this final report is devoted to the selection of redundancy within the Voyager spacecraft system. The section begins with a review of the mission value model, the medium for definition of the possible outcomes of the Voyager mission and for assignment of worth to these outcomes.

Discussed next is the development of a comprehensive piece-part failure data base, and the application of this data base to assigning reliability characteristics to the single-string and potentially redundant hardware elements of the spacecraft system. The concept of independent assemblies is then introduced, and the categorization of the system into families of independent assemblies is summarized.

Following the discussion of independent assemblies, correlation of the failure modes of the hardware elements of the spacecraft with the resulting outcomes of the mission is discussed. The major topics in this area are the independent assembly mathematical models and the mission map matrix.

A detailed summary of the optimization program system follows the failure modes and effects writeup. The optimization program system employs a variation of dynamic programming to extract from all possible system configurations with varying degrees of redundancy that subset of configurations with maximum mission expected worth (MEW) as a function of system weight, power, cost, etc.

Section 3 concludes with typical results of the optimization process, conclusions concerning the amount and type of redundancy which should be used in the Voyager spacecraft system, and recommendations for further areas of study and investigation.

1.4.3 SELECTION OF MISSION CONFIGURATIONS (SECTION 4)

Section 4 of this volume deals with the selection of the initial Voyager mission configuration, and the probable sequence of configurations to follow the initial choice. Applied decision theory, or decision analysis, is used as the medium for evaluation and selection.

The first step is to define a small-scale or pilot version of the Voyager project and analyze mission configuration selection within this pilot framework. The initial paragraphs of Section 4 review the pilot model structure, results, and implications on the more realistic, full-scale selection model.

Following the review of the pilot model is a discussion of the full-scale problem structure, viz., postulation of potential mission configurations, and development of a meaningful project accomplishment structure.

Given the problem definition, the decision structure is composed of four basic elements: (1) the value model, which determines the values associated with given levels of project accomplishments; (2) the cost model, which determines costs associated with potential mission configurations; (3) the probability model, which ascertains the probabilities of achieving given project outcomes with given mission configurations; and (4) the decision model, which selects that sequence of mission configurations which returns maximum expected value as a function of expected project cost. Each of these four models is discussed in detail.

A computer program system called the SPAN (Space Programs ANalysis) system was designed to create the decision structure and perform a variety of analyses. A portion of Section 4 is devoted to a discussion of SPAN.

Section 4 concludes with results, including typical preferred mission configurations and sequences, and recommendations for further activity.

1.5 DOCUMENTATION

During the course of the Application of Redundancy Study, nine technical reports and 35 technical memoranda were submitted to JPL. This documentation is referenced as appropriate throughout this final Redundancy Study report. The following is a complete listing of study documentation:

1.5.1 TECHNICAL REPORTS

Number	Title	Date	Author
VOY-C3-TR1	Nominal Voyager Mission Functional Flow Definition (Top, First and Second Levels)	21 Oct. 1966	L. Wagner
VOY-C3-TR2	Interim Report on Decision Modeling for the Selection of Voyager Mission Configurations	23 Nov. 1966	SRI (R. Howard, J. Matheson, G. Murray, A. Pollard), GE (E. Berger, A. Madarasz)
VOY-C3-TR3	Demonstration of Optimization of an Artificial Voyager Mission	15 Dec. 1966	Honeywell (D. Barnhill, J. Bass, D. Behun, T. Samsel), GE (E. Berger, J. Chestek)
VOY-C3-TR4	Nominal Voyager Mission Functional Flow Definition	13 Jan. 1967	L. Wagner
VOY-C3-TR5	Failure Rate Data Base for Voyager Spacecraft Redundancy Study (Interim Report)	24 Jan. 1967	Honeywell (R. Zamastil), GE (H. Nicely)
VOY-C3-TR6	Final Report on Pilot Decision Modeling for the Selection of Voyager Mission Configurations	31 Jan. 1967	SRI (R. Howard, J. Matheson, G. Murray, A. Pollard, R. Smallwood)
VOY-C3-TR7	Reliability Characteristics of Voyager Components--Voyager Spacecraft Redundancy Study	3 April 1967 (Rev; 17 June 1967)	Honeywell (R. Zamastil), GE (H. Nicely, C. Mayer)

VOY-C3-TR8	Failure Rate Data Base for Voyager Spacecraft Redundancy Study (Final Report)	8 May 1967 (Rev: 16 June 1967)	Honeywell (R. Zamastil), GE (H. Nicely)
VOY-C3-TR9	Voyager Independent Assembly Reference Tables for Voyager Spacecraft Redundancy Study	15 May 1967	C. Mayer

1.5.2 TECHNICAL MEMORANDA

Number	Title	Date	Author
VOY-C3-TM1	Abstracts of Trade Studies, Voyager Task C Application of Redundancy Study	27 Oct. 1966	J. Chestek, W. Johnston, R. Pahmeier, R. Shuck, J. Welch
VOY-C3-TM2	Nominal Voyager Mission Functional Flow Definition (Launch and Injection Phase)	31 Oct. 1966	L. Wagner
VOY-C3-TM3	Nominal Voyager Mission Functional Flow Definition (Transit Phase)	15 Nov. 1966	L. Wagner
VOY-C3-TM4	Definition of an Artifical Voyager Mission for Demonstration of Mission Optimization via Redundancy	14 Nov. 1966	Honeywell (D. Barnhill)
VOY-C3-TM5	Preliminary Voyager Mission Value Model	14 Nov. 1966	V. Klemas
VOY-C3-TM6	Nominal Voyager Mission Single-String Definition for Mid-Course/ Orbit Trim and Orbit Insertion Propulsion Subsystems	14 Nov. 1966	C. Gurney
VOY-C3-TM7	Nominal Voyager Mission Single-String Definition for Guidance and Control Subsystem	18 Nov. 1966	F. Spollen

Number	Title	Date	Author
VOY-C3-TM8	Nominal Voyager Mission Single-String Definition for Computer and Sequencer	16 Nov. 1966	J. Tanguy
VOY-C3-TM9	Nominal Voyager Mission Single-String Definition for Power Subsystem	18 Nov. 1966	R. Wray
VOY-C3-TM10	Nominal Voyager Mission Single-String Definition for Engineering Mechanics	30 Nov. 1966	R. Dawson
VOY-C3-TM11	Nominal Voyager Mission Single-String Definition for the Telecommunication System	18 Nov. 1966	E. Niemann, N. Robinson
VOY-C3-TM12	Nominal Voyager Mission Functional Flow Definition (Orbit Achievement Phase)	1 Dec. 1966	L. Wagner
VOY-C3-TM13	Nominal Voyager Mission Functional Flow Definition, Orbit Descent and Entry	14 Dec. 1966	L. Wagner
VOY-C3-TM14	Nominal Voyager Mission Functional Flow Definition, Orbiter Operations	16 Dec. 1966	L. Wagner
VOY-C3-TM15	Redundant Alternatives for Midcourse/Orbit Trim and Orbit Insertion Propulsion Subsystems	14 Dec. 1966	C. Gurney
VOY-C3-TM16	Nominal Voyager Mission Definition of Candidate Redundancy for Guidance and Control Subsystem	23 Dec. 1966	F. Spollen
VOY-C3-TM17	Nominal Voyager Mission Definition of Candidate Redundancy for Computer and Sequencer	27 Dec. 1966	J. Tanguy
VOY-C3-TM18	Nominal Voyager Mission Definition of Candidate Redundancy for Power	28 Dec. 1966	R. Wray

Number	Title	Date	Author
VOY-C3-TM19	Nominal Voyager Mission Definition of Candidate Redundancy for Engineering Mechanics	30 Dec. 1966	E. Dawson, C. Ockert
VOY-C3-TM20	Nominal Voyager Mission Definition of Candidate Redundancy for Telecommunications Subsystem	30 Dec. 1966	N. Robinson
VOY-C3-TM21	Definition of Mission Outcomes for Nominal Voyager Mission	27 Dec. 1966	B. Bachofer
VOY-C3-TM22	Nominal Voyager Mission Flight Sequence	23 Dec. 1966	H. Nicely
VOY-C3-TM23	Preliminary Requirements for Decision Modeling for the Selection of Voyager Mission Configurations	30 Dec. 1966	L. Hargrave
VOY-C3-TM24	Abstracts of Trade Studies, Voyager Task C Application of Redundancy Study	30 Dec. 1966	J. Chestek, W. Gurney, W. Johnston, C. Ockert, R. Pahmeier, D. Sergay, F. Spollen, J. Welch
VOY-C3-TM25	Voyager Mission Value Model	6 Feb. 1967	V. Klemas
VOY-C3-TM26	Trade Study on Data Multiplexing	15 Feb. 1967	R. Pahmeier
VOY-C3-TM27	Trade Study on Verification of Maneuver Attitude	15 Feb. 1967	J. Welch
VOY-C3-TM28	Trade Study on Attitude References and Initial Acquisition	14 Feb. 1967	J. Welch
VOY-C3-TM29	Trade Study on Degree of Active Thermal Control	29 Feb. 1967	C. Ockert
VOY-C3-TM30	Orbit Insertion Trade Study	13 Mar. 1967	J. Welch

Number	Title	Date	Author
VOY-C3-TM31	Emergency Telemetry Link	17 Mar. 1967	R. Pahmeier
VOY-C3-TM32	Spacecraft Emergency Routine Trade Study	17 Mar. 1967	D. Sergay, L. Wagner
VOY-C3-TM33	Trade Study on Digital vs. Analog Control Signal Data Processing	15 Mar. 1967	F. Spollen
VOY-C3-TM34	Trade Study on Methods of Accommodating Midcourse/ Orbit Trim Engine Malfunction	15 April 1967	R. Graser, C. Gurney
VOY-C3-TM35	Trade Study on Launch Guidance and Midcourse Correction Philosophy	8 April 1967	D. Pucher, E. Taylor, R. Salinger

1.6 ACKNOWLEDGEMENTS

The General Electric Company team that performed the Application of Redundancy Study consisted of four groups of diverse talents, contributions, and geographical distribution. This volume, as well as the 44 documents released during the study, represent the combined efforts of the redundancy team.

The Aeronautical Division of Honeywell, Minneapolis, Inc., contributed significantly in the area of system redundancy. Particular credit must be given J. G. Bass and P. R. Rebelein of the Honeywell team for their contributions.

From Menlo Park, California, the team from Stanford Research Institute contributed in large part to applying decision analysis to the mission configuration selection problem. Acknowledgement must be given the exceptional efforts of J. R. Matheson, A. Pollard, and N. Ward from our many SRI colleagues.

A sizeable team from the GE Space Technology Center, Valley Forge, contributed mainly in the areas of mission and system definition and system redundancy. The significant contributors were many, but special mention is merited by H. P. Nicely, C. Mayer, L. E. Wagner, V. Klemas and B. T. Bachofer, who led the Valley Forge team.

Coordination of the Redundancy Study was performed from the GE Pasadena Engineering Office. At PEO, the efforts of J. H. Chestek and E. L. Berger, and Miss M. B. Reynolds, in the mission configuration area were invaluable.

This final report represents the combined contributions of the above Application of Redundancy team, as edited by an appreciative Cognizant Engineer.

SECTION 2

MISSION AND SYSTEM DEFINITION

2.1 ORGANIZATION

The Voyager mission and system definition activity was divided into three major areas of endeavor, as suggested by Figure 2-1:

a. Mission Definition - Postulation of potential Voyager mission configurations and allowable sequences thereof. Identification of a nominal 1973 Voyager mission configuration and flight profile. Functional flow definition of the mission profile.

b. System Definition - Detailed development of the functional flow so that functions are correlatable with elements of spacecraft hardware. Definition of the single-string spacecraft system. Categorization of hardware as either single-string or potentially redundant. Description of hardware characteristics.

c. Trade Studies - Studies at the mission and system level to assist in the identification of the nominal Voyager mission configuration and the single-string spacecraft system, and to identify candidates for redundancy.

These three topics are reviewed in Sections 2.2 through 2.4.

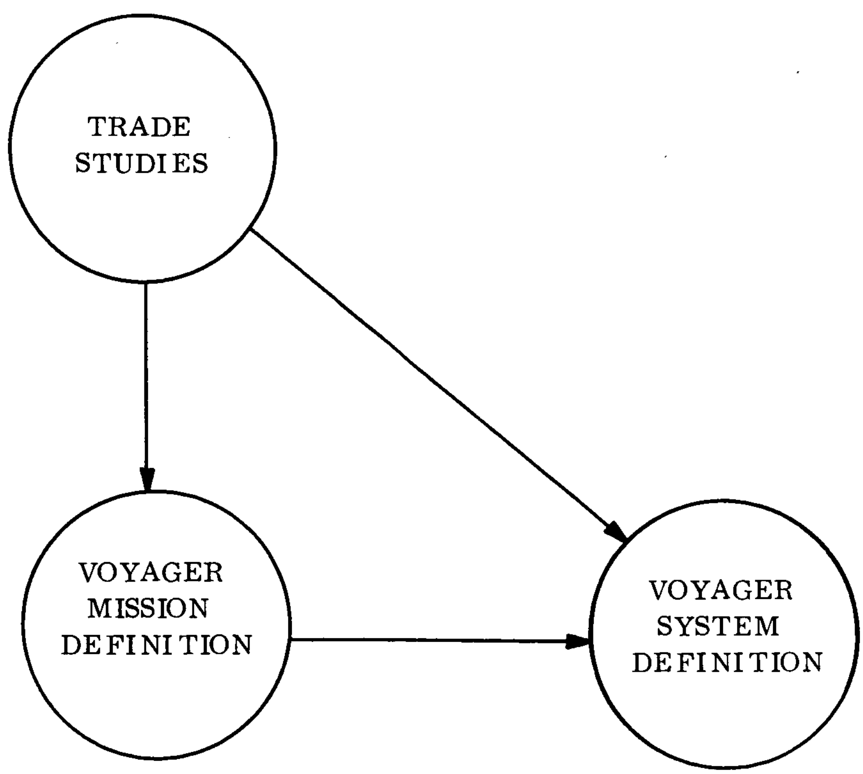


Figure 2-1. Voyager Mission and System Definition Organization

2.2 MISSION DEFINITION

2.2.1 GENERAL

Prior to the initiation of work on the pilot and full-scale mission configuration decision models (see Section 4), some initial configuration selection analysis was performed early in the study to provide the necessary groundwork for the system redundancy selection activity. This analysis consisted of defining some 40 potential mission configurations (Table 2-1) and logical selected sequences thereof. Figure 2-2 depicts the mission profile definition for the defined configurations in terms of the top-level mission phases. Functional breakdowns of each top-level mission phase and logical selected sequences of potential mission configurations were published in Bi-Monthly Progress Report No. 2 (VOY-CO-PR2) and are not repeated in this volume in the interest of brevity.

2.2.2 1973 REFERENCE MISSION

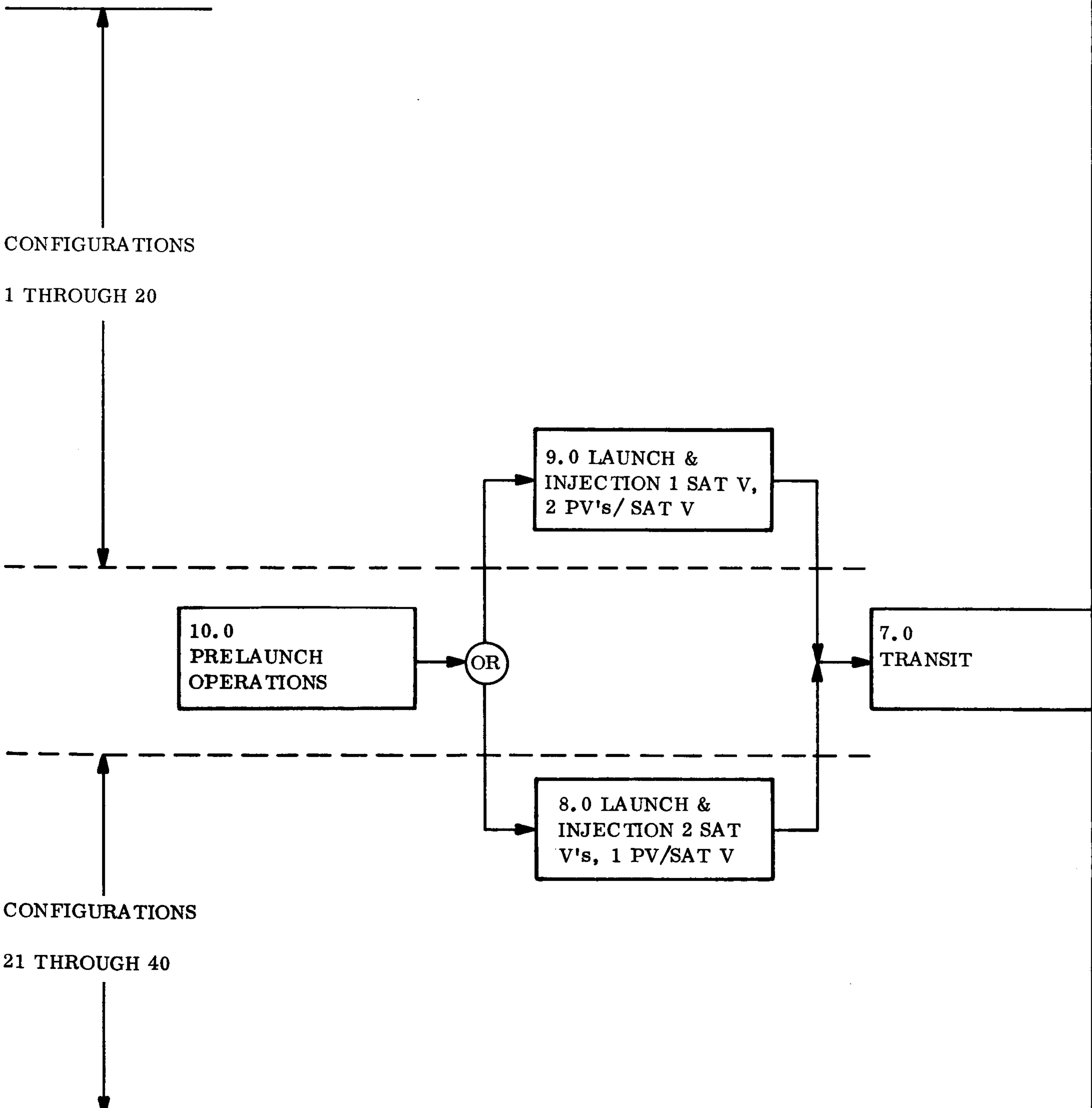
2.2.2.1 Reference Mission Configuration

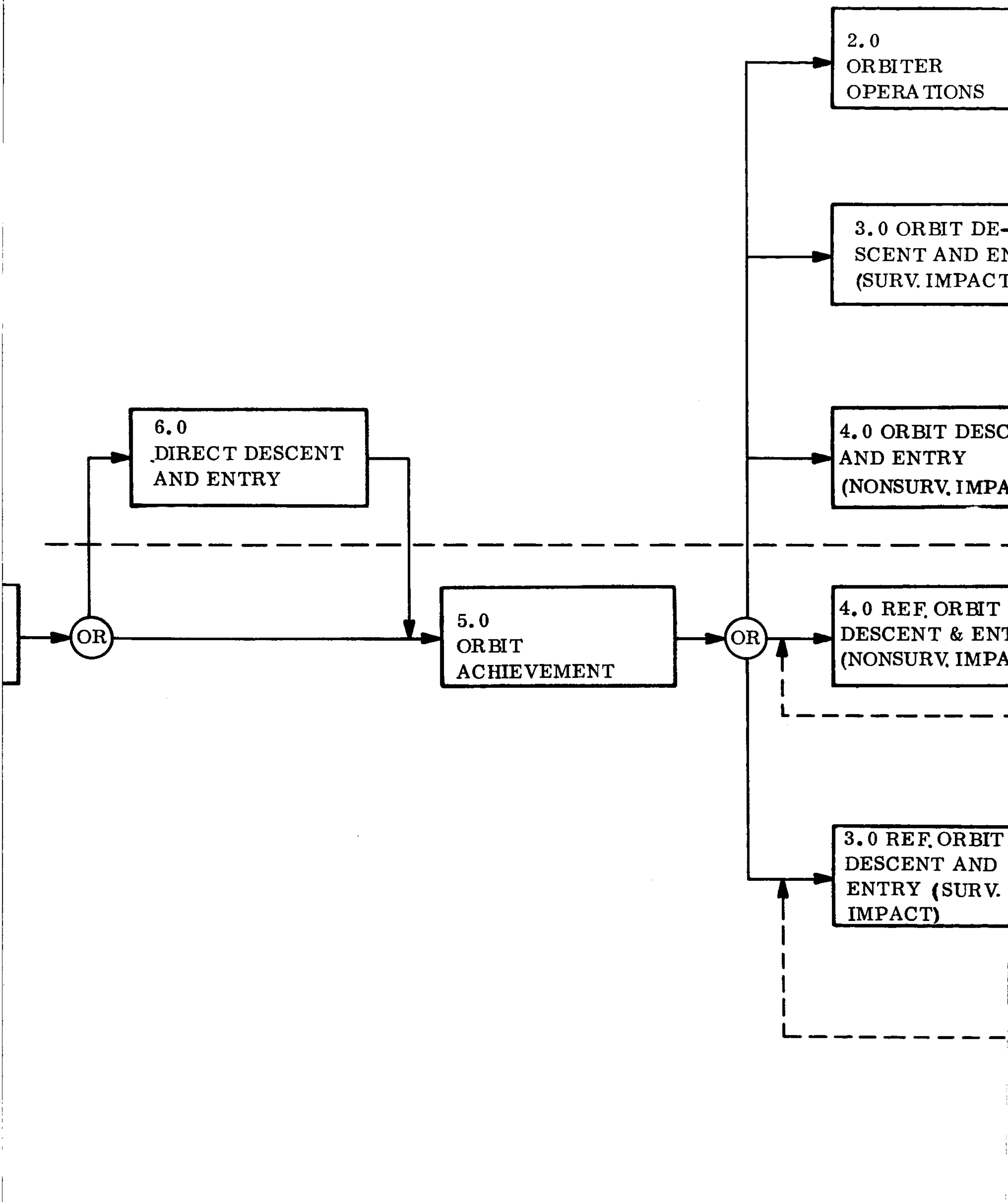
From among the 40 possibilities defined in Table 2-1, a typical 1973 mission configuration was selected as the reference configuration against which trade studies could be performed and the application of redundancy analyzed. This reference mission configuration consisted of one Saturn V launch vehicle with two planetary vehicles. Each planetary vehicle consisted of one spacecraft and one capsule. The reference mission profile contained three interplanetary trajectory corrections, two orbit trim maneuvers, and a 180-degree roll reorientation late in the orbiting mission to accommodate the planet scan platform field of view.

In general, the primary spacecraft functions and their implementation are similar to those defined in the General Electric Phase IA, Task B Study. The capsule configuration includes an active attitude control subsystem, aeroshell retardation during entry, propulsive retardation during terminal descent, relay link communications during orbit descent and entry, and establishment of a direct earth communications link and ground command capability during landed operations.

Table 2-1. Preliminary Potential Mission Configurations

Configuration Number	Number of SV's	Number of PV's Per SV	Number of Capsules Per PV	First Capsule Per PV				Second Capsule Per PV			
				Size	Entry	Survivable	Retardation	Size	Entry	Survivable	Retardation
1	1	2	2	Small	Direct	No	Aeroshell	Small	Direct	No	Aeroshell
2	1	2	2	Small	Direct	No	Aeroshell & Chute	Small	Direct	No	Aeroshell & Chute
3	1	2	2	Small	Orbit	No	Aeroshell	Small	Orbit	No	Aeroshell
4	1	2	2	Medium	Orbit	No	Aeroshell	Medium	Orbit	No	Aeroshell
5	1	2	2	Medium	Orbit	No	Aeroshell & Chute	Medium	Orbit	No	Aeroshell & Chute
6	1	2	1	Small	Direct	No	Aeroshell				
7	1	2	1	Small	Direct	No	Aeroshell & Chute				
8	1	2	1	Small	Orbit	No	Aeroshell				
9	1	2	1	Medium	Orbit	No	Aeroshell				
10	1	2	1	Medium	Orbit	No	Aeroshell & Chute				
11	1	2	2	Small	Direct	No	Aeroshell	Small	Orbit	No	Aeroshell
12	1	2	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting
13	1	2	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion & Impact Limiting	Medium	Orbit		Aeroshell, Rough Landing Propulsion & Impact Limiting
14	1	2	1	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting				
15	1	2	1	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion, & Impact Limiting				
16	1	2	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Small	Direct	No	Aeroshell
17	1	2	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion, & Impact	Small	Direct	No	Aeroshell
18	1	2	1	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion				
19	1	2	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion
20	1	2	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion, & Impact Limiting	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion
21	2	1	2	Small	Direct	No	Aeroshell	Small	Direct	No	Aeroshell
22	2	1	2	Small	Direct	No	Aeroshell & Chute	Small	Direct	No	Aeroshell & Chute
23	2	1	2	Small	Orbit	No	Aeroshell	Small	Orbit	No	Aeroshell
24	2	1	2	Medium	Orbit	No	Aeroshell	Medium	Orbit	No	Aeroshell
25	2	1	2	Medium	Orbit	No	Aeroshell & Chute	Medium	Orbit	No	Aeroshell & Chute
26	2	1	1	Small	Direct	No	Aeroshell				
27	2	1	1	Small	Direct	No	Aeroshell & Chute				
28	2	1	1	Small	Orbit	No	Aeroshell				
29	2	1	1	Medium	Orbit	No	Aeroshell				
30	2	1	1	Medium	Orbit	No	Aeroshell & Chute				
31	2	1	2	Small	Direct	No	Aeroshell	Small	Orbit	No	Aeroshell
32	2	1	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting
33	2	1	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion & Impact Limiting	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion & Impact Limiting
34	2	1	1	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting				
35	2	1	1	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion & Impact Limiting				
36	2	1	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Small	Direct	No	Aeroshell
37	2	1	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion, & Impact Limiting	Small	Direct	No	Aeroshell
38	2	1	1	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion				
39	2	1	2	Medium	Orbit	Yes	Aeroshell, Chute & Impact Limiting	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion
40	2	1	2	Medium	Orbit	Yes	Aeroshell, Rough Landing Propulsion, & Impact Limiting	Large	Orbit	Yes	Aeroshell & Soft Landing Propulsion


CONFIGURATIONS
1 THROUGH 20
9.0 LAUNCH & INJECTION 1 SAT V, 2 PV's/ SAT V
10.0 PRELAUNCH OPERATIONS
OR
7.0 TRANSIT
8.0 LAUNCH & INJECTION 2 SAT V's, 1 PV/SAT V
CONFIGURATIONS
21 THROUGH 40


2.0
ORBITER
OPERATIONS
3.0 ORBIT DE-
SCENT AND EN
(SURV. IMPACT
6.0
DIRECT DESCENT
AND ENTRY
4.0 ORBIT DESC
AND ENTRY
(NONSURV. IMPA
OR
5.0
ORBIT
ACHIEVEMENT
OR
4.0 REF. ORBIT
DESCENT & ENT
(NONSURV. IMPA
3.0 REF. ORBIT
DESCENT AND
ENTRY (SURV.
IMPACT)

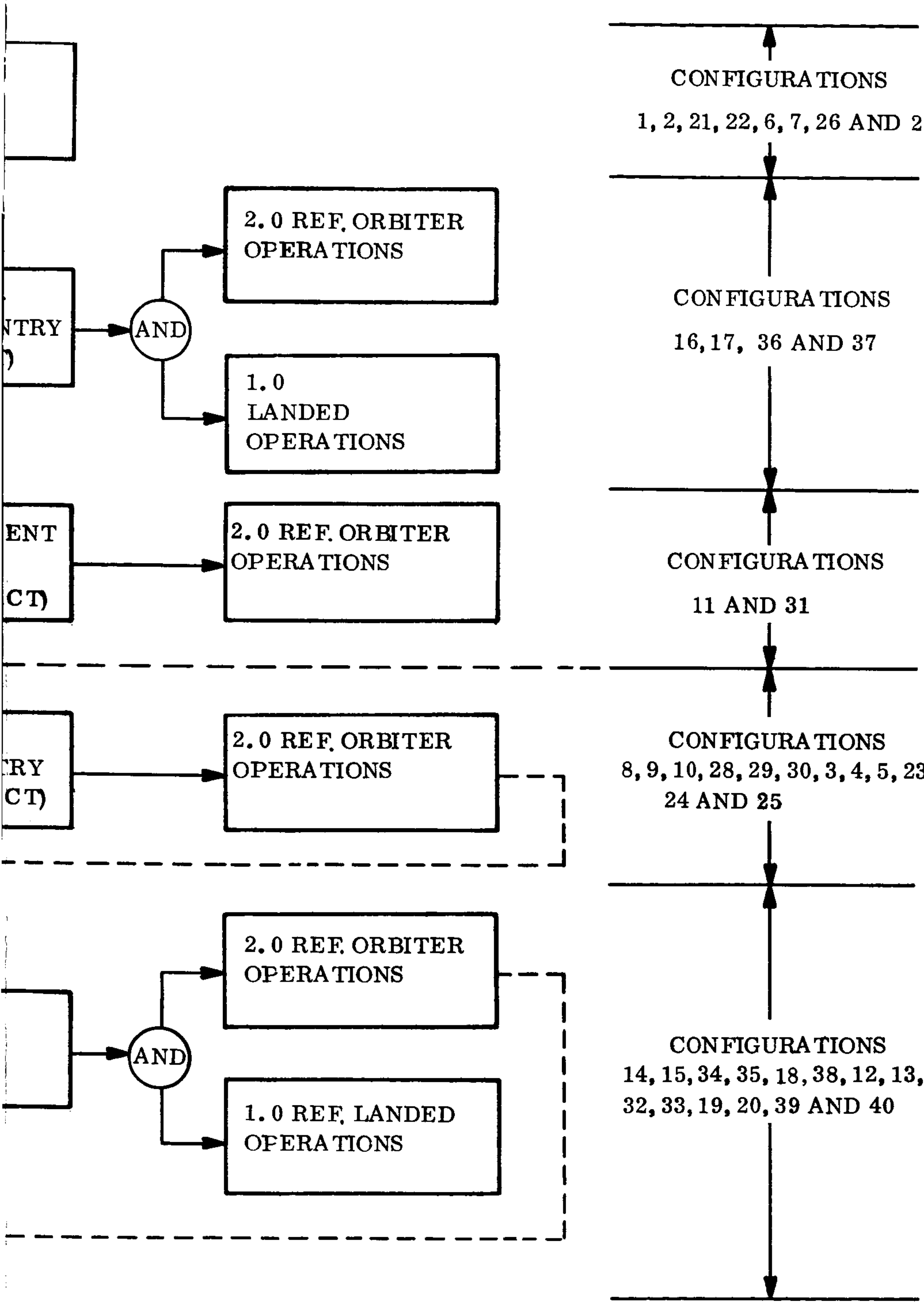


Figure 2-2. Top Level Functional Flow Diagrams for Preliminary Mission Configurations

2.2.2.2. Reference Mission Profile

Figure 2-3 is the top level functional flow diagram for the reference mission configuration. The top-level mission phases are defined as follows:

a. Prelaunch Operations (7.0): Arrival at Eastern Test Range through liftoff.

b. Launch and Injection (6.0): Liftoff through planetary vehicle separation.

c. Transit (5.0): Initiation of celestial reference acquisition through start of orbit insertion events.

d. Orbit Achievement (4.0): Initiation of orbit insertion events through start of capsule separation events.

e. Orbit Descent and Entry (3.0): Initiation of capsule separation events through:

    1. Confirmation of impact survival for the capsule via the relay link.

    2. Completion of descent and entry data transmission to earth by the spacecraft.

f. Orbiter Operations (2.0): All operations for the spacecraft following completion of descent and entry data transmission to earth through completion of the orbiter mission.

g. Landed Operations (1.0): All operations for a survivable impact capsule following confirmation of impact survival via the relay link until completion of the landed mission.

2.2.2.3 Nominal Flight Sequence

The top-level functional flow diagram (Figure 2-3) was initially broken down through the first and second levels of detail, in accordance with the functional flow guidelines set forth in Air Force Systems Command Manual 375-5, and released in Technical Report VOY-C3-TR1. At the first level of the functional flow, starting times and time durations were assigned to each function in accordance with the General Electric Phase IA, Task B Report.

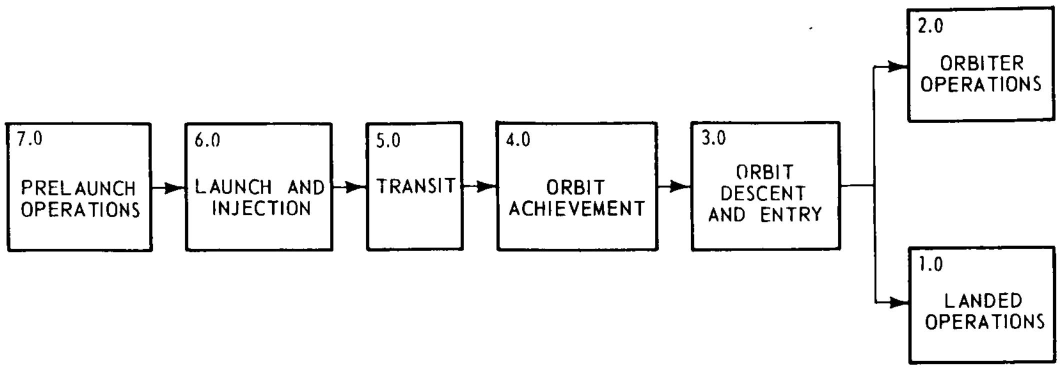


Figure 2-3. Nominal 1973 Mission Top Level Functional Flow Definition

Table 2-2 is the flight sequence for the nominal mission configuration and profile. All first level functions shown in Table 2-2 are mutually exclusive and continuous, except for support functions (denoted by parentheses) and the functions of Landed Operations, which are performed in parallel with those of Orbiter Operations. This flight sequence was published in Technical Memorandum VOY-C3-TM22.

2.3 SYSTEM DEFINITION

2.3.1 SINGLE-STRING FUNCTION FLOW DEFINITION

In order to define the functions to be performed by the spacecraft and the hardware required to perform these functions, each top-level mission phase of Figure 2-3 pertinent to the spacecraft and its interfaces was broken down to a level (usually the fourth or fifth level) at which the function to be performed could be correlated with discrete elements of spacecraft system hardware.

At this level, it is useful to recognize, isolate, and define a baseline spacecraft system void of any intentional reduendancy -- in other words, a system in which every element of hardware performs at least one in-line mission function. This fundamental, albeit fictitious, system is called the "single-string system" and may be considered the reference system to which redundancy is added.

Table 2-2. Nominal 1973 Mission Flight Sequence

Top-level Mission Phase	First Level Function Number	Function Description	Beginning Time of Function: Exact Days	Hours	Min	Sec	Simplified Hours	Time Interval of Function Hours
7.0 Prelaunch Operations	7.X	Prepare for Launch		Not Required			N.R.	N.R.
6.0 Launch and Injection	6.1	Achieve Parking Orbit	000	00	01	00	0.0	0.6
	6.2	Achieve Interplanetary Trajectory Injection	000	00	34	49	0.6	0.1
	6.3	Separate PV's from Launch Vehicle	000	00	44	25	0.7	0.0
	6.4	(Transmit Engineering and Systems Status Data)	000	00	01	00	0.0	0.7
	6.5	(Provide Power and Clocking for Subsystem Support)	000	00	01	00	0.0	0.7
	6.6	(Survive Launch and Injection Environment)	000	00	01	00	0.0	0.7
	6.7	(Provide Launch and Injection Ground Operations)	000	00	01	00	0.0	0.7
	6.8	(Provide Capability to Receive Ground Commands)	000	00	01	00	0.0	0.7
5.0 Transit	5.1	Acquire Celestial References	000	00	45	30	0.7	19.1
	5.2(#1)	Perform Interplanetary Cruise	000	19	50	00	19.8	40.2
	5.3	Perform Interplanetary Trajectory Correction No. 1	002	12	00	00	60.0	17.2
	5.2(#2)	Perform Interplanetary Cruise	003	05	13	01	77.2	630.8
	5.4	Perform Interplanetary Trajectory Correction No. 2	029	12	00	00	708.0	17.7
	5.2(#3)	Perform Interplanetary Cruise	030	05	41	26	725.7	3,462.3
	5.5	Perform Interplanetary Trajectory Correction No. 3	174	12	00	00	4,188.0	17.7
	5.2(#4)	Perform Interplanetary Cruise	175	05	41	26	4,205.7	150.3
	5.6	Separate Sterilization Canister	181	12	00	00	4,356.0	0.0
	5.2(#5)	Perform Interplanetary Cruise	181	12	00	00	4,356.0	24.5
	5.7	(Obtain and Transmit Data)	000	00	45	30	0.7	4,379.8
	5.8(#1)	(Provide Capability to Receive Ground Commands)	000	00	45	30	0.7	4,379.8
	5.9	(Provide Pyrotechnic Support for One-Shot Functions)	000	00	45	30	0.7	4,379.8
	5.10	(Provide Power and Clocking for Subsystems Support)	000	00	45	30	0.7	4,379.8
	5.11	(Provide Sequencing for Performing Functions)	000	00	45	30	0.7	4,379.8
	5.12	(Survive Transit Environment)	000	00	45	30	0.7	4,379.8
	5.13(#1)	(Provide Ground Operations)	000	00	45	30	0.7	4,379.8
4.0 Orbit Achievement	4.1	Perform Orbit Insertion	182	12	30	20	4,380.5	6.1
	4.2(#1)	Perform Orbital Operations	182	18	33	26	4,386.6	32.3
	4.3	Perform Orbit Trim No. 1	184	02	55	20	4,418.9	17.4
	4.2(#2)	Perform Orbital Operations	184	20	16	58	4,436.3	35.1
	4.9	Perform Orbit Trim No. 2	186	07	25	20	4,471.4	17.4
	4.2(#3)	Perform Orbital Operations	187	00	46	58	4,488.8	34.0

	4.4	(Obtain and Transmit Data)	182	12	30	20	4,380.5	142.3
	5.8(#2)	(Provide Capability to Receive Ground Commands)	182	12	30	20	4,380.5	142.3
	4.5	(Provide Pyrotechnic Support for One-Shot Functions)	182	12	30	20	4,380.5	142.3
	4.6	(Provide Power and Clocking for S/S Support)	182	12	30	20	4,380.5	142.3
	4.8	(Survive Orbit Achievement Environment)	182	12	30	20	4,380.5	142.3
	5.13(#2)	(Provide Ground Operations)	182	12	30	20	4,380.5	142.3
3.0 Orbit Descent & Entry	3.1	Separate Capsule from Spacecraft	188	10	48	54	4,522.8	6.0
	3.2	Support Capsule Descent and Entry (S/C)	188	16	48	54	4,528.8	1.7
	3.3	Return to Orbital Operations Mode (S/C)	188	18	29	54	4,530.5	6.7
	3.4	Perform De-Orbit Thrusting (Capsule)		Not Required			N.R.	N.R.
	3.5	Descend from Orbit (Capsule)		Not Required			N.R.	N.R.
	3.6	Enter Atmosphere (Capsule)		Not Required			N.R.	N.R.
	3.7	Perform Terminal Descent (Capsule)		Not Required			N.R.	N.R.
	3.8	Survive Impact (Capsule)		Not Required			N.R.	N.R.
	3.9	Obtain & Transmit Data (S/C)	188	10	48	54	4,522.8	14.4
	5.8(#3)	(Provide Capability to Receive Ground Commands-S/C)	188	10	48	54	4,522.8	14.4
	3.10	(Provide Pyrotechnic Support for One-Shot Functions - S/C)	188	10	48	54	4,522.8	14.4
	3.11	(Provide Power and Clocking for Subsystem Support - S/C)	188	10	48	54	4,522.8	14.4
	3.12	(Provide Sequencing for Performing Functions -(S/C)	188	10	48	54	4,522.8	14.4
	3.13	(Survive Orbit Descent and Entry Environment -(S/C)	188	10	48	54	4,522.8	14.4
	3.14	(Provide Support Function for Capsule Subsystems - (Capsule)		Not Required			N.R.	N.R.
	5.13(#3)	(Provide Ground Operations)	188	10	48	54	4,522.8	14.4
2.0 Orbiter Operations	2.1(#1)	Perform Orbital Operations	189	01	13	00	4,537.2	720.0
	2.3	Perform 180° Roll Reorientation	219	01	13	00	5,257.2	1.5
	2.1(#2)	Perform Orbital Operations	219	02	43	00	5,258.7	3,646.5
	2.4	(Obtain and Transmit Data)	189	01	13	00	4,537.2	4,368.0
	5.8(#4)	(Provide Capability to Receive Ground Commands)	189	01	13	00	4,537.2	4,368.0
	2.5	(Provide Pyrotechnic Support for One-Shot Functions)	189	01	13	00	4,537.2	4,368.0
	2.6	(Provide Power and Clocking for Subsystem Support)	189	01	13	00	4,537.2	4,368.0
	2.7	(Provide Sequencing for Performing Functions)	189	01	13	00	4,537.2	4,368.0
	2.8	(Survive Orbiter Operations Environment)	189	01	13	00	4,537.2	4,368.0
	5.13(#4)	(Provide Ground Operations)	189	01	13	00	4,537.2	4.368.0
1.0 Landed Operations	1.1	Orient Landing Package and Make Deployments	188	18	29	54	4,530.5	2.0
	1.2	Perform Landed Operations	188	20	29	54	4,532.5	48.0
	1.3	(Provide Support Functions for Capsule Subsystems)	188	18	29	54	4,530.5	50.0
	1.4.	(Provide Earth Ground Operations)	188	18	29	54	4,530.5	50.0

Key: ( ) Support Function

A sample of isolation of single-string system hardware via successive functional flow breakdowns is shown in Figure 2-4, where the top level function describing the transit of the planetary vehicle from earth to Mars is broken down into succeeding levels of detail until a single-string element of spacecraft hardware (in this case, a sun sensor) is isolated.

Detailed functional flow breakdowns to single-string hardware for the five top-level mission phases in which the spacecraft system is operational were released by mission phase during the first half of the study in the following five technical memoranda:

Document No.	Title
VOY-C3-TM2	Launch and Injection
VOY-C3-TM3	Transit
VOY-C3-TM12	Orbit Achievement
VOY-C3-TM13	Orbit Descent and Entry
VOY-C3-TM14	Orbiter Operations

2.3.2 DEFINITION OF POTENTIAL REDUNDANCY

As the single-string function flow diagrams were being developed and functions were broken down into subfunctions of increasing detail, alternate methods of performing functions were encountered. At each such point, the choice was made to select the best approach for the single-string system. Subsequently, the discarded alternatives were examined as candidates for functional redundancy. In addition, block, multichannel, and other types of redundancy were considered as possible additions to the single-string system. In this manner, an overly abundant reservoir of potential block and functional redundancy was proposed and correlated with the functional flow diagrams. It was from this pool of candidate redundancy that the actual system redundancy was selected.

Figure 2-5 illustrates this process and how it is reflected in the functional flow definition. The command to turn off the spacecraft midcourse/orbit trim engines is nominally

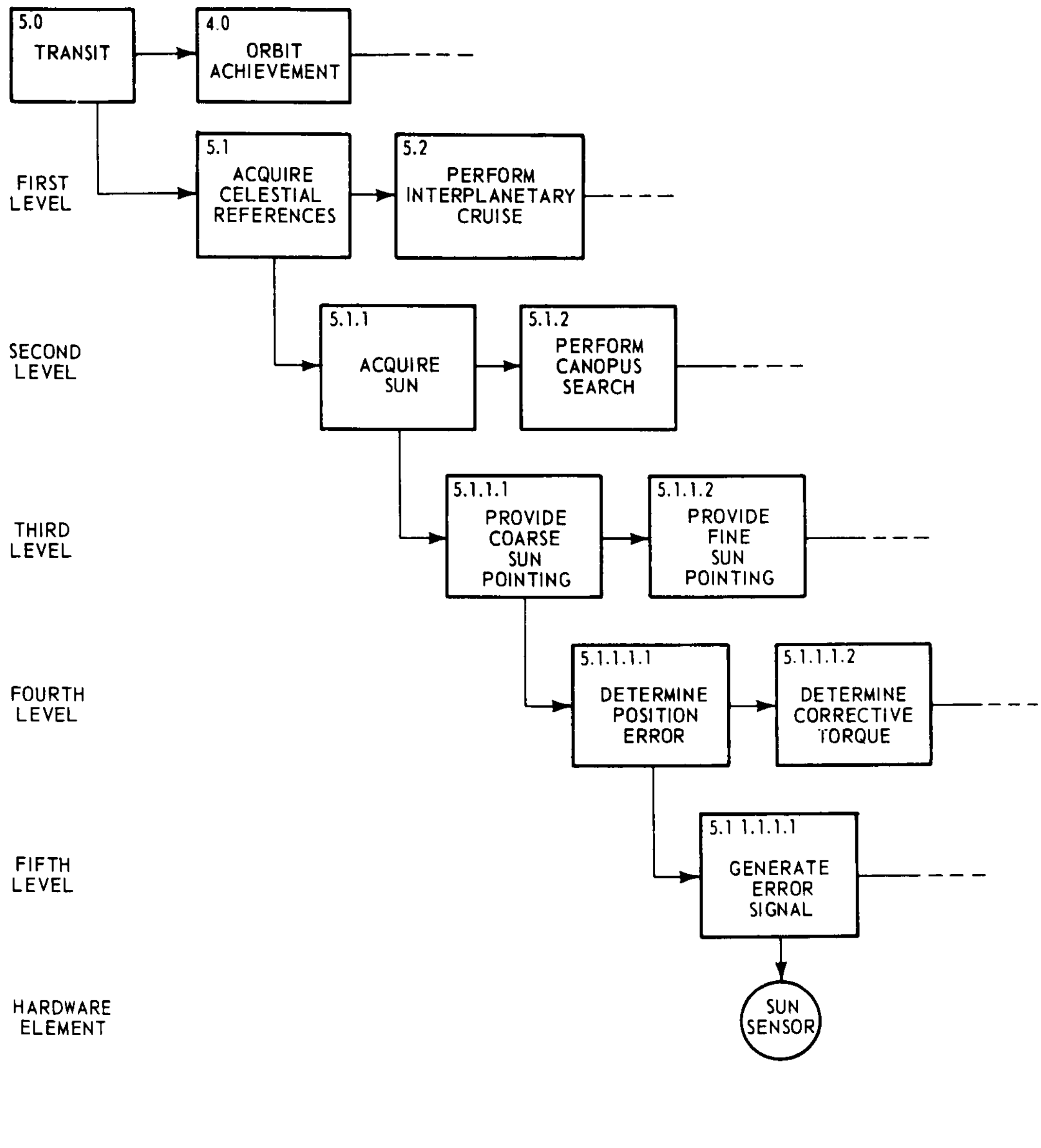


Figure 2-4. Typical Lower Level Breakdown of Functional Flow to Single-String Hardware

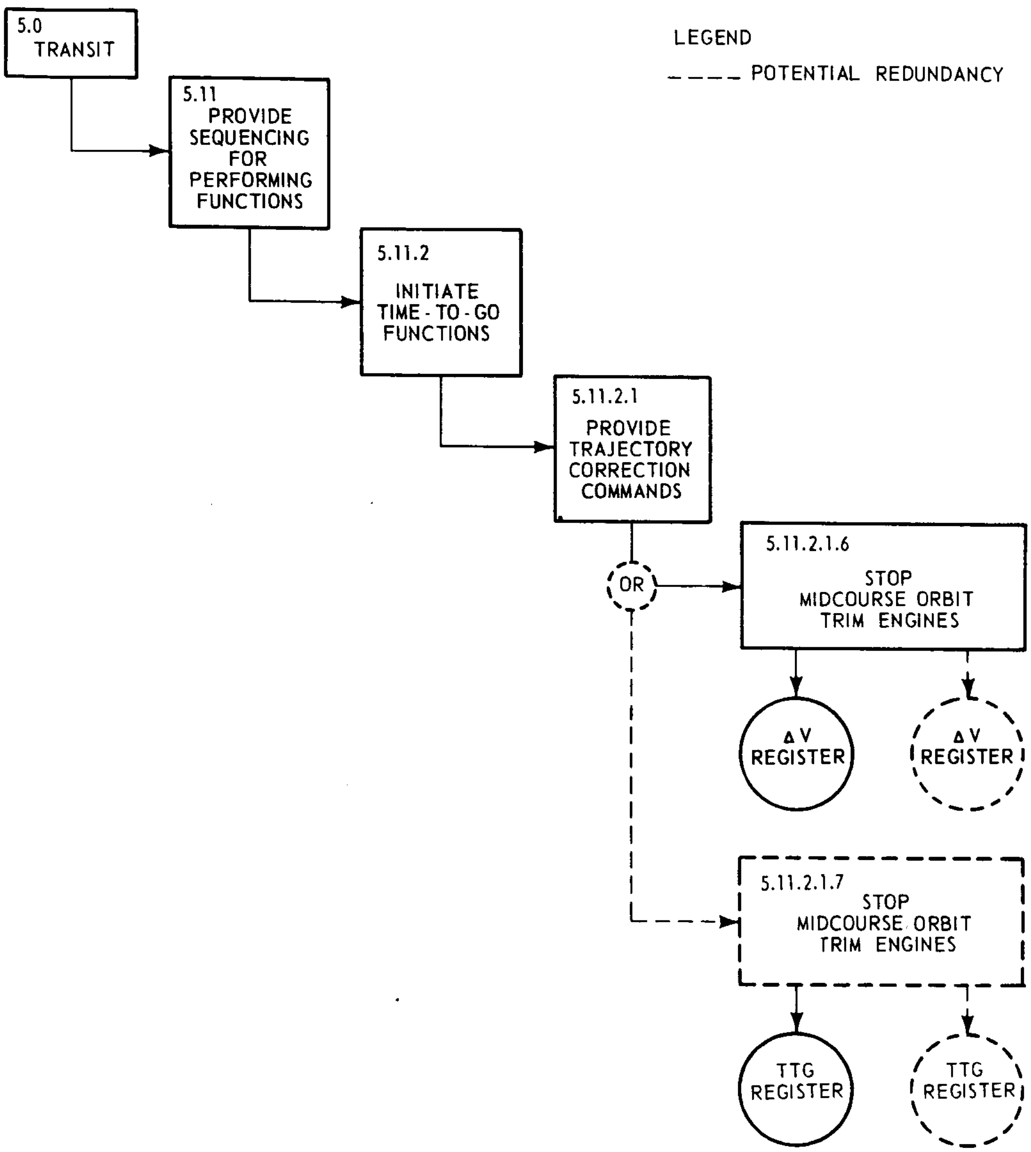


Figure 2-5. Typical Inclusion of Potential Redundancy in the Functional Flow

generated by the system ΔV register, which basically integrates the thrust level to a threshold corresponding to the desired ΔV. An additional block redundant ΔV register is shown as a candidate for redundancy. As a functional backup to the ΔV register in this application, it is proposed to use a time-to-go register. In this particular case, the proposed functionally redundant element, the TTG register, is also an element of the single-string system, because it is employed for in-line functions elsewhere in the mission. Also, a block redundant TTG register is proposed for the system.

The entire mission functional flow definition, including isolation of both single-string and potentially redundant hardware, was updated and consolidated into a single Technical Report: VOY-C3-TR4, "Nominal Voyager Mission Functional Flow Definition," which was released on 13 January 1967. A major accomplishment of the Redundancy Study, this volume of some 8000 functions marked the end of the functional flow definition phase.

2.3.3 DEFINITION OF HARDWARE CHARACTERISTICS

As the development of the lower level functional flow diagrams progressed, all hardware elements required in the single-string spacecraft were identified. These hardware elements were grouped into their parent subsystems and defined in detail via the following series of technical memoranda:

Document No.	Title
VOY-C3-TM6	Propulsion Subsystems
VOY-C3-TM7	Guidance and Control Subsystem
VOY-C3-TM8	Computer and Sequencer Subsystem
VOY-C3-TM9	Power Subsystem
VOY-C3-TM10	Engineering Mechanics Subsystems
VOY-C3-TM11	Telecommunications Subsystems

These technical memoranda provide a general description of the single-string subsystem(s) and of the individual elements or components which comprise that subsystem. Also, a failure modes and effects analysis is included for each hardware element. The individual hardware descriptions permit quantitative estimates of the hardware reliability characteristics to be made.

These technical memoranda include estimates of the penalties associated with each hardware element (weight, volume, and power requirements). The sum of the penalties associated with the single-string hardware elements provides a baseline weight, volume, and power requirement for the spacecraft, any excess over which may be allocated to redundant hardware.

As redundancy candidates were conceived and considered for addition to, or replacement of, single-string hardware elements, they were documented by parent subsystem via the following series of technical memoranda:

Document No.	Title
VOY-C3-TM15	Propulsion Subsystem Alternatives
VOY-C3-TM16	Guidance and Control Subsystem Alternatives
VOY-C3-TM17	Computer and Sequencer Subsystem Alternatives
VOY-C3-TM18	Power Subsystem Alternatives
VOY-C3-TM19	Engineering Mechanics Subsystem Alternatives
VOY-C3-TM20	Telecommunication Subsystem Alternatives.

These technical memoranda describe the redundancy candidates proposed for consideration in determining the optimum spacecraft configurations. Their topical content is identical to the aforementioned single-string description memoranda, TM6 through TM11.

2.4 TRADE STUDIES

Ten trade studies were performed during the Application of Redundancy Study, and the results of each study were released in a separate technical memorandum. These trade studies were performed for the following reasons:

a. To assist in the identification and definition of the reference mission configuration and profile and the single-string spacecraft system.

b. To identify candidates for redundancy, with special emphasis on functional redundancy.

c. To provide general system engineering support to the other three studies being performed under the Task C contract, with special emphasis on the Planetary Quarantine Study.

The trade study topics and the technical memoranda in which they are reported in detail are as follows:

Document No.	Title
VOY-C3-TM26	Data Multiplexing
VOY-C3-TM27	Verification of Maneuver Attitude
VOY-C3-TM28	Attitude References and Initial Acquisition
VOY-C3-TM29	Degree of Active Thermal Control
VOY-C3-TM30	Orbit Insertion
VOY-C3-TM31	Emergency Telemetry Link
VOY-C3-TM32	Spacecraft Emergency Routines
VOY-C3-TM33	Digital vs Analog Attitude Control Signal Data Processing
VOY-C3-TM34	Methods of Accommodating a Midcourse/Orbit Trim Engine Malfunction
VOY-C3-TM35	Launch Guidance and Midcourse Correction Philosophy

In the following 10 subsections, abstracts of the foregoing 10 trade studies are presented.

2.4.1 DATA MULTIPLEXING

The purpose of the data multiplexing study was to evaluate alternate techniques for combining low-rate, real-time data with high-rate, stored data for transmission to earth on a single carrier.

Four different types of multiplexing were considered:

a. Insertion of low-rate data (including sync necessary for data separation at earth) into gaps in the stored data stream.

b. Periodic displacement of stored data by real-time data (plus sync) during storage readout.

c. Conventional frequency multiplexing, where the two data streams are placed on separate subcarriers.

d. Conventional time multiplexing, where the two data streams are formatted to form a single data stream.

Since gaps in the stored data stream represent wasted transmitter power, the first technique was considered to determine if it was desirable to fill the gaps with useful real-time data. This scheme was rejected because the real-time data requirements cannot be met without the inclusion of a large real-time data buffer which requires more implementation complexity than the other techniques considered. Additional gaps could be placed on the stored data stream by the DAE to reduce or eliminate the buffering; however, the complexity of this technique also compared unfavorably with alternate techniques.

The second type of multiplexing considered (displacement of stored data by real-time data) offers high efficiency with minimum implementation complexity; however, the displaced stored data is destroyed. Although the percentage of data destroyed can be less for certain conditions than the percentage of data in error due to channel noise, experimenters might still find it objectionable. The technique, therefore, appears to offer more potential as a redundant backup than as a prime mode of operation.

Two implementations for frequency multiplexing were considered. They are identical except that one included additional circuits to optimize the power division between the two subcarriers each time the stored data rate was switched from one value to another. The added efficiency of the latter technique was found to be well worth the additional implementation complexity; therefore, this technique is recommended if a frequency multiplexing technique is used.

Two implementations for the time multiplexing technique also were considered. Both performed the same overall function and had identical efficiencies. The first implementation required two buffers on the stored data stream; one of which was being loaded while the real-time data and the other buffer were being read out. The second implementation used a single small buffer in the stored data stream which was read in and read out simultaneously at different rates. These differential rates were compatible, however, since read-out was halted when the buffer was empty so that real-time data could be inserted in the output data stream. During this time the buffer would again be loaded. Comparison of the two time multiplexing implementations revealed no clear-cut advantage of one buffering technique over the other; however, the differential-timing buffering technique was found to give a slightly lower calculated failure rate.

The final comparison of the conventional frequency and time multiplexing techniques showed that neither have severe disadvantages; however, their characteristics differ such that a preferred technique can be identified under certain conditions. The required ratio of stored to real-time data rates is a major influencing factor. Time multiplexing shows a significant efficiency advantage at low ratios; however, at high ratios frequency multiplexing is more efficient. In all cases, frequency multiplexing is the simpler to implement. It also does not require that high-rate data be detected immediately upon reception at earth to extract the real-time data. Assuming that high-rate data will be encoded, immediate decoding is therefore not required. Not only does this eliminate the relatively complex decoder from the real-time data path, but it also allows high-rate data to be predetection recorded upon reception and decoded later at a slower rate. Reduced-speed decoding is desirable, at least from the standpoint of decoder complexity.

On the basis of the above considerations and the Voyager data requirements found to be typical to date, frequency multiplexing is recommended over time multiplexing.

2.4.2 VERIFICATION OF MANUEVER ATTITUDE

The purpose of the attitude verification function is to provide an independent check to determine that the spacecraft is in the desired manuever attitude prior to the firing of the midcourse or orbit insertion engines and capsule separation. The most critical application of attitude verification relates to orbit insertion, where it is most important to avoid maneuvering in any erroneous direction which might result in violation of the planetary quarantine constraint.

The trade study made a comparative evaluation of several independent attitude verification techniques based on the application of the following components or operations:

a. Solar Aspect Sensors - Digital output, passive, flight proven, sensors yield continuous measurement of sun angle. Properly placed around the spacecraft, they can measure the vehicle orientation with respect to the sun with complete spherical coverage. They are flexible enough to accommodate various spacecraft configurations, are compatible with spacecraft digital data systems, and can be used for autonomous or earth-based verification.

b. High Gain Antenna Pointing - Requires the commanded gimballing of the antenna to a preselected position prior to the maneuver. It yields only singular point coverage, and requires earth cooperation. There is a risk to mission success if the antenna fails to come back to the home position, and the preclusion of continuous high-data rate during the maneuver itself.

c. Redundant Gyro Packages - Yields an error signal when the two gyro sets do not agree, but no indication of which one is correct, thus aborting a maneuver whenever any gyro fails.

d. Pre-maneuver Check Attitude Maneuver - Essentially a closed loop, return to origin (Sun/Canopus) rehearsal of maneuver systems and does not yield an actual error indication during the actual maneuver. It also increases gas consumption, component wear, and probability of failure.

e. Canopus Tracker - Used in the star field mapping mode. It yields positional information only as pitch/yaw rotations are in progress and does not effect final position verification if large stars are not in the sensor field of view. It is much more complex than the solar aspect sensor.

f. Telemetered Diagnostic Checks - Checks the gyro package and control system which can be analyzed on earth, but does not provide an independent measurement of vehicle attitude and thus yields no improvement in knowledge of the accuracy of maneuver attitude. This mode is recommended only for system operational diagnosis.

Based on the comparison of the various alternatives, it is recommended that digital solar aspect sensors be used to implement the independent verification function. This approach has the advantage of using simple, highly reliable techniques proven in operation with other space vehicles. The recommended system employs a two-way telecommunication link for earth analysis of the verification signal. It also is recommended that the solar aspect sensor signals control switch-over to the redundant set of gyros.

2.4.3 ATTITUDE REFERENCES

The objective of this study was to review briefly alternate attitude reference schemes. Alternates, considered in the Task C RTG Study because of the absence of sun pointing requirement for power acquisitions,were considered with respect to applicability to the solar powered Voyager spacecraft. Reference directions considered were Sun, Mars local vertical, Earth and Canopus. The implications of these celestial reference schemes on design, degrees of freedom, and operation of major spacecraft components (such as the high gain antenna, planet scan platform, solar panels and celestial reference sensors) were analysed to compare the relative advantages and disadvantages of each scheme. A total of 14 alternative orientation configurations were compared in tabular format.

Mars pointing vehicles generally eliminated PSP articulation requirements, but required articulation of the solar array. Earth oriented vehicles simplified the antenna pointing, but the complex task of earth sensing was undesirable.

The Sun/Canopus celestial references, as selected in the General Electric Task B Voyager spacecraft design, is still preferred because: (1) it uses readily acquired references, and (2) its fixed orientation relative to the sun significantly alleviates the solar radiation problem.

An alternative orientation which also is attractive makes use of a digital solar aspect sensor to maintain the vehicle attitude in a sun-biased direction, the third degree of freedom being determined by the direction to Canopus. This orientation has the advantage of permitting a fixed high gain antenna, although with some compromise of the solar power input.

2.4.4 DEGREE OF ACTIVE THERMAL CONTROL

This study analyzed the Voyager thermal control system in an effort to find ways to increase the reliability of the system. Partially passive control is concluded to be of value for special applications, such as the gyros, gimbal actuators and for electronic equipment having a constant power output during the mission. It is not recommended for general use with equipment having widely varying power levels, since an excessive amount of auxiliary heater power is required to keep equipment within permissible temperature ranges. As a reliability alternative, incorporating partially passive control helps if the louvers fail closed on a high power level bay. It is adverse for all other failure modes and for normal operation.

The study showed very strong benefits from internal coupling between electronic bays and internal structure, tanks, etc. These benefits reduce the severity of incident sun maneuver transients and can overcome the effects of louver failure for an entire bay or for two or three bays adjacent to each other by internal redistribution of the thermal loads.

A lightweight (10 pound) annular heat pipe arrangement shows the capability of transferring hundreds of watts of heat with negligible thermal gradients, providing an order of magnitude increase in the internal thermal coupling. This is valuable for missions to Venus and Mercury, since it can solve the difficult problem of incident sun maneuvering transients.

The results of the linkage study show the tape bar linkage to be superior to the pin-lever and rack-pinion systems.

Three actuator systems were studied including vapor-liquid bellows, bimetal coils, and the melting wax hydrostatic expansion capsule. The wax capsule has a unique advantage in energy/weight, but is not yet flight proven for vacuum environments, having been flown in spacecraft only in forced convection thermal control applications. Between the vapor liquid bellows and the bimetal coils, the trade is fairly close, with bimetal having the advantage of greater simplicity and more flight experience, while the bellows has faster response and higher force levels.

2.4.5 ORBIT INSERTION

The objective of this study was to investigate the effects of abnormal orbit insertion burns on the resulting aerocentric orbits. The specific errors that were considered were in the timing, direction and magnitude of the velocity increment.

Post-burn trajectories were determined and classified as hyperbolic fly-bys, safe orbits (from the planetary quarantine consideration), decay orbits (not acceptable from quarantine requirements), and hyperbolic or elliptical impacts.

The resulting data were reviewed to determine implications concerning possible requirements for on-board sensing or logic backup-firing commands.

Figure 2-6 shows the geometry of the encounter and orbit insertion for the case where the applied velocity increment is assumed to lie in the same plane as the approach hyperbola. The parameters η and α, respectively, describe the timing and direction of the applied velocity increment.

Figure 2-7 is a sample of the orbit response as a function of η and α, in this case for a 1974 encounter with a V_∞ of 3.5 km/sec, 1000 km periapsis altitude, and a nominal ΔV of 1.9 km/second. The nominal insertion condition is assumed to be a periapsis-to-periapsis transfer, described by the point so labeled. The dotted line describes that α-η history when the vehicle attitude relative to inertial space is fixed at the nominal insertion attitude. This figure reveals that, for the conditions shown, there is no possibility of quarantine violation for insertion maneuvers at any time provided that there is no large departure from nominal insertion attitude. Furthermore, there is no hazard of quarantine violation at any attitude if the insertion maneuver occurs within about ± 1.5 minutes of nominal.

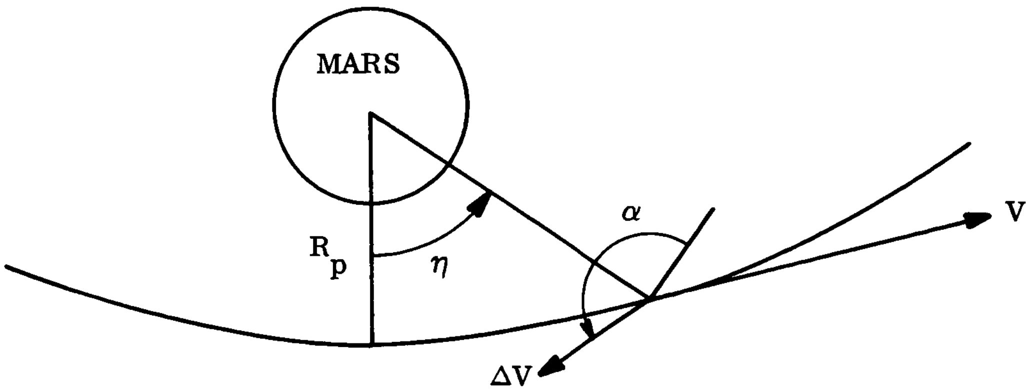


Figure 2-6. Mars Approach Geometry

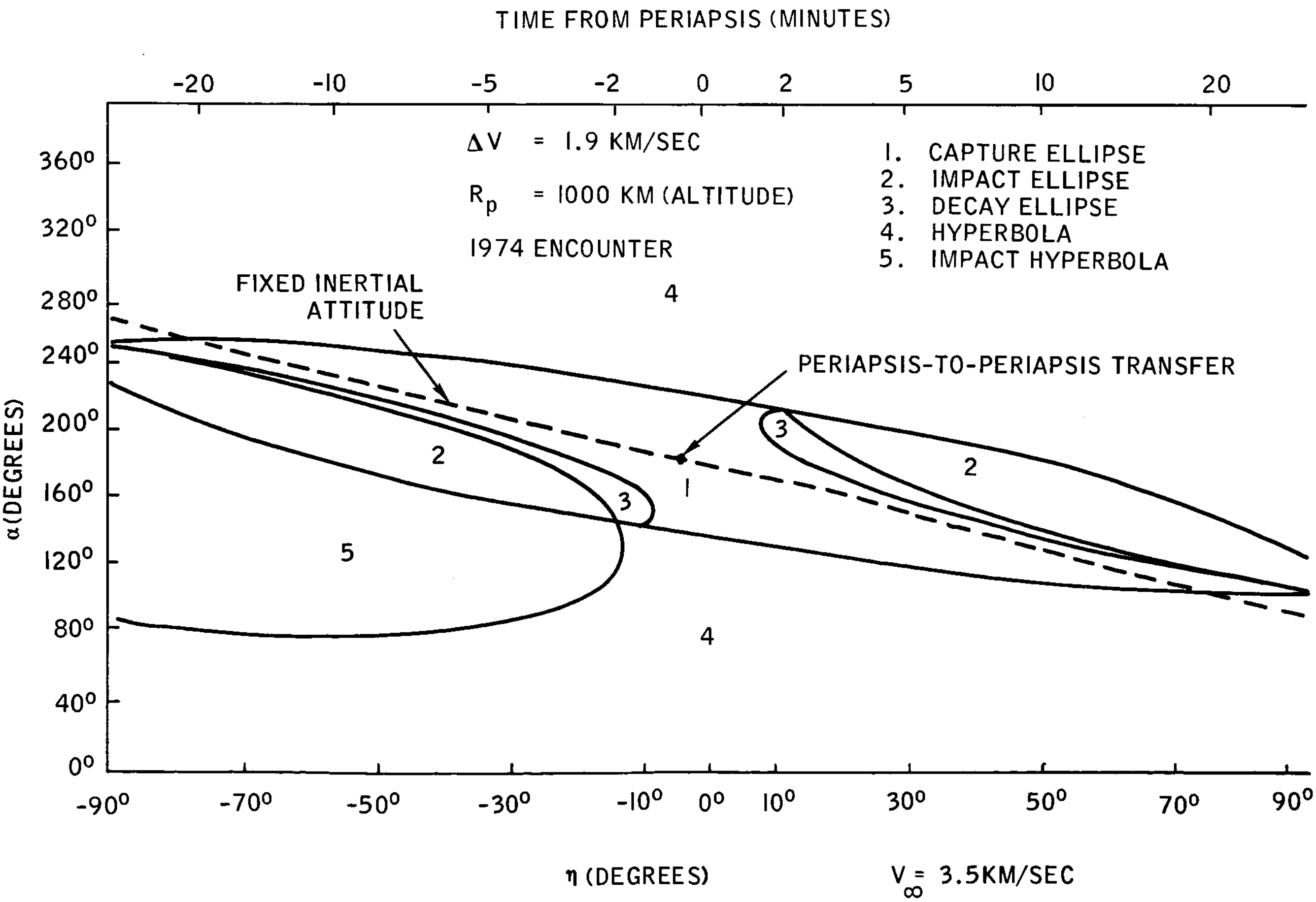


Figure 2-7. Orbit Responses as a Function of Timing and Direction of Insertion Maneuver

The study yielded results for both in-plane and out-of-plane insertion maneuvers and, in addition, showed the sensitivity of the resulting periapsis and apoapsis altitudes and apsidal rotation to the direction and timing of the insertion maneuver. Figure 2-8 is a sample curve from the report, showing apoapsis sensitivity to errors in direction and timing of insertion for a 1974 encounter with a ΔV of 1.8 km/second.

Encounter geometry phenomena that were considered as information sources for autonomous backup orbit insertion firing commands were: (1) vehicle-to Mars range, (2) crossing the Mars terminator, and (3) the angle between the vehicle-sun line and the Mars local vertical. The approaches were all rejected on the basis of excessive complexity of implementation and low accuracy reliability relative to the planetary quarantine constraint. A direct command link, as included in the GE Task B design, is still recommended as the primary means of initiating the orbit insertion burn in the event of a failure in the computer and sequencer, provided the timing of the burn is restricted so that attitude error cannot result in planetary impact.

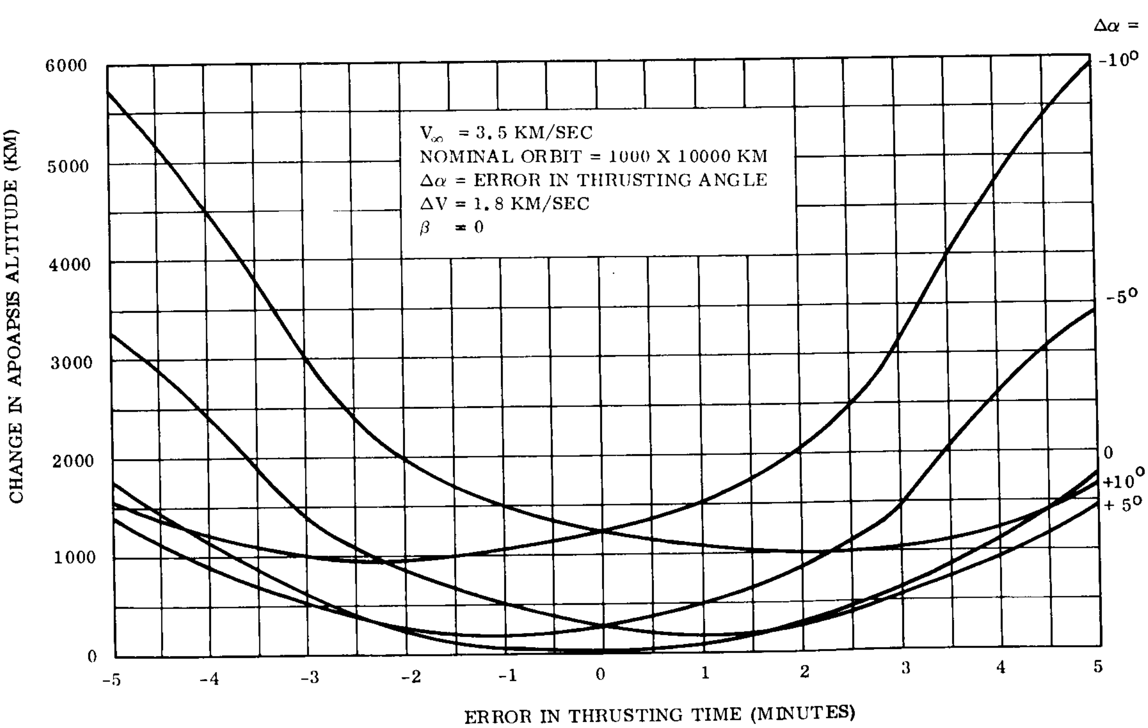


Figure 2-8. Apoapsis Sensitivity to Direction and Timing of Insertion (Periapsis-to-Periapsis Injection)

2.4.6 EMERGENCY TELEMETRY LINK

In this study the GE Task B telecommunication subsystem was evaluated to determine the merits of alternate methods of implementing and operating the system to enhance its capability of returning diagnostic data under various failure conditions. Techniques considered either tended to minimize the dependency of the emergency link on the various spacecraft subsystems that might have failed, or tended to increase the ability of the basic design to return useful diagnostic data in the event of a failure.

Relatively complex additions to the present system were found to be required to minimize the dependency of the emergency telemetry function on the various spacecraft subsystems. These additions do not appear advisable, not only because the probability of the failure conditions under which they offer an improvement is low, but also because the additional probability of saving the mission by ground action under these conditions is remote.

Some techniques for obtaining more useful data were found to offer advantages which might warrant their incorporation into the system. These include increased data rates (where available), data compression (especially where the information concerns parameter values leading to on-board switching), and recovery of data otherwise lost prior to signal acquisition at earth. No specific designs are recommended since, as indicated in the report, such designs should evolve as an integral part of the overall on-board and earth-based failure sensing and control philosophy.

2.4.7 SPACECRAFT EMERGENCY ROUTINES

The objective of this trade study was to identify: (1) critical system and subsystem level failures which could have a major effect on the mission outcome, and (2) ways of accommodating these failures with minimum degradation of the mission. Accommodation of the failures was permitted by utilizing modified primary components of other subsystems or by incorporating minimum cost (weight, power, etc.) backup techniques. System requirements, design features, weight and power penalties, and reliabilities were estimated to permit evaluation of the merit of incorporating these emergency routines into the spacecraft system design.

It was assumed that continuous ground monitoring and immediate (except for preparation and transmission time) ground command capability were available during maneuvers and the orbital phase of the mission. Emergency routines would be initiated by ground command in that situation, except for corrective or preventative action that cannot be delayed; e.g., overpressure in an engine.

In the cruise phase, it was assumed that intermittent ground monitoring was available and that necessary holding action emergency routines would be initiated immediately by on-board logic. Subsystems other than the failed one were assumed to be working properly at the time of each failure in all cases.

The approach consisted of reviewing the 1973 Voyager mission functional flow definition and identifying the areas of criticality. Possible failure of the spacecraft subsystems required to perform critical in-line and support functions were postulated, and methods of counteracting these failure were derived. Most of the failures and emergency routines concerned the guidance and control, propulsion, science data gathering, and science and engineering data transmission functions. As emergency routines were conceived, a recommendation was made as to whether the routine should be evaluated further.

Table 2-3 is a sample of postulated spacecraft system failures and candidate emergency routines to circumvent them.

2.4.8 DIGITAL VS ANALOG CONTROL SIGNAL DATA PROCESSING

This trade study compared guidance and control configurations employing digital sensors and/or processing against the Task B analog design, primarily from a reliability point of view.

During the study the following configurations were considered:

a. Analog sun sensors with digital processing.
b. Digital sun sensors with digital processing.
c. Digital sensors and processing for cruise and orbit modes only.

	System or Subsystem Failure	Mission Phase Where Applicable						First Level Function Failed	Mission Outcome	Candidate F Consi
		LI	T	OA	ODE	OO	LO			
1.0	Failure of Stabilized Platform in Instrument Unit (G&C Portion) of Launch Vehicle	X						6.1 Achieve Parking Orbit 6.2 Trajectory Injection	6.1 Mission Failure 6.2 Mission Failure, Deep Space Mission, or Far Flyby.	Backup (
2.0	Failure of LV to Inject PV's on Inter-planetary Trajectory within Limits of Mars Orbit Insertion Requirements	X	X					6.2 Trajectory Injection	Deep Space Mission or Far Flyby	

edundancy lered	S/C Emergency Routine(s)	Design Modifications, Hardware Resources, Etc.	Swit
yros	1.1 Utilize Gyros and Autopilot in Either Planetary Vehicle as a Back-Up to Stabilized Platform of the Launch Vehicle (as the Inertial Measuring Unit in the Apollo Spacecraft Command Module is Used)	Requires Complex LV/PV Interface Negotiations and Wiring of Interfacing Signals Through the In Flight Disconnect as well as Design Compatibility Modifications and Detail - Weight and Power Penalties are Negligible.	All Con
	2.1 Utilize all MC/OA Propulsive Capability (Allowing None for Orbit Trim Maneuvers) Keeping Capsules on Board.	None	Gro (No
	2.2 Separate Capsules and Utilize all MC/OA Propulsive Capability (Allowing None for Orbit Trim Maneuvers)	None	Gro (No
	2.3 Separate Capsules and Utilize only MC Allotted Propulsive Capability	None	Gro (No
	2.4 Separate Capsules and Utilize both MC/OA and Orbit Insertion Propulsive Capability to Achieve Either Near or Far Fly-By.	None	Gro (No
	2.5 Do not Separate Two PV1s Initially, but Utilize Entire Propulsive Capability of PVII to Correct Trajectory and then Separate.	Requires Shroud, PV Adapter Support, Additional Separation Scheme, Guidance and Control S/S Modifications, Etc. Weight Penalty ≈200 lbs - Power Requirements within Capability of Power S/S during Launch and Injection.	Gro (≈15
	2.6 Utilize a Portion of Orbit Insertion Propulsive Capability to Correct Trajectory and Insert into More Eccentric Orbit (With Capsules)	Requires Multiple Start (Liquid) Orbit Insertion Propulsion Subsystem	Gro (No
	2.7 Separate Capsules and Utilize a Portion of Orbit Insertion Propulsive Capability to Correct Trajectory and Insert into More Eccentric Orbit	Requires Multiple Start (Liquid) Orbit Insertion Propulsion Subsystem	Gro (No
	2.8 Combine Routine 2.5 with Either Routine 2.1 or 2.7 (i.e. Utilize Orbit Insertion Propulsive Capability of PVII and a Portion of that of PVI to Achieve a Degraded Orbit with PVI.)	Requires Design Modifications, Requirements, Etc. As Delineated for Routines 2.5, 2.6, and 2.7.	Gro (≈ 1

Table 2-3. System or Subsystem Failures and Emergency Routines (Partial Listing)

Command and ching Requirements	Approximate Probability Success	Effect of Emergency Routine on S/C and Mission	Further Investigation Recommendation
Switching by Ground mand (to LV and PV)	0.98	Enables Salvaging Failed Mission and Putting on Nominal Course	Not Recommended (Interface Complexity)
nd Command e Additional)	0.99	No Orbit Trim Capability (If Needed)	Recommended
nd Command e Additional)	0.98	No Orbit Trim Capability No ODE and LO Capsule Data	Recommended
nd Command e Additional)	0.98	No Orbit Descent and Entry and Landed Operations Data	Recommended
nd Command e Additional)	0.97	Achieve Either: 1. Near Fly-Bys 2. Far Fly-Bys	Recommended
nd Command Additional)	0.85	Results In: 1. PVI Nominal Mission 2. PVII Near or Far Fly-By.	Recommended
nd Command e Additional)	0.98	Converts two Deep Space Missions to Degraded Orbiting Missions	Recommended
nd Command e Additional)	0.97	Converts two Deep Space Missions to Degraded Orbiting Missions (Less ODE and LO Capsule Data).	Recommended
nd Command Additional)	0.85	Results In: 1. PVI Degraded Mission 2. PVII Near or Far Fly-By	Recommended

[redacted]

Most of the discussion is devoted to pitch and yaw loop operation of the attitude control electronics during the acquisition and cruise phases. The conclusions reached are extrapolated to the roll loop, autopilot, and to other phases, as required. Time sharing of digital equipment is considered where appropriate.

It is concluded that digital processing generally decreases guidance and control reliability over that obtainable with the Task B design, which uses analog sensors, analog processing and triple redundancy. The main factors leading to this conclusion are:

a. The processing performed by the attitude control electronics is simple and straightforward. There are no complex decisions to be made. The output choice to operate a solenoid or not involves summing two signals and detecting if a threshold value has been exceeded. Digital processing would become more competitive if the analog processing were more complex.

b. The error sensors which provide input data to the processor are all analog devices, although both digital and analog sun sensors are available.

c. For configuration 1, the analog-to-digital conversion equipment is a major hardware problem. Analog circuitry similar in design and quantities to the baseline Task B system must be provided to condition the sensor signals and to carry out the A/D conversion. In some types of A/D converters, the analog amplifier requirements are more stringent, and the effects of failure are more disasterous than in the baseline system. Maintaining sensor resolution throughout the conversion process is another serious problem.

d. For configuration 2, the digital hardware required is excessive, while there is only a limited reduction in analog equipment. A/D conversion equipment is still required for the gyro and Canopus sensor signals.

e. Configuration 3 has a weight advantage if the requirement for triple redundancy of the remaining analog attitude control electronics can be eliminated. Some of the proposed techniques are unproven. Assuming success in those areas, the reliability improvement is limited.

It is recommended that analog processing be retained for Voyager.

2.4.9 ACCOMMODATION OF ENGINE MALFUNCTION

A detailed trade study was conducted to identify and evaluate alternate methods of accommodating an engine malfunction in the Voyager midcourse/orbit trim propulsion system. The trade study was conducted using the GE Task B MC/OT system as the reference; however, the methods evaluated during this study are applicable to almost any four engine system used for the midcourse and orbit trim maneuvers.

Three basic methods of accommodating an engine malfunction were investigated:

a. Canted engines.

b. Autopilot engine-out detection, including:

   1. Jet vane angular position detection.

   2. Excessive vehicle rate detection.

   3. Gyro compensation network output detection.

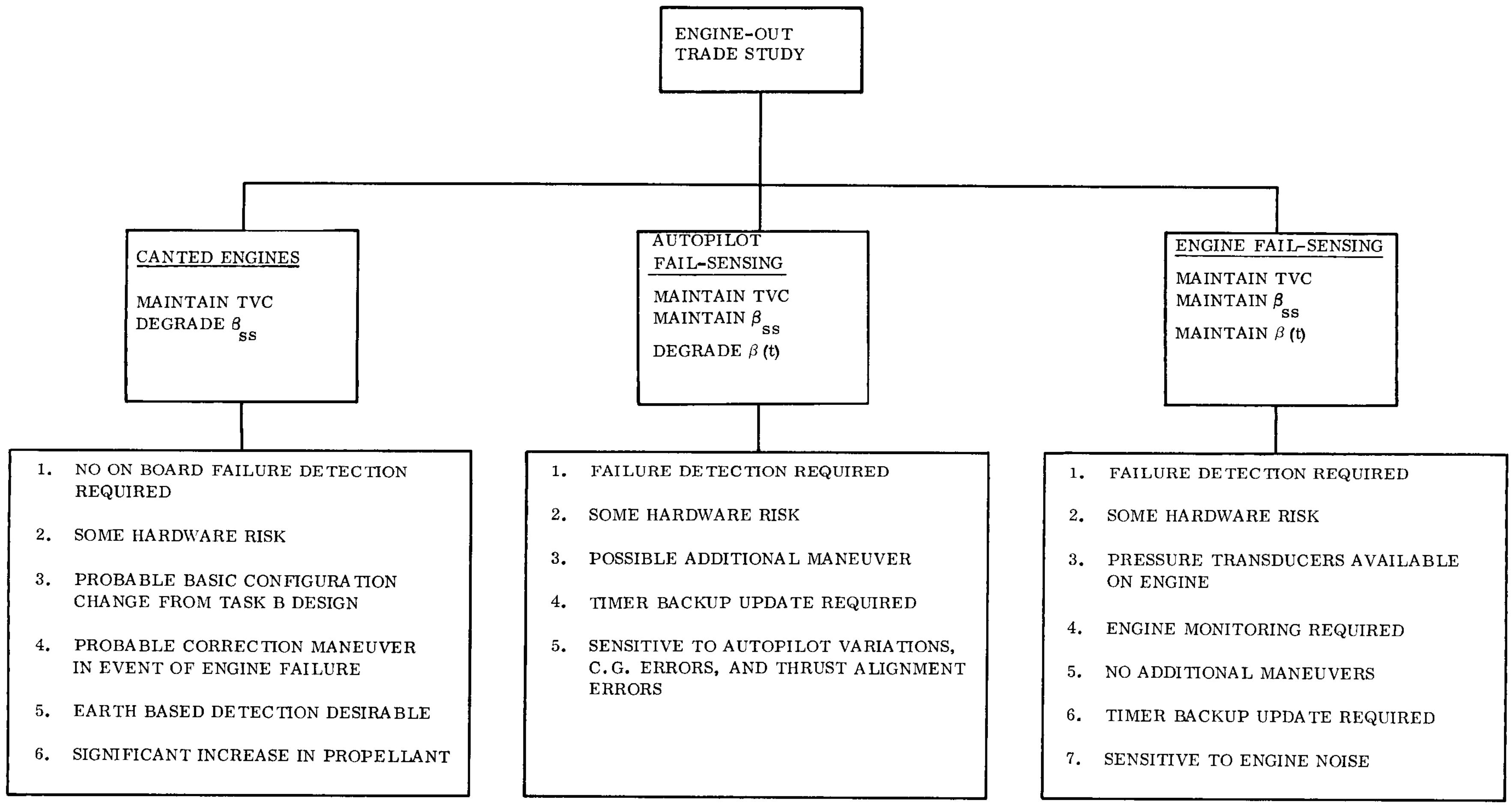
c. Engine-out detection in the engine itself; i.e., by sensing chamber pressure.

The study report presents the detailed analyses that were conducted on each method. The methods and their consequences are summarized in Figure 2-9. Table 2-4 shows the results of the probability analyses by presenting the individual maneuver probabilities of success for the three competing methods, for the Task B design without engine-out capability, and for a perfect design.

It is concluded that engine-out sensing is the preferred approach to accommodate an engine malfunction since it is independent of the autopilot loop, can easily be ground tested, and results in consistent performance regardless of the maneuver parameters.

2.4.10 LAUNCH GUIDANCE AND MIDCOURSE CORRECTION PHILOSOPHY

The prupose of this trade study was to assess the effect of various guidance and midcourse correction maneuver policies on the probability of mission success. The study and report



β_{ss} = STEADY STATE THRUST VECTOR POINTING ERROR

β (t) = INSTANTANEOUS THRUST VECTOR POINTING ERROR

Figure 2-9. Engine-out Tradeoff Summary

Table 2-4. Estimated Relative Probability of Success

Configuration	Midcourse Maneuver 1	Midcourse Maneuver 2	Midcourse Maneuver 3	Three-Orbit Trim Maneuver	Cumulative Midcourse	Cumulative
Present Design	0.974684	0.982690	0.987468	0.941714	0.945809	0.890681
Canted Engines	0.999655	0.999815	0.999892	0.999703	0.999362	0.999065
Autopilot Fail Sensing	0.999836	0.999891	0.999893	0.999700	0.999620	0.999320
Engine Fail Sensing	0.999828	0.999921	0.999960	0.999688	0.999709	0.999397
Perfect Design	0.999836	0.999924	0.999960	0.999703	0.999720	0.999423

NOTE: No consideration is made of failure during coast.

are divided in two parts: (1) the heliocentric transfer trajectory injection, which was concerned with the aiming point of the launch vehicle; and (2) the premission guidance policy, which was concerned with the basic guidance philosophy, and its application to representative trajectories.

2.4.10.1 Heliocentric Transfer Trajectory Injection

The minimum impulse first midcourse correction for each spacecraft is presented by aiming the launch vehicle at the center of the planet capture area and then deflecting the launch vehicle to ensure compliance with the allocated maximum allowable probability of planetary impact of 3×10^{-5}.

Alternatively, the launch vehicle can be placed on a trajectory having sufficient bias so that no deflection is required, and the midcourse correction of each planetary vehicle can be used to alter the trajectory to the desired aim point for planetary orbit insertion. The first approach must be selected if the biasing required by the second requires an unacceptably large increase in the velocity increment of the first midcourse maneuver of each spacecraft.

This portion of the trade study showed that, if the first midcourse correction of each spacecraft is in the order of 200 m/sec, the nominal ΔV required to achieve encounter separation for 1973, then placing the launch vehicle on a trajectory from which no deflection is required increases the size of the midcourse correction by less than 1 percent and is, therefore, the recommended approach.

2.4.10.2 Premission Guidance Policy

The purpose of this portion of the analysis was to determine the sequence of midcourse maneuvers which best reduces trajectory errors at planetary encounter. The analysis considered three aim point biasing techniques (radial, tangential, and minimum), the accuracy of midcourse velocity execution, and the probability of planetary impact.

A digital computer program was developed for computing the encounter errors with three midcourse corrections. Considerable parametric analyses were therefore feasible.

One trajectory was selected for analysis from each of the 1973, 1975, 1977, and 1979 Mars launch opportunities. In terms of final guidance errors, it was found that the times at which the second and third midcourse corrections are made is not significant until the guidance percentage errors are above about one percent. For larger errors, the best cases are a function of the mission year and the aim point bias. For the minimum bias, executing the second correction at midtrajectory produces the smallest error after three corrections, except for 1979, where the best second correction time is 40 days after injection.

The second and third midcourse velocity impulse magnitudes are minimum when the second correction is made 40 days after injection. For the most part, however, the differences in the total velocity impulse between the second correction at 40 days and at the midpoint in the trajectory are not very significant. The total velocity impulse magnitude is larger, however, when the second correction is made 30 days before encounter.

The minimum aim point bias was investigated in depth, since this bias produced the most favorable results. For the 1973 trajectory, the tangential bias is almost as good as the minimum; in 1975 and 1977, the radial bias is almost as good as the minimum bias; and in 1979, the radial bias is as good as the minimum.

SECTION 3

SELECTION OF SPACECRAFT SYSTEM REDUNDANCY

3.1 OBJECTIVES

The objectives of the system redundancy activity were to develop techniques for the selection of redundancy within the Voyager spacecraft system and to recommend a typical allocation of such redundancy.

Redundancy at the system level involves the number and types of hardware elements (i.e., black boxes or components) which should comprise the spacecraft system. All types of redundancy were considered to be within the scope of the study, including block, multi-channel, standby and functional redundancy. Redundancy below the black box level (i.e., the piece-part level) was not considered, except as required to determine the performance characteristics of the black box under consideration.

It was in this area of the study that the Aeronautical Division of Honeywell, Inc., Minneapolis, participated. Section 3.6, which describes the optimization computer program system, was authored by Honeywell.

3.2 ORGANIZATION

Described in this section is a new concept for the selection of spacecraft system redundancy--that of selecting redundancy to maximize the expected worth of the mission. In contrast to the conventional criterion of maximizing system reliability, this new technique is more applicable to complex spacecraft which perform in many-faceted mission situations.

The system redundancy activity was divided into four major areas (Figure 3-1):

a. Mission Outcome and Worth Definition - Definition of an exhaustive and mutually exclusive set of possible outcomes of the Voyager mission. Assignment of relative values, or worths, to these outcomes with the aid of a supporting rationale.

b. System Definition and Description - Categorization of the spacecraft system into independent assemblies. Formation of families of independent assemblies, each family consisting of a single-string independent assembly void of any intentional redundancy and alternate independent assemblies with varying degrees of redundancy. Generation of a piece-part failure data base. Employing the data base, assignment of reliability characteristics to the hardware elements comprising the system independent assemblies.

c. System Failure Modes and Mission Effects Analysis - Correlation of the failure modes of the hardware elements within each independent assembly with the performance modes of the assembly. Correlation of the performance modes of the independent assemblies which comprise the spacecraft system with the resulting outcomes of the mission.

d. System Design for Maximum Mission Worth - Development of a computer program system employing dynamic programming to select, from all possible system configurations with varying degrees of redundancy, that subset of system configurations, each member of which has a greater mission expected worth than all other systems of comparable weight, power, or cost. Exercise of the technique to recommend typical allocations of Voyager spacecraft redundancy.

