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SUBSYSTEM SIMULATION
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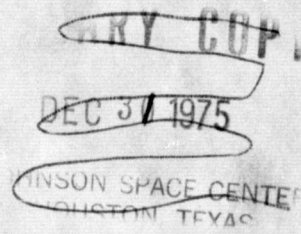
Task Report #5 (TR-5)

(NASA-CR-151005) SIMULATION VERIFICATION
TECHNIQUES STUDY. SUBSYSTEM SIMULATION
VALIDATION TECHNIQUES (McDonnell-Douglas
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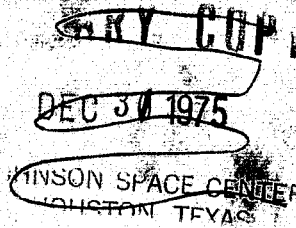
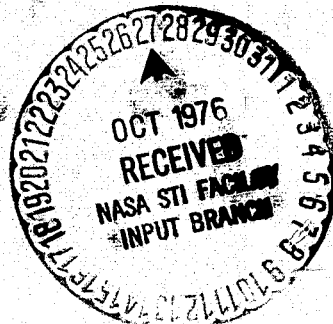
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T E C H N I Q U E S S T U D Y

Task Report #5 (TR-5)

SUBSYSTEM SIMULATION VALIDATION TECHNIQUES

30 December 1974

MDC E1201

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Prepared for: National Aeronautics and Space Administration
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Submitted under Contract NAS 9-13657

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LIST OF PAGES

ii to xii

1-1 to 1-2

2-1

3-1 to 3-4

4.1-1 to 4.1-3

4.2-1 to 4.2-2

4.3-1 to 4.3-7

4.4-1 to 4.4-3

4.5-1 to 4.5-5

4.6-1 to 4.6-3

4.7-1 to 4.7-408

5-1 to 5-5

6-1

7-1 to 7-5

TABLE OF CONTENTS

	<u>PAGE</u>
LIST OF FIGURES	v-x
LIST OF TABLES	xi-xii
SECTION 1 SUMMARY	1-1
SECTION 2 INTRODUCTION	2-1
SECTION 3 STUDY OBJECTIVES AND SCOPE	3-1
SECTION 4 STUDY TECHNICAL RESULTS	4.1-1
4.1 PERFORMANCE PARAMETER GUIDELINES	4.1-1
4.2 ALTERNATE REFERENCE DATA SOURCES	4.2-1
4.3 ENVIRONMENT MODULES	4.3-1
4.4 CREW STATION MODULES	4.4-1
4.5 VEHICLE CONFIGURATION MODULES	4.5-1
4.6 VEHICLE DYNAMICS MODULES	4.6-1
4.7 VEHICLE SUBSYSTEMS MODULES	4.7-1
4.7.1 Mechanical Subsystems	4.7-2
4.7.1.1 Landing/Deceleration Subsystem	4.7-2
4.7.1.2 Docking Mechanism	4.7-22
4.7.1.3 Separation Mechanisms	4.7-32
4.7.1.4 Actuation Mechanisms	4.7-63
4.7.1.5 Payload Deployment and Retrieval System	4.7-77
4.7.1.6 Hydraulic Power Subsystem	4.7-91
4.7.2 Purge and Vent Subsystem	4.7-98
4.7.3 Propulsion and Fuel Systems	4.7-102
4.7.3.1 Main Propulsion System and External Tank	4.7-102
4.7.3.2 Reaction Control Subsystem	4.7-130
4.7.3.3 Orbital Maneuvering System	4.7-157
4.7.3.4 Solid Rocket Motors	4.7-173
4.7.4 Power Generation Subsystems	4.7-182
4.7.4.1 Electrical Power Generation	4.7-182
4.7.4.2 Auxiliary Power Generation	4.7-199
4.7.5 Avionics Subsystems	4.7-220
4.7.5.1 Guidance, Navigation and Control	4.7-220
4.7.5.1.1 Inertial Measurement Unit	4.7-221
4.7.5.1.2 Strapdown Inertial Sensors	4.7-233
4.7.5.1.3 Propulsion Systems Interface Units	4.7-241
4.7.5.1.4 Star Tracker	4.7-245
4.7.5.1.5 Aero-Flight Control System	4.7-271

	<u>PAGE</u>
4.7.5.2 Communications and Tracking Subsystem	4.7-282
4.7.5.3 Controls and Displays	4.7-296
4.7.5.4 Operational Instrumentation	4.7-302
4.7.5.5 Electrical Power Distribution and Control	4.7-303
4.7.6 Environmental Control/Life Support System	4.7-318
4.7.6.1 Atmospheric Revitalization System	4.7-318
4.7.6.1.1 Atmospheric Revitalization Pressure Control System	4.7-319
4.7.6.1.2 Atmosphere Revitalization - Cabin Atmosphere Control Subsystem	4.7-370
4.7.6.2 Active Thermal Control System	4.7-386
4.7.6.3 Food, Water and Waste Management	4.7-400
 SECTION 5 METHODS FOR VALIDATING PERFORMANCE	 5-1
5.1 Validation Software Structure	5-1
5.2 Data Acquisition and Formatting	5-4
5.3 Comparison Methods and Criteria	5-4
 SECTION 6 CONCLUSIONS AND RECOMMENDATIONS	 6-1
 SECTION 7 REFERENCES	 7-1

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
3-1	Subsystem/Module Categories Covered	3-3
4.3-1	Natural Environment Module Interfaces	4.3-2
4.3-2	Ground Nav/Comm Module Interfaces	4.3-4
4.3-3	Payload/Target Module Interfaces	4.3-6
4.3-4	Prelaunch/Launch Module Interfaces	4.3-7
4.4-1	Visual System Software and Hardware Interfaces	4.4-2
4.4-2	Motion Base Software Interfaces	4.4-3
4.5-1	Aerodynamics Module Interfaces	4.5-2
4.5-2	Aerothermodynamics Module Interfaces	4.5-4
4.5-3	Mass Properties Module Interfaces	4.5-5
4.6-1	Overview of Dynamics Module Interfaces	4.6-1
4.7-1	Main Landing Gear Installation	4.7-3
4.7-2	Nose Gear Installation	4.7-5
4.7-3	LDS Nose Gear Steering Unit Design	4.7-6
4.7-4	LDS Main Gear Brake Anti-Skid Control	4.7-7
4.7-5	Chute Deployment Sequence	4.7-8
4.7-6	LDS Module Interfaces	4.7-11
4.7-7	LDS Reference Module Math Flow	4.7-12
4.7-8	Main Gear Air Spring Characteristics	4.7-21
4.7-9	Active and Passive Docking Mechanisms	4.7-23
4.7-10	DMS Module Interfaces	4.7-28
4.7-11	DMS Reference Module Functional Flow	4.7-29
4.7-12	Orbiter/ET and ET/SRB Attach Points	4.7-33
4.7-13	Typical Forward ET/SRB Separation Fitting	4.7-34
4.7-14	Typical Aft ET/SRB Separation Fitting	4.7-35

<u>FIGURE</u>		<u>PAGE</u>
4.7-15	Solid Rocket Booster	4.7-36
4.7-16	Nominal SRB Separation	4.7-37
4.7-17	Forward Orbiter/ET Separation Fitting	4.7-38
4.7-18	Aft Orbiter/ET Separation Fitting	4.7-39
4.7-19	Orbiter/ET Separation Maneuver	4.7-40
4.7-20	Separation Mechanisms Module Interfaces	4.7-42
4.7-21	Orbiter/ET Aft Separation Mechanism Reference Module	4.7-45
4.7-22	Block Diagram, Electromechanical Actuator	4.7-64
4.7-23	Block Diagram, Hydraulic Actuator	4.7-64
4.7-24	Feedback Control System Block Diagram	4.7-66
4.7-25	Electromechanical Actuator Module Interfaces	4.7-67
4.7-26	Hydraulic Actuator Module Interfaces	4.7-70
4.7-27	Actuator Reference Module Functional Flow Diagram	4.7-71
4.7-28	Reference Data OMS Gimbal Actuator Response	4.7-74
4.7-29	Reference Data OMS Gimbal Actuator Response	4.7-75
4.7-30	PDRM Mechanical Components	4.7-79
4.7-31	Simplified FUO Joint Reactions	4.7-81
4.7-32	PDRS Module Interfaces	4.7-84
4.7-33	PDRS Reference Module Functional Flow	4.7-86
4.7-34	HPS Schematic	4.7-92
4.7-35	HPS Module Interfaces	4.7-94
4.7-36	HPS Reference Module Functional Flow	4.7-95
4.7-37	HPS Load Profile	4.7-97
4.7-38	Purge Subsystem Flow Diagram	4.7-99
4.7-39	Orbiter Purge and Vent Subsystem	4.7-100
4.7-40	Main Propulsion Subsystem Schematic	4.7-104

<u>FIGURE</u>		<u>PAGE</u>
4.7-41	Main Propulsion Helium System	4.7-105
4.7-42	SSME Schematic	4.7-106
4.7-43	Orbiter Main Propulsion Subsystem	4.7-107
4.7-44	MPS Dedicated Displays	4.7-108
4.7-45	MPS Manual Controls	4.7-109
4.7-46	MPS/ET Module Interfaces	4.7-116
4.7-48	SSME Reference Module Elements	4.7-118
4.7-49	MPS/ET Reference Module Math Flow	4.7-120
4.7-50	High Pressure Fuel Turbine Torque Characteristics	4.7-128
4.7-51	RCS Forward Module Thruster Schematic	4.7-131
4.7-52	RCS Aft Module Thruster Schematic	4.7-132
4.7-53	Interconnected OMS & RCS Schematic	4.7-133
4.7-54	RCS Module Interfaces	4.7-135
4.7-55	RCS Reference Module Subroutine RCSENG	4.7-141
4.7-56	Interconnected OMS & RCS Schematic	4.7-158
4.7-57	OMS Left Pod Measurements Schematic	4.7-159
4.7-58	OMS Engine Measurements Schematic	4.7-160
4.7-59	OMS Payload Bay Kit Measurements Schematic	4.7-161
4.7-60	OMS Module Interfaces	4.7-162
4.7-61	OMS Thrust Reference Module	4.7-167
4.7-62	Reference Module Coordinate Systems	4.7-170
4.7-63	SRM Simulation Module Interfaces	4.7-174
4.7-64	SRM Reference Module Math Flow	4.7-177
4.7-65	Electrical Power Generation: FCP Subsystem Schematic	4.7-183
4.7-66	EPG: Fuel Cell Power Plant Schematic	4.7-184
4.7-67	Power Reactant Storage and Distribution Subsystem Schematic	4.7-186