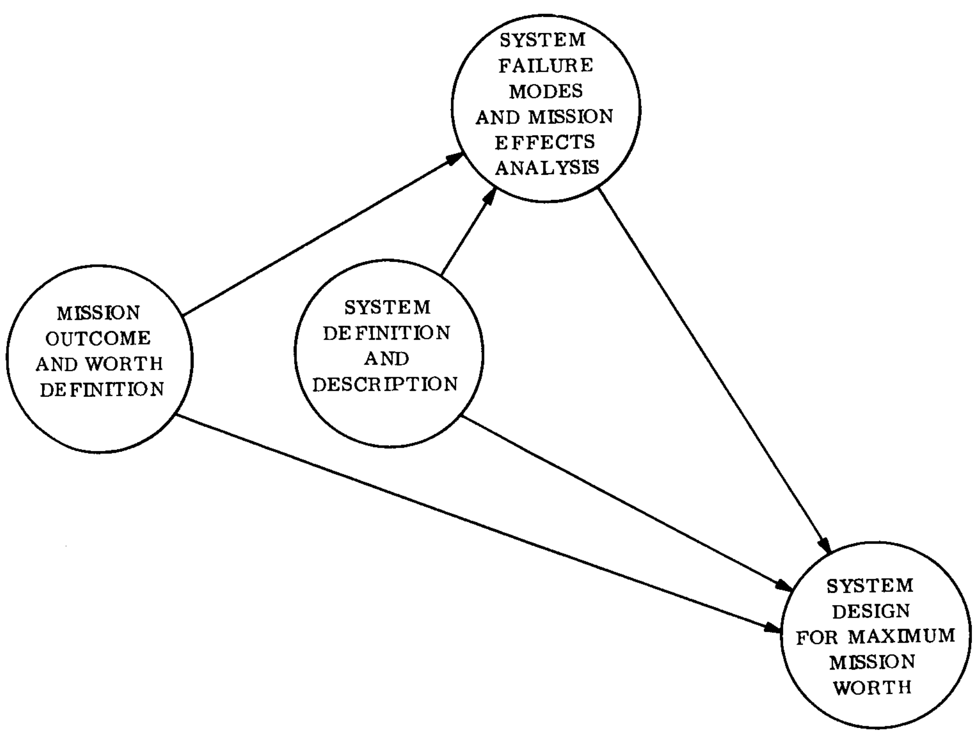


Figure 3-1. Selection of Spacecraft System Redundancy Organization

The first three topics are covered in Sections 3.3, 3.4 and 3.5. Section 3.6 describes the optimization program system and Section 3.7 discusses typical redundancy allocation results. Section 3.8 discusses conclusions and recommendations for further activity.

3.3 MISSION OUTCOMES AND VALUE

3.3.1 MISSION OUTCOME TREE

3.3.1.1 Mission Outcome Definition

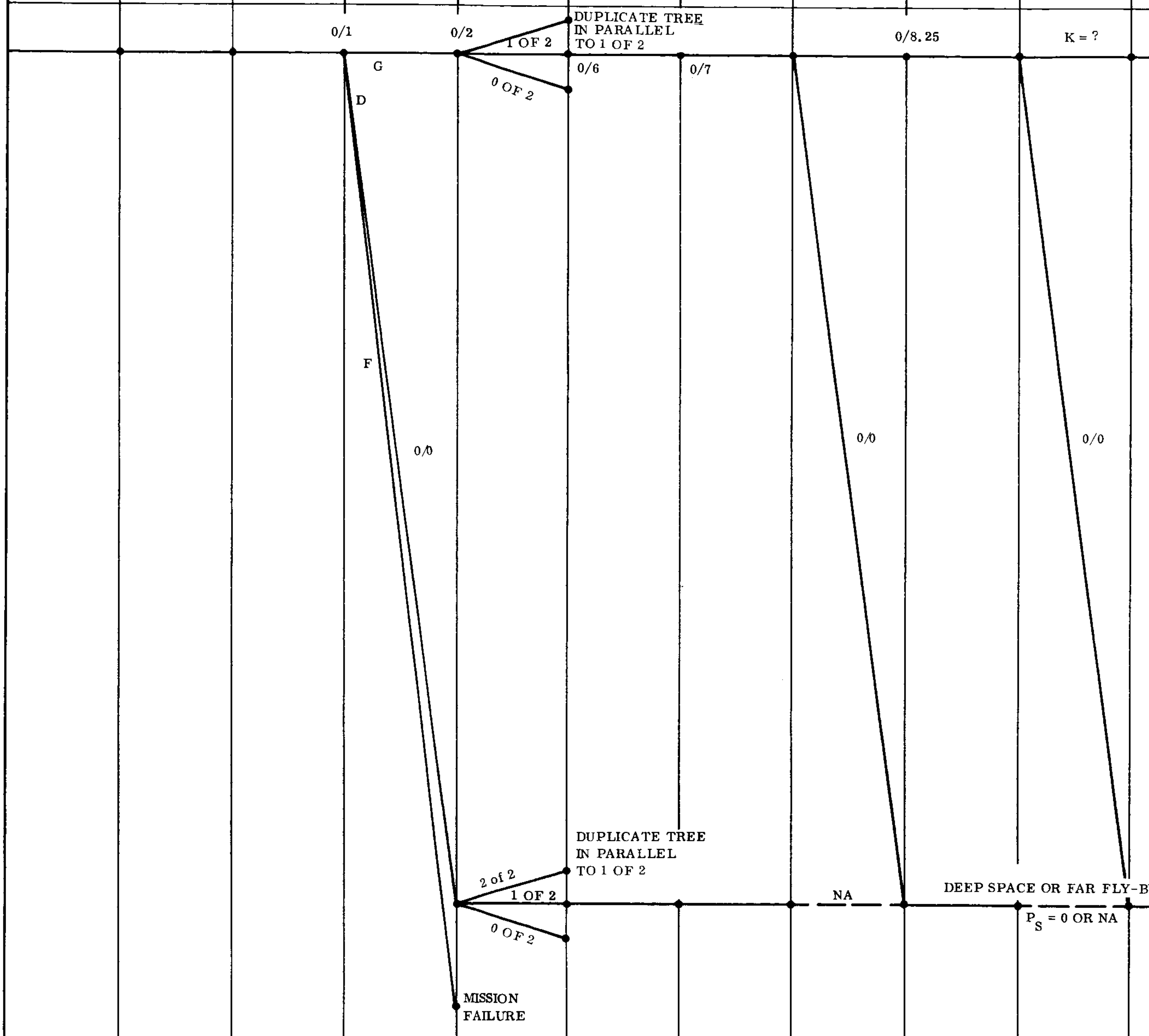
The method used to describe mission outcomes is a tree diagram which is constructed from the first level functions (or subphases) of the nominal Voyager mission profile. Figure 3-2 is the Voyager mission outcome tree. A given first level function may form multiple branches on the tree representing whether that function is performed in a good, degraded or failed manner. Horizontal lines represent good states. Branches with negative slopes represent either degraded or failed states.

Using the first level elements of the functional flow diagrams to describe mission outcomes provides a valuable link in the chain required to associate spacecraft hardware operating states to mission value. Values are assigned to mission outcomes, which are described by first level functions. First level functions, in turn, are broken down into subfunctions defining discrete hardware items required to perform these functions. Hardware failure modes (or operating states) are defined, and their effect on the functions to be performed can be described. Thus, given that probabilities may be established for the operating states of all single-string and potentially redundant hardware elements throughout the mission, the probabilities of the various valuable mission outcomes may be determined.

The functional flow definition for the nominal Voyager mission is discussed in Section 2. The first level functions (subphases) of the mission profile can be considered either in-line or support functions. In-line functions generally define the spacecraft trajectory functions and operating modes as they occur in the normal sequence of events. Support functions describe those functions which are required by a variety of in-line functions throughout one or more mission phases.

The mission outcome tree is constructed from in-line functions. Although they do not specifically appear on the mission outcome tree, support functions are accounted for when

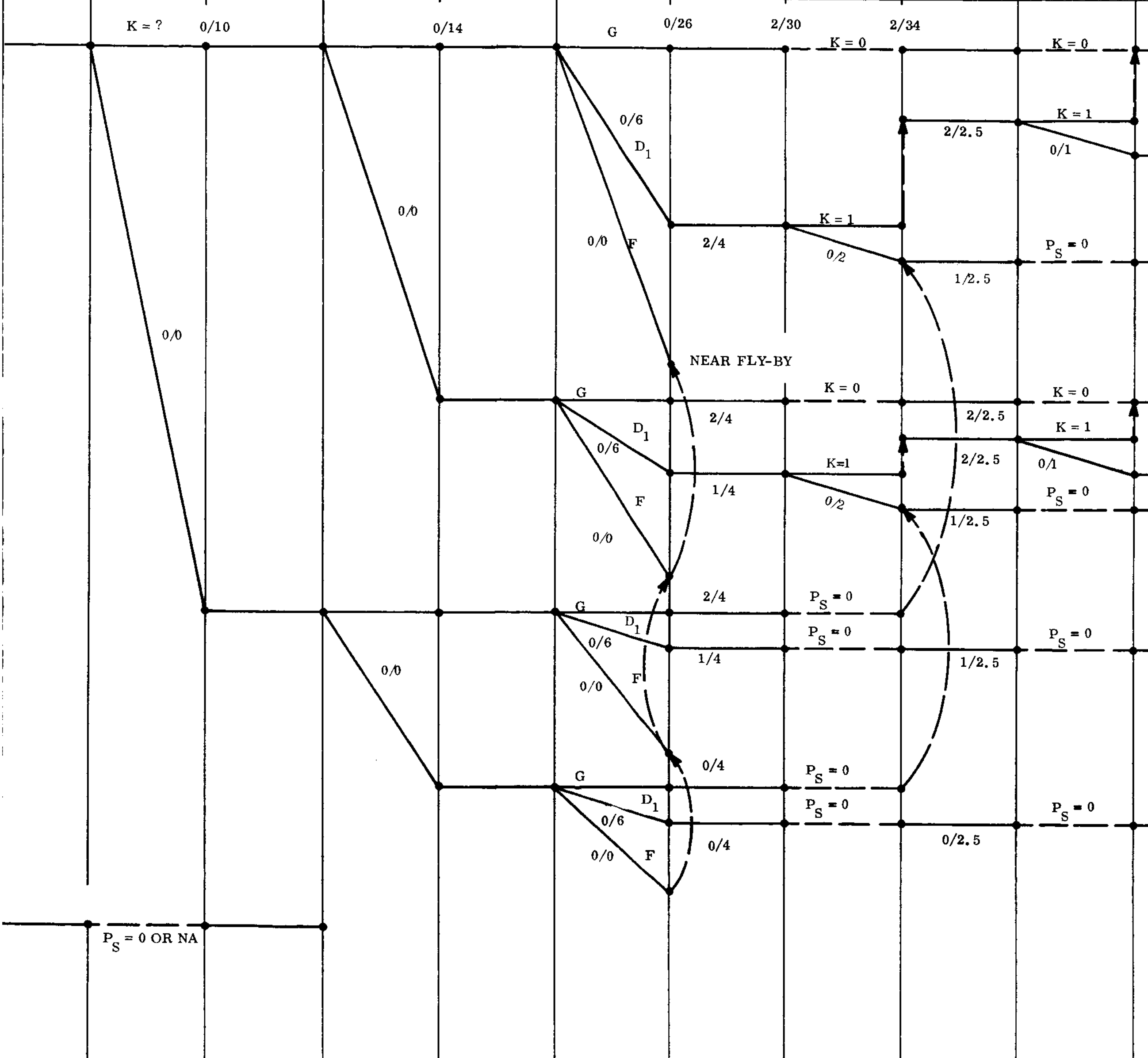
SUBPHASE	PREPARE FOR LAUNCH	ACHIEVE PARKING ORBIT	ACHIEVE INTERPLANE. TRAJECTORY INJECTION	SEPARATE P/V'S FROM LAUNCH VEH.	ACQUIRE CELESTIAL REFERENCES	INTERPLANE. CRUISE	INTERPLANE. TRAJECTORY CORRECTION NO. 1	INTERPLANE. CRUISE	INTERPLANE. TRAJECTORY CORRECTION NO. 2	INT
NUMBER	7.X	6.1	6.2	6.3	5.1	5.2	5.3	5.2	5.4	
HOURS	--	0.6	0.1	0.0	19.1	40.2	17.2	630.8	17.7	3
SCIENCE VALUE	-	-	-	-	-	-	-	-	-	
ENGINEERING VALUE	-	1	1	4	1	0.25	1	0.5	0.5	



5.7	1	1	1	1	1
D_1	0	0	0	0	0
D_2	1	1	1	1	1
F	0	0	0	0	0

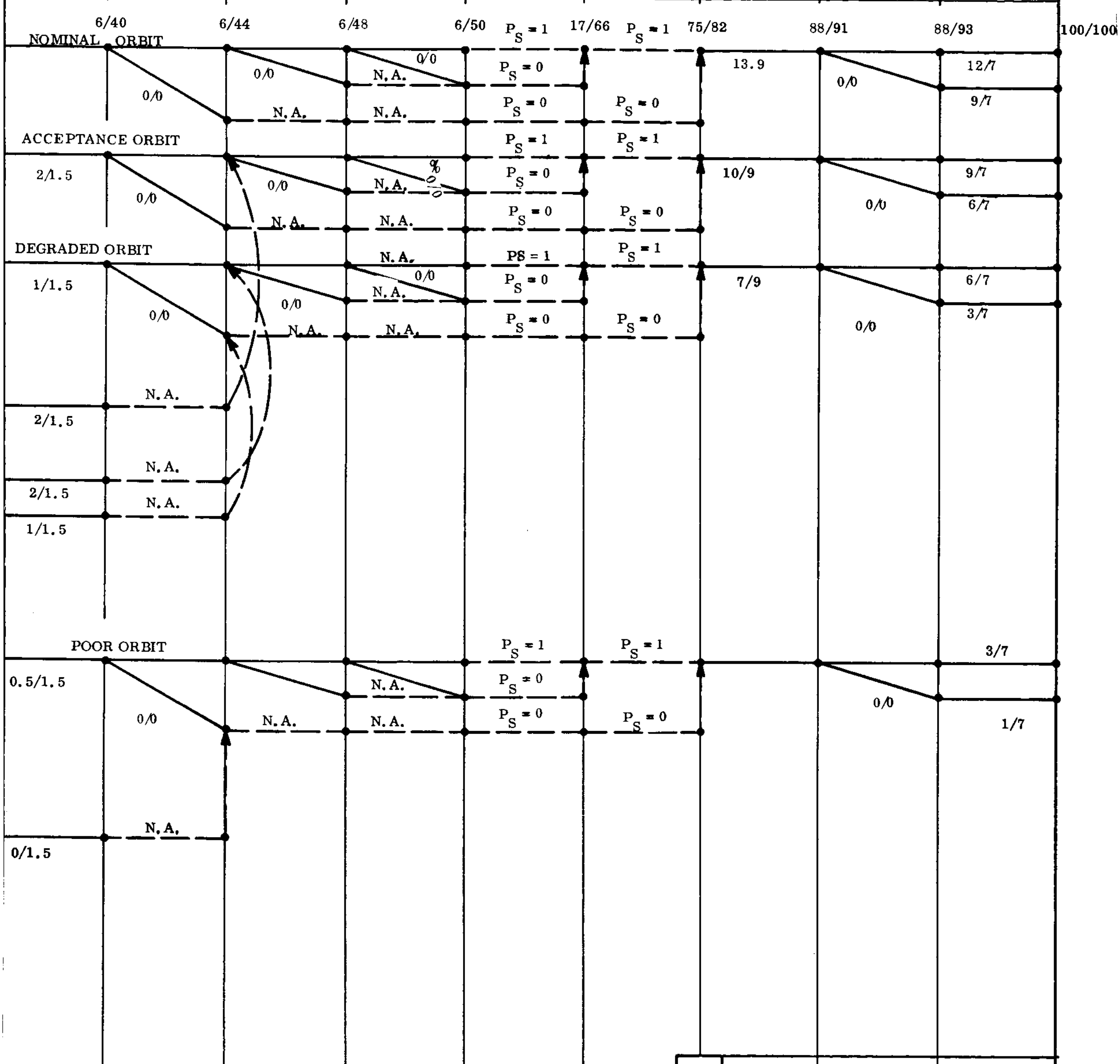
6.4	1	1	1
F	0	0	0

ERPLANE. CRUISE	INTERPLANE. TRAJECTORY CORRECTION NO. 3	INTERPLANE. CRUISE	SEPARATE STERILIZ. CANISTER	INTERPLANE. CRUISE	ORBIT INSERTION	ORBIT OPERATIONS	ORBIT TRIM NO. 1	ORBIT OPERATIONS	ORBIT TRIM NO. 2
5.2	5.5	5.2	5.6	5.1	4.1	4.2	4.3	4.2	4.9
62.3	17.7	150.3	0.0	24.5	6.1	32.3	17.4	35.1	17.4
-	-	-	-	–	-	2	-	[illegible]	-
0.5	0.25	-	4	-	12	4	4	2.5	2



1	1	1	1	1	4.4	1	1	1	1	1
0	0	0	0	0	D_1	0	0.333	0	0.445	0
1	1	1	1	1	D_2	1	0.667	1	0.555	1
0	0	0	0	0	F	0	0	0	0	0

ORBIT PERATIONS	SEPARATE CAPSULE	SUPPORT CAP- ULE DESCENT AND ENTRY	RETURN TO ORBIT OPERATIONS	EXP. WORTH CAP. DES- CENT AND ENTRY	EXP. WORTH CAP. LANDED OPERATIONS	ORBIT OPERATIONS	180° ROLL REQUIRE- MENTS	ORBIT OPERATIONS
4.2	3.1	3.2	3.3	--	--	2.1	2.3	2.1
34.0	6.0	1.7	6.7	--	--	720.0	1.5	3646.5
2	-	-	-	11	58	13	-	12
1.5	4	4	2	16	16	9	2	7



1.	3.9	1	1	1	1	1
0.428	D_1	0	0	0	1	1
0.572	D_2	1	1	1	0	1
0	F	0	0	0	0	1

2.4	1	1	1
D_1	0.863	1	0.769
D_2	0.591	1	0.308
D_3	0.408	1	0
F	0	0	0

Figure 3-2. Mission Outcome Tree

[redacted]

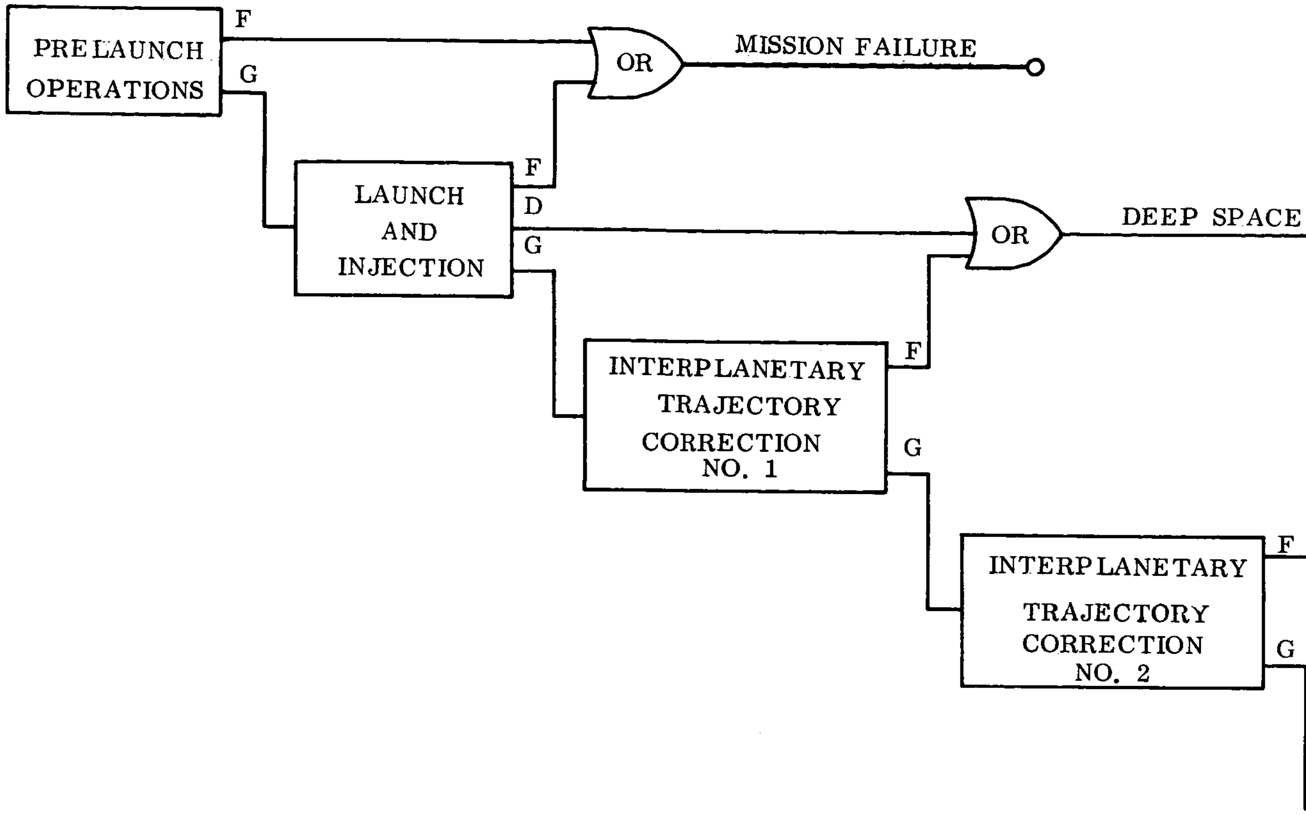
considering the probabilities of the various operating states for each in-line function. For example, for a given in-line function to be in the good state, all hardware elements associated with that function and all support functions required for that in-line function must be in specified operating states. The interfaces between the support functions and in-line functions are defined by cross references in the functional flow diagrams.

The support functions associated with obtaining and transmitting data are treated in a different way on the outcome tree. This is discussed in Subsection 3.3.3.2.

3.3.1.2 Trajectory Logic

Construction of the mission outcome tree required that a simplified but uniform rationale be used to determine the effect of the success or failure to perform the various functions associated with altering the planetary vehicle or spacecraft trajectory. For example, if the second interplanetary trajectory correction fails, is it still possible to achieve Mars orbit with the orbit insertion propulsion system? The trajectory logic of Figure 3-3 indicates that a far fly-by results; i.e., it was assumed that the orbit insertion propulsion subsystem is not capable of achieving a Mars orbit given failure to perform the second interplanetary trajectory correction. Exceptions to this simplified logic can be found; however, this logic is representative of most likely effects of the types of failures postulated.

The logic of Figure 3-3 is incorporated in the mission outcome tree (Figure 3-2). Table 3-1 defines, in general terms, the resulting trajectories and orbits. The deep space and far fly-by trajectories are combined in the mission outcome tree since it was anticipated that there would be little difference in their value. The near fly-by trajectory results from a failure at orbit insertion. Since it is unlikely that the planetary vehicle could be reoriented in sufficient time to acquire a significant amount of fly-by data, this outcome is not extended beyond the orbit insertion subphase.


PRELAUNCH OPERATIONS
F
G
OR
MISSION FAILURE
LAUNCH AND INJECTION
F
D
G
OR
DEEP SPACE
INTERPLANETARY TRAJECTORY CORRECTION NO. 1
F
G
INTERPLANETARY TRAJECTORY CORRECTION NO. 2
F
G

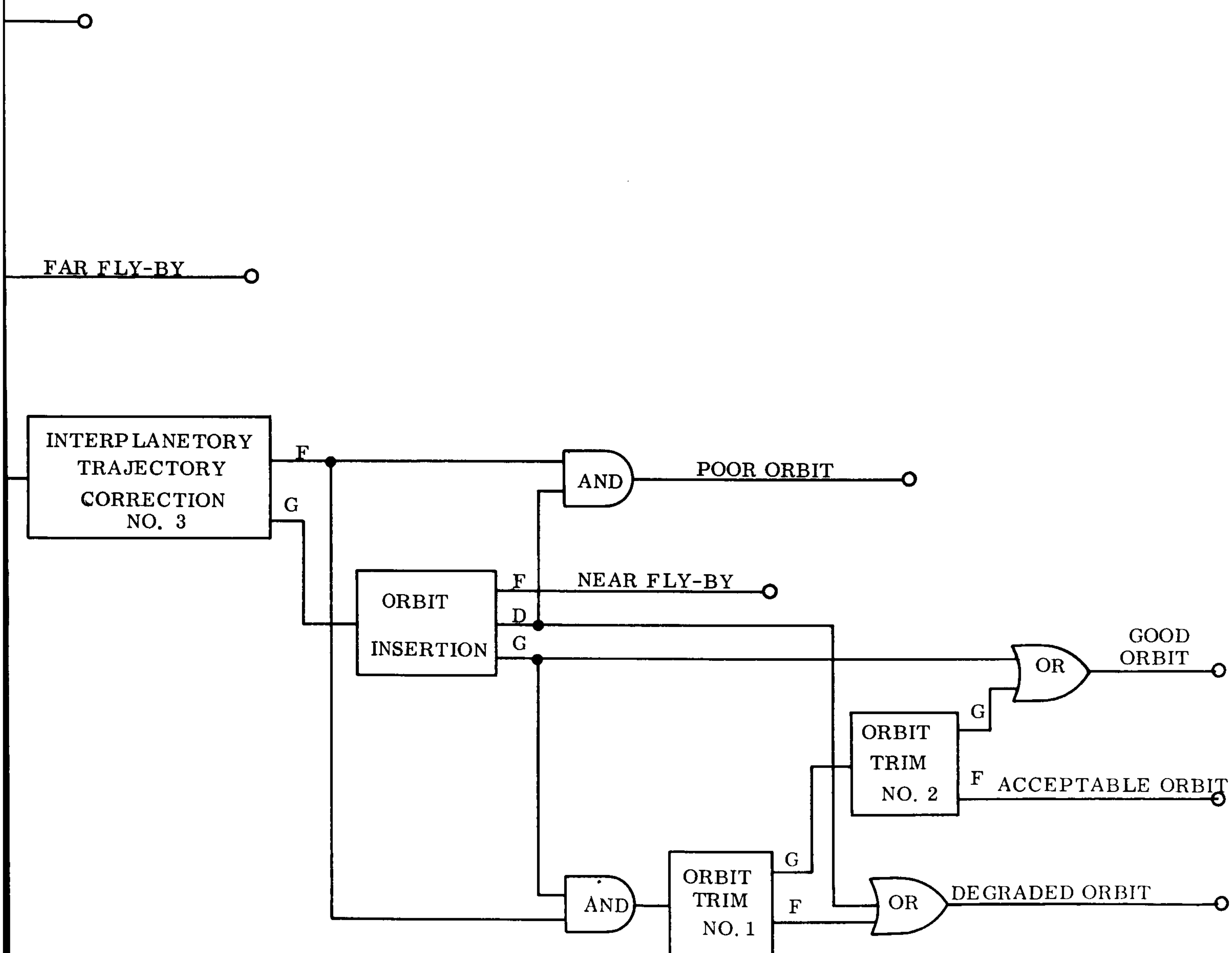


Figure 3-3. Simplified Trajectory Logic

[redacted]

Table 3-1. Definition of Trajectories and Orbits

Trajectory or Orbit	Description
Mission Failure	Earth escape trajectory not achieved.
Deep Space	Escape trajectory achieved but closest Mars encounter 50,000 km.
Far Fly-by	Closest Mars encounter between 5000 and 50,000 km. Some planetary data possible but value as Voyager mission questionable.
Near Fly-by	Closest Mars approach between 500 and 5000 km.
Poor Orbit	Orbit from which capsule will enter exceeds design range. If it survives, no entry or television data will be obtained due to telecommunications range. Orbit does not allow proper spacecraft mapping.
Degraded Orbit	Capsule descent television data will not be obtained. Entry data may be obtained. Orbit does not allow proper spacecraft mapping.
Acceptable Orbit	Capsule descent television data may be obtained. Entry data will be obtained. Orbit is good for spacecraft mapping.
Nominal Orbit	Orbit is good for both capsule and spacecraft functions.

Some trajectory functions may not have to be performed, depending on the results of the previous corrections. For example, the third midcourse correction might not be required if the second were successful and resulted in a trajectory very close to the nominal. Such functions are indicated by the letter k on the mission outcome tree (k is the probability that the function will be called on to perform). Note that k = 0 for the orbit trims if the planetary vehicle is already in a nominal orbit.

3.3.1.3 Interpretation of Mission Outcome Tree

The following interpretations should be used in reading the mission outcome tree (Figure 3-2).

a. Line N.A. - Horizontal dotted lines tagged N.A. indicate that the performance (or nonperformance) of that particular function is of no consequence, and no value is associated with that function on that path of the tree.

b. Line k - Horizontal dotted lines tagged k = 0 indicate that the particular function is not required on that path of the tree.

c. Line P_S - Horizontal dotted lines tagged $P_S = 0$ (used for orbit trim functions) indicate that the probability of success of that function is zero (i.e., the liquid propulsion subsystem has previously failed). Lines tagged $P_S = 0$ or $P_S = 1$ for the capsule functions are discussed in Subsection 3.3.3.3.

d. Arrows - Dotted lines with arrows are used to show coalescing of nodes to simplify drawing the tree.

3.3.2 VALUE RATIONALE

3.3.2.1 Types of Value

Direct value (or worth) arises from the new knowledge that a mission produces. For example, television maps of Mars or surface temperature data belong in this category. On the other hand, national prestige, providing stimuli for the economy, satisfying man's urge to explore, and other less tangible objectives are defined as having indirect value. For the system redundancy selection, only direct components of mission value are considered.

Direct value can be further subdivided into scientific and engineering value. For example, insertion of the planetary vehicle into a Mars orbit has little scientific value, yet it has important engineering value.

3.3.2.2 Scientific Value

The assignment of worth is a subjective undertaking; there seems to be no completely deterministic method of calculating worth. Rigorous approaches may lead to mathematical equations. However, there will always be some factor or constant in the expression which depends on human judgment. Recognizing the subjective nature of value and that the final value assignments must be made by Voyager project management, the following approach is used to derive scientific values. The objectives of the Voyager missions to Mars are stated* as:

> "Obtain information relevant to the existence and nature of extraterrestrial life; the atmospheric, surface and body characteristics of the planet; and the planetary environment by performing unmanned experiments on the surface of and in orbit about the planet."

With the aid of the 1965 Woods Hole report**, it is possible to break down the mission objectives into a more detailed list of scientific measurements. The grouping of experiments into categories is based on the priorities established in the Woods Hole report and is used for assigning worth numbers to the experimental categories shown in Table 3-2. Each experiment in the table is linked to instruments proposed for the 1973 spacecraft and capsule scientific payload***.

The emphasis in the Woods Hole priorities is on biological investigations, and this emphasis is reflected in our value assignments. However, emphasis also is placed on those environmental conditions which have an important though indirect bearing on biology. Therefore, the ratio between the indirect and direct categories is set at 65/35. Note that life detection is totally assigned to the landed package, whereas the environmental science is divided among the landed, descent and orbital phases.

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* "Voyager 1971 Preliminary Mission Description," Jet Propulsion Laboratory, October 15, 1965, page ii.

** "Space Research: Directions for the Future," Space Sciences Board, Woods Hole, Massachusetts, 1965, pages 13-15.

*** "Voyager '73 Instrumentation for Experiments," <u>Space/Aeronautics,</u> January 1967, page 56.

Table 3-2. Scientific Worth

Science Category	Scientific Weight		Instruments on Voyager 1973 Mission		
	Total	Mission Phase	Landed	Descent	Orbital
1. EXISTENCE OF LIFE Purpose: Detect presence of macro or microscopic organisms.	35	L - 35 D - 0 O - 0	25 - Life Detection 10 - TV	No Contribution	No Contribution
2. METEOROLOGY Purpose: Determine atmospheric and cloud dynamics.	23	L - 8 D - 6 O - 9	2 - Pressure Gage 2 - Temperature Gage 2 - Humidity 2 - Wind Velocity and Direction	1 - Accelerometer 1 - Pressure Gage 1 - Temperature Gage 3 - Mass Spectrometer	2 - Broad Band IR Spectrometer 1 - IR Radiometer 2 - Hi-Resolution IR Spectrometer 1 - UV Spectrometer 3 - Dual TV
3. SURFACE ENVIRONMENT Purpose: Determine topography, composition, thermal and radiation conditions.	42	L - 15 D - 5 O - 22	4 - Gas Chromatograph 2 - Spect. Radiometer 2 - α Spectrometer 2 - Subsurface Probe 5 - TV	5 - TV	2 - Broad Band IR Spectrometer 3 - IR Radiometer 3 - Hi-Resolution IR Spectrometer 2 - UV Spectrometer 10 - Dual TV 2 - γ-Ray Spectrometer

The following items have not been included in overall assignment of weights:

1. Instrument Additions:
   (a) A UV radiometer on the Lander would determine the surface UV flux. This has biological implications.
   (b) Addition of a magnetometer on the Orbiter would permit mapping of planetary magnetic fields. Implications regard the internal structure of the planet.
2. Other Planetology: Accurate tracking of Orbiter would result in determining planet's gravitational field shape and internal density distribution.
3. Certain particle and field experiments should perhaps be considered for Voyager '73, since later Voyager missions may include an RTG which may compromise such measurements.

Legend: L = Landed Operations Phase
D = Entry and Descent Phase
O = Orbital Operations Phase

The value numbers of Table 3-2 are further subdivided to show what fraction of the total value can be obtained during the orbital operations phase (O: 31 percent), the entry and descent phase (D:11 percent), and the landed operations phase (L: 58 percent).

The criteria employed for instrument selection and value assignments within the general categories of Table 3-2 are summarized as follows:

a. Interplanetary experiments are generally relegated to less sophisticated vehicles than Voyager.

b. Only conventional instrumentation available by 1973 is considered. Much of the instrumentation has been developed on other programs, such as Mariner and Surveyor. Experience and data obtained in these programs are taken into consideration.

c. Parameters to be measured are of a direct nature wherever possible.

d. Lander operation is based on a 150 pound survival package operable on the surface for approximately two days.

e. Minimum mobility and sample preparation capability are assumed in the landed phase.

3.3.2.3 Engineering Value

Each first level, in-line function contained in the Voyager mission functional flow diagrams is assigned a relative engineering value in terms of a percentage of the total engineering value. The following rules were adopted:

a. The value of a function performed for the first time during this mission is set at double that of a comparable function which has been performed during previous missions (e.g., sterilization canister separation).

b. In addition, the value of a function is doubled or tripled if it has extraordinary engineering significance; e.g., performance of orbit insertion.

c. The value of a function performed successfully during many previous missions is halved; e.g., achievement of parking orbit.

d. The value of a discontinuous function is halved for each repeat performance; e.g., trajectory corrections.

e. The value of continuous events is assumed to decrease exponentially with performance time; e.g., interplanetary cruise.

The engineering value assigned to the mission subphases according to these rules is tabulated in Table 3-3.

3.3.3 TREE VALUE ASSIGNMENTS

3.3.3.1 Outcome Tree Branch Values

The engineering value numbers in Table 3-3 are arranged in such a way as to be directly applicable to the in-line, first level functions shown in the top line of Figure 3-2, the outcome tree. The scientific value numbers can be transferred similarly from Table 3-2 to Figure 3-2. Accordingly, each in-line, first level function across the top of the mission outcome tree has both a scientific and an engineering value associated with it.

The mission outcome tree contains some branches denoting degraded modes of the first level functions. Obviously, a degraded mode should be credited with only a fraction of the total function scientific and engineering value. The assignment of fractional value numbers to the branches of the tree in Figure 3-2 is based on scientific and engineering judgment.

The worth of an outcome on the tree is simply the sum of the worth of the branches which are traversed to arrive at the outcome. Thus, the final step in assigning value is to sum the scientific and engineering value numbers assigned to the branches to arrive at total value numbers for each outcome. Combining scientific and engineering value is somewhat similar to comparing apples and oranges. Yet, if one considers each engineering achievement as a stepping stone toward more scientific return on a future mission, then the two are closely related. Since the primary goal of the Voyager program is scientific, the total engineering value should not exceed the scientific value. On the other hand, an early flight like the 1973 mission will be important in the development of a system capable of satisfying the overall Voyager project objectives, including landing complex biological laboratories

Table 3-3. Engineering Worth of Mission Subphases

Subphase	Worth	Subphase	Worth
6.0 Launch and Injection	**6**	**3.0 Orbit Descent and Entry**	**26**
6.1 Achieve Parking Orbit	1	3.1 Separate Capsule from Spacecraft	4
6.2 Achieve Interplanetary Trajectory Injection	1	3.2 Support Capsule Descent & Entry	4
6.3 Separate PV's from Launch Vehicle	4	3.3 Return to Orbital Operation Mode	2
		3.4 Perform De-orbit Thrusting (Caps)	
		3.5 Descend from Orbit (Caps)	8
		3.6 Enter Atmosphere (Caps)	
		3.7 Perform Terminal Descent (Caps)	
		3.8 Survive Impact (Caps)	8
5.0 Transit	**8**	**2.0 Orbiter Operation**	**18**
5.1 Acquire Celestial References	1	2.1 Perform Orbital Operations	9
5.2 Perform Interplanetary Cruise	0.25	2.2 Perform 180° Roll Reorientation	2
5.3 Perform Interplanetary Trajectory Correction No. 1	1	2.1 Perform Orbital Operations	7
5.2 Perform Interplanetary Cruise	0.5		
5.4 Perform Interplanetary Trajectory Correction No. 2	0.5		
5.2 Perform Interplanetary Cruise	0.5		
5.5 Perform Interplanetary Trajectory Correction No. 3	0.25		
5.2 Perform Interplanetary Cruise	-		
5.6 Separate Sterilization Canister	4		
5.2 Perform Interplanetary Cruise	-		
4.0 Orbit Achievement	**26**	**1.0 Landed Operation**	**16**
4.1 Perform Orbit Insertion	12	1.1 Orient & Deploy Lander Package	8
4.2 Perform Orbital Operations	4	1.2 Perform Landed Operation	8
4.3 Perform Orbit Trim No. 1	4		
4.2 Perform Orbital Operations	2.5		
4.4 Perform Orbit Trim No. 2	2		
4.2 Perform Orbital Operations	1.5		

in 1977 and 1979. Thus, the engineering value of the 1973 mission cannot be far below the scientific value. Therefore, equal weighting of scientific and engineering value is judged appropriate for the 1973 mission.

3.3.3.2 Quality Functions

Functions associated with obtaining and transmitting data may be considered as quality functions which modify the value of the in-line functions. The total value associated with performing orbital operations, for example, from a nominal spacecraft orbit should be realized only if the data obtained from such an operation is received on earth. Partial receipt of this data should result in partial realization of the total value. Accordingly, degraded states are defined for the functions associated with obtaining and transmitting data to accommodate less than perfect performance for these functions. These degraded states are defined in Table 3-4.

The tabulations at the bottom of the mission outcome tree list the value coefficients associated with the operating states of these quality functions for each mission phase. For example, during the transit phase, Function 5.7 - Obtain and Transmit Data, may have four possible states: good, degraded-one (D1), degraded-two (D2), or failed. These states are defined so that they are mutually exclusive and exhaustive.

3.3.3.3 Capsule Expected Value

For non-spacecraft functions, such as those performed by the capsule, engineering estimates are made of the probabilities that the functions will be successfully performed. Since both the probabilities and values of these functions are fixed, the capsule portion of the outcome tree is reduced to a single expected capsule value. This expected value is accrued for any mission outcome which provides the capsule system an opportunity to perform.

In the outcome tree of Figure 3-2, capsule expected value is divided into the value associated with orbit descent and entry and that associated with the landed operations. This division is necessary since it is possible to loose the capsule value associated with orbit descent and entry (e.g., the radio relay link on the spacecraft fails), but obtain that of landed operations. The probability of success numbers on the branches of the outcome tree indicate the probability that the capsule expected values will be obtained.

Table 3-4. Definition of Quality States

First Level Function	States of Interests
5.7 Obtain and Transmit Data (Transit)	G: Obtain all engineering data. D1: Obtain only science data. D2: Obtain only engineering data. F: All others.
4.4 Obtain and Transmit Data (Orbit Achievement)	Same states as for 5.7.
3.9 Obtain and Transmit Data (Orbit Descent and Entry)	Same states as for 5.7 (Note: Capsule relayed data is considered science data).
2.4 Obtain and Transmit Data (Orbiter Operations)	G: Obtain all engineering and science data. D1: Obtain less than all science data, but at least one type of video and one type IR data at a data rate comparable to that achievable with the 3 watt amplifier through the high gain antenna. Obtain all engineering data. D2: Obtain less science than D1, but at least some good video data, with or without engineering data. D3: Obtain engineering data only. F: All others.

3.3.4 DOCUMENTATION

The Voyager mission outcome tree was developed and first published in Technical Memorandum VOY-C3-TM21. The assignment of value and the supporting rationale to complete the mission value model is contained in Memorandum VOY-C3-TM25.

3.4 SYSTEM DEFINITION AND DESCRIPTION

To develop the system optimization tool for the application of redundancy, it is necessary to establish a hardware level at which a configuration can be uniquely and conveniently defined. The establishment of such a hardware level to serve as a common denominator is an evolutionary process. At one extreme are piece-parts, with their individual failure modes and failure rates. At the other extreme is the hardware associated with the major mission functions, such as interplanetary cruise and orbit injection. The piece-part level is certainly not desirable, since piece-part definition is often not available during the preliminary design phase when such a tool is required. In addition, grouping the total number of piece-parts into assemblies presents a formidable bookkeeping problem for just one system configuration, let alone a large number of different configurations. The mission function level also is not desirable, since it must be correlated with many hardware assemblies, some of which perform other mission functions.

In the process of developing the tool, the common denominator evolved by working simultanteously upward from the piece-part level and downward from the mission functions. The result was the definition of "families" of "independent assemblies" as the common denominator. Both of these terms are discussed in detail in later sections of this report,

Briefly, any Voyager spacecraft configuration consists of 51 unique independent assemblies, each a member of a different family. Members of the same family must perform the same functions, and only one member can be incorporated in any one particular spacecraft. One such member of each family is the single-string independent assembly, and others have redundancy incorporated in varying degrees. Since many candidates are often possible for any one family, a large number of spacecraft configurations is possible because of the large quantity of combinations.

The analogy depicted in Figure 3-4 is appropriate. Consider the Voyager spacecraft as a set of books, each volume in the set representing a member of a different family. Any one

Voyager spacecraft, for example, is specified when the 51 places for the books are each filled with a volume from the appropriate family. It is illegal to place a member of family 46 in the slot reserved for family 32. This concept is elaborated upon in the next section.

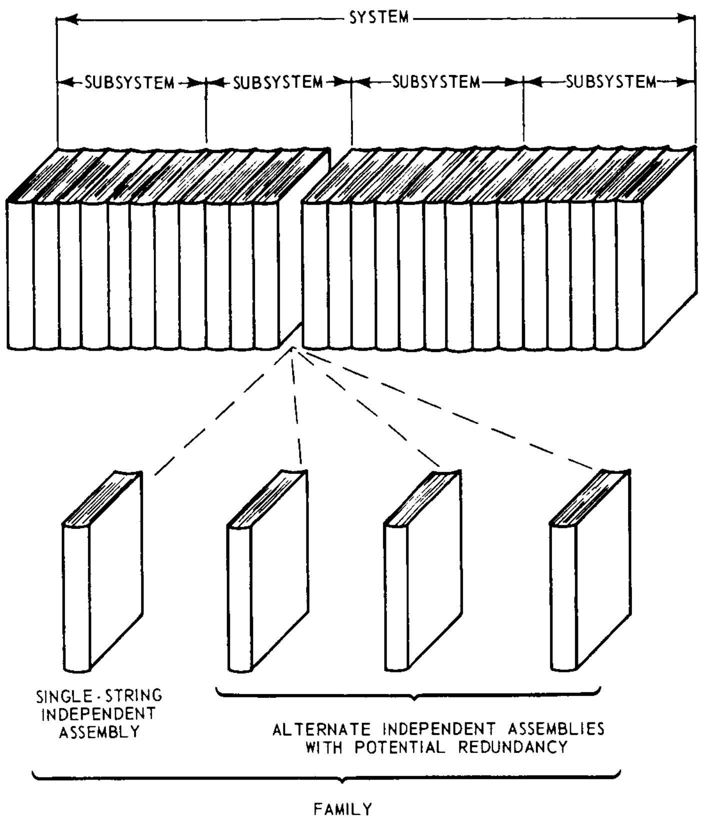

Figure 3-4. Concept of Independent Assemblies

3.4.1 INDEPENDENT ASSEMBLY AND FAMILY DEFINITION

To divide the Voyager configuration into hardware groupings of manageable size for the subsequent application of redundancy, the concepts of independent assemblies and families of independent assemblies were developed.

First, the Voyager spacecraft, as developed by General Electric during Task B, was divided into six subsystems:

a. Computer and Sequencer

b. Power

c. Guidance and Control

d. Engineering Mechanics

e. Propulsion

f. Telecommunications.

Each of the above Task B subsystems was then subdivided into several independent assemblies. Essentially, an independent assembly is a grouping of hardware elements, the failure modes or states of which are probabilistically independent of those of other independent assemblies.

At this point, the system categorization was correlated with the single-string and redundant alternate definition disucssed in Section 2.3, and a single-string implementation was associated with each independent assembly. In a few cases, the Task B independent assembly was identical to its single-string counterpart.

The need to discuss Task B independent assemblies as well as their single-string counterparts gave rise to the concept of a family of independent assemblies. Thus, the definition of an independent assembly was expanded to include the concept of a family:

a. An independent assembly can be replaced in its entirety by any other independent assembly from the same family of independent assemblies.

b. All functions performed by the single-string assembly of a family can be performed by any alternate independent assembly in that family.

The single-string independent assembly in each family thus constitutes a baseline reference for the application of redundancy within that particular family. In addition to the Task B independent assemblies, additional independent assemblies with varying degrees of redundancy were formulated from the potential redundancy previously proposed and discussed in Section 2.3.

The following is the final breakdown of the number of families and independent assemblies by subsystem:

Subsystem	Number of Families	Number of Independent Assemblies
Computer and Sequencer	12	37
Power	8	49
Guidance and Control	7	27
Engineering Mechanics	13	24
Propulsion	8	18
Telecommunications	3	11
Totals	51	166

Since 51 of the 166 assemblies are by definition single-string, 166-51 = 115 redundant alternate independent assemblies were postulated, or an average of 2.3 redundant independent assemblies per family.

As defined, a spacecraft system configuration is found by taking one and only one independent assembly from each family. Given 166 assemblies and 51 families, some 10^{21} possible systems can be formed. The task of extracting the best ones is indeed a trade study of the first order.

In order to account for launch vehicle and spacecraft science effects (the spacecraft science is not considered within the area of redundancy investigation for this study, but could be easily included in future work), eight science families and two launch vehicle families, each having only one independent assembly, are defined. These are referred to as pseudo-independent assemblies.

A complete computer printout listing of each independent assembly (including the family name and related data) is included on the foldout page that follows. Each independent assembly is uniquely identified by a three letter code. From left to right, the first letter denotes the subsystem (or system, in the case of the launch vehicle) as follows:

Subsystem	Symbol
Computer and Sequencer	C
Power	E
Guidance and Control	G
Launch Vehicle	L
Engineering Mechanics	M
Propulsion	P
Science	S
Telecommunications	T

The second letter represents the family of the subsystem, and the third letter represents the independent assembly of that family. The single-string independent assembly is always identified by A as its third letter. Any Task B independent assembly is identified with an asterisk immediately to the right of its three letter code.

To illustrate this breakdown, the guidance and control subsystem is divided into seven families of independent assemblies for which a total of 27 possible independent assemblies are defined. This breakdown is as follows:

Family Independent Assembly	Family Description	Number of Independent Assemblies
GA	Attitude Control Sensors and Electronics	6
GB	Gyros and Electronics	4
GD	Pneumatics Subassembly	7
GE	Attitude Electronics Power Supply	2
GF	Autopilot Electronics	3
GG	Logic Control Unit	3
GH	Gyro Package Power Supply	2
	Total	27

INDEPENDENT ASSEMBLY	FAMILY NAME	UNIT WT (LBS)	P RQMTS (WATTS)	NUMBER OF OUTPUT STATES
CAA	MASTER SEQUENCER	9.38	11.95	2
CAB	MASTER SEQUENCER	10.98	16.65	2
CAC	MASTER SEQUENCER	14.58	17.65	2
CAD	MASTER SEQUENCER	16.18	21.65	2
CAE	MASTER SEQUENCER	11.42	16.75	2
CAF*	MASTER SEQUENCER	13.02	21.45	2
CAG	MASTER SEQUENCER	16.62	22.45	2
CAH	MASTER SEQUENCER	18.22	26.45	2
CDA*	ENABLE SWITCH	0.00	0.00	2
CDB	ENABLE SWITCH	0.01	0.36	2
CDC	ENABLE SWITCH	0.04	1.08	2
CEA	GIMBAL SEQUENCER - PSP	1.05	1.35	2
CEB*	GIMBAL SEQUENCER - PSP	1.10	1.75	2
CEC	GIMBAL SEQUENCER - PSP	3.15	4.05	2
CFA	CAPSULE SEP REGISTER	.40	0.40	2
CFB*	CAPSULE SEP REGISTER	1.20	1.20	2
CGA	SOLID IGNITION REGISTER	.40	0.40	2
CGB*	SOLID IGNITION REGISTER	1.20	1.20	2
CHA	LIQUID ON/OFF REGISTERS	2.70	2.65	2
CHB	LIQUID ON/OFF REGISTERS	3.10	1.20	2
CHC	LIQUID ON/OFF REGISTERS	4.30	4.25	2
CHD	LIQUID ON/OFF REGISTERS	5.50	5.45	2
CHE	LIQUID ON/OFF REGISTERS	4.60	4.70	2
CHF	LIQUID ON/OFF REGISTERS	5.00	5.10	2
CHG	LIQUID ON/OFF REGISTERS	6.20	6.30	2
CHH*	LIQUID ON/OFF REGISTERS	7.40	7.50	2
CJA	MANEUVER REGISTERS	1.50	1.50	2
CJB*	MANEUVER REGISTERS	4.50	4.50	2
CKA	PSP SCI CONTROL	1.20	2.20	2
CKB*	PSP SCI CONTROL	1.20	2.60	2
CLA*	TELEM REGISTERS	0.70	2.90	2
CMA	POWER CONVERSION	3.00	20.00	2
CMB*	POWER CONVERSION	6.00	20.00	2
CNA	COUNTDOWN CHAIN	0.10	0.60	5
CNB*	COUNTDOWN CHAIN	0.30	1.80	5
CPA*	SOLAR ASPECT SENSOR	5.00	0.50	2
CPB	SOLAR ASPECT SENSOR	10.00	1.00	2
EAA*	AG'CD BATT + REGULATOR ASY	89.00	0.50	3
EAB	AG'CD BATT + REGULATOR ASY	101.00	0.62	3
EAC	AG'CD BATT + REGULATOR ASY	133.00	0.75	3
EBA*	AG-ZN BATT + REGULATOR ASY	36.50	0.50	2
EBB	AG-ZN BATT + REGULATOR ASY	43.50	0.60	2
EBC	AG-ZN BATT + REGULATOR ASY	50.50	0.70	2
EBD	AG-ZN BATT + REGULATOR ASY	57.50	0.80	2
EBE	AG-ZN BATT + REGULATOR ASY	64.50	0.90	2
EBF	AG-ZN BATT + REGULATOR ASY	71.50	1.00	2
ECA	CLOCKING + 2.4KC POWER ASY	6.50	28.00	3
ECB	CLOCKING + 2.4KC POWER ASY	6.70	28.10	3
ECC	CLOCKING + 2.4KC POWER ASY	6.70	28.10	3
ECD	CLOCKING + 2.4KC POWER ASY	6.90	28.20	3
ECE	CLOCKING + 2.4KC POWER ASY	11.50	41.00	3
ECF	CLOCKING + 2.4KC POWER ASY	11.70	41.10	3
ECG	CLOCKING + 2.4KC POWER ASY	11.90	41.20	3
ECH	CLOCKING + 2.4KC POWER ASY	12.10	41.30	3
ECJ	CLOCKING + 2.4KC POWER ASY	8.80	31.60	3
ECK	CLOCKING + 2.4KC POWER ASY	9.00	31.70	3
ECL	CLOCKING + 2.4KC POWER ASY	9.00	31.70	3
ECM	CLOCKING + 2.4KC POWER ASY	9.20	31.80	3
ECN	CLOCKING + 2.4KC POWER ASY	13.80	40.60	3
ECP	CLOCKING + 2.4KC POWER ASY	14.00	44.70	3
ECQ	CLOCKING + 2.4KC POWER ASY	14.20	44.80	3
ECR*	CLOCKING + 2.4KC POWER ASY	14.40	44.90	3

EDA	CD CHAIN + 400CPS PWR ASSY	4.50	10.00	4
EDB	CD CHAIN + 400CPS PWR ASSY	5.00	11.80	4
EDC	CD CHAIN + 400CPS PWR ASSY	5.10	10.20	4
EDD	CD CHAIN + 400CPS PWR ASSY	5.60	12.00	4
EDE	CD CHAIN + 400CPS PWR ASSY	7.50	14.00	4
EDF	CD CHAIN + 400CPS PWR ASST	9.00	15.80	4
EDG	CD CHAIN + 400CPS PWR ASSY	9.60	14.30	4
EDH	CD CHAIN + 400CPS PWR ASSY	10.10	16.10	4
EDJ	CD CHAIN + 400CPS PWR ASSY	6.50	12.50	4
EDK	CD CHAIN + 400CPS PWR ASSY	7.00	14.30	4
EDL	CD CHAIN + 400CPS PWR ASSY	7.20	12.80	4
EDM	CD CHAIN + 400CPS PWR ASSY	7.70	14.60	4
EDN	CD CHAIN + 400CPS PWR ASSY	10.50	16.50	4
EDP*	CD CHAIN + 400CPS PWR ASSY	11.00	18.30	4
EDQ	CD CHAIN + 400CPS PWR ASSY	11.70	16.90	4
EDR	CD CHAIN + 400CPS PWR ASSY	12.20	18.70	4
EEA	MAIN REGULATOR ASSY	10.50	30.60	2
EEB*	MAIN REGULATOR ASSY	23.00	46.80	2
EFA*	POWER LOGIC + SWITCHING	5.50	0.10	2
EFB	POWER LOGIC + SWITCHING	10.50	0.20	2
EGA	SOLAR ARRAY + ZENER REGUL	317.40	6.75	2
EGB*	SOLAR ARRAY + ZENER REGUL	319.40	7.50	2
EHA*	MAIN POWER HARNESS	30.00	6.00	2
EHB	MAIN POWER HARNESS	44.00	12.00	2
GAA	A/C SENSORS + ELECTRONICS	17.70	7.20	2
GAB*	A/C SENSORS + ELECTRONICS	24.30	28.20	2
GAC	A/C SENSORS + ELECTRONICS	26.90	27.90	2
GAD	A/C SENSORS + ELECTRONICS	21.00	15.60	2
GAE	A/C SENSORS + ELECTRONICS	22.00	16.10	2
GAF	A/C SENSORS + ELECTRONICS	18.40	7.90	2
GAG	A/C SENSORS + ELECTRONICS	17.90	7.45	2
GBA	GYROS AND ELECTRONICS	7.30	10.80	3
GBB*	GYROS AND ELECTRONICS	15.60	22.10	3
GBC	GYROS AND ELECTRONICS	20.60	26.60	3
GBD	GYROS AND ELECTRONICS	16.60	23.00	3
GDA	PNEUMATICS SUBASSEMBLY	108.20	0.30	2
GDB	PNEUMATICS SUBASSEMBLY	242.30	0.60	2
GDC	PNEUMATICS SUBASSEMBLY	216.30	0.60	2
GDE	PNEUMATICS SUBASSEMBLY	158.30	0.60	2
GDF	PNEUMATICS SUBASSEMBLY	109.20	0.30	2
GDG*	PNEUMATICS SUBASSEMBLY	239.20	0.60	2
GEA	A/C ELECT POWER SUPPLY	1.60	4.40	2
GEB*	A/C ELECT POWER SUPPLY	3.20	5.40	2
GFA*	AUTOPILOT ELECTRONICS	3.00	4.40	2
GFB	AUTOPILOT ELECTRONICS	7.00	9.80	2
GFC	AUTOPILOT ELECTRONICS	5.00	6.50	2
GGA*	LOGIC CONTROL UNIT	0.60	1.20	2
GGB	LOGIC CONTROL UNIT	1.80	3.60	2
GGC	LOGIC CONTROL UNIT	1.20	2.40	2
GHA	GYRO PACKAGE POWER SUPPLY	2.50	2.40	2
GHB*	GYRO PACKAGE POWER SUPPLY	5.00	4.80	2
MAA	THERMAL LOUVER ASSEMBLIES	106.00	0.00	2
MAB*	THERMAL LOUVER ASSEMBLIES	111.60	0.00	2
MBA*	INSULATION + THERM COATING	37.40	0.00	0
MCA	PYRO CONTROLLER	8.00	1.00	2
MCB*	PYRO CONTROLLER	11.50	2.00	2
MDA	S/C ADAPTER + SEP MECHAN	113.70	0.00	2
MDB*	S/C ADAPTER + SEP MECHAN	114.20	0.00	2
MDC	S/C ADAPTER + SEP MECHAN	128.20	0.00	2
MDD	S/C ADAPTER + SEP MECHAN	121.70	0.00	2

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MDE	S/C ADAPTER + SEP MECHAN	122.20	0.00	2
MDF	S/C ADAPTER + SEP MECHAN	136.20	0.00	2
MDH	S/C ADAPTER + SEP MECHAN	417.20	0.00	2
MDJ	S/C ADAPTER + SEP MECHAN	273.20	0.00	2
MEA*	METEROID SHIELD	70.10	0.00	0
MGA*	MAGNETOMETER DEPLOY MECHAN	1.00	0.00	2
MHA	PSP DEPLOY MECHAN	6.00	0.00	2
MHB*	PSP DEPLOY MECHAN	10.00	0.00	2
MLA*	PSP GIMBAL ASSEMBLY	21.50	6.00	2
MMA*	PSP STRUCT + THERMAL CONTR	8.00	0.00	0
MNA*	PRIMARY S/C STRUCTURE	391.40	0.00	0
MPA*	CAPSULE BIO-BARRIER	400.00	0.00	0
MQA*	S/C HARNESSING + UMBILICAL	4.50	0.00	0
MRA*	P/V IN-FLIGHT DISCONNECT	0.80	0.00	2
MRB	P/V IN-FLIGHT DISCONNECT	1.40	0.00	2
LAA	LAUNCH VEHICLE, BOOSTER	N.A.	N.A.	3
LBA	LAUNCH VEHICLE, TELEMETRY	N.A.	N.A.	2
PAA	PRESSURANT STORAGE ASSY	121.20	0.00	2
PAB	PRESSURANT STORAGE ASSY	123.20	0.00	2
PAC*	PRESSURANT STORAGE ASSY	125.20	0.00	2
PBA	PRESSURANT REGULATION ASSY	48.10	0.00	2
PBB*	PRESSURANT REGULATION ASSY	52.10	0.00	2
PCA	PROPELLANT STORAGE ASSY	1927.60	0.00	2
PCB	PROPELLANT STORAGE ASSY	1929.60	0.00	2
PCC*	PROPELLANT STORAGE ASSY	1931=60	0.00	2
PDA	THRUST CHAMBER ASSY	60.00	4.25	3
PDB	THRUST CHAMBER ASSY	62.00	4.25	3
PDC	THRUST CHAMBER ASSY	76.00	4.86	3
PDD*	THRUST CHAMBER ASSY	78.00	4.86	3
PMA*	SOLID ENGINE ASSY	9423.80	51.25	3
PNA*	TVC PRESSURANT STORE ASSY	26.70	0.00	2
PNB	TVC PRESSURANT STORE ASSY	27.20	0.00	2
PPA*	TVC PRESSURANT REGUL ASSY	1.70	0.00	2
PPB	TVC PRESSURANT REGUL ASSY	4.30	0.00	2
PQA*	TVC SUBASSEMBLY	151.20	0.00	2
SAA	MISC BAY HARDWARE	114.10	0.00	0
SBA	MISC BODY HARDWARE	1.90	0.00	0
SCA	BODY MOUNTED SCIENCE	104.00	N.A.	2
SDA	PSP SCIENCE	120.50	N.A.	4
SEA	SCIENCE ELECTRONICS	90.00	N.A.	2
SFA	DATA AUTOMATION EQUIPMENT	55.00	N.A.	2
SGA	S/C RADIO RELAY EQUIPMENT	30.00	12.00	2
SHA	ENTRY CAPSULE	2600.00	200.00	0
TAA	TELEMETRY ASSEMBLY	16.05	4.00	4
TAB*	TELEMETRY ASSEMBLY	16.85	4.10	4
TAC	TELEMETRY ASSEMBLY	24.75	4.50	4
TBA	DATA STORAGE ASSEMBLY	113.00	37.40	4
TBB*	DATA STORAGE ASSEMBLY	115.60	37.40	4
TCA	RADIO/COMMAND ASSEMBLY	130.70	180.80	9
TCB*	RADIO/COMMAND ASSEMBLY	174.70	196.90	9
TCC	RADIO/COMMAND ASSEMBLY	168.90	194.90	9
TCD	RADIO/COMMAND ASSEMBLY	173.70	196.90	9
TCE	RADIO/COMMAND ASSEMBLY	159.50	196.90	9
TCF	RADIO/COMMAND ASSEMBLY	174.10	194.90	9

* IDENTIFIES TASK B INDEPENDENT ASSEMBLIES

Family GB, for example, consists of the following set of four independent assemblies:

GB = Single-string design.

GBB = Block redundant gyros and electronics

GBC = Twin-axis gyros and associated electronics.

GBD = Block redundant gyros and electronics with majority logic sensing and switching.

In family GB, GBB is the GE Task B independent assembly.

3.4.2 INDEPENDENT ASSEMBLY COMPOSITIONS AND CHARACTERISTICS

To assess the reliability and constraints associated with each independent assembly, the detailed component (black box) composition of each independent assembly was tabulated and documented in Technical Report VOY-C3-TR9, "Voyager Independent Assembly Reference Tables for the Voyager Spacecraft Redundancy Study."

The component level within the independent assembly is that level at which, in general, failure characteristics of the hardware can be described in terms of a constant failure rate per unit time or a constant failure rate per number of cycles or trials. The calculation of component failure rates (and the failure rate data base from which component failure rates were derived) is discussed in detail in Subsection 3.4.3.

All independent assemblies also are defined in terms of cost, size, weight and power. A complete tabulation of costs per independent assembly is included in the system definition printout. In this study, the only cost used for system optimization via the application of redundancy is weight. However, the optimization computer program can handle up to four costs (e.g., weight, power, volume, and cost), but optimizing only on one at a time.

To illustrate the foregoing, Table 3-5 is an excerpt from Report VOY-C3-TR9, illustrating the tabulation of components in families GA and GB.

Table 3-5. Guidance and Control Independent Assembly Characteristics

Family Symbol: GA		Family Name: A/C Sensors and Electronics						
		Quantity of Components in Independent Assembly						
Component Reference No.	Component Description	GAA	GAB	GAC	GAD	GAE	GAF	GAG
15001A	Cruise Sun Sensor Electronics-pitch	1	3	3	2	2	1	1
15001B	Cruise Sun Sensor Electronics-yaw	1	3	3	2	2	1	1
15001C	Sun Gate Electronics-Course	1	1	1	1	1	1	1
15001D	Sun Gate Electronics-Fine	1	1	1	1	1	1	1
15001E1	Fine Sun Sensor By Pass Switch						1	
15001E2	Canopus Search By Pass Switch							1
15001F	Derived Rate Network	3	9	9	6	6	3	3
15001G	Summing & Threshold Electronics	3	9	9	6	6	3	3
15001I	Canopus Buffer Electronics	1	3	3	2	2	1	1
15001J	Acquisition Sun Sensor Electronics	2	6	6	4	4	2	2
15001L	Roll Bias Generator	1	3	3	2	2	1	1
15001M	Gyro Buffer Electronics	3	9	9	6	6	3	3
15001N1	Majority Voter		12	12				
15001P	Failure Detection & Switching Logic					1		
15001Q	A/C Electronics Switching Logic			1				
22001A	Sun Gate Sensor-Fine	1	1	1	1	1	1	1
22001B	Sun Gate Sensor-Coarse	1	1	1	1	1	1	1
22002	Cruise Sun Sensor	2	2	2	2	2	2	2
22003	Secondary Acquisition Sun Sensor	2	2	2	2	2	2	2
22004	Canopus Tracker #1	1	1	1	1	1	1	1
22005	Canopus Tracker #2	1	1	1	1	1	1	1
	Weight (pounds)	17.70	24.30	26.90	21.00	22.00	18.40	17.90
	Power (watts)	7.20	28.20	27.90	15.60	16.10	7.90	7.45
	Incremental weight (pounds)	-	6.60	9.20	3.30	4.30	0.70	0.20
	Incremental power (watts)	-	21.00	20.70	8.40	8.90	0.70	0.25

Family Symbol: GB		Family Name: Gyros and Electronics			
		Quantity of Components in Independent Assembly			
Component Reference No.	Component Description	GBA	GBB	GBC	GBD
15003A	Gyro-Single Degree of Freedom	3	6		6
15003B	Gyro Electronics	3	6	6	6
15003F	Torque Current Generator & Logic	3	6		6
15003H	Heaters & Temp. Control & Electronics	3	6		6
15003I	Two Axis Gyro			3	
15003J	Combined Two Axis Output Detector Logic & Switching			1	
15003K	Dual Red. Single Gyro Switching				3
15003S	Dual Red. Gyro Pkg. Switching		1		
	Weight (pounds)	7.30	15.60	20.60	16.60
	Power (watts)	10.80	22.10	26.60	23.00
	Incremental weight (pounds)	-	8.30	13.30	9.30
	Incremental power (watts)	-	11.30	15.80	12.20

A summary of weight and power for these families is found at the bottom of the tables. For convenience, weight and power are given both absolutely and incrementally above the single-string assembly.

Independent assemblies must also be described in terms of the output states of interest, the final column of the system definition printout. This concept is discussed in detail in Section 3.5.

3.4.3 RELIABILITY CHARACTERISTICS

In order to study redundancy within the spacecraft system, failure rates or reliabilities for the various components (i.e., black boxes) which make up a system must first be established. Further, this should be accomplished in some uniform manner so that the results of the study can be viewed with validity.

Accordingly, a standard failure data base at the piece-part level was developed to serve as the reference for assessing hardware reliabilities. It was published in interim form in Technical Report VOY-C3-TR5, and in final version in VOY-C3-TR8.

The piece-part data base was developed by first examining the available published failure rate literature and selecting sources of data for the data base. A rationale was then established to combine data from several sources and to project the resulting failure rate to the bases of 1970 and high reliability parts procurement.

It should be recognized that data was not available to the same extent in all areas. In some cases, the availability of information was excellent and predictions were readily accomplished, while in others, considerable extrapolation was necessary. Further sensitivity studies should be conducted in those areas where considerable extrapolation was involved to determine its effect upon the system configuration.

3.4.3.1 Failure Rate Data Base

It has been found that the use of past failure rate determinations to make future predictions leads to unduly pessimistic results, because the data base fails to account for improvements such as better parts availability, better design techniques, and technology changes (e.g., tubes to transistors to integrated circuits). To compensate for this, a better approach is to attempt to measure past failure rates versus time, and thus project more accurately the reliability growth of the piece-parts in question.

Similarly, by studying data on high reliability programs such as Minuteman and Apollo, high reliability improvement factors can be estimated to indicate the relative improvement to be expected by using high reliability parts over a lower reliability level. Three reliability levels were recognized in this study: (1) a standard level, (2) a level incorporating certain parts screening techniques, and (3) a high reliability level incorporating comprehensive part specifications, extensive screening techniques, and rigid process control.

To establish a meaningful failure rate data base, a careful selection of several sources was made according to the following criteria:

a. The sources had to be representative of aerospace applications.

b. The sources had to be representative of varying degrees or levels of reliability.

c. The sources had to be representative of leading aerospace manufacturers.

Using these criteria, 19 sources were selected for the piece-part failure rate data base. Indirectly, however, more than 19 sources were included in the data bank, since several of the sources were, in themselves, multiple sources.

The rationale used in obtaining the recommended part failure rates included several factors. First, it was assumed that Minuteman level parts would be used in Voyager to the greatest extent practicable. Therefore, Minuteman failure rates were used directly without adjustment for reliability growth. Apollo failure rates (via Honeywell, Inc.) were used in a similar manner for a limited number of parts for which data was inadequate. Reliability growth factors were then established for projection of failure rates from the various sources to a 1970 parts procurement period. For Mariner 1964, for example, it was assumed that the piece-parts were procured in 1962. A 2:1 reliability growth factor was estimated for mechanical and pyrotechnic parts for the time period from 1962 to 1970, and a 5:1 growth factor was estimated for electronic parts over the same eight-year period.

AOSO, another source, was assumed in its reliability level to lie between Mariner 1964 and programs such as Minuteman and Apollo. Because of the higher initial parts reliability, the trend toward growth saturation appears sooner and the potential reliability growth was assumed to be less than for parts starting at lower reliability levels. On this basis, a 2:1 reliability growth factor was assigned for all AOSO parts.

The AOSO, Apollo, Mariner, and Minuteman programs all incorporate a higher degree of reliability than does the average aerospace program. Therefore, no factors were included for adjusting those rates to a high reliability status; it was assumed parts used on these programs were already in that category.

For two other sources, Honeywell Inc. and MIL-STD-217A, the reliability growth factor for part failure rates was estimated to be over a 10-year period. The parts from these two sources, in general, were not representative of high reliability. Therefore, additional factors of 5:1 (for Honeywell) and 2:1 (for 217A) were established to translate these part rates to high reliability status.

The failure rate projections for parts requiring a more sophisticated failure rate evaluation, such as integrated circuits and gyros, were established by Redundancy Study reliability specialists. For cases where quantitative failure rate data did not exist or was inadequate, failure rates were derived by comparing the parts with other similar parts for which reliability information was available.

In summary, the ground rules and assumptions which were followed in developing the Voyager 1973 failure rate data base were:

a. Minuteman level parts were used to the greatest extent practicable. Minuteman and Apollo failure rates were used without adjustment for the Voyager 1970 parts procurement.

b. Curves (previously developed by Honeywell) showing the projected reliability growth for inertial components and integrated circuits were used for estimating the 1970 failure rates for these devices.

c. Factors to reflect (1) parts reliability growth and (2) upgrading to a high reliability status were used to obtain the 1970 failure rates for sources other than Minuteman and Apollo.

d. Where failure rate data was lacking or inadequate, failure rates were derived by comparing the part in question with another part of similar construction or performance for which reliability information was available.

The following example illustrates the failure rate development process:

Thermostat

Source: Honeywell
Failure rate = 0.370%/1000 hours

Reliability growth factor = 10:1 over a 10-year period

Period between establishing of rates and 1970 = 4 years

High reliability upgrading factor = 5:1

$$\text{Recommended 1970 failure rate} = \frac{(0.370)}{(10/4) \times (5)}$$

$$= 0.030\% \text{ per 1000 hours}$$

The remaining failure rates were derived in a similar manner using projection and adjustment factors previously defined.

Table 3-6 lists the recommended mechanical, pyrotechnic, and electronic part failure rates for the Voyager hardware reliability models, which were published in Report VOY-C3-TR8.

3.4.3.2 Component Reliabilities

The piece-part failure rates of Table 3-6 were employed as the basis for calculating reliabilities of both single-string and redundant alternate components or black boxes of hardware, by combining individual piece-part rates in appropriate manner to establish the overall rate for the components. A complete listing of all Voyager single-string and potentially redundant hardware reliabilities was published in Technical Report VOY-C3-TR7.

The development of failure rates on a component basis was a formidable task. Since the components ranged considerably in their complexity and degree of definition, various approaches were used to arrive at their reliabilities. Each component was categorized as one of the following:

a. The component corresponded directly to an identified piece part for which the failure rate was given in the piece part data base.

b. The component consisted of N identifiable piece parts, and failure of any given piece part caused failure of the component. The failure rate was defined as the sum of the N individual rates.

c. The component consisted on N identifiable piece parts, and failure of certain piece parts did not necessarily cause failure of the component. The component failure rate was defined as the sum of the rates of the piece parts which did contribute to failure.

d. The component design was not clearly defined in terms of individual piece parts. In these cases, the rate was determined from comparison with similar components, rather than by an individual piece part breakdown.

One of the tables in VOY-C3-TR7 is included as Table 3-7.

Table 3-6. Recommended Failure Rates for Voyager (1970)

Part Description	Recommended Failure Rate	Part Description	Recommended Failure Rate	Part Description	Recommended Failure Rate
Accelerometer	1.0000%/1,000 hours	Gear Train	0.1800%/1,000 hours (for medium loaded train)	Resistor, Metal Film	0.0001%/1,000 hours
Ball Bearings	0.0100% per 1,000 hours	Gyro	2.5000%/1,000 hours	Resistor, Power, WW	0.0002%/1,000 hours
Ball Screw	0.048% per 1,000 hours	Heater (Strip)	0.0010%/1,000 hours	Rocket Motor	1,360 failures per million cycles
Battery Cells, Silver Cadmium	0.0400% per 1,000 hours	Hybrid Coupler	0.0550%/1,000 hours	Sensor Tube	0.156%/1,000 hours
Battery Cells, Silver Zinc	0.0150%/1,000 hours	Hydraulic Motor Pump & Reservoir	0.3675%/1000 hours	Separation Switch	0.06 failures /10^6 trials
Bellows	0.0090% per 1,000 hours	Igniter Motor Assembly	5 failures per million cycles	Servo-Injector Valve	29.5 failures per million cycles
Cadmium Sulphide Cells	0.0076% per 1,000 hours	Inductor	0.0080%/1,000 hours	Silicon Control Rectifier	0.0100%/1,000 hours
Capacitor, Ceramic	0.0002%/1,000 hours	Integrated Circuit, Digital	0.0005%/1,000 hours		
Capacitor, Glass	0.0001%/1,000 hours	Integrated Circuit, Linear	0.0013%/1,000 hours	Sleeve Bearing	0.0200%/1,000 hours
Capacitor, Mica	0.0003%/1,000 hours	Klystron	0.2000%/1,000 hours	Solar Cell	0.0002%/1,000 hours
Capacitor, Paper	0.0002%/1,000 hours	Latch	0.01 failure per million actuations		
Capacitor, Tant., Foil	0.0003%/1,000 hours			Solenoid Valve (All failure modes except deviation from nominal response rate) (Deviation from nominal response rate)	0.52 failures per million cycles 0.13 failures per million cycles
Capacitor, Tant., Solid	0.0002%/1,000 hours	Magamp	0.0025%/1,000 hours	Spring Actuator	0.0525%/1,000 hours
Capacitor, Tantalum, Wet Slug	0.0008%/1,000 hours	Microswitch	0.100 failures per million cycles	Spring (Spiral Return Force) (heavy duty) (light duty) (cyclic)	0.0012%/1,000 hours 0.0001%/1,000 hours 1.05 failures per million cycles
Capacitor, Teflon	0.0001% per 1,000 hours	Mild Detonating Fuse (MDF)	30 failures per million firings		
Check Valve	0.1150% per 1,000 hours			Squib	5.0 failures/10^6 trials
Coil, R. F. Fixed	0.0053%/1,000 hours	Motor, Synchronous, Recorder	0.2500%/1,000 hours	Stepper Motor	0.0740%/1,000 hours
Coil, R. F. Variable	0.0080%/1,000 hours	Occultation Sensor	0.0076%/1,000 hours	Switch, Coaxial quiescent switch	0.025%/1,000 hours 0.250%/1,000 hours
		Orifice	0.0010%/1,000 hours		

Connector	0.0022 + 0.0003%/1,000 hrs per active pin	O-Rings	0.0042%/1,000 hours	Switch, Pressure	0.14 failures per million cycles per contact pair
Connector, Coaxial	0.0028%/1,000 hours per active pin	Pin Puller	0.01 failures/10^6 trials	Switch, R. F. quiescent / switch	0.020%/1,000 hours 0.200%/1,000 hours
Core, Magnetic	0.0001%/1,000 hours	Piston, Hydraulic	0.020%/1,000 hours	Tank-Bladder, Propellant	100 failures/million cycle
Crystal	0.0067%/1,000 hours	Potentiometer	0.0216%/1,000 hours	Thermistor	0.0060%/1,000 hours
Diode, General Purpose	0.0002%/1,000 hours	Pressure Tank	0.0029%/1,000 hours	Thermostat, Bimetallic	0.0300%/1,000 hours
Diode, Power	0.0018%/1,000 hours	Pressure Transducer	1.5050%/1,000 hours	Thrust Chamber	1 failure/10^6 cyc.
Diode, Switching (Computer)	0.0003%/1,000 hours	Reaction Jet	0.1470%/1,000 hours	Time Delay Pressure Switch	0.20 failures per million cycles per contact pair.
Diode, Zener (Low Pwr)	0.0021%/1,000 hours	Recorder, Tape, less motor	10.000%/1000 hours	Torque Motor Vane Actuator	0.7500%/1,000 hours
Diode, Zener (Med. Pwr)	0.0300%/1,000 hours	Regulator, Pressure	0.0500%/1,000 hours	Transformer, Power	0.0040%/1,000 hours
Diplexer	0.0500%/1,000 hours	Relay, General Purpose	0.05%/1,000 hours + 0.1%/1,000 hrs per contact pair per 10,000 actuations	Transformer, Pulse	0.0020%/1,000 hours
Explosive Valve	53.0 failures/10^6 trials	Relay, Magnetic Latching	0.05%/1,000 hours + 0.25%/1,000 hours per contact pair per 10,000 actuations	Transformer, Signal	0.0025%/1,000 hours
FET	0.0200%/1,000 hours	Relay, Reed	0.1 failures per 10^9 actuations	Transistor, Gen. Purpose	0.0006%/1,000 hours
Filter, Pressurant Propellant	0.0006%/1,000 hours	Relief Valve	0.1960%/1,000 hours	Transistor, Power	0.0049%/1,000 hours
Flex Pivot	0.0020%/1,000 hours	Resistor, Accurate, WW	0.0009%/1,000 hours	Transistor, Switching	0.0003%/1,000 hours
Freon Tank (Steady state) (Vibration state)	0.0001%/1,000 hours 200/10^6 cycles	Resistor, Carbon Comp.	0.0001%/1,000 hours	Traveling Wave Tube	1.1000%/1,000 hours
Fuse	0.0200%/1,000 hours	Resistor, Carbon Film	0.0018%/1,000 hours	Valve, Fill	0.0065%/1,000 hours
Gear	0.0002%/1,000 hours			Valve, Propellant	53 failures/10^6 cyc.

Table 3-7. Reliability Characteristics of Propulsion Subsystem (P) Components

COMPONENT REFERENCE NO.	COMPONENT DESCRIPTION	FAMILY	FAILURE RATE (%/1000 HRS UNLESS OTHER WISE NOTED)	STRESS NOTE
26002	Squib (Redundant Type)	PA, PC, PP	5 (c)	3
28001A1	Solid Engine Assembly-Less Nozzle	PM	900 (c)	3
28001A2	Solid Engine Assembly-Nozzle Only	PM	460 (c)	3
28001B	Hydraulic Pump and Reservoir	PQ	0.3675	2
28001C	Servo Injector Valve	PQ	29.5 (c)	3
28001D	Explosively Operated Valve - Normally Closed	PN, PP	53 (c)	3
28001E	Pressure Regulator	PP	0.0030	2
28001F	Freon and Tankage - Steady State	PQ	0.0001	2
28001F	Freon and Tankage - Vibration State	PQ	200 (c)	3
28001G	Burst Disk	PP, PQ	0.0070	2
28001H	Igniter Motor Assembly	PM	5 (c)	3
28001J	Nitrogen and Tankage	PN	0.0029	2
28001K	Explosively Operated Valve - Normally Open	PP	53 (c)	3
28002	Tapered Strut	PM	0.0000 (b)	N.A.
28003	Kick Ring	PM	0.0000 (b)	N.A.
28004	Tubular Strut	PM	0.0000 (b)	N.A.
28005	Kick Ring	PM	0.0000 (b)	N.A.
29001	Monopropellant Engine	PD	1.00 (c)	3
29002	Jet Vane Assembly	PD	3.3312	4
29003	Propellant Solenoid Valve (Quad)	PD	———	———
29003A	Propellant Solenoid Valve - Single	PD	0.65 (c) (f)	3
29003B	Solenoid Valve Driver	PD	0.0054	1
29004	Cavitating Venturi	PD	0.0000 (b)	N.A.
29005A	Burst - Disk, Premature Opening	PB, PC	0.0020	4
29005A	Burst - Disk, Fails to Open on Pressurization	PB, PC	0.0050	4
29005B	Relief Valve - Premature Opening	PB, PC	0.0570	4
29005B	Relief Valve - Not Opening on Pressurization	PB, PC	0.1418	4
29006	Two Position Explosive Valve	PB	79.5 (c)	3
29007	Filter	PA, PB, PC	0.0006	4
29007	Filter	PN, PP	0.0006	2
29008	Explosive Valve, Normally Closed	PA, PC, PD	53 (c)	3
29009	Explosive Valve, Normally Open	PA, PC	53 (c)	3
29010	Fill/Vent Valve	PN, PP, PA, PB, PC	0.0000 (b)	N.A.
29011	Pressure Switch	PB	0.14 (e)	4
29012	Pressure Regulator - Overpressurization	PB	0.1200	4
29012	Pressure Regulator - Underpressurization	PB	0.1200	4
29013	Pressure Transducer	PA, PC, PD (a)	0.0100	N.A.
29014	Lines, Trays, and Brackets	PA, PB	0.0000 (b)	N.A.
29015	Support Structure	PB	0.0000 (b)	N.A.
29016	Propellant Tank	PC	0.0016	4
29017	Bladder	PC	0.0013	4
29018	Pressurant Gas	PA	0.0000 (b)	N.A.
29019	Gas Tank	PA	0.0029	4
29020	Propellant Tank Support	PC	0.0000 (b)	N.A.
29021	Tank Support Tubes	PC	0.0000 (b)	N.A.
29022	Mounting Frames	PC, PD	0.0000 (b)	N.A.
29023 (d)	Monopropellant	PC	0.0000 (b)	N.A.

a) Nct required for operating success
b) Disregarded in computations because of low failure rate
c) Failures per million cycles or trials
d) Also identified as 30001
e) Failures per million cycles per contact pair
f) Considering all failure modes

3.4.3.3 Application of Stress Factors

In order to include environmental effects during the mission, an approximate approach was taken, viz., the failure rate of each of the components of hardware was multiplied by one of four stress factors:

a. Multiply the tabulated failure rate by 10 during launch motor and orbit injection motor burns, and multiply by unity during other time intervals.

b. Multiply the tabulated failure rate by 80 during launch motor and orbit injection motor burns, and multiply by unity during other time intervals.

c. Multiply the tabulated failure rate by unity at all times.

d. Multiply the tabulated failure rate by 80 during all motor burns, including midcourse burns, and multiply by unity during other time intervals.

In general, stress factor (a) was applicable to electronic components with Poisson reliability characteristics; stress factor (b) to mechanical components (except liquid engine components) with Poisson reliability characteristics; stress factor (c) to pyrotechnic components, cyclic devices, and one-shot devices; and stress factor (d) to liquid engine mechanical components with Poisson reliability characteristics.

3.5 HARDWARE FAILURE MODES AND MISSION EFFECTS

3.5.1 CONCEPT

The concept of independent assemblies was developed to accommodate the complex hardware failure modes-mission outcome correlation. It provides a systematic means of organizing single-string and potentially redundant hardware alternatives into intermediate level assemblies with common performance states which have a direct relationship on the success or failure of the mission subphases.

The hardware failure modes and mission effect analysis thus becomes a two step process. First, the failure modes of hardware elements which comprise each independent assembly are each correlated to the performance states defined for that family of independent assemblies. This correlation results in what are called the math models of the independent assemblies. The component failure characteristics discussed in Section 3.4 then provide the quantitative base used by the models to determine the probability of the independent assembly performance states. Such a model is constructed for each independent assembly.

The second step of the process relates the performance states of each independent assembly family to the mission outcome tree via the medium of a map matrix. This matrix indicates the independent assembly family performance states which are necessary to achieve each mission subphase. Since the probabilities of the performance states of any set of independent assemblies can be determined from their math models, the map matrix provides the logic to compute the probability of any subphase of the mission outcome tree. Thus, the correlation of hardware failure modes to mission outcomes is complete.

3.5.2 MATH MODELS

3.5.2.1 Process

Part of the definition of any independent assembly includes a description of the output states of interest of that particular independent assembly. The most common case is that of the two state independent assembly; i.e., a good and a failed output state of interest. Other independent assemblies have three output states of interest: good, degraded, and failed. Still other independent assemblies have more than three output states of interest denoted good, degraded state 1, degraded state 2, etc., and failed. Recall that all of the independent assemblies in one family have the same output states.

To illustrate independent assembly states, consider one of the guidance and control families, family GB, the Gyros and Electronics family. This family contains four independent assemblies, all of which have the same three output states, defined as follows:

a. Good - Gyro package operates in both position and rate mode about all axes.

b. Degraded - Gyro package operates in rate mode about all axes, but fails to operate in position mode about one or more axes.

c. Failed - All others.

For each of these independent assemblies, it is necessary to arrive at the probability that the independent assembly will be in one of its defined output states at various times throughout the mission. To accomplish this, a math model is developed to relate the operating states of the various hardware elements which make up that independent assembly to the output states defined for that independent assembly family. For each of the 166 independent assemblies, a different math model must be formulated. From a given model, the probabilities of that independent assembly being in one of its defined output states at any time in the mission may be calculated. As would be expected, similarities exist between the math models for independent assemblies belonging to the same family.

Formulation of the math model for any independent assembly generally involves the following steps:

a. A reliability block diagram is drawn to indicate which components within the independent assembly are required for the defined operating states. For the single-string independent assembly of a family, the reliability block diagram is usually a series string of all components which make up the independent assembly.

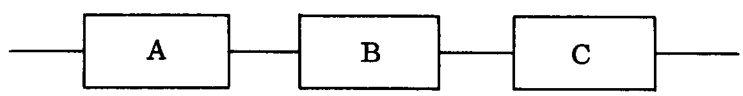
b. An operating time profile is developed for each component within the independent assembly to define its operating time history throughout the mission. For cyclic or one-shot devices, the appropriate number of operating cycles are defined.

c. Failure characteristics, the development of which has been discussed previously, are assigned to the various components which make up the independent assembly.

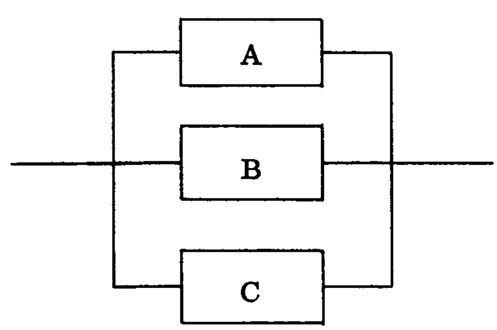
d. Items a, b, and c are converted to a state diagram for input to a computerized probability calculator.

3.5.2.2 Reliability Block Diagrams

For each of the 166 independent assemblies, reliability relationships are defined by drawing reliability block diagrams. Blocks on such diagrams are analogous to links of a chain. For example, in the following serial relationship,



components A, B, and C must all be working successfully for the assembly to be working successfully. In the following parallel (or block redundancy) relationship,



component A or B or C alone working successfully is sufficient for the assembly to be working successfully.

It should be noted on a reliability block diagram that the order of placing blocks in the chain has no significance. Also, explanations are required in a reliability block diagram if the relationships are more complicated than the foregoing parallel relationships.

Figure 3-5 contains actual reliability block diagrams of independent assemblies CFA and CFB, both of which are in family CF (Capsule Separation Register) of the computer and sequencer subsystem. CFA is the single-string candidate for this family, and CFB is a redundant alternative.

3.5.2.3 Operating Time Profiles

For each component in the reliability block diagram, an operating time profile is developed. The profile is segmented by mission subphases corresponding to those of the mission outcome tree. For each subphase the time profile further indicates whether the components are planned to be energized for the entire subphase or just a portion thereof, or are operated for a specific number of cycles during the subphase.

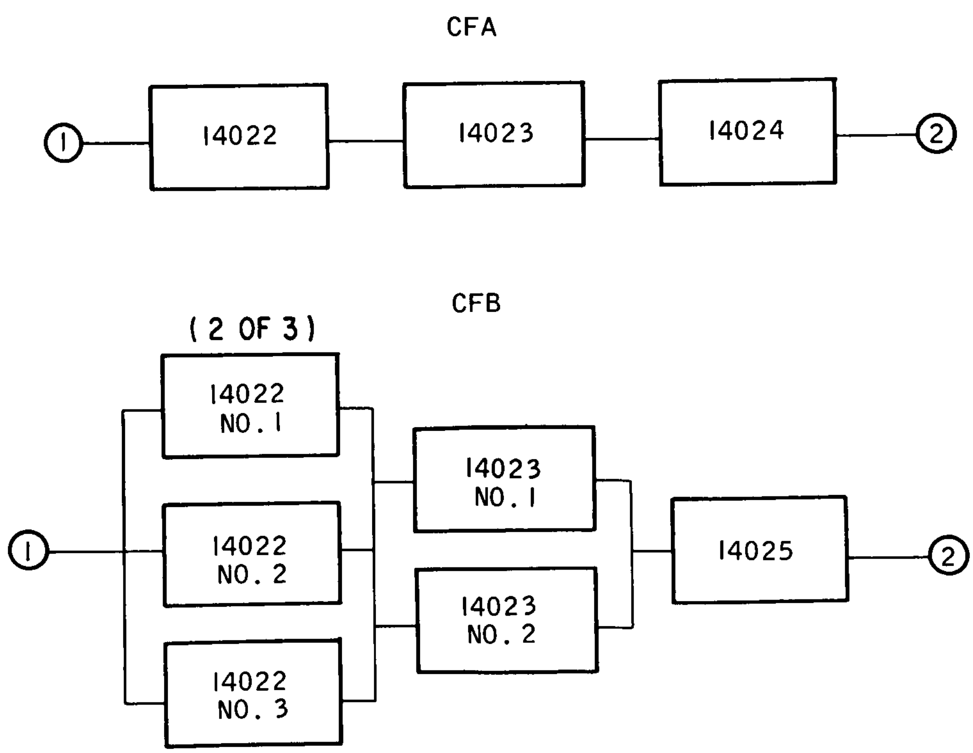


Figure 3-5. Typical Reliability Block Diagram, Family CF (Capsule Separation Register)

3.5.2.4 Failure Rate Assignments

Each of the components used in a particular independent assembly are thus identified as a block in a reliability block diagram and a line entry in the operating time profile. The reliability characteristics for each component, consisting of nonstressed failure rates and appropriate stress factors, are then determined from the failure data base. These rates, applied in accordance with the operating time profile, provide the quantitative data for the independent assembly math models.

3.5.2.5 State Diagrams

Using the reliability block diagrams and operating time profiles previously described, state diagrams are next developed for each of the independent assemblies. State diagrams depict all possible internal operating states of a particular independent assembly and define the allowable transitions from one state to another. Output states of interest are a subset of all possible internal states of each independent assembly.

Figure 3-6 is the state diagram for independent assembly CFB, for which the reliability block diagram is illustrated in Figure 3-5. In this example, there are six internal operating states of the independent assembly, indicated by the numbers in circles. Externally, family CF has two operating states (failed and good). The failed state is identically internal state (6). All other internal states represent good output states.

State (1) represents the initial state of this independent assembly at launch. The transition from state (1) to state (6), for example (denoted by the symbol λ_5), indicates the failure of component 14025 which is denoted by the symbol λ_{14025}. The transition from state (1) to state (2), denoted by the symbol λ_1, indicates failure of any one of the three majority voting components 14022 (where two out of three must work successfully). Thus, the λ_1 transition rate is equal to $3\lambda_{14022}$.

Similarly, the transition from state (2) to state (6), denoted by λ_4, indicates failure of component 14025 or one of the two remaining components 14022 (after one of the three has failed). Thus, $\lambda_4 = 2\lambda_{14022} + \lambda_{14025}$.

$\lambda_1 = 3\lambda_{14022} = 0.0729$

$\lambda_2 = 2\lambda_{14023} = 0.0012$

$\lambda_3 = 2\lambda_{14022} + \lambda_{14023} + \lambda_{14025} = 0.0512$

$\lambda_4 = 2\lambda_{14022} + \lambda_{14025} = 0.0511$

$\lambda_5 = \lambda_{14025} = 0.0025$

$\lambda_6 = \lambda_{14023} + \lambda_{14025} = 0.0031$

λ' IN % PER THOUSAND HOURS

$P_F = P(6)$

$P_F = 1 - P(6)$

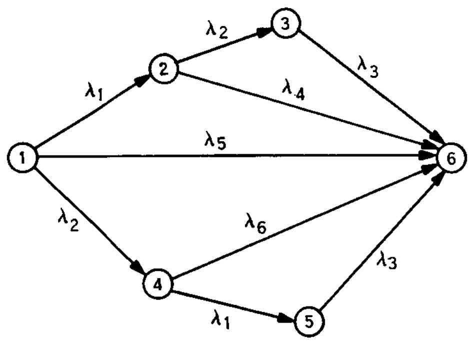


Figure 3-6. Typical State Diagram Family (Capsule Separation Register Independent Assembly CFB)

Transistion rates are, in general, identical to component failure rates, properly stressed.