<u>FIGURE</u>		<u>PAGE</u>
4.7-68	Electrical Power Generation Module Elements and Interfaces	4.7-187
4.7-69	Basic EPG Verification Data Source Flow Chart	4.7-194
4.7-70	PRSD Reference Module Overall Math Flow	4.7-196
4.7-71	PRSD Source Tank Reference Module Math Flow	4.7-197
4.7-72	Math Flow For Fluid Flow Calculations	4.7-198
4.7-73	APU Subsystem Operational Measurements	4.7-200
4.7-74	APU Module Elements and Interfaces	4.7-202
4.7-75	Flow Chart for APU Verification	4.7-205
4.7-76	APU Reference Module Math Flow	4.7-208
4.7-77	IMU Module Interfaces	4.7-222
4.7-78	Constant Rate Input Method	4.7-227
4.7-79	Closed Form Gimbal Angle Method	4.7-230
4.7-80	IMU Simulation Verification Techniques	4.7-232
4.7-81	Strapdown Inertial Sensor Module Interfaces	4.7-234
4.7-82	Strapdown Inertial Sensor Reference Module Math Flow	4.7-236
4.7-83	MEC/EIU Hardware Interfaces	4.7-242
4.7-84	Star Tracker Physical Arrangement	4.7-246
4.7-85	Star Tracker Functional Block Diagram	4.7-247
4.7-86	Typical Scan-Pattern Relationships	4.7-249
4.7-87	Star Tracker Module Interfaces	4.7-252
4.7-88	Star Tracker Reference Module Math Flow	4.7-253
4.7-89	Air Data System Functional Configuration (Orbiter 103)	4.7-274
4.7-90	Internal ADTA Functional Configuration	4.7-274
4.7-91	ADS Module Interfaces	4.7-276
4.7-92	Air Data System Reference Module	4.7-278

<u>FIGURE</u>		<u>PAGE</u>
4.7-93	Communications and Tracking Subsystem Block Diagram	4.7-283
4.7-94	Communications and Tracking Module Interfaces	4.7-285
4.7-95	Communications and Tracking Reference Module Math Flow	4.7-287
4.7-96	Coordinate Systems for Communications and Tracking	4.7-293
4.7-97	Communications and Tracking Check Point Generation Math Flows	4.7-294
4.7-98	Controls and Displays Module Interfaces	4.7-299
4.7-99	Electrical Power Distribution and Control Subsystem Schematic	4.7-304
4.7-100	Illumination Subsystem Schematic	4.7-305
4.7-101	EPD&C Module Elements and Interfaces	4.7-306
4.7-102	EPD&C Reference Module Math Flow	4.7-310
4.7-103	EPD&C Equivalent Circuit and Matrix Definitions	4.7-313
4.7-104	Atmosphere Revitalization Pressure Control Subsystem Schematic	4.7-320
4.7-105	Atmosphere Pressure Control, Airlock Support Subsystem Schematic	4.7-321
4.7-106	ARPCS Module Elements and Interfaces	4.7-326
4.7-107	Manifold Gas Reference Module Math Flow	4.7-336
4.7-108	Cabin Pressure Control Reference Module Math Flow	4.7-339
4.7-109	N ₂ Source/Distribution Network Reference Module Math Flow	4.7-350
4.7-110	N ₂ Source Flow Chart	4.7-356
4.7-111	Fluid Flow Subroutine Flow Chart	4.7-358
4.7-112	ARPCS Check-Point Driver Flowchart	4.7-360
4.7-113	ARPCS Checkpoint Sequence Flowchart	4.7-366
4.7-114	Environment Control and Life Support Subsystem Schematic	4.7-371
4.7-115	ECLSS Cabin Temperature, Humidity, and CO ₂ Control Schematic	4.7-372

<u>FIGURE</u>		<u>PAGE</u>
4.7-116	Primary Water Coolant Loop Schematic	4.7-373
4.7-117	Cabin Atmosphere Control System Module Elements and Interfaces	4.7-375
4.7-118	Water Coolant Loop Reference Module Flowchart	4.7-381
4.7-119	Cabin Atmosphere Control Reference Module Flowchart	4.7-384
4.7-120	Active Thermal Control System Schematic	4.7-387
4.7-121	ATCS Module Elements and Interfaces	4.7-390
4.7-122	ATCS Verification Overview	4.7-395
4.7-123	ATCS Reference Module Math Flow	4.7-397
4.7-124	ECLSS Water Management Subsystem	4.7-401
4.7-125	ECLSS Waste Management Subsystem	4.7-402
4.7-126	Potable Water Management Flow Chart	4.7-405
5-1	Validation Software Overall Flow	5-2

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
4.2-1	Alternate Data Sources: Pros & Cons	4.2-2
4.7-1	LDS Module Performance Parameters	4.7-10
4.7-2	DMS Initial Contact Limits	4.7-24
4.7-3	DMS Module Performance Parameters	4.7-26
4.7-4	Separation Mechanisms Module Performance Parameters	4.7-43
4.7-5	AMS Modules Performance Parameters	4.7-68
4.7-6	Check Case Commands for Aero Surface Actuator Response	4.7-73
4.7-7	PPRS Module Performance Parameters	4.7-82
4.7-8	HPS Module Parameters	4.7-93
4.7-9	P&V Module Parameters	4.7-101
4.7-10	MPS/ET Module Parameters	4.7-111
4.7-11	MPS/ET Onboard Processed Parameters	4.7-114
4.7-12	SSME Digital Model Subroutines	4.7-119
4.7-13	RCS Module Forward Parameters	4.7-136
4.7-14	RCS Module Aft Parameters	4.7-139
4.7-15	OMS Module Parameters	4.7-163
4.7-16	OMS Check Case Example	4.7-172
4.7-17	Solid Rocket Motor Module Parameters	4.7-175
4.7-18	SRM Reference Module Data Base Requirements	4.7-181
4.7-19	EPS Fuel Cell Parameters	4.7-188
4.7-20	EPS Power Reactant Storage and Distribution Parameters	4.7-189
4.7-21	APU Reference Module Parameters List	4.7-203
4.7-22	IMU Module Parameters	4.7-224

<u>TABLE</u>		<u>PAGE</u>
4.7-23	Strapdown Inertial Sensor Module Parameters	4.7-235
4.7-24	Star Tracker Module Parameters	4.7-251
4.7-25	Air Data System Module Parameters	4.7-275
4.7-26	Reference Module Data Base Source List	4.7-281
4.7-27	Communications and Tracking Module Parameters	4.7-284
4.7-28	Control and Display Module Parameters	4.7-300
4.7-29	EPD&C Module Parameters	4.7-307
4.7-30	ARPCS Module Parameters	4.7-327
4.7-31	Water Coolant Loop Model Input Data	4.7-376
4.7-32	Water Coolant Loop Model Output Data	4.7-377
4.7-33	Cabin Atmosphere Module Performance Parameters	4.7-378
4.7-34	Active Thermal Control Module Parameters	4.7-391
4.7-35	Food, Water and Waste Management Module Parameters	4.7-404
5-1	Validation Subroutines	5-3

SECTION 1

SUMMARY

This report discusses techniques for validation of software modules which simulate spacecraft onboard systems. The results presented in this report represent a portion of Task 2 -- the performance verification task -- of the Simulation Validation Techniques Study (SVTS). Task 2 is concerned with simulation validity; i.e., fidelity of representation of the real world. The outputs of this study task will support validation of the next generation of training and procedures-development simulators at JSC.

Specifically, these results will enable NASA/contractor personnel to:

- o obtain the basic reference data which establishes standards of simulation performance
- o develop the support software needed for check case generation and data formatting
- o develop the support software needed for realtime performance data acquisition and subsequent processing.

Section 3 of this report defines the objectives of this study task. Section 3 also provides an overview of the simulation software hierarchy for a Shuttle mission simulator. The major categories of simulation software are environment, crew station, vehicle configuration, vehicle dynamics, and vehicle subsystems. Vehicle subsystems simulation modules are covered in this report; all other categories were covered in a previous report (Ref. 1).

Section 4 presents the technical results of Task 2. Section 4.1 presents a set of guidelines for the identification of subsystem/module performance

parameters and "critical" performance parameters. Section 4.2 identifies various sources of reference data to serve as standards of performance for simulation validation.

Sections 4.3-4.6 very briefly discuss the environment, crew station, vehicle configuration, and vehicle dynamics simulation software, from the point of view of their interfaces with subsystem simulation software modules.

Section 4.7 provides a detailed presentation of our study results in the area of vehicle subsystems simulation modules. The vehicle subsystem hierarchy is expanded down to the lowest level modules of interest for performance verification. For each Vehicle Subsystem, we present a description of the subsystem, and a definition of the simulation software module for that subsystem (including a module interface diagram and a list of performance parameters). Sources of reference data for module validation are discussed, and a flowchart of a suitable reference module is provided. Finally, validation techniques appropriate to that module are identified, static and/or dynamic check case requirements are defined, and an estimate is made of the data base impact for module validation.

Section 5 presents our conclusions and recommendations. Section 6 is a list of references.

SECTION 2 INTRODUCTION

This report presents Subsystem simulation performance verification techniques defined during the Simulation Verification Techniques Study (SVTS) being conducted for NASA's Johnson Space Center under Contract NAS 9-13657. This study is being performed by McDonnell Douglas Astronautics Company - East at its Houston Operations facility. Keith L. Jordan, Simulation Development Branch, FSD, is Technical Monitor of the contract for the NASA.

The Simulation Verification Techniques Study is one of a number of studies being conducted by NASA-JSC in support of the development of training and procedures-development simulators for the Space Shuttle Program. The other studies were: Shuttle Vehicle Simulation Requirements, NAS 9-12836; Space Shuttle Visual Simulation System Design Study, NAS 9-12651, performed by McDonnell Douglas Electronics Company; Development of Simulation Computer Complex, NAS 9-12882; Crew Procedures Development Techniques, NAS 9-13660; and Advanced Crew Procedures Development Techniques, NAS 9-14354. The latter three studies were performed by McDonnell Douglas Astronautics Company - East at Houston Operations.

The present study is concerned with the development of self-test techniques for simulation hardware, and the validation of simulation performance. The report for the Hardware Verification Task (Ref. 2) has already been published. A report describing all results of SVTS Task 2 will be published at the end of January 1975.

SECTION 3

STUDY OBJECTIVES AND SCOPE

This report covers a portion of the work done under WBS 2.0 of the Simulation Verification Techniques Study.

3.1 PURPOSE

The purpose of WBS 2.0 is to develop methods for verifying simulation fidelity with respect to the real world; i.e., to ensure that the simulator responses presented to the crew are indiscernible from those which will be experienced during actual flight. During simulator development, performance verification (validation) is performed on individual software modules, at various stages of integration, and finally for the all-up simulator system. In addition, revalidation will be necessary from time to time during the simulator's operational lifetime, as modifications are made to hardware and/or software.

The outputs of this study task will support validation of the next generation of training and procedures-development simulators at JSC. Specifically, these results will enable NASA/contractor personnel to:

- o obtain the basic reference data which establishes standards of simulation performance
- o develop and use the support software needed for check case generation and data formatting
- o develop and use the support software needed for realtime performance data acquisition and subsequent processing.

WBS 2.0 is divided into three subtasks:

- o WBS 2.1, Definition of Performance Parameters: Analyze each Shuttle subsystem and simulation module; define a set of parameters which completely describe each subsystem/module.
- o WBS 2.2, Establishing Standards of Performance: Define methods to provide reference data to serve as standards of performance for module validation (e.g., batch programs, test data). Define data formats, determine data base impact.
- o WBS 2.3, Methods for Validating Performance: Define methods for realtime performance data acquisition and comparison with reference data; define comparison criteria.

3.2 SCOPE OF THIS REPORT

Each of these subtask efforts must be applied in the context of each subsystem/module, as well as in the context of integrated simulator system operation. Because of the considerable body of specialized information required, it is convenient to work on the performance parameter identification, reference data sources and validation methods peculiar to a module all at once, rather than dealing with different aspects of a particular module at three widely-separated times. For that reason, this report is organized on the basis of the simulation software module hierarchy, and includes module-oriented efforts which fall under all three WBS subtasks.

Figure 3-1 shows an overview of the simulation software module hierarchy developed for use in WBS 2.0. The software categories covered in our previous (Ref. 1) report -- Environment, Crew Station, Vehicle

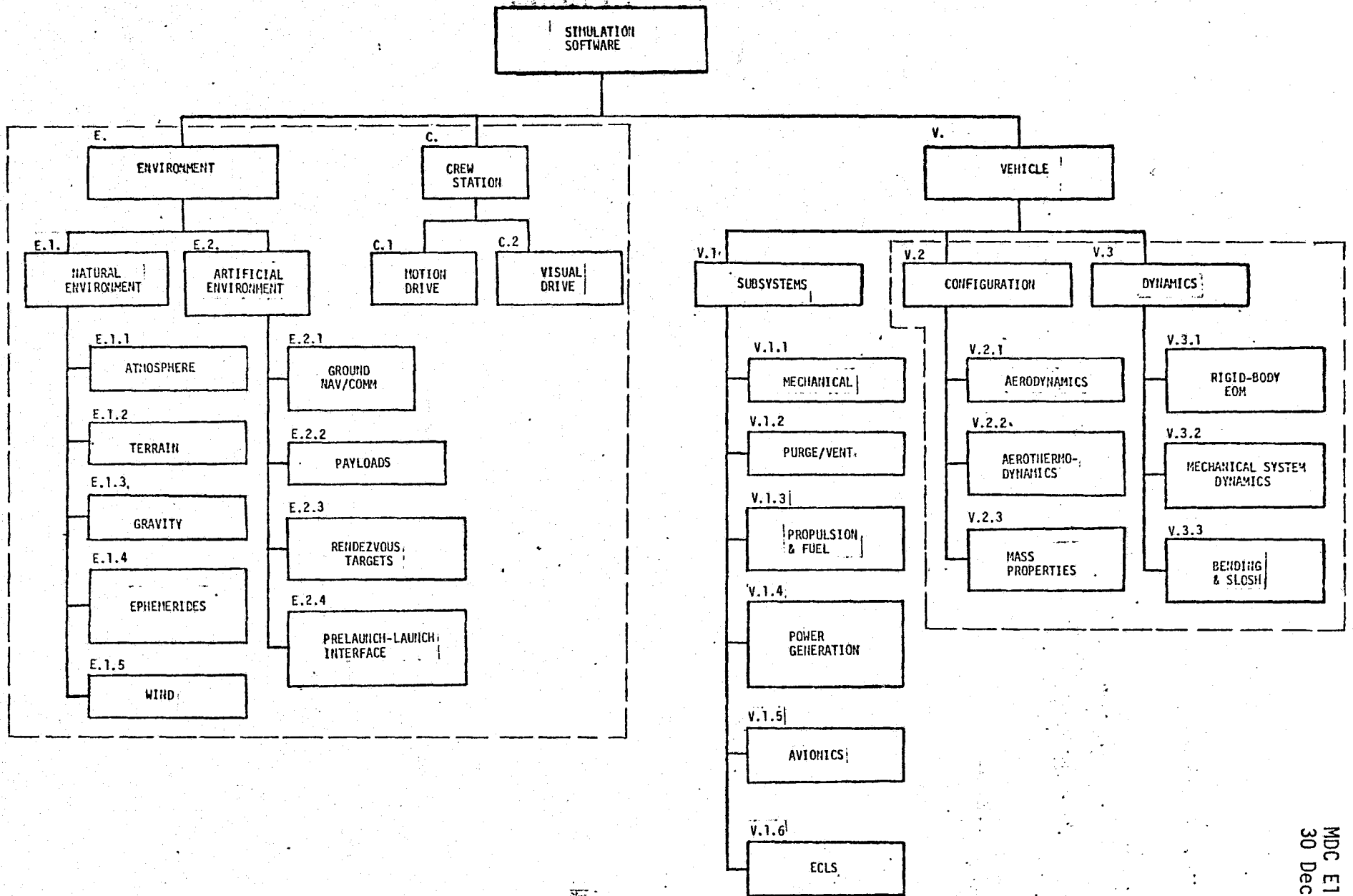


FIGURE 3-1 SUBSYSTEM/MODULE CATEGORIES COVERED IN THIS REPORT.

Configuration, and Vehicle Dynamics -- are enclosed in the dotted lines. This report covers vehicle subsystems simulation modules.

For each module covered, this report provides a description of the module's functions and operational modes, its stored data and inputs, and its performance parameters (including "critical" performance parameters as defined below). Sources of reference (standards) data are identified, and performance-verification techniques and support software are briefly discussed. Validation data base impact for each module is defined.

SECTION 4

STUDY TECHNICAL RESULTS

The focus of this report is vehicle subsystems simulation module validation, discussed in considerable detail in Section 4.7. Sections 4.1-4.6 provide brief introductory material to define the context in which the subsystems simulation analyses were performed.

4.1 PERFORMANCE PARAMETER GUIDELINES

In performing an analysis of each onboard subsystem and simulation software module, we must extract from its basic defining information a list of performance parameters, which completely describe the performance of the subsystem/module. By this we mean that any error or inadequacy in the simulation must show up in one or more of the designated performance parameters. We envision such a complete performance parameter list to be useful primarily in the exhaustive initial validation of the simulator.

In addition, we have further examined the complete parameter list for each module, designating a subset thereof as "critical" performance parameters. The primary utility of the critical performance parameter list would be in revalidating simulation modules after modifications or updates; we assume that if a module's critical parameters provide acceptable fidelity, it will not be necessary to check the rest of the performance parameters. Criteria for identification of performance parameters and critical performance parameters are given below.

4.1.1 Performance Parameters

The performance parameters for any onboard subsystem simulation module or for the total vehicle system simulation must have the following properties:

- a. They must be real-world variables (either continuous or discrete). Thus, synthetic variables which are defined for analysis and programming purposes -- e.g., auxiliary angles, counters, initialization flags -- cannot be performance parameters.
- b. They must be time-variable quantities, not constants; e.g., aerodynamic-coefficient tables are not performance parameters.
- c. All system "state variables" are performance parameters. (State variables may be defined as the dependent variables in the system differential equations, when the equations have been reduced to first order).
- d. Some outputs of a module may not be performance parameters. Outputs unrelated to the module's designated functions (e.g., power consumed and heat dissipated by an IMU) are "incidental outputs", not performance parameters.
- e. Some performance parameters of a module may not be outputs. Internal variables (either continuous or discrete) not normally output from a module will still be performance parameters, if they are real-world variables, and are essential to the representation of the performance parameters which are outputs.
- f. Every variable available to a flight computer or telemetered for ground-controller use should be a performance parameter of some module.

- g. Inputs to a module are never performance parameters for that module. (This rule prevents double-counting; thus no variable will ever be a performance parameter for more than one module.)