3.5.2.6 Logic Expressions

As an adjunct to state diagrams, it is often necessary to develop logic expressions to simplify a state diagram or to accommodate one-shot items (e.g., pyrotechnics) and cyclic devices of low frequency (e.g., liquid thrusters).

In the telecommunications families, for example, abundant logic expressions are required because of the complexity of the reliability relationships. In the propulsion families, logic expressions are required because of the large number of one-shot and low frequency cyclic devices.

As an illustration of the use of logic expressions, consider again independent assembly CFB, for which the state diagram is given in Figure 3-6. Figure 3-7 illustrates a breakdown of the math model into three separate state diagrams, one for the 14022 components, one for the 14023 components, and one for the 14025 component. At the bottom of the figure are logic expressions for their combination. In this example, a comparison between Figure 3-6 and Figure 3-7 does not suggest that the logic expression method is simpler. However, when the total number of components exceeds about 10, the logic expression method is found, in general, to be preferred.

3.5.3 MAP MATRIX

A map matrix is used to relate the operating states of the families which comprise the spacecraft to the mission outcome tree. The map provides the logic to describe what spacecraft hardware operating states are required to perform each spacecraft function in each mission subphase. Thus, given the probabilities for the hardware states throughout the mission, the probabilities of the various mission outcomes can be established.

A partial map matrix is shown in Figure 3-8. The rows of the matrix correspond to the output states of the families which make up the spacecraft; the columns of the matrix refer to the subphases of the mission outcome tree. The column subdivision in each subphase indicates the manner in which that subphase is performed. For example, the "Orbit Insertion" subphase could be performed such that the result is good (nominal orbit), degraded (non-nominal orbit), or failed (planetary orbit not achieved). The symbols at the cross points of the matrix, defined at the foot of the figure, relate the outcomes to the hardware states.

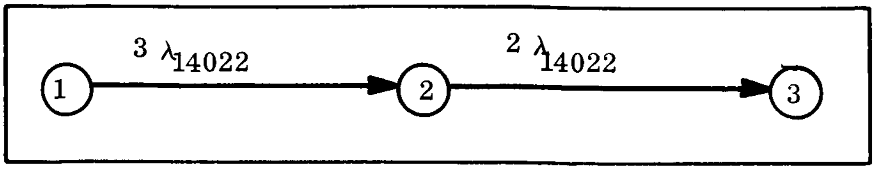
For example, consider function 4.1 (Orbit Insertion). In order to complete this function in the good state, the independent assemblies of families 1 through 4 must be in the good state, and 5 must be in either the good or degraded state, and 6 must be in the good or first degraded state. This may be interpreted in terms of a logic statement as follows:

$$4.1G = 1G \cap 2G \cap 3G \cap 4G\ (5G \cup 5D1) \cap (6G \cup 6D1).$$

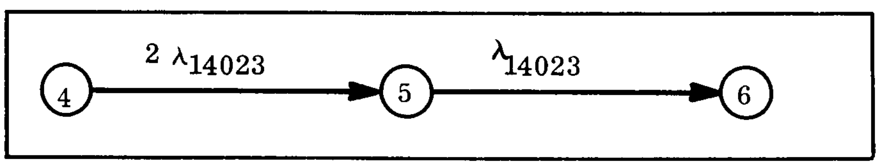
FAMILY : CAPSULE SEPARATION REGISTER

INDEPENDENT ASSEMBLY : CFB

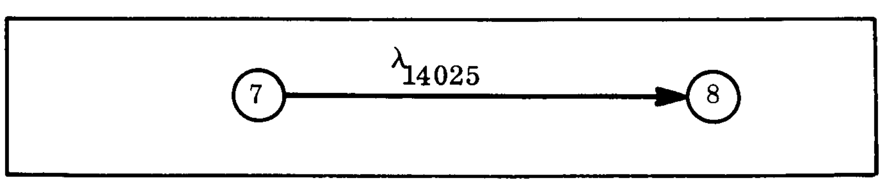
State Diagram for Component 14022



State Diagram for Component 14023



State Diagram for Component 14025



Logic Expressions

$P_F = P(3) \cup P(6) \cup P(8)$ $\qquad$ $P_G = 1 - P_F$

Figure 3-7. Combination of State Diagrams by Logic Expressions

Similarly, this can be written as an arithmetic equation involving the probabilities of these events to arrive at the probability of completing 4.1 satisfactorily:

$$P_{4.1G} = (P_{1G})\ (P_{2G})\ (P_{3G})\ (P_{4G})\ (1-P_{5F})\ (1-P_{6D2} - P_{6F}).$$

The use of this type of matrix to represent the logical relationships between family output states and mission functions may, at first, appear cumbersome. To the contrary, however, this matrix was used so that the arithmetic equations describing the probabilities of completing these mission-oriented functions could be formulated within the computer. Thus, changes in the matrix, being data inputs to the program system, can be readily accommodated in the computer.

Note that the Subphase 4.2 (Orbit Operations) of Figure 3-8 requires families one and two to be good, family six to be good or first degraded, and either family four or family five to be good. Families four and five represent an example of functional redundancy between two different independent assemblies during this subphase.

Figure 3-8 is a simplification of the actual map matrix used for the Voyager mission, which is shown in Figure 3-9. Several additional map symbols have been added to accommodate the logic among various independent assembly family output states, but the basic concept and use of the map matrix is the same. Note that each major mission phase begins with the specification of the independent assembly family states required to obtain and transmit data for that mission phase. These specifications apply throughout all mission subphases within that mission phase and describe the hardware performance necessary for the quality states of the mission outcome tree, as discussed in Section 3.3.

INDEPENDENT ASSEMBLY FAMILY	STATE	ORBIT INSERTION 4.1			ORBIT OPERATIONS 4.2		ORBIT TRIM NO. 1 4.3		ORBIT OPERATIONS 4.4	
		G	D	F	G	F	G	F	G	F
1	G	●	●		●		●		●	
	F			⬢						
2	G	●	●		●		●		●	
	F			⬢						
3	G	●								
	D		●							
	F			⬢						
4	G	●	●		Ⓐ		Ⓐ		Ⓐ	
	F			⬢						
5	G	Ⓐ	Ⓐ		Ⓐ		Ⓐ		Ⓐ	
	D	Ⓐ	Ⓐ							
	F			⬢						
6	G	Ⓑ	Ⓑ		Ⓑ		Ⓑ		Ⓑ	
	D1	Ⓑ	Ⓑ		Ⓑ		Ⓑ		Ⓑ	
	D2			⬢						
	F			⬢						
7	G						●			
	F									
8	G						●			
	F									

KEY:

● ALL FAMILY OUTPUT STATES ARE NECESSARY FOR THE GIVEN MISSION STATE.

○ ANY ONE OR MORE FAMILY OUTPUT STATES ARE NECESSARY FOR THE GIVEN MISSION STATE.

⬢ ANY FAMILY OUTPUT STATE IS A SUFFICIENT CONDITION FOR THE GIVEN MISSION STATE.

Figure 3-8. Partial Map Matrix

FAMILY OUTPUT STATE NO.	NAME OF FAMILY	FAM REF NO.	OUTPUT STATE	LAUNCH & INJECTION — OBT& XMT DATA 6.4 (G F)	1 ACN PKG ORBIT 6.1 (G F)	2 ACN IPTI 6.2 (G D F)	3 SEP PIV S * 6.3 (1/2 0/2)	TRANSIT — OBT&XMT DATA 5.7 (G D1 D2 F)	4 ACQ CEL REF 5.1 (G F)	5 IP CRU 5.2 (G F)	6 IPTC NO. 1 5.3 (G F)	7 IP CRU 5.2 (G F)	8 IPTC NO. 2 5.4 (G F)	9 IP CRU 5.2 (G F)	10 IPTC NO. 3 5.5 (G F)	11 IP CRU 5.2 (G F)	12 SEP STER CAN 5.6 (G F)	13 IP CUR 5.2 (G K)	ORBIT ACHIEVEMENT — OBT&XMT DATA 4.4 (G D1 D2 F)	14 ORBIT INSERT 4.1 (G D1 F)	15 ORB OPS 4.2 (G F)	16 ORB TRIM NO. 1 4.1 (G F)	17 ORB OPS 4.2 (G F)	18 ORB TRIM NO. 2 4.9 (G F)	19 ORB OPS 4.2 (G F)	ORBIT DESCENT & ENTRY — OBT&XMT DATA 3.9 (G D1 D2 F)	20 SEP CAP 3.1 (G F)	21 SUPT CODE 3.2 (G F)	22 RETN ORBIT OPS 3.3 (G F)	ORBITER OPERATIONS — OBT&XMT DATA 2.4 (G D1 D2 D3 F)	25 ORBIT OPS 2.1 (G F)	26 180° ROLL 2.3 (G F)	27 ORBIT OPS 2.1 (G F)
1	BODY MOUNTED SCIENCE	SC	G					●●											●●											●			
2			F																														
3	PSP SCIENCE	SO	G																●●											● ① ①			
4			DI																											① ①			
5			D2																											①			
6			F																														
7	SCIENCE ELECTRONICS	SE	G					●●											●●											●●●			
8			F																														
9	DATA AUTOMATION EQUIPMENT	SF	G					●●											●●											●●●			
10			F																														
11	S/C RADIO RELAY EQUIPMENT	SG	G																							●●							
12			F																														
13	PRESSURANT STORAGE ASSY	PA	G								●		●		●							●		●									
14			F																														
15	PRESSURANT REGULATION ASSY	PB	G								●		●		●							●		●									
16			F																														
17	PROPELLANT STORAGE ASSY	PC	G								●		●		●							●		●									
18			F																														
19	THRUST CHAMBER ASSY	PD	G								①		①		①							①		①									
20			DI								①		①		①							①		①									
21			F																														
22	SOLID ENGINE ASSY	PM	G																	●													
23			DI																	●													
24			F																	●													
25	TVC PRESSURANT STORE ASSY	PN	G																	●●													
26			F																	●													
27	TVC PRESSURANT REGUL ASSY	PP	G																	●●													
28			F																	●													
29	TVC SUBASSEMBLY	PQ	G																	●●													
30			F																	●													
31	A/C SENSORS + ELECTRONICS	GA	G						●	●	●	●	●	●	●	●	●	●		●●	●	●	●	●	●		●	●	●		●	●	●
32			F																	●													
33	GYROS AND ELECTRONICS	GB	G						①		●		●		●					●●	●	●	●	●	●		●	●	①		●	●	●
34			DI						①											●									①				
35			F																	●													
36	PNEUMATICS SUBASSEMBLY	GD	G						●	●	●	●	●	●	●	●	●	●		●●	●	●	●	●	●		●	●	●		●	●	●
37			F																	●													
38	A/C ELECT POWER SUPPLY	GE	G						●	●	●	●	●	●	●	●	●	●		●●	●	●	●	●	●		●	●	●		●	●	●
39			F																	●													
40	AUTOPILOT ELECTRONICS	GF	G								●		●		●					●●		●		●									
41			F																	●													
42	LOGIC CONTROL UNIT	GG	G						●	●	●	●	●	●	●	●	●	●		●●	●	●	●	●	●		●	●	●		●	●	●
43			F																	●													
44	GYRO PACKAGE POWER SUPPLY	GH	G						●		●		●		●					●●	●	●	●	●	●		●	●	●		●	●	●
45			F																	●													
46	MASTER SEQUENCER	CA	G						△	△		△		△		△	△	△		●●	△		△		△			△	△		△	△	△
47			F																	●													
48	ENABLE SWITCH	CD	G						●																								
49			F																														
50	GIMBAL SEQUENCER—PSP	CE	G																●●											●●			
51			F																														
52	CAPSULE SEP REGISTER	CF	G																								●						
53			F																														
54	SOLID IGNITION REGISTER	CG	G																	●●													
55			F																	●													
56	LIQUID ON/OFF REGISTERS	CH	G								●		●		●							●		●									
57			F																														
58	MANEUVER REGISTERS	CJ	G								●		●		●					●●		●		●			●					●	
59			F																	●													
60	PSP SCI CONTROL	CK	G																●●											●●●			
61			F																														
62	TELEM REGISTERS	CL	G																														
63			K																														
64	POWER CONVERSION	CM	G						●	△	●	△	●	△	●	△	△	△	■■	●●	△	●	△	●	△		●	△	△	■■■	△	●	△
65			F																	●													

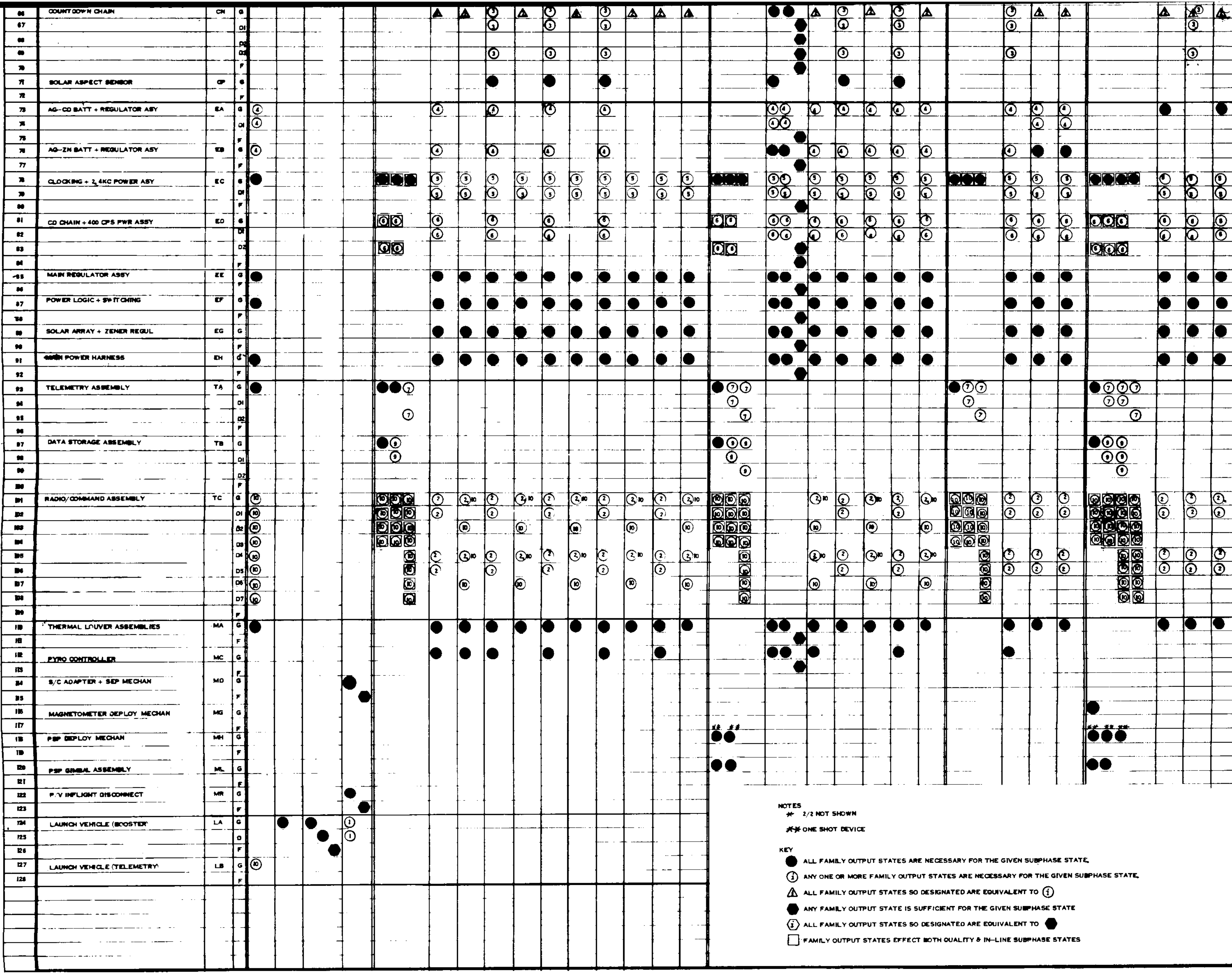


Figure 3-9. Voyager Map Matrix

3.6 OPTIMIZATION SYSTEM

This section describes the computer program system developed to evaluate and optimize the configuration of the Voyager spacecraft.

3.6.1 PURPOSE OF THE PROGRAM SYSTEM

Preceding sections discuss in detail the first three steps in the orderly procedure of designing the spacecraft to optimize the mission worth:

a. Definition of the mission profile and the spacecraft system, including potential redundancy.

b. Definition of mission outcomes, and assignment of relative value or worth to each outcome.

c. Analysis of the system failure modes, and relating system performance to mission outcomes.

The final step in the optimization procedure is the use of a computer program system which uses the results of the first three steps to determine that set of system configurations which provide the maximum mission expected worth over the range of a cost constraint. Cost in this context refers to the penalty associated with the use of each piece of system hardware and can be measured in either pounds, dollars, watts, or cubic feet. Weight is the primary cost constraint applied thus far, although power, volume, and dollar cost may also be used.

Unlike the conventional approach to system design (maximizing system reliability without considering the mission tradeoffs), the four step approach leads to the maximization of the expected worth of the mission; that is, optimizing the probabilities of reaching valuable mission outcomes. The computer program system utilizes a variation of dynamic programming to select the configurations that yield the highest mission expected worth from all configurations of comparable cost.

The output of the program system is a listing of preferred system configurations ordered by increasing system cost (e.g., weight) and mission expected worth. With this output listing, the system engineer is able to determine the optimally redundant system configuration at any total system cost to which he is constrained.

The computerized optimization approach which follows can be adapted to other complex systems where the large number of alternate system configurations makes a manual approach unmanageable. Detailed documentation of the total programming system is contained in a separate document, "System Specification for Voyager Spacecraft Redundancy Optimization Program."

3.6.2 PROGRAM SYSTEM ORGANIZATION

The redundancy optimization program system consists of four interacting computer programs which process information describing the mission and system to select the optimum spacecraft system configurations for given constraints. Before proceeding, it will be helpful to review certain terms which have been introduced in preceding paragraphs and are used repeatedly in the following pages.

A system is considered to consist of "families" of "independent assemblies." An independent assembly family is a portion of the system (i.e., a functional grouping of hardware) which can, in general, perform its assigned functions independently of the rest of the system. The Voyager spacecraft consists of 51 such families of independent assemblies. The functions of each family can be performed by one or more different groupings of hardware (i.e., one or more independent assemblies). Thus we have a family of independent assemblies.

One independent assembly associated with each family is called the single-string independent assembly. It is void of any intentional redundancy. The other independent assemblies comprising the family contain some degree of redundancy above the single-string member. The Voyager spacecraft consists of 51 different families of 166 such independent assemblies, or an average of two alternate assemblies in addition to the single-string independent assembly for each family. Approximately 10^{21} different system configurations can be obtained using these 166 independent assemblies.

The Voyager mission is postulated to consist of seven phases: (1) prelaunch operations, (2) launch and injection, (3) transit, (4) orbit achievement, (5) orbit descent and entry, (6) orbiter operations, and (7) landed operations. These are further subdivided into subphases, which are spacecraft operating modes as they occur in normal trajectory sequence. Examples of subphases are cruise, midcourse corrections, and orbit trims. There are 27 subphases in the Voyager mission.

An independent assembly can be further categorized according to the type of function it performs. In-line functions are associated with trajectory functions and other objectives which occur in the flight sequence of events. Quality functions are associated with collecting and transmitting data during the mission.

The four computer programs in the optimization system are:

a. Probability Calculator Driver Program (SIPDRV) - This program segregates each independent assembly into its proper category and determines the type of probability information which must be calculated for each.

b. Probability Calculator Subroutine (SIP- State Interpretive Program) - As a subroutine of the driver program, SIP calculates the probabilities of independent assemblies being in given performance states during given subphases of the mission.

c. Mission Expected Worth Calculator (MEW Calculator) - As a subroutine of the Optimization Program (OPT), MEW calculates the mission expected worth of system configurations designated by the optimization routine.

d. Optimization Program (OPT) - OPT employs a variation of Bellman's process of dynamic programming to identify the set of system configurations with dominant mission expected worth over the range of the cost constraint under consideration.

The relationship between these programs, the functions of each, and the data inputs to each are shown in Figure 3-10.

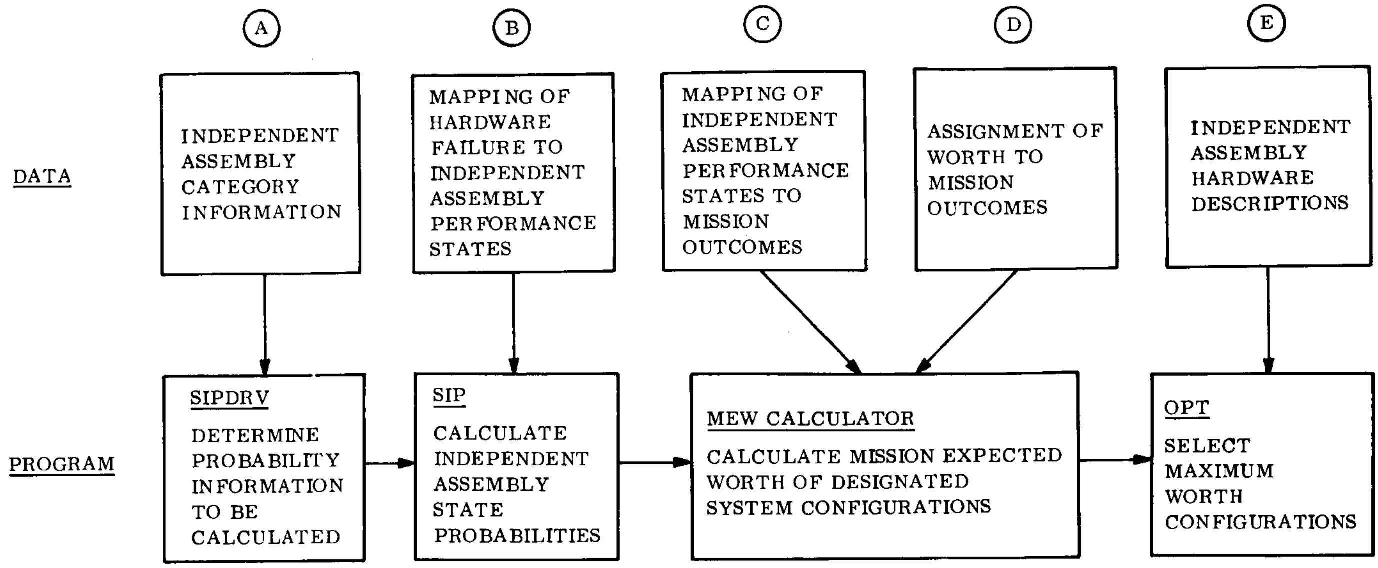


Figure 3-10. Optimization Program System Flow

The data input to each of the four programs is obtained from the following sources:

a. Independent Assembly Category Information - Identification of each independent assembly as belonging to one of five categories:

1. In-line independent assemblies* with fixed probabilities.

2. In-line independent assemblies with two output states.

3. In-line independent assemblies with more than two output states.

4. Quality-only independent assemblies for which probabilities must be calculated.

5. Quality-only independent assemblies with fixed probabilities.

* That is, independent assemblies which contribute to the performance of in-line functions on the mission outcome tree, as contrasted to those which contribute only to quality function.

b. Mapping of Hardware Failure Modes to Independent Assembly Performance States - The failure modes of the components within each independent assembly are related to the output states of the independent assembly. The data of interest to the computer system consists of state transition diagrams, which represent the possible states of equipment within the independent assemblies and the transition rates between these states, and logic expressions of the combination of internal independent assembly states which result in independent assembly output states.

c. Mapping of Independent Assembly Performance States to Mission Outcomes - The map matrix, which describes which combinations of the independent assembly output states result in performance of the various mission subphases.

d. Assignment of Worth to Mission Outcomes - The mission outcome tree structure is based on the performance of the 27 in-line, first level functions (subphases) of the mission profile. The terminal nodes on the tree define a set of exhaustive and mutually exclusive mission outcomes. Assigned to each branch of the tree is a worth, a subjective measure of the value associated with successfully accomplishing each first level function. The worth of a particular outcome is the sum of the worths of the branches traversed to reach that outcome.

e. Independent Assembly Hardware Description - The name, weight, volume, power and dollar cost of each independent assembly.

3.6.3 SYSTEM FUNCTION

The system functions essentially as two separate program pairs, because the extensive memory requirements, approximately 100K of core storage for each pair, can be met with few computers. The first pair are the Probability Calculator Driver (SIPDRV) and the Probability Calculator (SIP). The second pair are the Optimization Program (OPT) and MEW subroutine (MEW). Communication between the two pairs, which are run in sequence, is by a magnetic tape which contains the appropriate cumulative and conditional probability data generated by SIP and SIPDRV. The data is used by the MEW subroutine to calculate the mission expected worth of candidate configurations being evaluated by OPT.

For the first step, SIPDRV identifies the category into which each independent assembly falls and thereby the type of probability data required to describe the performance of each. SIPDRV then transfers to SIP the directions for obtaining the initial independent assembly output state probabilities. SIP then transforms the state transition diagrams into a set of simultaneous linear differential equations. The initial probabilities are represented by initial conditions applied to the differential equations. SIP then solves the equations using a classical fourth order Runge-Kutta algorithm and combines the solutions to obtain the probabilities of an independent assembly being in each of its output performance states during each mission subphase. Finally, the probabilities are stored on tape.

The OPT program selects a candidate system configuration and calls upon the MEW subroutine to compute the expected worth of the configuration. This is accomplished by multiplying the worth of each possible mission outcome by its probability of occurrence as determined by the probability of the independent assembly states and the mapping of the independent assembly states to the mission outcome tree. OPT then compares the MEW values of configurations of comparable cost and employs a dynamic programming type of sorting technique to extract and save the configurations with the highest MEW for given increments of cost. After all of the optimum configurations have been extracted, a listing of the configurations is printed.

3.6.4 OPTIMIZATION PROGRAM

The optimization process is performed by the Optimization Routine (OPT) which calls the Mission Expected Worth Calculator (MEW) subroutine to compute the worth of certain system configurations designated by the optimization routine. This subsection and the next describes both the routine and subroutine in terms of the purpose of each, their relationship to other programs in the program system, the conceptual approach employed by each, and the methods used by each.

3.6.4.1 Purpose

The Optimization Program provides a computerized technique capable of optimizing the redundant hardware configuration for the Voyager spacecraft system. It considers, in effect, a possible redundant configurations and selects those with highest mission expected worth as a function of cost. The program generates a preferred list of independent assembly configurations ordered by increasing cost constraint (weight, cost in dollars, volume, or power consumption) and the associated mission expected worth (MEW) for each configuration. In addition, a listing of configuration sensitivity coefficients is provided to show how incremental changes in configuration constraint result in incremental changes in MEW. This configuration and sensitivity information can serve as a significant aid to the system designer in selecting the most appropriate spacecraft redundancy configurations.

Since the selection of system redundancy among 51 families and a total of 166 independent assemblies leads to nearly 10^{21} possible system configurations, the Optimization Routine utilizes a variation of Bellman's dynamic programming to identify the preferred list of configurations.

3.6.4.2 Conceptual Approach

The approach to the problem of determining optimum configurations of independent assemblies for various cost allocations is based on a variation of dynamic programming. Several useful parameters are defined to implement the optimization process:

a. δ_o MEW - The increase in mission expected worth (MEW) gained by using an alternate assembly in place of the reference assembly* (the one with the lowest cost), when the reference assembly is used in all other families.

b. ΔMEW - The increase in MEW gained by using an alternate assembly in a particular family in place of the reference assembly, when all other families contain the assembly used in the MEW_{max} configuration. The MEW_{max} configuration is comprised of the alternate in each family having the largest δ_o MEW.

c. δ_oMEW/ΔW - In this ratio δ_o MEW is the parameter defined in (a) and ΔW is the increase in cost resulting from the use of this alternate.

The sorting approach considers each family of independent assemblies one at a time, takes each independent assembly within the family and forms all possible configurations with all configurations saved in the previous stages of the sorting, then extracts a new set of dominant configurations for use in the next state of the process. As shown in Figure 3-11, dynamic programming extracts from all the system configurations under consideration those which provide the highest MEW versus cost. The configurations saved are called the dominant configurations, as contrasted with the inferior or dominated configurations

* The reference independent assembly is usually the single-string independent assembly

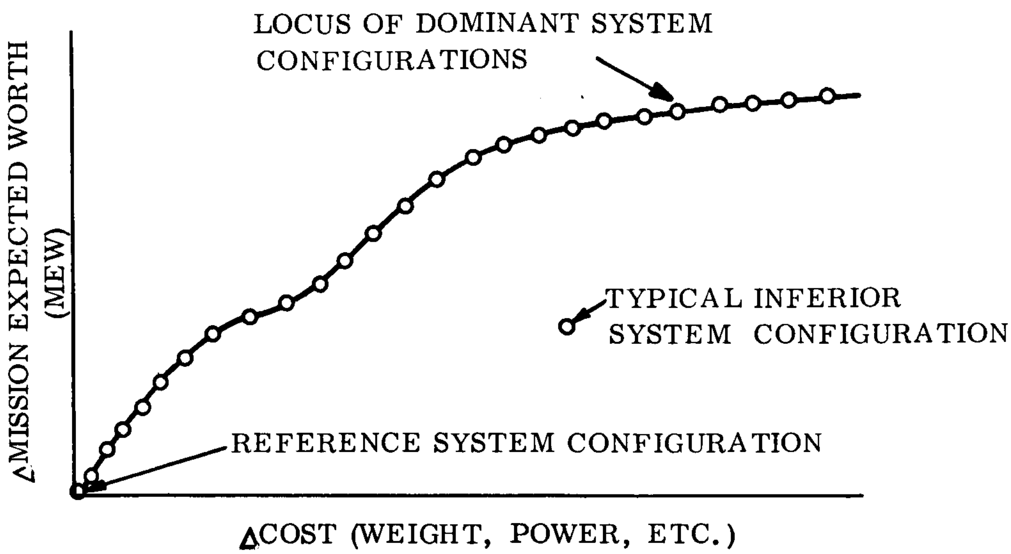


Figure 3-11. Goal of the Optimization Process

which provide lower MEW at comparable cost. The system designer can thus obtain a listing of the optimal configurations available for each cost he wishes to consider.

To ensure that the computer running time of the optimization process stays within reasonable bounds, several discarding criteria are available. The decision to use these involves a tradeoff between program running time and resolution between adjacent dominant configurations.

One of the criteria consists of zoning or gridding the cost scale into m segments. Only the configuration which provides the highest MEW within that segment is retained in the staging process. With this approach, it is not possible to guarantee that the ultimate optimal configuration for each cost range will be obtained. However, by taking a large m, the probability of selecting the optimal configuration improves at the expense of increased computer running time.

A second discard criterion consists of considering only those independent assemblies for which the increase in MEW for a given increase in cost (ΔMEW/ΔW) exceeds a prescribed value ϵ. As in the first option, an increase in ϵ to reduce running time increases the risk of discarding optimal configurations.

A third option results in discarding a configuration if another exists with higher MEW at a lower or identical cost. Called the "below-and-to-the-right" option, it results in ultimate resolution between adjacent configurations on the MEW-cost plot.

3.6.4.3 General Operations

The sorting technique begins by forming the reference configuration of the system (i.e., the lowest cost configuration) which is said to contain the "reference" independent assemblies. In the Voyager system definition, the reference configuration is identically the single-string system configuration. A single family is selected in which the reference independent assembly is replaced with each alternate independent assembly, one at a time. If, for example, four redundant alternate assemblies are contained in the first family, the resulting MEW-cost plot after the first pass could appear as in Figure 3-12.

In Figure 3-12, configurations 2 and 4 are eliminated if the "below-and-to-the-right" option is used, because they provide lower MEW at higher cost than 1 and 3, respectively. Thus, the reference configuration and configurations 1 and 3 will be retained as dominant configurations. If the gridding option is used and, for example, all five configurations fall in the first grid segment, then only the reference configuration and configuration 3 are saved.

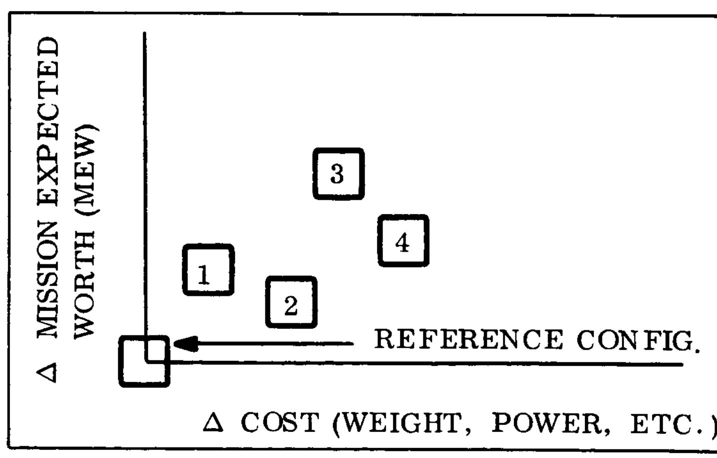


Figure 3-12. Configurations Retained After the First Stage

In the next stage of the sorting process, a second family is selected and its reference independent assembly replaced with each of the redundant alternates, one at a time, in all configurations retained after the previous stage. A new set of system configurations is derived using the dominant configurations from the last stage and the reference configuration as the building blocks. Discarding occurs again and a new set of dominant configurations is saved for the next stage. This cycle repeats until all independent assemblies in all families have been considered.

3.6.4.4 Program Flow

A step-by-step description of the operation of the optimization program follows. The steps correspond to the blocks of the flow chart (Figure 3-13):

a. Read into computer memory the following data:

   1. Identification and cost requirements for each independent assembly (single-string and redundant alternate).

   2. Identification of type of cost being analyzed (denoted by W).

   3. Resource constraint (W_{const}).

   4. Keep factor for $\Delta MEW/\Delta W$ (denoted by ϵ).

   5. Number of segments (m) between W_o and W_{const} (W_o is the cost of the reference configuration).

   6. Option switch to select the lower-and-to-the-right criterion.

   7. Option switch to inhibit the gridding.

b. Evaluate and print $MEW_{s/s}$ (single-string) and $W_{s/s}$ (cost of single-string configuration).

c. Form the reference configuration from the independent assemblies of lowest cost in each family. Evaluate MEW for this configuration, and call this MEW_o.

d. Calculate $\delta_o MEW_{ij}$ for each redundant alternate independent assembly, where i is the index of an alternate within that family, and $\delta_o MEW_{ij}$ is the magnitude of the difference between MEW_o and the value of MEW when the jth independent assembly is included in the configuration for the ith family and all other families contain the independent assembly used in the reference configuration.

   1. For each family of assemblies choose the independent assembly that gives the largest $\delta_o MEW_{ij}$. Form the configuration consisting of these selected assemblies and calculate MEW for this configuration. Denote this value

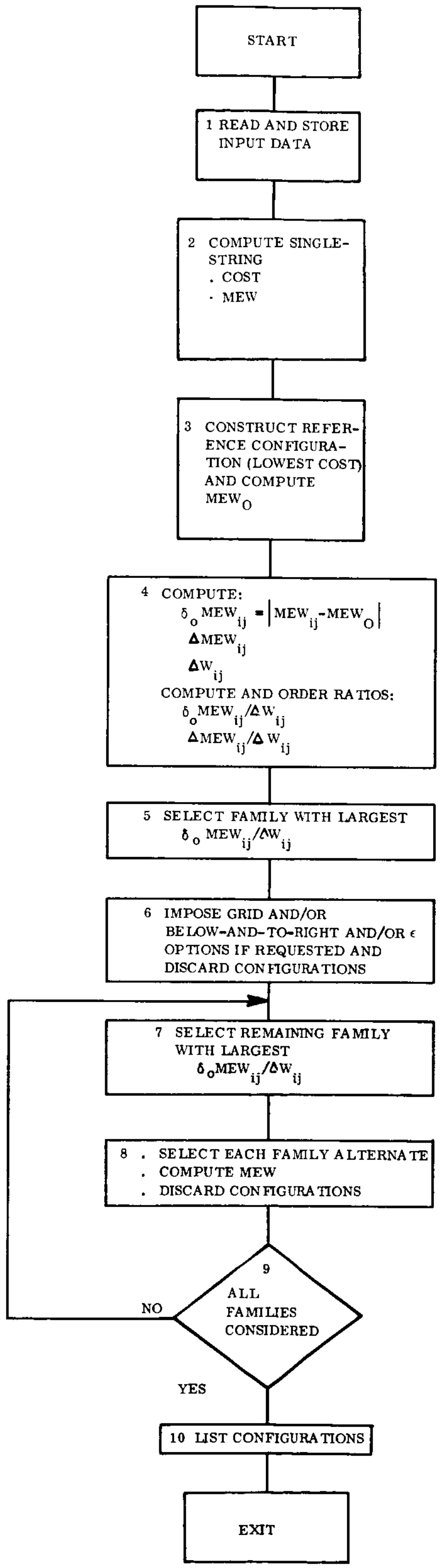


Figure 3-13. Optimization Program Flow Chart

by MEW_{max}. Print MEW_{max}, the cost, and the identification of this configuration.

2. Calculate ΔMEW_{ij} for each alternate, where ΔMEW_{ij} is the magnitude of the difference between the value of MEW for the configuration consisting of the jth alternate for family i and the alternate selected in (1) for all other families, and the same configuration except with the reference independent assembly in family i. Calculate ΔW_{ij}, where ΔW_{ij} is the difference between the cost of the jth independent assembly and the reference assembly in family i.

3. Form the ratios $\delta_o MEW_{ij}/\Delta W_{ij}$ and $\Delta MEW_{ij} / \Delta W_{ij}$ for each independent assembly. Sort these ratios in order of decreasing magnitude of $\delta_o MEW_{ij} / \Delta W_{ij}$.

4. Discard from further consideration any independent assemblies with $\Delta MEW_{ij} / \Delta W_{ij} < \epsilon$.

e. Choose the family of independent assemblies that includes the alternate with the largest $\delta_o MEW_{ij} / \Delta W_{ij}$.

f. Consider the configurations formed when calculating the $\delta_o MEW_{ij}$'s. Save the reference configuration. If the grid option is used, in each segment, save the configuration with the largest $\delta_o MEW_{ij}$, discarding the others from further consideration. If the below-and-to-the-right option is used, discard from further consideration any having a lower MEW value and a higher cost than another.

g. Choose the family of assemblies that includes the alternate with the largest $\delta_o MEW_{ij} / \Delta W_{ij}$ among those remaining in the list.

h. Form new configurations by adding each alternate for the selected family to the reference configurations and to those configurations saved as the best so far. Compare the MEW values for all new configurations and the previously saved configurations, and discard configurations by the gridding criterion or the below-and-to-the-right criterion, as applicable.

i. Repeat steps g and h until all families of independent assemblies have been considered.

j. Print the identification, MEW, and cost for all configurations saved.

3.6.5 MISSION EXPECTED WORTH CALCULATOR

In attempting to obtain optimum system configurations of independent assemblies as a function of total system cost, some measure of worth must be assigned to each considered configuration. Conventional reliability techniques employ the total probability of success as this measure, but for the many-faceted Voyager mission, a more comprehensive index of mission expected worth (MEW) is selected as the measure of system effectiveness. MEW, concisely, is the worth of each mission outcome multiplied by the probability of the system achieving that outcome, this product summed over all possible mission outcomes.

3.6.5.1 Purpose

The MEW Calculator utilizes the state probabilities computed by SIP and stored on tape (see Subsections 3.6.6 and 3.6.7). OPT reads the tape and stores the probabilities in memory for use by the MEW Calculator.

The computation of MEW for a given system configuration is a complex problem in itself, and so is handled by the MEW Calculator. This program evaluates the MEW equation using the correct data for the specified configuration and returns the value to the main Optimization Program. In the running of one problem, it is necessary to call the MEW routine many times.

3.6.5.2 Conceptual Approach

Mission expected worth is a function of independent assembly state probabilities, mission outcome values, and data quality values. (See Section 3.3 for a review of these terms.) In order to evaluate MEW, it is necessary to define the map matrix describing independent assembly performance relationships to quality and in-line functions, the mission outcome tree, and value coefficients, as described in previous sections.

In addition, the Probability Calculator Routinecalculates state probabilities for each independent assembly during each mission subphase with each possible initial condition for that assembly. These initial conditions are imposed on independent assemblies performing in-line functions at the beginning of each subphase, but only at the beginning of the mission for independent assemblies performing only quality functions. This probability data is stored and identified by independent assembly family, alternate within the family, mission subphase, output state, and initial condition.

Once the required mission cumulative and subphase conditional probabilities are known, the MEW Calculator computes the expected worth for system configurations as requested. The general expression for MEW is given by:

$$MEW = \sum_{\phi} \left(\sum_{b} P_b W_b \sum_{q} P_q Q_q \right),$$

where P_b = Probability that the system will be on mission outcome tree branch b during subphase ϕ

W_b = Worth of branch b of subphase ϕ

P_q = Probability that the system will be in quality state q during subphase ϕ

Q_q = Quality modifier for quality state q in subphase ϕ.

3.6.5.3 General Approach

In more detail, mission expected worth is defined as follows (Figure 3-14):

$$MEW = \sum_{i} \Delta MEW_i = \sum_{i} \left(\sum_{k} P_{ijk} \Delta V_{ijk} Q_{ijk} \right) = \sum_{i} \left[\sum_{k} P_{ijk} \Delta V_{ijk} \sum_{m} (q_{ijkm} a_{im}) \right]$$

where

i = Index of mission subphase.

MEW_i = MEW increment for the ith subphase.

j = Index of all outcome tree branches in mission subphase i which originate from a particular node (the jth node) at the start of the ith subphase.

k = The node numbers for a particular subphase running from top to bottom on the mission outcome tree at the end of subphase i.

P_{ijk} = Probability associated with getting to node k via branch jk in subphase i of the mission outcome tree.

ΔV_{ijk} = Value associated with traversing to node k via branch jk in subphase i of the mission outcome tree.

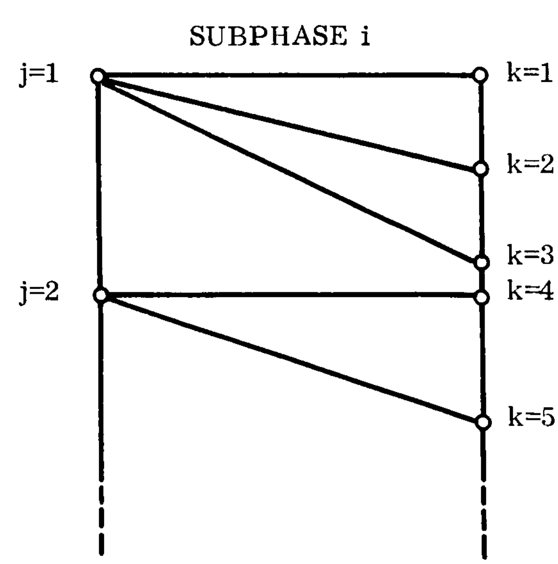


Figure 3-14. Terminology of the MEW Equation

Q_{ijk} = Data quality modifier for node k in subphase i.

m = Index of the state of data quality in subphase i.

q_{ijkm} = Probability that the quality of data will be in state m during subphase i for the tree branch beginning at node j, and ending at node k.

a_{im} = Quality coefficient associated with data quality being in state m during subphase i.

The value and quality coefficients, ΔV_{ijk} and a_{im}, are read in for each subphase. The probabilities, P_{ijk} and q_{ijkm} are products of probabilities that independent assemblies will be in required states at the end of a particular subphase; the multiplicands are generated by the Probability Calculator. The map matrix of symbols is examined to determine those independent assembly output states required to compute the probability of each mission outcome in each subphase.

Upon completion of the MEW computation, the resulting value is returned to the main optimization program.

3.6.5.4 Program Flow

The MEW Calculator flow chart is shown in Figure 3-15.

3.6.6 PROBABILITY CALCULATOR DRIVER PROGRAM

The probability calculator program consists of two programs, the Probability Calculator Driver Program (SIPDRV) and the Probability Calculator Subroutine, also called the State Interpretive Program (SIP). The driver segregates each independent assembly into its proper category, and determines the nature of probability information which must be calculated for each independent assembly. SIP is referenced only by the driver and is called to calculate independent assembly state probabilities.

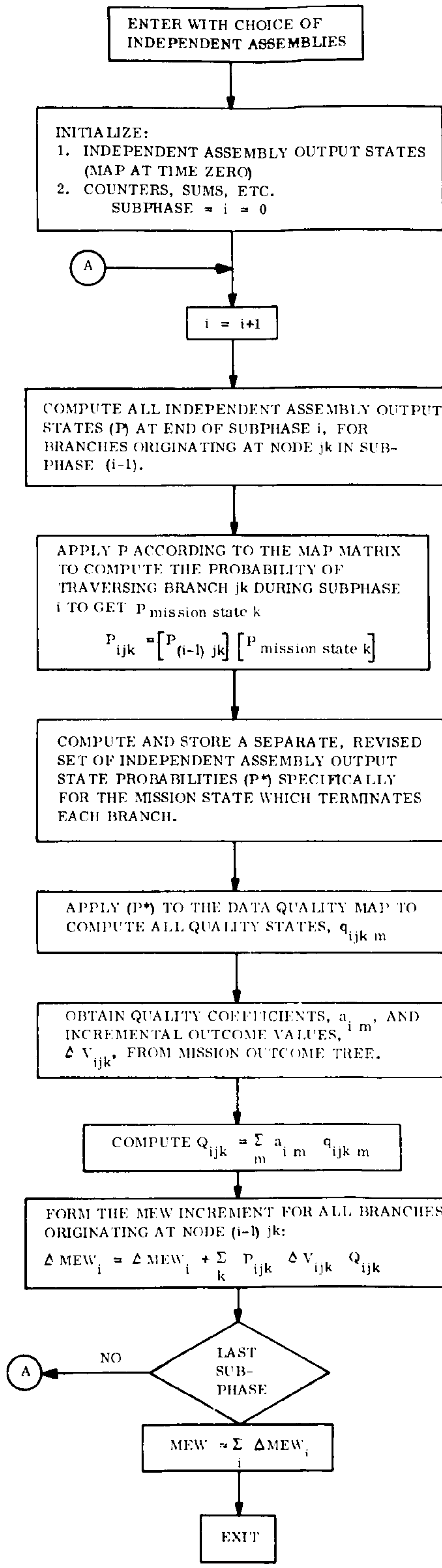


Figure 3-15. Mission Expected Worth Calculator Flow Chart

3.6.6.1 Purpose

The Driver Program (SIPDRV) is concerned with calculating and storing on tape the conditional probabilities required for the MEW Subroutine. The Voyager spacecraft independent assemblies are categorized into five different sets, and the method of determining the probabilities is different for each set. For in-line independent assemblies (i.e., independent assemblies associated with performing in-line functions as they occur in the flight sequence of events), probabilities conditioned at the start of each subphase are required. For quality-only independent assemblies (i.e., independent assemblies performing the functions of collecting and transmitting data), only cumulative probabilities conditioned at the start of the mission are required. Independent assemblies serving both functions are categorized as in-line independent assemblies. SIPDRV determines the proper set for each independent assembly and establishes the linkage with SIP for calculating the required probabilities.

3.6.6.2 Conceptual Approach

The first type of independent assembly (set 1) consists of in-line independent assemblies with fixed probabilities. In this case, no calculation is necessary and SIPDRV merely reads and stores on tape the fixed conditional probabilities.

Set 2 independent assemblies are those serving in-line functions that have only two states (good and failed). For these assemblies, SIPDRV calls SIP to calculate the independent assembly cumulative state probabilities at the end of each mission subphase, and then uses these cumulative probabilities to specify initial conditions to SIP for the calculation of conditional probabilities.

Those in-line independent assemblies not in set 1 or 2 are grouped in set 3. Here also, SIPDRV calls SIP to calculate the independent assembly state probabilities at the end of each mission subphase, given a good condition at time zero. In addition, SIPDRV specifies sets of initial conditions to SIP to calculate independent assembly conditional state probabilities at the end of each mission subphase; i.e., given each of the good and degraded conditions at the end of the previous subphase.

Quality-only independent assemblies without fixed probabilities are called set 4 independent assemblies. For these independent assemblies, SIPDRV call SIP to calculate only cumulative probabilities at the end of each mission subphase. These probabilities are stored directly for use by MEW.

Quality-only independent assemblies with fixed probabilities are in set 5, which is handled like set 1.

3.6.6.3 General Approach

For set 1 and 5 independent assemblies, SIPDRV reads from cards and stores on tape the fixed probabilities specified for each subphase for use by MEW.

For set 4 independent assemblies, SIPDRV calls SIP once for each subphase. SIP reads from cards the data required to calculate the independent assembly state probabilities for a subphase, and SIPDRV stores these cumulative probabilities for use by MEW.

For set 2 independent assemblies, SIP is also called by SIPDRV once for each subphase for cumulative probabilities. The conditional probabilities required by MEW are then calculated by SIPDRV as follows:

$$A_{G_N} | A_{G_{N-1}} = \frac{A_{G_N} \bigcap A_{G_O}}{A_{G_{N-1}} \bigcap A_{G_O}} \quad \text{and} \quad A_{F_N} | A_{G_{N-1}} = 1.0 - (A_{G_N} | A_{G_{N-1}})$$

The notation $A_{G_N} | A_{G_{N-1}}$ designates the conditional probability that a particular independent assembly is in the good state at the end of the Nth subphase, given the initial condition that it was in the good state at the end of the previous subphase. The numerator and denominator of the expression defining $A_{G_N} | A_{G_{N-1}}$ are the independent good state probabilities calculated by SIP for the Nth and (N-1)th subphases, respectively.

The conditional probability $A_{G_N} | A_{G_{N-1}}$ is calculated in the same manner as the multi-state independent assemblies of set 3. However, SIP is called additional times by SIPDRV to calculate the numerator of similar expressions defining the other required conditional probabilities. In such cases, SIPDRV generates the specified initial conditions prior to calling SIP by selecting certain internal state probabilities that have been saved from the previous subphase and setting all other internal states to zero. Control cards in the deck state the internal states to be used as initial conditions for each of the independent assembly states.

As an example, consider the calculation of the degraded state conditional probability;

$$A_{D_N} | A_{D_{N-1}} = \frac{A_{D_N} \cap \left\{ A_{D_{N-1}} | A_{G_O} \right\}}{A_{D_{N-1}} | A_{G_O}}$$

The denominator of this expression is obtained by SIP as in the computation of conditional probabilities for set 2 independent assemblies. The internal state probabilities associated with degraded state (D), calculated during this call to SIP, are saved and used as initial conditions for another call to SIP for the calculation of the numerator of the above expression. The conditional probability is then calculated and stored for use by MEW. This procedure is repeated for all required conditional probabilities at each mission subphase.

3.6.6.4 Program Flow

A control card placed at the beginning of each independent assembly data deck identifies the set to which the independent assembly belongs. The SIPDRV flow chart (Figure 3-16) tracks the program operation.

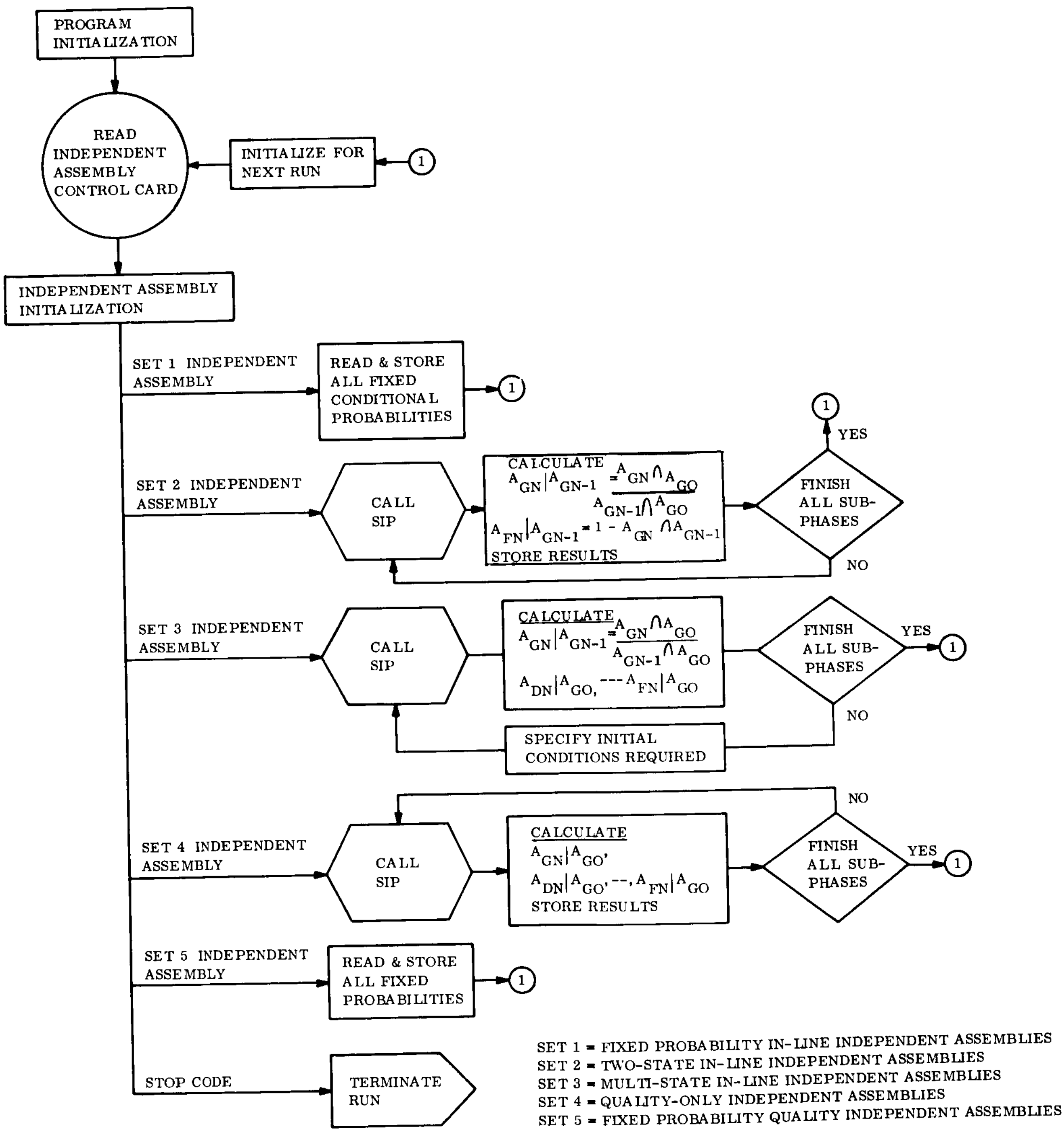


Figure 3-16. Probability Calculator Driver Flow Chart

3.6.7 PROBABILITY CALCULATOR SUBROUTINE

3.6.7.1 Purpose

The Probability Calculator Subroutine provides state probabilities for each independent assembly under consideration for inclusion in the spacecraft system, as required for the evaluation of mission expected worth. The program reads data describing the components comprising each assembly, including failure characteristics and interrelations. Based on this data, the program calculates the probabilities that the independent assemblies are in each of the defined states at the end of each mission subphase (given the required conditions at the beginning of each subphase). This information is stored on magnetic tape for use by the MEW Subroutine.

The SIP Driver Program uses these independent assembly state probabilities to calculate conditional probabilities required by the MEW Subroutine and, in the case of multi-state, in-line independent assemblies, it generates the initial conditions for SIP.

3.6.7.2 Conceptual Approach

The State Interpretive Program (SIP) uses:

a. A fourth order Runge-Kutta integration technique to solve differential equations generated internally from the independent assembly state diagrams.

b. Arithmetic operations to calculate independent assembly output state probabilities as a function of the internal state probabilities.

SIP employes the concept of state space to compute the internal independent assembly state probabilities as a function of time. It enables the solution of state differential equations without actually formulating them. This requires only describing the state diagram, the initial conditions, and the desired data output.

The state space concept is based on classical Markow methods. The possible internal conditions of the independent assembly are called states, and the totality is called state space. The states are mutually exclusive and exhaustive so that at any instant in time the assembly can exist in one (and only one) state. After the state space has been defined, a math model is constructed to relate the states to each other. This model consists of a state diagram (a set of arrows indicating the direction of the possible transitions from state-to-state), the transition rates between the various states, and a set of arithmetic statements defining the relationship between internal states and independent assembly output states. The computer program accepts this description, translates it into a set of simultaneous linear differential and arithmetic equations, and solves the equations as a function of time.

The integration in SIP is founded on the Poisson postulate:

> "Whatever the number of changes during the time interval $(0,t)$, the probability that a change occurs during $(t, t+h)$ is $\lambda h + o(h)$, and the probability that more than one change occurs in $o(h)$."

In this postulate, λ is the transition or failure rate, and $o(h)$ is a designator for terms involving second and higher order terms in h. Components having non-Poisson failure characteristics can be modeled as special cases or as psuedo-Poisson processes.

3.6.7.3 General Approach

SIP uses data either read from cards or generated by SIPDRV to calculate independent assembly state probabilities at specific points in time, viz., the ends of each mission subphase. A set of differential equations is established from the state diagram and transition rates, and they are solved by a fourth order Runge-Kutta integration method. Specified arithmetic operations are then performed on the internal state probabilities to calculate independent assembly output state probabilities.

3.6.7.4 Program Flow

Figure 3-17 is a flow diagram of SIP.

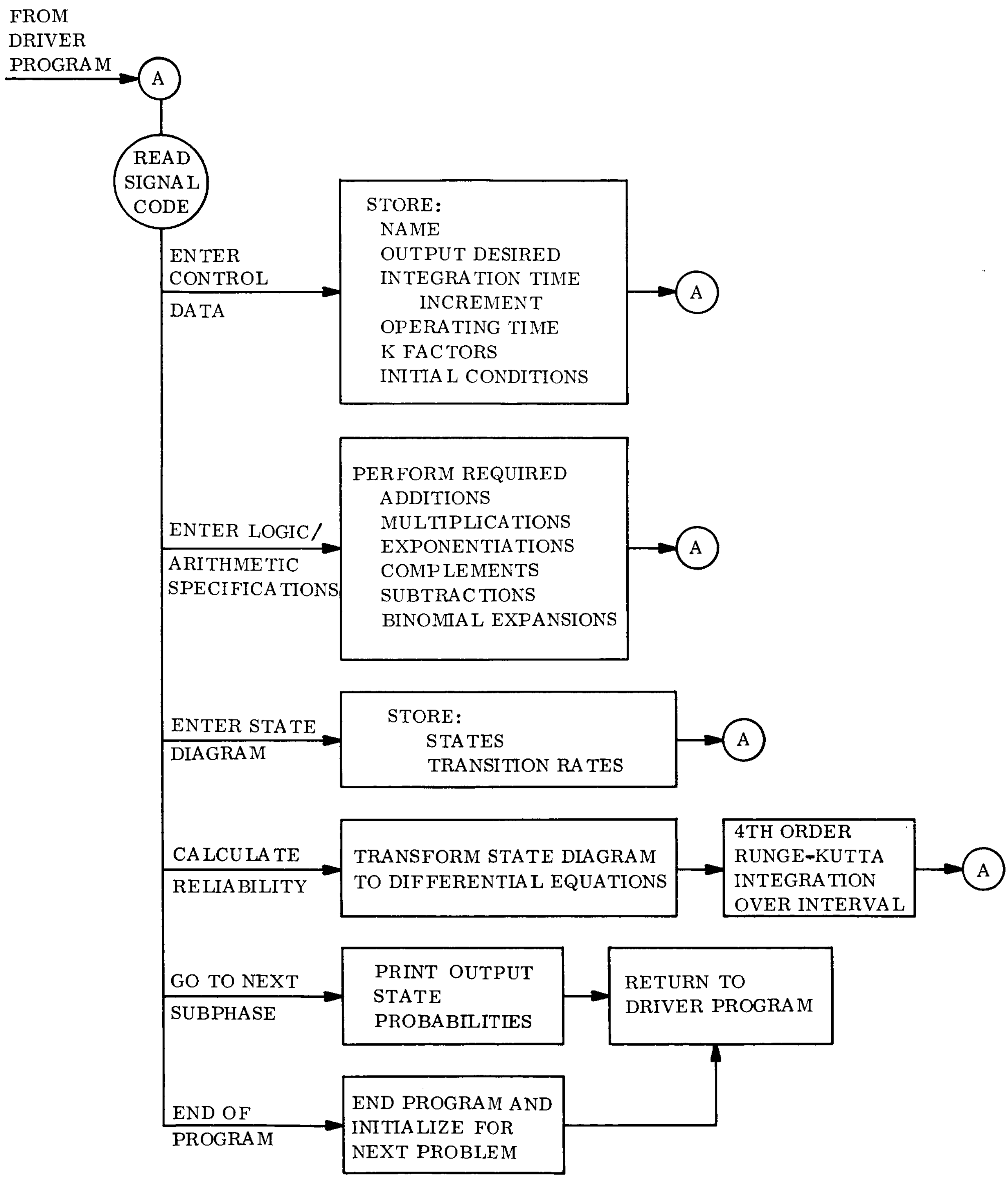


Figure 3-17. State Interpretative Program Flow Chart

3.7 RESULTS

3.7.1 PROBABILITY CALCULATOR RESULTS

The results of the probability calculator are obtained in two forms (Figure 3-18). The first form is the detailed printout which provides information used in each step of the calculation of cumulative and conditional probabilities, as well as the results of the computations. The second form is the probabilities in array form on magnetic tape for use by the optimization program.

3.7.1.1 Detailed Printout Results

The detailed printout results of the probability calculator are best illustrated by referring to a typical listing (Figure 3-19) that shows a portion of the probability output for independent assembly CHC (the liquid engine start-stop register).

The program first lists the name of the independent assembly under consideration. This is followed by the definition of the first mission subphase: viz., the times at which the

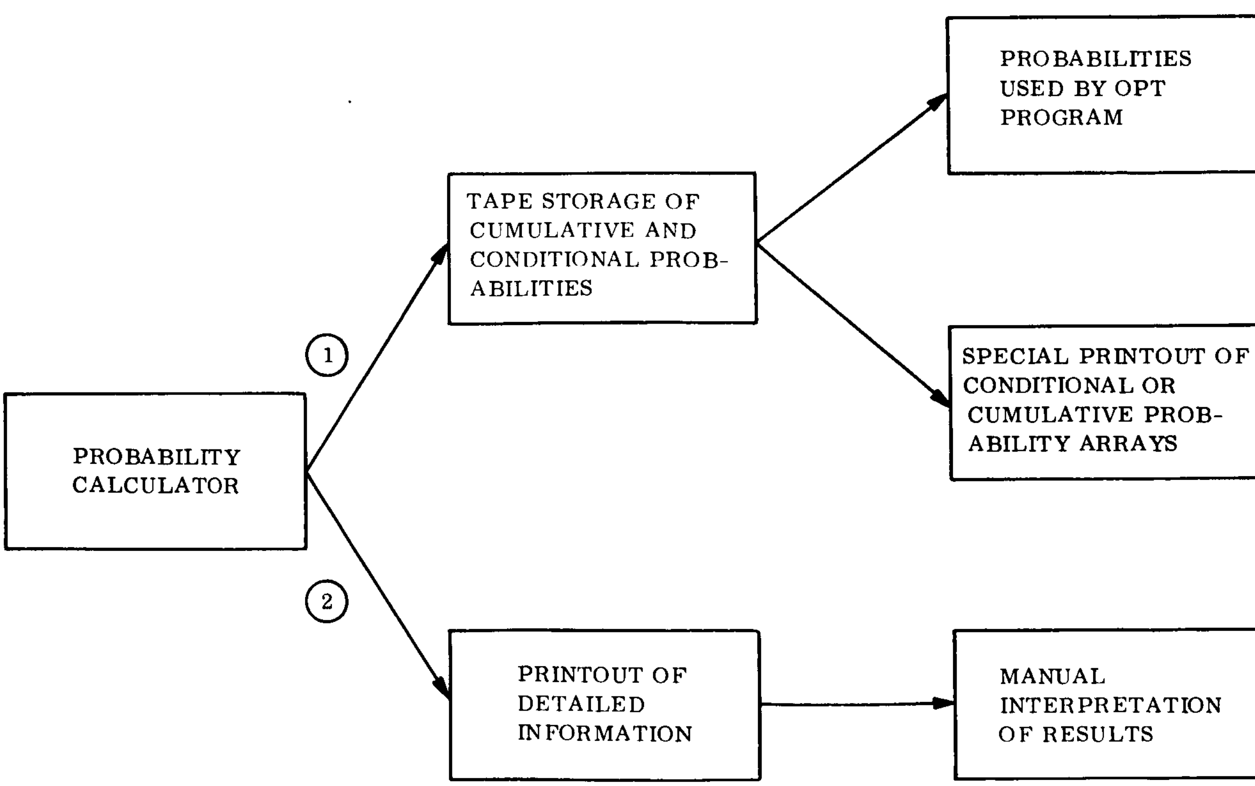


Figure 3-18. Results from the Probability Calculator

INDEPENDENT ASSEMBLY DESIGNATION

STATE INTERPRETATION PROGR

CMC LIQ E START STOP REG

INTEGRATION INCREMENT   INITIAL   TIME   END OF INTERVAL
0.006   0.   0.600

COLUMN HEADINGS' 2 — NUMBER OF OUTPUT STATES
GOOD   FAIL

DESIGNATIONS OR LOCATIONS ASSIGNED TO THE OUTPUT S

ANSWERS' 2
13   14

NUMBER OF INITIAL CONDITIONS OR
OR CONSTANTS TO BE READ IN

INITIAL CONDITIONS' 1
1 1.00000

STATE — 7 1.00000 — INITIAL CONDITION

ARROWS' 17 — NUMBER OF ARROWS IN STATE DIAGRAM

1	2	0.2916
1	4	0.0048
1	6	8.4948
2	3	0.0048
2	6	8.6892
3	6	8.6916
4	5	0.2916
4	6	8.4972
5	6	8.6916
7	8	0.0714
7	10	0.0012
8	9	0.0012
8	12	0.0476
9	12	0.0482
10	11	0.0714
10	12	0.0006
11	12	0.0482

FAILURE RATE (STRESSED VALUES) ASSOCIATED WITH EA
ARROW FOR THE PARTICULAR TIME INTERVAL (SUBPHAS

STATE DESIGNATION AT THE HEAD OF THE ARROW

STATE DESIGNATION AT THE TAIL OF THE ARROW

COMPLEMENTS' 1
15   6

COMPLEMENTS' 1
16   12

ARITHMETIC OPERATIONS REQUIRED TO COMPUTE PROBABILI
STATES AT END OF THE TIME INTERVAL

PRODUCTS' 1
2 13   15   16

COMPLEMENTS' 1
14   13

STATE PROBABILITIES AT THE END

CUMULATIVE TIME — TIME 0.60

GOOD   FAIL
0.99994903   0.000050[illegible]

INITIALIZATION FOR START OF SECOND PHASE

INTEGRATION INCREMENT   INITIAL   TIME   END OF INTERVAL
0.001   0.600   0.700

M

60300

K FACTOR
0

TATES

H
)

IES OF OUTPUT

F THE FIRST SUBPHASE

K FACTOR
1

ARROWS: 17

1	2	0.7290
1	4	0.0120
1	6	24.9870
2	3	0.0120
2	6	25.4730
3	6	25.4790
4	5	0.7290
4	6	24.9930
5	6	25.4790
7	8	0.0714
7	10	0.0012
8	9	0.0012
8	12	0.0476
9	12	0.0482
10	11	0.0714
10	12	0.0006
11	12	0.0482

NEW FAILURE RATES
SUBPHASE (STRESSE

TIME	GOOD	FAIL
0.70	0.99992403	0.00007597

INTEGRATION INCREMENT
0.000

THIRD SUBPHASE PRINTOUT

TIME	GOOD	FAIL
0.70	0.99992403	0.00007597

INTEGRATION INCREMENT
0.191

ARROWS: 17

1	2	0.0729
1	4	0.0012
1	6	0.3987
2	3	0.0012
2	6	0.4473
3	6	0.4479
4	5	0.0729
4	6	0.3993
5	6	0.4479
7	8	0.0714
7	10	0.0012
8	9	0.0012
8	12	0.0476
9	12	0.0482
10	11	0.0714
10	12	0.0006
11	12	0.0482

FOURTH SUBPHASE FA

TIME	GOOD	FAIL
19.80	0.99984790	0.00015210

INTEGRATION INCREMENT
0.402

ARROWS: 17

1	2	0.0729
1	4	0.0012
1	6	0.0050
2	3	0.0012
2	6	0.0536
3	6	0.0542
4	5	0.0729

NOTE: ARITHMETIC OPERATIONS ARE THE SAME AS THE FIRST SUBPHASE AND ARE NOT REPEATED

S FOR SECOND
D VALUES)

CUMULATIVE PROBABILITIES AT THE END OF THE SECOND SUBPHASE

INITIAL TIME	END OF INTERVAL	K FACTOR
0.700	0.700	1

INITIAL TIME	END OF INTERVAL	K FACTOR
0.700	19.800	1

ILURE RATES (UNSTRESSED)

FOURTH SUBPHASE RESULTS

INITIAL TIME	END OF INTERVAL	K FACTOR
19.800	60.000	1

Figure 3-19. Detailed Probability Calculator Listing

[redacted]

subphase begins and ends, the integration interval to be used in that subphase by the Runge-Kutta algorithm, and a factor to indicate whether memory should be cleared. The next two items specify the performance states of the independent assembly (good and failed) and their correlation with the internal operating states of the assembly (good = internal state 13; failed = internal state 14). The following item impresses initial conditions on the probability calculator. (In the example, states numbered 1 and 7 are initialized to a probability of one, and the remaining states retain an initial probability of zero.).

The large data item following initial conditions describes the state diagram for the first mission subphase. Each line describes an arrow from one internal state to another (1 to 2) with the corresponding failure rate for that particular transition (0.2916). Following this, the arithmetic operations required to compute the independent assembly output state probabilities are listed. For example, the probability of state 16 is equal to the product of the probabilities of states 2, 13, and 15. Finally, the desired output state probabilities are printed. This completes the first subphase. (In subsequent subphases, printout of the failure rates and arithmetic operations are only provided when they differ from the previous subphase.)

This independent assembly (Figure 3-19) has only two output states and thus does not require additional specifications for the computation of conditional probabilities. Where these are required, the steps are similarly detailed in the printout.

3.7.1.2 Tape Output Results

In addition to the detailed printout, the program also records on magnetic tape the necessary probability information (in array form) plus indexing and pointing arrays to be used by the optimization program in calculating MEW. A special printout program is written for listing the information in the probability array in block form. These probabilities are either conditional probabilities (for in-line independent assemblies) or cumulative probabilities (for quality independent assemblies).

Figure 3-20 shows a portion of this probability calculator output for two independent assemblies (TBA, data storage assembly; and ECB, clocking and 2.4 kc power assembly). The information appears in blocks of 30 values representing either the conditional or cumulative probability for each subphase. (Since there are only 27 subphases to the mission profile, the last three entries are always zero.) Cumulative probabilities are listed in order of G, D1, D2, ..., F. TBA is an example of cumulative probabilities for a four-state independent assembly. Conditional probabilities are listed in order of G/G, D1/G, D1/D1, D2/G, D2/D1, etc. ECB is an example of a three-state conditional printout.

3.7.1.3 Summary of Probability Results

A summary of the probability calculator results is listed in Table 3-8 (7 sheets). The cumulative probabilities of each independent assembly output state for the last mission subphase in which that independent assembly is required are summarized. The results from the probability calculator are truncated to four places. As might be expected, the alternates in each family having the lowest probabilities of failure are generally dominant as the selected alternates in maximum MEW configurations.

3.7.2 OPTIMIZATION RESULTS

The exercises to which the redundancy optimization tool was subjected during the study fell into two categories. First, it was used for a series of test runs to develop insight into and confidence in its operation. Second, it was exercised in its normal capacity to identify optimum configurations and to evaluate their sensitivities with respect to hardware probabilities, assignment of values, etc. Since it was a new tool, effort was concentrated primarily in the first area. The results of exercises in both areas are summarized in the following subsections.

3.7.2.1 Discarding by the Lower-and-to-the-Right (LATTR) Criterion

The optimization program discussed in Section 3.5 contains the option of discarding all configurations which lie below and to the right (i.e., lower MEW and higher cost) of any configurations saved to that point in the processing, regardless of the segment in which the configurations lie. Comparative runs were made with and without this (LATTR) option. In all runs, however, discarding within gridded segments was also employed, so that the effectiveness of LATTR was measured in the presence of segmented discarding.

PROBABILITY OF BEING IN THE GOOD STATE AT THE END OF THE 6TH SUBPHASE, GIVEN GOOD AT THE START OF THE MISSION

TB A										CUMULATIVE PROBABILITY
0.9967623	0.9951624	0.9951624	0.9949590	0.9945336	0.9926421	0.9860254	0.9840957	0.9486327	0.9467760	GOOD
0.9452673	0.9452673	0.9450207	0.9328169	0.9205253	0.9123815	0.8993246	0.8913683	0.8790090	0.8768447	
0.8762316	0.8738229	0.8738225	0.8738221	0.6501760	0.6497744	0.1453828	0.1453828	0.	0.	
0.0016161	0.0024112	0.0024112	0.0026012	0.0030010	0.0031666	0.0094049	0.0095625	0.0429623	0.0430538	DEGRADED ONE
0.0444716	0.0444716	0.0447023	0.0645101	0.0767211	0.0848038	0.0977034	0.1055633	0.1177025	0.1198222	
0.1204213	0.1227782	0.1227785	0.1227789	0.3319326	0.3322847	0.6018573	0.6018573	0.	0.	
0.0016161	0.0024112	0.0024112	0.0024107	0.0024097	0.0041181	0.0040906	0.0058332	0.0056230	0.0072992	DEGRADED TWO
0.0072876	0.0072876	0.0072857	0.0000288	0.0000605	0.0000869	0.0001563	0.0002003	0.0003015	0.0003230	
0.0003302	0.0003551	0.0003552	0.0003552	0.0073802	0.0074054	0.1152432	0.1152432	0.	0.	
0.0000041	0.0000121	0.0000121	0.0000240	0.0000491	0.0000652	0.0004695	0.0004977	0.0027699	0.0028573	FAILED
0.0029582	0.0029582	0.0029746	0.0026443	0.0026931	0.0027279	0.0028157	0.0028681	0.0029869	0.0030102	
0.0030169	0.0030438	0.0030438	0.0030438	0.0105112	0.0105355	0.1375167	0.1375167	0.	0.	
EC B										**CONDITIONAL PROBABILITY**
0.9999978	0.9999978	1.0000000	0.9999218	0.9998383	0.9999307	0.9974892	0.9999275	0.9863023	0.9999280	G/G
0.9994003	1.0000000	0.9999007	0.9999735	0.9998703	0.9999295	0.9998582	0.9999295	0.9998627	0.9999750	
0.9999916	0.9999719	1.0000000	1.0000000	0.9971348	0.9999932	0.9855789	0.	0.	0.	
0.0000003	0.0000001	0.0000000	0.0000716	0.0001507	0.0000645	0.0023622	0.0000664	0.0128849	0.0000664	D1/G
0.0005634	0.0000000	0.0000919	0.0000229	0.0001211	0.0000652	0.0001316	0.0000652	0.0001275	0.0000225	
0.0000064	0.0000251	0.0000000	0.0000000	0.0026957	0.0000056	0.0135649	0.	0.	0.	
0.	0.9999968	1.0000000	0.9999902	0.9999814	0.9999910	0.9997277	0.9999901	0.9985226	0.9999904	D1/D1
0.9999337	1.0000000	0.9999870	0.9999957	0.9999844	0.9999902	0.9999817	0.9999903	0.9999818	0.9999960	
0.9999958	0.9999933	1.0000000	1.0000000	0.9996891	0.9999964	0.9984440	0.	0.	0.	
0.0000006	0.0000021	0.0000000	0.0000066	0.0000110	0.0000048	0.0001486	0.0000061	0.0008127	0.0000056	F/G
0.0000363	0.0000000	0.0000075	0.0000037	0.0000085	0.0000053	0.0000102	0.0000053	0.0000098	0.0000025	
0.0000020	0.0000030	0.0000000	0.0000000	0.0001694	0.0000012	0.0008561	0.	0.	0.	
0.	0.0000032	0.0000000	0.0000098	0.0000186	0.0000090	0.0002723	0.0000099	0.0014774	0.0000096	F/D1
0.0000663	0.0000000	0.0000130	0.0000043	0.0000156	0.0000098	0.0000183	0.0000097	0.0000182	0.0000040	
0.0000042	0.0000067	0.0000000	0.0000000	0.0003109	0.0000036	0.0015560	0.	0.	0.	

PROBABILITY OF BEING FAILED AT THE END OF THE 27TH SUBPHASE, GIVEN THAT THE ASSEMBLY WAS GOOD AT THE END OF THE 26TH SUBPHASE

Figure 3-20. Probability Calculator Input to Optimization Program

Table 3-8. Probability Calculator Summary Results (Sheet 1 of 7)
(Note: All Probabilities Are Cumulative)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
CAA	27	0.9887	--	--	--	--	--	--	--	0.0113
CAB	27	0.9889	--	--	--	--	--	--	--	0.0111
CAC	27	0.9927	--	--	--	--	--	--	--	0.0073
CAD	27	0.9929	--	--	--	--	--	--	--	0.0071
CAE	27	0.9914	--	--	--	--	--	--	--	0.0086
CAF	27	0.9916	--	--	--	--	--	--	--	0.0084
CAG	27	0.9954	--	--	--	--	--	--	--	0.0046
CAH	27	0.9956	--	--	--	--	--	--	--	0.0044
CDA	4	1.0000	--	--	--	--	--	--	--	0.0000
CDB	4	1.0000	--	--	--	--	--	--	--	0.0000
CDC	4	1.0000	--	--	--	--	--	--	--	0.0000
CEA	27	0.9912	--	--	--	--	--	--	--	0.0088
CEB	27	0.9920	--	--	--	--	--	--	--	0.0080
CEC	27	0.9987	--	--	--	--	--	--	--	0.0013
CFA	20	0.9988	--	--	--	--	--	--	--	0.0012
CFB	20	0.9999	--	--	--	--	--	--	--	0.0001
CGA	14	0.9988	--	--	--	--	--	--	--	0.0012
CGB	14	0.9999	--	--	--	--	--	--	--	0.0001
CHA	18	0.9971	--	--	--	--	--	--	--	0.0029
CHB	18	0.9988	--	--	--	--	--	--	--	0.0012
CHC	18	0.9992	--	--	--	--	--	--	--	0.0008
CHD	18	0.9999	--	--	--	--	--	--	--	0.0001
CHE	18	0.9976	--	--	--	--	--	--	--	0.0024
CHF	18	0.9988	--	--	--	--	--	--	--	0.0012
CHG	18	0.9998	--	--	--	--	--	--	--	0.0002
CHH	18	0.9999	--	--	--	--	--	--	--	0.0001

Table 3-8. Probability Calculator Summary Results (Sheet 2 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
CJA	26	0.9931	--	--	--	--	--	--	--	0.0069
CJB	26	0.9984	--	--	--	--	--	--	--	0.0016
CKA	27	0.9875	--	--	--	--	--	--	--	0.0125
CKB	27	0.9883	--	--	--	--	--	--	--	0.0117
CLA	27	0.9916	--	--	--	--	--	--	--	0.0083
CMA	27	0.9645	--	--	--	--	--	--	--	0.0355
CMB	27	0.9977	--	--	--	--	--	--	--	0.0023
CNA	27	0.9987	0.0000	0.0000	0.0009	--	--	--	--	0.0004
CNB	27	0.9995	0.0000	0.0000	0.0002	--	--	--	--	0.0003
CPA	18	0.9103	--	--	--	--	--	--	--	0.0897
CPB	18	0.9920	--	--	--	--	--	--	--	0.0080
EAA	27	0.6937	0.2783	--	--	--	--	--	--	0.0279
EAB	27	0.7190	0.2579	--	--	--	--	--	--	0.0231
EAC	27	0.7359	0.2439	--	--	--	--	--	--	0.0202
EBA	22	0.9792	--	--	--	--	--	--	--	0.0208
EBB	22	0.9794	--	--	--	--	--	--	--	0.0206
EBC	22	0.9794	--	--	--	--	--	--	--	0.0205
EBD	22	0.9795	--	--	--	--	--	--	--	0.0205
EBE	22	0.9796	--	--	--	--	--	--	--	0.0204
EBF	22	0.9796	--	--	--	--	--	--	--	0.0204
ECA	27	0.9967	0.0000	--	--	--	--	--	--	0.0033
ECB	27	0.9967	0.0000	--	--	--	--	--	--	0.0021
ECC	27	0.9967	0.0012	--	--	--	--	--	--	0.0021
ECD	27	0.9967	0.0033	--	--	--	--	--	--	0.0000
ECE	27	0.9987	0.0000	--	--	--	--	--	--	0.0012
ECF	27	0.9987	0.0013	--	--	--	--	--	--	0.0000
ECG	27	0.9987	0.0013	--	--	--	--	--	--	0.0000
ECH	27	0.9987	0.0013	--	--	--	--	--	--	0.0000
ECJ	27	0.9976	0.0000	--	--	--	--	--	--	0.0024
ECK	27	0.9976	0.0003	--	--	--	--	--	--	0.0021
ECL	27	0.9975	0.0003	--	--	--	--	--	--	0.0022
ECM	27	0.9975	0.0003	--	--	--	--	--	--	0.0021
ECN	27	0.9996	0.0000	--	--	--	--	--	--	0.0003
ECP	27	0.9996	0.0003	--	--	--	--	--	--	0.0000
ECQ	27	0.9996	0.0003	--	--	--	--	--	--	0.0001
ECR	27	0.9996	0.0003	--	--	--	--	--	--	0.0000

Table 3-8. Probability Calculator Summary Results (Sheet 3 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
EDA	27	0.9926	0.0013	0.0053	--	--	--	--	--	0.0008
EDB	27	0.9927	0.0013	0.0056	--	--	--	--	--	0.0003
EDC	27	0.9972	0.0013	0.0009	--	--	--	--	--	0.0006
EDD	27	0.9980	0.0013	0.0005	--	--	--	--	--	0.0002
EDE	27	0.9978	0.0013	0.0001	--	--	--	--	--	0.0008
EDF	27	0.9980	0.0013	0.0004	--	--	--	--	--	0.0003
EDG	27	0.9981	0.0013	0.0000	--	--	--	--	--	0.0006
EDH	27	0.9985	0.0013	0.0000	--	--	--	--	--	0.0002
EDJ	27	0.9939	0.0000	0.0053	--	--	--	--	--	0.0008
EDK	27	0.9940	0.0000	0.0056	--	--	--	--	--	0.0003
EDL	27	0.9985	0.0000	0.0009	--	--	--	--	--	0.0006
EDM	27	0.9989	0.0000	0.0009	--	--	--	--	--	0.0002
EDN	27	0.9961	0.0000	0.0001	--	--	--	--	--	0.0003
EDP	27	0.9994	0.0000	0.0003	--	--	--	--	--	0.0003
EDQ	27	0.9994	0.0000	0.0000	--	--	--	--	--	0.0006
EDR	27	0.9998	0.0000	0.0000	--	--	--	--	--	0.0001
EEA	27	0.9960	--	--	--	--	--	--	--	0.0040
EEB	27	0.9999	--	--	--	--	--	--	--	0.0001
EFA	27	0.9845	--	--	--	--	--	--	--	0.0155
EFB	27	0.9997	--	--	--	--	--	--	--	0.0003
EGA	27	0.9953	--	--	--	--	--	--	--	0.0047
EGB	27	0.9961	--	--	--	--	--	--	--	0.0039
EHA	27	0.9697	--	--	--	--	--	--	--	0.0303
EHB	27	0.9828	--	--	--	--	--	--	--	0.0172
GAA	27	0.8992	--	--	--	--	--	--	--	0.1008
GAB	27	0.9605	--	--	--	--	--	--	--	0.0395
GAC	27	0.9662	--	--	--	--	--	--	--	0.0338
GAD	27	0.9646	--	--	--	--	--	--	--	0.0354
GAE	27	0.9682	--	--	--	--	--	--	--	0.0318
GAF	27	0.9098	--	--	--	--	--	--	--	0.0902
GAG	27	0.9075	--	--	--	--	--	--	--	0.0924
GBA	27	0.9793	0.0016	--	--	--	--	--	--	0.0191
GBB	27	0.9995	0.0001	--	--	--	--	--	--	0.0004
GBC	27	0.9956	0.0028	--	--	--	--	--	--	0.0016
GBD	27	0.9987	0.0003	--	--	--	--	--	--	0.0010

Table 3-8. Probability Calculator Summary Results (Sheet 4 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
GDA	27	0.9593	--	--	--	--	--	--	--	0.0407
GDB	27	0.9982	--	--	--	--	--	--	--	0.0018
GDC	27	0.9967	--	--	--	--	--	--	--	0.0033
GDE	27	0.9968	--	--	--	--	--	--	--	0.0032
GDF	27	0.9885	--	--	--	--	--	--	--	0.0115
GDG	27	0.9982	--	--	--	--	--	--	--	0.0018
GEA	27	0.9946	--	--	--	--	--	--	--	0.0054
GEB	27	0.9999	--	--	--	--	--	--	--	0.0001
GFA	27	1.0000	--	--	--	--	--	--	--	0.0000
GFB	27	1.0000	--	--	--	--	--	--	--	0.0000
GFC	27	1.0000	--	--	--	--	--	--	--	0.0000
GGA	27	0.9955	--	--	--	--	--	--	--	0.0045
GGB	27	0.9980	--	--	--	--	--	--	--	0.0020
GGC	27	0.9995	--	--	--	--	--	--	--	0.0005
GHA	27	0.9995	--	--	--	--	--	--	--	0.0005
GHB	27	1.0000	--	--	--	--	--	--	--	0.0000
MAA	27	1.0000	--	--	--	--	--	--	--	0.0000
MAB	27	1.0000	--	--	--	--	--	--	--	0.0000
MBA	27	1.0000	--	--	--	--	--	--	--	0.0000
MCA	20	0.9692	--	--	--	--	--	--	--	0.0308
MCB	20	0.9990	--	--	--	--	--	--	--	0.0009
MDA	3	0.9989	--	--	--	--	--	--	--	0.0011
MDB	3	0.9990	--	--	--	--	--	--	--	0.0010
MDC	3	0.9990	--	--	--	--	--	--	--	0.0010
MDD	3	0.9999	--	--	--	--	--	--	--	0.0001
MDE	3	1.0000	--	--	--	--	--	--	--	0.0000
MDF	3	1.0000	--	--	--	--	--	--	--	0.0000
MDH	3	1.0000	--	--	--	--	--	--	--	0.0000
MDJ	3	0.9991	--	--	--	--	--	--	--	0.0009
MEA	27	1.0000	--	--	--	--	--	--	--	0.0000

Table 3-8. Probability Calculator Summary Results (Sheet 5 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
MGA	27	1.0000	--	--	--	--	--	--	--	0.0000
MHA	27	1.0000	--	--	--	--	--	--	--	0.0000
MHB	27	1.0000	--	--	--	--	--	--	--	0.0000
MLA	27	0.9190	--	--	--	--	--	--	--	0.0810
MMA	27	1.0000	--	--	--	--	--	--	--	0.0000
MNA	27	1.0000	--	--	--	--	--	--	--	0.0000
MPA	12	1.0000	--	--	--	--	--	--	--	0.0000
MQA	27	1.0000	--	--	--	--	--	--	--	0.0000
MRA	3	1.0000	--	--	--	--	--	--	--	0.0000
MRB	3	1.0000	--	--	--	--	--	--	--	0.0000
LAA	3	0.8565	0.0433	--	--	--	--	--	--	0.1002
LBA	3	0.9702	--	--	--	--	--	--	--	0.0298
PAA	18	0.9999	--	--	--	--	--	--	--	0.0001
PAB	18	1.0000	--	--	--	--	--	--	--	0.0000
PAC	18	1.0000	--	--	--	--	--	--	--	0.0000
PBA	18	1.0000	--	--	--	--	--	--	--	0.0000
PBB	18	1.0000	--	--	--	--	--	--	--	0.0000
PCA	18	0.9999	--	--	--	--	--	--	--	0.0001
PCB	18	1.0000	--	--	--	--	--	--	--	0.0000
PCC	18	1.0000	--	--	--	--	--	--	--	0.0000

Table 3-8. Probability Calculator Summary Results (Sheet 6 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
PDA	18	0.9999	--	--	--	--	--	--	--	0.0001
PDB	18	0.9999	0.0000	--	--	--	--	--	--	0.0001
PDC	18	0.9999	0.0000	--	--	--	--	--	--	0.0001
PDD	18	0.9999	0.0000	--	--	--	--	--	--	0.0001
PMA	14	0.9986	0.0005	--	--	--	--	--	--	0.0001
PNA	14	0.9998	--	--	--	--	--	--	--	0.0002
PNB	14	0.9998	--	--	--	--	--	--	--	0.0002
PPA	14	0.9995	--	--	--	--	--	--	--	0.0005
PPB	14	0.9995	--	--	--	--	--	--	--	0.0005
PQA	14	0.9978	--	--	--	--	--	--	--	0.0022
SAA	27	1.0000	--	--	--	--	--	--	--	0.0000
SBA	27	1.0000	--	--	--	--	--	--	--	0.0000
SCA	27	0.8000	--	--	--	--	--	--	--	0.2000
SDA	27	0.2740	0.4730	0.1190	--	--	--	--	--	0.1340
SEA	27	0.9500	--	--	--	--	--	--	--	0.0500
SGA	22	0.9600	--	--	--	--	--	--	--	0.0400
SHA	27	1.0000	--	--	--	--	--	--	--	0.0000
TAA	27	0.9956	0.0195	0.0010	--	--	--	--	--	0.0039
TAB	27	0.9910	0.0007	0.0000	--	--	--	--	--	0.0002
TAC	27	0.9997	0.0001	0.0000	--	--	--	--	--	0.0002
TBA	27	0.1454	0.6019	0.1152	--	--	--	--	--	0.1375
TBB	27	0.1460	0.7607	0.0752	--	--	--	--	--	0.0180

Table 3-8. Probability Calculator Summary Results (Sheet 7 of 7)

Independent Assembly	Last Subphase	G	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F
TCA	27	0.5273	0.1781	0.0000	0.0671	0.0000	0.0000	0.0000	0.0000	0.2276
TCB	27	0.8849	0.0004	0.0729	0.0009	0.0000	0.0014	0.0000	0.0001	0.0392
TCC	27	0.8735	0.0004	0.0734	0.0009	0.0000	0.0001	0.0000	0.0000	0.0516
TCD	27	0.8301	0.0077	0.0692	0.0091	0.0000	0.0037	0.0000	0.0004	0.0800
TCE	27	0.8836	0.0004	0.0742	0.0009	0.0000	0.0014	0.0000	0.0001	0.0392
TCF	27	0.8748	0.0004	0.0721	0.0009	0.0000	0.0001	0.0000	0.0000	0.0516

In the runs made, the final configuration listings using LATTR correspond closely to those made without LATTR after elimination of the so-called interior configurations; i.e., configurations in the final listing with lower values of MEW and higher cost (weight) than other configurations. In other words, the final configuration listing obtained without LATTR essentially could be reduced to that obtained using LATTR by applying the LATTR criterion to the final listing and eliminating the interior configurations. Further, use of LATTR reduced computer processing time by up to 40 percent. It was generally concluded that use of the LATTR option with the gridding option was desirable.

3.7.2.2 Segment Size

Increasing the number of segments (reducing the segment size) into which the cost axis is divided increases the number of final configurations saved when the gridding option of discarding is employed, since only one configuration is saved for each segment. Runs were made increasing the number of segments from 5 to 30 to 150 segments. In general, the best configuration in each segment was identically the best configuration (that with the highest MEW) for the same range of cost when the original segment was subdivided into smaller segments. By expanding each segment into subsegments, configurations of lower cost and slightly lower MEW than the original configuration were identified. Thus, using more segments provides the designer with a set of nearly equivalent configurations from which to choose. At the same time, however, computer processing time triples (increasing from 5 to 150 segments).

At the other extreme, however, too few segments yield interior configurations in the final configuration listing. Figure 3-21 shows the results of three optimization runs which were identical except for using 5, 30 and 150 segments. (The keep factor and abbreviated MEW conditions are explained in following sections and are not germaine to this comparison.) Dips in the 5-segment and 30-segment curves below the 150-segment curve indicate interior configurations; these seem to be more prevalent in the early part of the plot where the MEW-cost slope is steeper. Thus, there seems to be some evidence to suggest that many segments should be used.