4.1.2 Critical Performance Parameters

Guidelines for selection of a subset of critical performance parameters from the set of performance parameters of a module are somewhat less clear-cut than those for initial selection of performance parameters. A performance parameter may be denoted as a critical performance parameter for one or more of the following reasons:

- a. It is a particularly significant indicator of simulation validity for its associated module.
- b. Its accuracy has a long-term or cumulative impact upon the simulation validity; e.g., orbital drag forces, consumables expenditure rates.
- c. It is readily available to the crew (by permanent or callable display), and plays a key role in crew operational procedures.
- d. It is communicated to the flight computer(s) and plays a key role in computer control of vehicle systems.

4.2 ALTERNATE REFERENCE-DATA SOURCES

The Standards of Performance sought in this task are sources of reference data representing the real world, against which the simulation fidelity is to be evaluated. Four basic classes of reference-data source are considered in this study:

- o Closed-form solutions: exact or approximate formulas giving answers to be compared to the output of simulation routines.
- o Independent math models: parallel software development for the explicit purpose of providing reference data for module validation.
- o Existing analysis/simulation programs: established, previously-validated programs which can be exercised with check-case data to provide outputs directly comparable to simulation module outputs.
- o Test data: vehicle and/or subsystem data from an actual laboratory or flight environment.

Table 4.2-1 briefly lists advantages and disadvantages of each of the four basic classes of reference-data source. These considerations will be discussed in greater detail in a later report.

TABLE 4.2-1 ALTERNATE DATA SOURCES: PROS & CONS

DATA SOURCE	ADVANTAGES	DISADVANTAGES
Closed-Form Solutions	Simplicity Accuracy	Feasibility Scope
Independent Math Models	Scope Compatibility Control	Workload
Existing Analysis/Simulation Programs	Scope	Availability Documentation Incompatibility
Test Data	Fidelity	Timeliness Availability Scope Incompatibility Documentation

4.3 ENVIRONMENT MODULES

Environmental conditions external to the Shuttle vehicle interface with and influence the performance of the vehicle and its subsystems. The total environment is considered in two basic divisions -- natural environment and artificial environment.

4.3.1 Natural Environment

The natural environmental factors influencing the Shuttle vehicle include the earth's atmosphere, winds, gravitational potential, sun/moon/star positions, and terrain elevation. The atmosphere and wind produce aerodynamic affects, generating forces and moments on the vehicle. Gravitational potential is another important source of forces and moments. The sun, moon and star positions provide guidance and navigation inputs. Finally, the terrain near the landing site reflects radar altimeter signals, used for altitude measurement during Orbiter approach and landing. Figure 4.3-1 shows the interfaces of the natural environment module with other simulation modules.

4.3.2 Artificial Environment

The artificial environment consists of external systems and equipments which provide the Orbiter with certain services -- data, power, fuel, cooling -- or request such services from the Orbiter. The three artificial environment modules discussed in this section are ground navigation/communications, payloads and rendezvous targets, and prelaunch/launch interface.

4.3.2.1 Ground Navigation/Communications

Ground-based navigation and communications equipment provides data and command inputs to the Orbiter through its communication and tracking subsystem.

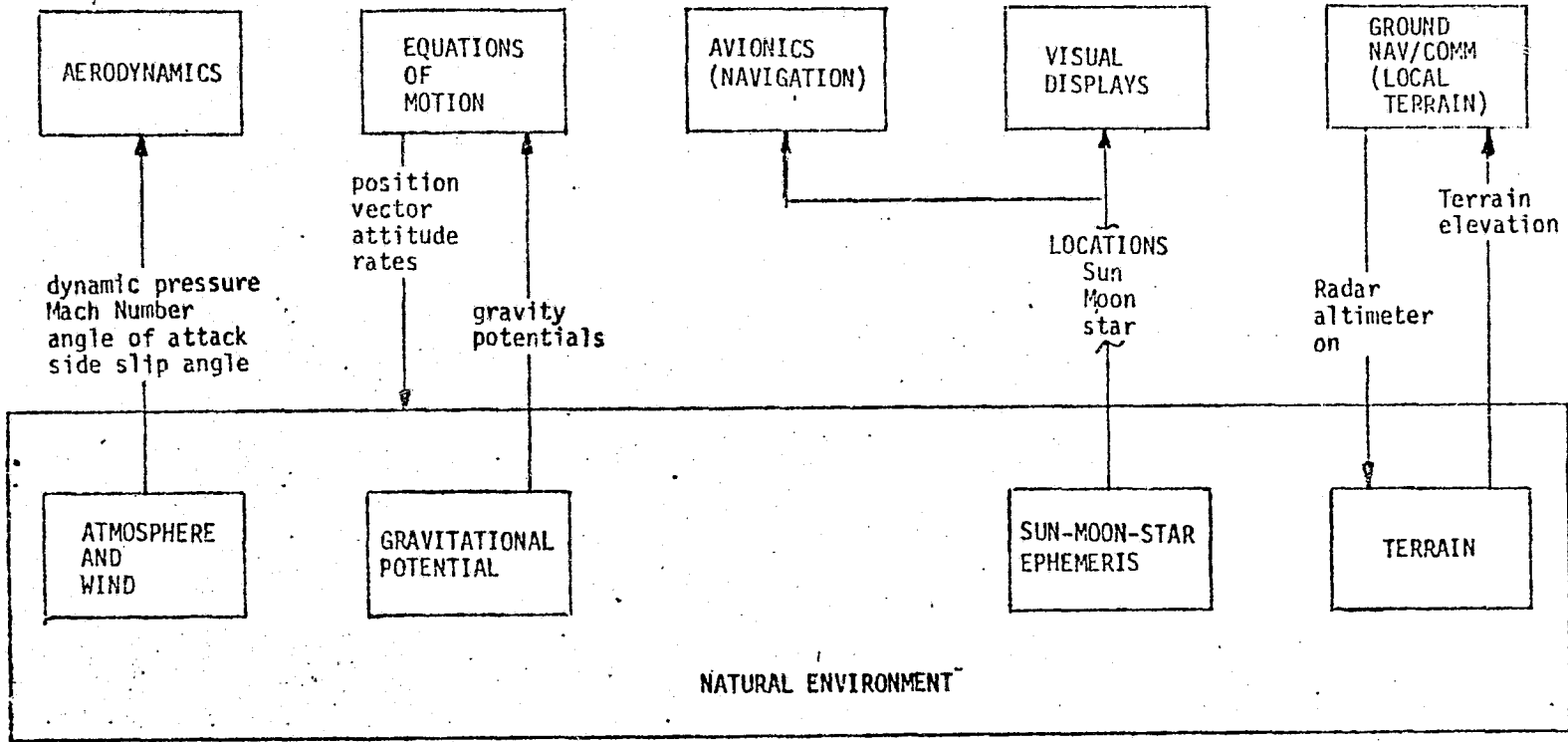


FIGURE 4.3- 1 |. NATURAL ENVIRONMENT MODULE, FUNCTIONAL ELEMENTS AND INTERFACES

The ground systems planned for use during Shuttle operations are:

- o Dual-antenna S-band telemetry
- o UHF voice
- o STDN/TDRS (NASA systems)
- o SGLS (DoD system)
- o Aeroflight nav aids: TACAN, MSBLS

Figure 4.3-2 shown the interfaces between the ground nav/comm simulation module and other simulation modules.

The ground nav/comm simulation module will simulate the transmitted signal strengths and received signal strengths of ground-to-orbiter and Orbiter-to-ground communication links, by use of antenna pointing and antenna gain-pattern computations.

4.3.2.2 Payloads and Rendezvous Targets

A wide variety of payloads and rendezvous targets will be deployed and retrieved by the Shuttle during its operational lifetime; for example:

- o Cryo tug
- o Agena high-energy payload
- o Interim tug
- o Large Space Telescope
- o ESRO space lab
- o Earth observation satellites

In addition, Orbiter-to-orbiter rendezvous and docking maneuvers may be undertaken; e.g., for rescue purposes.