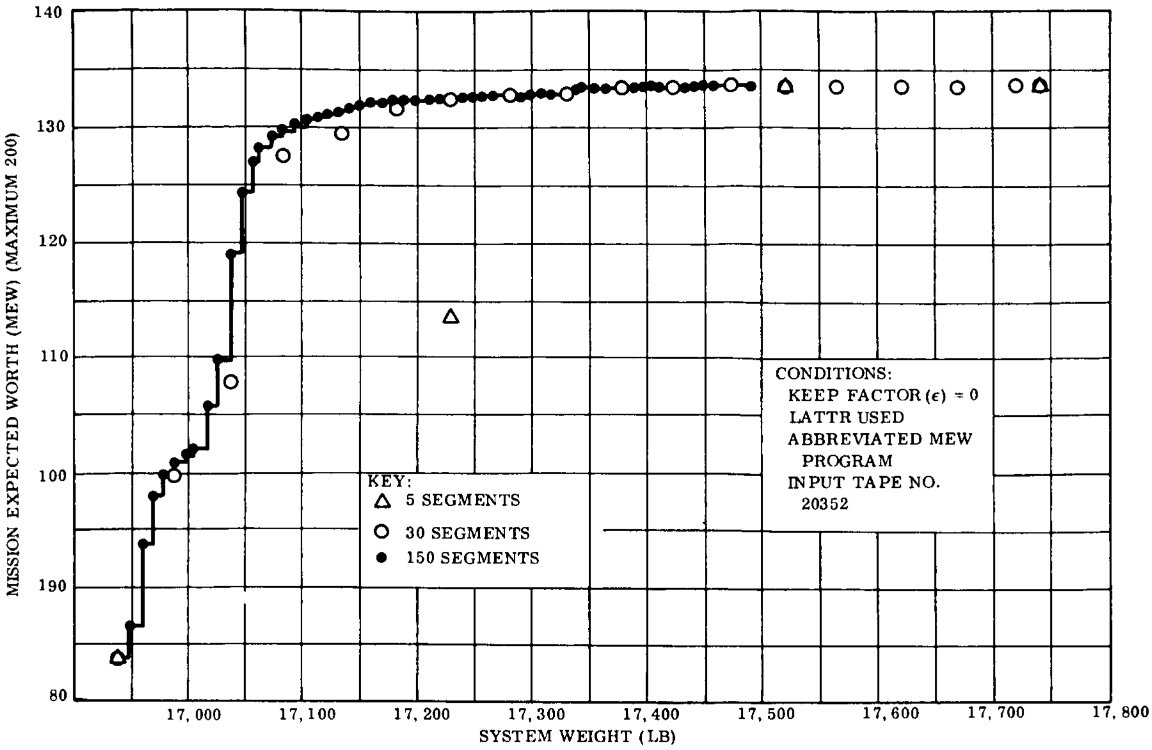


Figure 3-21. Optimization Results Using 5, 30 and 150 Segments

A maximum cost (weight) constraint may be placed on the system configuration, which effectively reduces the span of the cost scale over which configurations are selected. For a given number of segments, specifying a cost constraint has the effect of reducing the segment size. Employing such a constraint was generally found to be desirable, since it had the same effect as increasing the number of segments and eliminated the development of configurations outside the range of cost interest.

3.7.2.3 Full Versus Abbreviated MEW Calculation

The subroutine which evaluates MEW for any desired configuration was programmed so that a portion, rather than all, of the mission outcomes defined by the mission outcome tree could be considered. One such abbreviation of interest consists of considering only the upper branch of the outcome tree (i.e., the nominal mission profile) and eliminating all lower branches describing various degraded missions. Such an abbreviation was found to reduce the time required to calculate MEW by more than an order of magnitude. Since MEW is called many times in the optimization process, this reduction has a significant effect on the total running time for optimization.

The value of MEW computed using this abbreviated formulation is obviously less than the full MEW, which considers the degraded mission outcomes with their associated values. Experience (supported by intuition) showed that this difference between the full and abbreviated MEW became smaller as more reliable configurations were considered. For the best configurations, this difference was around 1.5 percent; and even for less reliable configurations, it was within 5 or 6 percent. Optimization runs using both the full and abbreviated MEW programs generally yielded identical configurations at higher costs, although some differences did occur among the configurations saved in the lower cost segments. Further, the ordered listing of independent assemblies ranked by $\delta_0 MEW/\Delta W$ (see Section 3.5) was somewhat changed when using the different MEW programs.

Nevertheless, it appears that the short MEW calculation may validly be used for investigation of configurations at higher weights, which is, after all, the general region of interest. The full MEW calculation appears necessary when investigating configurations in the region of the single-string configuration.

3.7.2.4 Use of the Keep Factor (ϵ)

The optimization program provides the option to eliminate candidate independent assemblies from consideration if their addition produces too small an increase in MEW for the added cost. The value of $\Delta MEW/\Delta W$ below which independent assemblies are not to be considered is known as the keep factor, ϵ.

Figure 3-22 illustrates the results of several runs with varying ϵ values. The initial effect of increasing the value of ϵ was to truncate the MEW-cost plot of dominant configurations at an upper value of cost. Further increases in ϵ not only increased the truncation of the plot, but also caused dropouts in the curve and a reduction in the value of the ordinate below the optimum curve. Increasing ϵ also reduced the computer processing time, since fewer independent assemblies were considered.

The results of Figure 3-22 may be explained based upon the following reasoning. The keep factor basically eliminates independent assemblies below a given MEW-cost slope, with MEW calculated with respect to the MEW_{max} configuration. Since the slope of the MEW-cost curve is generally decreasing, one would expect increasing ϵ to shorten the curve from the right, with occasional intermediate dropouts as the decreasing slope departs from monotonicity.

3.7.2.5 Sensitivity to Launch Vehicle Reliability

A series of optimization runs were made to determine the sensitivity of the selection of spacecraft system configurations to the probability of success of the launch vehicle. Nominally, a value of 0.85 was used as the probability of successful performance of the launch vehicle from liftoff through interplanetary trajectory injection (see LAA of Table 3-8). Additionally, values of 1.00 and 0.55 were investigated as extremes. Figure 3-23 shows these results.

As was expected, the value of MEW was found to be directly proportional to the launch vehicle reliability. The selected configurations, however, were not found to be sensitive to the launch vehicle. The same configurations were selected in each of these runs, even though their MEW values were substantially different.

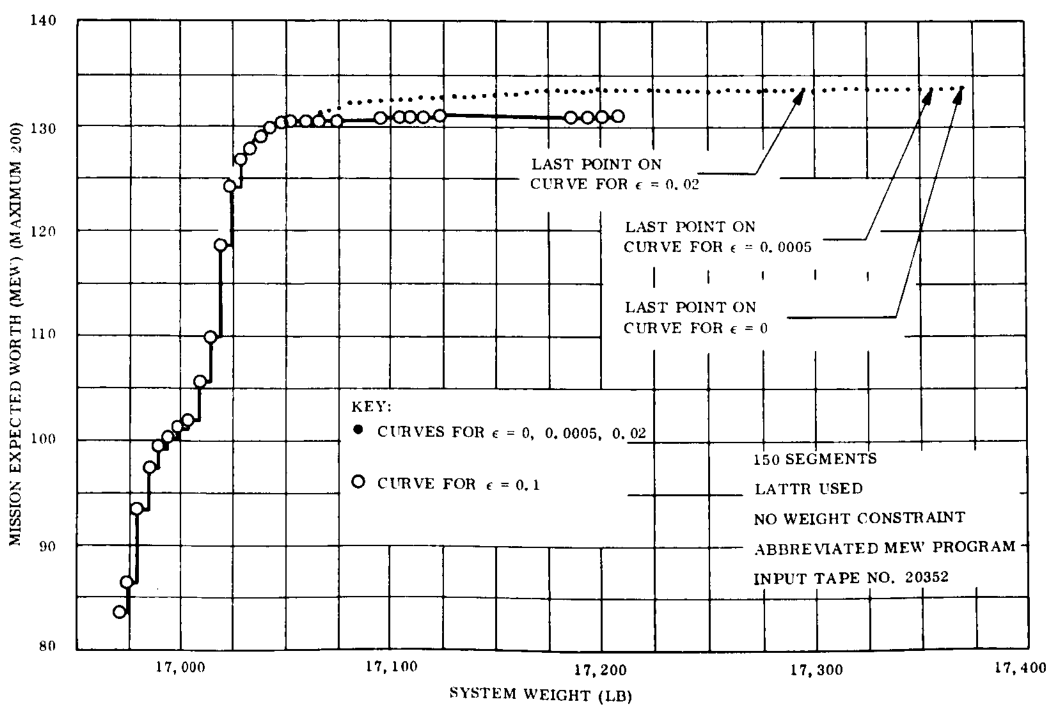


Figure 3-22. Optimization Results with Varying Keep Factors (ϵ)

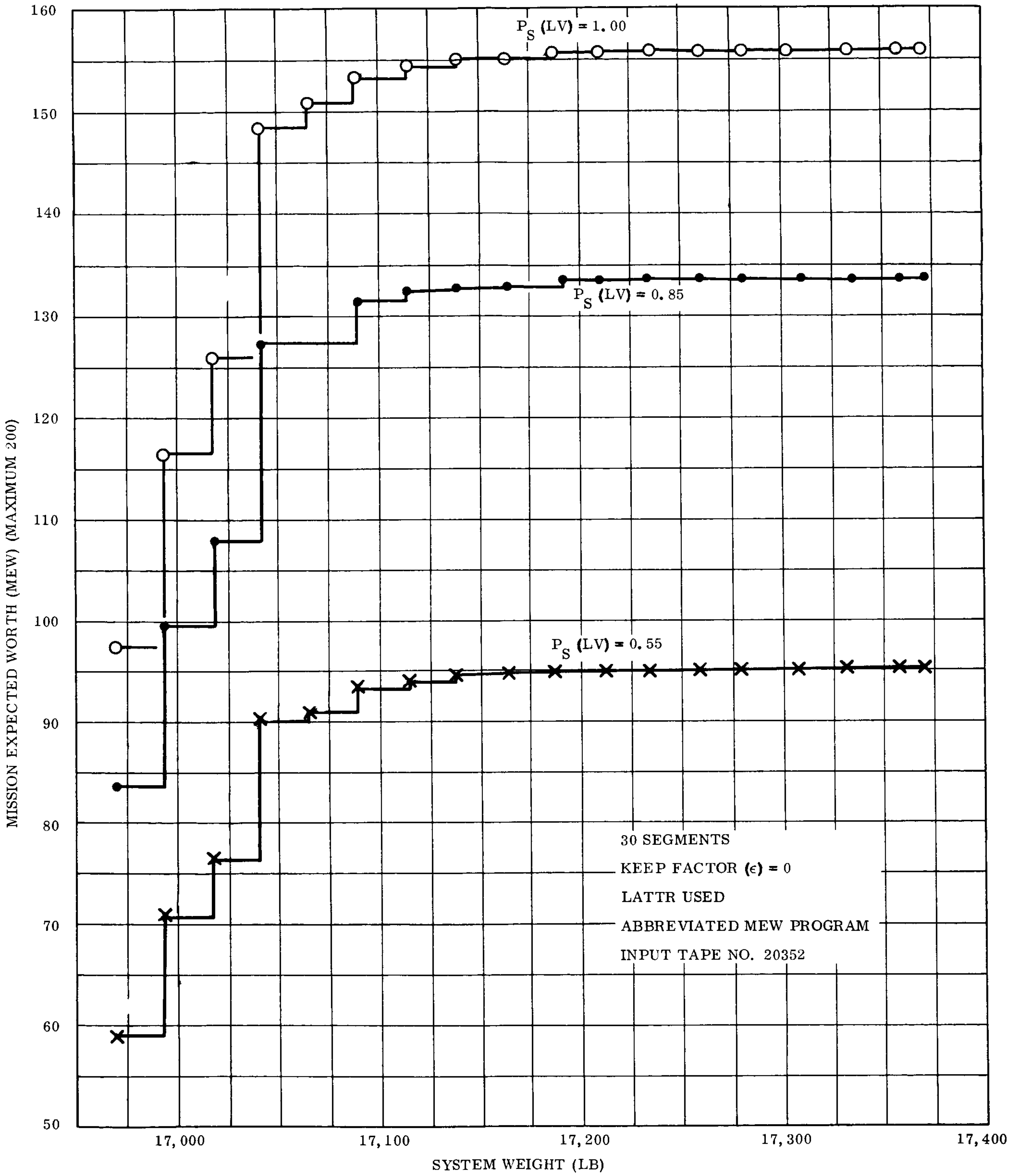


Figure 3-23. Optimization Results with Varying Launch Vehicle Reliabilities

3.7.2.6 Sensitivity to Science Equipment Reliability

A similar set of sensitivity runs was made varying the probability of successful operation of the scientific equipment aboard the spacecraft. The extreme values in this case ranged from perfect equipment to equipment with twice the nominal failure rate. The results were similar to those for the launch vehicle sensitivity runs, except that MEW was found to be far less sensitive to changes in scientific payload reliability. This may be explained by realizing that one-half of the value of the 1973 mission is engineering in nature. Of the remaining scientific half of the mission, the major value portion is obtained from the capsule, rather than from spacecraft science. Thus, changes in the reliability of the spacecraft scientific equipment can only affect a fraction of total mission expected worth.

3.7.2.7 Sensitivity to Mission Value Assignments

Another series of exercises was performed to determine the sensitivity of the configuration selection to the apportionment of value among the branches of the mission outcome tree. Four different value distributions were considered in addition to the nominal value assignments identified in Figure 3-2. These five sets of values are listed in Table 3-9 and may be summarized as follows:

a. Nominal value apportionment.

b. All of the value on the spacecraft. That value nominally assigned to the capsule is assigned to the spacecraft in the orbiter operations phase of the mission.

c. All of the value on the capsule.

d. All of the value to the spacecraft in subphase 27, the last mission subphase. In this case, the spacecraft must complete its total mission successfully, including six months of orbital operations, to receive any value.

e. All value to the spacecraft in subphase 25. This corresponds to the preceding situation, except that only one month of orbital operations is required.

Figure 3-24 shows the results of these runs. Note that MEW is generally sensitive to changes in value assignment. In particular, the 6-month requirement of successful orbital operation for any value return drastically reduced MEW from its nominal range.

Mission Phase And Subphase / Value Category	Lau In 1
(1) Nominal Value Assignment	1.0
(2) All Value on Spacecraft	1.0
(3) All Value on Capsule	--
(4) All Value on Spacecraft After Long-Term Orbital Operations	--
(5) All Value on Spacecraft After Short-Term Orbital Operations	--

ch And ection		Transit										Orbit Achi			
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1
1.0	4.0	1.0	0.25	1.0	0.5	0.5	0.5	0.25	--	4.0	--	12.0	6.0	4.0	4.
1.0	4.0	1.0	0.25	1.0	0.5	0.5	0.5	0.25	--	4.0	--	12.0	6.0	4.0	4.
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-

Table 3-9. Value Categories Used in Value Sensitivity Runs

evement			Orbit Descent And Entry			Capsule Operations		Orbiter Operations			
7	18	19	20	21	22	23	24	25	26	27	Total
.5	2.0	3.5	4.0	4.0	2.0	27.0	74.0	22.0	2.0	19.0	200.0
.5	2.0	3.5	4.0	4.0	2.0	--	--	73.0	2.0	69.0	200.0
-	--	--	--	--	--	54.0	146.0	--	--	--	200.0
-	--	--	--	--	--	--	--	--	--	200.0	200.0
-	--	--	--	--	--	--	--	200.0	--	--	200.0

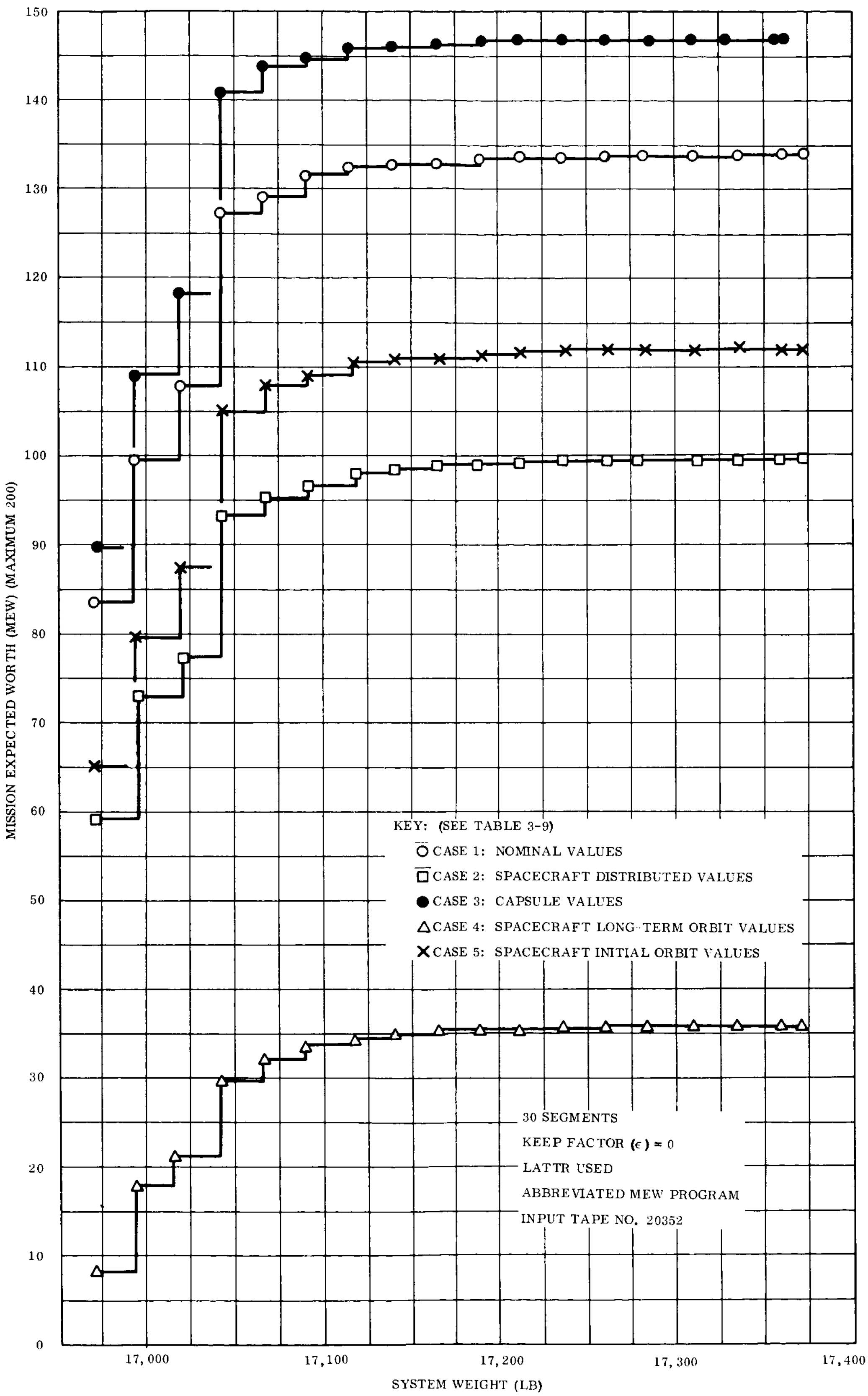


Figure 3-24. Optimization Results with Varying Value Assignments

The configuration selection, however, was found to be less sensitive to value changes, particularly when values were not shifted between the capsule and spacecraft systems. For example, the configurations selected for various system weights are either quite similar or identical for the value curves of cases 1, 2, 4, and 5 (Figure 3-24). When all of the value was placed on the capsule system in case 3, changes occurred in those independent assemblies not required to deliver the capsule. In particular, those independent assemblies associated with obtaining orbital science reverted to the single-string alternate implementation. Thus, spacecraft configuration selection was found to be somewhat insensitive to the distribution of mission value within the spacecraft system, but not among systems.

3.7.2.8 Configuration Recommendations

The optimization program exercise that provided most of the insight into the amount and type of redundancy that should be employed within the spacecraft system was the so-called reference run, with the following conditions:

a. 150 segments.
b. Lower-and-to-the-right criterion employed.
c. Keep factor = ϵ = 0.
d. Abbreviated MEW program.

The results of the reference run are presented in two forms. Figure 3-25 is a plot of MEW versus total system weight. Figure 3-26 is an independent assembly tabulation of each of the system configurations on the curve of Figure 3-25. The top line of Figure 3-26 gives the configuration having the highest MEW value, called the maximum MEW configuration. The alternates for this configuration are listed from left to right across the page according to their ranking in the δ_0 MEW/ΔW listing computed at the beginning of the optimization process. For all configurations listed below the maximum MEW configuration (i.e., all configurations of less weight), only those alternates which differ from the maximum MEW configuration are shown. In other words, a blank under a family column implies that the alternate from that family for that configuration is the same independent assembly as is used in the maximum MEW configuration. To simplify the chart further, those families which have no redundant alternate plus those where the single-string alternate appeared in all final configurations are not shown.

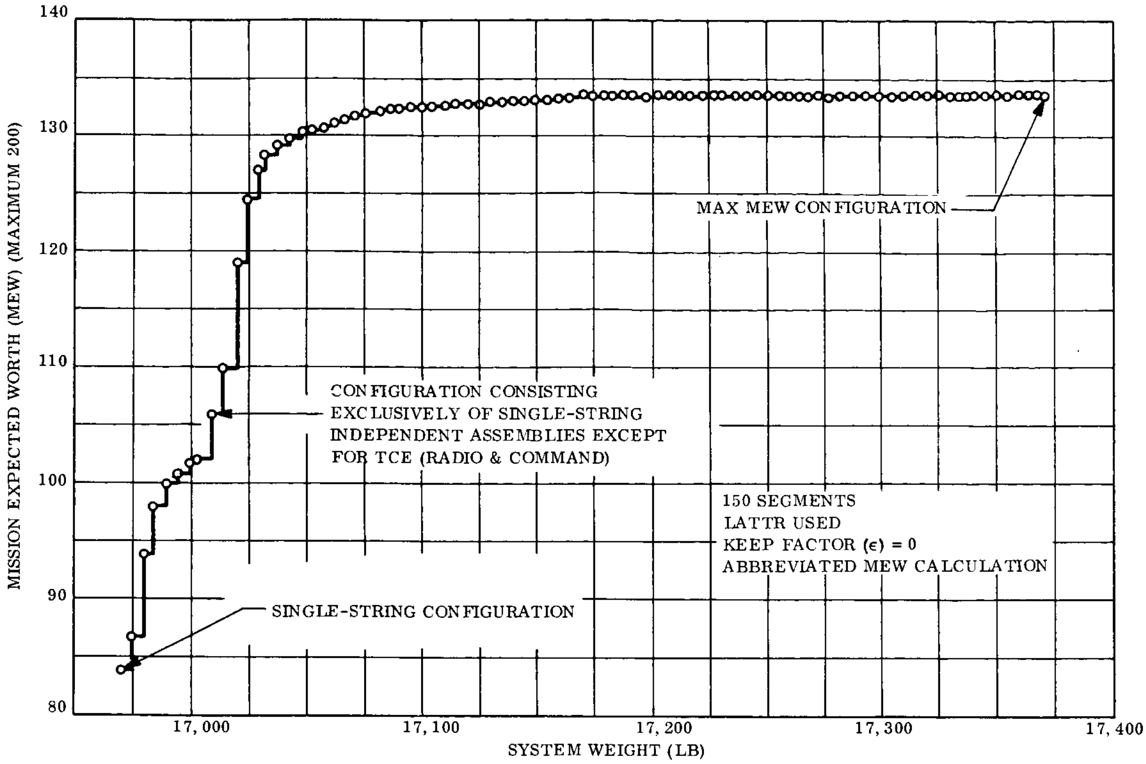


Figure 3-25. Optimization Results, Reference Run

It is interesting to note that nearly all of the increase in MEW occurs within the first 15 increments in weight. Furthermore, study of the configuration patterns of Figure 3-26 shows that this occurs in two stages. The configurations of the first seven increments are made up by gradually adding weight in one or more of families, as shown in the chart. In the eighth increment, the TCA (Radio and Command)alternate is replaced by the TCE alternate, while all other families revert to their single-string alternates. The increase in MEW at this point is almost 50 percent of the maximum attainable increase over single-string with the set of available redundant alternates. The following seven configurations essentially duplicate the pattern of the first seven segments. Beyond this point, the value of MEW levels off to a maximum value of 133.8 out of a maximum of 200 (66.9 percent).

The behavior of the MEW weight curve of Figures 3-25 and 3-26 suggests the following interpretation: a relatively few spacecraft system families have a dominant role in effecting the value of MEW. These families are characterized by the following two conditions:

MEW	WEIGHT (POUNDS)	INDEPENDENT ASSEMBLY FAMILY																																		
		CK	CP	GA	MC	TC	CM	GG	TB	GE	CN	EF	CJ	CG	CF	CH	GB	EH	TA	ED	CA	EC	EE	GD	CE	EG	PN	EA	MD	GH	EB	PC	GF	PD	MR	MH
133.8115	17370.22	B	B	E	B	B	B	C	B	B	B	B	B	B	B	D	B	B	C	R	H	P	B	B	C	B	B	C	F	B	F	B	B	B	B	B
133.8115	17366.22																																			A
133.8106	17362.22																																C	A		A
133.8093	17358.22																															A	A	A		A
133.8052	17353.22																														E		A	A		A
133.8043	17348.22																												E				C	A		A
133.8030	17343.62																												E			A	A	A	A	A
133.7989	17338.62																												E		E		A	A	A	A
133.7931	17334.22																												E		D		C	A		A
133.7878	17329.32																		B										E		E	A	A	A		A
133.7833	17323.22																												E		C	A	A	A		A
133.7744	17319.32																		B										E		C		C	A		A
133.7731	17314.72																		B										E		C	A	A	A	A	A
133.7622	17309.72																		B										E		B		A	A	A	A
133.7480	17304.72																		B										E		A		C	A	A	A
133.7366	17300.22																		B										E	A	A		A	A	A	A
133.7280	17294.72																		B	D									E		A	A	A	A		A
133.7157	17286.22																							E												
133.7157	17282.22																							E												A
133.7154	17280.22																							E										A		A
133.7145	17275.62																							E									A	A	A	A
133.7097	17270.62																							E							E		C	A	A	A
133.7091	17266.22																							E					E					A		A
133.7073	17260.22																							E					E			A	A	A		A
133.7031	17255.22																							E					E	E			A	A		A
133.6979	17251.62																							E					E	D				A	A	A
133.6961	17246.22																													D	A	A	A	A		A
133.6885	17241.22																							E					E	C			A	A		A
133.6792	17236.72																		B					E					E	C				A	A	A
133.6774	17231.32																		B					E					E	C	A	A	A	A		A
133.6665	17226.32																		B					E					E	B		A	A	A		A
133.6523	17221.32																		B					E					E	A		C	C	A		A
133.6511	17217.32																		B					E					E		A	A	A	A		A
133.6333	17212.72																		B	D				E					E	A	C	A	A	A		A
133.6212	17207.62																		B	D				E					E	A	B	A	A	A	A	A
133.5740	17203.02					E													B	D				E					E	A	A		A	A		A
133.5069	17198.22																		B					E				B	E	A	A	A	A	A	A	A
133.5053	17192.32																		B					E				B			A		A	A		A
133.4917	17187.32																		B					E				B	E	A	A	A	A	A		A
133.4797	17182.82																		B					E				B	E		A	A	A	A		A
133.4722	17178.72																		B	D				E				B	E	A	A	A	A	A		A
133.4283	17173.62																		B	D				E		A		B	E	A	A	A	A	A		A
133.3811	17169.02					E													B	D				E		A		B	E	A	A	A	A	A	A	A
133.3023	17163.92					E													B	D		D		E				B	E	A	A	A	A	A		A
133.1726	17159.02					E													B	D				E				A	E	A	A	A	A	A		A
133.1381	17153.92					E													B	D		D		E		A		B	B	A	A	A	A	A		A
133.0289	17149.32					E													B	D		D		E		A		A	E	A	A	A	A	A	A	A
132.9303	17143.92					E													B	D		D		F				A	B	A	A	A	A	A		A
132.9127	17139.62																		B					F				B	E		A		C	A	A	A
132.9014	17135.12																		B					F				B	E	A	A		A	A	A	A
132.8931	17129.62																		B	D				F				B	E		A	A	A	A		A
132.8494	17125.12																		B	D				F		A		B	E	A	A	A	A	A		A
132.8223	17120.32					E													B	D	G			F				B	E	A	A	A	A	A		A
132.7240	17114.82					E													B	D		D		F				B	E	A	A	A	A	A		A
132.6050	17110.72					E													B	D		D		F				B	B		A		A	A	A	A
132.5866	17105.72					E													B	D		D		F			A	B	B	A	A	A	A	A	A	A
132.4525	17100.82					E																D	A			A		A	E			A	A	A		A
132.3552	17096.22					E													B	D		D		F				A	B	A	A		A	A	A	A
132.3151	17091.22					E													B	D		D		F		A	A	A	A	A	A	A	A	A	A	A
132.1596	17085.82					E													B	D				F		A		A	B	A	A	A	A	A		A
132.0925	17081.72					E													B	D	G	D	A	F				A	B	A	A	A	A	A	A	A
131.8500	17076.52																		B	D	F	D	A	F				A	B	A	A	A	A	A	A	A
131.6464	17071.48					E													B	D	A	D	A	F		A		A	B	A	A	A	A	A		A
131.3058	17067.22					E												A	B	D		D	A	F			A	A	B	A	A	A	A	A	A	A
131.0401	17062.08					E											A		B	D	A	D	A	F		A	A	A	B	A	A	A	A	A	A	A
130.8689	17057.48					E												A	B	D	A	D	A	F		A		A	B	A	A	A	A	A		A
130.4430	17052.43					E		A								B		A	B	D	A	D	A	F	B	A		A	B	A	A	A	A	A		A
130.2665	17047.58					E											A	A	B	D	A	D	A	F		A	A	A	A	A	A	A	A	A	A	A
129.8430	17042.53					E		A								B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
129.0532	17037.93					E		A					A	A	A	B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
128.0621	17032.93					E		A				A	A	A	A	B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
126.8847	17028.33					E		A	A	A	A	A	A	A	A	B	A	A	B	D	A	C	A	F	B	A	A	A	A	A	A	A	A	A	A	A
124.1552	17023.43					E	A	A	A	A	A	A	A	A	A	A	A	A	A	C	A	A	A	F	B	A	A	A	A	A	A	A	A	A	A	A
118.8325	17018.68				A	E	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
109.7728	17013.83		A		A	E	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	B	A	A	A	A	A	A	A	A	A	A	A
105.7581	17008.98	A	A	A	A	E	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
101.9608	17003.73					A		A								B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
101.3518	16999.13					A		A					A	A	A	B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
100.5890	16994.13					A		A				A	A	A	A	B	A	A	B	D	A	D	A	F	B	A	A	A	A	A	A	A	A	A	A	A
99.7176	16989.53					A		A	A	A	A	A	A	A	A	B	A	A	B	D	A	C	A	F	B	A	A	A	A	A	A	A	A	A	A	A
97.5870	16984.63					A	A	A	A	A	A	A	A	A	A	A	A	A	A	C	A	A	A	F	B	A	A	A	A	A	A	A	A	A	A	A
93.4823	16979.88				A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
86.4888	16975.03		A		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	B	A	A	A	A	A	A	A	A	A	A	A

PROGRAMS OPTIONS
150 Segments
Lattr Used
Keep Factor $(-\epsilon) = 0$
Abbreviated MEW Program

NOTES:
(1) Families Which Are Not Listed Employ The Single-String Alternate In Every System Configuration.
(2) Blanks Indicate That The Alternate For That Configuration Is The Same As That Used In MEW Max.Configuration On The Top Line Of The Figure.
(3) The Ordering Of Families From Left To Right Is By Decreasing Rank Of δ_o MEW/ΔW

Figure 3-26. Detailed System Configurations, Reference Run

3-99

a. The reliability of the single-string independent assembly is sufficiently low and the mission role of that family is sufficiently critical as to account for a substantial loss of mission expected worth by using the single-string assembly.

b. A redundant alternate independent assembly with significantly improved reliability is defined.

One obviously fruitful future course of action suggests itself immediately from the above results--to examine additional redundant alternate independent assemblies for these key families.

A means of studying the relative effect of a particular independent assembly on mission expected worth was suggested late in the study. It consists of computing MEW for the system with all families except the one independent assembly under consideration assumed to have perfect reliability. Then, the independent assemblies would be ranked according to their MEW values in perfect system configurations. The families with the lowest values of MEW would indeed be fertile areas for additional redundancy and a significant resulting improvement in overall mission expected worth.

3.7.2.9 System Reliability

Some insight into the correlation between MEW and the more familiar reliability figure of merit may be gained from Figure 3-27. The upper curve represents the MEW-cost plot for nominal value apportioned throughout the various mission subphases. In this case, partial value is awarded for partial success. The lower curve represents the assignment of all value to completion of the total mission, assumed to be completion of one month of orbital operation for the 1973 mission; i.e., case 5 of Figure 3-24. Thus, for example, a spacecraft configuration that weighs about 17,350 pounds would have a probability of 56 percent of successfully completing its entire mission (including the effect of the launch vehicle). It also would have a mission expected worth of about 134 of 200 worth points distributed throughout the mission (about 67 percent).

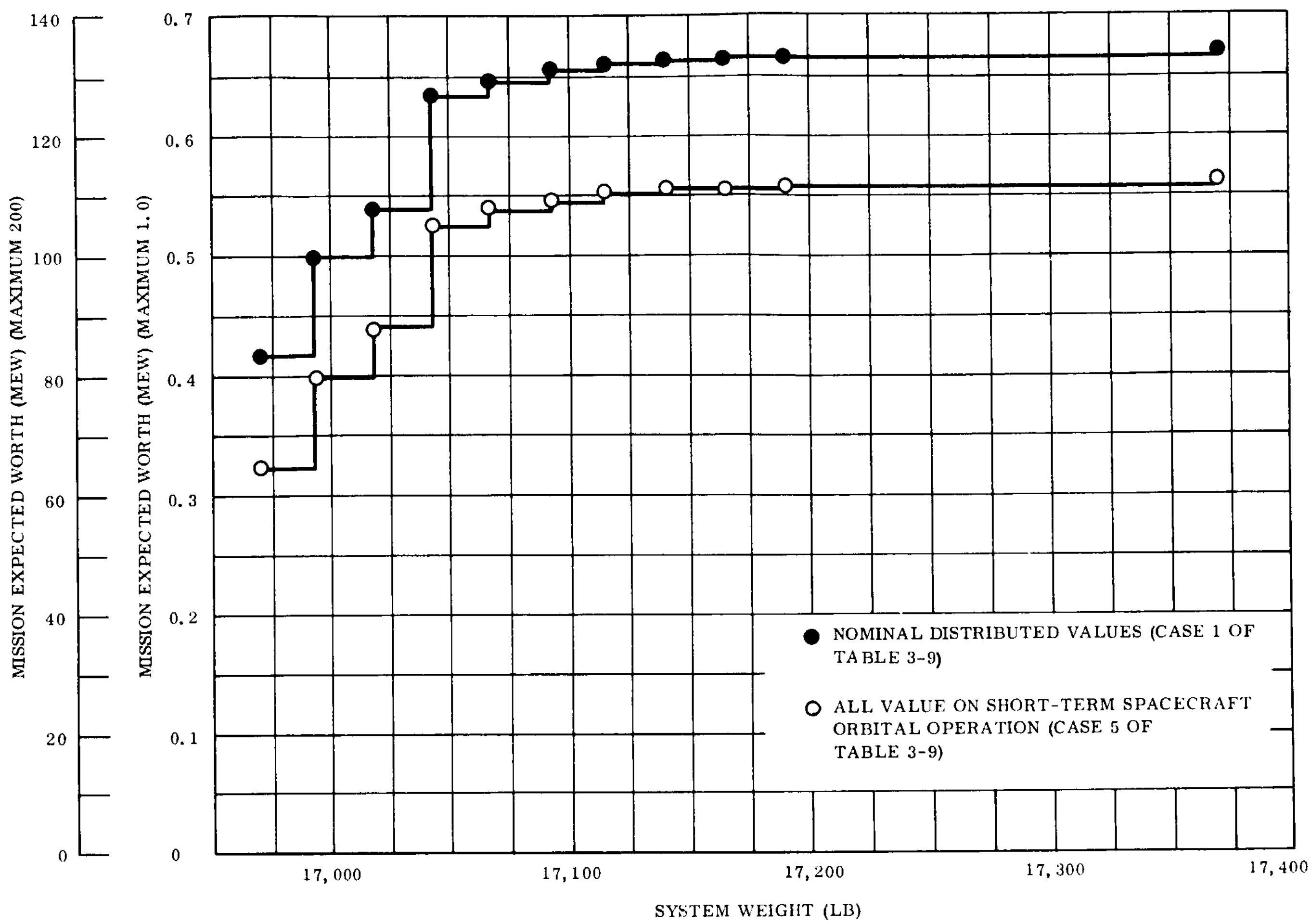


Figure 3-27. Comparison of Mission Expected with Reliability

3.7.2.10 Expected Worth of the Nominal 1973 Voyager Mission

All of the results presented to this point have been for a mission configuration consisting of one launch vehicle, one spacecraft, and one capsule; i.e., one launch vehicle and one planetary vehicle (spacecraft and capsule).

The nominal Voyager mission configuration consists of one launch vehicle and two planetary vehicles. The resulting MEW-cost curve for the nominal two-on-one mission configuration (assuming that no additional worth is accrued by repeating mission objectives) is contrasted with the one-on-one configuration in Figure 3-28 for two cases of launch vehicle reliability: nominal (P_S = 0.85) and perfect (P_S = 1.0).

Figure 3-28 reveals that, for the nominal Voyager mission configuration, the expected worth of the mission is about 81 percent of the maximum attainable worth.

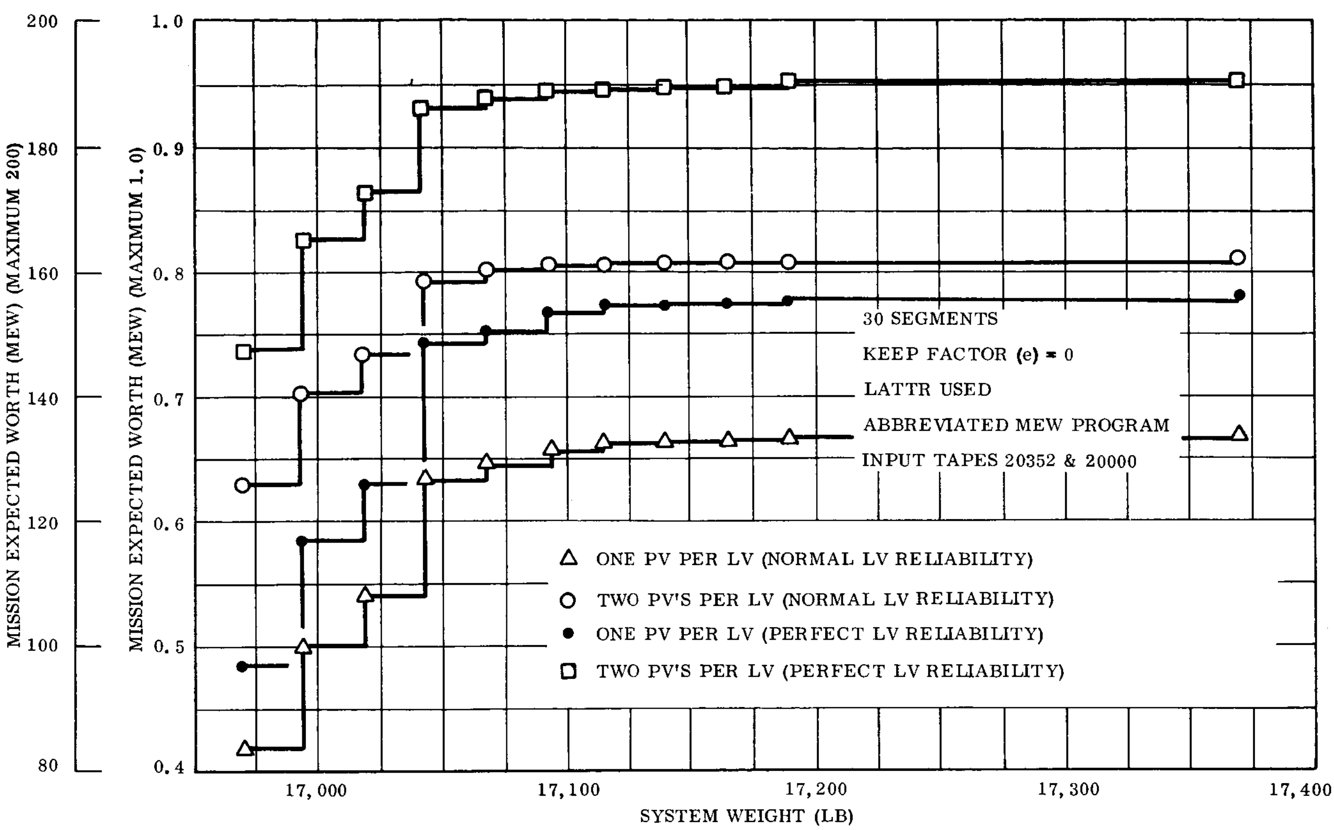


Figure 3-28. Mission Expected Worth with 1 and 2 Planetary Vehicles/Launch Vehicles

3.8 CONCLUSIONS

3.8.1 ASSUMPTIONS, APPROXIMATIONS AND ANALYSES OF ERRORS

3.8.1.1 Configuration Optimization Method

Because it is impractical to consider all of the possible 10^{21} system configurations in the configuration optimization process, only certain of the system configurations are evaluated and carried forth in the configuration building process in accordance with the configuration comparison and discarding criterion. Ideally, any partial configurations discarded cannot be those which might ultimately be preferred.

In parallel with the development of this tool, a study was initiated to determine if, under all known conditions, the present optimization method -- or more precisely, the present method of ordering configurations in the buildup to preferred configurations could result in the discarding of any preferred configurations. This study revealed that, under certain combinations of circumstances, the preferred configurations might indeed be dropped. However, by comparing optimization results using two different methods of ordering configuration for the computation of MEW, confidence was established that these situations do not generally arise.

In parallel with the foregoing study, Stanford Research Institute also was independently engaged to analyze this problem. This investigation revealed that, although the present optimization procedure cannot be proven to yield the true optimum (because certain variables cannot be separated in the mission expected worth equation), neither can it be proven not to yield the true optimum over reasonable ranges of input data. SRI also concluded that difficulties would be encountered with all optimization procedures presently available, and that the dynamic programming technique of Section 3.5 is probably the best approach. SRI observed that the optimization procedure will rarely yield the wrong answer, and if it does, the error will be small.

The two independent studies discussed above agreed that (1) the present optimization method is imperfect, but that (2) the likelihood of not selecting preferred configurations of significance is extremely small.

3.8.1.2 Method for Computing Mission Expected Worth

The calculation of mission expected worth is by accrual; i.e., proceeding from left-to-right in the mission outcome tree, a running sum of expected worth is accumulated. In each subphase, the branch probabilities are multiplied by their respective values, and these products are added to the subtotal that has been accumulated through the previous mission subphase. This procedure is repeated until all subphases have been calculated.

The subphase branch probabilities are computed in accordance with the mission outcome tree, the map matrix, and the output state probabilities for the independent assemblies. However, a rigorous calculation of MEW also entails consideration of all possible combinations of the subphase-by-subphase histories of independent assembly states. The prohibitive manual analysis and computational time requirements for such an exact solution were obviated by using the approximation of independent assembly conditional probabilities discussed in Subsection 3.6.6.

A task was undertaken to determine the extent of error (if any) introduced in the optimization process as a result of the conditional probability approximation. This effort was successful to the extent that it identified the specific nature of the approximation. However, efforts to bound the approximation error in any absolute sense were not successful. On the other hand, comparisons among selected optimization runs gave confidence that any errors resulting from the conditional approximation are apparently small.

In order to remove the need for approximation in the calculation of MEW, two other tasks were initiated in parallel with the above error analysis. The first task sought to determine if MEW could be computed exactly and more simply without using conditional probabilities. The study team was given considerable freedom to make reasonable assumptions.

Initially, this effort appeared promising if certain assumptions could be made. A closer examination of this approach revealed, however, that its computational difficulties may be as great as those involved in the present approximation method. Therefore, this method does not currently promise a simpler method of calculating MEW.

The second task tried to determine if MEW could be computed exactly using an interpretive computer program (to be developed) to read in the mission outcome tree and map matrix, develop logic expressions for the computation of MEW, and reduce them to arithmetic expressions suitable for computation on a general purpose computer. The feasibility of such an interpretive program was demonstrated. It still remains to be determined whether the time required to compute MEW by this technique is within reason.

3.8.1.3 Probability Calculator Methodology

The computation of the output state probabilities for the independent assemblies generally requires the solution of a set of simultaneous differential equations. The SIP method of solving these differential equations involves nominally 100 numerical integrations per mission subphase using a fourth order Runge-Kutta integration technique.

A study of results from identical probability calculator runs on the Honeywell 1800 (48-bit) system and the General Electric 635 (36-bit) system revealed that the Honeywell 1800 yielded probabilities accurate to six places to the right of the decimal point, while the General Electric 635 yielded probabilities accurate to only four places. In these identical runs, it was noted that the precision obtained was only about one-half that obtainable on the computing system.

A limited study revealed that the Runge-Kutta technique itself may result in significant propagation of truncation errors, which are compounded by the large number of integrations per mission subphase. A small-scale test was then conducted to determine the effect of using fewer integrations per subphase. This test revealed that the computational accuracy of the probability calculator improved somewhat with reduced integrations, and the computer running time was significantly reduced.

A check of other computations made by the program system did not uncover any other areas where truncation leads to errors. In summary, the Runge-Kutta technique for solving the state diagram differential equations must be regarded as less than ideal because of the propagation of truncation errors.

3.8.2 RECOMMENDATIONS FOR FURTHER STUDIES

3.8.2.1 Configuration Optimization Methodology

It is observed in Subsection 3.8.1 that the configuration dynamic discarding process could, in some instances, result in the discarding of preferred configurations. One fruitful area for further study would be to investigate several different methods of ordering independent assemblies in the buildup process to determine the effect, if any, of ordering on the selection of preferred configurations.

If it is determined that the selection of preferred configurations is insensitive to the ordering method, then confidence in the accuracy of the present ordering method will be increased even more. If, on the other hand, it is determined that the selection of the preferred configuration is sensitive to the ordering method, then the study should be continued to determine the optimal ordering method. Indeed, it may be shown that two or even more different ordering methods should be used in the same optimization study to ensure that preferred configurations are not discarded.

3.8.2.2 Methodology for Calculating Mission Expected Worth

The approximations involved in calculating MEW are reviewed in Subsection 3.8.1. Two studies were discussed regarding the elimination of these approximations: (1) to determine if MEW could be computed exactly and more simply, and (2) to determine whether an interpretive computer program could be developed to permit an exact calculation of MEW.

Further study is desirable in both of these areas. In particular, in the second study area, it is recommended that the interpretive computer program approach be studied in more detail to see whether the computer time requirements are practical.

3.8.2.3 Reduction of System Computing Time

The present optimization program system requires considerable computer time. This time can be divided into two categories:

a. One-shot runs. Required for the calculation of independent assembly state probabilities on an assembly-by-assembly basis.

b. Production runs. One for each MEW-cost curve desired.

The total one-shot computer time for the probability calculator is approximately 60 hours (on the GE 635), which includes 20 hours of basic calculation and 40 hours of rerun. The time for a production run varies from about one-half hour to three hours, depending upon the parameters selected; e.g., the number of grid segments, abbreviated vs full MEW calculation, etc.

To reduce the time required for one-shot runs, it is recommended that the number of probability calculator integrations per subphase be analyzed toward the goal of a significant reduction. This study must, of course, consider the inaccuracy introduced by fewer integrations. A test run has already revealed that one-shot computer time can be reduced by as much as a factor of five by reducing the number of integration intervals.

It is also recommended that techniques be explored to reduce the production run time, with particular reference to reducing the upper range of running time (i.e., three hours) when all parameters are set for maximum resolution.

3.8.2.4 Further Use of the Tool

The preceding three subsections are concerned with the methodology of the redundancy optimization tool itself. This subsection is devoted to a more realistic question--viz., what can the tool do for Voyager ?

There is no question that the results of Section 3.7, with particular reference to the configurations of Subsection 3.7.2.8, lend considerable insight into the amount and type of redundancy which should be applied within the spacecraft system.

The quality of the output of the system redundancy tool is proportional to the quality of the input; i.e., the definition of the single-string spacecraft system and potential redundancy. For this study, this input definition was performed within the framework of the General Electric Phase IA, Task B design. Since the Task B design is nearly two years old at the time of this writing, it would seem appropriate to re-examine the input definition in light of the system design evolution through Tasks C and D.

Specifically, it is strongly recommended that the mission and system definition input to the tool be remodeled and the optimization system be re-exercised to reflect evolutionary changes in the mission profile and system design since Task B, with special reference to the system design update of Phase IA, Task D.

Secondly, recent work by the GE Long-Life Space Systems Program has revealed that failure mechanisms may be grouped into two categories:

a. Non-systematic Failures. Those that occur in only one component of a type.

b. Systematic Failures. Those that occur in all components of one type.

Block redundancy is obviously effective against non-systematic, but not systematic failures. Functional redundancy is a safeguard against systematic failures.

The hardware reliability models discussed in Section, 3.4 and 3.5 basically recognize only non-systematic (or random) failures. The Long-Life Program has shown, however, that systematic failures are equally if not more prevalent in complex spacecraft systems than non-systematic failures. This has strong implications of the ratio of functional to block redundancy which should be designed into the spacecraft.

Accordingly, it is strongly suggested that any redefinition effort include modifying the hardware reliability models to reflect systematic as well as random failures.

3.8.3 CONCLUSIONS

The most important single conclusion that can be drawn from this effort is that a workable tool for the design of redundancy within a spacecraft system has been developed. Although designed for the Voyager mission and the Voyager spacecraft system, the tool is adaptable to other spacecraft in complex mission environments.

In the development of this tool, decisions often had to be made whether or not to simplify an assemblage of information. For example, a decision had to be made whether or not to consider degraded modes of hardware performance, whether or not to consider degraded modes of mission performance, etc. In nearly all cases, the decision was not to simplify the tool and to avoid assumptions and approximations. By employing this strategy, it was recognized that some facets of the tool would probably be unnecessarily complicated. However, this strategy did permit rapid simplification as soon as such complications were clearly recognized. In contrast, a strategy to simplify at every turn would have required either several iterations of the development cycle or a tool of little value.

In the spirit of the preceding statement, and based on the findings of the several optimization runs of Section 3.7, it can be concluded that the proper level of complexity was generally designed into the tool, with perhaps one exception. In the Radio and Command assembly (TC), nine output states were defined, including seven degraded states. It now appears that the number of output states could have been significantly reduced--perhaps to five output states.

It is believed that this study has demonstrated the power of the configuration optimization tool in the conceptual design stages of a spacecraft program. No longer need subsystem engineers compete with one another for each ounce of weight. Redundancy can now be applied to the system design in an optimum and integrated manner.

This system optimization tool can be made even more powerful if the refinements suggested in the previous sections can be incorporated. The potential of this tool, however, can only be realized if it is used as a dynamic aid to the continuing design of the Voyager spacecraft.

SECTION 4

SELECTION OF MISSION CONFIGURATIONS

4.1 OBJECTIVES

The objectives of the mission redundancy activity were to develop techniques for the selection of the initial Voyager mission configuration, and the probable sequence of configurations to follow the initial configuration, and to recommend a typical sequence of mission configurations.

Mission configuration selection is meant to connote the number and types of systems which should be employed at a given launch opportunity, with particular reference to the number and types of launch vehicles, spacecraft, and capsules. During the course of the study, the capsule system was redefined as two systems: (1) the capsule bus system and (2) the surface laboratory system. It was felt, however, that recognizing the subdivision at that point would not appreciably aid the study and, accordingly, the capsule system as defined in this section includes both the bus and the surface laboratory.

It is in this area of activity that Stanford Research Institute (SRI) of Menlo Park, California, was engaged to apply the principles of "decision analysis" to the selection of Voyager mission configurations. Major portions of this section were authored by SRI; viz., Sections 4.3, 4.4, 4.7, 4.10, 4.11, and 4.12 in their entirety, and portions of Sections 4.5 and 4.8.

4.2 ORGANIZATION

The mission configuration selection activity was divided into several areas of activity (Figure 4-1):

a. Pilot Model: Definition of a small-scale or pilot version of the Voyager project, and selection of optimum mission configurations and sequences within this pilot framework.

b. Problem Structure: Definition of potential mission configurations to be considered in the problem structure. Definition of a comprehensive and mutually exclusive set of project outcomes.

c. Decision Model: Definition of the state variables and generation of the mission configuration decision tree.

d. Probability Model: Modeling of the probabilities of potential mission configurations achieving given project outcomes.

e. Cost Model: Modeling of the costs of potential mission configurations.

f. Value Model: Modeling of the relative values of possible outcomes of the project.

g. Mission Configuration Selection: Development of a computer program system employing decision analysis to select the initial Voyager mission configuration and probable subsequent sequence of configurations. Exercise of the tool to recommend a typical preferred 1973 mission configuration and subsequent sequences.

Section 4 is organized generally along the lines of Figure 4-1. A brief introduction to decision analysis and its application to Voyager is given in Sections 4.3 and 4.4. Section 4.5 then reviews the pilot phase of the mission configuration selection effort. The problem structure (i.e., potential mission configurations and project outcomes) is reviewed in Section 4.6. The four basic models of the configuration selection system (the decision model, probability model, cost model, and value model) are reviewed in Sections 4.7 through 4.10. Section 4.11 discusses the SPAN (Space Programs ANalysis) system, the computer program system which creates the decision structure and performs the necessary analyses to extract optimum configurations and sequences. Finally, Sections 4.12 and 4.13 discuss typical results and present conclusions and recommendations.

4.3 DECISION ANALYSIS

Decision analysis, an applied extension of statistical decision theory, is a procedure for the logical and quantitative analysis of the factors that influence a decision. A decision, in this context, is an allocation of resources as opposed to a generalized mental commitment to follow a given course of action or to pursue given objectives. A logical decision is one that selects the most economic alternative in terms of the preferences of the decision-maker. The values and costs of the possible courses of action and their possible outcomes, and the probability of these outcomes, are determined on the basis of the knowledge and experience

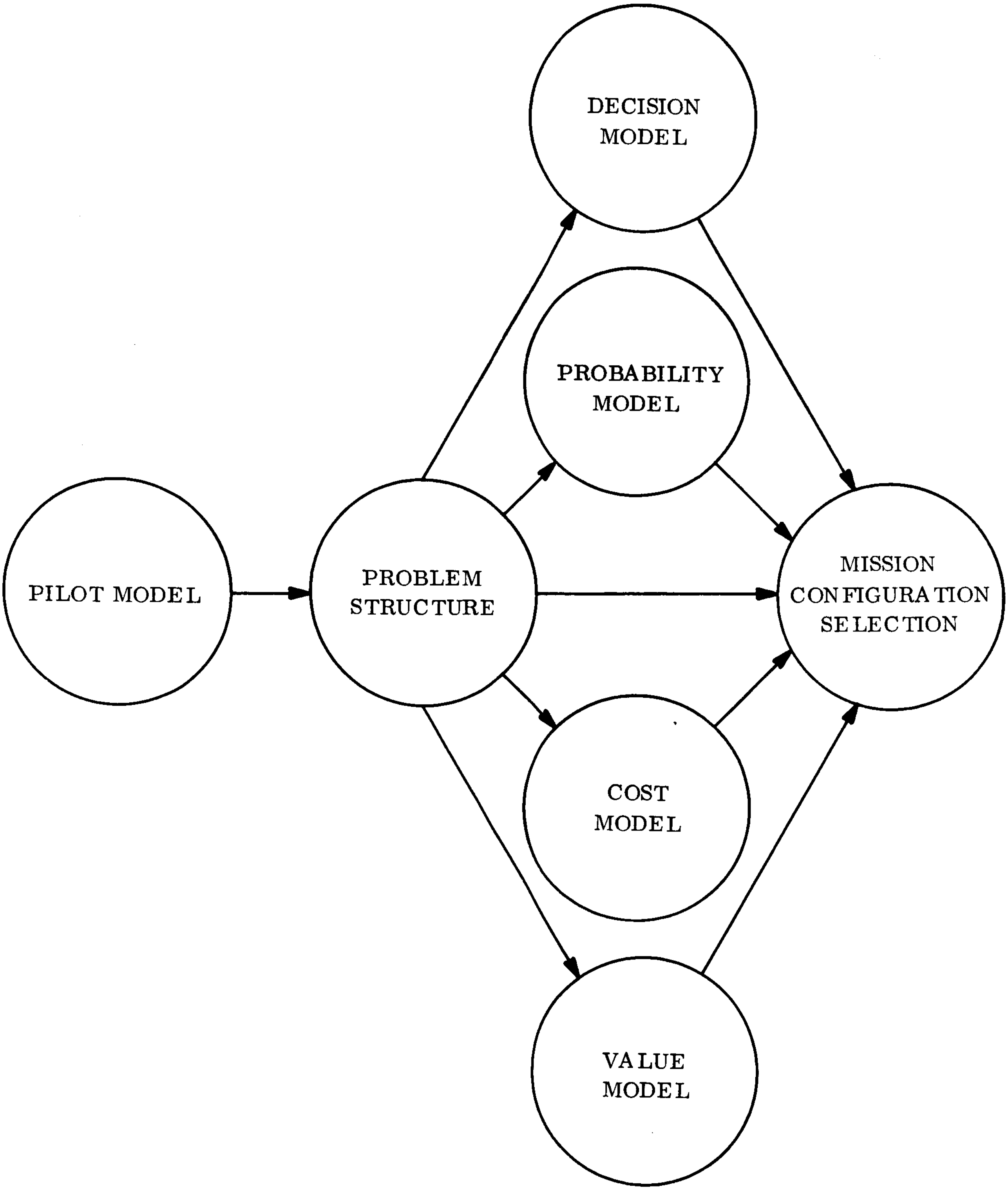


Figure 4-1. Selection of Voyager Mission Configurations Organization

available to the decision-maker. A quantitative analysis is one that places the decision in an unambiguous structure in which numerical quantities encode the factors that influence the decision in order to quantitatively weigh these factors. Decision analysis incorporates the fundamentals of decision theory as a means of quantifying the decision process while maintaining the logical basis for a rational decision.

Decision making requires the study of uncertainty. Most decisions would be easy if there were no uncertainties in the outcomes resulting from a course of action. When the outcomes are uncertain, even simple decisions become more difficult to analyze. The theory of probability provides the basis for the meaningful treatment of uncertainty. Probability is a state of mind and not of things. All prior experience must be used in measuring probabilities. If we have seen a lot of data, such as a million flips of a bent coin, the overwhelming data will be the predominate influence on the probability assignment to heads on the next flip. If we have never flipped a bent coin before, the probability measurement must depend on judgment and prior experience, possibly including physical models we might build to describe the dynamics of flipping a bent coin. If we have seen only a few flips of the bent coin, we must combine our prior experience with the limited new data. The inferential theory of probability, based on Bayes' interpretation, provides a means of logically combining the new data with the prior probability assessment.

To allocate resources logically, values must be placed on outcomes. Because the outcomes and hence the values are uncertain, criteria must be established for choosing among various value lotteries. The theory of utility provides a basis for encoding the risk aversion of the decision-maker; i.e., the desire to substitute an alternative with lower expected value but lower risk for an alternative with higher expected value and higher risk. In many cases, the time preferences of the decision-maker must also be incorporated.

The primary purpose of decision analysis is to increase the likelihood of good outcomes by making good decisions. A good outcome is one we would like to occur. A good decision is one logically consistent with the information and preferences of the decision-maker. Decision analysis provides a framework for making good decisions; only chance determines the ultimate outcome.

The principles on which decision analysis is based were conceived in the days of Bernoulli, Bayes, and Laplace, 200 to 300 years ago. Since then these principles have been studied extensively and turned into elaborate theories. Recently, operations research has applied these principles to operational problems, and then management science brought them to repetitive management problems. Decision analysis is the natural next step into the one-of-a-kind major decisions. During the last 10 years, decision analysis has been applied primarily to industrial and business decisions -- decisions such as new product introductions, strategic planning of business operations, and experimental program planning. Recently, applications have been made to governmental problems. The decison analysis of space projects is a significantly new application.

4.4 NATURE OF THE VOYAGER PROBLEM

In conceiving and carrying out a space program, decisions are made at many levels. At the national level, for example, decisions must be made regarding the amount of funding to be allotted to the space program at the expense of other national goals. Within NASA, total space program funding must be divided between manned and unmanned programs. Within unmanned programs, funds must be divided into such projects as planetary exploration versus earth resources satellites.

In all cases, the type of inputs required for making the decisions are essentially the same. For each alternative available to the decision maker, he needs to know the range of possible outcomes, the costs and values of each alternative-outcome pair, and the probabilities of each outcome.

This initial application of decision analysis to a space project, Voyager, was undertaken in the following postulated context:

> "A Voyager project for the unmanned exploration of Mars has been approved with an initial launch scheduled for 1973. Preliminary studies have indicated that the Saturn V launch vehicle, which can put 40,000 to 70,000 pounds on a trajectory to Mars, is optimum for this project. It is desired to place orbiters around Mars as well as to land vehicles on Mars to collect the scientific

data. In the preliminary studies that showed the Saturn V to be the appropriate launch vehicle, general characteristics desired of the orbiter and landing vehicle were also determined."

While the problem is constrained significantly by this statement, the manager of such a Voyager project still has many decisions to make. The following are examples:

a. Should one, two, or perhaps more Saturn V's be used at each launch opportunity?
b. Assuming that the orbiter is to serve as a "bus" for delivering the landing vehicle to the vicinity of Mars, should each bus carry one or more landing vehicles?
c. Should the total capability of the Saturn V be used to carry a single, heavy planetary vehicle (one orbiter with one or more landers), or should two lighter planetary vehicles be carried to provide redundancy at the system level?
d. Given the desired characteristics of the orbiter and lander postulated previously, should the maximum desired capability be designed into the first vehicles, or should a more evolutionary design approach be taken? If evolutionary, what steps in sophistication are logical?

In short, the Voyager project manager must define more precisely the mission configurations--the number of launch vehicles, the orbiters and capsules to be employed, and the capabilities of the orbiters and capsules. In particular, the mission configuration must be selected for the first launch, and a policy or strategy must also be established for determining what to do at subsequent launches. As is discussed, the first choice cannot be logically made without considering the overall project objectives and the configuration sequences available to satisfy those objectives.

4.5 PILOT PHASE

To develop the application of decision analysis to the problem posed, a two phase program was adopted. The first phase (pilot phase) consisted of defining a simplified version of the previously described decision. To the maximum extent possible, however, the essential features of the problem were accurately represented, and only the dimensionality reduced. This smaller problem allowed easier development of the modeling approach, and exercising the model provided insight into the level of detail required in structuring the inputs to the decision. The pilot phase also provided a mechanism for discussion of the model itself, and the usefulness of its results.

4.5.1 PILOT PROBLEM DEFINITION

For the development of the pilot model, it was postulated that the Voyager project manager had already answered many of the questions previously posed. In fact, he had decided that:

a. Only a single Saturn V will be launched at each opportunity.
b. Only one capsule will be carried to Mars by each orbiter.
c. Two planetary vehicles will be carried on each Saturn V.
d. The design characteristics of the orbiter have been established, and a single basic orbiter design will be used throughout the project.

The remaining decision, then, concerns the desired capability of the initial capsule and the desired steps in the evolution of the capsule to the eventual level of capability required. Should he, for example, elect to provide the eventual level of capability in the initial capsule in the face of uncertainties in the Martian environment and difficulties in developing complex equipment to survive the prelaunch sterilization environment? Or should he choose a much simpler capsule that can obtain some information about the Martian environment to be factored into the design of subsequent, more complex vehicles? Which approach yields the highest expected value from the project, and what are the relative costs?

Four possible capsule configurations were postulated, representing steps in sophistication from the simplest useful capsule to the most complex one capable of obtaining all the data desired. These four configurations are illustrated in Figure 4-2, along with the level of achievement they can produce if they are successful.

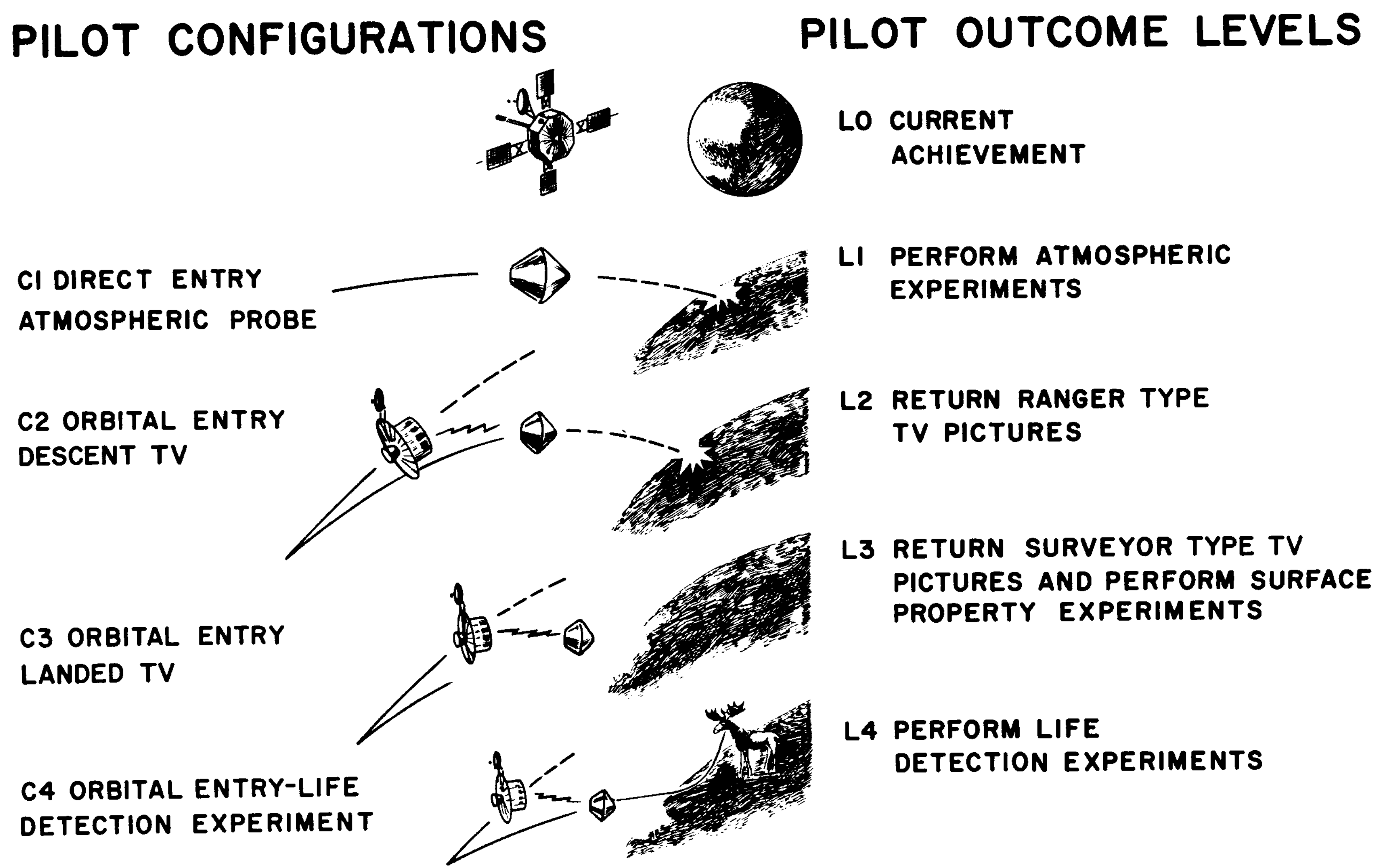


Figure 4-2. Pilot Phase Definition

The first configuration (C1) is a simple atmospheric probe that is not intended to survive impact with the Martian surface. It is separated from the orbiter as the planetary vehicle approaches Mars and is deflected to an impact trajectory by a small rocket. It contains instruments that measure such parameters as density profile and composition of the Martial atmosphere during the entry phase. If it is successful, it achieves an outcome that is denoted as level 1 (L1).

The second configuration (C2) is carried into Martian orbit with the orbiter and subsequently deorbited. It also contains the instruments for measuring atmospheric properties, and in addition contains a television camera for returning pictures of the Mars surface during the late descent phases. If totally successful, it achieves L1, atmospheric measurements, plus L2, descent television. It can, of course, achieve L1 only if a failure prevents it from returning the television pictures. For the pilot model, it is assumed that it cannot achieve L2 without achieving L1. For most cases, this assumption is reasonable.

The third configuration (C3) is the first one intended to survive impact and operate after landing on Mars. It also enters from orbit, contains the atmospheric experiments plus descent television, and can carry out relatively simple surface experiments and provide closeup television after landing. If totally successful, it can achieve L3 (surface experiments plus landed television) as well as L2 and L1. With partial success, it can achieve L2 and L1, or just L1.

The fourth configuration (C4) is the most sophisticated lander considered. It contains all the experiments discussed above plus the capability to carry out meaningful life detection experiments on the surface of Mars. Total success then leads to L4 + L3 + L2 + L1. Partial success leads to lesser levels of achievement.

The decision to be made is the selection of a policy for mission configuration choices; that is, the choice of an initial mission and a rule for determining the choice of each successive mission, depending on the earlier mission choices and their known outcomes.

4.5.2 DECISION TREE

The heart of the decision model is a decision tree that represents the structure of all possible sequences of decisions and outcomes, and contains slots into which cost, value, and probability inputs must be fed. As illustrated in Figure 4-3, the tree contains two types of nodes (decision nodes and chance nodes) and two types of branches (alternative branches and outcome branches). Emanating from each decision node is a set of alternative branches, each branch representing one of the configurations available for selection at that point of decision in the project. Each chance node is followed by a set of outcome branches, one branch for each outcome that may be achieved from that point in the project represented by that chance node. Probabilities of occurrence and values are assigned to each of these outcomes. Costs are assigned to each decision alternative.

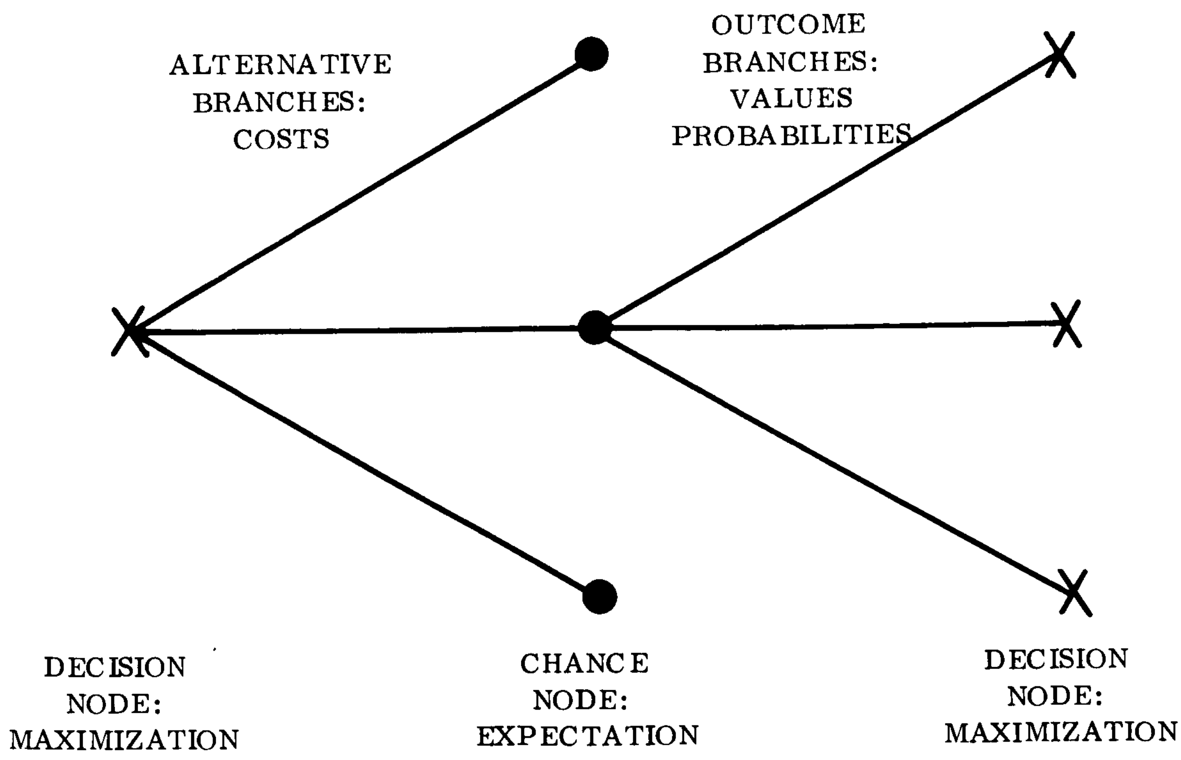


Figure 4-3. Tree Relationships

Two fundamental operations, expectation and maximization, are used to determine the most economic decision from the tree. At each chance node the net expected (mean) value (NEV) is computed by multiplying the probability of each outcome by the sum of its value and the NEV of the node following that outcome and summing over all such products (outcomes) following the node. At each decision node, the NEV of each alternative is calculated as the expected value of the following node (successor node) less the cost of the alternative. The optimum decision is found by maximization of these values over the set of possible alternatives; i.e., by selecting the alternative of highest NEV.

4.5.3 ORDER OF EVENTS

The particular sequencing of mission configuration decisions and outcomes is a significant feature of the Voyager project. As illustrated in Figure 4-4, the initial event of significance is the selection of the 1973 mission configuration. But since lead time considerations

	1968	'69	'70	'71	'72	'73	'74	'75	'76	'77	'78	'79	• • •
1st Mission	Select					Launch	Outcome						
2nd Mission					Select			Launch	Outcome				
3rd Mission							Select			Launch	Outcome		
4th Mission									Select			Launch	Outcome
5th Mission											Select		• • •

Figure 4-4. Order of Events

require that the 1975 configuration decision be made in 1972, the second mission decision must be made before the first mission results are obtained. Similarly, the 1977 decision must be made before the results of the 1975 mission are obtained, although after the 1973 mission results. In general, then, a mission configuration decision must be made in ignorance of the results of the previous mission.

4.5.4 CONSTRAINING OF CONFIGURATION SEQUENCES

Some logic must be applied in defining what configurations can be selected at each decision node. Obviously, it does not make sense to choose a C1 when the program has already reached outcome level 2, so this choice is not permitted in the decision tree. Other restrictions can also be made which are not quite so obvious. For this pilot model, the following logic is applied:

a. It is assumed that the most complex lander will not be available in 1973 because of the development time required.

b. Sequences in which a complex lander is followed with a simpler one are not considered; that is, the complexity of the capsule only increases time.

c. Because of the order of events just discussed, whereby one vehicle is in flight and another being fabricated for the next opportunity, some logic was required to determine what will be done in the event of failure of the vehicle in flight. Failure is specifically defined as no improvement in the previous level of success as a result of the current flight. We postulated that should failure occur, the next configuration chosen could not be more complex than the one being constructed. That is, no advance was allowed in the face of failure.

d. The achievement of level 4 is assumed to terminate the program. Additionally, we postulated that two failures in succession, where again failure means no advance in level of achievement, terminated the program. These two factors constrained the overall tree size.

4.5.5 TREE EXAMPLE

A completed decision tree for the pilot Voyager project, with the additional assumption that L2 is the highest level of success, is presented in Figure 4-5. The models that produce the numerical probabilities, values, and costs used in the example are discussed later.

Node 1, at the left side of the tree, is the initial decision to select either a C1 or a C2 for the first launch opportunity. The box designated L0 above this node indicates that the state at this node is the baseline level of achievement. Suppose a C1 is selected. The cost of that C1 is $850 million, indicated by the "-850" written under that branch.

As a result of this choice, the next node is decision node 2. The box designated L0, C1 above this node indicates that the state at this node is the current level of achievement and a C1 is being constructed for the first launch. Now either a C1 or C2 must be selected for the second launch. If a C1 is selected, the cost is 575, and the next node is chance node 7.

The two branches following node 7 represent the possible outcomes of the first launch. The L0' outcome, failure to better L0 on the first try, occurs with probability 0.1, whereas the L1 outcome occurs with probability 0.9. The value of the L0' outcome is zero, whereas the value of the L0 outcome is 1224.

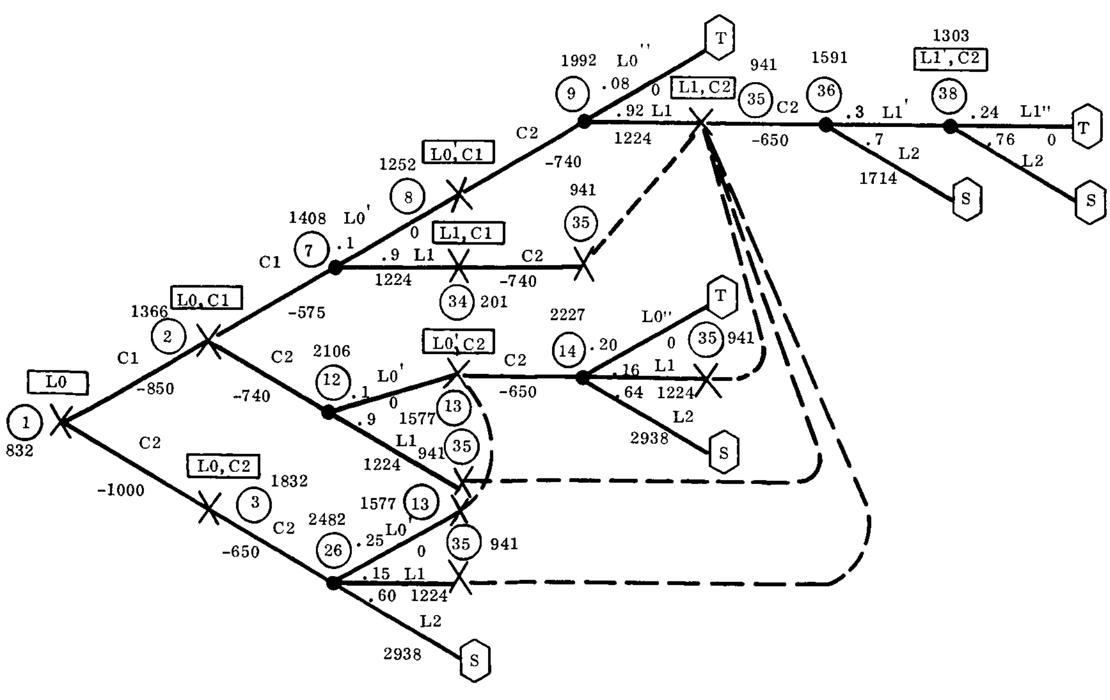


Figure 4-5. Example Decision Tree

Follow the case of the L1 outcome to decision node 34. The state L1, C1 at this node means that the highest level of success is L1 and a C1 is being constructed for the next launch. Since L1 has already been achieved at this point in the tree, a C2 is the only configuration that may be launched in the third opportunity, at a cost of 740. This leads to decision node 35, where the state is L1, C2.

Node 35 in the example tree illustrates coalescence of nodes, a feature vital to maintaining a manageable tree size. Node 35 on the upper path through the tree can be reached from four other paths through the tree, as indicated in the figure. If the coalescence did not occur, the portion of the tree following node 35 would have to be repeated four additional times. In the full pilot tree, coalescence resulted in a reduction of the number of branches in the tree by a factor of 30.

Along the path 1-2-7-34-35, at decision node 35 a C2 must be selected for the fourth opportunity. At chance node 36, the outcome of the third launch is either an L1' (failure to better L1 with one attempt, which leads to node 38), or an L2 (which achieves a value of 1714 and successfully completes the program). These outcomes occur with probability 0.3 and 0.7, respectively.

If L1' is the outcome, chance node 38 is reached where the outcome of the fourth launch is represented. The probability of L1'' is 0.24, and the probability of L2 is 0.76. Note that the probability of L2 has increased over that of node 36 (0.7 to 0.76) because of the experience gained with the earlier attempt.

The reader can similarly follow and interpret many other paths through the tree. A decision policy is a complete selection of particular alternatives at all decision nodes. This limits the set of all possible paths to a smaller subset. (It is impossible, for example, to reach node 26 if a C1 is chosen at node 1.) The probabilities, values, and costs of these paths then determine the characteristics of the decision policy.

The most economic decision policy, given the input data specifications, is the policy that maximizes the net expected value of the project; i.e., expected value less expected cost.

A technique that eliminates many of the nonoptimum policies from explicit consideration is called the "roll-back" technique. It starts from the right side of the tree and progresses left to the beginning of the tree, making all decisions and calculations in reverse chronological order. Thus, when each decision is made, only policies that optimize decisions for the following decision nodes are considered.

Consider node 38 in Figure 4-5. At this chance node, the probability of achieving L1", which is worth nothing, is 0.24, and the probability of achieving L2, which is worth 1714, is 0.76. Thus, the NEV of node 38 is 0.24(0) + 0.76(1714) = 1303. This number is written near node 38.

The calculation are carried out backward in this manner through the tree. The first decision node with more than one choice is node 2. If a C1 is selected, it costs 575 and leads to node 7 with a NEV of 1408, which yields 1408 - 575 = 833. If a C2 is selected, it costs 740 and leads to node 12 with a NEV of 2106, which yields 2106 - 740 = 1366. Since 1366 is greater than 833, the most economic decision is to select a C2 at node 2, which results in NEV(2) = 1366.

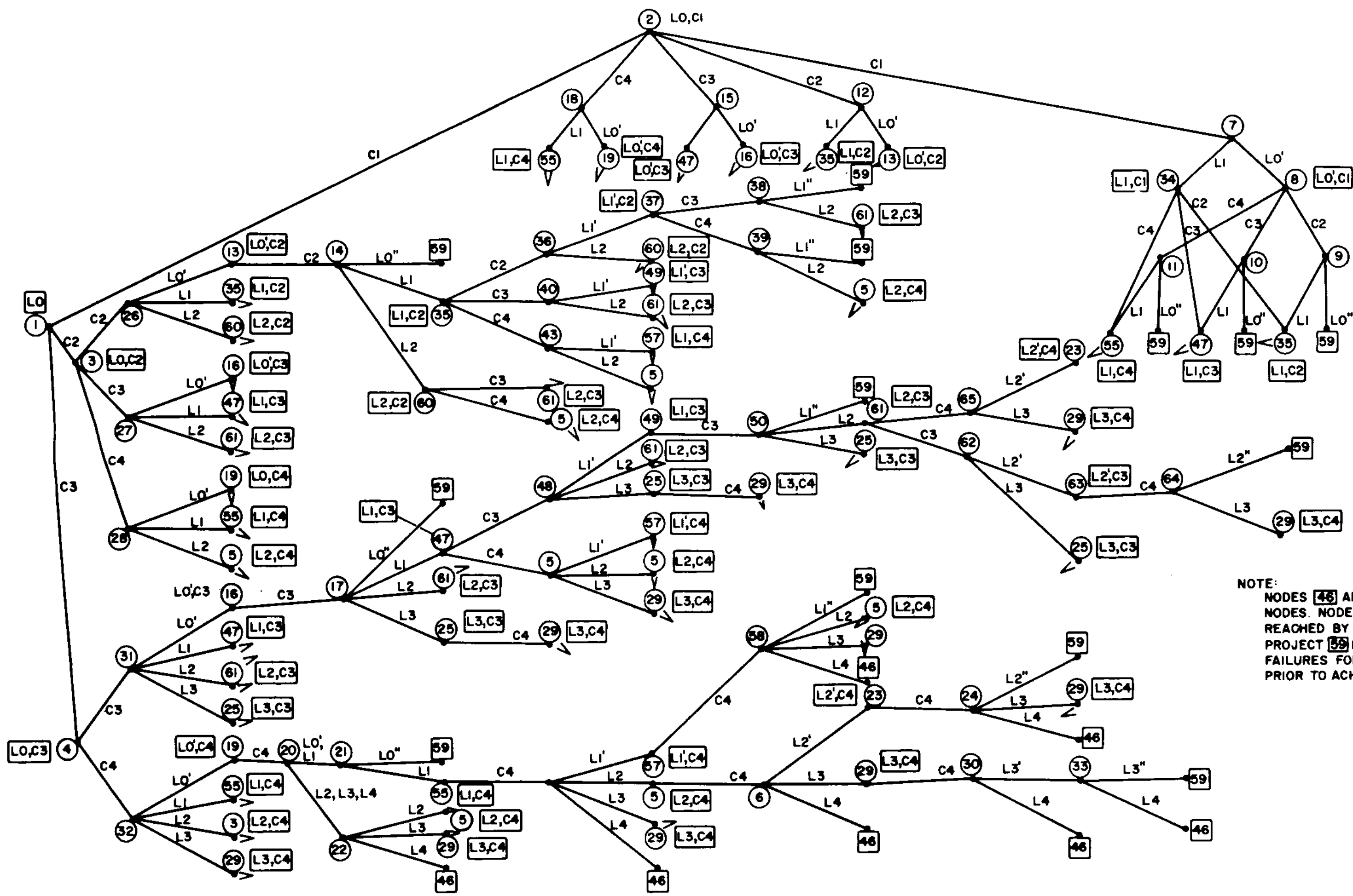
Finally, the first decision is a choice between a C1 with an NEV of 516 or a C2 with a NEV of 832. Maximum NEV is achieved by the choice of a C2 resulting in NEV(1) = 832. This is the NEV of the entire project at the time the first decision is made.

The full pilot decision tree is shown in Figure 4-6.

4.5.6 PILOT PROBABILITY MODEL

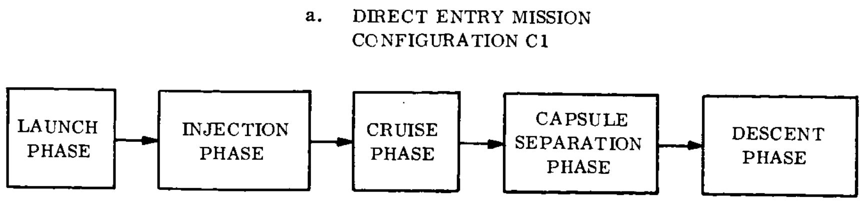
In practice, it is difficult to estimate the probabilities to be attached to the outcome branches leaving probabilistic nodes. Available data and engineering judgment are more easily applied to the estimation of success probabilities for more elementary operations. A probability model can then combine these inputs into the desired outcome branch probabilities.

For purposes of the pilot analysis, probability estimates were obtained by applying engineering judgment to the various phases of the mission top level function flow diagrams pictured in Figure 4-7. In addition to estimating initial probabilities, it was necessary to estimate how subsequent mission probabilities would be affected by results obtained on early flights.



NOTE:
NODES 46 AND 59 ARE THE TERMINAL NODES. NODE 46 CORRESPONDS TO L4 AND IS REACHED BY ACHIEVING A TOTALLY SUCCESSFUL PROJECT 59 IS REACHED WHEN TWO SUCCESSIVE FAILURES FORCE TERMINATION OF THE PROJECT PRIOR TO ACHIEVING L4.

Figure 4-6. Pilot Decision Tree



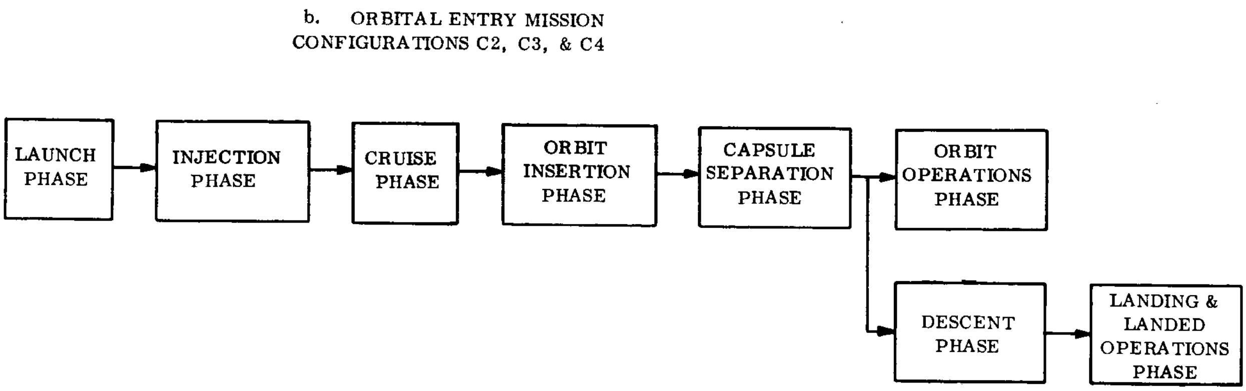


Figure 4-7. Voyager Mission Flow Diagrams

The results of this analysis for configurations C1 and C2 are tabulated in Figure 4-8. Noting that a prime (') attached to a level symbol indicates failure in an attempt to better that level, we see that the probability of failing to reach L1 with a C1 from L0 is 0.10; the probability of failing to reach L1 with a C1 after failing once is 0.08. The general philosophy of this model is that success increases the probability of achieving desirable outcomes, and so does failure (designs are improved due to information gained in the failure), although to less extent. Thus, the probability of failing with a C2 starting at L0 is 0.25; the probability of failing with the same configuration starting at L0' is 0.20, with the remaining 0.05 of probability being spread proportionately over the other outcomes.

4.5.7 PILOT COST MODEL

The costs attached to the alternative branches in the decision tree are constructed by the cost model using representative system cost data as tabulated in Figure 4-9. It is assumed that second and subsequent copies of hardware systems (bus, capsules) could be produced at half the

CONFIGURATION C1

		NEXT LEVEL		
		L0'	L0''	L1
PREVIOUS LEVEL	L0	0.10	—	0.90
	L0'	—	0.08	0.92

CONFIGURATION C2

		NEXT LEVEL					
		L0'	L0''	L1	L1'	L1''	L2
PREVIOUS LEVEL	L0	0.25	—	0.15	—	—	0.60
	L0'	—	0.20	0.16	—	—	0.64
	L1	—	—	—	0.30	—	0.70
	L1'	—	—	—	—	0.24	0.76

Figure 4-8. Transition Probability Inputs

PREVIOUS CAPSULE CONSTRUCTED	CAPSULE COST OF			
	C 1	C 2	C 3	C 4
NONE	$150 M	$ 300 M	$600 M	$1000 M
C1	$ 75 M	$ 240 M	$ 600 M	$1000 M
C2	–	$ 150 M	$ 480 M	$1000 M
C3	–	–	$300 M	$ 800 M
C4	–	–	–	$ 500 M
	COST OF BUS FIRST TIME $400 M, SUBSEQUENT TIMES $200 M OTHER COSTS $300 M			

Figure 4-9. Pilot Cost Inputs

initial cost of developing and producing the first system. Also, configuration production experience on a C1, C2, or C3 contributes a 20 percent reduction to the cost of producing a C2, C3, or C4, respectively.

4.5.8 PILOT VALUE MODEL

The value of various accomplishment in the Voyager project can be divided into assigned values and derived values. The assigned values are the values of the Voyager project accomplishments to the world external to the Voyager project. Derived values are the contribution of earlier mission accomplishments to the probability of success in later Voyager missions. Assigned values must be determined directly. The derived contributions are incorporated by increases in the probability of success in future missions, thus increasing the probability of eventually achieving future assigned values.

Assigned value itself can be divided into two kinds of value, direct and indirect value. Direct value is the value of the knowledge produced by the outcomes, such as visual records of Mars and characterization of Martian biology. Direct value is achieved independently of the means of gaining the knowledge. Indirect value is the value of obtaining and possessing the knowledge (rather than the knowledge itself), such as technological spin-off, national prestige, satisfaction of the urge to explore Mars, and the competitive pleasure of being first in space. Both direct and indirect values provide the total incentive for the Voyager project and, to make project decision rationally, both must be included in the evaluation of project outcomes.

To derive a value function, a value tree was constructed by considering first the major components of assigned value, both direct and indirect, and then the subcategories of each type, identified in more and more detail until no further distinction was necessary. Then, each tip of the tree was subdivided into four categories, each corresponding to the contribution of one of the four achievements to the value subcategory represented by that tip.

Specifically, the value tree that served as the value function in the pilot analysis is pictured in Figure 4-10. The number 1.0 attached to the node at the extreme left represents the total value of all the objectives of the pilot Voyager project (thus, the value of achieving L1, L2, L3, and L4). The four branches emanating from this node represent the four major categories of value recognized by the pilot model. The number 0.62 attached to the upper branch represents the fraction of total value assigned to science. Two branches emanate from the science node, and 60 percent of the science value falls into the category of biological science. The 0.37 attached to the biological science node represents the fraction of total value attached to biological science and is obtained by taking 60 percent of 0.62 (the fraction of total value attached to all science). Finally, the bottom branch following the biological science node indicates that 78 percent of the biological science value is achieved by jumping from L3 to L4.

The final step in value modeling is to obtain the fraction of total value to be attached to achieving each of the four levels. If we add all the contributions to achieving L1 (contribution to world opinion, U.S. public favor, physical science, etc.) the result is the fraction of value that should be attached to achieving L1. The same process is followed for reaching L2 from L1, L3 from L2, and L4 from L3. The results of such a calculation are in the lower-left corner of Figure 4-10.

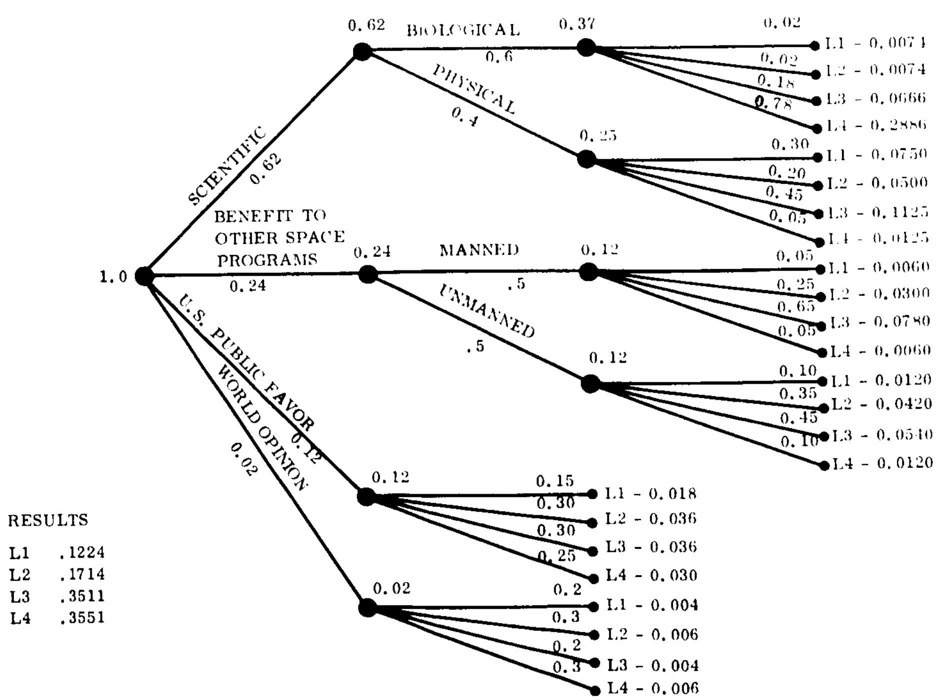


Figure 4-10. The Pilot Value Tree

4.5.9 RATIONALE FOR SELECTING THE OPTIMAL POLICIES

A policy is a setting of each decision node in the decision tree; i.e. it is a complete strategy for conducting all missions in the Voyager project.

The selection of a policy limits the number of paths that might be transversed through the decision tree. However, there are still many alternative paths that can be transversed, and they are determined by individual mission successes and failures as the project unfolds. These vagaries of chance are encoded in the probability model. Thus, for each policy, a probability distribution can be derived over all the paths that can possibly be taken. Using the cost and value models, a cost and value can be assigned to each path. Thus, each policy is represented by a lottery on cost and value, as illustrated in Figure 4-11.

To select an optimum policy, we must decide between many different cost-value lotteries. Figure 4-12 illustrates three different policy lotteries in the cost-value plane. Policy 3 tends to have costs similar to policy 2, but lower values than policy 2. Policy 3 also tends to have higher costs than policy 1, but similar values. Thus policy 3 does not look very desirable. However, policy 2 tends to have both higher values and higher costs than policy 1, and we must determine whether the chances of higher values are worth the chances of higher costs.

In general, the risk aversion preferences of the decision-maker must be encoded to make this decision. To gain insight into this example, let us assume that the decision-maker wishes to base his decisions on the expected value and cost of each policy. Thus, each policy lottery is replaced by a single point at the expected cost and the expected value of that policy. These points are exhibited for nine hypothetical policies in Figure 4-13.

The policies in Figure 4-13 can be separated into three classes: totally dominated policies, marginally dominated policies, and dominant policies. A policy is totally dominated if there is at least one other policy that has both a lower expected cost and a higher expected value. Policies 6, 7, 8 and 9 are totally dominated policies. Totally dominated policies can be dropped from further consideration. This simplifies decision-making, because the bulk of the possible policies are of this type.

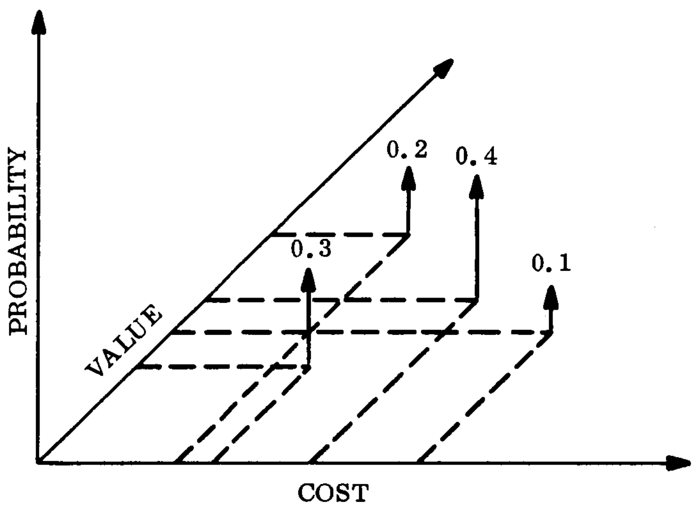


Figure 4-11. Representation of a Policy

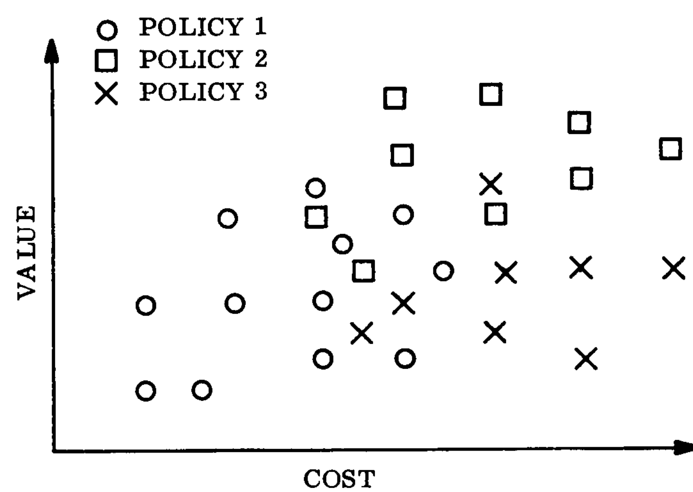


Figure 4-12. Comparison of Policies

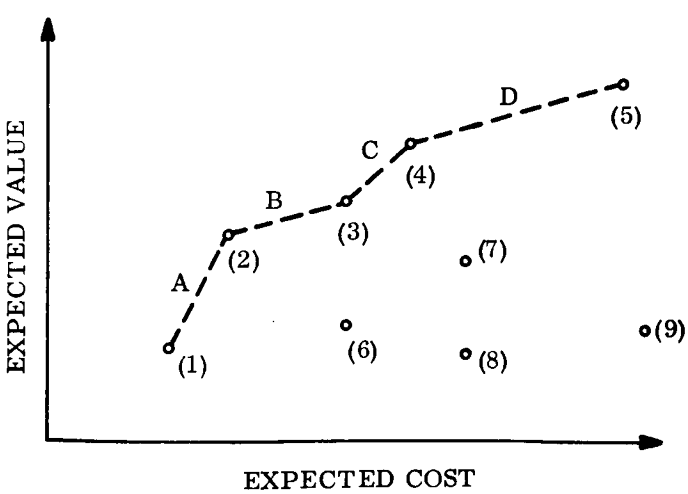


Figure 4-13. Expected Values of Alternative Policies

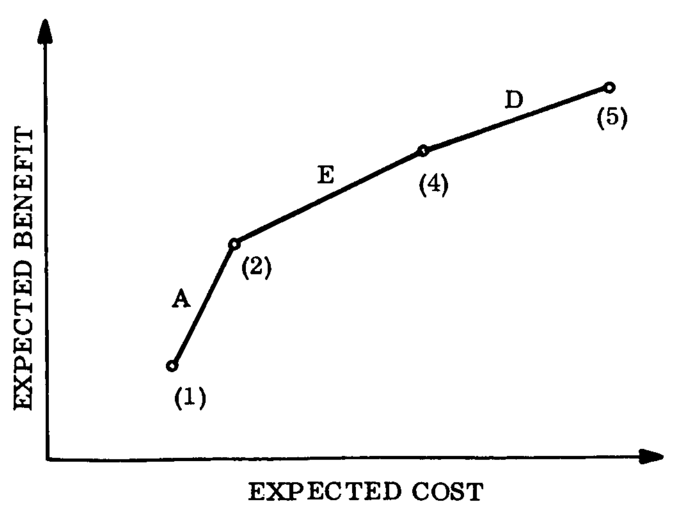


Figure 4-14. Dominant Policies

The remaining policies connected by a dashed line in Figure 4-13 are called envelope policies and are of two types: marginally dominated policies and dominant policies. Policy 3 is an example of a marginally dominated policy. The slopes of the lines A, B, and C in Figure 4-13 show the marginal return from increasing the funding level from 1 to 2 to 3, and from 3 to 4. The marginal return B is less than the marginal return C. This means that increasing the funding from 2 to 3 brings less return per unit cost than the increase in funding from 3 to 4. Since each program is competing for funds with other programs, it would be unusual to find that directing funds from other programs is worthwhile up to point 3, but is not worthwhile beyond 3. For this reason, marginally dominated policies such as 3 were eliminated from contention.

The remaining policies, 1, 2, 4, and 5, are called dominant policies. The selection has been reduced to this set, which is shown in Figure 4-14. Analysis of the decision tree produces this set of dominant policies and their associated expected costs and benefits.

4.5.10 DETERMINATION OF DOMINANT POLICIES AND PROFIT INTERPRETATION

To determine the dominant policies, a number of alternative policies must be compared. For example, in the 60-node pilot tree, there are approximately 2,000 policies. However, the roll-back process of decision tree evaluation presented earlier also provides a method of finding the dominant policies without evaluating each policy explicitly. Recall that in Subsection 4.5.5, expected costs were subtracted from expected values. To do this, value points are converted to dollars by multiplying each point by a conversion factor λ. Since the entire value tree is assigned one point, λ is a dollar value assignment to the Voyager project.

Figure 4-15 shows the construction of expected profit from an expected cost-expected value plot and an assignment of λ. Picture this result as obtained by shining a light beam across the figure from the direction of the upper right hand corner, so that the rays of the beam have slope λ^{-1}. The expected profit for the policy is determined by the shadow of the light beam on the expected cost axis, with increasing profit to the left.

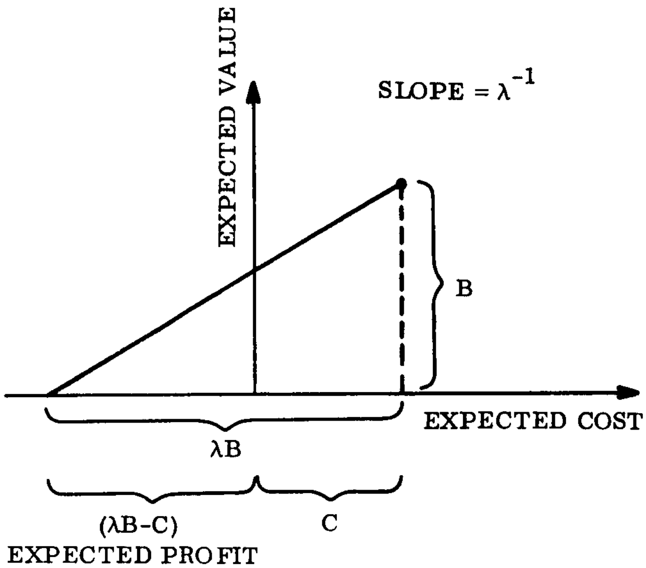


Figure 4-15. Construction of Profit

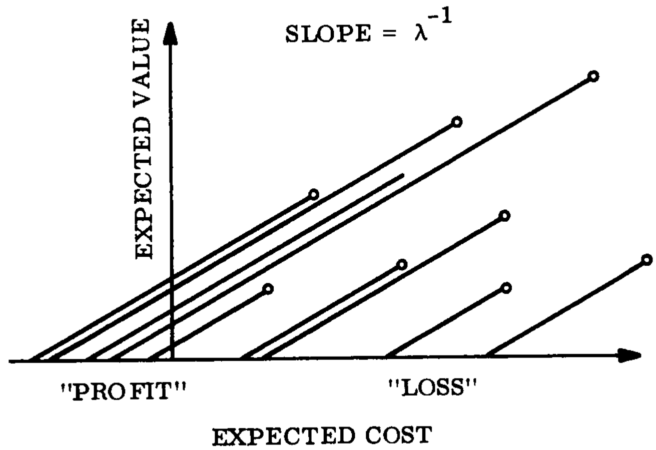


Figure 4-16. Shadows of Policy Points

If the light beam is shined on all the policy points simultaneously, as in Figure 4-16, the shadows of the policies on the expected cost axis give the expected profit for each policy. The policy with the leftmost shadow is the policy of maximum expected profit, and thus it is the policy that results from evaluation of the decision tree for the given λ. If the light is shir more vertically from the top, lower cost policies have the leftmost expected profit shadow; and as the light is shined more horizontally from the right, higher cost policies have the leftmost expected profit shadow. Consideration of the geometry of this problem shows that sweeping the light from vertical to horizontal (λ from zero to infinity) will produce exactly the dominant set of policies illustrated in Figure 4-14. Thus, successive evaluations of the decision tree for different assignments will sweep out the dominant policies. Algorithms hav been developed that sweep out the entire set with high efficiency.

4.5.11 RESULTS AND CONCLUSIONS

Figure 4-17 lists several policies, as well as interpretations of the policies, and shows their expected costs and expected value fractions. Policy 1 (P1) consists of flying an initial C3 followed by C4's until the program terminates, either by achievement of L4 or by two failures in succession. P2 is an initial C1 followed by C4's, and P3 is two C1's followed by C4's. These are the three optimum policies, and the interpretations show that as higher dollar value is attached to the project, the policies become more conservative. These policies are plotted in Figure 4-18.

POLICY	INTERPRETATION	EXPECTED COST	Expected Fraction of Total Value	
			BALANCED	LIFE
1	C3, C4	$ 4124 M	0.802	0.669
2	C1, C4	$ 4443 M	0.815	0.720
3	C1, C1, C4	$ 5031 M	0.827	0.730
4	C2, C3, C4	$ 4488 M	0.769	
5	C2, C3 (except C4 @ L1)	$ 4816 M	0.759	
6	Stepwise	$ 5885 M	0.729	
7	C3 till L1, C4	$ 4555 M	0.796	
8	C1 then as in 7	$ 4609 M	0.805	
9	C3 till L2, C4	$ 4630 M	0.795	
10	C1, C1, L1 → C4 / LO' → C3 till L2, C4	$ 5092 M	0.825	
11	C1, C1, C3, C4	$ 5167 M	0.816	
12	C1, C1, C3 till L2, C4	$ 5720 M	0.813	
13	C2, C3, C4	$ 6475 M	0.735	

Figure 4-17. Comparison of Several Policies

Policy P6, the stepwise policy, is to start with a C1 and advance the configuration sophistication by one step whenever possible. This policy has the lowest expected fraction of total value. Policy P10 is an example of a complicated policy. It begins with two C1's. If the first C1 achieves L1, the project continues with C4's. If the first C1 achieves L0' (it fails), C3's are flown until L2 is attained, and then C4's follow. Interpretation of other policies can be read from Figure 4-17.

All possible policies for the pilot Voyager decision tree lie within the dashed lines of Figure 4-18. Policies P1, P2, and P3 are the dominant policies. Policy P1 is the minimum expected cost policy, whereas P3 is the maximum expected value fraction policy. Policy P2 is a tradeoff policy with expected values and costs between those of P1 and P2. P2 is optimum for intermediate project dollar value while P3 and P1 are optimum for high and low extremes, respectively.

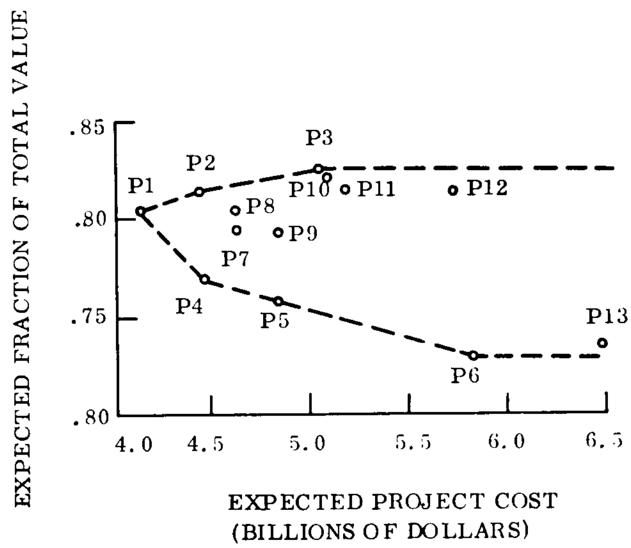


Figure 4-18. Comparison of Policies for Balanced Value Assignments

The remainder of the policies shown are all totally dominated policies. Of course, there are many more policies that were not examined. All of these policies, however, are either totally dominated or marginally dominated. The methods described in Subsection 4.5.10 allow determination of the dominant policies (P1, P2, P3, in this case) without explicity considering most of these dominated policies.

Figure 4-19 illustrates optimal policies for two different value tree assignments, the balanced value assignment described in Figure 4-10, and an assignment of all value to the life experiment (L4). The dominant policies are found by varying the dollar value assignment to the Voyager project (λ) as described in the previous section. For both value assignments, the dominant set of policies consists of policies P1, P2, and P3.

Work with the pilot model provided encouragement that this approach is truly useful. The decision tree provides a means of explicitly describing the possible sequences of alternatives and outcomes and the options open to the decision-maker at any decision point. The input models provide a language for explicitly describing probabilities, values, and costs in the project.

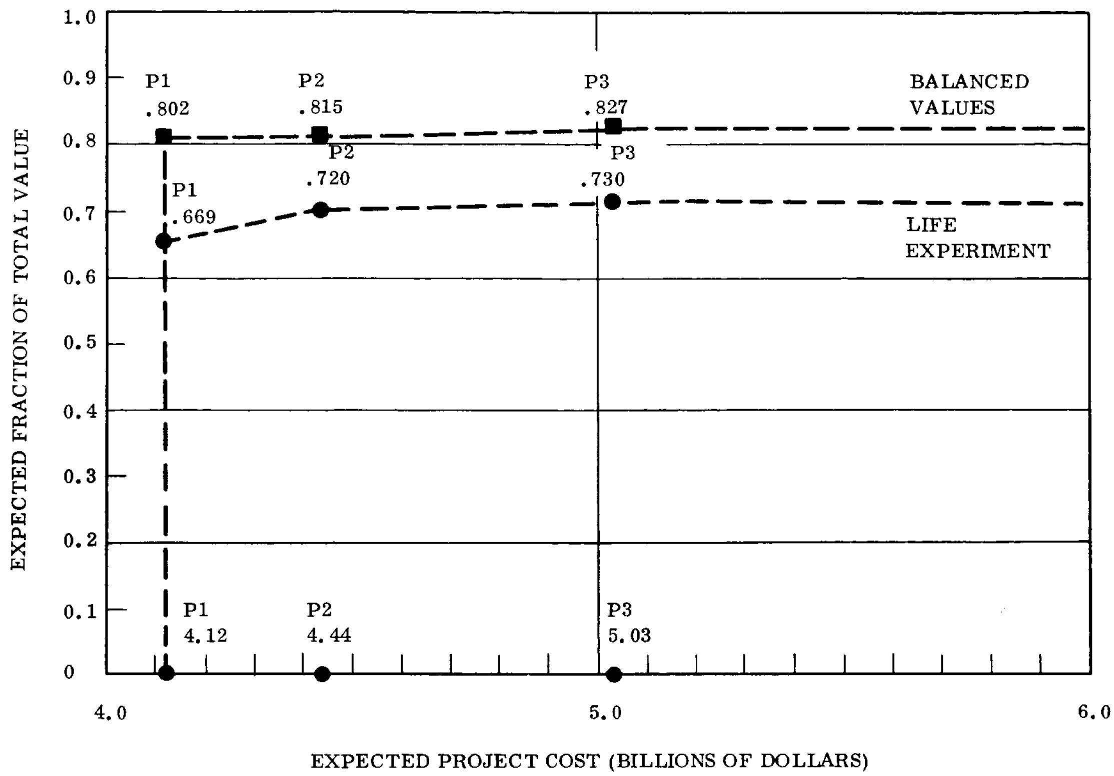


Figure 4-19. Dominant Policies for Different Value Assignments

It was found that exercising the model with varying inputs provided insight into the relative importance of the many factors involved and their interrelationships. Those using this model were able to predict in advance the effect of changing value, cost, or probability input with reasonable accuracy. The fact that the ability to do this greatly improved indicates the improvement in understanding of the interrelationship of the many factors involved.

Based on the promising results of working with the pilot model, a full-scale model was developed, encompassing most of the factors involved in selecting the actual Voyager mission configuration. It includes nearly all the realistic configurations available within the context of using a Saturn V launch vehicle. It provides a more precise structure for the assignment of initial values, probabilities, and costs, and for updating probabilities and costs based on results achieved. Table 4-1 is a summary comparison of the complexity of the pilot model with the more complete model. In addition to the comparisons listed in Table 4-1, some of the ground rules postulated for the pilot model that affect the available choices at each decision node were found to be undesirable, and these were modified in the more complete model. The remainder of this section is devoted to the full-scale model.

Two technical reports on the pilot model were issued during the study. An interim report (VOY-C3-TR2) was released on 23 November 1966, and a final report (VOY-C3-TR6) was published on 31 January 1967. The final report references some material from the interim report.

Table 4-1. Comparison of Pilot and Full-Scale Models

Parameter	Pilot Model	Full-Scale Model
Number of Decision Tree Nodes	60	3200
Number of Potential Mission Configurations	4	14
Number of Project Outcomes	5	56
Computing System Employed	Time-sharing (GE 235)	Batch process (GE 635)

4.6 PROBLEM STRUCTURE

4.6.1 POTENTIAL MISSION CONFIGURATIONS

The major constraint upon the selection of potential mission configurations for the full-scale decision model is the size of the decision tree resulting from many alternative configurations being available at each decision node. To keep the computer program system running time short, and thus encourage exercising the tool, it is considered desirable to keep the size of the decision tree small enough to permit all of the data and programs to be contained in the core memory of a large-scale computer. On the other hand, it is equally desirable to provide a spectrum of configuration choices at each decision node to avoid constraining the solution with preconceived answers.

The total number of potential mission configurations is far too large if all of the parameters of interest are allowed to vary. To illustrate, the decision model could be asked to consider all possible combinations of:

- Orbiter designs of varying capability.
- Capsule designs of varying capability.
- Use of launch vehicles other than Saturn V for early missions.
- One or more Saturn V launch vehicles in each opportunity.
- One or more planetary vehicles on each launch vehicle.
- One or more capsules of the same or different design on each planetary vehicle.
- Capsule entry mode; i. e., direct or from orbit.
- Capsule terminal deceleration mode; i. e., parachute or retrorocket.
- Capsule landing mode; i. e., nonsurvivable, rough landing, or soft landing.
- Landed capsule data return to earth; i. e., direct or via relay through the Mars orbiter.

4.6.1.1 Simplifying Considerations

Several thousand potential configurations could be formed by suitable combinations of the above choices. This number is at least two orders of magnitude too large for a reasonably sized decision tree and, accordingly, several initial simplifications are applied to the configuration parameters.

It is first observed that the design of the spacecraft orbiter is relatively insensitive to a wide range of mission concepts. For example, as the mission profile changed from the Phase IA, Task A concept of direct capsule entry to orbital entry in Task B, the only major difference in the planetary vehicle design was in the size of the propulsion system. Changes did occur in other spacecraft subsystems, but they are small compared to the propulsion system change and the changes required for the capsule. Hence, it is concluded that one basic orbiter design could cover the entire spectrum of mission configurations.

It is considered highly desirable to consider a range of capsule types from simple atmospheric probes through the complex, soft landed, biological laboratory. Based upon pilot model results, it is felt that this range is adequately characterized by five capsule types:

a. A small nonsurvivable atmospheric probe capable of returning entry data and atmospheric profiles.

b. A small, nonsurvivable probe capable of atmospheric and entry experiments and descent television.

c. A soft lander, of medium size, capable of atmospheric and entry experiments, optional descent television, surface television, and simple surface experiments.

d. A large soft lander, capable of entry and atmospheric measurements, optional descent television, sophisticated life detection experiments, surface television, and some surface experiments. It is assumed that this lander could not be made available in time for the first Voyager launch in 1973, so a fifth capsule type, available in 1973, was proposed.

e. A large soft lander, identical to (d), except that the payload devoted to biological experiments is replaced by a complete set of sophisticated, non-biological, surface experiments.

It is further recognized that some of the possible configuration choices are better settled by detailed engineering trade studies. For example, the choice between parachute and rocket final deceleration, or between rough and soft landing, requires considerable engineering study to develop the necessary probability, cost, and value data to describe the alternatives to the decision model. Moreover, after the engineering studies are complete, it is likely that the correct solution will be apparent without the need for decision analysis. For choices of this type, it was decided to leave the decision outside the decision tree, and to accommodate varying input costs, probabilities, and values in the submodels with the trade study results.

Other real project considerations (e.g., launch vehicle capability, mission operations capability, etc.) further constrained the number of choices. For example, it is presently planned for the mission operations system to support data return from a maximum of four Voyager systems at the same time. Configurations consisting of more than two orbiters and two landed capsules would require revision to the mission operations system. Accordingly, the choices available are assumed to be limited to a maximum of four systems capable of simultaneous, long-term, data return. Thus, the capability of two Saturn V's to launch more than four such systems per opportunity is not assumed to be available. Combinations such as an orbiter and two soft landers on each of two launch vehicles, or two orbiters each with a soft lander on each of two Saturns, are not included in the mission configuration alternatives.

Furthermore, the payload and volume limitations of the Saturn V launch vehicle prohibit multiple large capsules per planetary vehicle with two planetary vehicles per launch vehicle. Additionally, it is considered unlikely that NASA will undertake the development of two new capsule types for a single Voyager launch opportunity. Hence, all dual capsule (per planetary vehicle) configurations are restricted to combinations of the nonsurvivable atmospheric probe (assumed to have been initially developed for the Mariner 1971 Mars mission) with either of the small probes or the medium-sized soft lander. Further, the dual capsules are required to be identical for both planetary vehicles.

4.6.1.2 Selection of Potential Mission Configurations

Given the preceding considerations, five potential mission configurations immediately suggest themselves, viz., two planetary vehicle configurations in which each planetary vehicle consists of an orbiter and one of the five basic capsule types. The two planetary vehicles could be launched either by the same Saturn V, or alternately on separate Saturn V launch vehicles. This selection of one or two launch vehicles is left as an input to the decision model to reduce the number of potential mission configurations in the model itself.

Three other configuration alternatives are also conspicuous. These combinations are dual capsule configurations, in which the planetary vehicle contains both an atmospheric probe and one of the three simplest capsule configurations previously described. Again, two planetary vehicles could be flown, employing either one or two Saturn V launch vehicles.

Because of the significance which atmospheric measurements on Mars can have for later missions, and because the pilot model solutions frequently contained a flyby spacecraft with a direct entry probe (C1), it was decided to include as a potential mission configuration for 1971,the Mariner Mars flyby and atmospheric probe combination.

Finally, it is recognized that either cost or technical development difficulties could preclude the availability of the Voyager capsule system for the 1973 mission, and it was decided to include some configuration alternatives without a capsule. The first and most obvious of these alternatives was the Saturn V with two Voyager orbiters. Two other attractive choices employed one or two Saturn IB launch vehicles (in combination with the Voyager spacecraft propulsion system) to place the spacecraft on an interplanetary trajectory to Mars. These configurations offer a minimum cost Voyager option for 1973, and it was elected to include within the decision model the option for either one or two launch vehicles.

A pseudo-mission configuration not available in the pilot model: viz., the ability to skip any opportunity and await the outcome of the mission in progress, in order to make subsequent decisions with greater knowledge of the Mars environment and existing hardware capability, is accommodated in the full-scale decision model.

Finally, it is recognized that the project should not be required to continue flying Voyager missions at every opportunity if the expected profit of additional missions is low. Hence, at every decision node, there is the option to terminate the program following the flight of the configuration then under construction.

The resulting number of potential mission configurations is fourteen. To limit the decision tree even further, additional restrictions are defined. The Mariner Mars 1971 configuration is permitted only in 1971. The three noncapsule configurations are permitted only in 1973. No nonsurvivable probes are permitted after 1975, excepting the dual atmospheric probe and medium lander, which is allowed in 1977. The resulting allowable mission configurations and the years of availability are summarized in Table 4-2.

4.6.2 PROJECT OUTCOMES

In the pilot model, only five project outcomes are modeled, and these are all capsule outcomes. Orbiter outcomes are not introduced as a variable in the project outcome structure. Obviously, a much finer distinction among capsule outcomes and consideration of orbiter outcomes is in order for the full-scale model. Like the configurations, however, the outcomes had to be limited to keep the number of branches following chance nodes, and hence the size of the decision tree, within bounds. Several methods are used to reduce the number of project outcomes to a suitably small number. One is to combine outcomes of low probability or low value with other outcomes. This follows because the decision tree operates upon expected value; i.e., the product of probability and value. Hence, whenever the product of value and probability for an outcome is low, due to low probability or low value, that outcome can be combined with outcomes of larger expected value with little loss in accuracy. This criterion is used extensively in limiting outcomes (especially capsule outcomes) in the decision model.

Another simplification is to assume equivalence between partial success of sophisticated capsules and full success of less sophisticated capsules. For example, descent television pictures are considered equivalent whether taken by a large soft lander or by a nonsurvivable descent television probe. Again, this rationale was invoked primarily to simplify the number of capsule outcomes.

Table 4-2. Potential Mission Configurations

Configuration	Configuration Description	Nominal Definition					Major Configuration Options				Availability Year of Launch					
		Launch Vehicle	No. of Launch Vehicles	No. of Orbiters	No. of Capsules	Descent TV	Direct Entry Atmospheric Probe	Capsule Entry Mode: Orbital or Direct	Two Saturn V Launch Vehicles	Landed Relay vs. Direct Link	'71	'73	'75	'77	'79	'81
1	Cancel Project	NA	0	0	0	NA	NA	NA	NA	NA	X	X	X	X	X	X
2	Skip Opportunity	NA	0	0	0	NA	NA	NA	NA	NA	X	X	X	X	X	X
3	Mariner '71	SLV 3	2	0	2	no	yes	no	no	NA	X					
4	Voyager Jr.	SIB	1	1	0	NA	NA	NA	no	NA		X				
5	Two Voyager Jr.'s	SIB	2	2	0	NA	NA	NA	no	NA		X				
6	Orbiter Only	SV	1	2	0	NA	NA	NA	yes	NA		X				
7	Orbiter with Atmospheric Probe	SV	1	2	2	no	no	yes	yes	NA		X	X			
8	Orbiter with Descent TV Probe	SV	1	2	2	yes	no	yes	yes	NA		X	X			
9	Orbiter with Medium Soft Lander	SV	1	2	2	yes	no	yes	yes	yes		X	X	X	X	X
10	Orbiter with Surface Laboratory	SV	1	2	2	yes	no	yes	yes	yes		X	X	X	X	X
11	Orbiter with Biological Laboratory	SV	1	2	2	yes	no	yes	yes	yes			X	X	X	X
12	Orbiter with Two Atmospheric Probes	SV	1	2	4	no	* yes	no	yes	NA		X	X			
13	Orbiter with Atmospheric Probe & Descent TV Probe	SV	1	2	4	** yes	* yes	no	yes	NA		X	X			
14	Orbiter with Atmospheric Probe &Medium Soft Lander	SV	1	2	4	** yes	* yes	no	yes	yes		X	X	X		

* Atmospheric Probe Only
** Sophisticated Capsule Only

Further simplification is achieved by employing the concept of bonus value for repeated capsule and orbiter achievements. This is implemented by assigning value for the first achievement of a mission outcome, e.g., long-term orbital operations, and then assigning a constant bonus value for successive achievements of the same mission outcome.

4.6.2.1 Orbiter Outcomes

Within the present Voyager project concept, the orbiter outcomes which exhibit distinctly different value, either to the orbiter or to the capsule, are:

a. Failure of the orbiter before Mars encounter.

b. Failure of the orbiter at the time of orbit insertion.

c. Achievement of Mars orbit, but failure immediately thereafter so as to preclude orbiter support of the capsule separation and descent maneuver.

d. Orbit achievement and survival long enough to permit successful capsule separation and descent, and relay of capsule data.

e. Orbit achievement, support of capsule descent, and short-term operation of orbital science.

f. Orbit achievement and survival in orbit for the full duration of the mission plan.

g. Repeated long-term operation in orbit.

First, the seven listed orbiter outcomes were reduced to five by utilizing repeat value to replace orbiter outcome (g), and combining outcomes (d) and (e) into one outcome. The combination is justified on the basis that the probability of failure from the time of capsule descent through the time associated with short-term orbital operation was adjudged to be low.

Given the resulting five orbiter outcomes, a second iteration reduces the number to four. This is accomplished by combining outcome (c) with outcomes (d) and (e), again using a probabilistic argument that having survived cruise and orbit insertion, it would be extremely unlikely for the spacecraft to fail prior to support of capsule descent.

The resulting list of orbiter outcomes is as follows:

a. Failure before Mars encounter.

b. Failure at the time of orbit insertion.

c. Achievement of Mars orbit, support of capsule separation and descent, and short-term orbital operation.

d. Orbit achievement and orbital operation for the planned mission duration.

These four orbiter outcomes are the rows of the project outcome matrix of Table 4.3. It should be noted that, for the Mariner 1971 configuration, complete success of the spacecraft can not advance the outcome state beyond level one, because the spacecraft is not planned to be about the planet.

Table 4-3. Project Outcome Matrix

Orbiter Outcomes		Capsule Outcomes													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Present Achievement: Flyby	X	X	X											
2	Failure at Orbit Insertion	X	X	X											
3	Short-Term Orbital Operation	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	Long-Term Orbital Operation	X	X	X	X	X	X	X	X	X	X	X	X	X	X

X = Allowable capsule and orbiter outcome combinations with nominal potential mission configurations

4.6.2.2 Capsule Outcomes

Capsule outcomes are defined by first defining a set of basic capsule achievements, and then forming outcomes by judiciously recognizing combinations of achievements.

4.6.2.2.1 Capsule Achievements

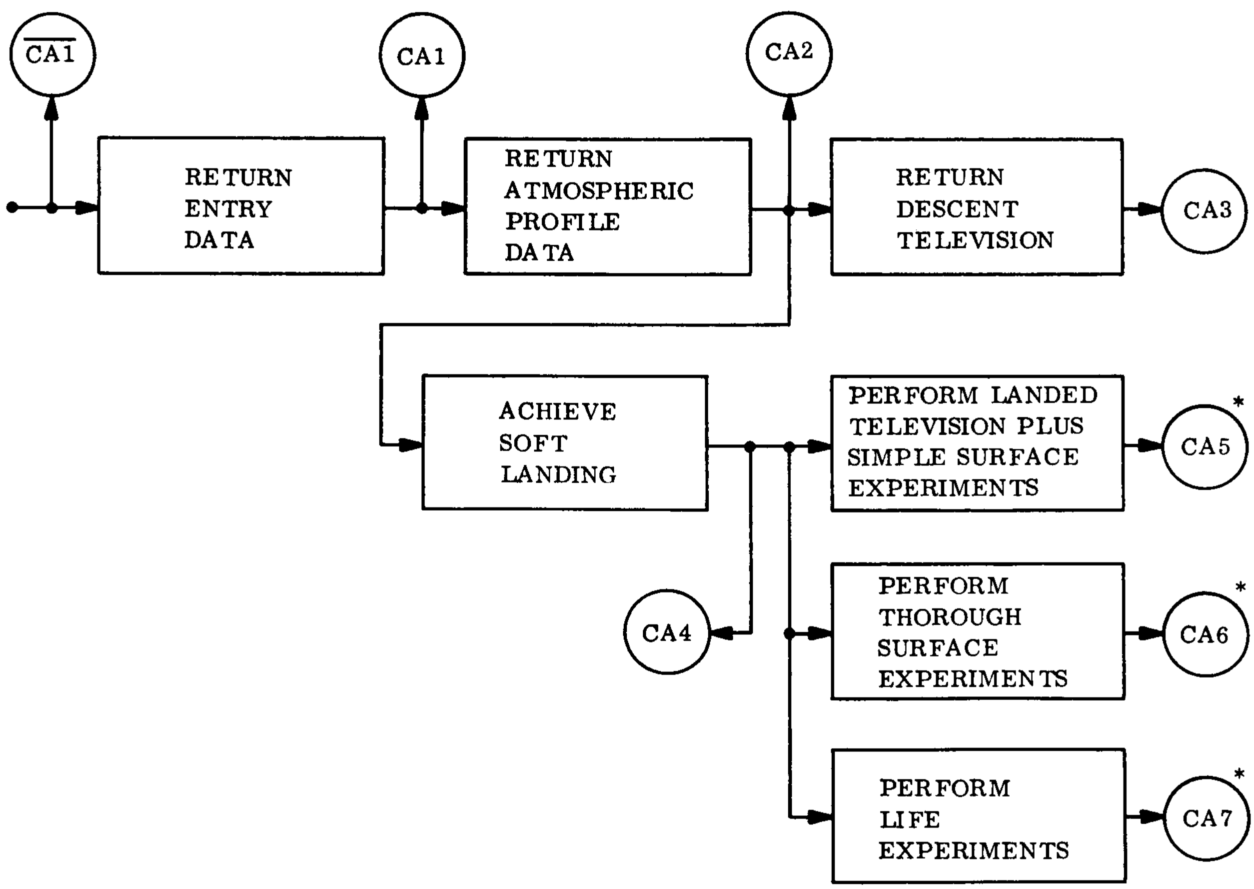
Figure 4-20 is a capsule functional flow diagram which describes seven basic capsule achievements, CA1 through CA7. Failure during the entry phase of the capsule mission, denoted by $\overline{\text{CA1}}$, is considered important, not because of its value but because of its adverse effect on the probability of successful entry in future missions.

Return of entry data (CA1) and return of a complete atmospheric profile (CA2) are considered valuable achievements. The latter implies survival of the capsule, not only through entry but through descent to the surface of the planet, including such events as deployment of parachutes and separation of the capsule heat shield, if and as required. Descent television (CA3), as indicated in Figure 4-20, is modeled to occur with or without an attempt to achieve soft landing.

Achievement of soft landing, even without meaningful experiments conducted on the surface, is considered an engineering achievement worthy of recognition by the decision model. Failure to achieve soft landing ($\overline{\text{CA4}}$) is also considered important because of its implication on the probabilities of success of subsequent attempts.

Rounding out the list of capsule achievements are three basic surface experiment achievements, modeled to reflect the capabilities of the medium lander (CA5), the biological laboratory (CA5 and CA7), and the physical laboratory (CA5 and CA6).

Possible combinations of these capsule achievements, together with the baseline level of achievement (CA0, no capsule attempt), still lead to a number of capsule outcomes much larger than could be permitted in the decision tree. Consequently, it was necessary to employ the techniques described previously to reduce the number of outcomes to an acceptable level. Table 4-4 indicates the combinations of capsule achievements which were finally selected as being representative capsule outcomes.



*ASSUMED TO HAVE ADDITIONAL VALUE IF REPEATED

Figure 4-20. Capsule Achievements

Table 4-4. Capsule Outcome

	Capsule Outcomes	CA0 No Mars Entry Attempt	$\overline{CA1}$ Failure at Mars Entry	CA1 Entry and Data Return	CA2 Return Atmospheric Profile	CA3 Return Descent Television	$\overline{CA4}$ Failure at Soft Landing	CA4 Achieve Soft Landing	CA5 Perform Landed TV with Simple Surface Experiments	CA6** $CA6^-$ Perform Thorough Surface Experiments	CA6** $CA6^+$	CA7 Perform Major Life Experiments
1	Present Level	X										
2	Mars Entry Failure		X									
3	Atmospheric Data			X	X							
4	Atmospheric Data with Soft Landing Failure			X	X		X					
5	Atmospheric Data and Descent Television			X	X	X						
6	Atmospheric Data and Descent Television with Soft Landing Failure			X	X	X	X					
7	Successful Soft Landing			X	X	X		X				
8	Landed Television			X	X	X		X	X			
9	Landed Physical Experiments			X	X	X		X		X	X	
10	Landed Biological Experiments			X	X	X		X		X		X
11	Landed Physical Experiments and Television			X	X	X		X	X	X	X	
12	Landed Biological Experiments and Television			X	X	X		X	X	X		X
13	Landed Biological and Physical Experiments *			X	X	X		X		X	X	X
14	All Landed Experiments *			X	X	X		X	X	X	X	X

* These outcomes cannot be achieved on a single mission

** The two columns represent the assumption that the biological lander has roughly half the surface experiments of the physical laboratory.

4.6.2.2.2 Formulation of Outcomes

To describe the rationale for the selection of the capsule outcomes of Table 4-4, the underlying bases for assigning value to the several capsule achievements of Figure 4-20 must be considered. First, it is considered that the landed experiments will carry by far the great bulk of value in the Voyager capsule mission. In other words, determination of the atmospheric and descent television are considered of minor value compared with the surface experiments from a scientific point of view. However, they are quite important in achieving a successful soft landing, which is a precursor to the important landed experiments. Hence, much of the value of early capsule achievements will be derived in nature, since the accomplishment of the achievement will increase the probability of success in later landed missions. An oversimplification is that the concern is to reduce three unknowns for future success: atmospheric properties, surface winds, and surface features.

4.6.2.2.3 Entry and Descent Outcomes

Referring to Table 4-4, the first outcome beyond the baseline outcome (CO1) is capsule outcome two (CO2), failure in an attempt at Mars atmospheric entry. As discussed previously, this outcome is principally of derived value because of its (negative) effect on subsequent mission probabilities.

The next major capsule outcome (CO3) is to survive the atmospheric entry into Mars and return data about the atmosphere. This is of scientific interest, although its greater value lies in ensuring capsule design adequacy for Mars entry. In this aspect, return of even unmodulated capsule radio carrier following entry is of value, in that it indicates adequate knowledge of the Mars atmosphere with respect to the capsule entry design. However, it is unlikely that this result would occur. The entry science instruments will probably be redundant, and the probability that the capsule could survive entry and not return the data is low.

The same argument can be extended to the atmospheric profile data, in that a capsule which survived entry and returned entry data would almost certainly also return the atmospheric data for which it was designed. Hence, it seemed reasonable to combine both entry and atmospheric data return into a single capsule outcome (outcome three of Table 4-4).

Outcome five (CO5) is selected as the return of descent television from a nonsurvivable probe. Descent television is thought to have some assigned value, but, again, its major value is its influence on future mission success. Descent television can provide sufficiently high resolution photographs of the Mars surface to ensure that a soft lander can be designed to accommodate the surface features that can reasonably be expected in future missions. Further, if the capsule contains attitude sensors, then the translation history of the capsule as it nears the surface could provide an indication of surface winds, another important variable in the design of a soft landing system. Thus, descent television is recognized as a major factor in the knowledge of the Mars landing environment.

The next major outcomes of significance in the exploration of Mars concern failure in an attempt to soft land. This outcome was modeled with descent television return (CO6) and without (CO4). It is assumed that any capsule capable of soft landing must have achieved entry success and is assumed to have provided, at least by inference, entry and atmospheric data.

4.6.2.2.4 Landed Outcomes

Successful soft landing is selected as the first landed outcome. Again, this could be accomplished with or without descent television. However, if successful soft landing is accomplished, credit is given for the return of descent television, entry and atmospheric data. The rationale behind the inclusion of descent television value in soft landing recognizes that such television has three principle components of value:

a. High resolution observation of the surface features, principally as an aid in the design of future soft landers.

b. A means of obtaining near-surface wind measurements for the same reason.

c. Location of the landing site, by correlation of high altitude descent photographs with photographs taken from the orbiter.

Substantially all of these values are reasoned to accrue from a successful soft lander, regardless of the success of the descent television experiment. Television pictures of surface features, for example, could be obtained from a successful soft lander, albeit over a smaller surface area. Near surface winds might possibly be inferred from landing radar telemetry. The longitude of the lander on the surface could probably be determined from the timing of occultation of the lander signal (to the orbiter or to earth). Its latitude could be deduced with good accuracy from the spacecraft geometry and attitude at the time of capsule separation. Thus, the value of descent television is included in capsule outcome seven (C07).

Capsule outcomes CO8 through CO14 represent combinations of capsule achievements CA5, CA6, and CA7, taken one, two, and three at a time. It is assumed that the biological laboratory could perform roughly half the surface physical experiments of the surface physical laboratory. Since full physical and biological experiment capability is not modeled aboard a single capsule, capsule outcomes CO13 and CO14 cannot be attained in a single mission.

Referring to Table 4-3, combinations of the four orbiter and 14 capsule outcomes result in 56 project outcomes. Some of these 56 outcomes are not, however, attainable with the nominal set of potential mission configurations of Table 4-2. For example, with orbiter outcome one, only direct entry capsule outcomes can be realized, and since the only direct entry capsules are the atmospheric probes of dual capsule configurations 12, 13 and 14, the maximum capsule outcome level is three with orbiter outcome one. A like argument suffices for orbiter outcome two. Thus, the number of project outcomes is fixed at 34, as shown in Table 4-3, for the 14 potential mission configurations previously discussed. It should be noted, however, that if the configuration entry mode option (i.e., direct entry for larger capsules) is exercised, the pattern and number of allowable project outcomes would be changed.

4.6.2.3 Assumptions

4.6.2.3.1 Dependence of Mission Events

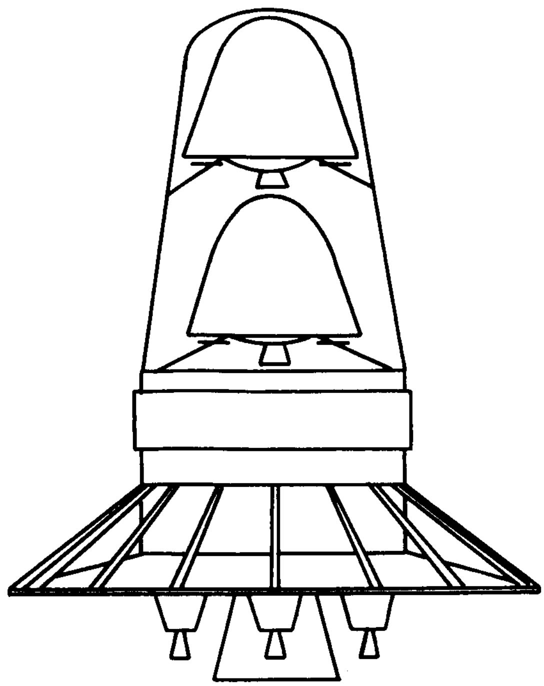
It is recognized that an important requirement on the decision model is that it correctly accounts for the dependence of mission events upon preceding events. For example, if a single launch vehicle launches two planetary vehicles on a Mars trajectory, then the outcomes of these separate planetary vehicles are not independent, but are conditioned upon launch vehicle success. In this example the dependence is evident, but there are other cases in which seemingly dependent events can be approximated as independent. To reduce the complexity of the decision structure, it is important to recognize as many situations as possible in which mission events can be considered independent of one another.

A typical case is the separation of two capsules from a single planetary vehicle. Mounted one above the other, there is a temptation to assume that successful separation of the lower or second entry vehicle should be conditioned upon having successfully released the first. In fact, some thought led to the conclusion that this is almost certainly not the case, and that the separation of these two capsules could be taken as independent events.

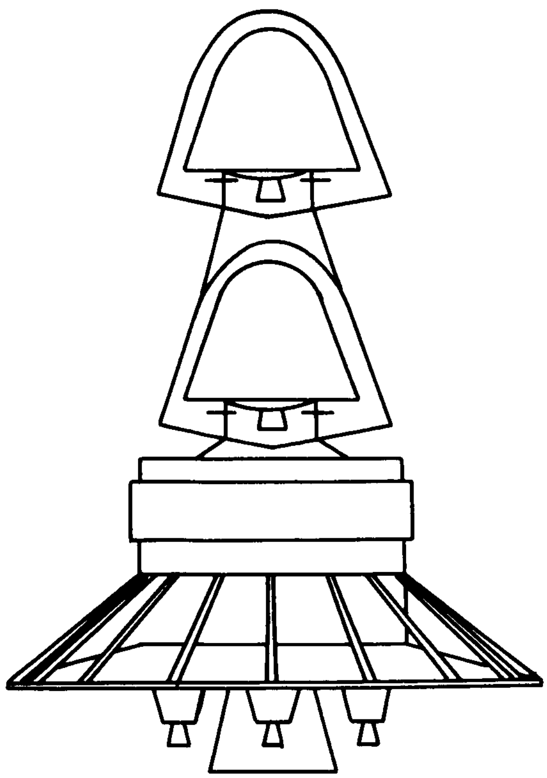
Consider two separate cases, as diagrammed in Figure 4-21. In 4-21a both capsules share a common biobarrier while in Figure 4-21 they are in independent but identical biobarriers. In both cases the flight sequence is assumed to be that the upper biocarrier is first separated, followed by the first capsule, followed by the second (or lower half) biobarrier, and finally separation of the second capsule. Both of these cases are similar, in that functional redundancy exists because separation of the second biobarrier (or lower half of the common biobarrier) necessarily releases any unseparated capsule or biobarrier above so that the lower capsule can be separated. This situation permits the assumption that dual capsule separations can be taken as independent events. In fact, reliability-conscious designers would prefer such independence of operation.

By an exactly similar argument, it can be shown that the separation of the first and second planetary vehicles from the Saturn V launch vehicle can be considered as independent events.

Another question of independence arose in considering the effect of failure to separate a direct entry capsule prior to attempting Mars orbit. Such a failure would reduce the propulsive velocity change at Mars orbit insertion, resulting in a different orbit. The



a. SEPARATION SEQUENCE OF TWO CAPSULES IN COMMON BIOBARRIER



b. SEPARATION SEQUENCE OF TWO CAPSULES IN IDENTICAL BIOBARRIERS

Figure 4-21. Dual Capsule Separation Sequences value of the orbiter is therefore not completely independent of the direct capsule separation event. However, the nature of the orbital change is that the period of the orbit is increased, but the periapsis remains about the same. The primary effect is to reduce, over a given mission lifetime, the number of times the spacecraft will be at periapsis, and thereby the quantity, but not the quality, of the orbital science. This effect is thought relatively minor enough to approximate orbit insertion as independent of direct entry capsule separation.

4.6.2.3.2 Multiple Successes Within a Mission

Most of the potential mission configurations employ two planetary vehicles per opportunity. Clearly, either none, one or two of them may succeed in reaching a given project outcome. The approximation is made that the outcome of the mission is the highest outcome achieved by a planetary vehicle within the mission, regardless of whether it is achieved by one or two planetary vehicles. For outcomes to which repeat value is applicable, the approximation is then made that repeating the outcome in the same mission is of little or no value, since the nature of the experiments on both planetary vehicles would probably be identical.

4.6.2.3.3 Last Opportunity

The restriction is placed on the decision structure that no missions could be launched after the 1981 opportunity. This extra mission, beyond present NASA plans for a Voyager project from 1973 to 1979, is inserted because the decision structure can skip launch opportunities to await results from previous missions, thereby yielding four flight (or less) sequences ending in 1981.

Voyager flights after 1981 are not considered for two reasons. First, it is felt there would be little interest in Voyager to Mars at dates later than 1981. Second, and more important, it is felt that the inclusion of events after 1981 would have a small effect upon the decision of major current interest; i.e., what to fly in 1973.

4.7 DECISION MODEL

The most striking difference in the full-scale model, when compared to the pilot model, is its increased detail and corresponding increase in size. Section 4.6 illustrates the many additional considerations in the full-scale model. In spirit, then, the full-scale model is a more realistic version of the pilot model, detail having been accepted up to reasonable limits.

As with the pilot model, the heart of the full-scale model is the decision tree, an explicit representation of the structure of the Voyager project sequential decision process. While the pilot model has about 60 nodes in its tree, the full-scale model decision tree has on the order of 3200 nodes. As a tree grows to this size, it becomes cumbersome and time consuming to prepare. This is especially true when the intention is to experiment with the rules by which the tree was generated to evaluate the realism of the decision model. Accordingly, the full-scale tree was not drawn, but rather, computer programs were developed to generate the tree and store it in memory according to specified input rules. These programs are discussed in the following subsections.

4.7.1 STATE VARIABLES

In the pilot model, specification of three state variables (current level of project achievement, indication of success or failure of the previous mission, and configuration under construction) completely described a decision node of the pilot tree. For example: L1', C2 indicates that the current project level of success is level one (return of atmospheric data), that the previous mission was a failure, and that the configuration under construction is C2 (orbital entry, nonsurvivable probe, with atmospheric experiments and descent television).

One additional state variable specification, the configuration chosen to follow the configuration currently under construction, suffices to define a chance node. For example: L1', C2, C2 indicates current project success level one, failure of the previous mission, current construction of a C2, and construction of a second C2 to follow.

Obviously, a significantly larger set of state variables is needed to describe the full-scale decision tree. Table 4-5 is a complete listing and description of the full-scale state variables.

There are six types of parameters associated with the full-scale tree: decision nodes, chance nodes, terminal nodes, costs, values, and probabilities. These six basic parameters are defined in Table 4-5 in terms of their functional dependence on the state variables. For example, a decision node is characterized by the form: D, TIME, PROJECT ORBITAL OUTCOME, PROJECT CAPSULE OUTCOME, CONFIGURATION UNDER CONSTRUCTION. The D identifies the variable type (decision node), while the succeeding list of four state variables completely specifies the decision node. D, 5, OOLORB, COATM, VOVBL (for example) is interpreted as follows: the D identifies a decision node; the 5 places the point of time as 1973; OOLORB indicates that the project orbital outcome is long-term orbital operation; COATM indicates that a nonsurvivable probe has returned atmospheric data; and VOVBL tells us that the biological laboratory is the configuration currently under construction.

4.7.2 TREE GENERATION

By defining the state variables and their possible values, part of the information necessary to generate the decision tree is available. The set of all potential mission configurations, of all possible project capsule outcomes, and of all possible project orbital outcomes is specified. Still required, however, are the node succession rules: viz., the outcome capabilities of the various configuration, which outcomes can succeed which outcomes, what combinations of orbital and capsule outcomes are possible, which configurations are available as a function of time, and also explicit specification as to how the project terminates. The foundation for these rules is included in Section 4.6.

As previously mentioned, the tree is constructed by means of a computer program which incorporates the state variables and succession rules. The operation of the tree generation program can be illustrated by generating a small segment of the tree by hand. Consider the decision node D, 7, OOORB, COLTV, VOTVSF, and the construction of its successors

Table 4-5. List of State Variables

TIME	ORBITAL OUTCOMES*	CAPSULE OUTCOMES**	MISSION CONFIGURATIONS***	OOLORB REPEAT INDICATOR*	CA5 REPEAT INDICATOR****	CA6 REPEAT INDICATOR****	CA7 REPEAT INDICATOR****
1 1969 or earlier	1 OOZERO	1 COZERO	1 VSTOP	1 NOB: OOLORB	1 NCR5: CA5	1 NCR6: CA6	1 NCR7: CA7
2 1970	2 OONORB	2 CONOEN	2 VSKIP	not repeated	not repeated	not repeated	not repeated
3 1971	3 OOORB	3 COATM	3 VMAR	2 OB: OOLORB repeated	2 CR5: CA5 repeated	2 CR6: CA6 repeated	2 CR7: CA7 repeated
4 1972	4 OOLORB	4 COATMS	4 VSIB				
5 1973		5 CODTV	5 V2SIB				
6 1974		6 CODTVS	6 VOORB				
7 1975		7 COLAND	7 VOATM				
8 1976		8 COLTV	8 VODTV				
9 1977		9 COSURF	9 VOLTV				
10 1978		10 COBIOL	10 VOTVSF				
11 1979		11 COTVSF	11 VOVBL				
12 1980		12 COBITV	12 VODATM				
13 1981		13 COBISF	13 VODDTV				
14 1982		14 COALEX	14 VODLTV				
15 1983							

* Refer to Table 4-3

** Refer to Table 4-4

*** Refer to Table 4-2

**** Refer to Table 4-20

Definition of Decision Tree Nodes and Parameters in Terms of State Variables

a. Decision Node Name

= D, Time, Orbiter Outcome, Capsule Outcome, Configuration under Construction

b. Chance Node Name

= C, Time, Orbiter Outcome, Capsule Outcome, Configuration under Construction, Configuration Selected to Follow

c. Terminal Node Name

= T, Time, Orbiter Outcome, Capsule Outcome, VSTOP

d. Cost Name

= CO, Time, Orbiter Outcome, Capsule Outcome, Configuration under Construction, Configuration Selected to Follow

e. Value Name

= V, Initial Orbiter Outcome, Initial Capsule Outcome, Resultant Orbiter Outcome, Resultant Capsule Outcome, OOLORB Repeat Indicator, CA5 Repeat Indicator, CA6 Repeat Indicator, CA7 Repeat Indicator

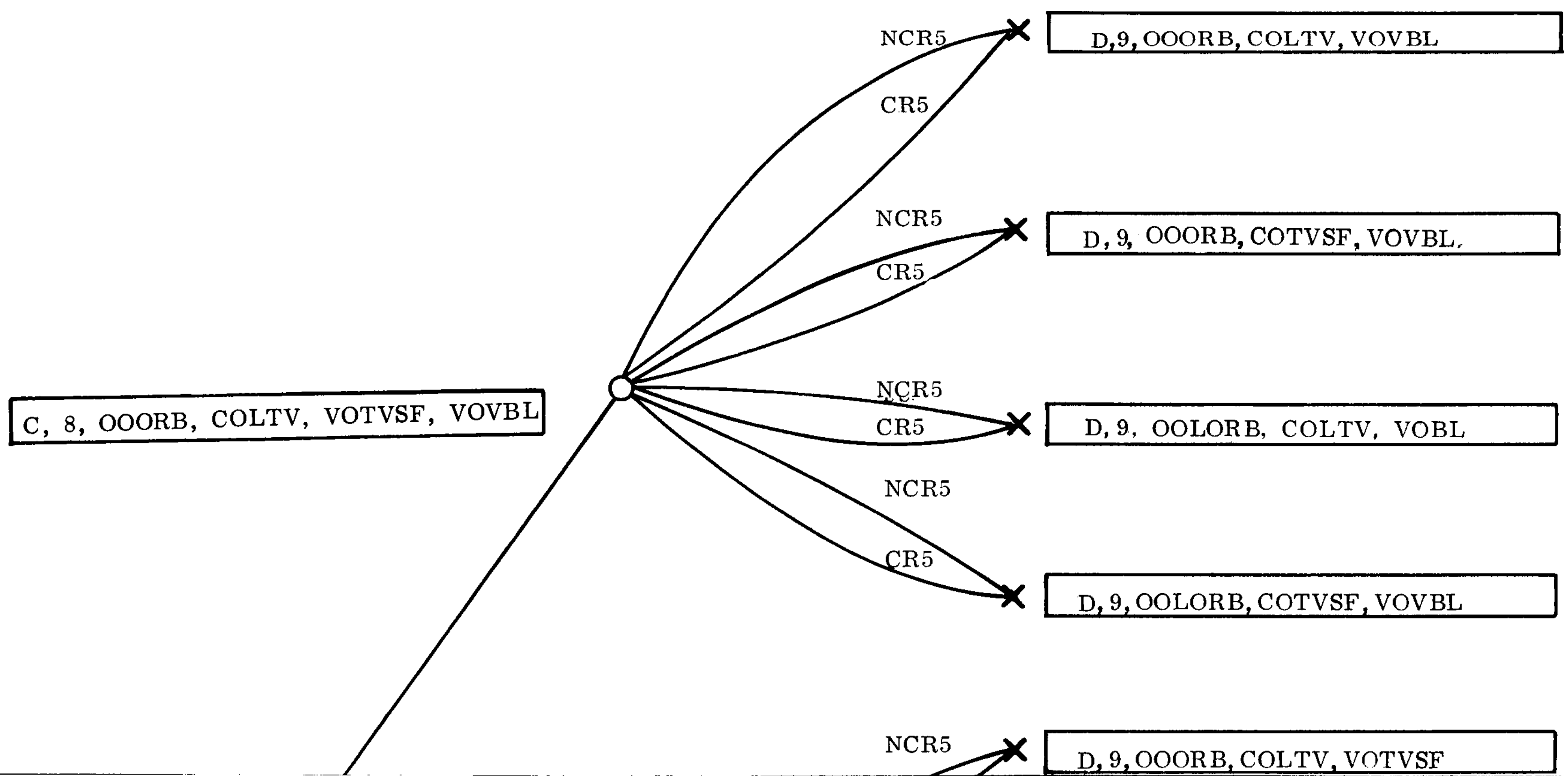
f. Probability Name

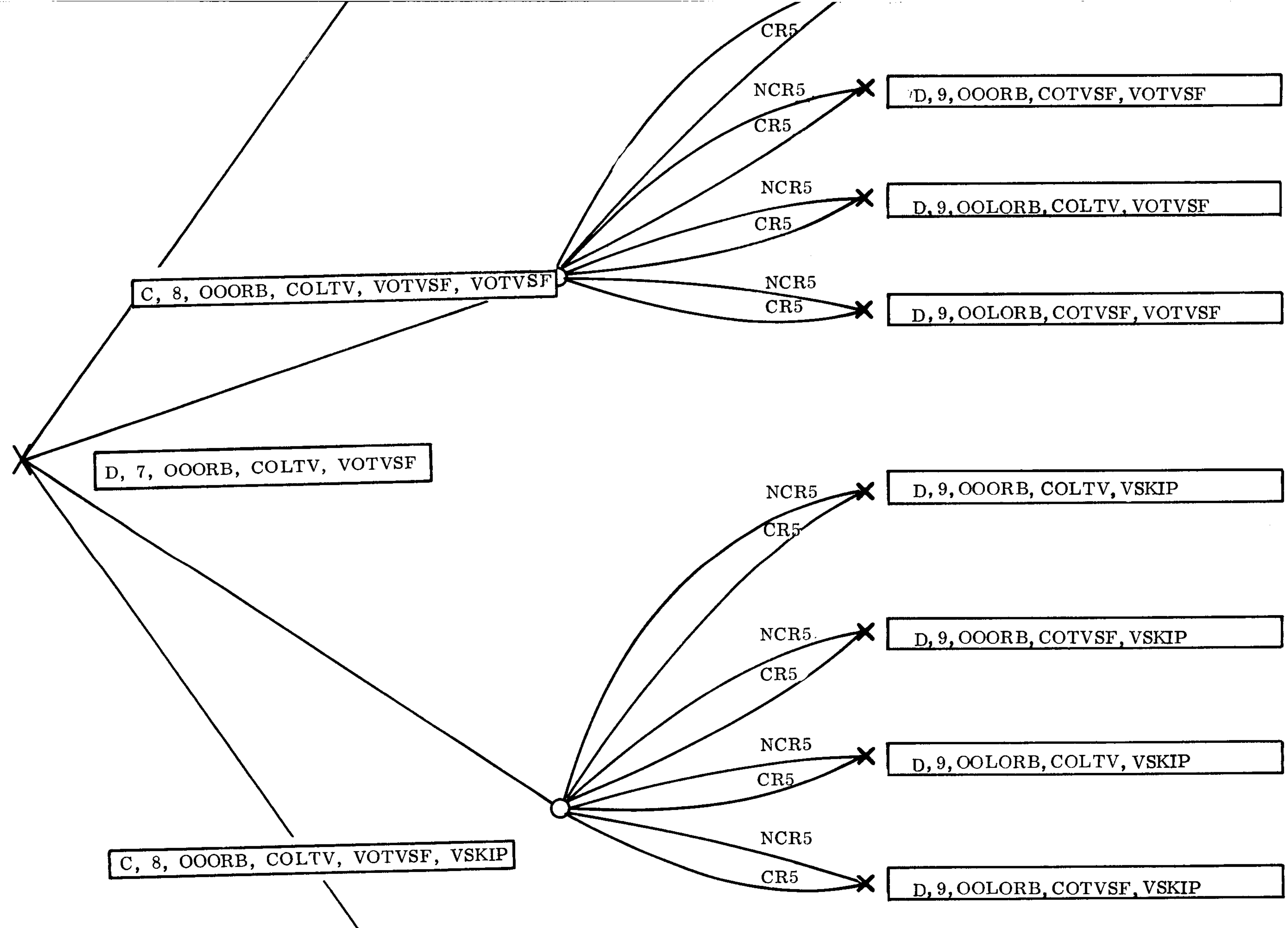
= P, Time, Initial Orbiter Outcome, Initial Capsule Outcome, Resultant Orbiter Outcome, Resultant Capsule Outcome, Configuration, OOLORB Repeat Indicator, CA5 Repeat Indicator, CA6 Repeat Indicator, CA7 Repeat Indicator and the successors to its successors (Figure 4-22). Although the number of configurations available in decision year seven (1975, the year of the decision for 1977) is four (see Table 4-2), only VOTVSF and VOVBL, in addition to skipping the opportunity or stopping the project, may follow VOTVSF. Thus, the initial decision node is succeeded by the four chance nodes shown in Figure 4-22. The cost associated with choosing the uppermost alternative, for example, is CO, 7, OOORB, COLTV, VOTVSF, VOVBL.

Consider next the successors to the uppermost chance node. As the VOTVSF configuration is capable of achieving the full range of orbital outcomes, the project orbital outcome may or may not be advanced from OOORB (short-term operations) to OOLORB (long-term operations). The only capsule achievement which VOTVSF is capable of adding to the set already achieved is CA6 (surface physical experiments). Thus, the four successor nodes shown are the possible combinations of the two orbital outcomes (OOORB and OOLORB) and the two capsule outcomes (COLTV and COTVSF). However, landed television (CA5) is a capsule achievement for which there is repeat value, and the VOTVSF configuration has that capability. Hence, each successor node may be reached via one of two possible paths: one path corresponding to no repeat of the television achievement, the other implying successful repeat of that achievement.

The logic for generating the successors to the other three chance nodes is quite similar. For the lower-most chance node, since project termination (VSTOP) was selected, terminal rather than decision nodes, are reached.

Figure 4-23 is a gross flow diagram of the computer program which generates the decision tree. The input data that must be supplied to the program include the node succession rules, specified in the form of seven matrices, and the name of the first node in the tree. These seven arrays, and their nominal values (as suggested in Section 4. 6). are illustrated and described in Figures 4-24 through 4-30.


C, 8, OOORB, COLTV, VOTVSF, VOVBL
NCR5
CR5
D,9, OOORB, COLTV, VOVBL
NCR5
CR5
D, 9, OOORB, COTVSF, VOVBL,
NCR5
CR5
D, 9, OOLORB, COLTV, VOBL
NCR5
CR5
D, 9, OOLORB, COTVSF, VOVBL
NCR5
D, 9, OOORB, COLTV, VOTVSF


C, 8, OOORB, COLTV, VOTVSF, VOTVSF
D, 7, OOORB, COLTV, VOTVSF
C, 8, OOORB, COLTV, VOTVSF, VSKIP
CR5
NCR5
CR5
D, 9, OOORB, COTVSF, VOTVSF
NCR5
CR5
D, 9, OOLORB, COLTV, VOTVSF
NCR5
CR5
D, 9, OOLORB, COTVSF, VOTVSF
NCR5
CR5
D, 9, OOORB, COLTV, VSKIP
NCR5
CR5
D, 9, OOORB, COTVSF, VSKIP
NCR5
CR5
D, 9, OOLORB, COLTV, VSKIP
NCR5
CR5
D, 9, OOLORB, COTVSF, VSKIP

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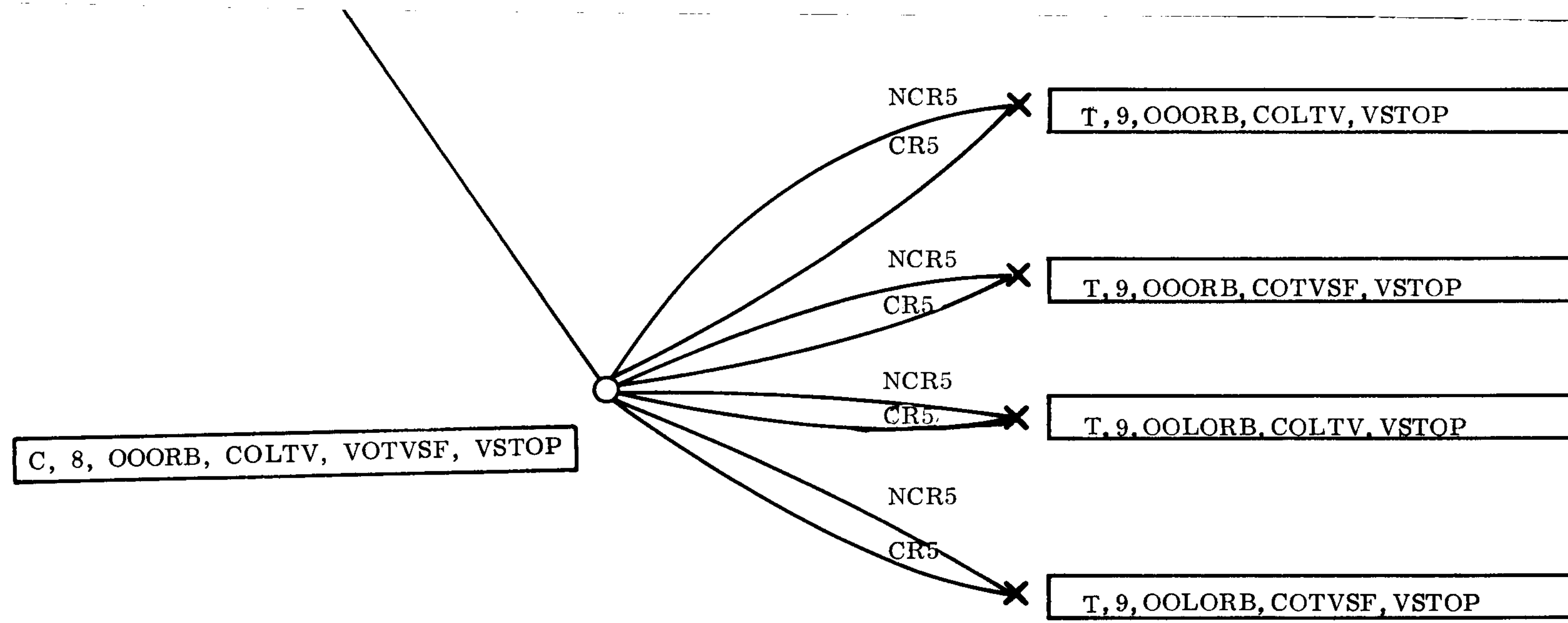


Figure 4-22. Segment of Full-Scale Decision Tree

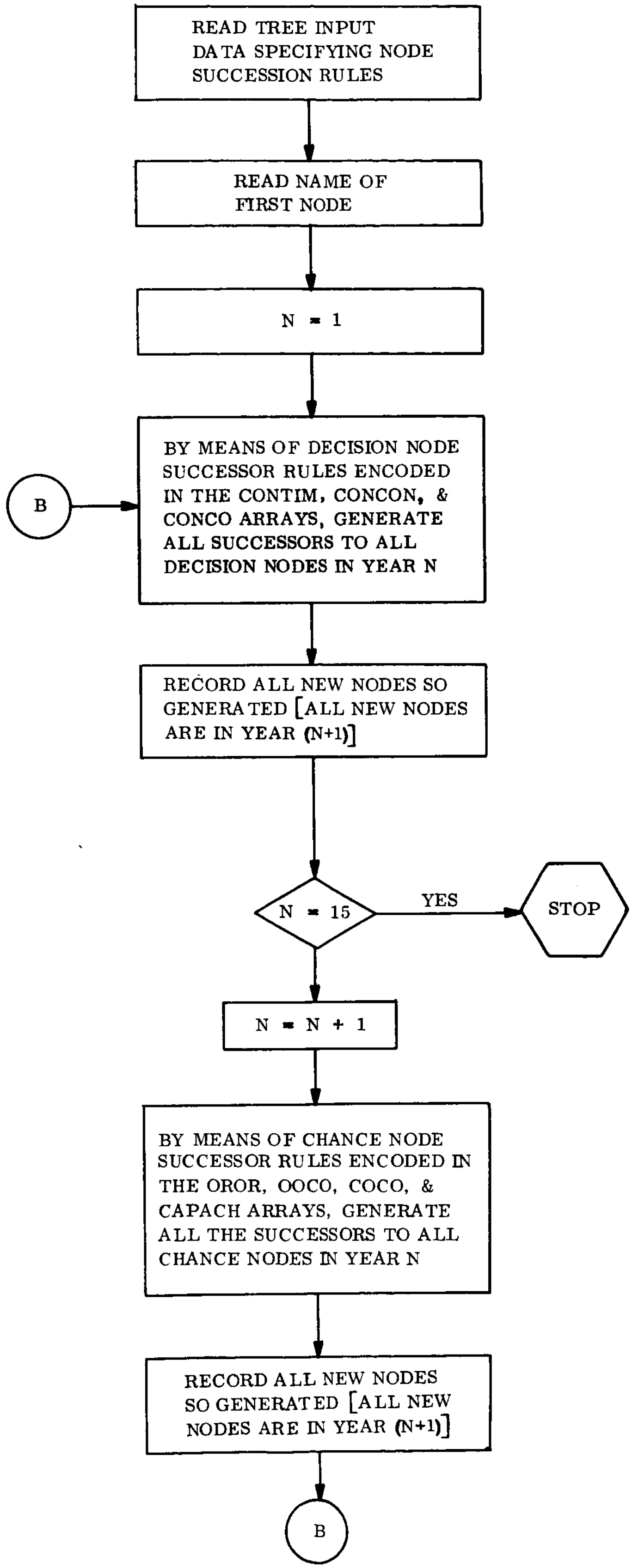


Figure 4-23. Flow Diagram of the Tree Generation Program

The CONTIM matrix specifies the availability (1 = available, 0 = not available) of mission configurations for the various opportunities (years 3, 5, 7, 9, 11, and 13 of the program).

	Year of Opportunity														
Mission Configuration	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1
2	0	0	1	0	1	0	1	0	1	0	1	0	1	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
8	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
9	0	0	0	0	1	0	1	0	1	0	1	0	1	0	0
10	0	0	0	0	1	0	1	0	1	0	1	0	1	0	0
11	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0
12	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
14	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0

Figure 4-24. CONTIM Matrix

The CONCON array summarizes the ground rules imposed upon the model with regard to the question of which configurations may be succeeded by which configurations. If the entry in row R, column C is 1, then configuration R may succeed configuration C. If the entry is 0, configuration R may not be chosen if configuration C is presently under construction. Approximately, the CONCON matrix embodies the assumption that a given configuration will not be succeeded by a less sophisticated configuration. *

		Predecessor Configuration													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Successor Configuration	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	1	1	0	0	0	0	0	0	0	0	0	0	0
	5	0	1	1	0	0	0	0	0	0	0	0	0	0	0
	6	0	1	1	0	0	0	0	0	0	0	0	0	0	0
	7	0	1	1	1	1	1	1	0	0	0	0	1	0	0
	8	0	1	1	1	1	1	1	1	0	0	0	1	1	0
	9	0	1	1	1	1	1	1	1	1	0	0	1	1	1
	10	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	11	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	12	0	1	1	1	1	1	1	0	0	0	0	1	0	0
	13	0	1	1	1	1	1	1	1	0	0	0	1	1	0
	14	0	1	1	1	1	1	1	1	1	0	0	1	1	1

* The assumption was made that if a mission opportunity is skipped during or after the seventh year, then only configurations 10 or 11 may follow the skip. This is effected by changing column 2 of CONCON to 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0.

Figure 4-25. CONCON Matrix

The CONCO matrix specifies the set of configurations which may be flown as a function of project capsule outcome. Thus, if there is a 1 in row R, column C, then configuration R may be selected when the project capsule outcome is C. This matrix is used to eliminate configurations which cannot possibly add any additional value to the project.

	Project Capsule Outcome													
Mission Configuration	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	0	0	0	0	0	0	0	0	0	0	0
5	1	1	1	0	0	0	0	0	0	0	0	0	0	0
6	1	1	1	0	0	0	0	0	0	0	0	0	0	0
7	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	1	1	1	0	0	0	0	0	0	0	0	0	0	0
9	1	1	1	1	1	1	1	1	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13	1	1	0	0	0	0	0	0	0	0	0	0	0	0
14	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4-26. CONCO Matrix

The OROR matrixes encode the information as to which orbital outcomes may follow a given orbital outcome. Thus, if row R, column C is 1, orbital outcome C is a possible project orbital outcome after the mission, if the project orbital outcome prior to the mission was R.

a. OROR 1 (Configurations 4-14)

		Resultant Orbiter Outcome			
		1	2	3	4
Initial Orbiter Outcome	1	1	1	1	1
	2	0	1	1	1
	3	0	0	1	1
	4	0	0	0	1

b. OROR 2 (Configuration 3)

		Resultant Orbiter Outcome			
		1	2	3	4
Initial Orbiter Outcome	1	1	0	0	0
	2	0	1	0	0
	3	0	0	1	0
	4	0	0	0	1

Figure 4-27. OROR Matrix

The COCO matrixes encode the information as to which capsule outcomes may follow a given capsule outcome. Thus, if row R, Column C is 0, capsule outcome C is not a possible project capsule outcome after the mission, if the project capsule outcome prior to the mission was R.

a. COCO 1 (Configurations 3, 7, 12)

	Resultant Capsule Outcome													
Initial Capsule Outcome	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
2	0	1	1	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

b. COCO 2 (Configurations 4-6)

	Resultant Capsule Outcome													
Initial Capsule Outcome	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 4-28. COCO Matrix (Sheet 1 of 3)

c. COCO 3 (Configurations 8 and 13)

Initial Capsule Outcome	Resultant Capsule Outcome													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1	0	1	0	0	0	0	0	0	0	0	0
2	0	1	1	0	1	0	0	0	0	0	0	0	0	0
3	0	0	1	0	1	0	0	0	0	0	0	0	0	0
4	0	0	0	1	1	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

d. COCO 4 (Configurations 9 and 14)

Initial Capsule Outcome	Resultant Capsule Outcome													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
2	0	1	1	1	0	1	1	1	0	0	0	0	0	0
3	0	0	1	1	0	1	1	1	0	0	0	0	0	0
4	0	0	0	1	0	1	1	1	0	0	0	0	0	0
5	0	0	0	0	1	1	1	1	0	0	0	0	0	0
6	0	0	0	0	0	1	1	1	0	0	0	0	0	0
7	0	0	0	0	0	0	1	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 4-28. COCO Matrix (Sheet 2 of 3)

e. COCO 5 (Configuration 10)

Initial Capsule Outcome	Resultant Capsule Outcome: 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	0	1	0	1	1	1	1	0	1	0	0	0
2	0	1	0	1	0	1	1	1	1	0	1	0	0	0
3	0	0	1	1	0	1	1	1	1	0	1	0	0	0
4	0	0	0	1	0	1	1	1	1	0	1	0	0	0
5	0	0	0	0	1	1	1	1	1	0	1	0	0	0
6	0	0	0	0	0	1	1	1	1	0	1	0	0	0
7	0	0	0	0	0	0	1	1	1	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0	1	0	0	0
9	0	0	0	0	0	0	0	0	1	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	1	1	1
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	1
13	0	0	0	0	0	0	0	0	0	0	0	0	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

f. COCO 6 (Configuration 11)

Initial Capsule Outcome	Resultant Capsule Outcome: 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	0	1	0	1	1	1	0	1	0	1	0	0
2	0	1	0	1	0	1	1	1	0	1	0	1	0	0
3	0	0	1	1	0	1	1	1	0	1	0	1	0	0
4	0	0	0	1	0	1	1	1	0	1	0	1	0	0
5	0	0	0	0	1	1	1	1	0	1	0	1	0	0
6	0	0	0	0	0	1	1	1	0	1	0	1	0	0
7	0	0	0	0	0	0	1	1	0	1	0	1	0	0
8	0	0	0	0	0	0	0	1	0	0	0	1	0	0
9	0	0	0	0	0	0	0	0	1	0	1	0	1	1
10	0	0	0	0	0	0	0	0	0	1	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	1
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 4-28. COCO Matrix (Sheet 3 of 3)

The OOCO matrix specifies the various possible combinations of project orbital outcomes and project capsule outcomes. Thus, if row R, Column C is 0, it is never possible for the project outcome state to be orbital outcome R, capsule outcome C. (See Table 4-3).

		Capsule Outcomes													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Orbiter Outcomes	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 4-29. OOCO Matrix

The CAPACH matrix relates mission configurations to capsule achievements which have repeat value. Column 1 represents the first capsule achievement with repeat value; i.e., landed television (CA5). Similarly, column 2 represents surface experiments (CA6) and column 3 represents life detection experiments (CA7). A 1 in row R, column C, indicates that configuration R is capable of achieving (and therefore repeating) the corresponding capsule achievement.

		Capsule Achievement		
		5	6	7
Configuration	1	0	0	0
	2	0	0	0
	3	0	0	0
	4	0	0	0
	5	0	0	0
	6	0	0	0
	7	0	0	0
	8	0	0	0
	9	1	0	0
	10	1	1	0
	11	1	0	1
	12	0	0	0
	13	0	0	0
	14	1	0	0

Figure 4-30. CAPACH Matrix

4.8 PROBABILITY MODEL

4.8.1 INTRODUCTION

The primary goal of the probability model is to provide a logical structure within which probabilities of particular outcomes can be calculated for all possible states of the project. There is a great amount of information available from the many engineers working on the project, and the aim of the probability model is to develop a logical language to transform this information into the numbers that are necessary for the decision analysis.

The first step in the construction of the probability model is to select the set of project outcomes that will be used to describe the results of a particular mission configuration. This is described in Section 4.6. Let us momentarily designate the possible outcomes of a particular mission by (L_0, L_1, L_2...). If S denotes a particular state of the Voyager project as described by the state variables introduced in Section 4.7, then the purpose of the probability model is to provide a logical structure for the calculation of the probability of each mission outcome conditioned upon having attained the state S. In standard probability notation, the goal is to calculate $p\ (L_i/S)$ for all i.

An important element in the construction of the probability model is the functional flow definition of the mission profile for a given mission configuration. Although the functional flow diagrams are not explicit enough for direct translation into outcome probabilities, they are indispensable to the precise formulation of the model.

The primary mechanism for representing the probability model is the transition diagram. An illustration of a transition diagram is shown in Figure 4-31. Each node in the transition diagram represents a particular state of a mission; a branch from one node to another represents a transition between the two states. The probability associated with each branch is the conditional probability that the mission will make the transition to the successor node, given its arrival at the preceding node. The transition diagram contains all possible states of the mission, so that the probabilities of all branches leaving each

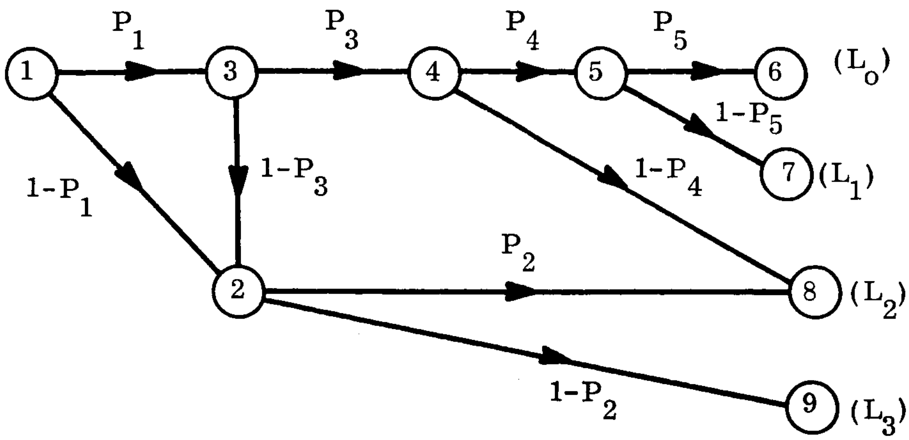


Figure 4-31. Example Transition Diagram

node must sum to unity. Those nodes that have no branches emanating from them represent the various outcomes of the mission.

To calculate the probability of each of the outcomes conditioned upon each state of the project, one approach is to construct a transition diagram for each state of the Voyager project. In practice, however, the most important variable of the state, S (with respect to probabilities), is the mission configuration that has been selected. Further, since there are similarities among the various configurations, it is convenient to construct a single transition diagram and then alter it according to the configuration under consideration. This approach is discussed more fully in Subsection 4.8.2.

Once the transition diagram has been constructed and the transition probabilities have been computed, the calculation of the outcome probabilities $p(L_i | S)$ is straightforward. If a path product is defined as the product of the probabilities associated with a particular path through the transition diagram, then probability of a particular outcome is just the sum of all the path products from the first node to the node associated with that outcome. For example, in Figure 4-31, the probability of L_1 is just $p_1p_3p_4(1-p_5)$, and the probability of L_2 is $p_1p_3(1-p_4) + p_1(1-p_3)\,p_2 + (1-p_1)p_2$. Thus, an algorithm for calculating outcome probabilities consists of the following three steps:

a. Set the probability at the first node equal to 1.0.

b. For each node in the transition diagram and each branch emanating from the node, multiply the probability associated with the node by the probability associated with the branch, and add the product to the probability associated with the terminal node of the branch. For a node that has no branches emanating from it, omit this operation. Do not carry out this operation for a node until the probability for that node has been completely calculated. (This latter condition implies that only certain sequences of calculations are legitimate. However, once a transition diagram has been specified, it is a simple operation to calculate such a legitimate sequence of calculations. This sequence can be stored and then used in all subsequent calculations of the outcome probabilities.)

c. The probability associated with each of the output nodes is the probability of the outcome associated with that node.

An important component of the probability model is knowledge of the environment in which the mission configuration must operate. This can make, for example, the probabilities of future outcomes dependent upon the outcomes already achieved. It was felt that there were three major events in the mission profile which could sufficiently improve our knowledge of environmental factors to require recognition in the probability model:

a. Orbit Insertion - There is some uncertainty concerning the interaction between the propulsion system and the rest of the spacecraft (such as the autopilot) in a zero g, high vacuum space environment during orbit insertion which cannot, probably, be adequately removed during the ground test program. The first successful orbit achievement of the spacecraft will enhance confidence that the vehicle has been correctly designed. Thus, provision is made in the probability model to recognize this increased confidence following the initial, successful orbit insertion.

b. Entry - Initial successful entry of a capsule into the Martian atmosphere is recognized in the probability model such that it can lead to improved probabilities of future successful entries.

c. Soft Landing - The third change in future probabilities concerns the attempt to soft land. This probability can be favorably influenced either by obtaining descent television pictures or by actually soft landing.

As an example of the effect of environmental factors, consider the environmentally sensitive mission event represented by a transition from node n-1 to node n of the transition diagram; i.e., the branch from node n-1 to node n, to which the probability p is assigned. If W_n denotes achievement of the state represented by the nth node,

$$p_n = p\,(W_n \,|\, W_{n-1})$$

Assume further that there is a particular environment variable (e) associated with the transition from node n-1 to node n. Then the equation can be expanded into

$$p_n = \int_{\text{all } e} p(e \,|\, W_{n-1})\, p\,(W_n \,|\, W_{n-1}, e)\, de.$$

The probability $p\,(e \,|\, W_{n-1})$ represents the probability density function for the environment parameter (e) conditioned upon the attainment of the (n-1)th node by the mission. The probability $W_n | W_{n-1}, e$ is the probability of a transition from node n-1 to node n conditioned upon knowledge of the environment parameter e.

To carry out the integration described by the above equation, some approximations are necessary. Specifically, it is assumed that the transition probability $W_n | W_{n-1}, e$ is of the form shown in Figure 4-32. In other words, it is assumed that the mission hardware associated with the transition from node n-1 to node n is designed for a particular range of the environment parameter from e_1 to e_2. If the parameter e does in fact lie within this interval, then the hardware will be successful with probability p_h; if the environment lies outside the design region, then the probability of successful operation is zero. For an approximation of this form, the foregoing expression for the transition probability reduces to

$$p = p_e p_h,$$

where

$$p_e = \int_{e_1}^{e_2} p(e \mid W_{n-1})de$$

is the probability that e lies within the design interval (e_1, e_2).

This approximation can also be described graphically in the transition diagram; this is portrayed in Figure 4-33. In Figure 4-33b, the transition from node n-1 to node n is divided into two separate events. The first corresponds to the environment parameter lying within the design interval, and the second even corresponds to the successful operation of the hardware when the environment lies within the necessary interval.

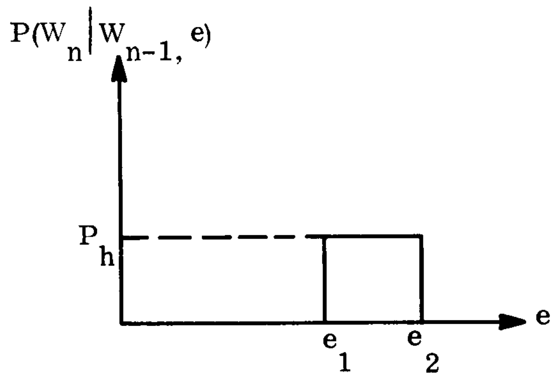


Figure 4-32. Environmental Probability Assumption.

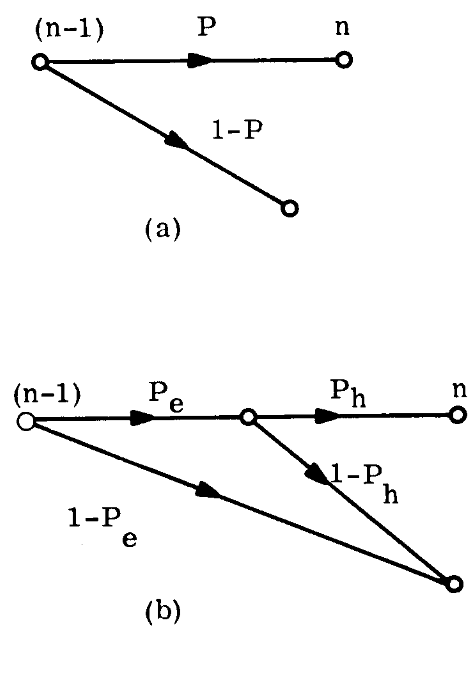


Figure 4-33. Example of Inclusion of Environmental Knowledge Confidence in the Transition Diagram

4.8.2 MISSION DESCRIPTION AND THE TRANSITION DIAGRAM

4.8.2.1 Introduction

The mission functional flow profile, described in Section 2, was condensed into a functional flow diagram illustrated in Figure 4-34. The outcomes associated with the Voyager mission profile can be generally categorized as:

a. Orbiter outcomes.