4.3-4

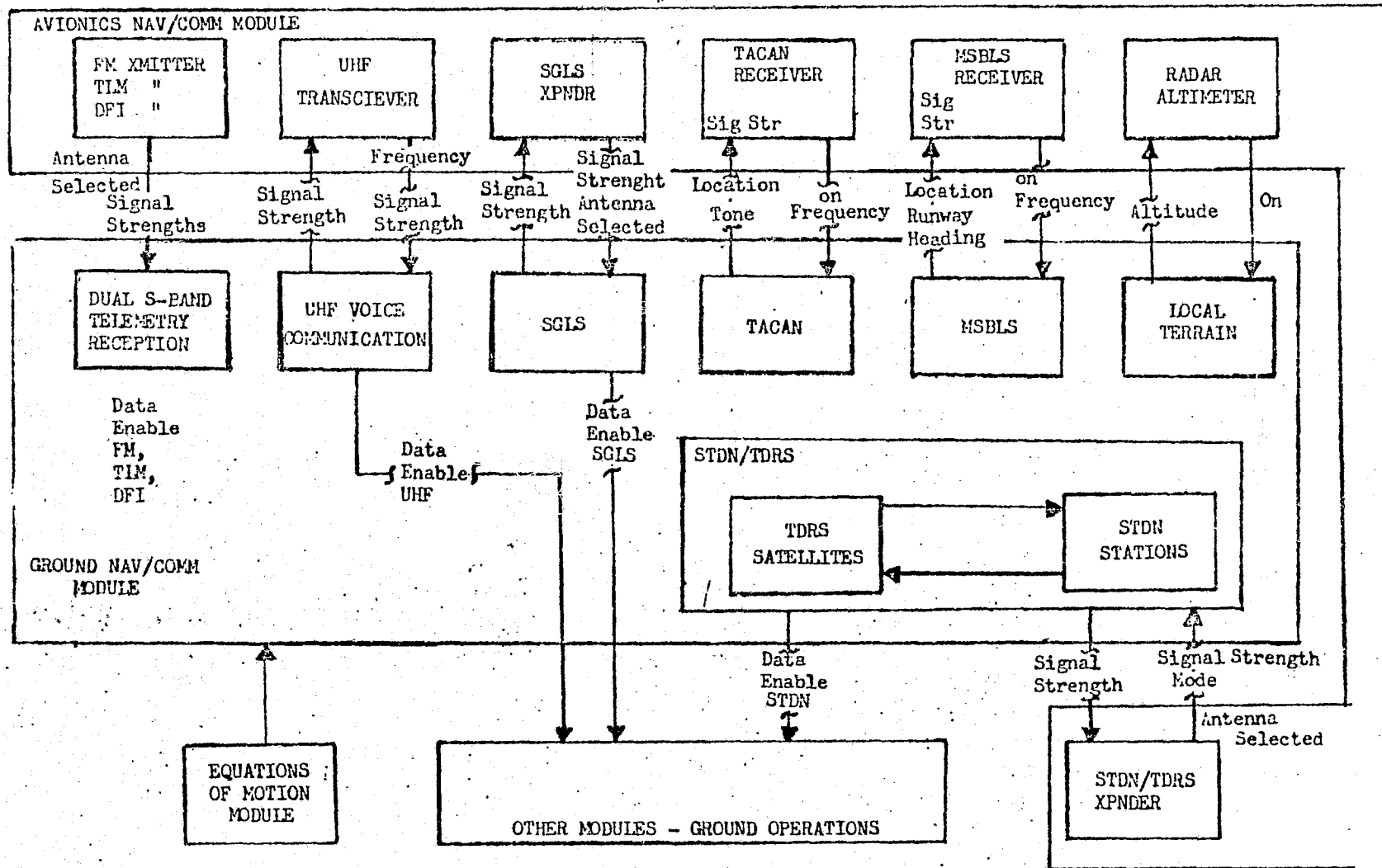


FIGURE 4.3-2 GROUND NAV/COMM MODULE FUNCTIONAL ELEMENTS, AND MODULE INTERFACES

The payload/target (P/T) simulation module must provide for maneuvers (if any) made by the P/T when free-flying (post-deployment or pre-retrieval), for onboard consumables usage affecting the P/T mass properties, and for command and data transfer between the Orbiter and the P/T. Figure 4.3-3 identifies the major functional elements of the P/T simulation module, and shows its interfaces with other modules.

4.3.2.3 Prelaunch/Launch Interface

In the final phase of the prelaunch countdown, ground-based systems are interfaced with the Shuttle vehicle for the following functions:

- o Communications and instrumentation (RF and hardline)
- o Electrical power
- o Environmental control
- o Hydraulic power
- o Purge, vent and pressurization
- o Mechanical hold-down until successful engine startup is verified

These functions are indicated on the module interface diagram, Fig. 4.3-4. We do not anticipate a very detailed implementation of prelaunch/launch functions on any upcoming JSC simulator.

4.3-6

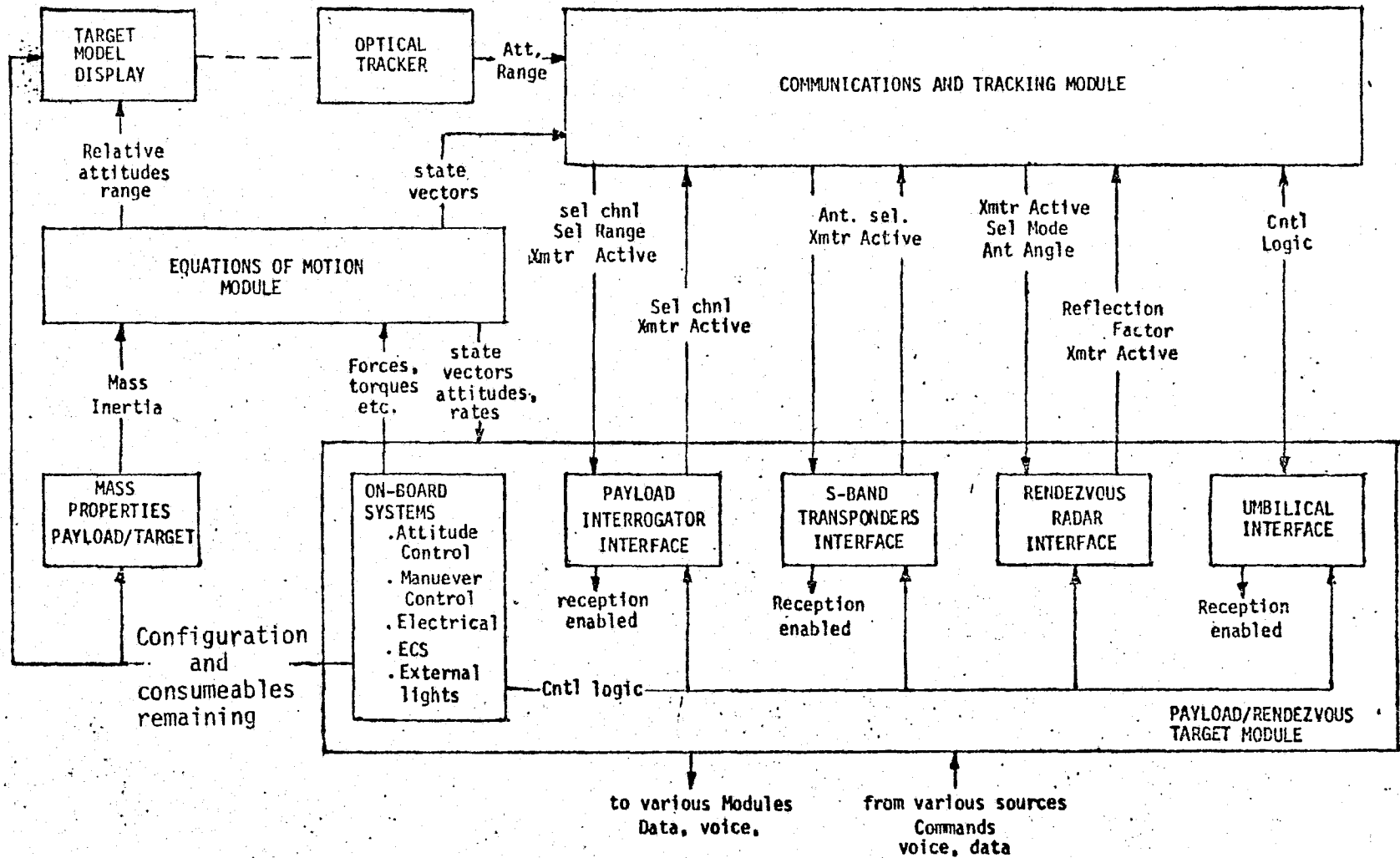


FIGURE 4.3-3 PAYLOAD/RENDEZVOUS TARGET MODULE, FUNCTIONAL ELEMENTS AND INTERFACES

4.3-7

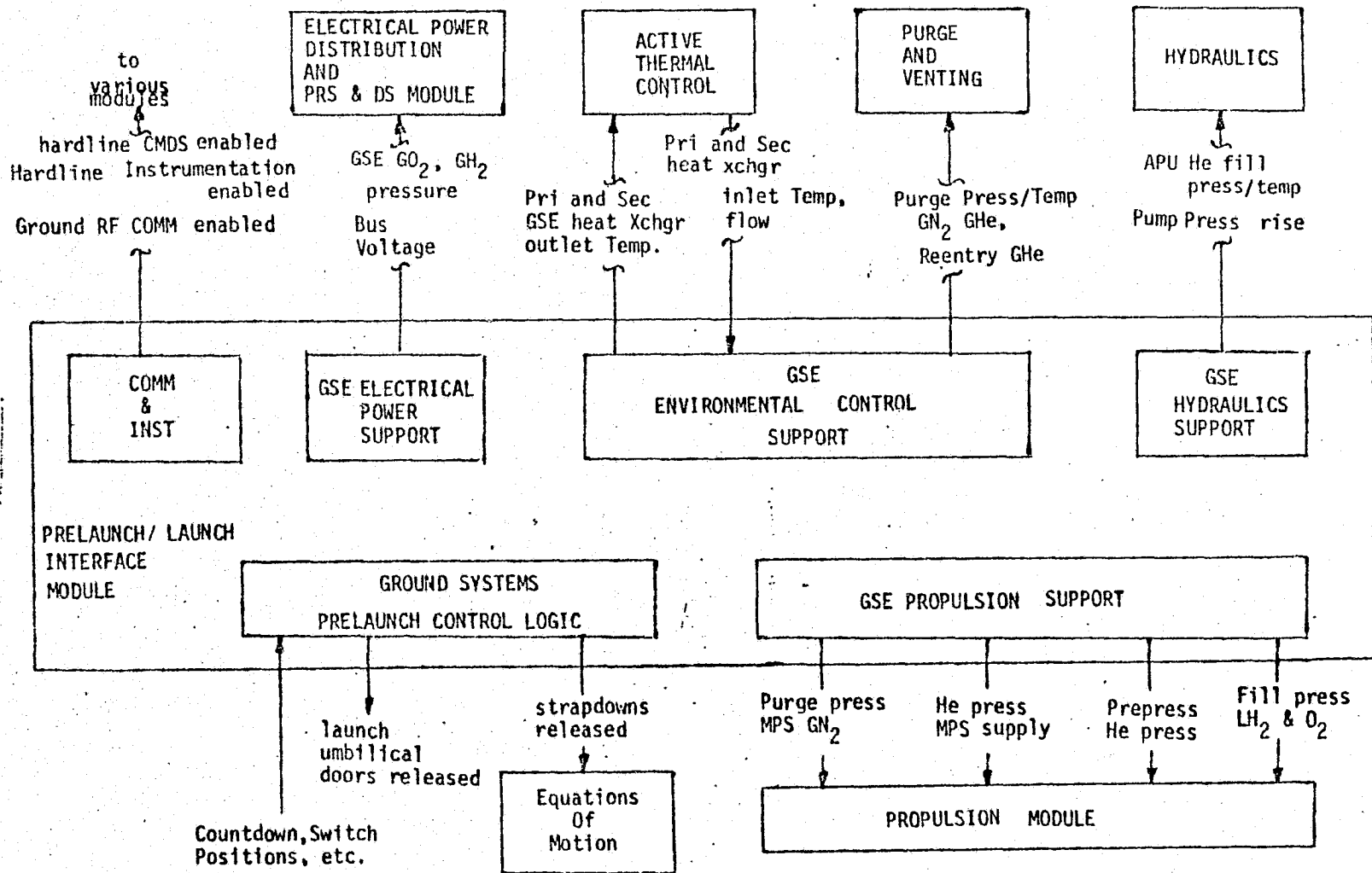


FIGURE 4.3-4. PRELAUNCH/LAUNCH INTERFACE MODULE, FUNCTIONAL ELEMENTS AND INTERFACES.