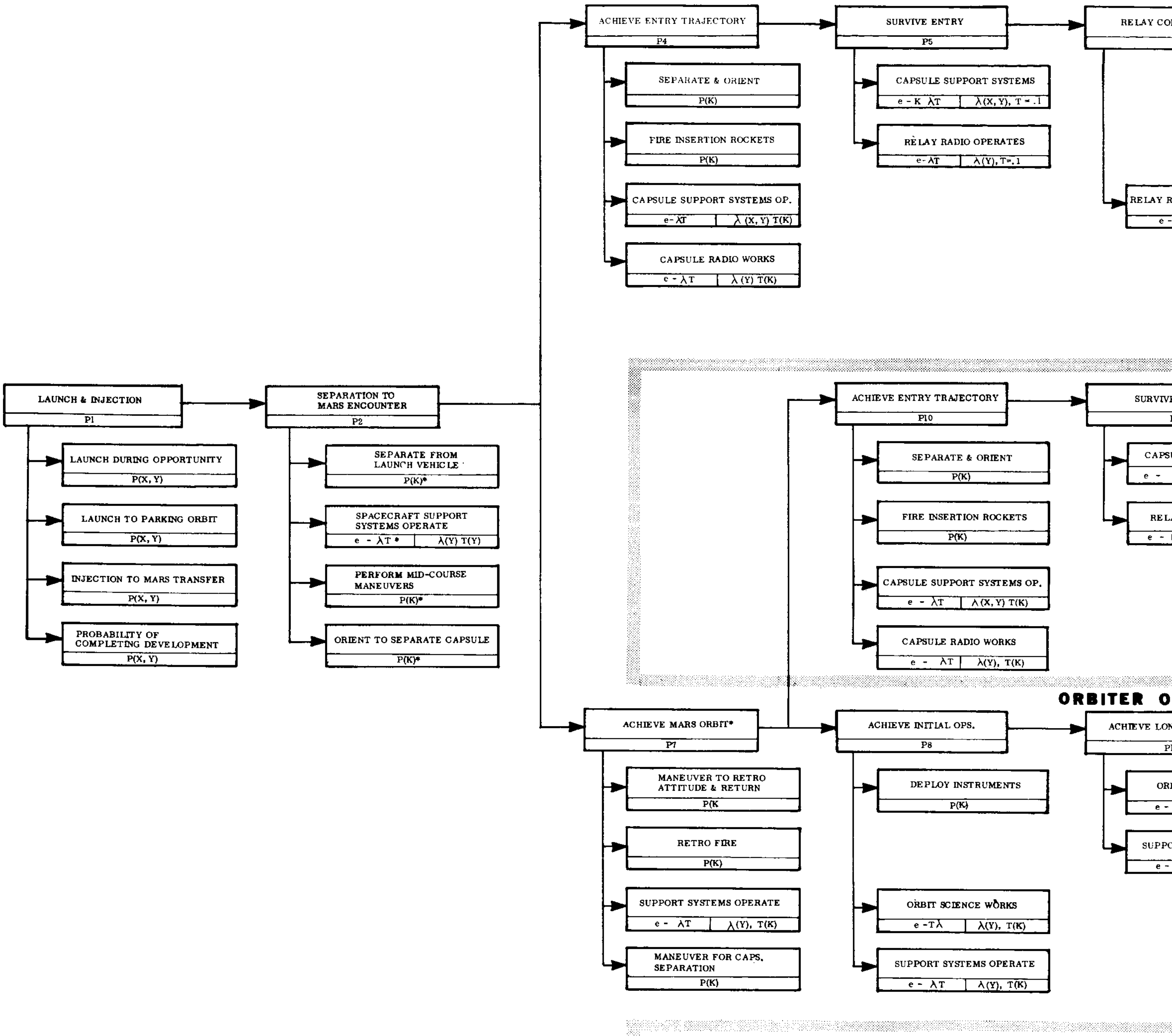
b. Direct entry probe outcomes.

c. Orbital entry capsule outcomes.

Each of the major functions of Figure 4-34 is subdivided to that level where probabilities of successful operation can be generated from available data sources or estimated.

The following notation is used on the flow diagram of Figure 4-34:

$P(K)$:	The probability, as calculated from input data, is assumed to be constant for all Voyager mission configurations.
$P(X, Y)$:	The probability is dependent on both the mission configuration (X) and year of launch (Y).
$\lambda(Y)$:	The failure rate of the hardware is a function of launch year.
$T(Y)$:	The time duration of the mission phase is a function of launch year.
$\lambda(X, Y)$:	The hardware failure rate is a function of both configuration (X) and year of launch (Y).
$T(K)$:	The event operating time is a constant.
$T(N)$:	The time required for long term orbit success increases with launch year (as soon as one orbiter has had long term success).

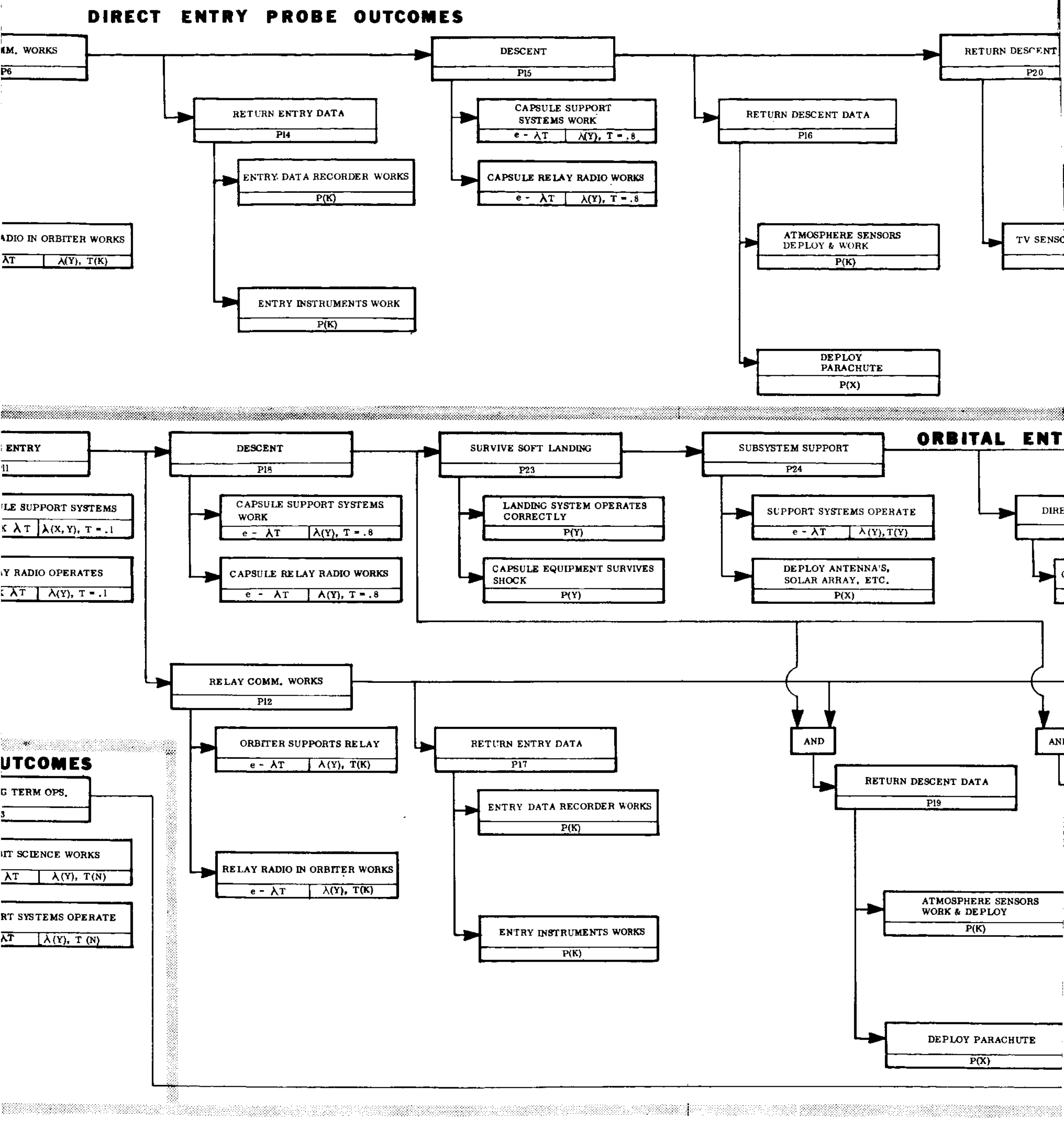


NOTATION:

P(NUMBER) PROBABILITY USED IS TR

P(K) MEANS THE PROBABILITY AS A CONSTANT FOR ALL

* MEANS THAT THIS PROBA THAN FOR VOYAGER.



ANSITION DIAGRAM.

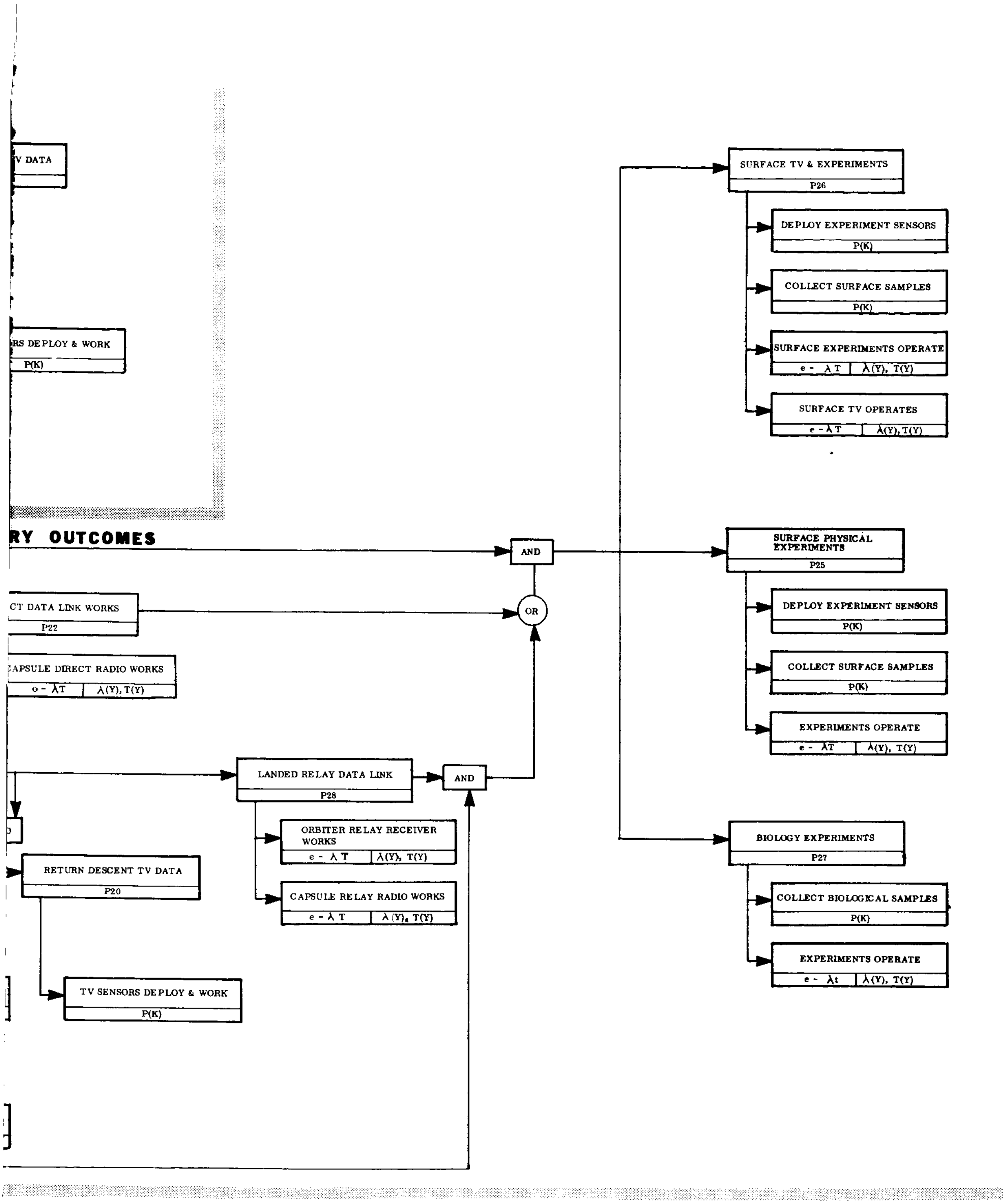
, CALCULATED FROM INPUT DATA, IS TAKEN VOYAGER MISSION CONFIGURATIONS.

BILITY FOR MARINER IS MODELED DIFFERENTLY

P(X, Y) MEANS THE PROBABILITY IS DEPENDENT UPON BOTH MISSION CONFIGURATION (X) AND YEAR OF LAUNCH (Y).

λ(Y) MEANS THIS FAILURE RATE IS A FUNCTION OF LAUNCH YEAR.

T(Y) MEANS OPERATING TIME USED IS A FUNCTION OF LAUNCH YEAR.



λ(X, Y)	MEANS FAILURE RATE IS A FUNCTION OF CONFIGURATION AND LAUNCH YEARS.
T(K)	MEANS THAT OPERATING TIME IS AN INPUT CONSTANT.
T(N)	MEANS THAT LONG TERM ORBIT SUCCESS REQUIRES INCREASING DURATION WITH LAUNCH YEAR AS SOON AS ONE ORBITER HAS HAD LONG TERM SUCCESS.
P(Y)	MEANS A PROBABILITY DEPENDENT UPON LAUNCH YEAR.
P(X)	MEANS PROBABILITY IS DEPENDENT UPON CONFIGURATION.

Figure 4-34. Probability Model Mission Functional Flow

[redacted]

P(Y): The probability is dependent only upon launch year.

P(X): The probability is dependent only upon mission configuration.

In the first two mission phases, the Mariner 1971 configuration is modeled differently from the other configurations, and these changes are denoted on the functional flow diagram by an asterisk (*).

In the following paragraphs, the probabilistic equations which describe the functions of the flow diagram, and nominal input data for these functions are discussed in detail.

4.8.2.2 Orbiter Outcomes

Five major functions are involved in the orbiter outcomes:

a. Launch and injection.
b. Separation to Mars encounter.
c. Achieve Mars orbit.
d. Achieve initial orbital operations.
e. Achieve long term orbital operations.

The last two functions are directly correlated with orbital outcomes 3 (OOORB) and 4 (OOLORB). Failure in the third function leads to outcome 2 (OONORB).

4.8.2.2.1 Launch and Injection (P1)

Successful launch and injection (P1) is described by the following equation:

$$P1 = \left[PA11(X,Y)\right]\left[P_L(X,Y)\right]\left[P_O(X,Y)\right]\left[P_I(X,Y)\right]$$

$PA11(X, Y)$ = The probability of successfully developing the configuration (X) in time for launch in year (Y).

$P_L(X, Y)$ = The probability of successfully launching the configuration (X) within the year of opportunity (Y) during the launch window.

$P_O(X, Y)$ = The probability of successfully completing the launch of the configuration (X) and obtaining a parking orbit within the launch year (Y).

$P_I(X, Y)$ = The probability of successfully injecting the configuration (X) onto the Mars interplanetary trajectory in the year of opportunity (Y).

$P_L(X, Y)$, the probability of successfully launching the configuration during the launch window, depends upon the number of launch vehicles being readied. If only one launch vehicle is being prepared, the probability is a simple estimate for the vehicle being launched. If two vehicles are being prepared, then the probability is that of launching at least one. For Saturn V launches:

$$P_L(X, Y) = \left[PA1(Y)\right] \left[2 - N_S(X)\right] + \left[PA2(Y)\right] \left[N_S(X) - 1\right]$$

where

$PA1(Y)$ = The probability of a launch within the window of one Saturn V launch vehicle in the year of opportunity.

$PA2(Y)$ = The probability of one Saturn V launch within the window, given two launch vehicles are readied in the year.

$N_S(X)$ = The number of Saturn V vehicles being prepared (i.e., one or two).

For Mariner 1971 (i.e., the Atlas-Centaur):

$$P_L(X, Y) = PA9,$$

where

$PA9$ = The probability of one launch within the window, given two launch vehicles.

For the two Saturn IB launches:

$$P_L(X, Y) = \text{PA5 for configuration 4 (VSIB)}$$

$$P_L(X, Y) = \text{PA6 for configuration 5 (V2SIB)}$$

where

PA5 = The probability of a launch within the window of one SIB, given that only one is being prepared.

PA6 = The probability of a launch within the window of one SIB, given two in preparation.

$P_O(X, Y)$, the probability of successfully completing the launch and obtaining a parking orbit, is given by:

$P_O(X, Y) = \text{PA3}(Y)$, for the Saturn V.

$P_O(X, Y) = \sqrt{\text{PA10}}$, for the Atlas-Centaur (Mariner 1971).

$P_O(X, Y) = \text{PA7}$, for the Saturn IB.

$P_I(X, Y)$, the probability of successful interplanetary trajectory injection, is given by:

$P_I(X, Y) = \text{PA4}(Y)$, for the SIVB stage of the Saturn V.

$P_I(X, Y) = \sqrt{\text{PA10}}$, for the Centaur of Mariner 1971.

$P_I(X, Y) = \text{PA8}$, for the SIB configurations.

4.8.2.2.2 Separation to Mars Encounter (P2)

This phase covers the time period from separation of the planetary vehicle(s) from the injection booster to Mars encounter. For Voyager missions with direct entry capsules, P2 is given by:

$$P2 = \left[PB3\right] \left[e^{-\lambda_V(Y)T_V(Y)}\right] \left[PMID\right] \left[PB5\right] .$$

For those without direct entry capsules,

$$P2 = \left[PB3\right] \left[e^{-\lambda_V(Y)T_V(Y)}\right] \left[PMID\right] .$$

PB3	=	The probability of Voyager planetary vehicle separation from the launch vehicle.
$\lambda_V(Y)$	=	The equivalent failure rate of the spacecraft system.
$T_V(Y)$	=	The time from separation to direct entry capsule soft landing or impacting the planet.
PMID	=	The probability of successful performance of midcourse maneuvers.
PB5	=	The probability of a successful orientation for direct entry (or orbital entry) capsule separation and return to cruise (or orbit) attitude.

PMID, the probability of completing midcourse maneuvers, is in turn given by:

$$PMID = PB4 \left\{ (1-PCM_2) + (PCM_2) \; (PB4) \; \left[(1-PCM_3) + PCM_3 \; PB4\right]\right\}$$

where

PB4	=	The probability of a successful Voyager midcourse (or orbit trim) maneuver.
PCM_i	=	The probability of having to conduct the ith midcourse, given that the (i-1)th has been conducted.

For Mariner 1971, the probability of a successful cruise (P2) is given by:

$$P2 = (PB1)(PB2)$$

where

PB1 = The probability of separation of the Mariner planetary vehicle from the Centaur.

PB2 = The probability of a successful Mariner cruise from separation to the time of direct entry capsule planet impact.

4.8.2.2.3 Achieve Mars Orbit (P7)

The orbit achievement phase has important ramifications. Successful performance of orbit insertion is necessary for both orbital entry capsule outcomes and subsequent orbital outcomes. The equation which describes successful orbit achievement for all configurations capable of orbiting (i.e., 4 through 14) is:

$$P_7 = (PB6)\ (PB7)\ \left[e^{-\lambda_V(Y)T_{OI}}\right] \left\{(PB5)\ OC(X) + \left[1-OC(X)\right]\right\}$$

where

PB6 = The probability of successfully orienting for the orbit insertion maneuver and returning to attitude after firing.

PB7 = The probability of a successful retro firing.

T_{OI} = The time from encounter to soft landing or impact of the orbital entry capsule.

OC(X) = An index which identifies if the mission configuration contains an orbital entry capsule.

4.8.2.2.4 Initial Orbital Operations (P8)

Initial orbital operations depend upon the success of deploying and operating orbital science instruments for a limited time in orbit. Mathematically,

$$P8 = (PD1)\ e^{-\left[\lambda_V (Y) + \lambda_{SI}(Y)\right] T_{SO}},$$

where PD1 = The probability of deployment of instruments (e.g., booms, covers, PSP, etc.).

$\lambda_{SI}(Y)$ = The equivalent failure rate of the orbital science hardware.

T_{SO} = The time of operation in orbit to obtain value for short term orbital science.

4.8.2.2.5 Long Term Orbital Operations (P13)

The main difference between this equation and the short term equation is that the time required to obtain full science value is dependent upon the year of opportunity.

$$P13 = e^{-\left[\lambda_V (Y) + \lambda_{SI}(Y)\right]\left[T_{LO}\right] P(Y)},$$

where T_{LO} = The nominal time of operation in orbit to obtain long term orbital science value.

$P(Y)$ = A multiplier which increases the time an orbiter must survive to achieve complete science value as a function of year of opportunity.

4.8.2.3 Direct Entry Probe Outcomes

As illustrated in the functional flow of Figure 4-34, seven major functions describe the the profiles of direct entry probes:

a. Achieve entry trajectory.

b. Survive entry.

c. Relay communications.

d. Return entry data.

e. Survive descent.

f. Return descent data.

g. Return descent television.

Return of entry or descent data leads to capsule outcome 3 (COATM). Return of descent television accomplishes outcome 5 (CODTV). Failure to survive entry leads to outcome 2 (CONOEN).

4.8.2.3.1 Achieve Entry Trajectory (P4)

The successful achievement of a direct entry trajectory (for all configurations which have a direct entry probe) is given by:

$$P4 = (PC4)\ (PC5)\ e^{-\left[\lambda_C(X,Y) + \lambda_{CRR}(Y)\right] T_D},$$

where PC4 = The probability that the capsule will separate from the planetary vehicle and orient properly for entry.

PC5 = The probability that the capsule entry rocket will fire and provide a ΔV which is within entry trajectory design limits.

$\lambda_C(X,Y)$ = The equivalent failure rate of the capsule support subsystem equipment.

T_D = The time duration from the start of capsule checkout to the start of atmospheric entry of the direct entry capsule.

$\lambda_{CRR}(Y)$ = The failure rate of the capsule relay radio equipment.

4.8.2.3.2 Survive Entry (P5)

The probability of successful direct entry of the capsule, given the entry environment is within the design limits of the capsule, is expressed mathematically as:

$$P5 = e^{-\left[(EK)\ \lambda_C\ (X,Y) + \lambda_{CRR}(Y)\right]\ (0.1)},$$

where EK = The entry environment stress multiplier for capsule support equipment failure rate.

The entry time is assumed to be one-tenth of an hour.

4.8.2.3.3 Relay Communications (P6)

The orbiter end of the relay communications link is one of the more important functions in the successful achievement of capsule outcomes. Without it, the direct entry capsule cannot achieve any outcomes, regardless of its performance.

Successful relay radio operation in the planetary vehicle from the beginning of capsule checkout to capsule impact is given by:

$$P6 = e^{-\left[\lambda_{ORR}(Y)\right]\left[T_D + 0.1 + 0.8\right]},$$

where λ_{ORR} = The failure rate of the orbiter relay radio, given that the orbiter supplies all support functions.

Entry time is taken as one-tenth of an hour, and descent time as eight-tenths of an hour.

4.8.2.3.4 Return Entry Data (P14)

The return of entry data is dependent upon the successful performance of the entry science instruments and the playback of the entry recorders. The equation for P14 is given in terms of these two probabilities.

$$P14 = (PC6)(PC7)$$

where PC6 = The probability that the entry data recorder works, given a successful entry.

PC7 = The probability that entry science works, given a successful entry.

4.8.2.3.5 Survive Descent (P15)

The survival of the capsule during descent is divided into operation of the capsule subsystems and operation of capsule relay radio through descent. Descent time is assumed to be eight-tenths of an hour. From entry survival to impact,

$$P15 = e^{-\left[\lambda_C(X, Y) + \lambda_{ORR}(Y)\right](0.8)}$$

4.8.2.3.6 Return Descent Data (P16)

Return of descent data, given a successfully descending capsule, requires that the atmospheric sensors deploy and operate. If a parachute is used in the descent phase, then its deployment must also be considered.

$$P16 = (PC8)\,(PC9)\left[1-C(X)\right] + \left[(PC8)\right]\left[C(X)\right],$$

where PC8 = The probability that atmospheric sensors deploy and operate.

PC9 = The probability that the descent parachute successfully deploys.

C(X) = An index which indicates if the configuration employs descent parachutes.

4.8.2.3.7 Return Descent Television (P20)

The successful return of descent television is modeled as the probability of successfully deploying and operating the descent television camera and electronics. P15, descent survival, includes provision for radio return of the television information. For all configurations which carry a direct entry probe, the successful return of descent television is given by:

$$P20 = PC10.$$

4.8.2.4 Capsule

Fourteen major functions in Figure 4-34 describe the profiles of orbital entering capsules. Seven of these functions are identical to the seven functions which describe a direct entry probe. The remaining seven are associated with soft landing and landed operations. The 14 are as follows:

a. Achieve entry trajectory.

b. Survive entry.

c. Relay communications.

d. Return entry data.

e. Survive descent.

f. Return descent data.

g. Return descent television.

h. Survive soft landing.

i. Landed subsystem support.

j. Landed direct data link to earth.

k. Landed relay data link to earth via spacecraft.

l. Surface physical experiments.

m. Surface television and limited experiments.

n. Surface biological experiments.

4.8.2.4.1 Achieve Entry Trajectory (P10)

The probability of successfully achieving an entry trajectory for the orbital entry capsule employs the same equation as for the direct entry capsule (P4), except that the time from except that the time from capsule checkout to entry of the capsule may be different.

$$P10 = (PC4)\ (PC5)\ e^{-\left[\lambda_C(X, Y) + \lambda_{CRR}(Y)\right](T_O)}$$

where T_O = The time from capsule checkout until the orbital entry capsule enters the atmosphere of Mars.

4.8.2.4.2 Survive Entry (P11)

The probability of a successful entry of an orbital entry capsule, given that the environment encountered is within the design limits of the capsule, is given by the same expression used for a direct entry capsule; i.e.,

$$P11 = P5.$$

4.8.2.4.3 Relay Communications (P12)

Here again, the same expression used for the direct entry probe (P6) applies for the orbital entry capsule, with the exception of the time period to entry.

$$P12 = e^{-\lambda_{ORR}(Y)\ (T_O + 0.1 + 0.8)}.$$

4.8.2.4.4 Return Entry Data (P17)

The probability of successful return of entry data from an orbital entry capsule is assumed equal to the same probability for a direct entry capsule:

$$P17 = P14$$

4.8.2.4.5 Survive Descent (P18)

The probability of surviving descent for an orbital entry capsule is assumed equal to that for its direct entry counterpart:

$$P18 = P15 .$$

4.8.2.4.6 Return Descent Data (P19)

Again, the assumption that the probability applies to both types of capsules is made:

$$P19 = P16.$$

4.8.2.4.7 Return Descent Television (P20)

The probability of returning descent television is also assumed independent of the type of entry capsule.

$$P20 = PC10.$$

4.8.2.4.8 Survive Soft Landing (P23)

Given that the landing environment actually encountered is within the design limits of the lander, the probability that the lander will survive the soft landing is divided into the landing system operating correctly and the capsule equipment surviving the landing shock:

$$P23 = \left[PC11(Y)\right] \left[PC12(Y)\right],$$

where PC11(Y) = The probability that the soft landing system operates properly.

PC12(Y) = The probability that the capsule equipment survives the landing shock.

4.8.2.4.9 Landed Subsystem Support (P24)

The landed capsule must have operational support from its subsystems throughout the entire landed phase of the mission. The probability of having subsystem support is given as:

$$P24 = PC13(X) \quad e^{-\left|\lambda_C(X, Y)\right| T_L(Y)}.$$

where PC13(X) = The probability of successful deployment of lander support equipment; e.g., antennas, solar panels, etc.

$T_L(Y)$ = The time required to complete a complete set of surface experiments to the point where full landed science value can be obtained.

4.8.2.4.10 Landed Direct Data Link to Earth (P22)

If the landed capsule system is designed to establish a direct link to earth, the probability of it working, given that subsystem support is available, is given by:

$$P22 = e^{-\left[\lambda_{CDL}(Y)\right]\left[T_L(Y)\right]},$$

where λ_{CDL} = The failure rate of the capsule direct radio link equipment.

4.8.2.4.11 Landed Relay Data Link to Earth via Spacecraft (P28)

The relay data link operation throughout the period of surface operation is dependent upon both the orbiter and the capsule relay radio equipment working.

$$P28 = e^{-\left[\lambda_{ORR}(Y) + \lambda_{CRR}(Y)\right]\left[T_L(Y)\right]}$$

4.8.2.4.12 Surface Physical Experiments (P25)

The probability of successful deployment of surface physical experiment sensors, collection of surface samples, and the conduct of surface experiments, given capsule subsystem support, is given by:

$$P25 = (PS1)\,(PS2)\,e^{-\left[\lambda_S(Y)\right]\left[T_L(Y)\right]},$$

where PS1 = The probability of successful deployment of experiment sensors.
PS2 = The probability of collecting surface samples for the surface laboratory.
$\lambda_S(Y)$ = The equivalent failure rate for physical experiment hardware.

4.8.2.4.13 Surface Television and Limited Experiments (P26)

The probability of successful surface television and related limited experiments is composed of the following subfunctions:

a. Deployment of sensors.

b. Collection of surface samples.

c. Operation of limited surface experiments.

d. Operation of surface television.

In relationship to the complex physical experiments of the physical laboratory, the limited experiments of the television lander are assumed to be about one-half as complex, and the experiment portion of P26 is taken as the square root of P25.

$$P26 = \sqrt{P25}\ e^{-\left[\lambda_{TV}(Y)\right]\left[T_L(Y)\right]},$$

where $\lambda_{TV}(Y)$ = The failure rate for landed television, given subsystem support.

4.8.2.4.14 Surface Biological Experiments (P27)

The biological experiments are divided into collecting samples and conducting experiments upon the samples. The probability of successful biological experiments, given capsule subsystem support is:

$$P27 = (PS3)\ e^{-\left[\lambda_{B}(Y)\right]\left[T_L(Y)\right]},$$

where PS3 = The probability that biological sensors and sample collection devices will deploy and operate.

$\lambda_B(Y)$ = The equivalent failure rate for the science hardware of a landed biological laboratory.

4.8.2.5 Transition Diagram

In Subsections 4.8.2.2, 4.8.2.3 and 4.8.2.4, the major mission functions of the launch vehicle, orbiter, direct entry capsule and orbital entry capsule are discussed. This subsection discusses the general transition diagram which combines the probabilities of the of the major functions to arrive at orbiter and capsule outcome probabilities. While the nominal set of mission configurations is limited to 14, the transition diagram is generalized so that alternate mission configurations can also be evaluated, as desired. Figure 4-35 is the general transition diagram. Each node of the diagram is numbered; and these node numbers and the successor node numbers are supplied to the computer as basic input data. The computer then builds the transition tree and calculates the probability of being at each terminal node with the procedure discussed in Subsection 4.8.1.

Generally, success branches are horizontal and failure branches nonhorizontal. To aid in following the diagram, a shorthand notation is included on the tree. For example, the legend $OE \cap \overline{R}$ is shorthand for the intermediate node describing a successful orbital entry capsule without a relay link back to the orbiting spacecraft.

Each column of the transition diagram contains one of three basic parameters:

a. Mission phase probabilities (e.g., P1, P2, P4, etc.) describing operation of configuration hardware and generated according to the formulae of the preceding subsections.

b. Environmental probabilities, discussed in the introduction, and amplified in succeeding subsections.

c. Configuration switches.

SV	PV	CAPSULE (DIRECT) SEPARATION THROUGH ENTRY				
P_1	P_2	$ENTRY_X$	$P_3(E)$	P_4	P_5	P_6
LAUNCH AND INJECTION	SEPARATION THROUGH ENCOUNTER	DIRECT ENTRY CAPSULE	DIRECT ENTRY ENVIRONMENT	DIRECT ENTRY TRAJECTORY ACHIEVEMENT	DIRECT ENTRY SURVIVAL	OPERABLE DIRECT ENTRY RELAY

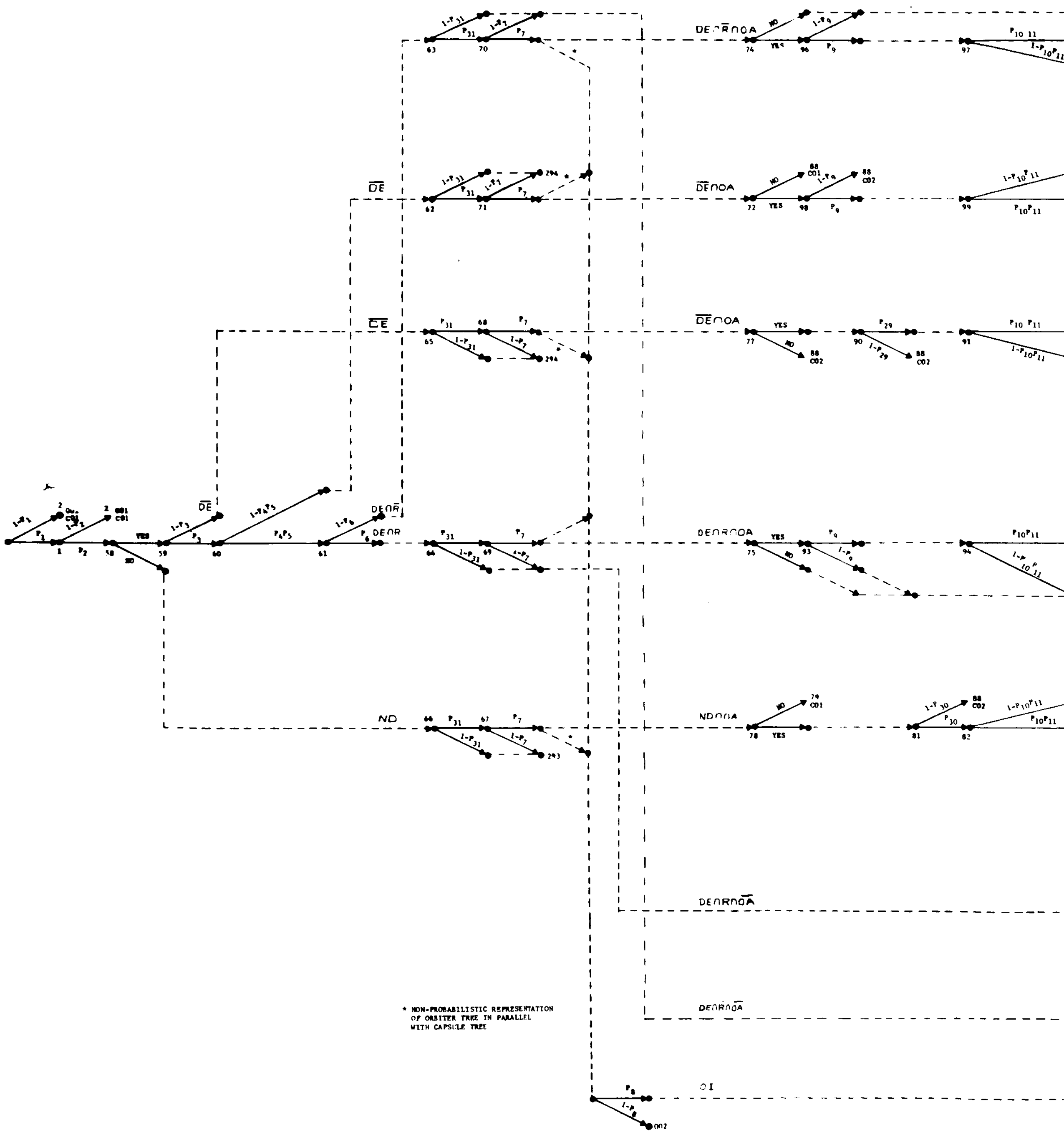
LEGEND DE: ENTRY SURVIVAL OF DIRECT ENTRY CAPSULE
R: OPERABLE ENTRY & DESCENT RELAY
ND: NO DIRECT ENTRY CAPSULE ON THIS CONFIGURATION

INITIAL ORBITER OPERATIONS			
P_{31}	P_7		P_8
ORBIT ACHIEVEMENT CONFIDENCE	ORBIT ACHIEVEMENT		INITIAL ORBITER OPERATIONS

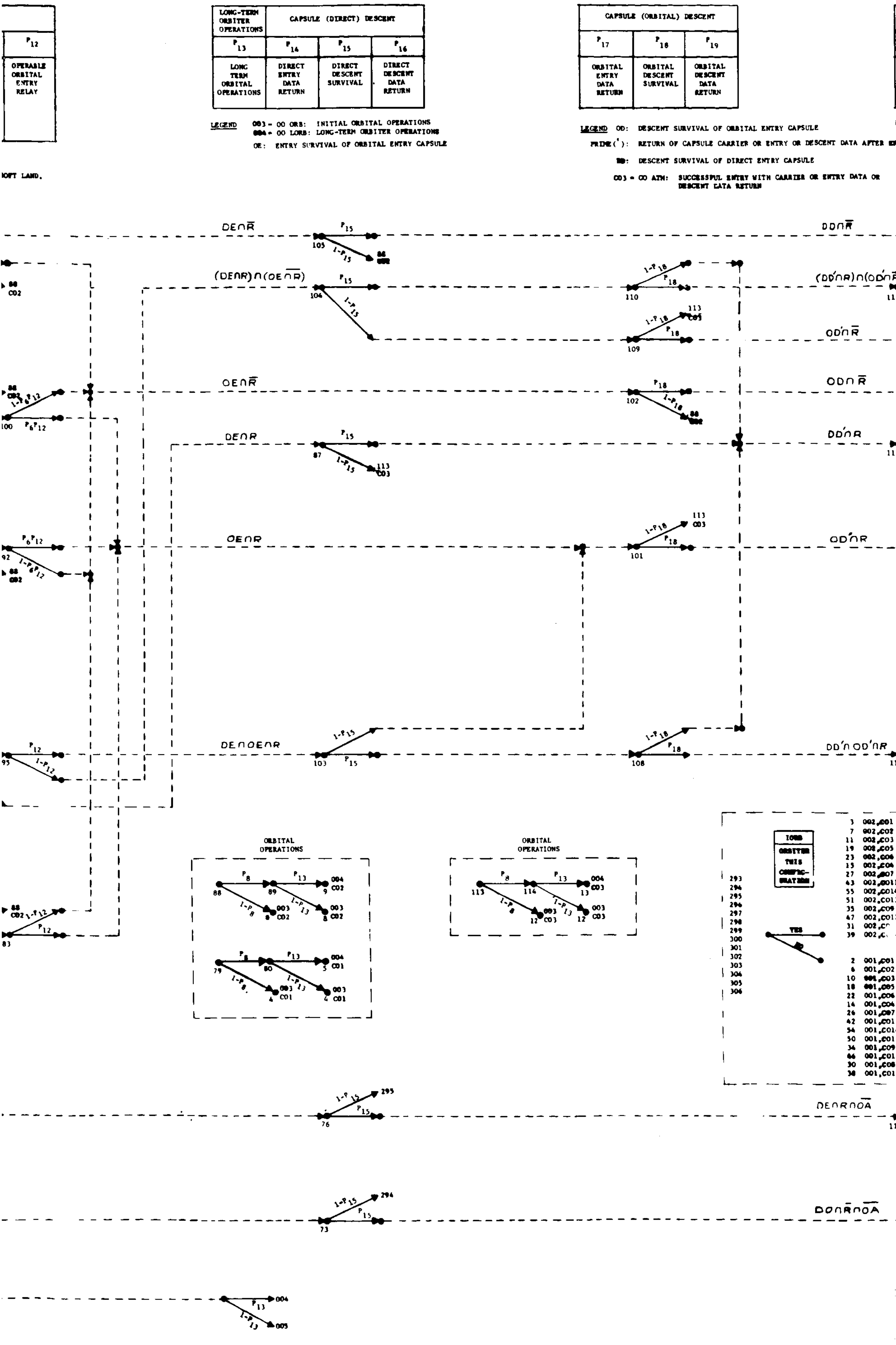
LEGEND 001 = 00 ZERO: CURRENT ORBITER ACHIEVEMENT (FLYBY)
C01 = CO ZERO: CURRENT CAPSULE ACHIEVEMENT (NONE)
OA: SPACECRAFT ORBIT ACHIEVEMENT
OI: SUCCESSFUL ORBITER INITIAL OPERATIONS
002 = 00 NORB: FAILURE IN ATTEMPTING ORBIT INSERTION
C02 = CO NOEN: FAILURE OF CAPSULE AT ENTRY

CAPSULE (ORBITAL) SEPARATION THROUGH ENTRY					
$J\ ENTRY_X$	$P_9(E)$	$P_{29}(E)$	$P_{30}(E)$	P_{10}	P_{11}
ORBITAL ENTRY CAPSULE	ORBITAL ENTRY ENVIRONMENT GIVEN CORRECT DIRECT ENTRY ENVIRONMENT	ORBITAL ENTRY ENVIRONMENT GIVEN INCORRECT DIRECT ENTRY ENVIRONMENT	ORBITAL ENTRY ENVIRONMENT	ORBITAL ENTRY TRAJECTORY ACHIEVEMENT	ORBITAL ENTRY SURVIVAL

IF TWO CAPSULES ENTER ONLY THE ORBITAL ENTRY CAPSULE CAN



* NON-PROBABILISTIC REPRESENTATION OF ORBITER TREE IN PARALLEL WITH CAPSULE TREE



P12
OPERABLE ORBITAL ENTRY RELAY
LONG-TERM ORBITER OPERATIONS
CAPSULE (DIRECT) DESCENT
P13
P14
P15
P16
LONG TERM ORBITAL OPERATIONS
DIRECT ENTRY DATA RETURN
DIRECT DESCENT SURVIVAL
DIRECT DESCENT DATA RETURN
LEGEND 003 = 00 ORB: INITIAL ORBITAL OPERATIONS
004 = 00 LORB: LONG-TERM ORBITER OPERATIONS
OE: ENTRY SURVIVAL OF ORBITAL ENTRY CAPSULE
CAPSULE (ORBITAL) DESCENT
P17
P18
P19
ORBITAL ENTRY DATA RETURN
ORBITAL DESCENT SURVIVAL
ORBITAL DESCENT DATA RETURN
LEGEND OD: DESCENT SURVIVAL OF ORBITAL ENTRY CAPSULE
PRIME ('): RETURN OF CAPSULE CARRIER OR ENTRY OR DESCENT DATA AFTER E
DD: DESCENT SURVIVAL OF DIRECT ENTRY CAPSULE
C03 = CO ATM: SUCCESSFUL ENTRY WITH CARRIER OR ENTRY DATA OR DESCENT DATA RETURN
SOFT LAND.
DEn$\overline{R}$
(DEnR)n(OEn$\overline{R}$)
OEn$\overline{R}$
DEnR
OEnR
DEnOEnR
ODn$\overline{R}$
(OD'nR)n(OD'n$\overline{R}$)
OD'n$\overline{R}$
ODn$\overline{R}$
DD'nR
OD'nR
DD'nOD'nR
DEnRnO$\overline{A}$
DOnRnOA
ORBITAL OPERATIONS
ORBITAL OPERATIONS
TOSS
ORBITER THIS CONFIGURATION
YES
NO

4-85-1

DESCENT TELEVISION		
TVD_X	TVO_X	P_{20}
DIRECT ENTRY CAPSULE DESCENT TELEVISION?	ORBITAL ENTRY CAPSULE DESCENT TELEVISION?	DESCENT TELEVISION RETURN

DUBLE PRIME ("): RETURN OF DESCENT TELEVISION

TRY

SOFT LANDING						
DSL_X	OSL_X	$P_{21}(E)$	P_{23}	P_{24}	$ADIR_X$	P_{22}
DIRECT ENTRY CAPSULE SOFT LANDER?	ORBITAL ENTRY CAPSULE SOFT LANDER?	SOFT LANDING ENVIRONMENT	SOFT LANDING	CAPSULE SUBSYSTEMS OPERATIONAL	DIRECT COMM LINK TO EARTH?	OPERABLE EARTH LINK

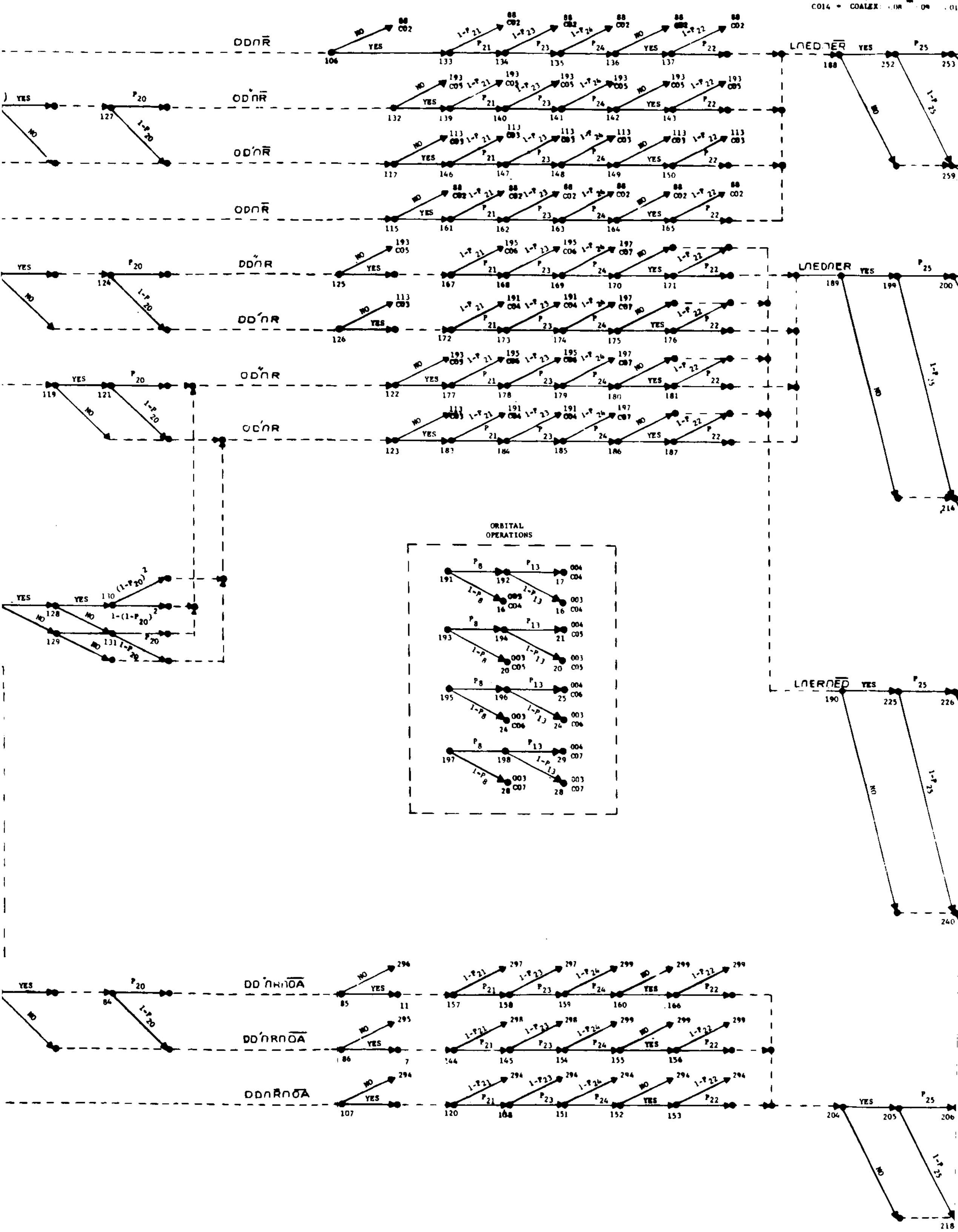
LEGEND

L: SOFT-LANDED CAPSULE WITH OPERATIONAL SUBSYSTEMS TO SUPPORT EXPERIMENTS
ED: OPERABLE DIRECT LINK FROM CAPSULE TO EARTH
ER: SPACECRAFT TO EARTH RELAY OPERABLE AT SOFT LANDING
C04 = COATMS: C03 (COATM) WITH FAILURE TO SOFT LAND
C05 = CODTV: DESCENT TELEVISION DATA RETURN WITH NON-SURVIVABLE PROBE
C06 = CODTVS: C05 (CODTV) WITH FAILURE TO SOFT LAND
C0 = COLAND: SUCCESSFUL SOFT LANDER

SPE_X	P_{25}	
CAPSULE CAPABLE OF SURFACE PHYSICAL EXP'TS?	PERFORMANCE OF SURFACE PHYSICAL EXP'TS?	CA

LEGEND

08 = COLTV: LANDED TELEVISI
09 = COSURF: SURFACE PHYSICA
C0? = COBIOL: BIOLOGICAL EXPE
C011 = COTVSF: C08 09
C012 = COBITV: C08 C010
C013 = COBISF: C09 C010
C014 = COALEX: C08 09 C01



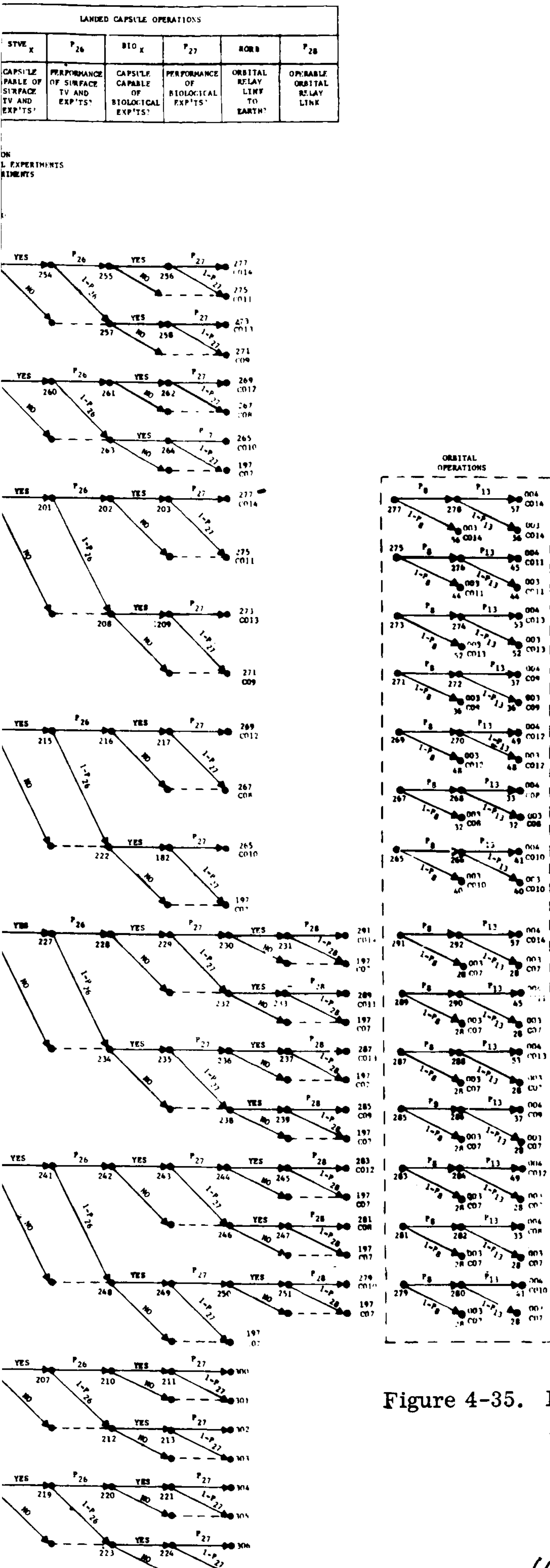


Figure 4-35. Probability Transition Diagram

[redacted]

4.8.2.5.1 Switches

The transition diagram is generalized to accommodate a variety of mission configurations with the concept of switches; i.e., the tree branches with the words "yes" and "no." A probability of unity is assigned to the correct answers to the switch query (and zero to the incorrect). The 12 switches employed in the transition diagram are defined as follows:

IORB(X): Does this configuration have an orbiter?
IENTRY(X): Does this configuration have a direct entry capsule?
JENTRY(X): Does this configuration have an orbital entry capsule?
TVD(X): Does the direct entry capsule have descent television?
TVO(X): Does the orbital entry capsule have descent television?
DSL(X): Is the direct entry capsule a soft lander?
OSL(X): Is the orbital entry capsule a soft lander?
RDIR(X): Does the landed capsule employ a direct communications link to earth?
RORB(X): Does the capsule employ a communications link to earth via the orbiter?
SPE(X): Is the capsule capable of surface physical experiments?
STVE(X): Is the capsule capable of limited physical experiments and surface television?
BIO(X): Is the capsule capable of biological experiments?

4.8.2.5.2 Environmental Probabilities

In addition to the switches and the equipment functions, the transition diagram includes environmental probabilities dependent upon specific levels of capsule and orbiter outcome. Four probabilities reflect the entry environment uncertainty, one probability reflects the soft landing environment, and one probability reflects the orbit insertion environment.

4.8.2.5.2.1 Direct Entry Environment (P3). The probability that the range of the predicted direct entry environment associated with the capsule design contains the actual environment to be encountered depends upon the level of capsule and orbiter outcomes.

For COATM (CO3) or higher, it has been assumed that:

P3 = 1.0

For COZERO (CO1), and OOZERO through OOORB (OO1 through OO3):

P3 = PC1

where PC1 = Today's estimate of the probability that the range of the predicted direct entry environment associated with the capsule design contains the actual environment to be encountered.

For COZERO and CONOEN (CO1 and CO2)

P3 = PC2

where PC2 = Today's estimate of the probability that future direct entry capsules will be designed to the actual environment to be encountered, given that the environment has been observed from orbit for several months.

For CONOEN (CO2), and OOZERO through OOORB (OO1 through OO3):

P3 = PC3

where PC3 = Today's estimate of the probability that future direct entry capsules will be designed to the actual environment to be encountered, given a failure to enter on the last observed mission.

4.8.2.5.2.2 Orbital Entry Environment

a. Given a Successful Direct Entry From this Planetary Vehicle (P9)

The design range on entry environment for an orbital entry capsule is assumed to be larger than the design range for a direct entry counterpart; hence:

P9 = 1.0

b. Given an Unsuccessful Direct Entry from this Planetary Vehicle (P29)

P29 = PC21 (X)

where PC21(X) = Today's estimate that an orbital entry capsule will be successful, given that a direct entry capsule has failed to enter from this planetary vehicle.

c. Given No Direct Entry Capsule on this Planetary Vehicle (P30)

The probability that an orbital entry capsule will encounter the expected environment, given that there is no direct entry capsule, is given by the following equation:

P30 = (P3)(P9) + (1-P3) (P29)

4.8.2.5.2.3 Soft Landing Environment (P21). The probability that the range of the landing environment associated with the soft lander design contains the actual environment to be encountered depends upon the level of capsule and orbiter outcome.

For capsule outcomes less than or equal to COATM (CO3), and orbiter outcomes less than or equal to OONORB (OO2):

P21 = PC15

where PC15 = Today's estimate of the probability that the first try at soft landing will encounter an environment within the soft landing design limits.

For capsule outcomes less than or equal to COATM (CO3), and OOORB (OO3) or OOLORB (OO4):

P21 = PC16

where PC16 = Today's estimate of the probability that the soft landing environment is within the soft lander design limits, given orbital observation of the surface for at least a short-term duration.

For COATMS (CO4), and OOORB (OO3) or OOLORB (OO4):

P21 = PC17

where PC17 = Today's estimate of the probability that the soft landing environment is within soft lander design limits, after a failure to soft land and orbital observation of the surface for at least a short-term duration.

For CODTV (CO5), and all orbiter outcomes:

P21 = PC18

where PC18 = Today's estimate of the probability that the soft landing environment will be within the design range of the soft lander, given that descent television of the surface has been obtained.

For CODTVS (CO6), and all orbiter outcomes:

P21 = PC19

where PC19 = The probability that the soft landing environment is within the design range of the soft lander, given that descent television has been obtained prior to a soft landing failure.

For capsule outcomes greater than or equal to COLAND (CO7) and all orbiter outcomes:

P21 = PC20

where PC20 = The probability that the soft landing environment is within the design range of the soft lander, given a successful soft lander on a previous mission.

4.8.2.5.2.4 Inference Probability of Orbit Injection (P31). The probability of a successful orbit injection depends upon the uncertainty surrounding the stresses induced by the insertion engine firing. For OOORB (OO3) and OOLORB (OO4), a successful orbit injection has been achieved, in which case:

P31 = 1.0

For orbiter outcomes OOZERO (OO1) and OONORB (OO2):

P31 = PB8

where PB8 = Today's estimate of the confidence that the probability of a successful orbit insertion is the correct value.

4.8.2.6 Nominal Probability Data

Nominal data employed in the probability model was gathered from many sources, including other probability models, reliability calculations and engineering estimates. Table 4-6 (Sheets 1 through 6) is a listing of the actual hardware and environmental data employed in the probability model for nominal exercises. Table 4-7 is a listing of the transition diagram switch settings as a function of mission configuration.

4.8.3 FINAL GENERATION OF OUTCOME PROBABILITIES

For the transition diagram of Figure 4-35, there are, in general, 56 possible outcomes for each mission (i.e., all possible combinations of the four orbiter outcomes and the 14 capsule outcomes). Each evaluation of the transition tree produces a set of 56 probabilities, which can be visualized as arranged in a matrix with four rows for the orbiter outcomes and 14 columns for the capsule outcomes. (See Table 4-3.) Let this matrix of outcome probabilities be labeled Q, where q_{ij}, the (i, j)th element of this matrix, is the joint probability of the ith orbiter outcome and jth capsule outcome for the particular mission under consideration. The Q matrix is illustrated in the following diagram:

Table 4-6. Nominal Probability Data (Sheet 1 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
P1: Launch and Injection								
PA1		0	0.9813	0.9828	0.9658	0.961	0.961	Launch SV within window.
PA2		0	0.9875	0.9885	0.977	0.9735	0.9735	Launch one SV within window when two are to be launched.
PA3		0	1.0	1.0	1.0	1.0	1.0	SV launch to parking orbit.
PA4		0	0.8	0.843	0.876	0.901	0.92	SV interplanetary trajectory injection
PA5		--	0.9900	--	--	--	--	Launch one SIB within window.
PA6		--	0.9930	--	--	--	--	Launch one SIB within window when two are to be launched.
PA7		--	0.9930	--	--	--	--	SIB launch to parking orbit.
PA8		--	0.999	--	--	--	--	SIB interplanetary trajectory injection.
PA9		0.98	--	--	--	--	--	Launch one of two Mariner '71's within window.
PA10		0.90	--	--	--	--	--	Atlas-Centaur launch to interplanetary trajectory.
PA11	VSTOP	1.0	1.0	1.0	1.0	1.0	1.0	Deliverability of mission configuration.
	VSKIP	1.0	1.0	1.0	1.0	1.0	1.0	
	VMAR	0.99	1.0	1.0	1.0	1.0	1.0	
	VSIB	0	0.99	1.0	1.0	1.0	1.0	
	V2SIB	0	0.99	1.0	1.0	1.0	1.0	
	VORB	0	0.99	1.0	1.0	1.0	1.0	
	VOATM	0	0.98	0.999	1.0	1.0	1.0	
	VODTV	0	0.97	0.995	1.0	1.0	1.0	
	VOLTV	0	0.95	0.99	1.0	1.0	1.0	
	VOTVSF	0	0.92	0.98	1.0	1.0	1.0	
	VOVBL	0	0	0.95	0.99	1.0	1.0	
	VODATM	0	0.98	0.99	1.0	1.0	1.0	
	VODDTV	0	0.96	0.99	1.0	1.0	1.0	
	VODLTV	0	0.94	0.98	1.0	1.0	1.0	
P2: Separation to Mars Encounter								
PB1		0.999	--	--	--	--	--	Mariner separation.
PB2		0.75	--	--	--	--	--	Mariner cruise.
PB3		--	0.998	0.998	0.998	0.998	0.998	Voyager planetary vehicle separation.
PB4		--	0.985	0.985	0.985	0.985	0.985	Voyager orbit trim or midcourse maneuver.
PB5		---	0.99	0.99	0.99	0.99	0.99	Voyager planetary vehicle capsule separation orientation.
PCM2		--	0.90	0.90	0.90	0.90	0.90	Need for second Voyager midcourse.
PCM3		--	0.60	0.60	0.60	0.60	0.60	Need for third Voyager midcourse.
λ_V(VLAMB)		--	0.713×10^{-4}	0.397×10^{-4}	0.237×10^{-4}	0.15×10^{-4}	0.102×10^{-4}	Voyager spacecraft system failure rate.
T_V(VTIME)		--	4872	5016	5496	5856	4944	Time from Voyager separation to encounter (hours).
P3: Direct Entry Environment								
PC1		0.9	0.9	0.9	0.9	0.9	0.9	Baseline environment.
PC2		0.98	0.98	0.98	0.98	0.98	0.98	Given orbital observation.
PC3		0.9	0.9	0.9	0.9	0.9	0.9	Given previous entry failure.

Table 4-6. Nominal Probability Data (Sheet 2 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
P4: Achieve Direct Entry Trajectory								
PC4		0.94	0.94	0.94	0.94	0.94	0.94	Capsule separation.
PC5		0.9899	0.9899	0.9899	0.9899	0.9899	0.9899	Capsule entry trajectory.
T_D(TSTSFD)		30	30	30	30	30	30	Time from capsule checkout to entry (hours).
λ_C(CLAMB)	VSTOP	0	0	0	0	0	0	Capsule system failure rate.
	VSKIP	0	0	0	0	0	0	
	VMAR	0.26×10^{-4}	0	0	0	0	0	
	VSIB	0	0	0	0	0	0	
	V2SIB	0	0	0	0	0	0	
	VORB	0	0	0	0	0	0	
	VOATM	0	0.202×10^{-4}	0.165×10^{-4}	0.137×10^{-4}	0.117×10^{-4}	0.101×10^{-4}	
	VODTV	0	0.408×10^{-4}	0.305×10^{-4}	0.231×10^{-4}	0.185×10^{-4}	0.151×10^{-4}	
	VOLTV	0	0.801×10^{-4}	0.53×10^{-4}	0.365×10^{-4}	0.264×10^{-4}	0.202×10^{-4}	
	VOTVSF	0	0.998×10^{-4}	0.616×10^{-4}	0.399×10^{-4}	0.275×10^{-4}	0.202×10^{-4}	
	VOVBL	0	1.200×10^{-4}	0.699×10^{-4}	0.430×10^{-4}	0.283×10^{-4}	0.202×10^{-4}	
	VODATM	0	0.202×10^{-4}	0.165×10^{-4}	0.137×10^{-4}	0.117×10^{-4}	0.101×10^{-4}	
	VODDTV	0	0.408×10^{-4}	0.305×10^{-4}	0.234×10^{-4}	0.185×10^{-4}	0.151×10^{-4}	
	VODLTV	0	0.801×10^{-4}	0.503×10^{-4}	0.365×10^{-4}	0.264×10^{-4}	0.202×10^{-4}	
λ_{CRR}(CRRLAM)		0.475×10^{-4}	0.400×10^{-4}	0.333×10^{-4}	0.277×10^{-4}	0.234×10^{-4}	0.200×10^{-4}	
P5: Survive Direct Entry								
λ_C(CLAMB)				(See P4)				
λ_{CRR}(CRRLAM)				(See P4)				
EK (EKFACT)		1000	1000	1000	1000	1000	1000	Entry failure rate stress factor.
P6: Relay Communications								
λ_O(ORRLAM)		0.25×10^{-4}	0.2×10^{-4}	0.165×10^{-4}	0.137×10^{-4}	0.116×10^{-4}	0.1×10^{-4}	Spacecraft relay radio failure rate.
T_D(TSTSFD)				(See P4)				
P7: Achieve Mars Orbit								
PB5				(See P2)				
PB6		--	0.98	0.98	0.98	0.98	0.98	Orbit insertion orientation.
PB7		--	0.98	0.98	0.98	0.98	0.98	Orbit insertion retrofire.
λ_V(VLAMB)				(See P2)				
T_{OI}(TETSLO)		--	200	200	200	200	200	Time from encounter to capsule landing (hours).

Table 4-6. Nominal Probability Data (Sheet 3 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
				P8: Initial Orbital Operations				
PD1		--	0.98	0.98	0.98	0.98	0.98	Deployment of instruments.
λ_V(VLAMB)				(See P2)				
λ_{SI}(SCILAM)		--	0.527×10^{-4}	0.32×10^{-4}	0.201×10^{-4}	0.138×10^{-4}	0.101×10^{-4}	Failure rate of orbital science.
T_{SO}(SORBTM)		--	500	500	500	500	500	Time of short term operations (hours)
				P9: Orbital Entry Environment Given Good Direct Entry				
		1.0	1.0	1.0	1.0	1.0	1.0	
				P10: Achieve Orbital Entry Trajectory				
PC4				(See P4)				
PC5				(See P4)				
λ_C(CLAMB)				(See P4)				
λ_{CRR}(CRRLAM)				(See P4)				
T_O (TCTSLO)		--	10	10	10	10	10	Time from capsule checkout to capsule landing (hours).
				P11: Survive Orbital Entry (See P5)				
				P12: Relay Communications				
λ_{ORR}(ORRLAM)				(See P6)				
T_O (TCTSLO)				(See P10)				
				P13: Long Term Orbital Operations				
λ_V(VLAMB)				(See P2)				
λ_{SI}(SCILAM)				(See P8)				
T_{LO}(ORBTM)		--	2160	2160	2160	2160	2160	Time of long term orbital operations (hours).
P(Y) (ORBRPT)		--	1	2	4	5	6	Multiplier of the above line.
				P14: Return Direct Entry Data				
PC6		0.99	0.99	0.99	0.99	0.99	0.99	Entry data recorder.
PC7.		0.99	0.99	0.99	0.99	0.99	0.99	Entry science instruments.

Table 4-6. Nominal Probability Data (Sheet 4 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
				P15: Survive (Direct Entry) Descent				
λ_C(CLAMB) λ_{CRR}(CRRLAM)				(See P4) (See P4)				
				P16: Return (Direct Entry) Descent Data				
PC8 PC9		0.98 0.9954	0.98 0.9954	0.98 0.9954	0.98 0.9954	0.98 0.9954	0.98 0.9954	Atmospheric sensor deployment. Descent parachute.
				P17: Return Orbital Entry Data (See P14)				
				P18: Survive (Orbital Entry) Descent (See P15)				
				P19: Return (Orbital Entry) Descent Data (See P16)				
				P20: Return Descent Television				
PC10		0.93	0.93	0.93	0.93	0.93	0.93	Operation of descent television.
				P21: Soft Landing Environment				
PC15 PC16 PC17 PC18 PC19 PC20		-- -- -- -- -- --	0.70 0.75 0.70 0.85 0.90 0.95	0.70 0.75 0.70 0.85 0.90 0.95	0.70 0.75 0.70 0.85 0.90 0.95	0.70 0.75 0.70 0.85 0.90 0.95	0.70 0.75 0.70 0.85 0.90 0.95	Baseline. Given orbital observation. Given landing failure and orbital observation. Given descent television. Given landing failure and descent television. Given landing success.

Table 4-6. Nominal Probability Data (Sheet 5 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
P22: Landed Direct Data Link to Earth								
λ_{CDL}(CDLLAM)		--	1.5×10^{-4}	0.882×10^{-4}	0.562×10^{-4}	0.394×10^{-4}	0.305×10^{-4}	Failure rate of landed capsule direct radio.
T_L(VSRFTM)		--	50	1000	3000	4000	5000	Time of landed operations (hours).
P23: Survive Soft Landing								
PC11		--	0.9903	0.992	0.9933	0.9943	0.995	Soft landing system.
PC12		--	0.928	0.9455	0.9572	0.9649	0.97	Equipment shock survival.
P24: Landed Subsystem Support								
PC13	VOLTV	--	1.0	1.0	1.0	1.0	1.0	Landed equipment deployment.
	VOTVSF	--	1.0	1.0	1.0	1.0	1.0	
	VOVBL	--	1.0	1.0	1.0	1.0	1.0	
	VODLTV	--	1.0	1.0	1.0	1.0	1.0	
λ_C(CLAMB)				(See P4)				
T_L(VSRFTM)				(See P22)				
P25: Surface Physical Experiments								
PS1		--	0.9	0.9	0.9	0.9	0.9	Deployment of experiments.
PS2		--	0.9	0.9	0.9	0.9	0.9	Collection of surface samples.
λ_S(SLAMB)		--	3.56×10^{-4}	1.45×10^{-4}	0.66×10^{-4}	0.338×10^{-4}	0.2×10^{-4}	Physical experiments failure rate.
T_L(VSRFTM)		--		(See P22)				
P26: Surface Television and Limited Experiments								
PS1				(See P25)				
PS2				(See P25)				
λ_S(SFLAMB)				(See P25)				
λ_{TV}(TVLAMB)		--	1.05×10^{-4}	0.475×10^{-4}	0.24×10^{-4}	0.142×10^{-4}	0.1×10^{-4}	Failure rate of landed television.
T_L(VSRFTM)				(See P22)				

Table 4-6. Nominal Probability Data (Sheet 6 of 6)

Parameter	Configuration	Year 71	73	75	77	79	81	Abbreviated Definition
P27: Biological Experiments								
PS3		--	0.85	0.85	0.85	0.85	0.85	Deployment of sensors and collection devices.
λ_B(VBILAM)		--	7.98×10^{-4}	3.26×10^{-4}	1.58×10^{-4}	0.85×10^{-4}	0.513×10^{-4}	Failure rate of biological science hardware.
T_L(VSRFTM)				(See P22)				
P28: Landed Relay Data Link to Earth								
λ_{CDL}(CDLLAM)				(See P22)				
T_L(VSRFTM)				(See P22)				
P29: Orbital Entry Environment, Given Direct Entry Failure								
	VODATM	--	0.8	0.8	0.8	0.8	0.8	
	VODDTM	--	0.5	0.5	0.5	0.5	0.5	
	VODLTV	--	0.5	0.5	0.5	0.5	0.5	
P30: Orbital Entry Environment Given No Direct Entry Capsule This Vehicle (Dependent on P3, P9, P29)								
P31: Orbit Insertion Inference								
PB8		--	0.97	0.97	0.97	0.97	0.97	Confidence that probability of insertion is correct.

Table 4-7. Configuration Switches

		Switch Symbol															
Configuration		NLV*	NSC*	IENTRY	JENTRY	OSL	DSL	TVD	TVO	RDIR	RORB	SPE	STVE	BIO	NOSVLV*	IORB	CHUTE*
1	VSTOP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	VSKIP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	VMAR	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	1
4	VSIB	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
5	V2SIB	2	2	0	0	0	0	0	0	0	0	0	0	0	1	1	0
6	VORB	1	2	0	0	0	0	0	0	0	0	0	0	0	1	1	0
7	VOATM	1	2	0	1	0	0	0	0	0	0	0	0	0	1	1	1
8	VODTM	1	2	0	1	0	0	0	1	0	0	0	0	0	1	1	1
9	VOLTV	1	2	0	1	1	0	0	1	1	0	0	1	0	1	1	0
10	VOTVSF	1	2	0	1	1	0	0	1	1	0	1	1	0	1	1	0
11	VOVBL	1	2	0	1	1	0	0	1	1	0	0	1	0	1	1	0
12	VODATM	1	2	1	1	0	0	0	0	0	0	0	0	1	1	1	1
13	VODDTV	1	2	1	1	0	0	0	1	0	0	0	0	0	1	1	1
14	VODLTV	1	2	1	1	1	0	0	1	1	0	0	1	0	1	1	0

<u>Legend:</u>

1 = Yes
0 = No
* = Switch not shown on transition diagram

NLV = Number of launch vehicles
NSC = Number of spacecraft
NOSVLV = Number of Saturn V's
CHUTE = Parachute this configuration?

		Capsule Outcome													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Orbiter Outcome	1	q_{11}	q_{12}	q_{13}	q_{14}	...	...	...	...	...	...	...	...	...	...
	2	q_{21}	q_{22}	q_{23}	...	...	...	...	...	...	...	...	...	...	...
	3	q_{31}	q_{32}	...	...	...	...	...	...	...	...	...	...	...	...
	4	q_{41}	...	...	...	...	...	...	...	...	...	...	...	...	...

Matrix Q applies to the outcomes of a single planetary vehicle. For those mission configurations that involve two vehicles, it is assumed that the vehicles are identical and operate independently of one another. The development that follows can be easily extended to the case in which either of these two assumptions is relaxed. However, both of these assumptions are consistent with the nominal mission configurations under consideration.

The first step in calculating the mission outcome probabilities with two spacecraft per mission is to combine the outcome probability matrixes for the two spacecraft into a single outcome probability matrix for the entire mission. Thus, there are three matrixes similar to the Q matrix: one for each of the two planetary vehicles, and one for the mission. Since the two vehicles are identical, we need only calculate an outcome probability matrix for one of the vehicles.

To construct the mission outcome probability matrix, it is assumed that the mission outcome is the maximum of the two vehicle outcomes. That is, if the first vehicle achieves orbiter outcome i_1 and capsule outcome j_1, and the second vehicle achieves orbiter outcome i_2 and capsule outcome j_2, then the orbiter outcome for the mission is max (i_1, i_2) and the capsule outcome for the mission is max (j_1, j_2). In this case the mission outcome probability matrix (denoted as Q') is calculated by a simple enumeration of all the possible combinations of vehicle orbiter and capsule outcomes that yield a particular mission orbiter and capsule outcome. Thus, the probability of mission orbiter outcome i and mission capsule outcome j is

$$q'_{ij} = 2q_{ij} \sum_{k=1}^{i} \sum_{\ell=1}^{j} q_{k\ell} - q_{ij}^{2} + 2 \sum_{k=1}^{j-1} q_{ik} \sum_{\ell=1}^{i-1} q_{\ell j}$$

The last term above must be omitted if either i or j is equal to one.

In practice, however, there are situations in which the orbiter and capsule outcomes for the mission are not such a simple function of the vehicle orbiter and capsule outcomes. Assume, for example, that if one of the planetary vehicles achieves capsule outcome j, and the other achieves capsule outcome k, then the mission capsule outcome is m rather than max (j, k). If the rule for combining orbital outcomes remains unchanged, then the following expression must be subtracted from the value of $q'_{i,\max(j,k)}$ above:

$$2q_{ij} \sum_{\ell=1}^{i} q_{\ell k} + 2q_{ik} \sum_{\ell=1}^{i} q_{\ell j} - 2q_{ij}\, q_{ik} .$$

This quantity must also be added to the previously calculated value for $q'_{i,m}$. This alteration to the mission outcome probabilities must be carried out for each orbiter outcome. It is assumed that j is not equal to k; Thus, if so, the correction factor must be divided by two.

This technique is used to calculate the mission outcome probability matrixes for those mission configurations that involve two planetary vehicles. Of all possible outcome combinations, there are 10 special cases of this type. These are listed in Table 4-8.

Table 4-8. Special Combinations of Outcomes from Two Planetary Vehicles

Capsule Outcomes	Mission Outcome
4, 5	6
8, 9	11
8, 10	12
9, 10	13
10, 11	14
9, 12	14
8, 13	14
11, 12	14
11, 13	14
12, 13	14

A second consideration with two planetary vehicles concerns those transitions in the transition diagram that are not independent between the vehicles. The most common examples of these dependencies are the various environmental probabilities in the transition diagram. For example, if the entry environment is such that a successful direct capsule entry is achieved from one spacecraft, then capsules from the second spacecraft will also experience a favorable environment for both orbital and direct entry.

Another such dependency is the launching of two planetary vehicles by a single booster. In this case, the launch and injection probability in the transition diagram is obviously not independent between the two planetary vehicles.

To illustrate the handling of this problem, consider the case where there is only a single transition in the transition diagram that involves a dependency between the two planetary vehicles. The probability associated with this dependent transition is p. In this case, the mission outcome probability matrix can be calculated by the following procedure:

a. Set the probability associated with the dependent transition in the transition diagram equal to zero and then calculate the planetary vehicle outcome probability matrix Q.

b. Calculate the mission outcome probability matrix Q' from the above matrix using the logic summarized in Table 4-8.

c. Repeat steps (a) and (b) with the probability of the dependent transition set equal to one.

d. Multiply the mission outcome probability matrix Q' in step (b) by (1-p), multiply the mission outcome probability matrix in step (c) by p, and add the two matrixes together. The sum is the desired mission outcome probability matrix for the two-vehicle configuration.

To extend this procedure to the situation in which there are many dependent transitions in the transition diagram, as is the case for the probability model, all possible combinations of dependent transitions must be listed. A planetary vehicle outcome probability matrix (Q) and a mission outcome probability matrix (Q') are then calculated for each possible combination of dependent transitions. Each mission outcome probability matrix is then multiplied by the actual probability of that particular combination of dependent transitions, and the sum of these matrixes is then the desired mission outcome probability matrix for the two vehicle configurations. The application of this procedure to the transition diagram of Figure 4-35 is summarized in Table 4-9.

Table 4-9. Combinations of Dependent Probabilities

Values of Transition Probabilities Used in Calculating Vehicle Outcome Probability Matrix Q				Probability of the Particular Sequence (i.e., multiplier of the mission matrix Q').
P31	P21	P3	P9 P29 P30	
0	0	0	0	(1-P31) (1-P21) (1-P3) (1-P29)
0	0	0	1	(1-P31) (1-P21) (1-P3) P29
0	0	1	0	(1-P31) (1-P21) P3 (1-P9)
0	0	1	1	(1-P31) (1-P21) P3 P9
0	1	0	0	(1-P31) P21 (1-P3) (1-P29)
0	1	0	1	(1-P31) P21 (1-P3) P29
0	1	1	0	(1-P31) P21 P3 (1-P9)
0	1	1	1	(1-P31) P21 P3 P9
1	0	0	0	P31 (1-P21) (1-P3) (1-P29)
1	0	0	1	P31 (1-P21) (1-P3) P29
1	0	1	0	P31 (1-P21) P3 (1-P9)
1	0	1	1	P31 (1-P21) P3 P9
1	1	0	0	P31 P21 (1-P3) (1-P29)
1	1	0	1	P31 P21 (1-P3) P29
1	1	1	0	P31 P21 P3 (1-P9)
1	1	1	1	P31 P21 P3 P9

For the two planetary vehicle per booster configurations, the 16 above combinations are calculated with P1 set at one, and each of the probabilities in the right hand column is multiplied by P1. A second calculation is made with P1 set to zero, and the resulting matrix is multiplied by (1-P1).

4.9 COST MODEL

4.9.1 APPROACH

The method for determining the cost associated with each decision node involves the estimation of a nominal or baseline cost for the mission configuration being considered; this nominal cost is then modified in accordance with the state of the project existing at the time of the decision. The project states of concern to the cost model are represented by the following four state variables:

a. Year of launch opportunity.
b. Outcome of previous orbiter flight.
c. Outcome of previous capsule flight.
d. Mission configuration in process at the time of decision regarding the next configuration to be processed.

Nominal costs for each of the mission configurations are estimated by dividing the cost into six categories:

a. Capsule.
b. Orbiter.
c. Management.
d. Integration and operations.
e. Launch vehicle.
f. Science payload instrumentation.

Modifying factors to these nominal costs, I_1 through I_4, are estimated for each possible state of the above four variables, respectively.

In order to limit the amount of detail in the cost model, the following ground rules and assumptions are followed:

a. The decision to skip a Mars launch opportunity involves some cost commitment to carry the project over until the next decision.

b. The decision to discontinue the Voyager program involves only run-out costs on the configuration already in process; i.e., no new cost commitments.

c. The decision at a decision node selects the configuration to be launched approximately four years later and the cost attached to it; it does not affect the cost of the configuration which is in process for launch approximately two years later.

d. The outcomes from configurations selected approximately four years earlier are available and may affect the cost attached to the decision. These outcomes are represented by state variable modifiers I_2 and I_3.

e. The configuration in process, which will be launched about two years after the decision, is known and can affect the cost attached to the decision, as this configuration is in an advanced developmental stage at the time of the decision. This effect is represented by state variable modifier I_4.

f. The year of launch for the configuration being considered affects its cost, due to advancements and increased knowledge. This is represented by I_1.

g. No project state variables other than the above four are significant in estimating the cost attached to the decision.

h. The values of state variable modifiers I_1, I_2, and I_3 are independent of the configuration under consideration.

i. State variable modifier I_4, representing the effect of the configuration in process, is dependent on the configuration being considered. Therefore, the values of I_4 are estimated separately for each configuration to be considered.

The project cost estimates obtained through the use of this cost model are not based upon sufficient enough detail to justify their absolute acceptance. They are, however, suitable for determining the sensitivity of project decisions to cost, and their absolute values are found to be in general agreement with known Voyager budgetary planning for those configuration sequences which have been considered to date for Voyager.

4.9.2 COST EQUATION

The cost equation for processing a Voyager mission configuration for one launch opportunity contains six terms, with each term subject to modification by the project state variable modifiers.

$$S_n = C_n + O_n + M_n + T_n + LV_n + PL_n$$

where:

S_n = Nominal cost of processing a selected Voyager mission configuration, n, from design through post-launch operations

C_n = Capsule portion of S_n

O_n = Orbiter portion of S_n

M_n = Program management portion of S_n

T_n = Flight integration and operations portion of S_n

LV_n = Launch vehicle portion of S_n

PL_n = Science payload instrumentation portion of S_n.

Nominal costs are then modified in accordance with the state of project as follows:

$$SM_n = M_c C_n + M_o O_n + M_n + M_t T_n + M_{lv} LV_n + M_{pl} PL_n$$

where:

SM_n = Total cost of processing a selected Voyager mission configuration, n, as modified according to the state of the project

M_c = Capsule cost modifier

$= I_1 I_2 I_3 I_4$

M_o = Orbiter cost modifier

$= I_1 I_2 I_3 I_4$

M_t = Flight configuration integration and operations cost modifier

$= I_1 I_2 I_3 I_4$

M_{lv} = Launch vehicle cost modifier

$= I_1 I_2 I_3 I_4$

M_{pl} = Scientific payload cost modifier

$= I_1 I_2 I_3 I_4.$

4.9.3 DEVELOPMENT OF NOMINAL COST DATA

The principal cost elements in processing a Voyager mission configuration are the costs of the orbiter, capsule, science payload, and launch vehicle. The costs of integration and program management are less significant.

Previous Voyager studies performed by General Electric for a wide range of spacecraft and capsule concepts (e.g., NASA Contract NAS-W696; JPL Contract 95D847) provided a reservoir of program cost information. When plotted as a function of system complexity, data from these studies generally fall within the band shown in Figure 4-36. The points indicated in the band were selected as the base for estimating the nominal contractor orbiter, capsule and science payload costs. Nominal launch vehicle costs were estimated as follows:

Saturn V	$120M
Saturn 1B/Centaur	$ 30M
Atlas/Centaur	$ 12M

A list of typical work sheet data used for estimating the nominal cost of one configuration (VOTVSF) is included as Table 4-10. NASA costs related to the capsule, orbiter, management, and integration and operations categories were estimated as one-half of the corresponding contractor costs. Launch vehicles and science payloads were treated as GFE items, with all of the cost shown under the NASA (GFE) category. Table 4-11 lists the basic weights and costs associated with the potential mission configurations.

4.9.4 COST MODIFIERS

The modification of nominal costs in accordance with project states is accomplished by multiplying each nominal cost element by the appropriate cost modifiers. As discussed in Subsection 4.9.2, each modifier is the product of the state variable modifiers I_1 through I_4. Estimates of the appropriate values for these modifiers are made for each of the 14 mission configurations.

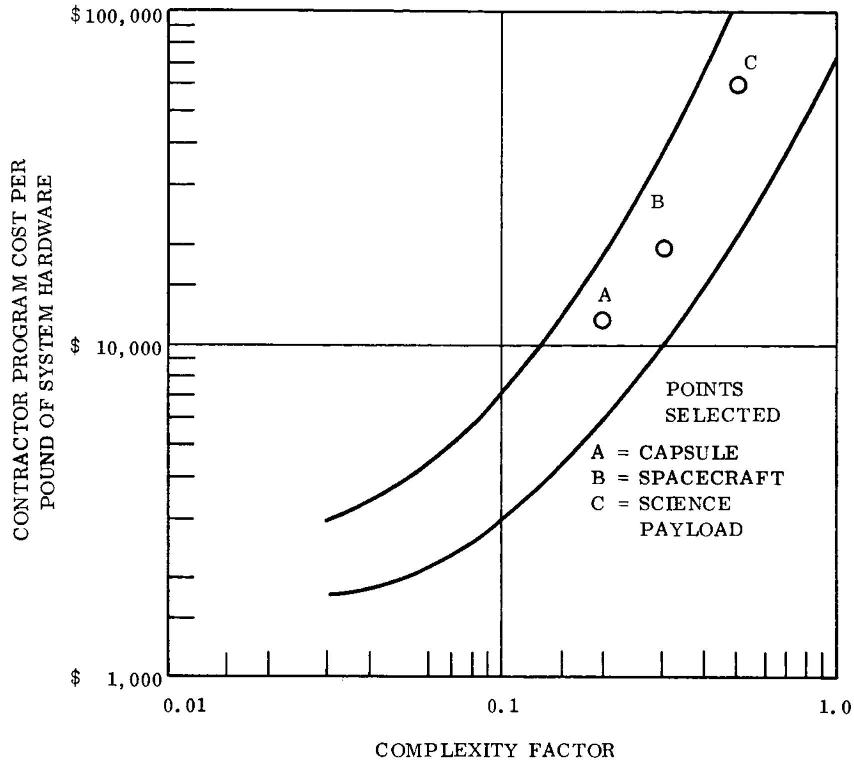


Figure 4-36. Cost vs. System Complexity

Typical cost modifier work sheet data (Table 4-12) is shown for one configuration (VOTVSF). From the modifier data on this sheet and the nominal cost data of Table 4-10, it is possible to compute the cost of processing the example configuration (VOTVSF) for any values of the state variables at a decision node.

A sample cost computation based on these estimated nominal costs and modifier values is listed below for a Voyager mission sequence from 1973 through 1979:

Year	Mission Configuration		Project States I_1	I_2	I_3	I_4	Cost ($ M)
1973	9	VOLTV	6	1	1	3	1086
1975	10	VOTVSF	8	1	3	9	968
1977	11	VOVBL	10	3	8	10	877
1979	11	VOVBL	12	4	11	11	691
		Sample: Total Project Cost.....					$3622

Table 4-10. Typical Cost Work Sheet Data

(Estimated Nominal Costs Configuration: 10-VOTVSF)

Category	Dry Weight (Pounds)	Flight Units Required	Complete Ground Units Required	Total Weight (Pounds)	Estimated Complexity Factor	Dollars per Pound	$M Contractor Cost	$M NASA or GFE Cost	Total Nominal Cost ($M)	
Capsule										
ATM	500	---	---	---	0.20	$12K	---			
DTV	1000	---	---	---	0.20	$12K	---			
LTV	3000	---	---	---	0.20	$12K	---			
TVSF	4700	2	4	28,200	0.20	$12K	338	169	507	C_{10}
VBL	4700	---	---	---	0.20	$12K	---			
Spacecraft										
Voyager	2100	2	4	12,600	0.3	$20K	252	126	378	0_{10}
Mariner	800	---	---	---	0.3	$20K	---			
Management	---	---	---	---	---	---	30	15	45	M_{10}
Integration & Operations	---	---	---	---	---	---	30	13	45	T_{10}
Launch Vehicle	---	---	---	---	---	---	---	120	120	LV_{10}
Payload										PL_{10}
Orbiter	400	2	3	2,000	0.5	$60K	---	120	120	
Capsule	300	2	3	1,500	0.5	$60K	---	90	90	
				Total Nominal Cost ($M)			650	655	1305	S_{10}

Table 4-11. Configuration Weight and Cost Characteristics

Configuration	Capsule Weight (lb)	Capsule *Payload Weight (lb)	Spacecraft Weight (lb)	Spacecraft *Payload Weight (lb)	Nominal Configuration Cost ($M)
1. VSTOP	---	---	---	---	0
2. VSKIP	---	---	---	---	55
3. VMAR	400	100	800	150	270
4. VSIB	---	---	2100	400	501
5. V2SIB	---	---	2100	400	618
6. VOORB	---	---	2100	400	678
7. VOATM	400	100	2100	400	783
8. VODTV	800	200	2100	400	855
9. VOLTV	2800	250	2100	400	1086
10. VOTVSF	4700	300	2100	400	1305
11. VOVBL	4700	600	2100	400	1440
12. VODATM	400	100	2100	400	810
13. VODDTV	800	200	2100	400	912
14. VODLTV	2800	250	2100	400	1140

*Payload weight includes instrumentation packages only, and excludes related structures and supporting components, which are included in the vehicle weight.

The cost equation is programmed to permit the computation of the cost of any configuration under any state variable condition of interest. Nominal cost data, as suggested in Tables 4-10, 4-11 and 4-12, are employed for most exercises. The program is designed, however, to facilitate change or updating of any nominal costs or cost modifiers.

4.10 VALUE MODEL

The pilot model results show that the optimum decision policy produced by the decision tree program is sensitive to the quantitative assignment of values to outcomes, as one would expect intuitively. Furthermore, when costs are assigned to each possible configuration, the optimum decision policy is found to be sensitive to the number of dollars assigned to each value point. These results illustrate the importance of developing a value model; that is, a rational structure for making the value assignment, by breaking down value into more fundamental quantities that may be determined more easily and precisely.

4.10.1 NATURE OF VALUE

The application of logic to the decisions of the Voyager project requires as one of its fundamental steps the construction of a value function on the possible outcomes of the project. That is, we must construct a scale of values that specifies the preferences of the decision maker for one outcome as opposed to another. We can think of the problem as analogous to the one we face if we have someone buy a car for us: we must tell him what features of a car are important to us and to what extent. How do we value performance relative to comfort, appearance relative to economy of operation, etc.?

Table 4-12. Typical Cost Modifier Work Sheet Data

Table of Cost Modifiers (Configuration: 10-VOTVSF)

	Modifier	Variable States		Capsule	Orbiter	Mgt.	I&O	LV	PL
I_1	Year of Opportunity	4	1971	1.00	1.00	1.00	1.00	1.00	1.00
		6	1973	1.00	1.00	1.00	1.00	1.00	1.00
		8	1975	0.95	0.95	0.95	0.95	0.95	0.95
		10	1977	0.93	0.93	0.93	0.93	0.93	0.93
		12	1979	0.91	0.91	0.91	0.91	0.91	0.91
		14	1981	0.90	0.90	0.90	0.90	0.90	0.90
I_2	Orbiter Outcome	1	OOZERO	1.00	1.00	1.00	1.00	1.00	1.00
		2	OONORB	1.00	1.30	1.00	1.00	1.00	1.00
		3	OOORB	1.00	0.75	1.00	1.00	1.00	1.00
		4	OOLORB	1.00	0.70	1.00	1.00	1.00	1.00
I_3	Capsule Outcome	1	COZERO	1.00	1.00	1.00	1.00	1.00	1.00
		2	CONOEN	1.20	1.00	1.00	1.00	1.00	1.00
		3	COATM	0.90	1.00	1.00	1.00	1.00	1.00
		4	COATMS	1.30	1.00	1.00	1.00	1.00	1.00
		5	CODTV	0.85	1.00	1.00	1.00	1.00	1.00
		6	CODTVS	1.20	1.00	1.00	1.00	1.00	1.00
		7	COLAND	0.80	1.00	1.00	1.00	1.00	1.00
		8	COLTV	0.75	1.00	1.00	1.00	1.00	0.95
		9	COSURF	0.75	1.00	1.00	1.00	1.00	0.90
		10	COBIOL	0.70	1.00	1.00	1.00	1.00	0.80
		11	COTVSF	0.70	1.00	1.00	1.00	1.00	0.80
		12	COBITV	0.70	1.00	1.00	1.00	1.00	0.80
		13	COBISF	0.70	1.00	1.00	1.00	1.00	0.80
		14	COALEX	0.70	1.00	1.00	1.00	1.00	0.80
I_4	Configuration in Process	2	VSKIP	1.00	1.00	1.00	1.00	1.00	1.00
		3	VMAR	1.00	1.00	1.00	1.00	1.00	1.00
		4	VSIB	1.00	0.80	1.00	1.00	1.00	0.95
		5	V2SIB	1.00	0.80	1.00	1.00	1.00	0.95
		6	VOORB	1.00	0.75	1.00	1.00	0.80	0.95
		7 or 12	VOATM OR VODATM	0.95	0.75	1.00	1.00	0.80	0.90
		8 or 13	VODTV OR VODDTV	0.90	0.75	1.00	1.00	0.80	0.75
		9 or 14	VOLTV OR VODLTV	0.85	0.75	1.00	1.00	0.80	0.75
		10	VOTVSF	0.70	0.70	1.00	1.00	0.80	0.70
		11	VOVBL	0.70	0.70	1.00	1.00	0.80	0.70
Nominal Costs ($M) for Configuration				507	378	45	45	120	210
Total Nominal Cost ($M) for Configuration						1,305			

The need for specifying the value function grows out of the desire to utilize the potential of analytical and logical methods to extend and improve our more intuitive concepts, and the desire to delegate many of the detailed decisions to lower-level decision-makers. Analytical and logical methods allow us to take direct account of many more factors, including the dimension of uncertainty, in order to make better decisions. However, to obtain maximum benefit from these methods, we must be willing to specify a value function, especially in a complex sequential decision process such as the Voyager project.

4.10.2 DERIVED AND ASSIGNED VALUES

In constructing the value function, careful distinction must be drawn between derived and assigned components of value. The assigned component of value is the one we obtain as an explicit benefit of the project. For example, conducting a life experiment on Mars has an assigned scientific value that is very high. Similarly, placing a spacecraft in orbit around Mars has an assigned value as an engineering accomplishment. However, placing the spacecraft in orbit also has a derived value because of its importance in achieving later assigned values, like the conduction of life experiments. A derived value component is therefore one that accrues to an accomplishment because of its contribution to achieving future assigned values.

If the project is terminated at some date, it will be credited with all of the assigned values it had achieved prior to that date, but not with any derived values that had not been realized in assigned form. The assigned values could only be realized by continuation of the project. The same accomplishment may have both assigned and derived values. The assigned values are determined by factors outside the project; the derived values stem from the assigned values and the probabilistic structure of the problem.