4.4 CREW STATION MODULES

Visual and motion simulation are of crucial importance in the flight crew's subjective perception of the simulation fidelity. Highly specialized software and hardware are necessary to accomplish visual and motion simulation, particularly over the widely varying dynamical and operational regimes of Shuttle missions.

Figure 4.4-1 shows the interfaces involved in visual simulation. Different types of hardware will be required to provide the various visual-scene elements. Each hardware unit will require its own software driver module, with control provided by a visual-system control module, using inputs from the simulation software. Several distinct fields must be generated, to provide forward and aft out-the-window views as well as TV displays for the payload manipulator station.

Motion-base drive software is designed to create the most realistic possible perception of vehicle motions and accelerations within the constraints imposed by the motion-base hardware, without introducing spurious cues due to abruptly reaching actuator travel limits. The functions of the motion-base software, as indicated in the interface diagram of Figure 4.4-2, include transformation of vehicle motions into actuator displacements, compensation for hardware response, and travel-limiting functions such as look-ahead, washout, and bleed-back.

4.4-2

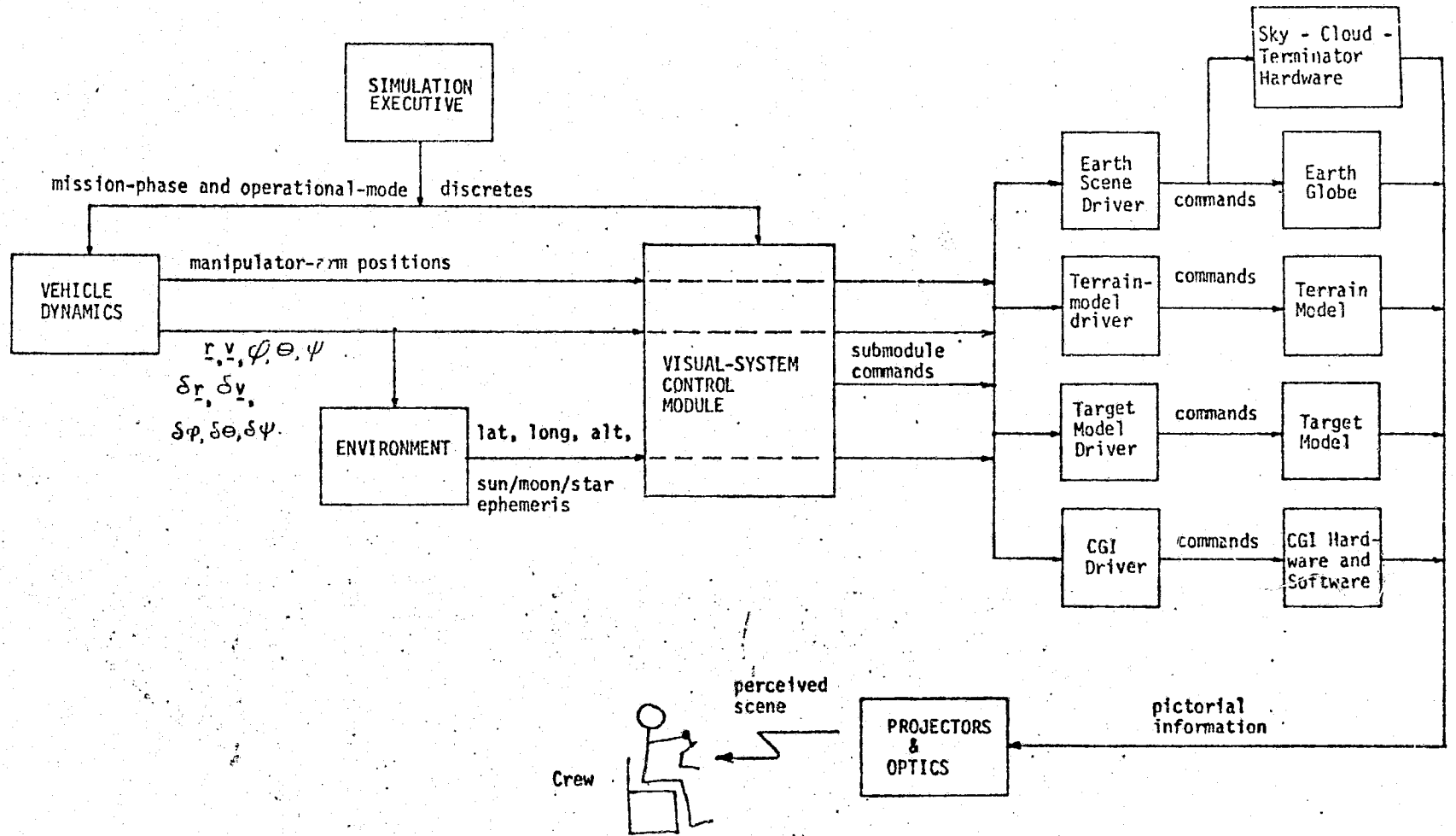


FIGURE 4.4-1: VISUAL SYSTEM SOFTWARE AND HARDWARE INTERFACES

4.4-3

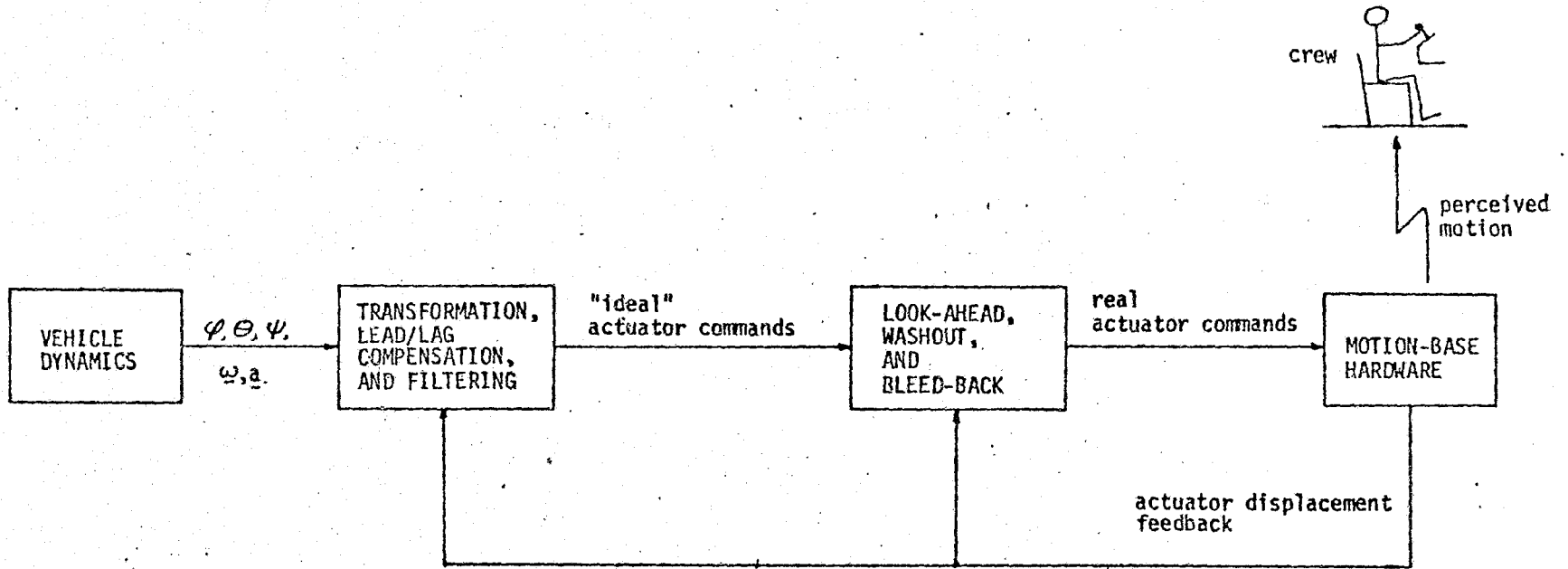


FIGURE 4.4-2 MOTION-BASE SOFTWARE INTERFACES

4.5 VEHICLE CONFIGURATION MODULES

The Shuttle vehicle configuration, and hence its response to external influences and vehicle system operation, changes during the course of a mission. The modules falling in the vehicle configuration category are aerodynamics, aerothermodynamics, and mass properties.

4.5.1 Aerodynamics

Significant aerodynamic forces and moments occur act on the Shuttle during the ascent, entry, aeroflight, and approach & landing mission phases. The forces vary with atmospheric conditions, Shuttle velocity, and Shuttle vehicle configuration; the moments also vary with vehicle c. g. position.

The aerodynamics simulation module must access tabular data appropriate to the current vehicle configuration and dynamical regime, then use the tabular data to compute forces and moments in terms of an appropriate axis set. Major configuration changes occur as the SRB's and the ET are separated from the vehicle; minor configuration changes occur with landing gear and drag chute deployment. Aerosurface positions, ground effects and ET/SRB proximity also influence the vehicle aerodynamics. These interfaces are shown in Figure 4.5-1.