4.10.3 DIRECT AND INDIRECT VALUES

We can think of the assigned value function in terms of both direct and indirect contributions. The direct values of the Voyager project arise from the various kinds of knowledge that the project will produce; for example, visual records of Mars, significant data on both the biological and physical environment, engineering capability, and operational experience.

From these direct contributions we as a nation derive indirect contributions such as national prestige, favorable world opinion, etc. The existence of the indirect components can be demonstrated by observing that if a race of galactic explorers were to offer us solid information of the type we have listed under direct contributions (such as a Martian atlas, a guide to the Martian flora and fauna, etc.), the price we would offer would probably be less than the cost of the Voyager project. Part of the satisfaction comes from having done it ourselves, and the value function must include this characteristic of the project.

4.10.4 CONSTRUCTION OF A VALUE SCALE

The first step in constructing the value function is to establish an ordinal scale of values that states for each pair of outcomes the outcome that we prefer. The next step is the construction of a cardinal scale that allows us to compare the strength of preference. One way to develop such a scale is to assign points to the different outcomes and adjust values until decision makers are satisfied with the results. The final step is the construction of an absolute dollar scale that interprets points directly in terms of dollar benefits. The ordinal and cardinal point scales can be established by intuitive comparisons within the project; the absolute dollar scale requires the comparison of the Voyager project with other space projects.

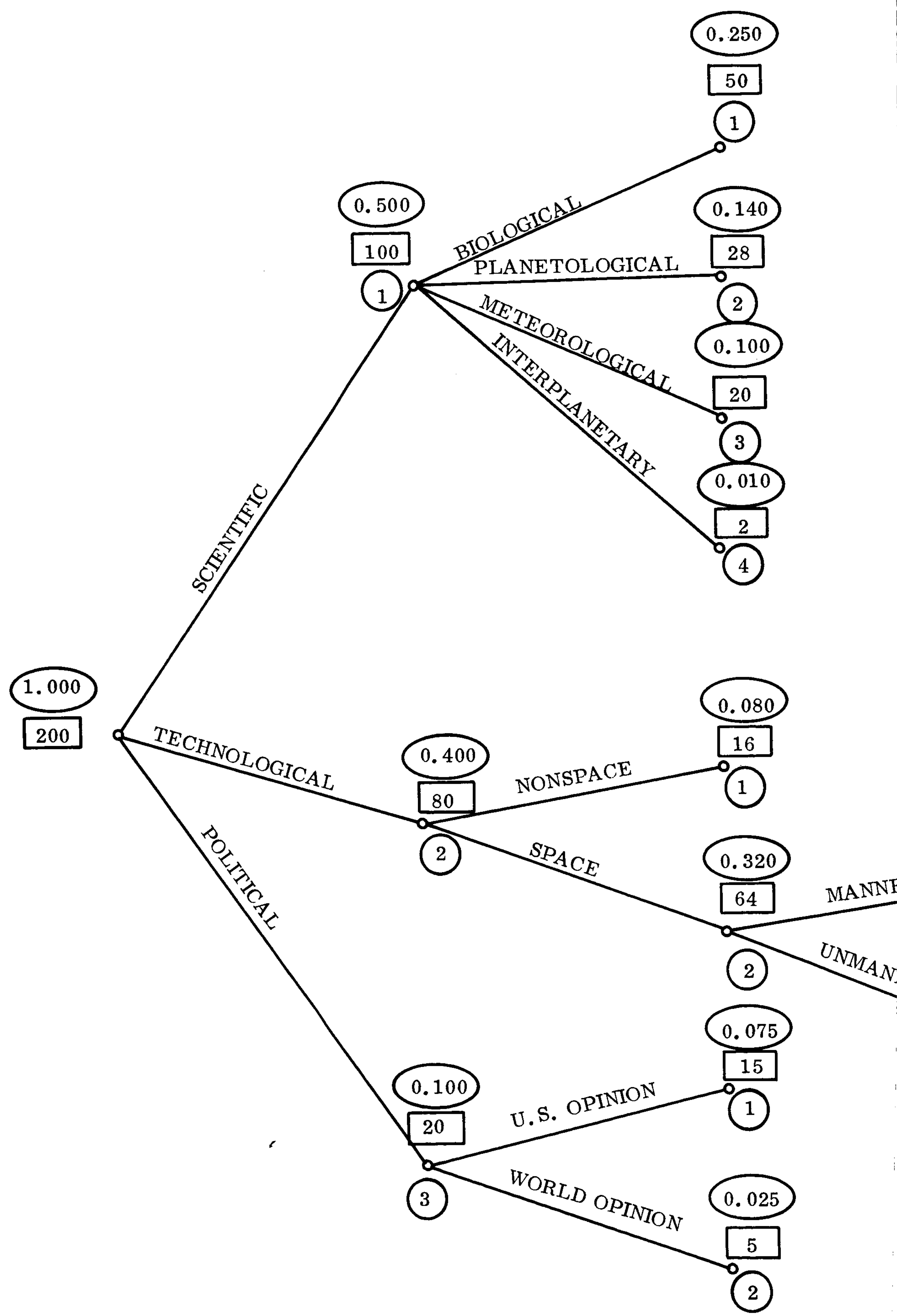
We can illustrate the use of cardinal and absolute value scales by returning to the car purchase example of Subsection 4.10.1. We could tell our agent, who will buy the car for us, the dollar value we assign to each component of a car's value. We might say, for example, that given our use characteristics, a car that runs 18 miles to a gallon of gas is worth $40 a year more to us than a car that runs only 15 miles, and that foam rubber seats are worth $50 more to us than ordinary seats. When we had similarly specified the dollar value of all possible features, including those whose values might not be additive, then our agent would be able to go into the market place, determine the value and price of every offered car and return with the most profitable car for us (which might, of course, be no car at all). Notice in following this philosophy that we do not care if, in fact, there are any cars for sale that have all or any part of the features that we have valued. The establishment of the value function depends remotely, if at all, on the spectrum of cars available.

The point value (cardinal) approach is similar except that we assign points to each of the components of value, individually and jointly. Then we would fix a purchase budget for our agent and send him out to find the best car (highest points) within that budget. Of course, we might be very sorry if we found out that he could have purchased a much better car for a little more money, or if he paid very dearly for the last few points he obtained. However, since we can often convert point value scales to absolute dollar value scales by assigning a dollar value to each point, the essential difference in the two schemes lies in whether we want to find the most profitable course of action with or without budgetary constraints.

It should be emphasized that the main role of the value function is to serve as a framework for discussion of preferences. The value function encodes preferences consistently; it does not assign them. Consequently, the decision-maker can insert alternative value specifications to determine the sensitivity of decisions to changes in the value function. The process of assigning the value is naturally an iterative one, with components of value being added and eliminated as understanding of the problem grows.

4.10.5 VALUE TREE

To aid in constructing the value function, the problem can be visualized as one of evaluating a value tree like that shown in Figure 4-37. This tree is drawn by considering first the major assigned components of value, both direct and indirect, then the subcategories of each type identified in more and more detail until no further distinction is necessary. Position is specified in the tree by a vector x; thus the node $x = 3, 2$ corresponds to the node attained by following the third branch at the first node and the second branch at the second node. The originating node is followed by three branches that represent three major components of value: scientific benefit, technological benefit, and political benefit. At the node $x = 1$, scientific benefit is divided into four types. At the node $x = 2$, technological benefit is divided between space and nonspace. Space related benefit is then further categorized. The process may be carried on as far as we like.


1.000
200
SCIENTIFIC
0.500
100
1
BIOLOGICAL
0.250
50
1
PLANETOLOGICAL
0.140
28
2
METEOROLOGICAL
0.100
20
3
INTERPLANETARY
0.010
2
4
TECHNOLOGICAL
0.400
80
2
NONSPACE
0.080
16
1
SPACE
0.320
64
2
POLITICAL
0.100
20
3
U.S. OPINION
0.075
15
1
WORLD OPINION
0.025
5
2

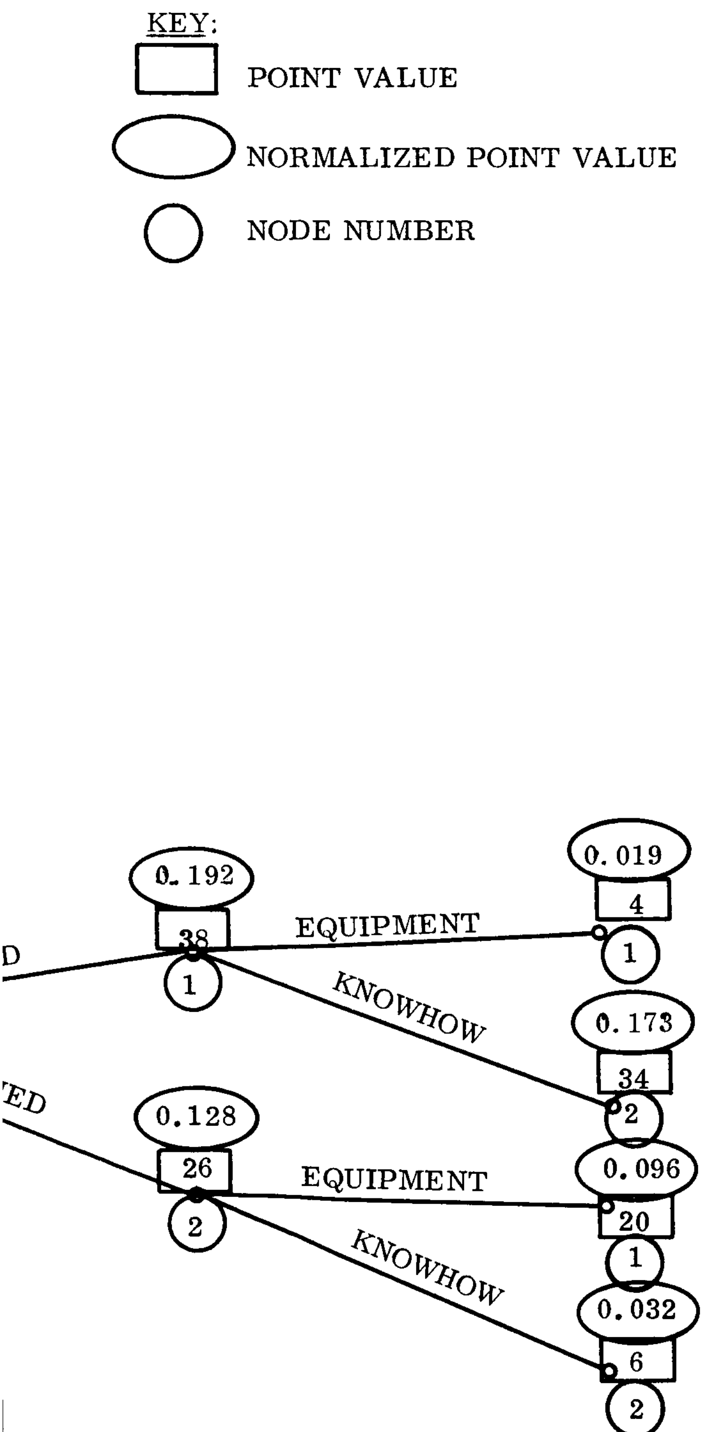


Figure 4-37. Partially Completed Value Tree

The value function at any node x is defined as v(x). In the tree structure, the value of any node is the sum of the values of its successor nodes,

$$v(x_1, x_2, \ldots, x_n) = \sum_{x_{n+1}} v(x_1, x_2, \ldots, x_n, x_{n+1}).$$

To illustrate the assignment of value in the tree, consider the following node values as nominally representative of the NASA/OSSA value preference: *

$V(1,1) = 50 \quad V(1,2) = 28 \quad V(1,3) = 20 \quad V(1,4) = 2$

$V(2,1) = 16$

$V(2,2,1,1) = 4 \quad V(2,2,1,2) = 36$

$V(2,2,2,1) = 18 \quad V(2,2,2,2,) = 6$

$V(3,1) = 15 \quad V(3,2) = 5$

These figures are indicated within the boxes on the value tree and imply a scientific knowledge value of $V(1) = V(1,1) + V(1,2) + V(1,3) + V(1,4) = 100$, a political benefit value of $V(3) = V(3,1) + V(3,2) = 20$, etc.

From these point assignments, Mars meteorological science, for example, is judged to be worth 10 times as much as interplanetary science, and U.S. public opinion is valued three times as highly as world opinion.

Point values can be interpreted more readily if we place them in a normalized scale by dividing each by the sum of all. Thus, a normalized value function v*(x) is defined as

$$v^*(x) = \frac{1}{V} v(x).$$

*No NASA/OSSA or JPL endorsement of these values is intended to be conveyed here.

The normalized value function for each node appears in ovals in Figure 4-37 and is the fraction of total value attributable to that node. This biological knowledge accounts for 25 percent of total value, while U.S. public favor earns only 7.5 percent of total value.

The complete value tree allows us to assign values to any proposed project. If a project is certain to achieve some of the total values, then it would be credited with those values. If it has a probability less than one of achieving some total value, then it is credited with its expected contribution. The evaluation of projects can be performed at any vertical cross-section of the tree. If the cross-section is taken near the left-hand end of the tree, the value computation will be rather approximate. As the components of value are more carefully broken down and the evaluation is performed to the right of the tree, the value computation becomes more precise. Of course, no plan for the project is expected to have a perfect value score.

4.10.6 COMPLETING THE VALUE TREE

Up to this point, the value tree has not been developed to the point where it can supply the kinds of values demanded by the decision tree. The decision tree wants to know answers to questions like: "What is it worth if a mission configuration takes the project from capsule outcome COLTV to capsule outcome COTVSF, and in the process repeats orbiter outcome OOLORB?" To answer such a question, we must obviously know the value of achieving each of the orbital outcomes and each of the capsule achievements, and of repeating some of them.

In general, each capsule achievement or orbital outcome contributes value in several of the categories represented by the tips of the partially completed value tree of Figure 4-37. On the other hand, the contributions of all the orbital outcomes and capsule achievements to biological knowledge, for example, must sum to 25 percent. Thus, each value tree final node can be broken down into the contributions made by the full set of orbital outcomes and capsule achievements to that category.

Figure 4-38 illustrates the final structure that is tacked onto each tip of the value tree of Figure 4-37 to complete it in this manner. The tip structures for each of the tips of Figure 4-37, with normal weightings, are shown in Figures 4-39 through 4-49.

Thus, to calculate the total value of CA3, for example, we need only sum the biological value of CA3, the planetological value of CA3, the meteorological value of CA3, etc.

In the case of capsule achievements, like CA5, which have repeat value, the node representing that achievement is further sub-divided between the value of the initial attainment and the sum of all repeat values (assuming a maximum number of possible repeats). Then, by taking $1/n_{max}$ (where n_{max} is the maximum possible number of repeats) of the node representing the value of all n_{max} repeats, a node representing the value of one repeat is generated.

4.10.7 CONCLUSION

In developing this model, we found it difficult to look at the entire project, and by intuition or judgement assign values to each outcome. In order to encode our feeling about the outcomes, we described the value assignment process with the value tree and, by assigning values to each node in the tree, deduced the value of any project outcome. The value tree method of value assignment proved to be useful in assessing the value function of the Voyager project.

Our main goal was to provide the decision-maker with a consistent and convenient way to encode his preferences. Only when this step was accomplished could the mission configuration question be settled by logical means.

4.11 THE SPAN SYSTEM

The decision tree and the three submodels for probabilities, values and costs were all programmed within the framework of a program system called SPAN (Space Programs ANalysis). This section describes this versatile program system.

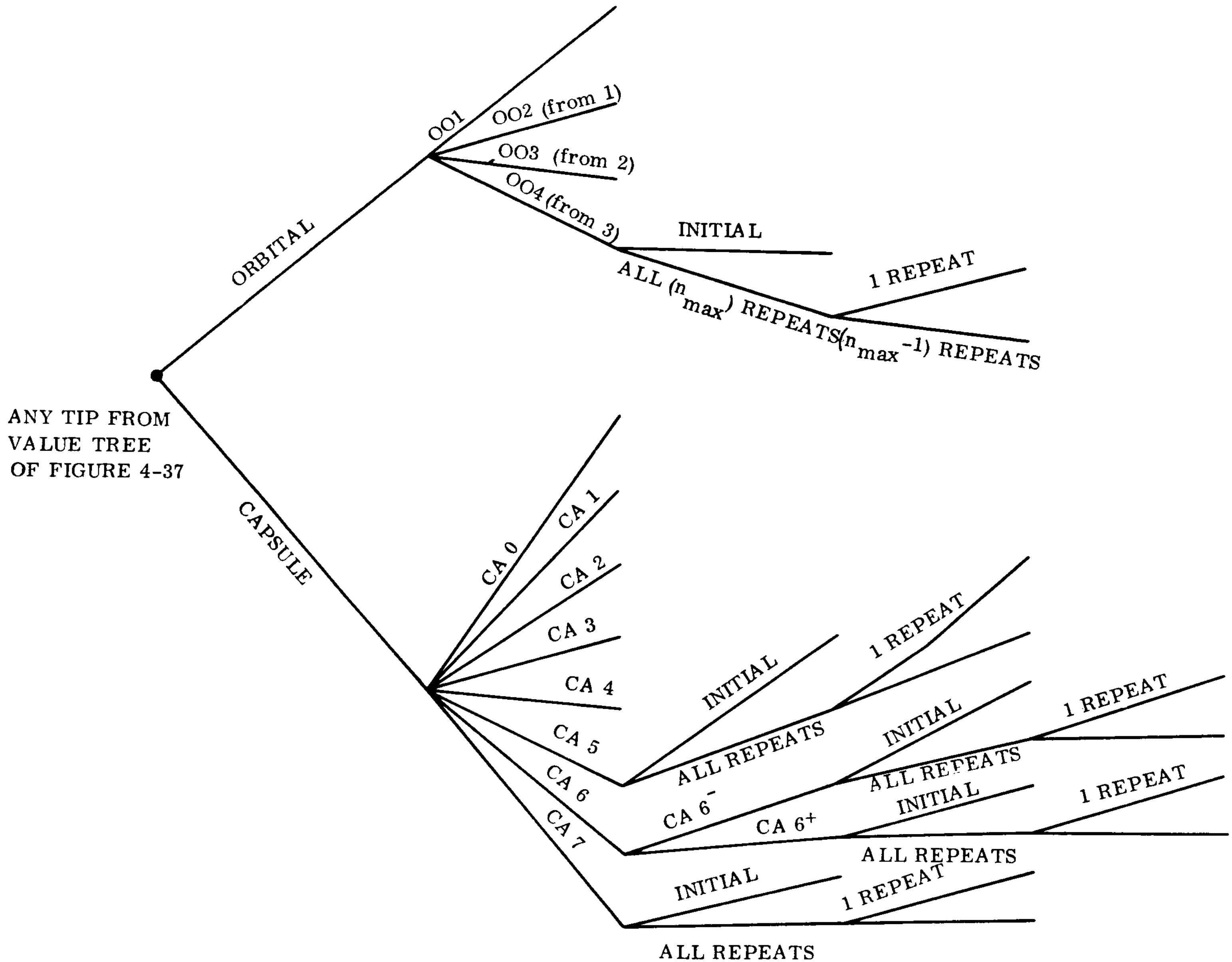


Figure 4-38. Value Tree Tip Structure

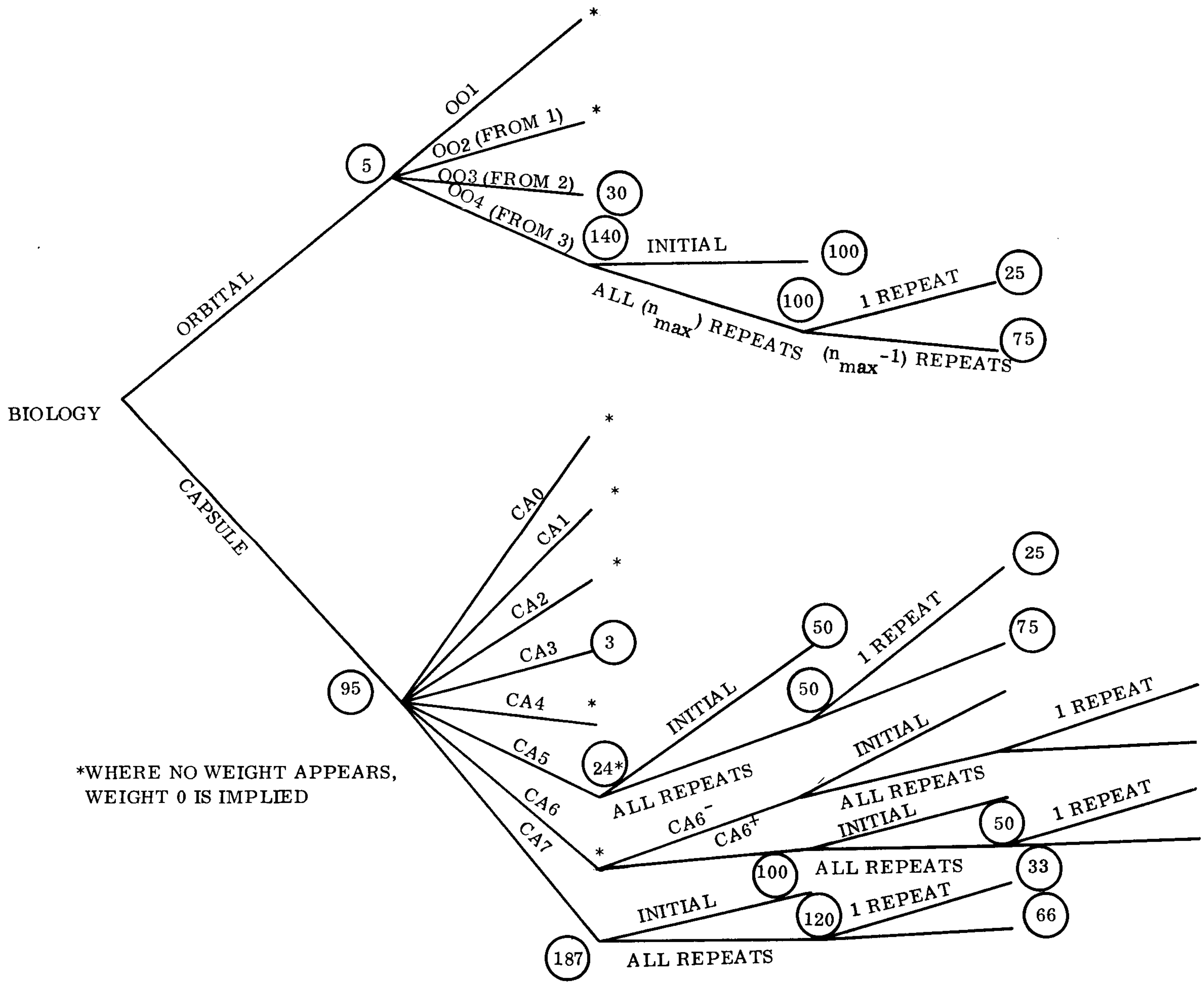


Figure 4-39. Tip Structure for Biological Science Category

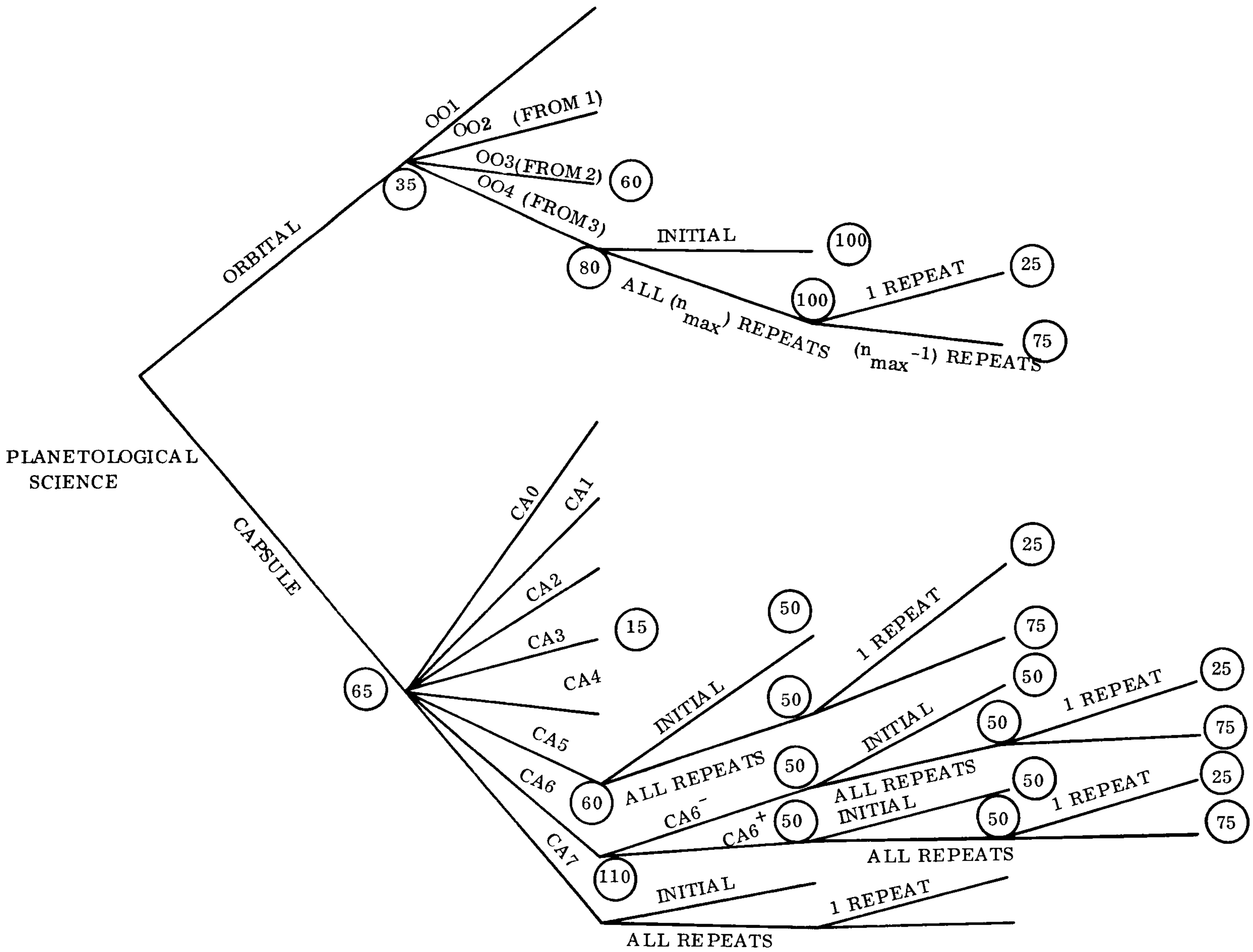


Figure 4-40. Tip Structure for Planetological Science Category

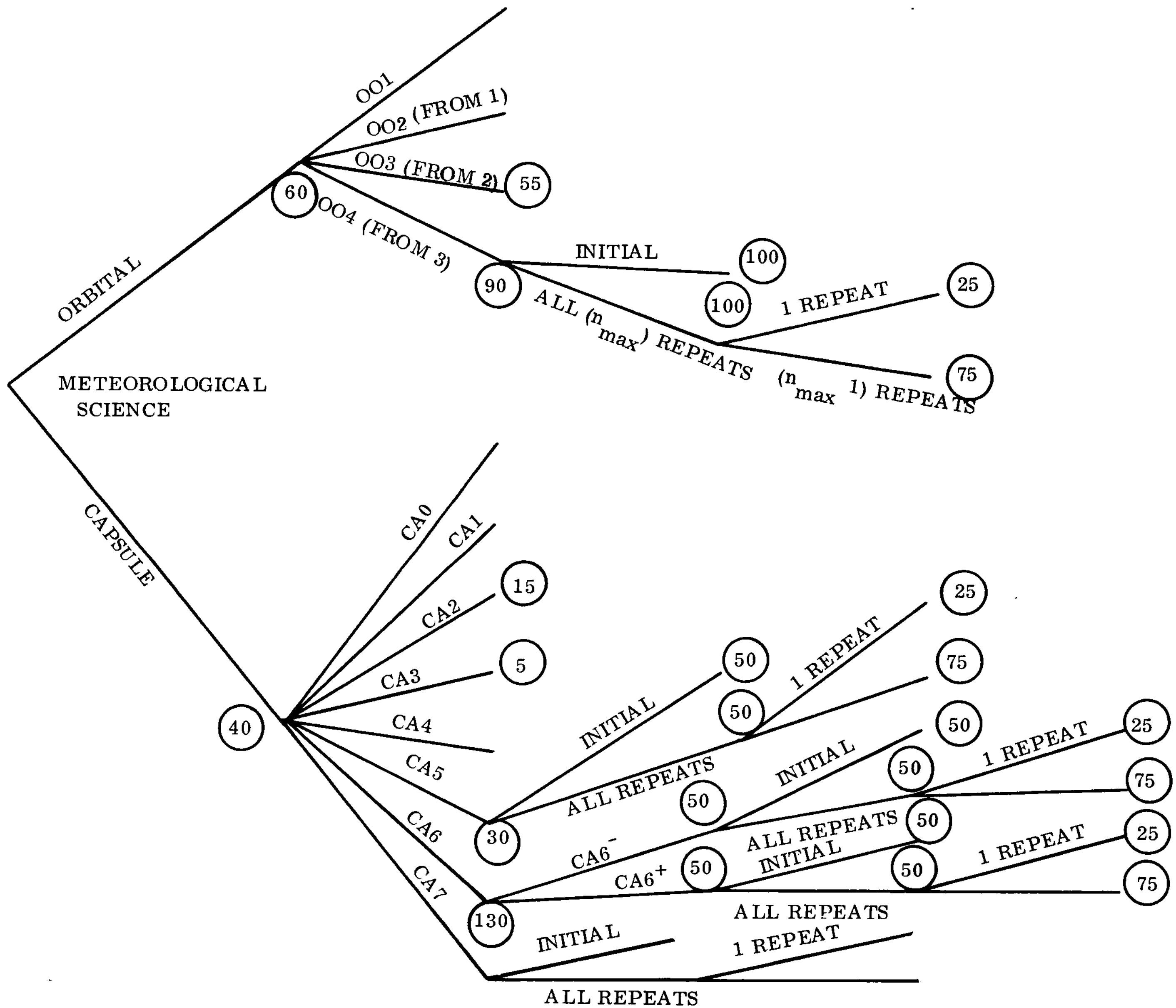


Figure 4-41. Tip Structure for Meteorological Science Category

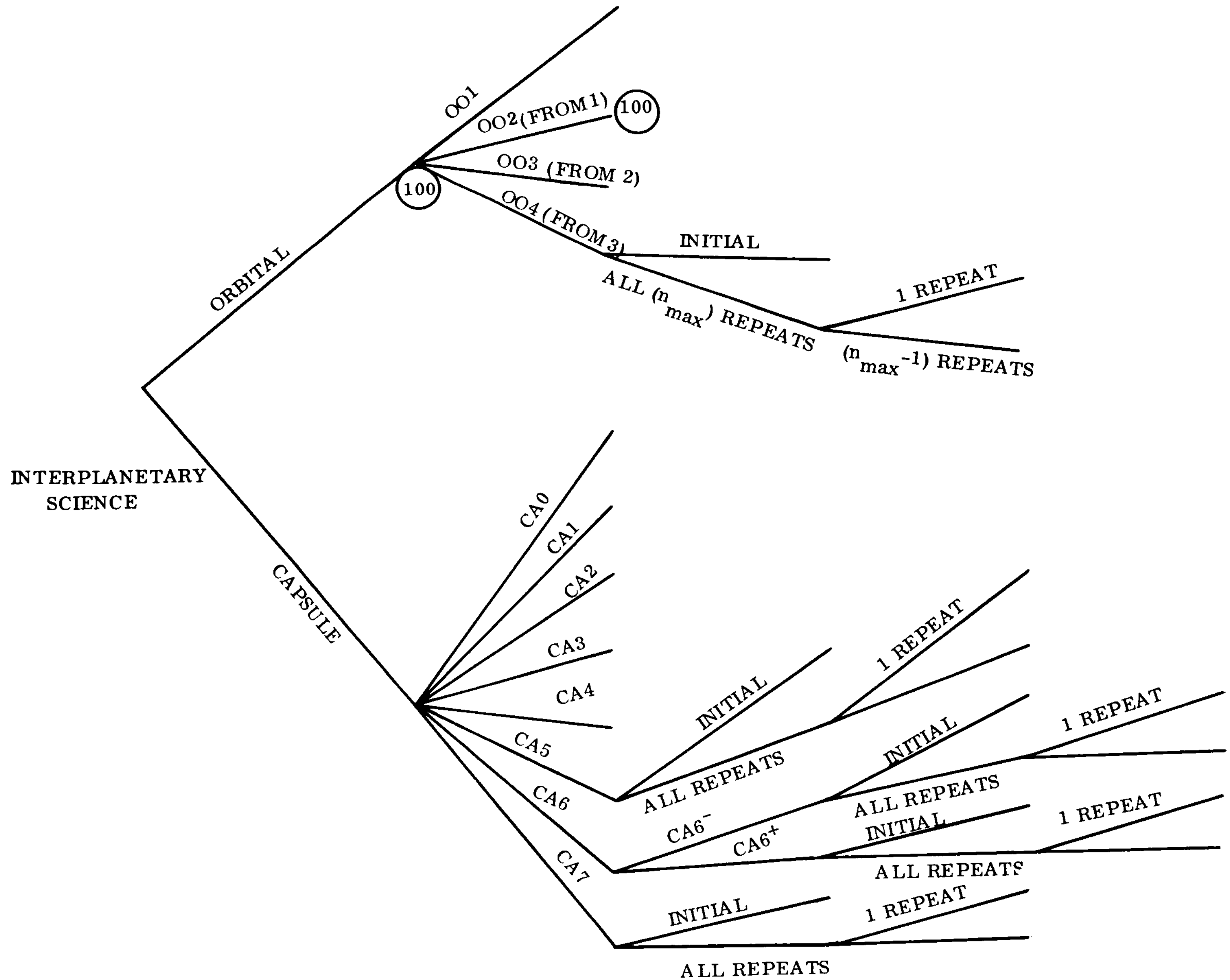


Figure 4-42. Tip Structure for Interplanetary Science Category

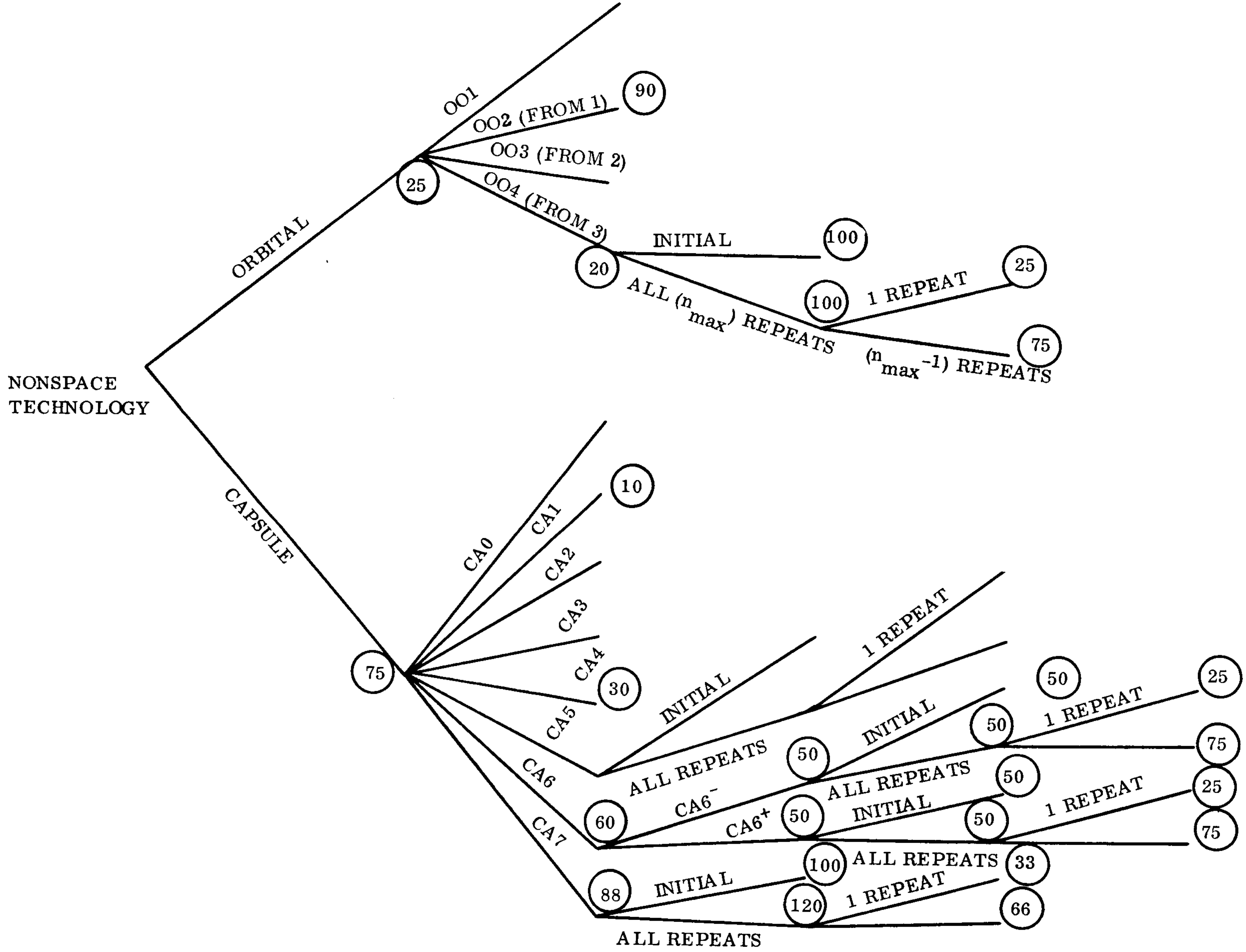


Figure 4-43. Tip Structure for Nonspace Technology Category

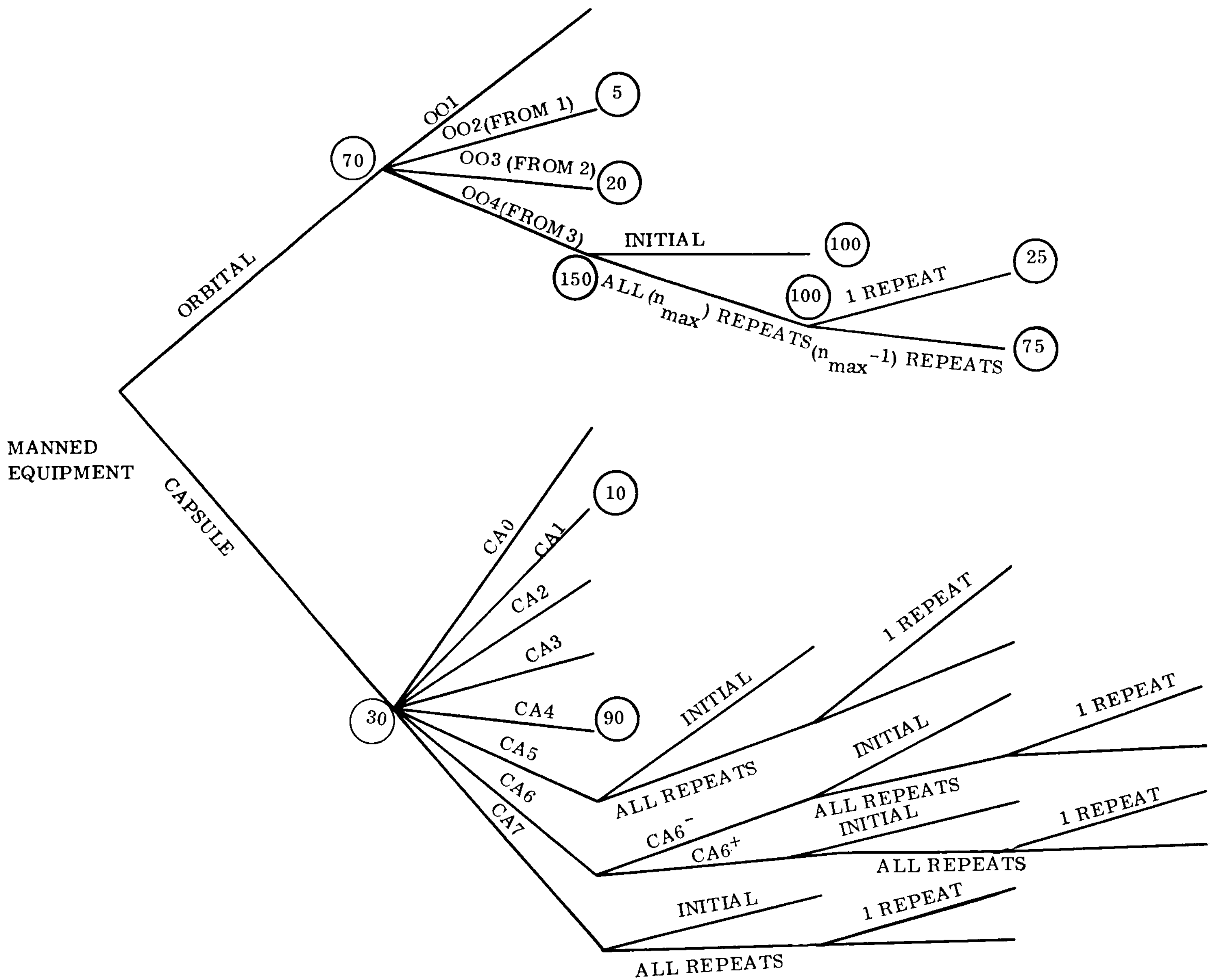


Figure 4-44. Tip Structure for Manned Equipment Category

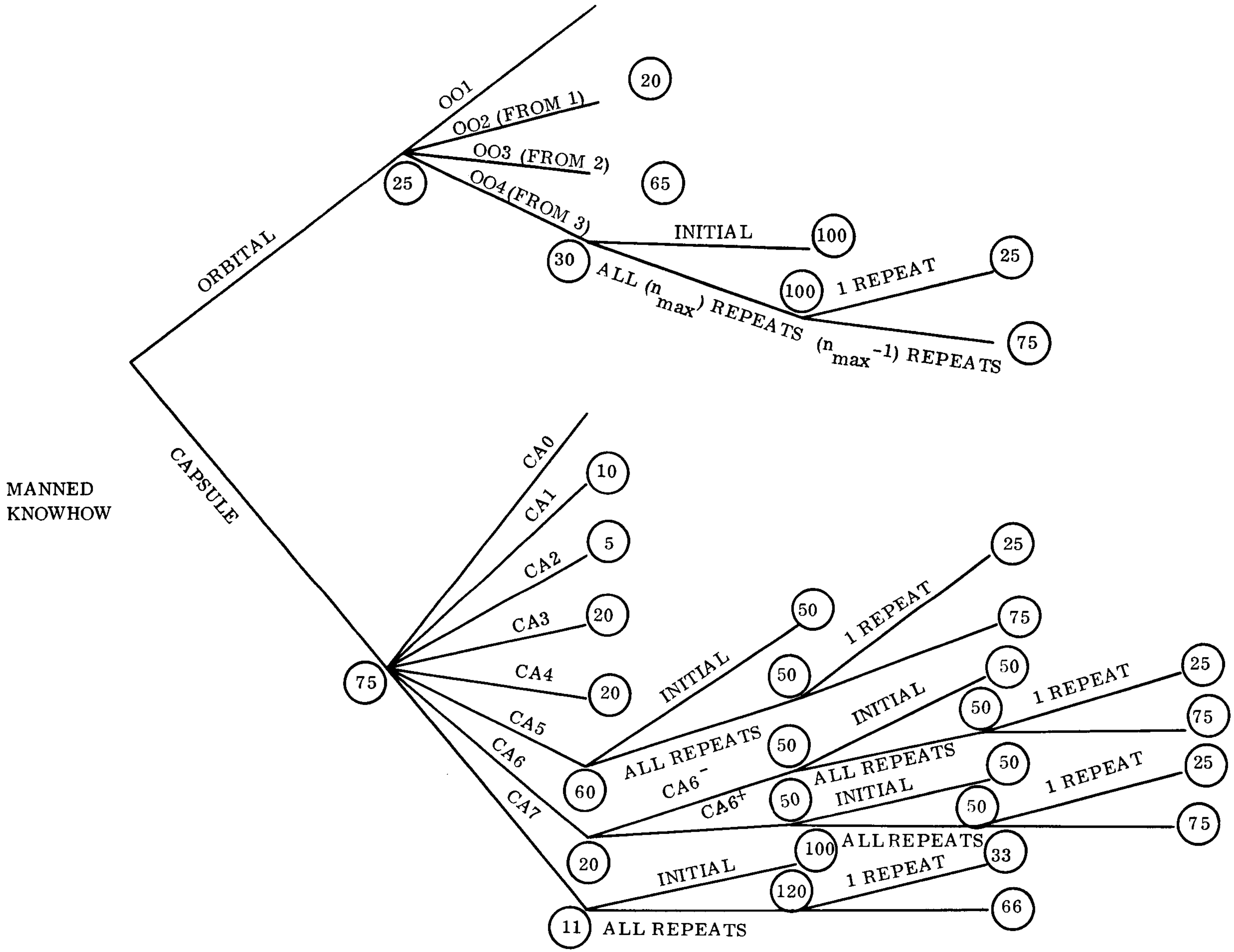


Figure 4-45. Tip Structure for Manned Knowhow Category

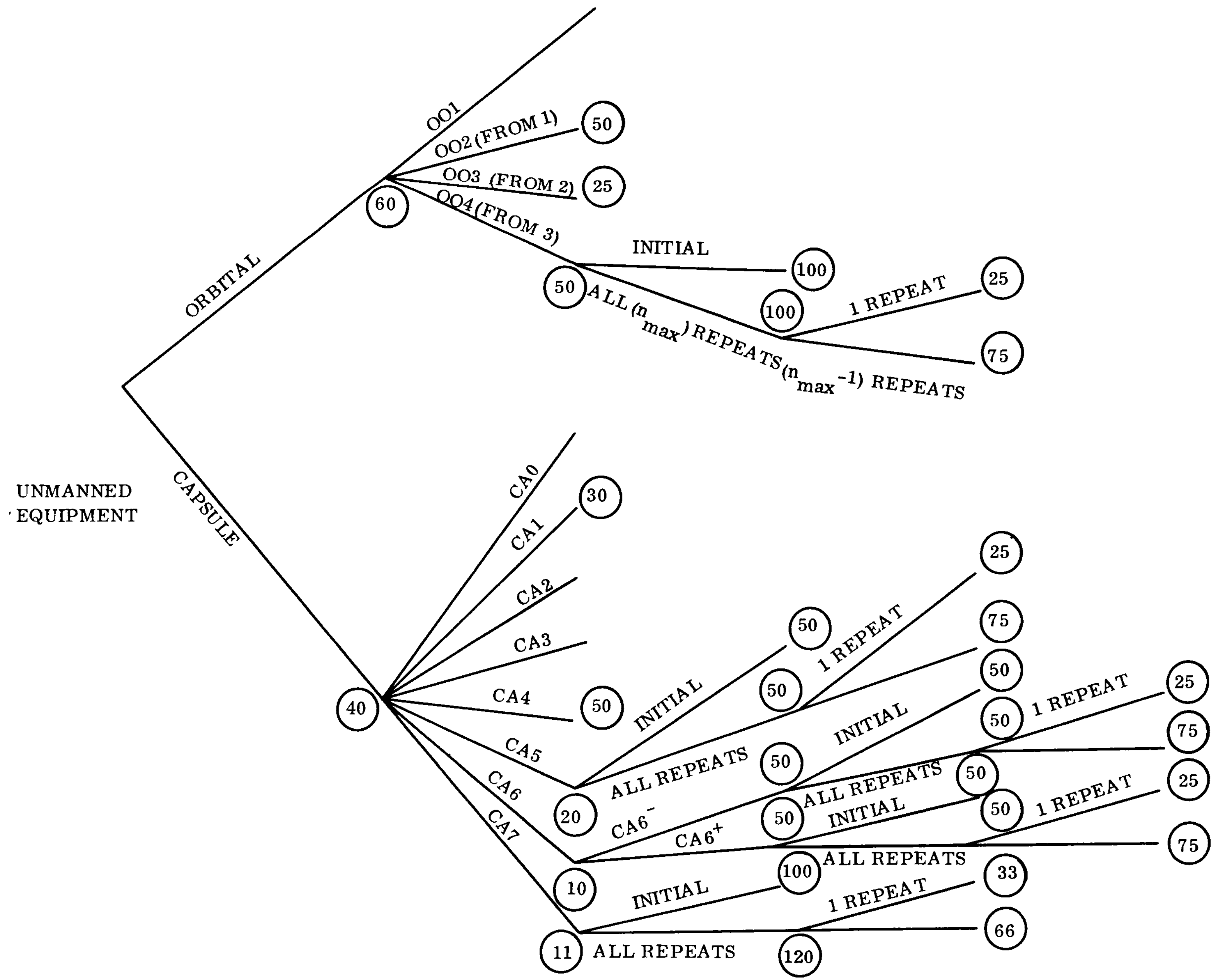


Figure 4-46. Tip Structure for Unmanned Equipment Category

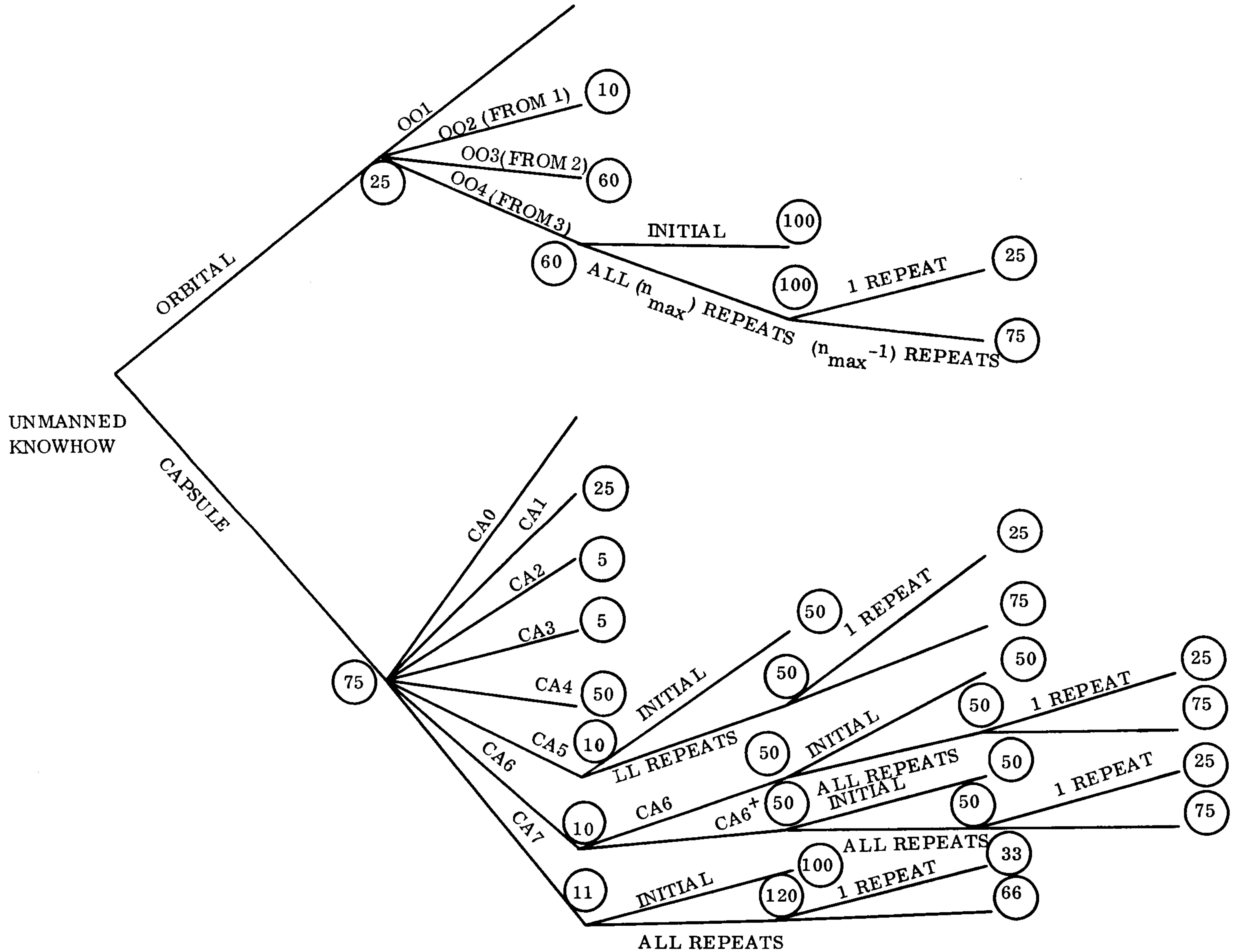


Figure 4-47. Tip Structure for Unmanned Knowhow Category

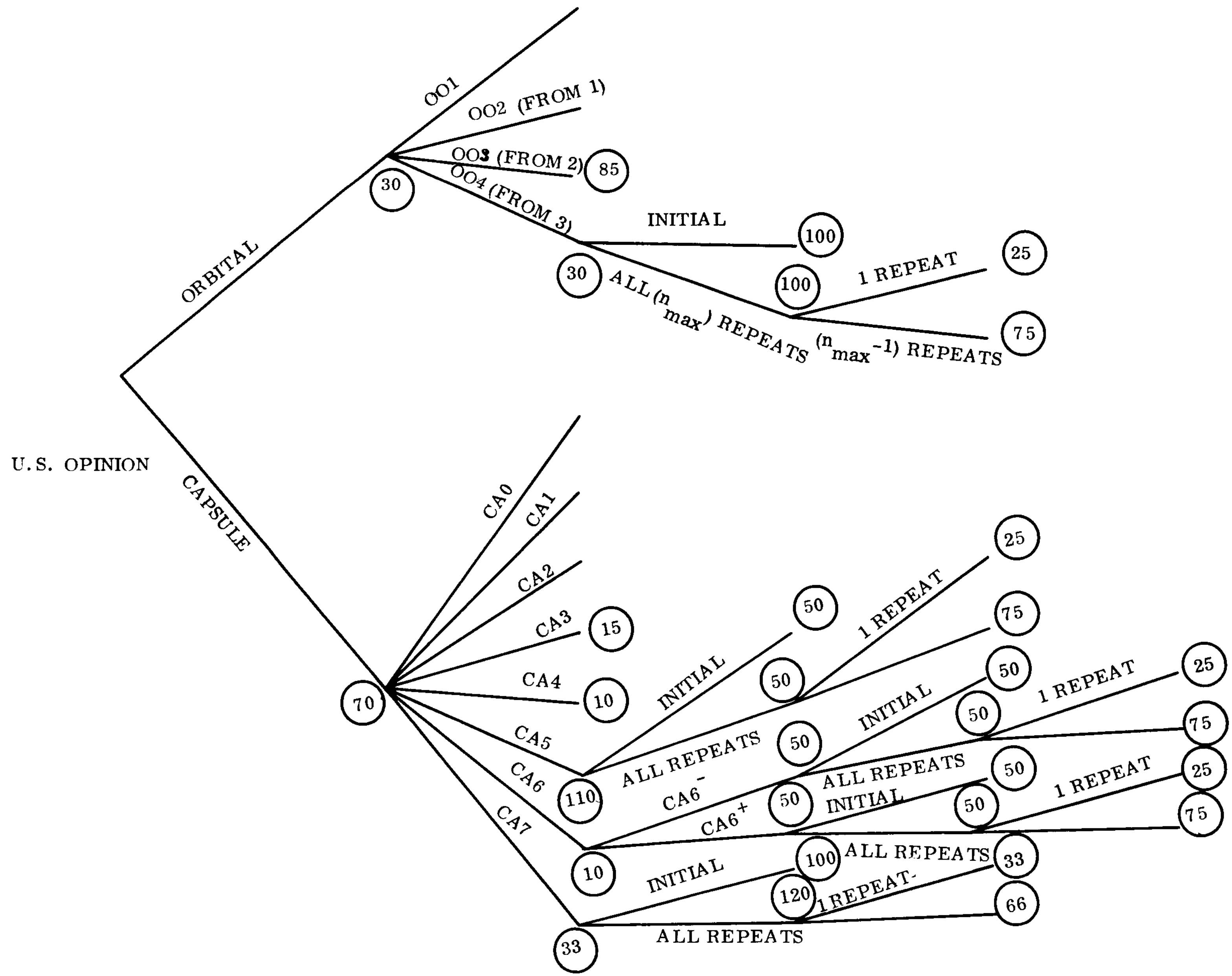


Figure 4-48. Tip Structure for U.S. Opinion Category

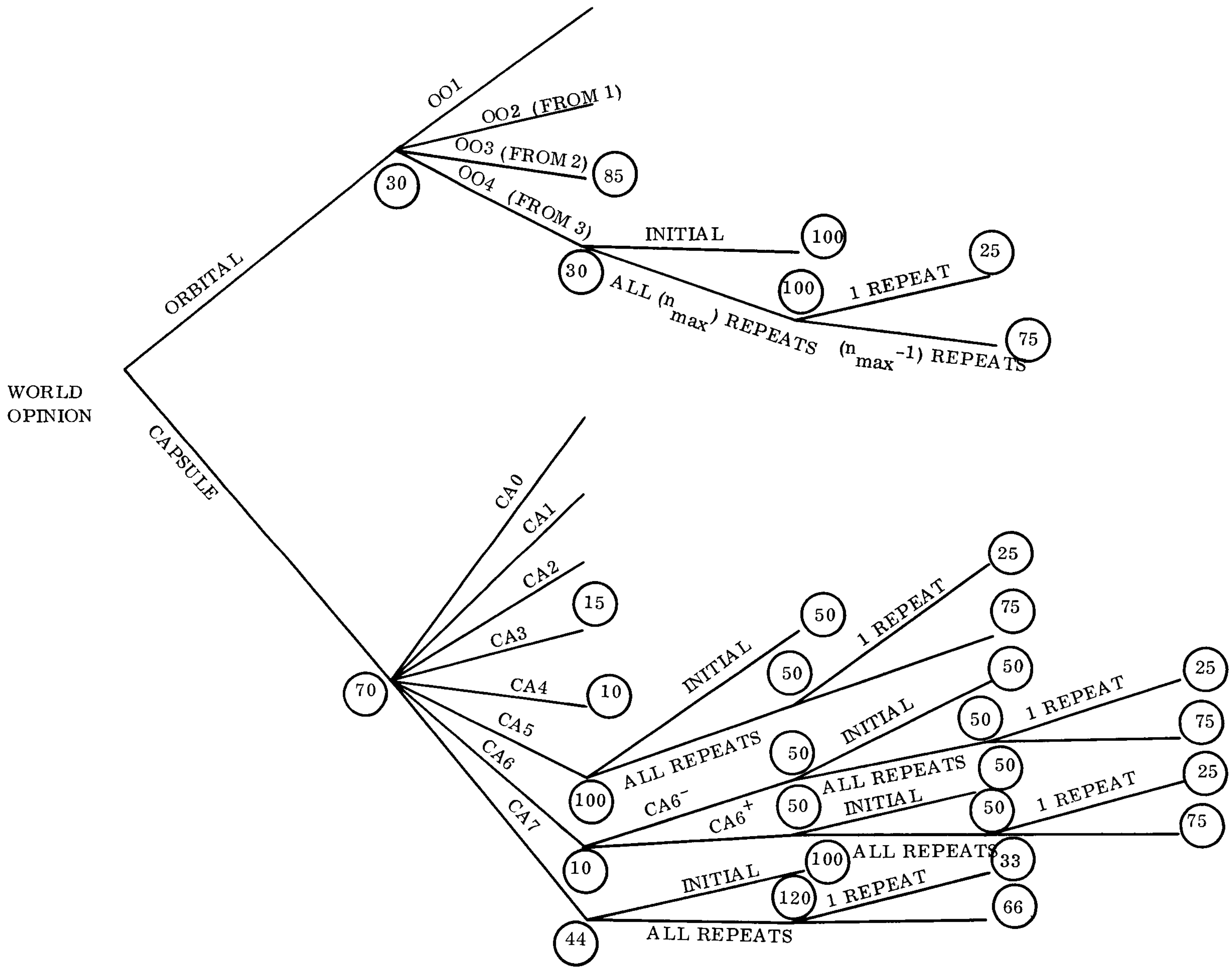


Figure 4-49. Tip Structure for World Opinion Category

4.11.1 INTRODUCTION

SPAN is a system of computer programs designed to operate in a General Electric 635 computer and written in the Fortran IV language. Its objectives are to accept information descriptive of the decision model in quasi-English format on punched cards, to produce the model so described, to analyze the model according to predetermined methods, and to yield the results of these analyses in hard copy form.

There are four distinct phases to SPAN operation, as depicted in Figure 4-50. These are:

Phase I:	Decision Model Structure Data Input and Conversion
Phase II:	Decision Model Parametric Data Input and Conversion
Phase III:	Decision Model Generation
Phase IV:	Decision Model Analyses and Output.

4.11.2 SPAN SYSTEM SUMMARY DESCRIPTION

Control of overall SPAN system operation is governed by a single control program resident in the computer memory (see Figure 4-50). This program accepts user control specifications in punched card form to guide it in accomplishing the desired tasks. Among these specifications is the ability to command complete or partial system operation, according to the user's requirements. In the former case, phases one through four are applied in order, and the system operates from start to finish for the user. In the latter case, system operation may be initiated and terminated at any phase, with means for coupling this incomplete operation with prior or subsequent runs.

Phase I (Figure 4-52) produces the decision tree structure in tabular form from user specifications. This structure serves as the basis for all subsequent modeling activity.

Phase II (Figure 4-52) accepts further information from the user and complements the decision model structure of Phase I with parameters of cost, value and probability.

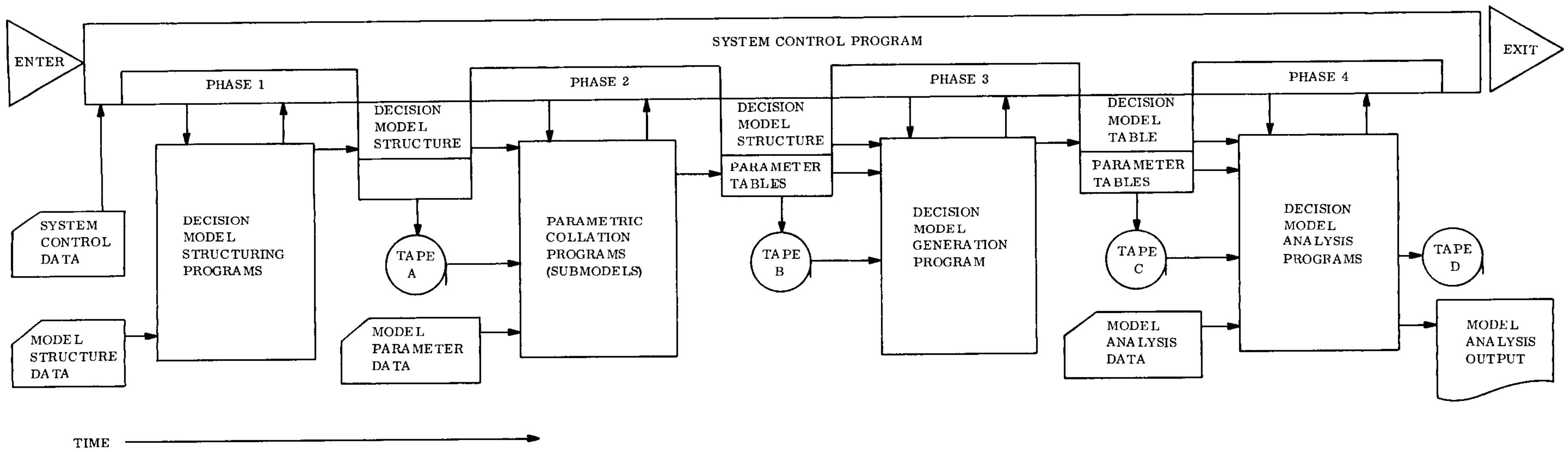


Figure 4-50. SPAN System Operation

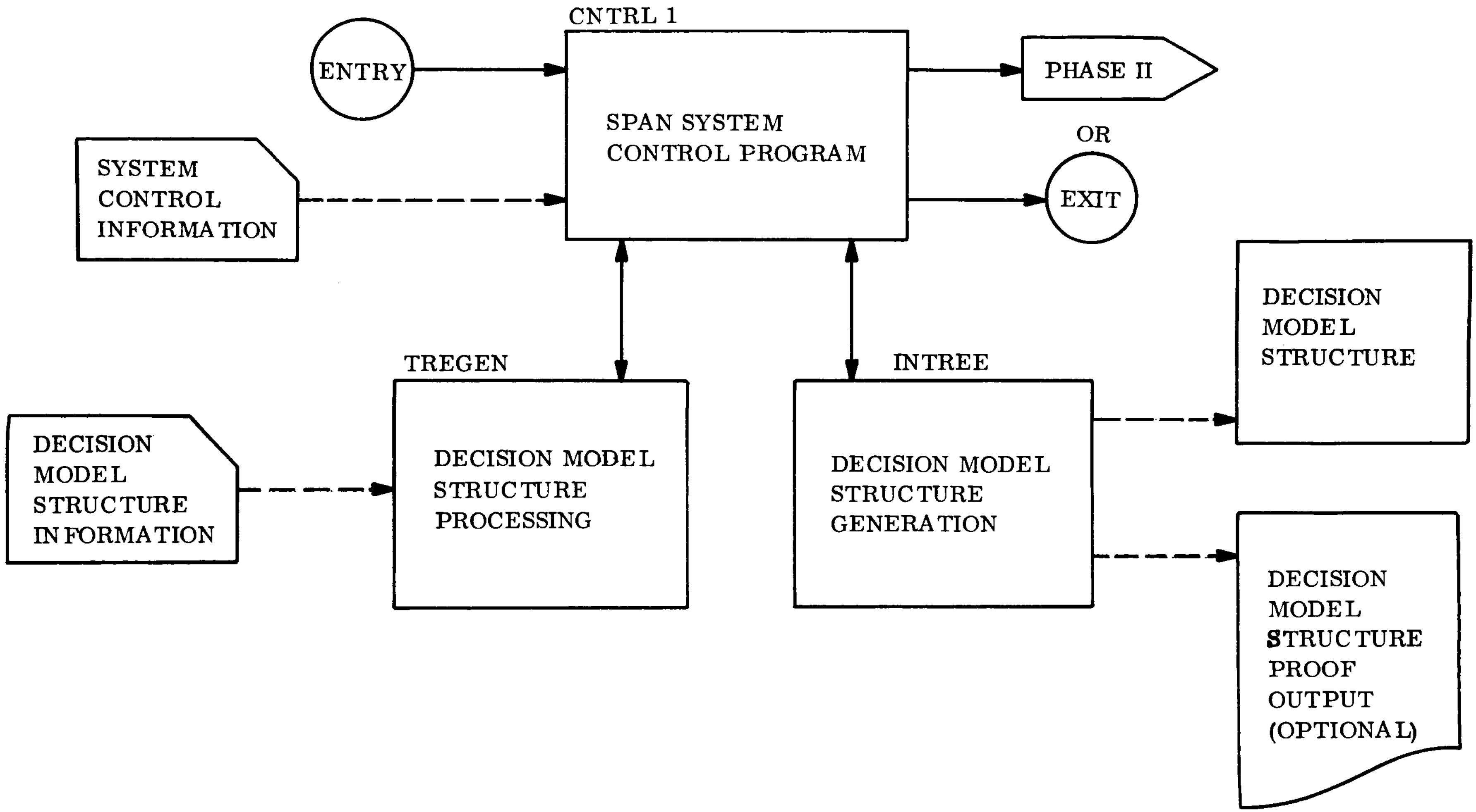


Figure 4-51. SPAN System Phase I Operation

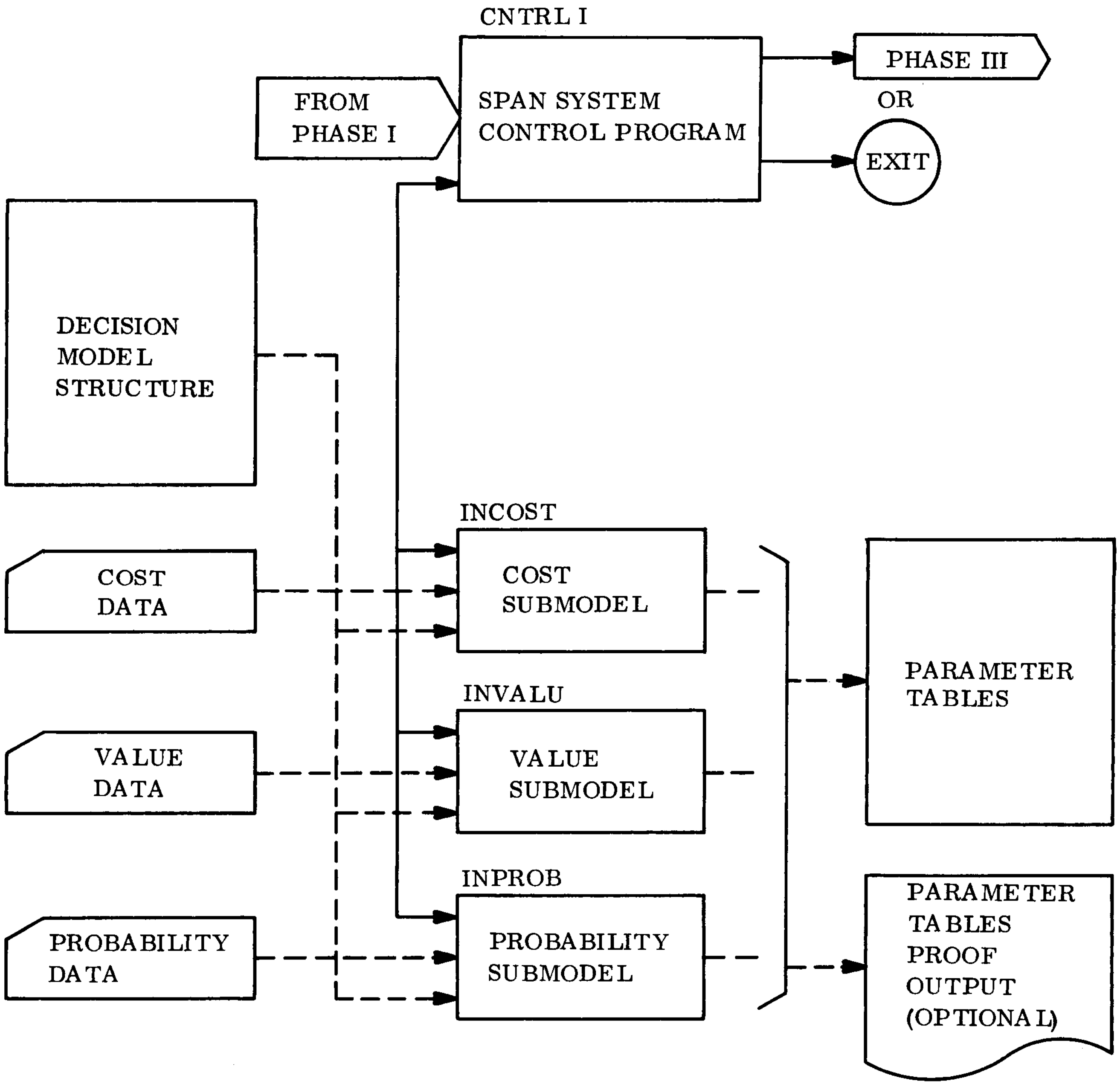


Figure 4-52. SPAN System Phase II Operation

Phase III (Figure 4-53) generates the full decision model by merging the model structure created in Phase I and the parametric information from Phase II.

In Phase IV (Figure 4-54), the user designates the analyses to be performed on the decision model generated in Phase III. The analyses are performed, and the results are produced in hard copy form.

Conclusion of SPAN operation provides the user with a magnetic tape upon which the decision model undergoing analysis is recorded for possible subsequent use.

4.11.3 DATA STRUCTURE FOR DECISION MODELING AND ANALYSIS

The decision tree concept discussed in Sections 4.5 and 4.7 is automated by the SPAN system. The completed decision model is represented in tabular form, with each entry corresponding to one of three node types: decision node, chance node or terminal node.

Creation of the decision model table commences in Phase I where the nodal structure of the tree is generated from input specifications. Each table entry at this point describes the type of node (decision, chance, terminal), its identification or name, and subentries identifying which other nodes structurally succeed it. In Phases II and III, parametric information on cost, value, and probability is correlated with the links (or branches) between the node (as represented by the entry) and each of its successor nodes (as represented by subentries).

Generation of parameters occurs during Phase II operations by operating on cost, value and probability input data. The decision model structure created during Phase I is referenced to generate separate parameter tables for cost, value, and probability, and only those parameters which are required by the decision tree are generated. In Phase III, the decision model table is completed by linking entries (nodes) to their subentries (successor nodes) by costs, values, and probabilities from the parameter table.

Figure 4-55, illustrates the correlation between the graphic and tabular representation of a node in the decision model structure.

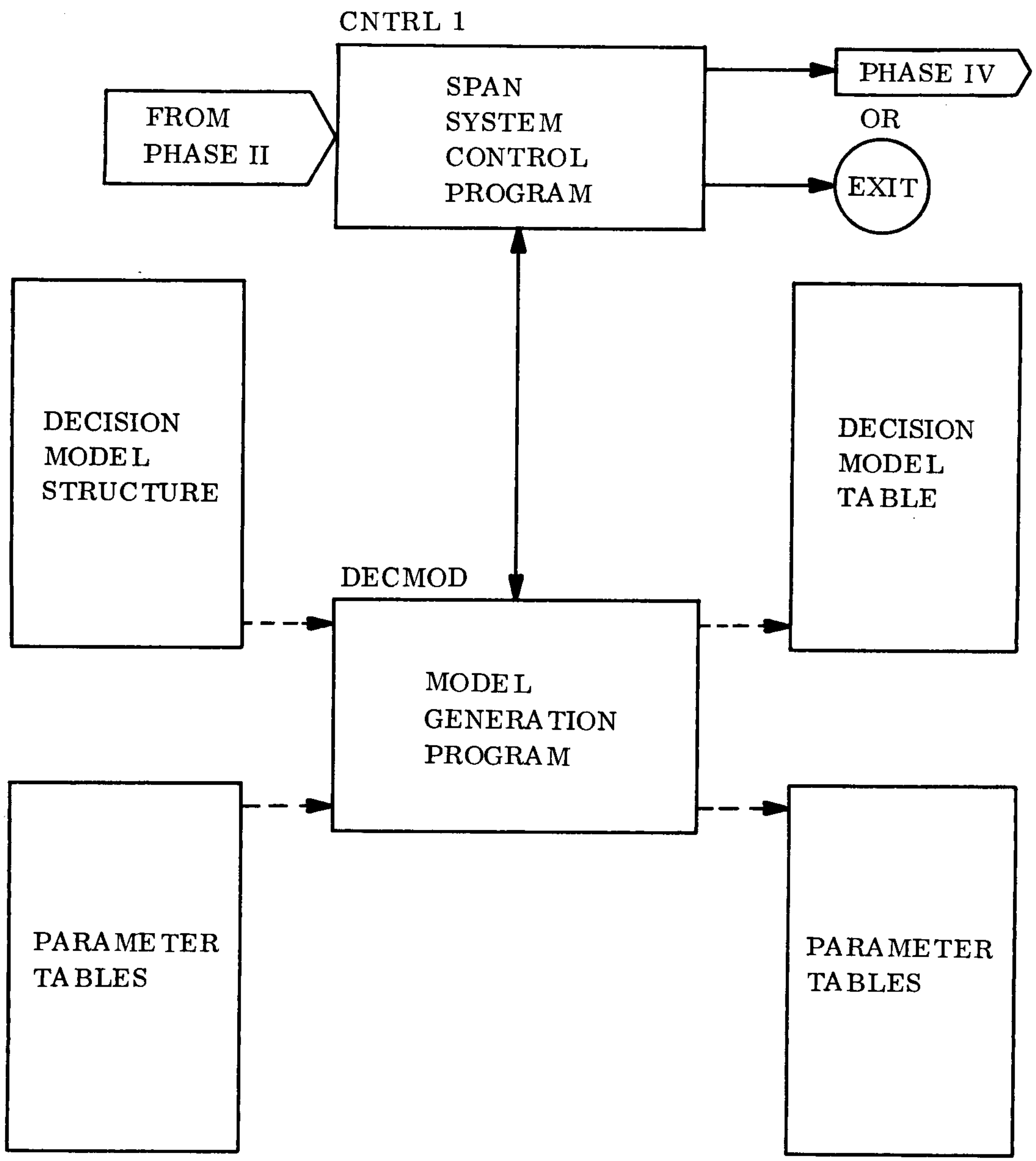


Figure 4-53. SPAN System Phase III Operation

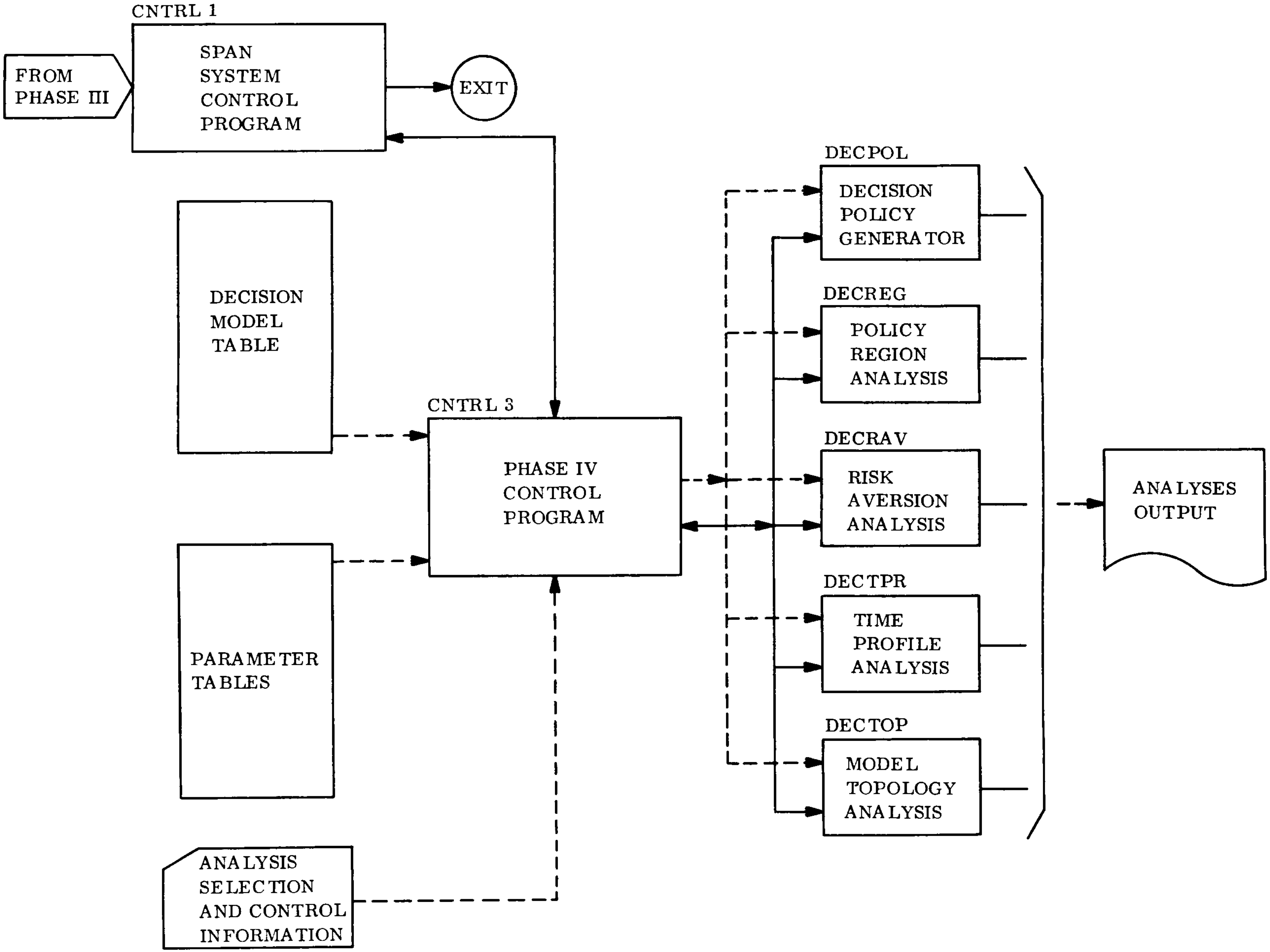


Figure 4-54. SPAN System Phase IV Operation

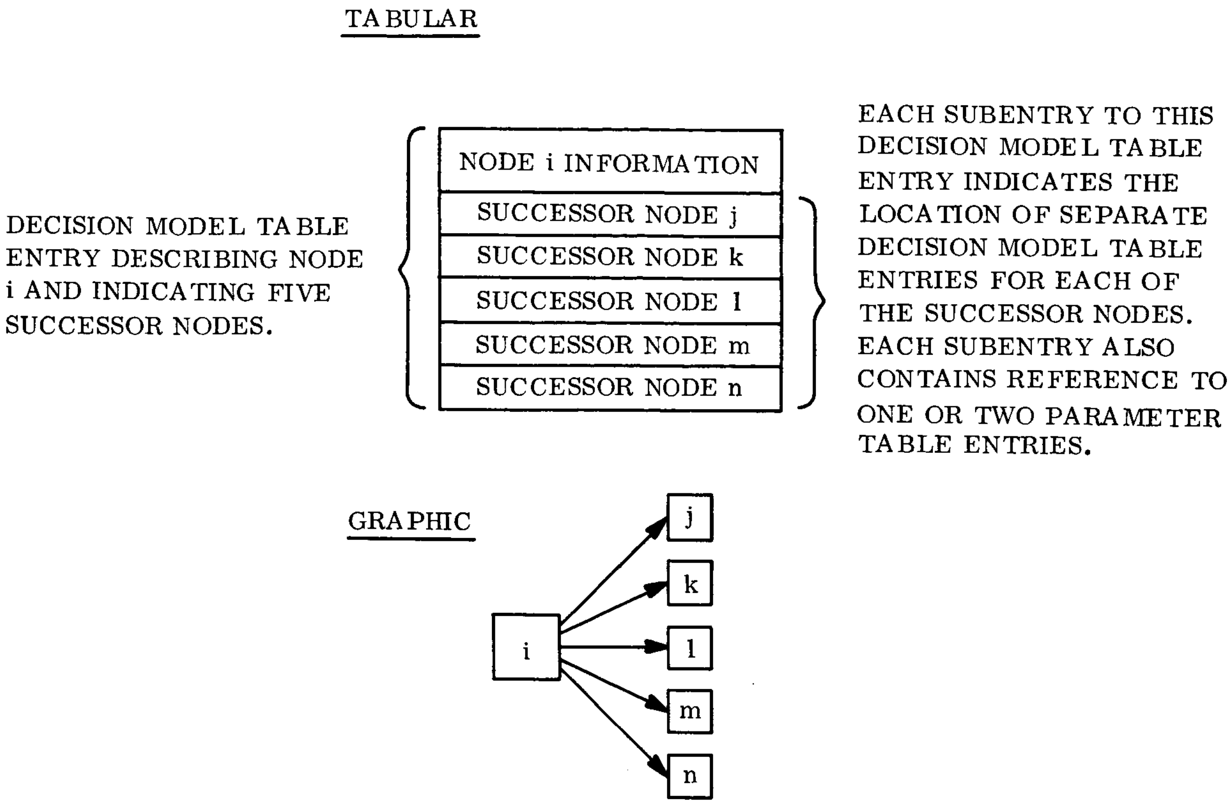


Figure 4-55. Correlation Between Graphic and Tabular Nodal Representations

Each node in the decision model table has a name, and these node names are carried in another SPAN system table (the name table). Each decision model table entry references the name table entry where the name is stored. In like fashion, the names of each cost, value, and probability amount in the parameter tables are also stored in a name table. Access tc these names is required by some Phase IV analysis routines where the nodes need to be cited in a manner recognizable to the user.

4.11.4 SPAN SYSTEM CONTROL (CNTRL1)

Upon initiation of SPAN system operation, program CNTRL1 gains immediate control and, guided by user specifications on punched cards, governs the following tasks:

a. Selection of the initial phase of operation. CNTRL1 yields control to the initial phase of operation specified or to the next phase as control is passed from one phase to the next.

b. Arranging for information on magnetic tape to be loaded into the computer when system operation begins at other than Phase I.

c. Arranging for information to be recorded on magnetic tape (for subsequent use) when system operation concludes at other than Phase IV.

d. Arranging for optional printing of intermediate results as specified.

e. Regaining control from the concluded operation of Phases, I, II, III, or IV.

4.11.5 PHASE I: MODEL STRUCTURING

4.11.5.1 TREGEN

When entered from CNTRL1, TREGEN accepts information from the user describing the decision tree, as explained in Section 4.7. This information is printed for proofing purposes and then converted into contextual identifiers which are grouped by node. Thus, each group contains the name identifying the node to which the group relates, as many names as are needed to identify all successors to this node, and the names of the (yet to be computed) costs, values, and probabilities leading to the successor nodes.

When this naming and grouping has been completed, TREGEN records its output on magnetic tape for subsequent reference by the INTREE program and yields control to CNTRL1.

4.11.5.2 INTREE

INTREE, upon gaining control from CNTRL1, converts the data produced by TREGEN into a preliminary version of the decision model table discussed in Section 4.11.3. Entries to the decision model table are created from each TREGEN nodal group and are cross referenced to other decision model table entries corresponding to the successor nodes to the main node of the group. INTREE thus establishes each node and parameter name as an entry in a separate name table and stores a cross reference index to the name table in lieu of the name itself.

At the conclusion of INTREE operation, every node cited in the TREGEN output accounts for one entry in a preliminary decision model table and one entry in the name table. Similarly each cost, value, and probability parameter accounts for one entry in the name table. INTREE then yields control back to CNTRL1.

4.11.6 PHASE II: PARAMETRIC COLLATION

4.11.6.1 INCOST

INCOST is entered from CNTRL1 if specified by the user during Phase II operation. Using nominal cost data and cost modifiers (see Section 4.9), INCOST calculates the mission configuration costs for branches emanating from decision nodes and for terminal nodes, as listed in the decision model table. The final output of INCOST is a cost parameter table which contains only those branch cost required by the decision model structure. INCOST establishes the linkage between each decision model table entry and its cost parameter by referencing the entry in the parameter name table to the location of the actual dollar cost in the parameter table. Control reverts to CNTRL1 at the conclusion of INCOST operation.

4.11.6.2 INVALU

As with INCOST, INVALU is entered from CNTRL1 if instructed by the user during Phase II operation. INVALU accepts as input the value tree structure and actual branch values, as discussed in Section 4.10, and calculates the values associated with chance and terminal nodes listed in the decision model table. Final output from INVALU are normalized point values in the parameter table. At the conclusion of INVALU, control is again returned to CNTRL1.

4.11.6.3 INPROB

INPROB is also entered from CNTRL1 if called upon by the user to produce the probabilities required by the chance nodes of the decision model table and store them in the parameter table. As explained in Section 4.8, inputs to INPROB include a transition diagram, the environmental and hardware probabilities of Table 4-6, and the configuration switch settings of Table 4-7. When concluded, INPROB yields control to CNTRL1.

4.11.7 PHASE III: DECISION MODEL GENERATION (DECMOD)

DECMOD completes the decision model table. When entered from CNTRL1 to initiate Phase III operation, DECMOD changes the references from the decision model table to the parameter table to direct linkages, rather than indirect via the name table. The decision model table and parameter table thus represent the complete decision model. The name table is, however, retained for use in subsequent Phase IV operation. Upon completion of Phase III, control reverts again to CNTRL1.

4.11.8 PHASE IV: DECISION MODEL ANALYSIS

4.11.8.1 <u>CNTRL3</u>

When Phase IV is called for by the user, CNTRL1 relinquishes control to the Phase IV control program, CNTRL3. CNTRL3 examines user specifications identifying the particular analyses to be performed, calls the appropriate analysis programs, and controls each until analysis is completed. The programs that may be called are:

DECPOL - Decision Policy Generation
DECREG - Decision Policy Region Analysis
DECRAV - Decision Policy Risk Aversion Analysis
DECTPR - Decision Policy Time Profile Analysis
DECTOP - Decision Model Topological Analysis
DECSAV - Saves the Decision Model on Tape
DECRES - Restores the Decision Model from Tape

These programs are described in the following sections. Upon processing the last analysis program request, CNTRL3 returns control to CNTRL1, which then concludes SPAN system operation.

4.11.8.2 <u>DECPOL</u>

The heart of the Phase IV analysis routines, DECPOL is entered from CNTRL3 when specified by the user. Upon gaining control, DECPOL examines the specified operating parameters and then proceeds into its analytical operations.

The input to DECPOL is the decision model generated as output from Phase III. DECPOL analyzes the tree by the roll-back technique explained in Section 4. 5. 5 and determines the optimum policy for the tree and parameters in hand. After this policy has been determined, DECPOL prints out all of the nodes or just selected nodes in the decision tree along with the expected cost, expected value, and net expected value of each.

One variable which plays a key role in the computations for policy determination is the conversion factor λ (see Section 4. 5. 10), i. e., the dollar value assignment to the entire project. Variation of λ affects the policy and expected value determined by DECPOL. DECPOL also provides the option to discount cost or value as a function of time.

The DECPOL output may take several forms at the option of the user. One option allows the printing of all nodes, all reachable nodes, or all reachable decision nodes.

The user may also impress constraints upon the selection of decision node successors by imposing a fixed policy on selected portions of the decision model. The resultant policy will not necessarily be optimum, but does permit the analyst to compare selected policies. A fixed policy output can also be produced by the DECPOL analysis upon request. This output can subsequently be used in whole or in part as fixed policy input by the user.

Decision policy analysis is required by other Phase IV analysis programs and in this context, DECPOL is considered a subroutine to these programs. Upon conclusion of policy analysis, DECPOL returns control to CNTRL3, if it was called upon for an individual operation, or to that Phase IV program which called it into use as a subroutine.

4.11.8.3 DECREG

DECREG is essentially the full-scale implementation of the policy region search discussed in Section 4.5.10. It operates when called for by CNTRL3. Basically, it plots the net expected value (NEV) of the origin node of the decision tree as a function of a selected set of point values, λ_i. The subroutine is given an upper and lower limit for the range of λ to be explored. A typical DECREG output is illustrated in graphical form in Figure 4-56. From the curve of Figure 4-56, a dominant policy cost-benefit curve like that of Figure 4-19 may be constructed.

In its operation, DECREG calls upon DECPOL for repeated operations as a subroutine. By a search algorithm, the break points (λ_i) in the DECREG curve are determined. At each of these break points, DECPOL prints out the policy, i.e., the net expected value, expected value, expected cost, and selected nodal information. The DECREG printout thus consists of several DECPOL printouts ordered on λ_i. This listing can be reordered on expected cost to produce a listing of dominant policies as a function of expected cost (i.e., like Figure 4-19).

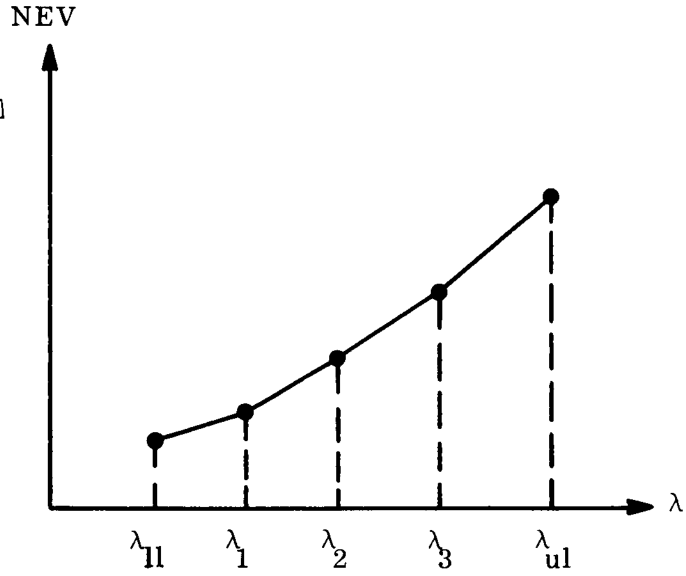


Figure 4-56. The DECREG Output

4.11.8.4 DECRAV

DECRAV is entered from CNTRL3 when called for by the user. DECRAV is similar to DECPOL in its methodology, but evaluates the decision model for the optimum policy as a function of the risk aversion characteristics of the decision maker, rather than on expected value. A primary input variable to DECRAV is the risk aversion coefficient. Varying this coefficient permits evaluation of policy sensitivity to risk aversion. Output from DECRAV is accomplished through DECPOL as a subroutine. Upon conclusion of risk aversion analyses by DECRAV, control is returned to CNTRL3.

4.11.8.5 DECTPR

DECTPR is also accessed by CNTRL3. DECTPR operates on a prior policy generated by DECPOL and evaluates it for time profile information. Specifically, DECTPR plots expected value, expected cost, and net expected value as a function of elapsed project time, and also provides probability distributions on any of these variables at any point in the project. Output from DECTPR is in the form of cumulative and incremental cost and value profiles. Upon the conclusion of DECTPR, control is returned to CNTRL3.

4.11.8.6 DECTOP

DECTOP performs a topological analysis of the decision model. When called for by CNTRL3, it provides summary information on the topology of the decision tree, such as the number of nodes of each type, the number of possible policies, etc. Control is returned to CNTRL3 at the conclusion of DECTOP operation.

4.11.8.7 DECSAV

When entered from CNTRL3, DECSAV places the tabular decision model onto magnetic tape, and then returns control to CNTRL3. This can be subsequently used to re-establish the decision model in the computer through DECRES.

4.11.8.8 DECRES

DECRES complements the DECSAV program. Entered from CNTRL3 upon user request, DECRES restores from magnetic tape all decision model information placed there by DECSAV. Once this operation is complete, CNTRL3 regains control.

4.11.9 UTILITY ROUTINES

The SPAN system contains eight subroutines which provide utility functions to more than one program. These are:

4.11.9.1 STGEN

STGEN is the symbol table generation subroutine. Given a node or parameter name, it creates an entry in the corresponding name table and returns control with the appropriate name table index as the return argument.

4.11.9.2 STTLU

The symbol table look-up subroutine, STTLU, given a node name, yields as an output argument the reference to the corresponding decision model table entry.

4.11.9.3 ENCODE

ENCODE is the name encoding subroutine. It converts any specified name into the binary identifier used within the computer, yielding this as its return argument.

4.11.9.4 DECODE

DECODE, the name decoding subroutine, converts any binary identifier to an alphabetic or numeric (symbolic) name yielded as a return argument.

4.11.9.5 NODADR

The node addressing subroutine, NODADR, yields decision model table entry locations in a predetermined sequence for evaluation.

4.11.9.6 RDTAPE

This subroutine loads into computer memory decision model information previously stored on magnetic tape.

4.11.9.7 WRTAPE

This subroutine places decision model information onto magnetic tape for subsequent use by the SPAN system.

4.11.9.8 DECPRF

This subroutine yields a proof listing of the decision model table.

4.12 RESULTS

The principle objective of this effort was to develop a useful technique for the selection of Voyager mission configurations and sequences. Following the pilot phase (Section 4.5), a more full-scale modeling effort was undertaken, the results of which are described in Sections 4.6 through 4.10. The full-scale model was then embodied in a set of computer programs called the SPAN system (Section 4.11). Discussed in this section are the results of a few, initial exercises of the SPAN system. Review of these results has not only provided insight into the operationof the model and some of the dominant factors in configuration selection, but has emphasized the need for further exhaustive exercise of the models to recommend a project strategy with confidence. In this sense, the results presented here are meant to be illustrative, rather than comprehensive and conclusive.

To assist in the interpretation of the results, a reference glossary of configuration and outcome codes is listed on the following page.

4.12.1 SUBMODEL RESULTS

The basic philosophy and structure of the probability, cost, and value submodels is discussed in Sections 4.8, 4.9, and 4.10, respectively. Nominal sets of input data for each of the submodels were compiled from several sources. The outputs of the three submodels comprise the costs, values, and probabilities required as basic input by the decision tree. Thus, the submodel inputs, as transformed by the submodel structures, produce the decision tree input.

This subsection describes submodel output as a function of input. For each submodel, the output resulting from the nominal set of input data is illustrated. The input data is also varied to observe the sensitivity of submodel output (i.e., decision model input) to submodel input.

4.12.1.1 The Value Model

4.12.1.1.1 Nominal Data

Figure 4-57 is an actual computer printout sheet that summarizes the value submodel input for the nominal set of input data. The value tree drawn by the computer to display the input

Glossary of Configuration and Outcome Codes

Configurations

1	VSTOP	Discontinue the project
2	VSKIP	Skip the next opportunity
3	VMAR	Mariner '71
4	VSIB	Single Voyager orbiter with single SIB
5	V2SIB	Two Voyager Orbiters with two SIB's
6	VORB	Two Voyager orbiters with single SV
7*	VOATM	Nonsurvivable atmospheric probe
8*	VODTV	Nonsurvivable descent TV probe
9*	VOLTV	Survivable landed television capsule
10*	VOTVSF	Survivable capsule with TV and physical experiment
11*	VOVBL	Survivable capsule with TV and biological experiment
12**	VODATM	Orbital and direct entry atmospheric probes
13**	VODDTV	Orbital entry descent TV and direct entry atmospheric probes
14**	VODLTV	Orbital entry landed television capsule and direct entry atmospheric probe

*Single SV with two planetary vehicles and one capsule per PV
**Single SV with two planetary vehicles and two capsules per PV

Orbiter Outcomes

1	OOZERO	Fly-by
2	OONORB	Failure to achieve orbit
3	OOORB	Short-term orbital operation
4	OOLORB	Long-term orbital operation

Capsule Outcomes

1	COZERO	No attempt at entry
2	CONORN	Failure at entry
3	COATM	Atmospheric data (nonsurvivable probe)
4	COATMS	Atmospheric data (survivable lander)
5	CODTV	Descent television (nonsurvivable probe)
6	CODTVS	Descent television (survivable lander)
7	COLAND	Soft landing
8	COLTV	Landed television
9	COSURF	Surface physical experiments
10	COBIOL	Surface biological experiments
11	COTVSF	Surface television and physical experiments
12	COBITV	Surface television and biological experiments
13	COBISF	Surface biological and physical experiments
14	COALEX	All surface experiments

data is identical to that of Figure 4-37, except that all values are normalized to a maximum value of 1.000. The number attached to each branch is the relative importance (normalized to a maximum of 1.000) of the subcategory represented by that branch in the category represented by the node from which it emanates. The decimal fractions attached to each node represent the value of the category represented by that node, normalized so that the value of the initial node of the tree (i.e., the total value of the project) is 1.000.

For the nominal input data displayed on the value tree, Figure 4-58 illustrates the output of the value model, viz., the value (out of a maximum of 1.000) attached to each orbital outcome and capsule achievement. These results were obtained by attaching the tip structures of Figures 4-39 through 4-49 to the value tree and summing like tip categories to arrive at the contributions of each orbital outcome or capsule achievement. Note that 63.8 percent of the value is attached to initial achievements, with the remainder allocated to repetitions. Also, approximately 70 percent of the value is placed on capsule performance, and 30 percent on the performance of the orbiting spacecraft. The most valuable capsule achievements are landed television (CA5 at 8.3 percent initially) and the life detection experiments (CA7 at 12.1 percent initially). Initial short-term operation of the spacecraft in orbit about the planet (OOORB) is also valued highly at 10.9 percent.

4.12.1.1.2 Sensitivity of Value Model Output to Input

Figures 4-59 through 4-62 illustrate the implications on decision tree value input (value submodel output) of two extreme value functions.

In the value tree of Figure 4-59, all value has been placed on the manned equipment subcategory of space technology. Figure 4-60 demonstrates the effect of such an evaluation on the relative importance of the various orbital outcomes and capsule achievements. Note that the highly valued accomplishments are orbit achievement and short-term orbital operation, descent television, soft landing, and landed television. Life detection contributes insignificantly to the total value when all of the value emphasis is placed on Voyager as medium for the development of equipment for manned exploration of Mars.

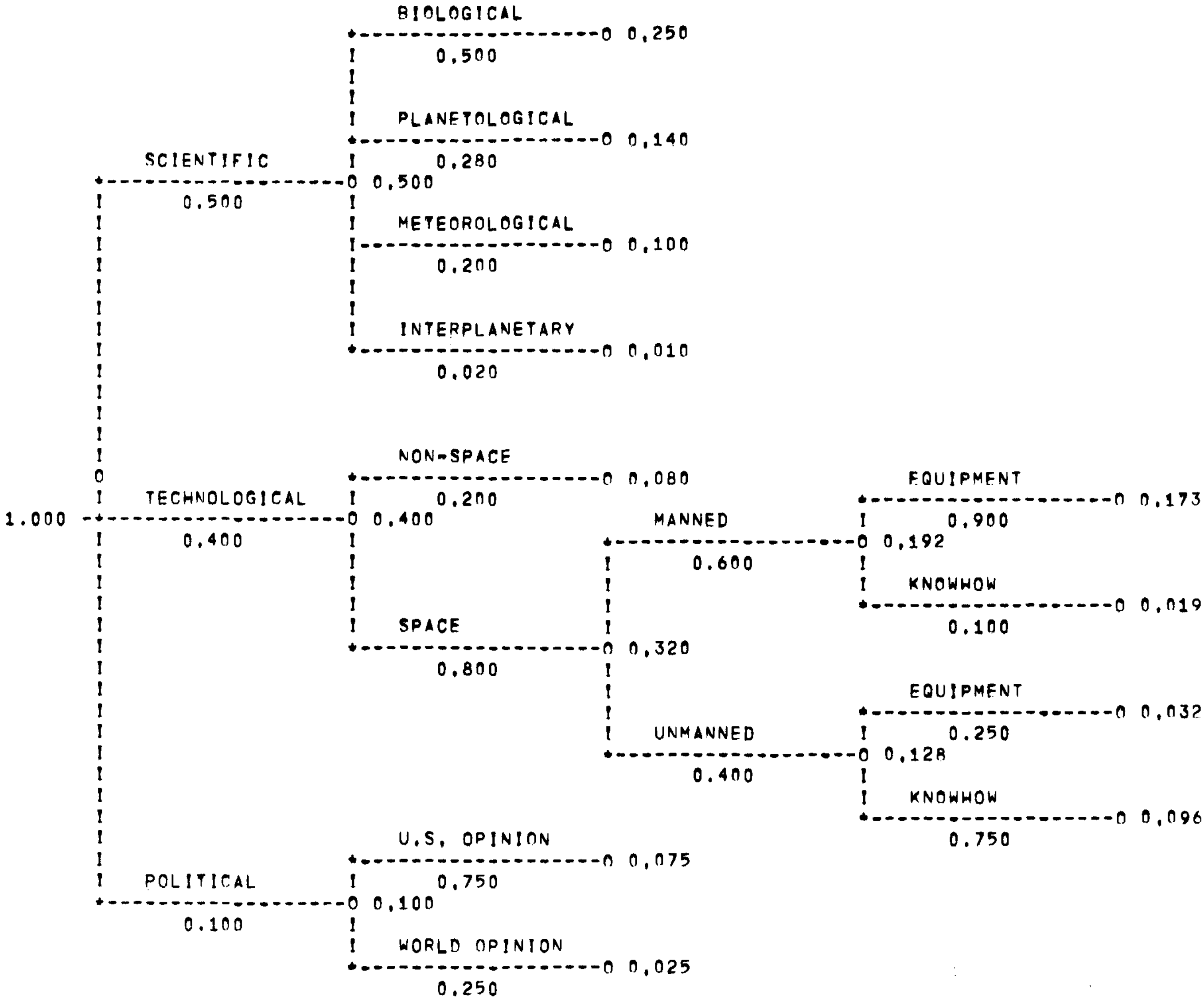


Figure 4-57. Value Model Nominal Input Data

ACHIEVEMENT VALUE SUMMARY

ACH.	FIRST TIME	ONE REPT	REST REPTS
OONORB	0,058		
OOORB	0,109		
OOLORB	0,068	0,017	0,051
CA1	0,028		
CA2	0,009		
CA3	0,036		
CA4	0,060		
CA5	0,083	0,021	0,063
CA6-	0,033	0,008	0,024
CA6+	0,033	0,008	0,024
CA7	0,121	0,049	0,097
	-----	-----	-----
TOTALS	0,638	0,103	0,260

Figure 4-58. Value Model Nominal Output Data

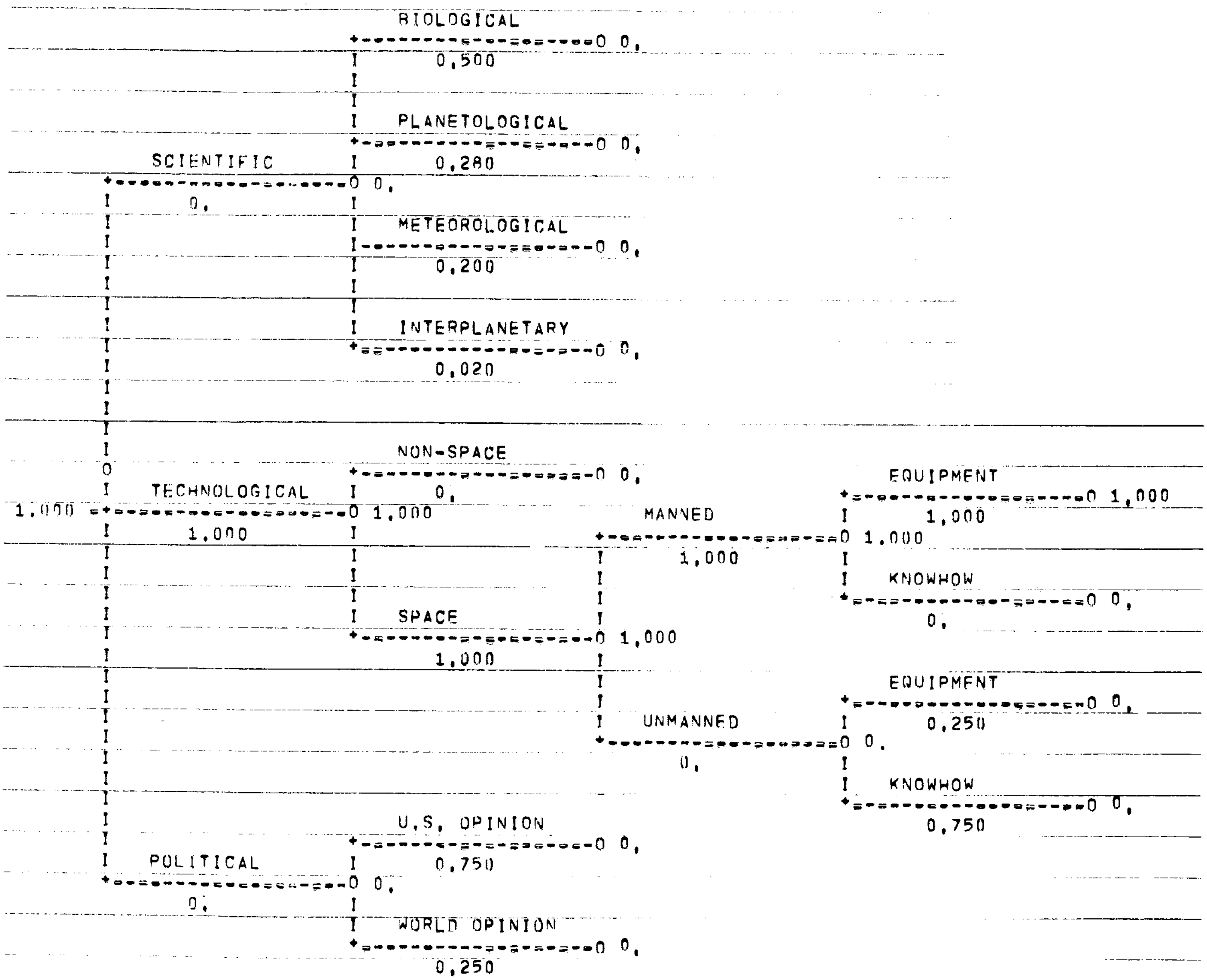


Figure 4-59. Value Model Input Data (All Value on Manned Equipment Benefit)

ACHIEVEMENT VALUE SUMMARY

ACH.	FIRST TIME	ONE REPT	REST REPTS
00NORB	0,043		
00ORB	0,141		
00LORB	0,033	0,008	0,024
CA1	0,051		
CA2	0,026		
CA3	0,103		
CA4	0,103		
CA5	0,154	0,039	0,116
CA6-	0,026	0,006	0,019
CA6+	0,026	0,006	0,019
CA7	0,026	0,010	0,021
TOTALS	0,731	0,070	0,199

Figure 4-60. Value Model Output Data (All Input Value on Manned Equipment Benefit)

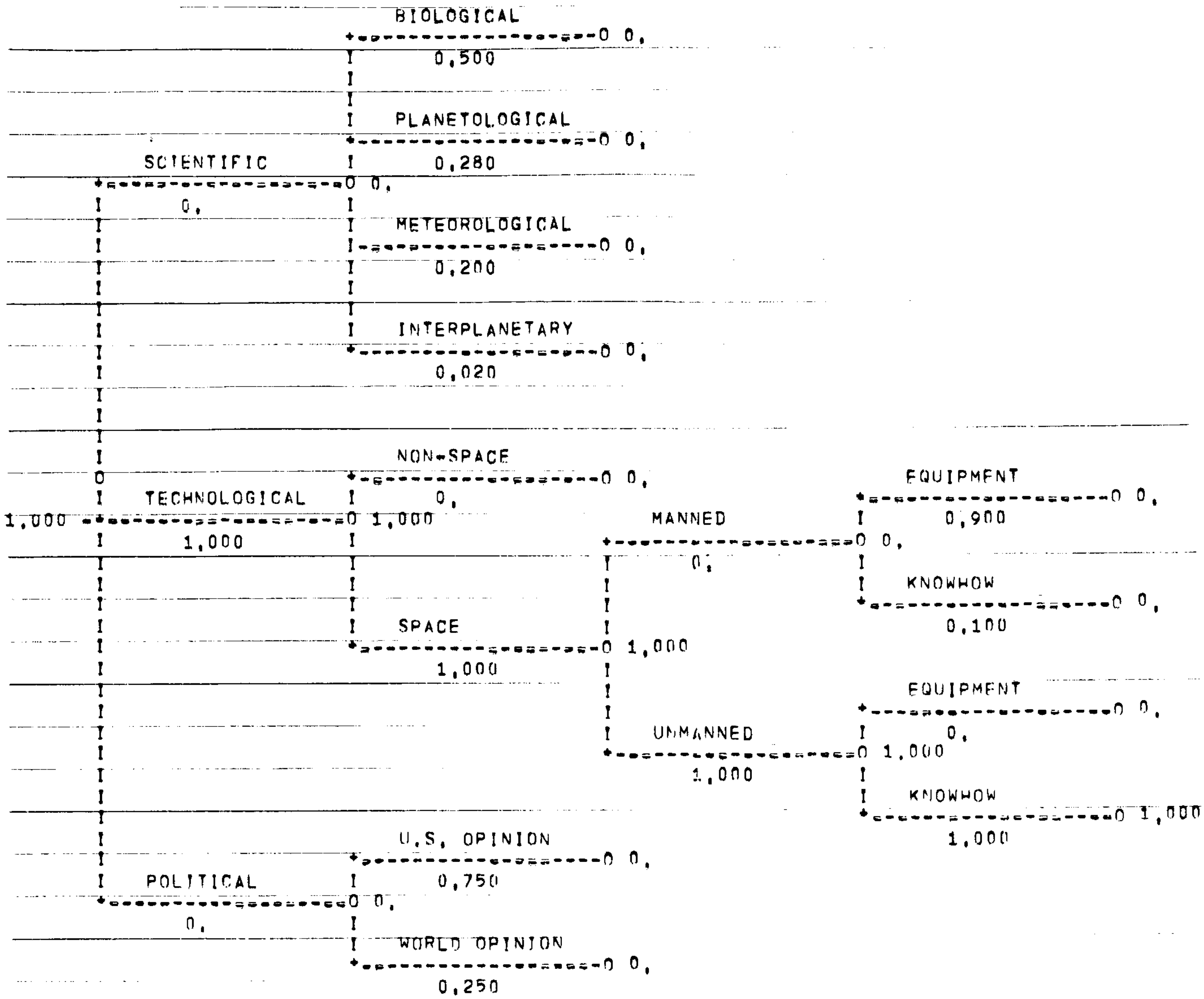


Figure 4-61. Value Model Input Data (All Value on Unmanned Knowhow Benefit)

ACHIEVEMENT VALUE SUMMARY

ACH,	FIRST TIME	ONE REPT	REST REPTS
OONORB	0,240		
OOORB	0,120		
OOLORB	0,120	0,030	0,090
CA1	0,099		
CA2	0,		
CA3	0,		
CA4	0,165		
CA5	0,033	0,008	0,025
CA6-	0,008	0,002	0,006
CA6+	0,008	0,002	0,006
CA7	0,017	0,007	0,013
TOTALS	0,811	0,049	0,140

Figure 4-62. Value Model Output Data (All Input Value on Unmanned Knowhow Benefit)

All the weight in the value tree of Figure 4-61 has been placed on the unmanned knowhow subcategory of space technology (i.e., Voyager as a medium for developing the knowhow for future unmanned missions to Mars and other planets). Notice that in Figure 4-62 this results in a strong shift of value to the orbiter, with the achievement of a successful soft-landing about the only capsule achievement of significant import.

4.12.1.2 The Cost Model

The cost model was programmed and run with nominal data as specified in Section 4.9. The results of the cost model are too numerous to list. Table 4-13 is typical of the results; it depicts the cost of each configuration, given that it is used as the first configuration in the project and in the first year it is available.

TABLE 4-13. CONFIGURATION COSTS IF THE PROJECT STARTS WITH THE CONFIGURATION IN THE FIRST YEAR OF ITS AVAILABILITY

Configuration	First Available Year of Launch	Cost ($M)
VSTOP	1971	0
VSKIP	1971	55
VMAR	1971	270
VSIB	1973	501
V2IB	1973	618
VOORB	1973	678
VOATM	1973	783
VODTV	1973	855
VOLTV	1973	1086
VOTVSF	1973	1305
VOVBL	1975	1368
VODATM	1973	810
VODDTV	1973	912
VODLTV	1973	1140

4.12.1.3 The Probability Model

4.12.1.3.1 Nominal Data

A computer printout sheet summarizing the nominal probability model input data appears as Figure 4-63, which is basically the probability parameters of Table 4-6 in computer input format.

The decision tree contains 2300 outcome nodes and 20, 000 outcome branches emanating from these nodes. This requires the probability model to supply some 600 probability distributions and over 5000 individual probabilities. Just a sample of this output with nominal input data is given in Tables 4-14 through 4-22. These tables depict the probability of nine representative configurations achieving all project outcomes, given that the configuration is employed in the first year that it is available and that the current stage of the project is OOZERO and COZERO. The tables are in computer numerical language and are readily decoded with the aid of Table 4-5.

4.12.1.3.2 Sensitivity of Probability Model Output to Input

A sample illustration of the probability model sensitivity to input is given in Tables 4-23 and 4-24. These tables depict the outcome probability distributions for the VOLTV and VOTVSF configurations, given that the landing environmental confidence (P21) is unity. Comparison of Table 4-24 with Table 4-21 reveals, for example, that the probability of completely successful operation of the VOTVSF increases by over 50 percent if the landing environment is known.

```
PA1          0,       0,98130 0,98280 0,96580 0,96100 0,96100
PA2          0,       0,98750 0,98850 0,97700 0,97350 0,97350
PA3          0,       1,00000 1,00000 1,00000 1,00000 1,00000
PA4          0,       0,80000 0,84300 0,87600 0,90100 0,92000
PA5          0,99000
PA6          0,99300
PA7          0,95000
PA8          0,95000
PA9          0,98000
PA10         0,90000
PA11   (  1,*) 1,00000 1,00000 0,99000 0,      0,      0,      0,      0,      0,      0,      0,      0,      0,      0,
PA11   (  2,*) 1,00000 1,00000 1,00000 0,99000 0,99000 0,99000 0,98000 0,97000 0,95000 0,92000 0,      0,98000 0,96000 0,94000
PA11   (  3,*) 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 0,99900 0,99500 0,99000 0,98000 0,95000 0,99000 0,99000 0,98000
PA11   (  4,*) 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 0,99000 1,00000 1,00000 1,00000
PA11   (  5,*) 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000
PA11   (  6,*) 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000 1,00000
PB1          0,99900
PB2          0,75000
PB3          0,99800
PB4          0,98500
PB5          0,99000
PB6          0,98000
PB7          0,98000
PB8          0,97000
PC1          0,90000
PC2          0,98000
PC3          0,90000
PC4          0,94000
PC5          0,98990
PC6          0,99000
PC7          0,99000
PC8          0,98000
PC9          0,99520
PC10         0,93000
PC11         0,       0,99030 0,99200 0,99330 0,99430 0,99500
PC12         0.       0,92800 0,94550 0,95720 0,96490 0,97000
PC13   (  0,*) 0.      0,      0,      0,      0,      0,      0,      0,      1,00000 1,00000 1,00000 0.      0,      1.00000
PC15         0,70000
PC16         0,75000
PC17         0,70000
PC18         0,85000
PC19         0,90000
PC20         0,95000
PC21   (  0,*) 0.      0,      0,      0,      0,      0,      0,      0,      0,      0,      0,      0,80000 0,50000 0.50000
PD1          0,98000
PS1          0,90000
PS2          0,90000
PS3          0,85000
PCM2         0,90000
PCM3         0,60000
PARAME
EKFACT          1000,0
ORBRTP             1,0         1,0          2,0          4,0          5,0          6,0
                  NLV         NSC  IENTRY  JENTRY        OSL     DSL     TVD     TVO    RDIR    RORB     SPE    STVE     BIO  NOSVLV    IORB
ITAB   (  1,*)      0           0       0       0          0       0       0       0       0       0       0       0       0       0       0
ITAB   (  2,*)      0           0       0       0          0       0       0       0       0       0       0       0       0       0       0
ITAB   (  3,*)      2           2       1       0          0       0       0       0       0       0       0       0       0       0       0
ITAB   (  4,*)      1           1       0       0          0       0       0       0       0       0       0       0       0       0       1
ITAB   (  5,*)      2           2       0       0          0       0       0       0       0       0       0       0       0       1       1
ITAB   (  6,*)      1           2       0       0          0       0       0       0       0       0       0       0       0       1       1
ITAB   (  7,*)      1           2       0       1          0       0       0       0       0       0       0       0       0       1       1
ITAB   (  8,*)      1           2       0       1          0       0       0       1       0       0       0       0       0       1       1
ITAB   (  9,*)      1           2       0       1          1       0       0       1       1       0       0       1       0       1       1
ITAB   ( 10,*)      1           2       0       1          1       0       0       1       1       0       1       1       0       1       1
ITAB   ( 11,*)      1           2       0       1          1       0       0       1       1       0       0       1       1       1       1
ITAB   ( 12,*)      1           2       1       1          0       0       0       0       0       0       0       1       0       1       1
ITAB   ( 13,*)      1           2       1       1          0       0       0       1       0       0       0       0       0       1       1
ITAB   ( 14,*)      1           2       1       1          1       0       0       1       1       0       0       1       0       1       1
HOURS
TETSLO    200,0
TCTSLO     10,0
SORBTM    500,0
ORBTM    2160,0
TSTSFD     30,0
VSRFTM      1,0     50,0 1000,0 3000,0 4000,0 5000,0
VTIME       0,    4872,0 5016,0 5496,0 5856,0 4944,0
FAILUR
VLAMB       0,          0,713E-04 0,397E-04 0,237E-04 0,150E-04 0,103E-04
CLAMB (*,  1)  0,          0,        0,        0,        0,        0,
CLAMB (*,  2)  0,          0,        0,        0,        0,        0,
CLAMB (*,  3)  0,260E-04   0,        0,        0,        0,        0,
CLAMB (*,  4)  0,          0,        0,        0,        0,        0,
CLAMB (*,  5)  0,          0,        0,        0,        0,        0,
CLAMB (*,  6)  0,          0,        0,        0,        0,        0,
CLAMB (*,  7)  0,          0,202E-04 0,165E-04 0,137E-04 0,117E-04 0,101E-04
CLAMB (*,  8)  0,          0,408E-04 0,305E-04 0,234E-04 0,185E-04 0,151E-04
CLAMB (*,  9)  0,          0,801E-04 0,530E-04 0,365E-04 0,264E-04 0,202E-04
CLAMB (*, 10)  0,          0,998E-04 0,616E-04 0,399E-04 0,275E-04 0,202E-04
CLAMB (*, 11)  0,          0,120E-03 0,699E-04 0,430E-04 0,283E-04 0,202E-04
CLAMB (*, 12)  0,          0,202E-04 0,165E-04 0,137E-04 0,117E-04 0,101E-04
CLAMB (*, 13)  0,          0,408E-04 0,305E-04 0,234E-04 0,185E-04 0,151E-04
CLAMB (*, 14)  0,          0,801E-04 0,530E-04 0,365E-04 0,264E-04 0,202E-04
CRRLAM     0,475E-04 0,400E-04 0,333E-04 0,277E-04 0,234E-04 0,200E-04
ORRLAM     0,250E-04 0,200E-04 0,165E-04 0,137E-04 0,116E-04 0,100E-04
SC1LAM     0,        0,527E-04 0,320E-04 0,204E-04 0,138E-04 0,101E-04
CDLLAM     0,        0,150E-03 0,882E-04 0,562E-04 0,394E-04 0,305E-04
SFLAMB     0.        0,356E-03 0,145E-03 0,660E-04 0,338E-04 0,200E-04
TVLAMB     0,        0,105E-03 0,475E-04 0,240E-04 0,142E-04 0,100E-04
VBILAM     0,        0,798E-03 0,326E-03 0,158E-03 0,850E-04 0,513E-04
```

Note: See Table 4-6 for Review of Probability Codes

Figure 4-63. Probability Model Nominal Input Data

TABLE 4-14. VMAR PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
4	1	1	1	1	3	1	1	1	1	0.11956
4	1	1	1	2	3	1	1	1	1	0.12059
4	1	1	1	3	3	1	1	1	1	0.75985
4	1	1	1	4	3	1	1	1	1	0.
4	1	1	1	5	3	1	1	1	1	0.
4	1	1	1	6	3	1	1	1	1	0.
4	1	1	1	7	3	1	1	1	1	0.
4	1	1	1	8	3	1	1	1	1	0.
4	1	1	1	9	3	1	1	1	1	0.
4	1	1	1	10	3	1	1	1	1	0.
4	1	1	1	11	3	1	1	1	1	0.
4	1	1	1	12	3	1	1	1	1	0.
4	1	1	1	13	3	1	1	1	1	0.
4	1	1	1	14	3	1	1	1	1	0.
4	1	1	2	1	3	1	1	1	1	0.
4	1	1	2	2	3	1	1	1	1	0.
4	1	1	2	3	3	1	1	1	1	0.
4	1	1	2	4	3	1	1	1	1	0.
4	1	1	2	5	3	1	1	1	1	0.
4	1	1	2	6	3	1	1	1	1	0.
4	1	1	2	7	3	1	1	1	1	0.
4	1	1	2	8	3	1	1	1	1	0.
4	1	1	2	9	3	1	1	1	1	0.
4	1	1	2	10	3	1	1	1	1	0.
4	1	1	2	11	3	1	1	1	1	0.
4	1	1	2	12	3	1	1	1	1	0.
4	1	1	2	13	3	1	1	1	1	0.
4	1	1	2	14	3	1	1	1	1	0.
4	1	1	3	1	3	1	1	1	1	0.
4	1	1	3	2	3	1	1	1	1	0.
4	1	1	3	3	3	1	1	1	1	0.
4	1	1	3	4	3	1	1	1	1	0.
4	1	1	3	5	3	1	1	1	1	0.
4	1	1	3	6	3	1	1	1	1	0.
4	1	1	3	7	3	1	1	1	1	0.
4	1	1	3	8	3	1	1	1	1	0.
4	1	1	3	9	3	1	1	1	1	0.
4	1	1	3	10	3	1	1	1	1	0.
4	1	1	3	11	3	1	1	1	1	0.
4	1	1	3	12	3	1	1	1	1	0.
4	1	1	3	13	3	1	1	1	1	0.
4	1	1	3	14	3	1	1	1	1	0.
4	1	1	4	1	3	1	1	1	1	0.
4	1	1	4	2	3	1	1	1	1	0.
4	1	1	4	3	3	1	1	1	1	0.
4	1	1	4	4	3	1	1	1	1	0.
4	1	1	4	5	3	1	1	1	1	0.
4	1	1	4	6	3	1	1	1	1	0.
4	1	1	4	7	3	1	1	1	1	0.
4	1	1	4	8	3	1	1	1	1	0.
4	1	1	4	9	3	1	1	1	1	0.
4	1	1	4	10	3	1	1	1	1	0.
4	1	1	4	11	3	1	1	1	1	0.
4	1	1	4	12	3	1	1	1	1	0.
4	1	1	4	13	3	1	1	1	1	0.
4	1	1	4	14	3	1	1	1	1	0.

TABLE 4-15. VSIB PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	4	1	1	1	1	0.39884
6	1	1	1	2	4	1	1	1	1	0.
6	1	1	1	3	4	1	1	1	1	0.
6	1	1	1	4	4	1	1	1	1	0.
6	1	1	1	5	4	1	1	1	1	0.
6	1	1	1	6	4	1	1	1	1	0.
6	1	1	1	7	4	1	1	1	1	0.
6	1	1	1	8	4	1	1	1	1	0.
6	1	1	1	9	4	1	1	1	1	0.
6	1	1	1	10	4	1	1	1	1	0.
6	1	1	1	11	4	1	1	1	1	0.
6	1	1	1	12	4	1	1	1	1	0.
6	1	1	1	13	4	1	1	1	1	0.
6	1	1	1	14	4	1	1	1	1	0.
6	1	1	2	1	4	1	1	1	1	0.20274
6	1	1	2	2	4	1	1	1	1	0.
6	1	1	2	3	4	1	1	1	1	0.
6	1	1	2	4	4	1	1	1	1	0.
6	1	1	2	5	4	1	1	1	1	0.
6	1	1	2	6	4	1	1	1	1	0.
6	1	1	2	7	4	1	1	1	1	0.
6	1	1	2	8	4	1	1	1	1	0.
6	1	1	2	9	4	1	1	1	1	0.
6	1	1	2	10	4	1	1	1	1	0.
6	1	1	2	11	4	1	1	1	1	0.
6	1	1	2	12	4	1	1	1	1	0.
6	1	1	2	13	4	1	1	1	1	0.
6	1	1	2	14	4	1	1	1	1	0.
6	1	1	3	1	4	1	1	1	1	0.11767
6	1	1	3	2	4	1	1	1	1	0.
6	1	1	3	3	4	1	1	1	1	0.
6	1	1	3	4	4	1	1	1	1	0.
6	1	1	3	5	4	1	1	1	1	0.
6	1	1	3	6	4	1	1	1	1	0.
6	1	1	3	7	4	1	1	1	1	0.
6	1	1	3	8	4	1	1	1	1	0.
6	1	1	3	9	4	1	1	1	1	0.
6	1	1	3	10	4	1	1	1	1	0.
6	1	1	3	11	4	1	1	1	1	0.
6	1	1	3	12	4	1	1	1	1	0.
6	1	1	3	13	4	1	1	1	1	0.
6	1	1	3	14	4	1	1	1	1	0.
6	1	1	4	1	4	1	1	1	1	0.28076
6	1	1	4	2	4	1	1	1	1	0.
6	1	1	4	3	4	1	1	1	1	0.
6	1	1	4	4	4	1	1	1	1	0.
6	1	1	4	5	4	1	1	1	1	0.
6	1	1	4	6	4	1	1	1	1	0.
6	1	1	4	7	4	1	1	1	1	0.
6	1	1	4	8	4	1	1	1	1	0.
6	1	1	4	9	4	1	1	1	1	0.
6	1	1	4	10	4	1	1	1	1	0.
6	1	1	4	11	4	1	1	1	1	0.
6	1	1	4	12	4	1	1	1	1	0.
6	1	1	4	13	4	1	1	1	1	0.
6	1	1	4	14	4	1	1	1	1	0.

TABLE 4-16. V2SIB PROBABILITY MODEL NOMINAL OUTPUT DATA (See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	5	1	1	1	1	0.15762
6	1	1	1	2	5	1	1	1	1	0.
6	1	1	1	3	5	1	1	1	1	0.
6	1	1	1	4	5	1	1	1	1	0.
6	1	1	1	5	5	1	1	1	1	0.
6	1	1	1	6	5	1	1	1	1	0.
6	1	1	1	7	5	1	1	1	1	0.
6	1	1	1	8	5	1	1	1	1	0.
6	1	1	1	9	5	1	1	1	1	0.
6	1	1	1	10	5	1	1	1	1	0.
6	1	1	1	11	5	1	1	1	1	0.
6	1	1	1	12	5	1	1	1	1	0.
6	1	1	1	13	5	1	1	1	1	0.
6	1	1	1	14	5	1	1	1	1	0.
6	1	1	2	1	5	1	1	1	1	0.27126
6	1	1	2	2	5	1	1	1	1	0.
6	1	1	2	3	5	1	1	1	1	0.
6	1	1	2	4	5	1	1	1	1	0.
6	1	1	2	5	5	1	1	1	1	0.
6	1	1	2	6	5	1	1	1	1	0.
6	1	1	2	7	5	1	1	1	1	0.
6	1	1	2	8	5	1	1	1	1	0.
6	1	1	2	9	5	1	1	1	1	0.
6	1	1	2	10	5	1	1	1	1	0.
6	1	1	2	11	5	1	1	1	1	0.
6	1	1	2	12	5	1	1	1	1	0.
6	1	1	2	13	5	1	1	1	1	0.
6	1	1	2	14	5	1	1	1	1	0.
6	1	1	3	1	5	1	1	1	1	0.12119
6	1	1	3	2	5	1	1	1	1	0.
6	1	1	3	3	5	1	1	1	1	0.
6	1	1	3	4	5	1	1	1	1	0.
6	1	1	3	5	5	1	1	1	1	0.
6	1	1	3	6	5	1	1	1	1	0.
6	1	1	3	7	5	1	1	1	1	0.
6	1	1	3	8	5	1	1	1	1	0.
6	1	1	3	9	5	1	1	1	1	0.
6	1	1	3	10	5	1	1	1	1	0.
6	1	1	3	11	5	1	1	1	1	0.
6	1	1	3	12	5	1	1	1	1	0.
6	1	1	3	13	5	1	1	1	1	0.
6	1	1	3	14	5	1	1	1	1	0.
6	1	1	4	1	5	1	1	1	1	0.44992
6	1	1	4	2	5	1	1	1	1	0.
6	1	1	4	3	5	1	1	1	1	0.
6	1	1	4	4	5	1	1	1	1	0.
6	1	1	4	5	5	1	1	1	1	0.
6	1	1	4	6	5	1	1	1	1	0.
6	1	1	4	7	5	1	1	1	1	0.
6	1	1	4	8	5	1	1	1	1	0.
6	1	1	4	9	5	1	1	1	1	0.
6	1	1	4	10	5	1	1	1	1	0.
6	1	1	4	11	5	1	1	1	1	0.
6	1	1	4	12	5	1	1	1	1	0.
6	1	1	4	13	5	1	1	1	1	0.
6	1	1	4	14	5	1	1	1	1	0.

TABLE 4-17. VOORB PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	6	1	1	1	1	0.30258
6	1	1	1	2	6	1	1	1	1	0.
6	1	1	1	3	6	1	1	1	1	0.
6	1	1	1	4	6	1	1	1	1	0.
6	1	1	1	5	6	1	1	1	1	0.
6	1	1	1	6	6	1	1	1	1	0.
6	1	1	1	7	6	1	1	1	1	0.
6	1	1	1	8	6	1	1	1	1	0.
6	1	1	1	9	6	1	1	1	1	0.
6	1	1	1	10	6	1	1	1	1	0.
6	1	1	1	11	6	1	1	1	1	0.
6	1	1	1	12	6	1	1	1	1	0.
6	1	1	1	13	6	1	1	1	1	0.
6	1	1	1	14	6	1	1	1	1	0.
6	1	1	2	1	6	1	1	1	1	0.22254
6	1	1	2	2	6	1	1	1	1	0.
6	1	1	2	3	6	1	1	1	1	0.
6	1	1	2	4	6	1	1	1	1	0.
6	1	1	2	5	6	1	1	1	1	0.
6	1	1	2	6	6	1	1	1	1	0.
6	1	1	2	7	6	1	1	1	1	0.
6	1	1	2	8	6	1	1	1	1	0.
6	1	1	2	9	6	1	1	1	1	0.
6	1	1	2	10	6	1	1	1	1	0.
6	1	1	2	11	6	1	1	1	1	0.
6	1	1	2	12	6	1	1	1	1	0.
6	1	1	2	13	6	1	1	1	1	0.
6	1	1	2	14	6	1	1	1	1	0.
6	1	1	3	1	6	1	1	1	1	0.09337
6	1	1	3	2	6	1	1	1	1	0.
6	1	1	3	3	6	1	1	1	1	0.
6	1	1	3	4	6	1	1	1	1	0.
6	1	1	3	5	6	1	1	1	1	0.
6	1	1	3	6	6	1	1	1	1	0.
6	1	1	3	7	6	1	1	1	1	0.
6	1	1	3	8	6	1	1	1	1	0.
6	1	1	3	9	6	1	1	1	1	0.
6	1	1	3	10	6	1	1	1	1	0.
6	1	1	3	11	6	1	1	1	1	0.
6	1	1	3	12	6	1	1	1	1	0.
6	1	1	3	13	6	1	1	1	1	0.
6	1	1	3	14	6	1	1	1	1	0.
6	1	1	4	1	6	1	1	1	1	0.38151
6	1	1	4	2	6	1	1	1	1	0.
6	1	1	4	3	6	1	1	1	1	0.
6	1	1	4	4	6	1	1	1	1	0.
6	1	1	4	5	6	1	1	1	1	0.
6	1	1	4	6	6	1	1	1	1	0.
6	1	1	4	7	6	1	1	1	1	0.
6	1	1	4	8	6	1	1	1	1	0.
6	1	1	4	9	6	1	1	1	1	0.
6	1	1	4	10	6	1	1	1	1	0.
6	1	1	4	11	6	1	1	1	1	0.
6	1	1	4	12	6	1	1	1	1	0.
6	1	1	4	13	6	1	1	1	1	0.
6	1	1	4	14	6	1	1	1	1	0.

TABLE 4-18. VOATM PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	7	1	1	1	1	0.30962
6	1	1	1	2	7	1	1	1	1	0.
6	1	1	1	3	7	1	1	1	1	0.
6	1	1	1	4	7	1	1	1	1	0.
6	1	1	1	5	7	1	1	1	1	0.
6	1	1	1	6	7	1	1	1	1	0.
6	1	1	1	7	7	1	1	1	1	0.
6	1	1	1	8	7	1	1	1	1	0.
6	1	1	1	9	7	1	1	1	1	0.
6	1	1	1	10	7	1	1	1	1	0.
6	1	1	1	11	7	1	1	1	1	0.
6	1	1	1	12	7	1	1	1	1	0.
6	1	1	1	13	7	1	1	1	1	0.
6	1	1	1	14	7	1	1	1	1	0.
6	1	1	2	1	7	1	1	1	1	0.22279
6	1	1	2	2	7	1	1	1	1	0.
6	1	1	2	3	7	1	1	1	1	0.
6	1	1	2	4	7	1	1	1	1	0.
6	1	1	2	5	7	1	1	1	1	0.
6	1	1	2	6	7	1	1	1	1	0.
6	1	1	2	7	7	1	1	1	1	0.
6	1	1	2	8	7	1	1	1	1	0.
6	1	1	2	9	7	1	1	1	1	0.
6	1	1	2	10	7	1	1	1	1	0.
6	1	1	2	11	7	1	1	1	1	0.
6	1	1	2	12	7	1	1	1	1	0.
6	1	1	2	13	7	1	1	1	1	0.
6	1	1	2	14	7	1	1	1	1	0.
6	1	1	3	1	7	1	1	1	1	0.
6	1	1	3	2	7	1	1	1	1	0.01417
6	1	1	3	3	7	1	1	1	1	0.07845
6	1	1	3	4	7	1	1	1	1	0.
6	1	1	3	5	7	1	1	1	1	0.
6	1	1	3	6	7	1	1	1	1	0.
6	1	1	3	7	7	1	1	1	1	0.
6	1	1	3	8	7	1	1	1	1	0.
6	1	1	3	9	7	1	1	1	1	0.
6	1	1	3	10	7	1	1	1	1	0.
6	1	1	3	11	7	1	1	1	1	0.
6	1	1	3	12	7	1	1	1	1	0.
6	1	1	3	13	7	1	1	1	1	0.
6	1	1	3	14	7	1	1	1	1	0.
6	1	1	4	1	7	1	1	1	1	0.
6	1	1	4	2	7	1	1	1	1	0.04994
6	1	1	4	3	7	1	1	1	1	0.32503
6	1	1	4	4	7	1	1	1	1	0.
6	1	1	4	5	7	1	1	1	1	0.
6	1	1	4	6	7	1	1	1	1	0.
6	1	1	4	7	7	1	1	1	1	0.
6	1	1	4	8	7	1	1	1	1	0.
6	1	1	4	9	7	1	1	1	1	0.
6	1	1	4	10	7	1	1	1	1	0.
6	1	1	4	11	7	1	1	1	1	0.
6	1	1	4	12	7	1	1	1	1	0.
6	1	1	4	13	7	1	1	1	1	0.
6	1	1	4	14	7	1	1	1	1	0.

TABLE 4-19. VODTV PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	8	1	1	1	1	0.31667
6	1	1	1	2	8	1	1	1	1	0.
6	1	1	1	3	8	1	1	1	1	0.
6	1	1	1	4	8	1	1	1	1	0.
6	1	1	1	5	8	1	1	1	1	0.
6	1	1	1	6	8	1	1	1	1	0.
6	1	1	1	7	8	1	1	1	1	0.
6	1	1	1	8	8	1	1	1	1	0.
6	1	1	1	9	8	1	1	1	1	0.
6	1	1	1	10	8	1	1	1	1	0.
6	1	1	1	11	8	1	1	1	1	0.
6	1	1	1	12	8	1	1	1	1	0.
6	1	1	1	13	8	1	1	1	1	0.
6	1	1	1	14	8	1	1	1	1	0.
6	1	1	2	1	8	1	1	1	1	0.22051
6	1	1	2	2	8	1	1	1	1	0.
6	1	1	2	3	8	1	1	1	1	0.
6	1	1	2	4	8	1	1	1	1	0.
6	1	1	2	5	8	1	1	1	1	0.
6	1	1	2	6	8	1	1	1	1	0.
6	1	1	2	7	8	1	1	1	1	0.
6	1	1	2	8	8	1	1	1	1	0.
6	1	1	2	9	8	1	1	1	1	0.
6	1	1	2	10	8	1	1	1	1	0.
6	1	1	2	11	8	1	1	1	1	0.
6	1	1	2	12	8	1	1	1	1	0.
6	1	1	2	13	8	1	1	1	1	0.
6	1	1	2	14	8	1	1	1	1	0.
6	1	1	3	1	8	1	1	1	1	0.
6	1	1	3	2	8	1	1	1	1	0.01417
6	1	1	3	3	8	1	1	1	1	0.00448
6	1	1	3	4	8	1	1	1	1	0.
6	1	1	3	5	8	1	1	1	1	0.07302
6	1	1	3	6	8	1	1	1	1	0.
6	1	1	3	7	8	1	1	1	1	0.
6	1	1	3	8	8	1	1	1	1	0.
6	1	1	3	9	8	1	1	1	1	0.
6	1	1	3	10	8	1	1	1	1	0.
6	1	1	3	11	8	1	1	1	1	0.
6	1	1	3	12	8	1	1	1	1	0.
6	1	1	3	13	8	1	1	1	1	0.
6	1	1	3	14	8	1	1	1	1	0.
6	1	1	4	1	8	1	1	1	1	0.
6	1	1	4	2	8	1	1	1	1	0.04982
6	1	1	4	3	8	1	1	1	1	0.01260
6	1	1	4	4	8	1	1	1	1	0.
6	1	1	4	5	8	1	1	1	1	0.30873
6	1	1	4	6	8	1	1	1	1	0.
6	1	1	4	7	8	1	1	1	1	0.
6	1	1	4	8	8	1	1	1	1	0.
6	1	1	4	9	8	1	1	1	1	0.
6	1	1	4	10	8	1	1	1	1	0.
6	1	1	4	11	8	1	1	1	1	0.
6	1	1	4	12	8	1	1	1	1	0.
6	1	1	4	13	8	1	1	1	1	0.
6	1	1	4	14	8	1	1	1	1	0.

TABLE 4-20. VOLTV PROBABILITY MODEL NOMINAL OUTPUT DATA (See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	9	1	1	1	1	0.33076
6	1	1	1	2	9	1	1	1	1	0.
6	1	1	1	3	9	1	1	1	1	0.
6	1	1	1	4	9	1	1	1	1	0.
6	1	1	1	5	9	1	1	1	1	0.
6	1	1	1	6	9	1	1	1	1	0.
6	1	1	1	7	9	1	1	1	1	0.
6	1	1	1	8	9	1	1	1	1	0.
6	1	1	1	9	9	1	1	1	1	0.
6	1	1	1	10	9	1	1	1	1	0.
6	1	1	1	11	9	1	1	1	1	0.
6	1	1	1	12	9	1	1	1	1	0.
6	1	1	1	13	9	1	1	1	1	0.
6	1	1	1	14	9	1	1	1	1	0.
6	1	1	2	1	9	1	1	1	1	0.21597
6	1	1	2	2	9	1	1	1	1	0.
6	1	1	2	3	9	1	1	1	1	0.
6	1	1	2	4	9	1	1	1	1	0.
6	1	1	2	5	9	1	1	1	1	0.
6	1	1	2	6	9	1	1	1	1	0.
6	1	1	2	7	9	1	1	1	1	0.
6	1	1	2	8	9	1	1	1	1	0.
6	1	1	2	9	9	1	1	1	1	0.
6	1	1	2	10	9	1	1	1	1	0.
6	1	1	2	11	9	1	1	1	1	0.
6	1	1	2	12	9	1	1	1	1	0.
6	1	1	2	13	9	1	1	1	1	0.
6	1	1	2	14	9	1	1	1	1	0.
6	1	1	3	1	9	1	1	1	1	0.
6	1	1	3	2	9	1	1	1	1	0.01409
6	1	1	3	3	9	1	1	1	1	0.
6	1	1	3	4	9	1	1	1	1	0.00047
6	1	1	3	5	9	1	1	1	1	0.
6	1	1	3	6	9	1	1	1	1	0.00672
6	1	1	3	7	9	1	1	1	1	0.00716
6	1	1	3	8	9	1	1	1	1	0.06133
6	1	1	3	9	9	1	1	1	1	0.
6	1	1	3	10	9	1	1	1	1	0.
6	1	1	3	11	9	1	1	1	1	0.
6	1	1	3	12	9	1	1	1	1	0.
6	1	1	3	13	9	1	1	1	1	0.
6	1	1	3	14	9	1	1	1	1	0.
6	1	1	4	1	9	1	1	1	1	0.
6	1	1	4	2	9	1	1	1	1	0.04938
6	1	1	4	3	9	1	1	1	1	0.
6	1	1	4	4	9	1	1	1	1	0.00129
6	1	1	4	5	9	1	1	1	1	0.
6	1	1	4	6	9	1	1	1	1	0.02212
6	1	1	4	7	9	1	1	1	1	0.02264
6	1	1	4	8	9	1	1	1	1	0.26805
6	1	1	4	9	9	1	1	1	1	0.
6	1	1	4	10	9	1	1	1	1	0.
6	1	1	4	11	9	1	1	1	1	0.
6	1	1	4	12	9	1	1	1	1	0.
6	1	1	4	13	9	1	1	1	1	0.
6	1	1	4	14	9	1	1	1	1	0.

TABLE 4-21. VOTVSF PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	10	1	1	1	1	0.35189
6	1	1	1	2	10	1	1	1	1	0.
6	1	1	1	3	10	1	1	1	1	0.
6	1	1	1	4	10	1	1	1	1	0.
6	1	1	1	5	10	1	1	1	1	0.
6	1	1	1	6	10	1	1	1	1	0.
6	1	1	1	7	10	1	1	1	1	0.
6	1	1	1	8	10	1	1	1	1	0.
6	1	1	1	9	10	1	1	1	1	0.
6	1	1	1	10	10	1	1	1	1	0.
6	1	1	1	11	10	1	1	1	1	0.
6	1	1	1	12	10	1	1	1	1	0.
6	1	1	1	13	10	1	1	1	1	0.
6	1	1	1	14	10	1	1	1	1	0.
6	1	1	2	1	10	1	1	1	1	0.20915
6	1	1	2	2	10	1	1	1	1	0.
6	1	1	2	3	10	1	1	1	1	0.
6	1	1	2	4	10	1	1	1	1	0.
6	1	1	2	5	10	1	1	1	1	0.
6	1	1	2	6	10	1	1	1	1	0.
6	1	1	2	7	10	1	1	1	1	0.
6	1	1	2	8	10	1	1	1	1	0.
6	1	1	2	9	10	1	1	1	1	0.
6	1	1	2	10	10	1	1	1	1	0.
6	1	1	2	11	10	1	1	1	1	0.
6	1	1	2	12	10	1	1	1	1	0.
6	1	1	2	13	10	1	1	1	1	0.
6	1	1	2	14	10	1	1	1	1	0.
6	1	1	3	1	10	1	1	1	1	0.
6	1	1	3	2	10	1	1	1	1	0.01378
6	1	1	3	3	10	1	1	1	1	0.
6	1	1	3	4	10	1	1	1	1	0.00045
6	1	1	3	5	10	1	1	1	1	0.
6	1	1	3	6	10	1	1	1	1	0.00650
6	1	1	3	7	10	1	1	1	1	0.00195
6	1	1	3	8	10	1	1	1	1	0.01035
6	1	1	3	9	10	1	1	1	1	0.00503
6	1	1	3	10	10	1	1	1	1	0.
6	1	1	3	11	10	1	1	1	1	0.04888
6	1	1	3	12	10	1	1	1	1	0.
6	1	1	3	13	10	1	1	1	1	0.
6	1	1	3	14	10	1	1	1	1	0.
6	1	1	4	1	10	1	1	1	1	0.
6	1	1	4	2	10	1	1	1	1	0.04817
6	1	1	4	3	10	1	1	1	1	0.
6	1	1	4	4	10	1	1	1	1	0.00125
6	1	1	4	5	10	1	1	1	1	0.
6	1	1	4	6	10	1	1	1	1	0.02143
6	1	1	4	7	10	1	1	1	1	0.00592
6	1	1	4	8	10	1	1	1	1	0.03463
6	1	1	4	9	10	1	1	1	1	0.01619
6	1	1	4	10	10	1	1	1	1	0.
6	1	1	4	11	10	1	1	1	1	0.22442
6	1	1	4	12	10	1	1	1	1	0.
6	1	1	4	13	10	1	1	1	1	0.
6	1	1	4	14	10	1	1	1	1	0.

TABLE 4-22. VODATM PROBABILITY MODEL NOMINAL OUTPUT DATA
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	12	1	1	1	1	0.31301
6	1	1	1	2	12	1	1	1	1	0.
6	1	1	1	3	12	1	1	1	1	0.
6	1	1	1	4	12	1	1	1	1	0.
6	1	1	1	5	12	1	1	1	1	0.
6	1	1	1	6	12	1	1	1	1	0.
6	1	1	1	7	12	1	1	1	1	0.
6	1	1	1	8	12	1	1	1	1	0.
6	1	1	1	9	12	1	1	1	1	0.
6	1	1	1	10	12	1	1	1	1	0.
6	1	1	1	11	12	1	1	1	1	0.
6	1	1	1	12	12	1	1	1	1	0.
6	1	1	1	13	12	1	1	1	1	0.
6	1	1	1	14	12	1	1	1	1	0.
6	1	1	2	1	12	1	1	1	1	0.
6	1	1	2	2	12	1	1	1	1	0.03042
6	1	1	2	3	12	1	1	1	1	0.19149
6	1	1	2	4	12	1	1	1	1	0.
6	1	1	2	5	12	1	1	1	1	0.
6	1	1	2	6	12	1	1	1	1	0.
6	1	1	2	7	12	1	1	1	1	0.
6	1	1	2	8	12	1	1	1	1	0.
6	1	1	2	9	12	1	1	1	1	0.
6	1	1	2	10	12	1	1	1	1	0.
6	1	1	2	11	12	1	1	1	1	0.
6	1	1	2	12	12	1	1	1	1	0.
6	1	1	2	13	12	1	1	1	1	0.
6	1	1	2	14	12	1	1	1	1	0.
6	1	1	3	1	12	1	1	1	1	0.
6	1	1	3	2	12	1	1	1	1	0.00265
6	1	1	3	3	12	1	1	1	1	0.09013
6	1	1	3	4	12	1	1	1	1	0.
6	1	1	3	5	12	1	1	1	1	0.
6	1	1	3	6	12	1	1	1	1	0.
6	1	1	3	7	12	1	1	1	1	0.
6	1	1	3	8	12	1	1	1	1	0.
6	1	1	3	9	12	1	1	1	1	0.
6	1	1	3	10	12	1	1	1	1	0.
6	1	1	3	11	12	1	1	1	1	0.
6	1	1	3	12	12	1	1	1	1	0.
6	1	1	3	13	12	1	1	1	1	0.
6	1	1	3	14	12	1	1	1	1	0.
6	1	1	4	1	12	1	1	1	1	0.
6	1	1	4	2	12	1	1	1	1	0.00941
6	1	1	4	3	12	1	1	1	1	0.36289
6	1	1	4	4	12	1	1	1	1	0.
6	1	1	4	5	12	1	1	1	1	0.
6	1	1	4	6	12	1	1	1	1	0.
6	1	1	4	7	12	1	1	1	1	0.
6	1	1	4	8	12	1	1	1	1	0.
6	1	1	4	9	12	1	1	1	1	0.
6	1	1	4	10	12	1	1	1	1	0.
6	1	1	4	11	12	1	1	1	1	0.
6	1	1	4	12	12	1	1	1	1	0.
6	1	1	4	13	12	1	1	1	1	0.
6	1	1	4	14	12	1	1	1	1	0.

TABLE 4-23. VOLTV PROBABILITY MODEL OUTPUT DATA WITH NOMINAL INPUT DATA EXCEPT FOR UNITY LANDED ENVIRONMENTAL CONFIDENCE
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	9	1	1	1	1	0.33076
6	1	1	1	2	9	1	1	1	1	0.
6	1	1	1	3	9	1	1	1	1	0.
6	1	1	1	4	9	1	1	1	1	0.
6	1	1	1	5	9	1	1	1	1	0.
6	1	1	1	6	9	1	1	1	1	0.
6	1	1	1	7	9	1	1	1	1	0.
6	1	1	1	8	9	1	1	1	1	0.
6	1	1	1	9	9	1	1	1	1	0.
6	1	1	1	10	9	1	1	1	1	0.
6	1	1	1	11	9	1	1	1	1	0.
6	1	1	1	12	9	1	1	1	1	0.
6	1	1	1	13	9	1	1	1	1	0.
6	1	1	1	14	9	1	1	1	1	0.
6	1	1	2	1	9	1	1	1	1	0.02170
6	1	1	2	2	9	1	1	1	1	0.
6	1	1	2	3	9	1	1	1	1	0.
6	1	1	2	4	9	1	1	1	1	0.
6	1	1	2	5	9	1	1	1	1	0.
6	1	1	2	6	9	1	1	1	1	0.
6	1	1	2	7	9	1	1	1	1	0.
6	1	1	2	8	9	1	1	1	1	0.
6	1	1	2	9	9	1	1	1	1	0.
6	1	1	2	10	9	1	1	1	1	0.
6	1	1	2	11	9	1	1	1	1	0.
6	1	1	2	12	9	1	1	1	1	0.
6	1	1	2	13	9	1	1	1	1	0.
6	1	1	2	14	9	1	1	1	1	0.
6	1	1	3	1	9	1	1	1	1	0.
6	1	1	3	2	9	1	1	1	1	0.02013
6	1	1	3	3	9	1	1	1	1	0.
6	1	1	3	4	9	1	1	1	1	0.00067
6	1	1	3	5	9	1	1	1	1	0.
6	1	1	3	6	9	1	1	1	1	0.00960
6	1	1	3	7	9	1	1	1	1	0.01023
6	1	1	3	8	9	1	1	1	1	0.08761
6	1	1	3	9	9	1	1	1	1	0.
6	1	1	3	10	9	1	1	1	1	0.
6	1	1	3	11	9	1	1	1	1	0.
6	1	1	3	12	9	1	1	1	1	0.
6	1	1	3	13	9	1	1	1	1	0.
6	1	1	3	14	9	1	1	1	1	0.
6	1	1	4	1	9	1	1	1	1	0.
6	1	1	4	2	9	1	1	1	1	0.07054
6	1	1	4	3	9	1	1	1	1	0.
6	1	1	4	4	9	1	1	1	1	0.00184
6	1	1	4	5	9	1	1	1	1	0.
6	1	1	4	6	9	1	1	1	1	0.03160
6	1	1	4	7	9	1	1	1	1	0.03235
6	1	1	4	8	9	1	1	1	1	0.38294
6	1	1	4	9	9	1	1	1	1	0.
6	1	1	4	10	9	1	1	1	1	0.
6	1	1	4	11	9	1	1	1	1	0.
6	1	1	4	12	9	1	1	1	1	0.
6	1	1	4	13	9	1	1	1	1	0.
6	1	1	4	14	9	1	1	1	1	0.

TABLE 4-24. VOTVSF PROBABILITY MODEL OUTPUT DATA WITH NOMINAL INPUT DATA EXCEPT FOR UNITY LANDED ENVIRONMENTAL CONFIDENCE
(See Table 4-5 for Review of State Variable Codes)

Year	FROM		TO		Config.	REPEATS				Prob.
	OO	CO	OO	CO		OO4	CA5	CA6	CA7	
6	1	1	1	1	10	1	1	1	1	0.35189
6	1	1	1	2	10	1	1	1	1	0.
6	1	1	1	3	10	1	1	1	1	0.
6	1	1	1	4	10	1	1	1	1	0.
6	1	1	1	5	10	1	1	1	1	0.
6	1	1	1	6	10	1	1	1	1	0.
6	1	1	1	7	10	1	1	1	1	0.
6	1	1	1	8	10	1	1	1	1	0.
6	1	1	1	9	10	1	1	1	1	0.
6	1	1	1	10	10	1	1	1	1	0.
6	1	1	1	11	10	1	1	1	1	0.
6	1	1	1	12	10	1	1	1	1	0.
6	1	1	1	13	10	1	1	1	1	0.
6	1	1	1	14	10	1	1	1	1	0.
6	1	1	2	1	10	1	1	1	1	0.02102
6	1	1	2	2	10	1	1	1	1	0.
6	1	1	2	3	10	1	1	1	1	0.
6	1	1	2	4	10	1	1	1	1	0.
6	1	1	2	5	10	1	1	1	1	0.
6	1	1	2	6	10	1	1	1	1	0.
6	1	1	2	7	10	1	1	1	1	0.
6	1	1	2	8	10	1	1	1	1	0.
6	1	1	2	9	10	1	1	1	1	0.
6	1	1	2	10	10	1	1	1	1	0.
6	1	1	2	11	10	1	1	1	1	0.
6	1	1	2	12	10	1	1	1	1	0.
6	1	1	2	13	10	1	1	1	1	0.
6	1	1	2	14	10	1	1	1	1	0.
6	1	1	3	1	10	1	1	1	1	0.
6	1	1	3	2	10	1	1	1	1	0.01968
6	1	1	3	3	10	1	1	1	1	0.
6	1	1	3	4	10	1	1	1	1	0.00065
6	1	1	3	5	10	1	1	1	1	0.
6	1	1	3	6	10	1	1	1	1	0.00928
6	1	1	3	7	10	1	1	1	1	0.00278
6	1	1	3	8	10	1	1	1	1	0.01479
6	1	1	3	9	10	1	1	1	1	0.00718
6	1	1	3	10	10	1	1	1	1	0.
6	1	1	3	11	10	1	1	1	1	0.06983
6	1	1	3	12	10	1	1	1	1	0.
6	1	1	3	13	10	1	1	1	1	0.
6	1	1	3	14	10	1	1	1	1	0.
6	1	1	4	1	10	1	1	1	1	0.
6	1	1	4	2	10	1	1	1	1	0.06881
6	1	1	4	3	10	1	1	1	1	0.
6	1	1	4	4	10	1	1	1	1	0.00179
6	1	1	4	5	10	1	1	1	1	0.
6	1	1	4	6	10	1	1	1	1	0.03061
6	1	1	4	7	10	1	1	1	1	0.00845
6	1	1	4	8	10	1	1	1	1	0.04948
6	1	1	4	9	10	1	1	1	1	0.02313
6	1	1	4	10	10	1	1	1	1	0.
6	1	1	4	11	10	1	1	1	1	0.32060
6	1	1	4	12	10	1	1	1	1	0.
6	1	1	4	13	10	1	1	1	1	0.
6	1	1	4	14	10	1	1	1	1	0.

4.12.2 DECISION MODEL RESULTS

This subsection contains the results of initial, limited exercising of the SPAN system. First, a nominal dollar value per value point (one value point = total value of Voyager value tree) is selected, and the optimal policy for this point value and nominal input data is described and discussed. Then, the sensitivity of this policy to the assigned point value is examined. Other discussions include policy analysis for various levels of risk aversion, cost and value time discounting, and combinations of risk aversion and discounting. Finally, the question of launch vehicle redundancy (i.e., one versus two Saturn V's) is analyzed. The final portion of this subsection summarizes the preliminary conclusions of this decision analysis and recommendations for future activity.

4.12.2.1 Decision Policy for Nominal Input Data (DECPOL)

To obtain project profiles comparable to those which have previously been considered for Voyager, results with the pilot model and early analysis with the full scale model suggested that a λ (see Section 4.5.10) at $20 billion was appropriate, and this value was taken as nominal for these preliminary exercises. The optimal decision policy for the completely nominal case (i.e., nominal submodel inputs and nominal point dollar value) is summarized in Table 4-25.

TABLE 4-25. OPTIMAL DECISION POLICY FOR NOMINAL INPUT DATA AND NOMINAL DOLLAR EVALUATION (PRELIMINARY EXERCISES)

1971:	VMAR
1973:	VOTVSF
1975-81:	VOVBL
Expected Value	= 0.692
Expected Cost	= $5131.7 million
Net Expected Value	= $8712.3 million

This policy can be interpreted as always flying the most sophisticated configuration available.

4.12.2.2 Policy Sensitivity to Project Evaluation (DECREG)

The assignment of dollar value per value point was varied from zero to infinity with nominal submodel data inputs to derive the entire set of dominant policies, using the DECREG program of Section 4.11.8.3. The results of this regional analysis are plotted in cost-benefit space in Figure 4-64. The dominant policy set was found to contain some 20 policies, the expected costs and values of which can be read from the figure.

It can be seen that the nominal policy of Table 4-25 is identically that policy which returns maximum expected value; i.e., Policy 1 of Figure 4-64. Within the framework of these preliminary exercises, a detailed evaluation of the remaining 19 lower valued, lower cost policies was not performed. This is indeed a fertile area for further analysis.

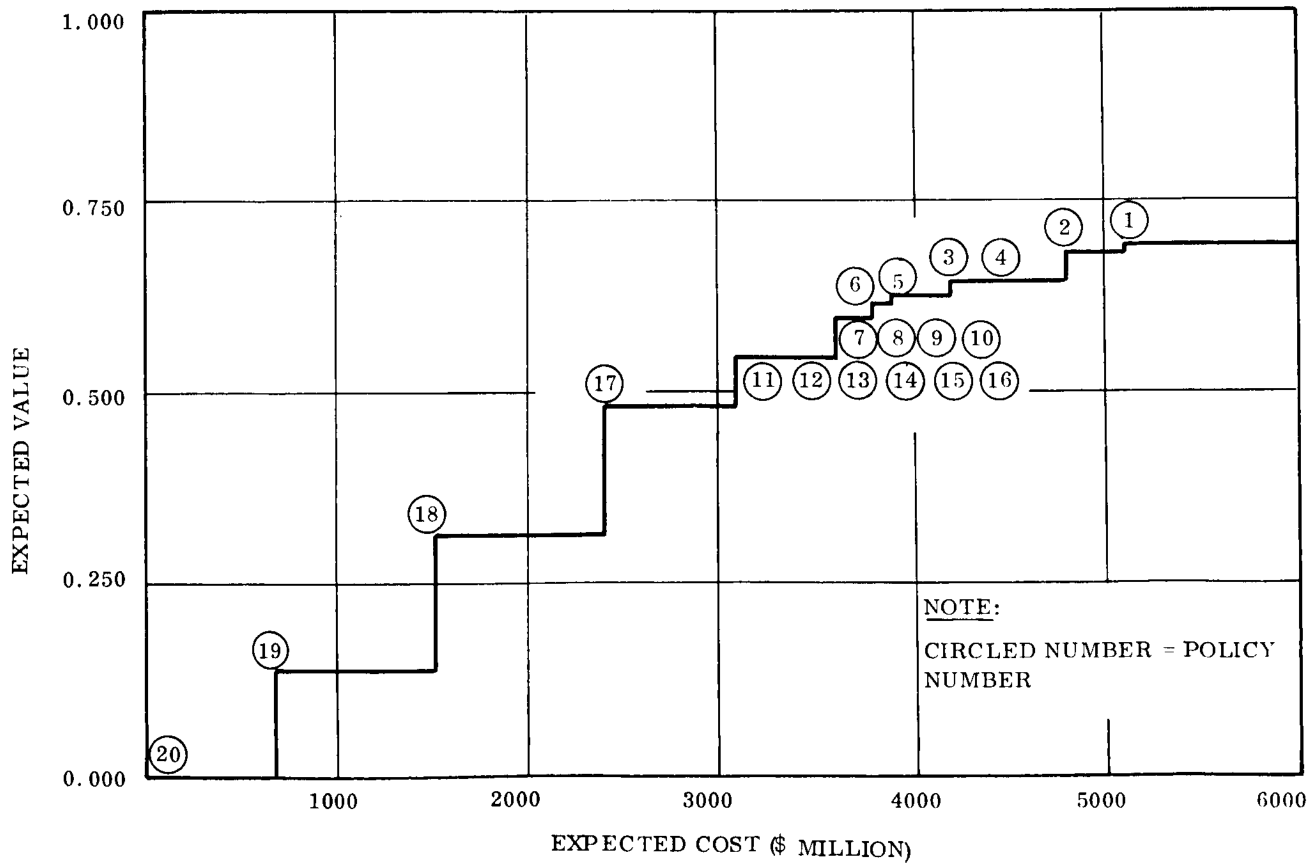


Figure 4-64. Dominant Policies for Nominal Input Data

4.12.2.3 Policy Sensitivity to Time Preference (DECPOL with value and cost discounting)

In a project such as Voyager, it may be desirable that valuable outcomes occur earlier in time and that costs are incurred later in time; this is the phenomenon of time preference. Perhaps the simplest example of time preference is a bank deposit (X) that is paying interest at a rate r per year. At the end of time period (T), the amount in the bank account will have grown to

$$Y = (1 + r)^{T} X$$

Dividing the above equation by $(1 + r)^T$, the amount of funds Y promised T years hence is worth

$$X = \left(\frac{1}{1 + r}\right)^{T} Y;$$

and if we define the discount factor

$$\beta = \left(\frac{1}{1 + r}\right),$$

then this becomes

$$X = \beta^{T} Y.$$

X is called the "present value" of Y.

In the decision tree analysis programs, when the value and cost of a node are calculated, the values and costs of its successor nodes are discounted by the discount factors β_V and β_C, respectively. These factors can be varied to test sensitivity to time preference.

For the nominal data, several policies for cost and value discounting are given in Table 4-26. In cases one through three, both costs and values were discounted by the same factor. Since values of mission outcomes occur after the cost, this has the effect of lowering the values relative to the costs. Case one is simply a repeat of the nominal policy; VMAR, VOTVSF, followed by VOVBL's. The discount factor of 0.909 in case two is equivalent to an interest rate of 10 percent. The result is that a VOLTV is substituted for the more costly VOTVSF in 1973. The discount factor of 0.833 in case three is equivalent to an interest rate of 20 percent. The result is the same as the case two policy with the addition of a stopping rule. Thus the program can be stopped after the 1979 mission (or even the 1977 mission) if three principal components of value (long term orbital operation, landed television, and life detection experiments) have been achieved.

Table 4-26. Sensitivity of Optimal Decision Policy to Value and Cost Discounting (Nominal Input Data and Dollar Evaluation)

Sensitivity Run Number	1	2	3
β_C	1.0	0.909	0.833
β_V	1.0	0.909	0.833
Policy	1971: VMAR 1973: VOTVSF 1975-81: VOVBL	1971: VMAR 1973: VOLTV 1975-81: VOVBL	1971: VMAR 1973: VOLTV 1975-77: VOVBL 1979-81: VSTOP if OOLORB and COBITV VOVBL otherwise
Expected Value	0.692	0.335*	0.181*
Expected Cost	$5.132B	$3.045B*	$1.993B*

*Discounted value and cost

Exercises discounting just value or just cost were not performed in the preliminary set of exercises. Such exercises in combination with regional search analysis are another fruitful area of investigation.

4.12.2.4 Policy Sensitivity to Risk Preference (DECRAV)

Whenever outcomes are uncertain, there is risk involved in undertaking a project. It is, of course, desirable to avoid unnecessary risk, but some "calculated" risk must be taken, for the only way to avoid all risk is to cancel the project completely. A "fair gambler" would evaluate a risky investment on an expected value basis; a risk-preferrer would evaluate the risky investment higher than its expected value; and a risk-averter would evaluate the risky investment lower than its expected value. It is useful to have a quantitative method of treating various risk preferences in the decision process.

4.12.2.4.1 Theory of Risk Preference

The descriptor of risk aversion (or risk preference) is termed the risk aversion coefficient, A. The more positive A, the more averse the decision-maker is to risk. Negative values of A denote risk preference. A = 0 denotes neither risk preference or aversion; i.e., an expected value decision-maker. For the Voyager decision analysis, the entire reasonable spectrum of risk aversion can be covered by varying A from zero to 0.01 (in units of 1/million dollars).

The basis for encoding risk perferences is the theory of utility and the generally accepted exponential utility function

$$u(x) = \frac{1 - e^{-Ax}}{1 - e^{-A}} ,$$

where A is the risk aversion coefficient. This function is plotted for A = 0, 0.5, and 1.0 in Figure 4-65. Simply stated, for positive values of A, this equation describes that the utility the decision-maker attaches to a random variable (such as value) is not directly proportional to the variable, but rather asymstatically approaches a limit (according to the given universe exponential relationship) as the variable is increased.

The counterpart of expected value in risk aversion decision-making is the certainty equivalent. In other words, at a decision node, the alternative with the highest certainty equivalent, rather than the highest expected value, is selected. Depending upon the magnitude of A, this tends to bias the decision process against those alternatives which lead to outcomes of high value but of low probability of occurrence (i.e., the "long-shot").

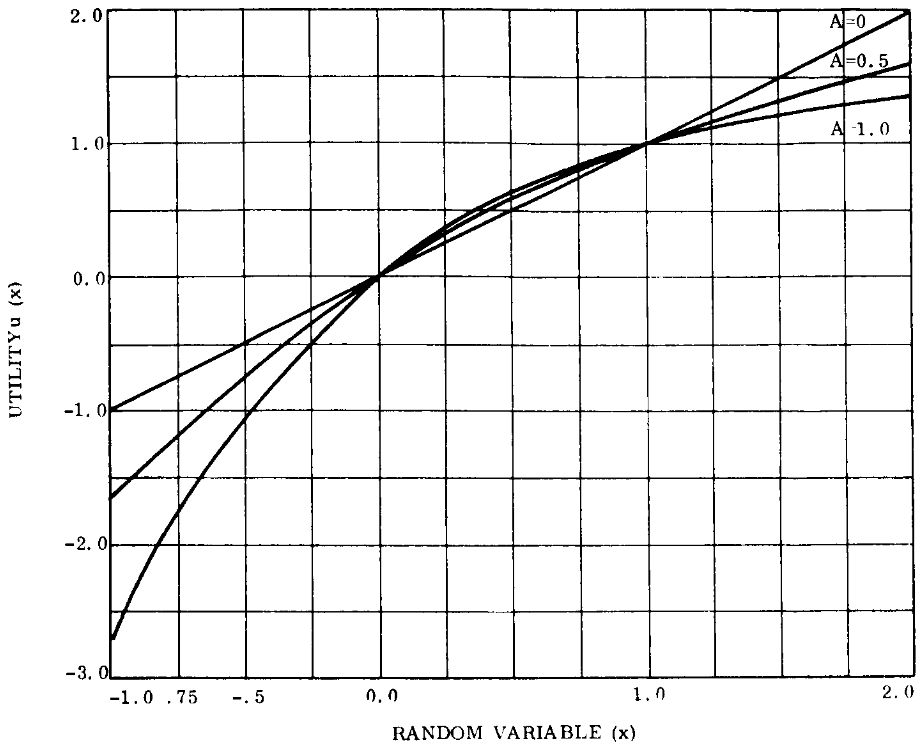


Figure 4-65. Exponential Utility Function

Mathematically, at each change node, if x_i are the values of the N possible outcomes and p(i) is the probability function of i, then the certainty equivalent, $\tilde{x}$, is given by:

$$\tilde{x} = -\frac{1}{A} \ln \sum_{i=1}^{N} e^{-Ax_i} \, p(i)$$

For A = 0, this expression reduces to

$$\tilde{x} = \sum_{i=1}^{N} x_i \, p(i) \quad ,$$

which is identically the expression for $\bar{x}$, the expected value of x.

In the risk aversion analysis program (DECRAV), the foregoing equation is used to replace each lottery on net value by its certainty equivalent. Decisions are then made by maximizing the certainty equivalent of net value.

As an example, consider the case of a 50-50 chance at a $1.00 prize; e.g., the chance to guess the flip of a coin for a $1.00 prize. The expected value decision maker (A = 0) would pay exactly 50 cents for this lottery. A risk averter would pay less according to his own value of A; specifically, he would pay the certainty equivalent for his own value of A. Figure 4-66 is a plot of certainty equivalent as a function of A for this 50-50 chance at $1.00. For example; a risk aversion coefficient of 1.0 (1/dollars) corresponds to a certainty equivalent of 38 cents.

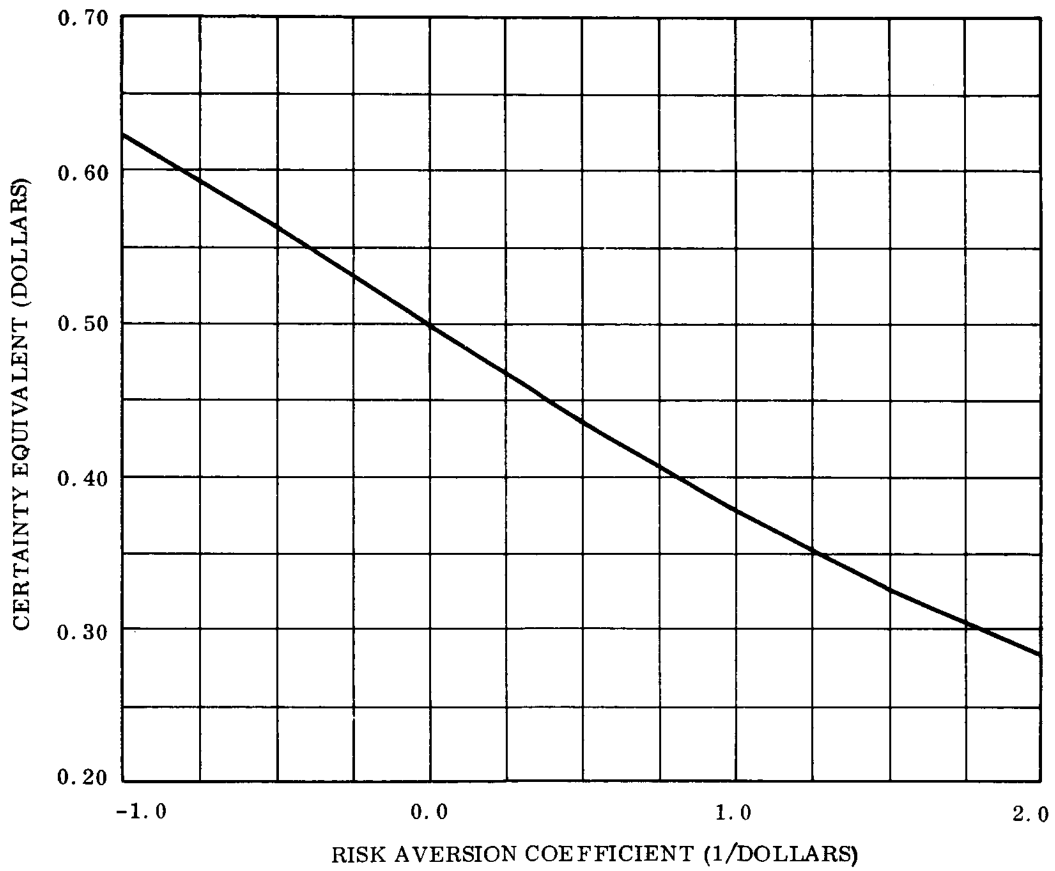


Figure 4-66. Certainty Equivalent of a 50-50 Chance of $1.00 as a Function of the Risk Aversion Coefficient A

4.12.2.4.2 Risk Sensitivity Exercises

The nominal data set was analyzed with the risk aversion program for several values of risk aversion coefficient A: 0.00001, 0.0001, 0.001, and 0.01 (in units of 1/million dollars). When the actual exercises were carried out, the results of Table 4-27 were obtained.

Since A = 0.00001 represents little risk aversion, in case four, the policy is identical to the nominal policy. In case five, a moderately risk averse case, the 1973 shot changes from a VOTVSF to a VOLTV. Case six is strongly risk averse, and the policy contains many decisions which depend on the previous outcomes in order to hedge against risk. Case seven is so strongly risk averse that the best choice is not to start the project at all and be sure of zero value and cost.

Case six demonstrates an interesting sequential policy. First a VMAR and a V2SIB are selected for 1971 and 1973. Then, if the VMAR outcome is COATM, a VODTV and a VOLTV are selected for 1975 and 1977, while otherwise a VODATM and a VODLTV are selected for these launches. In any event, a VOLTV is selected for 1979. The selection for a 1981 launch is a VOTVSF if the 1977 capsule outcome is COLAND; if it is COLTV, the 1981 launch is a VOVBL; otherwise the 1981 launch is a VOLTV.

TABLE 4-27. SENSITIVITY OF OPTIMAL DECISION POLICY TO RISK AVERSION (NOMINAL INPUT DATA AND DOLLAR EVALUATION)

Sensitivity Run Number	4a	5a	6a	7a
A	0.00001	0.0001	0.001	0.01
Policy	1971: VMAR 1973: VOTVSF 1975-81: VOVBL	1971: VMAR 1973: VOLTV 1975-81: VOVBL	1971: VMAR 1973: V2SIB 1975: VODATM if COZERO or CONOEN VODTV if COATM 1977: VODLTV if COZERO or CONOEN VOLTV otherwise 1979: VOLTV 1981: VOTVSF if COLAND VOVBL if COLTV VOLTV otherwise	1971: VSTOP
Certainty Equivalent	$8.666B	$8.160B	$1.948B	0
Expected Value	0.692	0.682	0.520	0
Expected Cost	$5.132B	$4.963B	$3.861B	0

4.12.2.5 Policy Sensitivity to Joint Time and Risk Preference (DECRAV with value and cost discounting)

Time and risk preferences can be treated together by applying the methods of Subsections 4.12.2.3 and 4.12.2.4 simultaneously. The model was analyzed for sensitivity to joint time and risk preference by using the risk aversion coefficients of the Subsection 4.12.2.4 (A = 0.00001, 0.0001, 0.001, and 0.01) and by using two discount factors: 0.909 (corresponding to 10 percent) and 0.833 (corresponding to 20 percent). The value and cost discount factors were always kept identical.

For the 0.909 discount factor, the results of Table 4-28 were obtained. Because of the discounting, the slightly risk averse case 4b selects VOLTV for 1973, rather than the nominal VOTVSF, which agrees with the corresponding expected value policy. The moderately risk averse case 5b uses the VODLTV in 1975 if the outcome of the 1971 launch is CONOEN; otherwise a VOVBL is used. The strongly risk averse case 6b uses the V2SIB in 1973, and in 1975 again the configuration choice depends on the 1971 VMAR outcome. The remainder of this policy is complicated. In the extremely risk averse case 7b the best decision is not to undertake the project.

For a discount factor of 0.833, the results of Table 4-29 were obtained. The slightly risk averse case 4c now selects VSTOP when first a VOVBL achieves OOLORB and COBITV. If this occurs before the last possible attempt in the project, one repeat VOVBL, which is under construction when the VSTOP is selected, should be launched.

For the moderately risk averse case 5c, the policy progresses more slowly. It starts with a VMAR followed by a V2SIB. In 1975 and 1977, a VOVBL is used only if the VMAR outcome was COATM; otherwise a VODTV is selected. Then, VSTOP is selected as soon as a VOVBL achieves both OOLORB and COBITV.

For moderate risk aversion (A = 0.0001), policies can be compared as a function of discount rate. For no discounting (case 5a, Table 4-27), the policy is VMAR, VOLTV, followed by VOVBL's. For a discount rate of 0.909 (case 5b, Table 4-28), basically the same policy is

TABLE 4-28. JOINT SENSITIVITY OF OPTIMAL DECISION POLICY TO DISCOUNTING AND RISK AVERSION (NOMINAL INPUT DATA AND DOLLAR EVALUATION; COST AND VALUE DISCOUNT OF 0.909)

Sensitivity Run Number	4b	5b	6b	7b
A	0.00001	0.0001	0.001	0.01
Policy	1971: VMAR 1973: VOLTV 1975-81: VOVBL	1971: VMAR 1973: VOLTV 1975: VODLTV if CONOEN VOVBL otherwise 1977-81: VOVBL	1971: VMAR 1973: V2SIB 1975: VODATM if COZERO or CONOEN VODTV if COATM REMAINDER OF POLICY COMPLICATED	1971: VSTOP
Certainty Equivalent	$3.612B	$3.265 B	$.652B	0
Expected Value	0.335*	0.333 *	0.197*	0
Expected Cost	$3.045B*	$3.034B *	$1.755B*	0

*Discounted values and costs.

TABLE 4-29. JOINT SENSITIVITY OF DECISION POLICY TO DISCOUNTING AND RISK AVERSION (NOMINAL INPUT DATA AND DOLLAR EVALUATION; COST AND VALUE DISCOUNT OF 0.833)

Sensitivity Run Number	4c	5c	6c	7c
A	0.00001	0.0001	0.001	0.01
Policy	1971: VMAR 1973: VOLTV 1975-77: VOVBL 1979-81: VSTOP if OOLORB and COBITV VOVBL otherwise	1971: VMAR 1973: V2SIB 1975: VOVBL if COATM VODTV otherwise 1977: VODTV if OOZERO and CONOEN, or OONORB and CONOEN VOVBL otherwise 1979-81: VSTOP if OOLORB and COBITV VOVBL otherwise	1971: VMAR 1973: V2SIB 1975: VODATM if COZERO or CONOEN VSTOP if COATM 1977: VSTOP	1971: VSTOP
Certainty Equivalent	$1.606B	$1.402B	$0.194B	0
Expected Value	0.181*	0.168*	0.082*	0
Expected Cost	$1.993B*	$1.762B*	$0.769B*	0

*Discounted values and costs.

used, except for a possible VODLTV in 1975. For a discount rate of 0.833 (case 5c, Table 4-29), the policy changes markedly, starting with VMAR and V2SIB, followed by VOVBL's if the VMAR achieves COATM, but otherwise a VODTV is in 1975 and 1977, then followed by VOVBL's. If a VOVBL achieves both OOLORB and COBITV, VSTOP is selected.

4.2.12.6 Launch Vehicle Redundancy

In this section, the tradeoff between a project employing one Saturn V at each (Saturn) opportunity and one employing two Saturn V's at each opportunity is analyzed.

Figure 4-67 is a plot of the net expected value of the project as a function of Saturn V reliability for one and two Saturn V's per launch. Both input data and project evaluation were held at nominal values in the runs of Figure 4-67, and the Saturn V launch vehicle reliability (PA4 of Table 4-6) was varied once above and once below its nominal value of 0.8.

It can be seen from the figure that the crossover in launch vehicle reliability (through interplanetary injection) is at about 0.79 for nominal input data and project evaluation. Above this reliability, the cost of the additional Saturn V does not seem to be merited by its incremental increase in project value. Below it, two Saturn V's per opportunity would seem preferable. This conclusion must, however, be qualified as tentative subject to analysis of its sensitivity to input values, costs, and probabilities, and to the project evaluation factor λ.

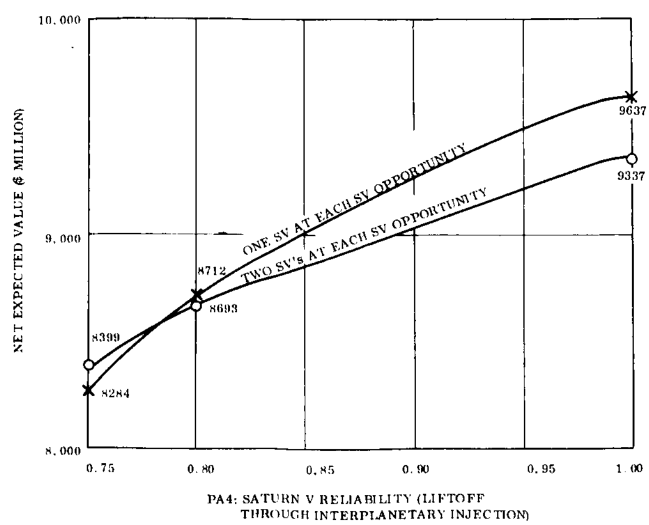


Figure 4-67. Project Net Expected Value as a Function of Saturn V Launch Vehicle Reliabil[ity]

4.13 CONCLUSIONS AND RECOMMENDATIONS

The objective of this effort was to develop a logical procedure for selecting Voyager mission configurations which reflected technical feasibility, NASA project objectives, the economic environment of the project, and was dynamically adaptive to project history. The treatment of these factors on a quantitative basis provided an accurate language for communication. In the course of this work, many discussions over value systems and probability assignments were enhanced by the availability of this language.

This report presents the evolution of the mission configuration decision model from the underlying philosophy of decision analysis through a pilot phase and finally to the full-scale phase. Illustrative results of the full-scale phase are presented in the Section 4.12.

The decision model results of the Section 4.12 utilize exclusively nominal probabilities, costs, and values, as derived in Sections 4.8 through 4.10. No attempt was made to examine the sensitivity of the resulting policies to variations in these three critical variables. In this respect, the results of Section 4.12 and the implications must be considered preliminary in nature.

Nevertheless, several trends in the results seem to be strong enough to draw a few general conclusions:

First, for the nominal costs, probabilities, and (particularly) values previously discussed, an ambitious unmanned Mars project seems to offer the highest return of expected value. In 1971, a Mariner flyby with an atmospheric probe (VMAR) is suggested. In 1973, large surface landers with extensive television and physical experiment capability (VOTVSF) are proposed. From 1975 through 1981, landers of the VBL class are desirable.

This project profile is not too different from the current (July 1967) NASA plan for Mariner/ Voyager Mars. Differences exist principally in the 1973 mission, in which NASA plans a medium lander more of the VOLTV class, and in the addition of the 1981 mission.

Interestingly enough, if preference for risk aversion and value and cost discounting is added to the decision procedure, policies even more similar to the unmanned Mars project profile result. The VOTVSF choice in 1973 reverts to VOLTV, and the last mission of the series can be earlier than 1981, provided that satisfactory outcomes have been realized.

Inference can be drawn from the results of the preceding section that the use of single non-survivable capsules with Voyager spacecraft (VOATM and VODTV) is usually not desirable. Dual capsule configurations (per spacecraft) with nonsurviving capsules, where the first capsule enters prior to orbit insertion and the second after achieving orbit (i.e. VODATM, VODDTV, and VODLTV), are occasionally recommended in tradeoff policies.

For Saturn V launch vehicle reliabilities (through interplanetary injection) above 0.8, multiple Saturn V vehicles per opportunity do not seem to be justified economically. Since current SV reliability estimates are usually greater than or equal to this figure, it would appear that a project profile employing single Saturn V's per opportunity is the more desirable.

It is strongly recommended that further sensitivity analyses be performed on the decision model. In particular, the sensitivity of the optimal policies to value apportionments, probability assessments, and project evaluation should be investigated in detail. Various tradeoff policies of lesser value and cost than the optimal policy should also be analyzed in detail to obtain a more complete picture of the options available for project planning.

The natural continuation of this work is to further exercise and develop this decision-making tool. In order to carry this out most profitably, it is important that NASA Voyager personnel in responsible decision making positions, and their staff, become familiar with the potential applications of this model. In this way, important feedback can be provided for further development, and equally important understanding can be developed in NASA so that this decision tool can ultimately be fully utilized.