4.5.2 Aerothermodynamics

Aerodynamic heating during entry is a major constraint on the vehicle guidance. For maximum downrange travel, the Orbiter is operated near its maximum heat loading; therefore, bondline temperatures are closely monitored by the flight crew. Heat transfer through the TPS, the vehicle structure and the windows affects the temperatures of various internal compartments. This directly affects the heat dissipation required of the ECLSS, and indirectly

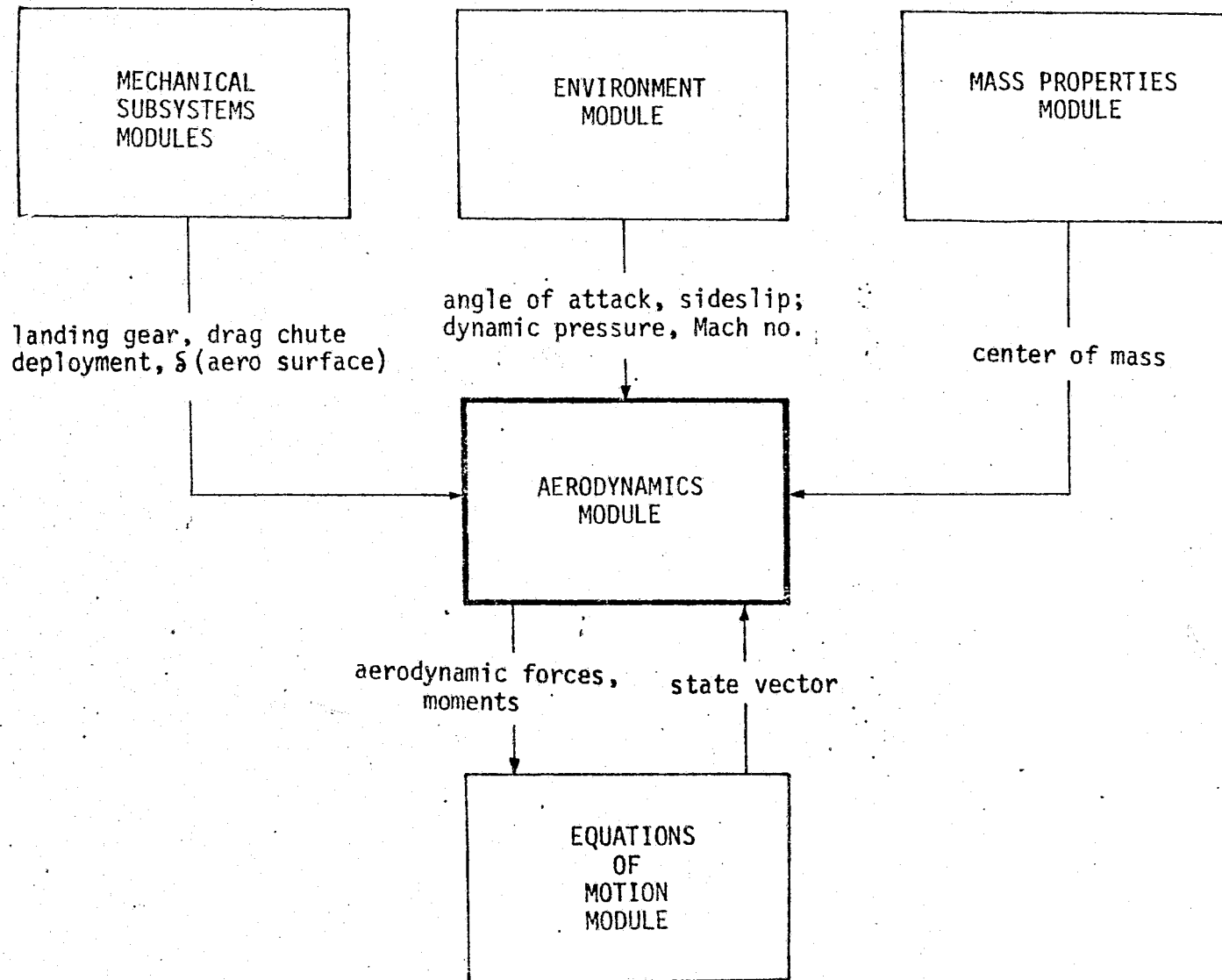


FIGURE 4.5-1 AERODYNAMICS MODULE INTERFACES

affects the performance of equipment, such as avionics, located in these compartments.

Aerothermodynamics simulation module interfaces are shown in Fig. 4.5-2.

4.5.3 Mass Properties

Shuttle vehicle mass properties -- mass, moments and products of inertia, and c. g. position -- are involved in aerodynamics and vehicle dynamics computations. The mass properties simulation module performs the bookkeeping and transformations necessary to update these parameters as propellants are consumed, SRB's and ET are separated, and payloads are stowed and unstowed. Similar, although simpler, computations are performed for certain payloads and rendezvous targets.

Mass properties simulation module interfaces are shown in Fig. 4.5-3.

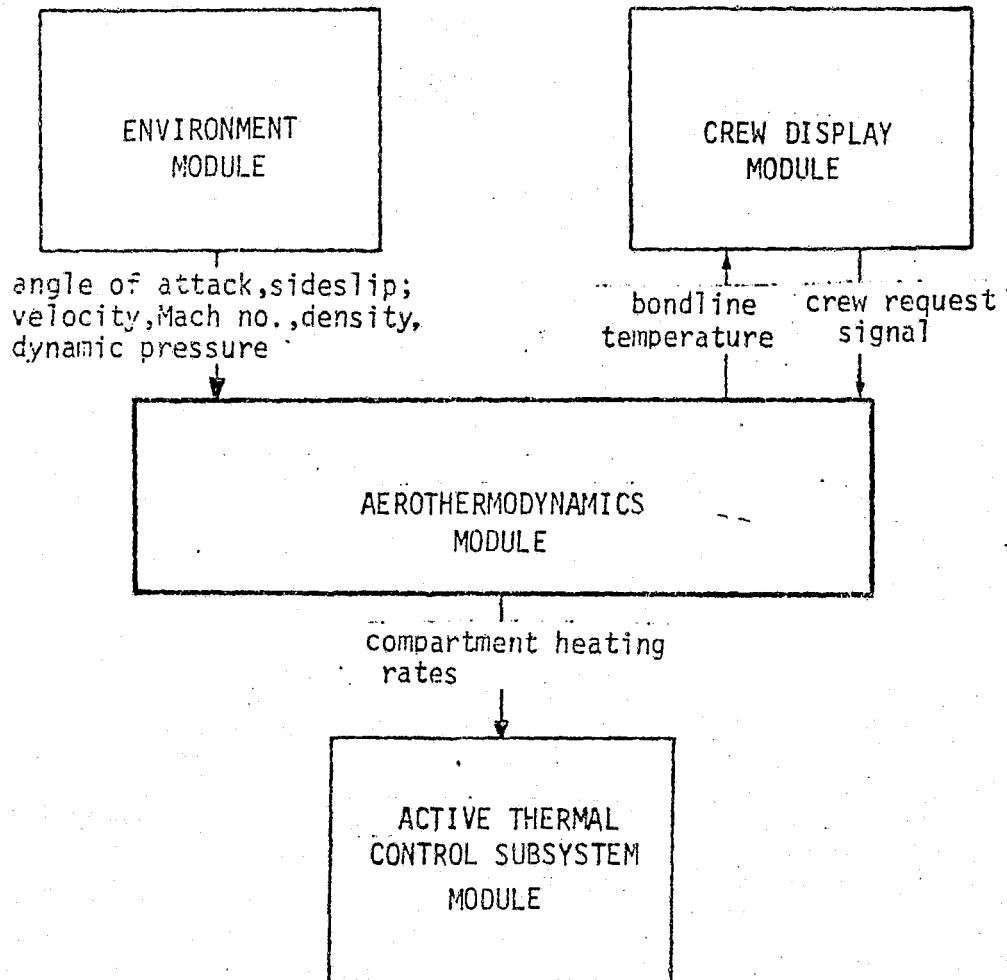


FIGURE 4.5-2 AEROTHERMODYNAMICS MODULE INTERFACES

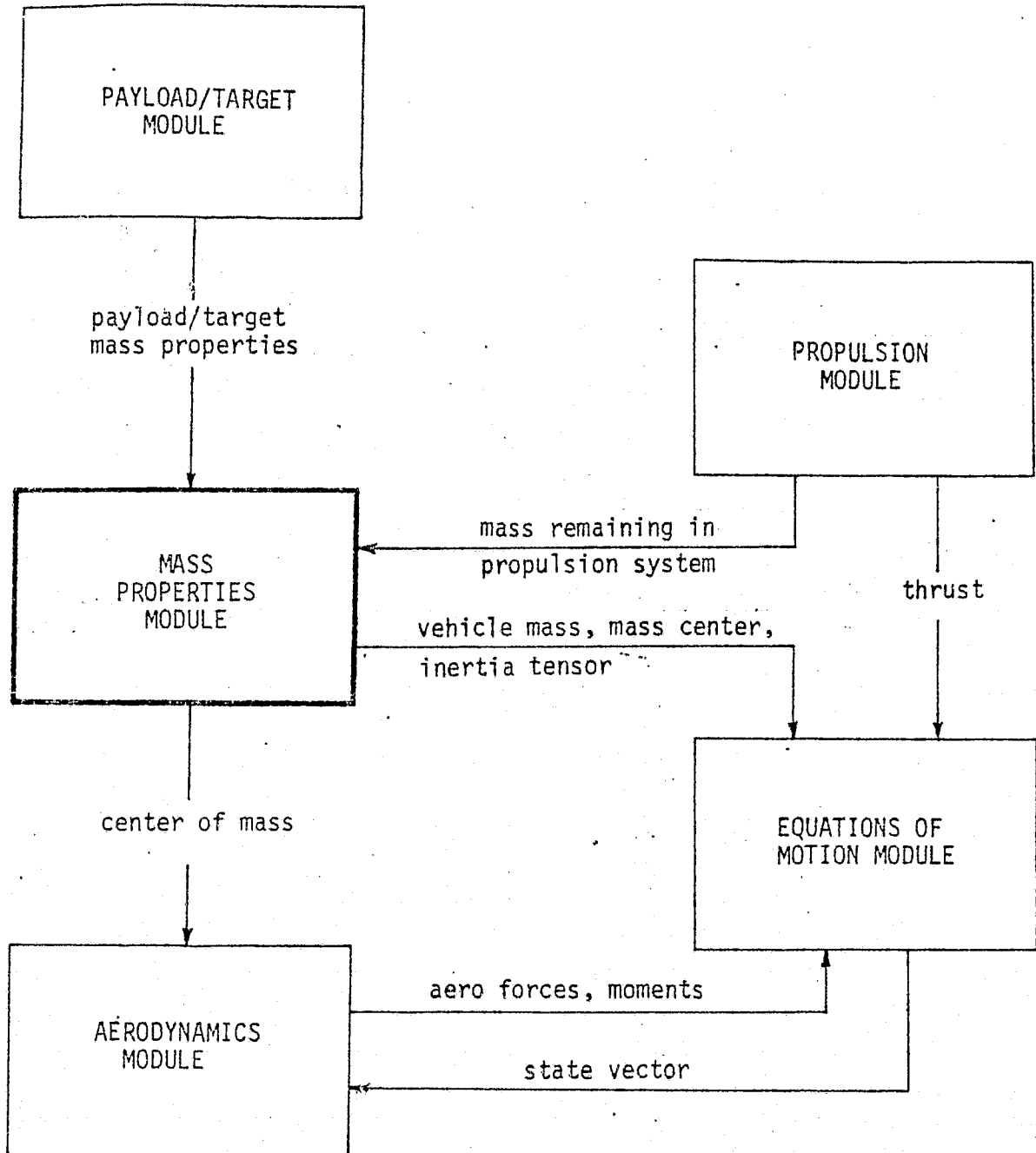


FIGURE 4.5-3 . MASS PROPERTIES MODULE INTERFACES

4.6 VEHICLE DYNAMICS MODULES

Vehicle dynamics simulation is the core of any spacecraft simulator. The dynamics simulation modules interface with or otherwise influence the results of most of the rest of the simulation; these interfaces and influences are indicated by Fig. 4.6-1. We are concerned with three categories of dynamical phenomena -- rigid-body equations of motion (EOM), mechanical-system dynamics, and bending and slosh dynamics -- and their corresponding simulation software modules.

Rigid-body EOM include translational (point-mass) dynamics of the Shuttle vehicle, rotational dynamics, and multiple-body dynamics. Translational dynamical computations are performed during all Shuttle mission phases; however, different computational methods may be used in the different dynamical regimes. Rotational dynamics are computed throughout the mission, using essentially the same computational method (direction cosines or quaternions), possibly varying the computational rate. Multiple-body dynamics are necessary only during discrete mission phases; e. g., separation of the Orbiter from a carrier aircraft, separation of SRB's and ET from the Orbiter, and post-deployment/pre-retrieval relative motions of a payload/target.

The internal dynamics of such mechanical subsystems as the landing gear, docking mechanism and PDRS are driven by the external dynamics of the Orbiter motion relative to the runway or an external object such as a payload or another Orbiter. In turn, these mechanical systems impose reaction forces and moments upon the Orbiter and the external object. These forces and moments depend upon the relative states and rates, masses and inertias of the objects

4.6-2

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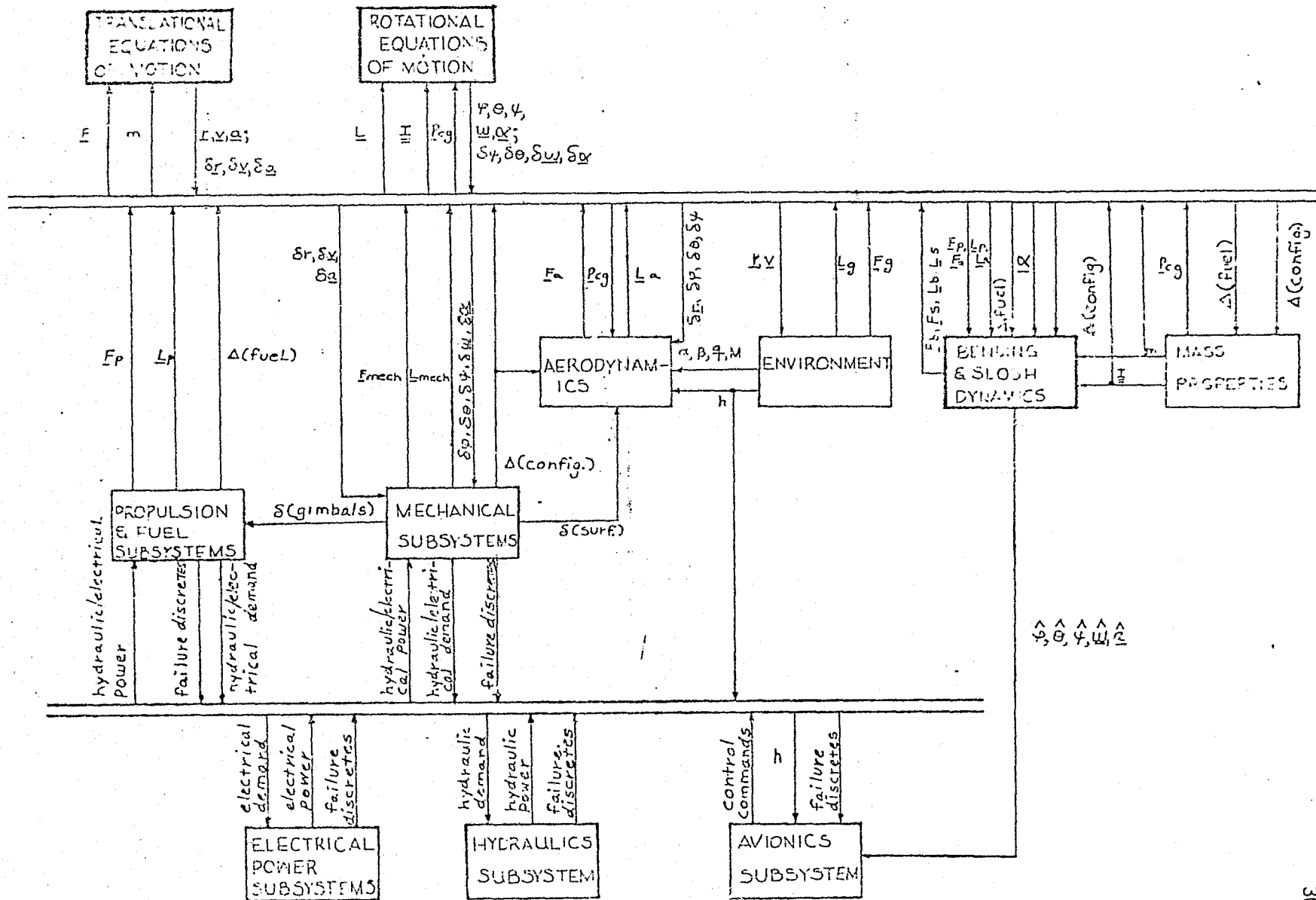


FIGURE 4.6-1 OVERVIEW OF DYNAMICS MODULE INTERFACES. (DATA TRANSFER IS NORMALLY VIA COMMON STORAGE, WHETHER SHOWN DIRECT OR BUSSED ON THIS FIGURE.)

involved, the design parameters of the springs, dampers and actuators in the mechanical systems, and the location of the points of application of the mechanical-system forces.

Body bending and fuel slosh phenomena represent additional dynamical degrees of freedom of the vehicle. Rigid-body and non-rigid-body dynamics drive each other by a process of momentum interchange. In addition to their dynamical effects, body bending dynamics also contribute to the outputs of onboard inertial sensors -- gyros and accelerometers. The magnitude of these effects varies with sensor longitudinal position, being minimal at "nodes" and maximal at "antinodes" of the various normal modes of body bending.

4.7 VEHICLE SUBSYSTEMS MODULES

Vehicle subsystems simulation fidelity is particularly important, because it is these simulation modules which interface most directly with the flight crew and the flight computers. Subsystem simulations also tend to be rather complex, with a great number of parameters (both discrete and continuous) which must be accurately represented for configuration monitoring, malfunction simulation, and propagation of malfunction effects.

This section deals with all onboard subsystems in the following categories: Mechanical, Purge/Vent & Drain, Propulsion & Fuel, Power Generation, Avionics, and Environmental Control/Life Support.

4.7.1 Mechanical Subsystems

This section describes those subsystems involved in the transfer and application of mechanical power. This includes Landing/Deceleration, Docking Mechanisms, Separation Mechanisms, Actuation Mechanisms, the Payload Deployment and Retrieval System, Hydraulics, and Pyrotechnics. Pyrotechnics, however, are not treated as a separate category; rather, pyrotechnic components are treated under whatever system they form a part of.

A detailed discussion of the Landing/Deceleration Subsystem is presented. The remaining mechanical subsystems are described with less detail, because they have many components - springs, dampers, actuators, etc. - which are similar to components found in the Landing/Deceleration Subsystem.

4.7.1.1 Landing/Deceleration Subsystem (LDS)

The LDS functionally provides for extension and retraction of the nose (NLG) and main (MLG) landing gear, shock attenuation of landing impact, deceleration and directional control during landing rollout, and a stable rolling platform for all ground maneuvering and landing operations (Ref. 3).

LDS Description

The principle components of the LDS consist of (Ref. 4):

- main and nose gears, fairing doors, and actuating and locking mechanisms
- nose wheel steering
- wheels, tires and brakes
- brake control and anti-skid system
- drag chute and deployment mechanism

Landing gear layout is a conventional tricycle configuration with twin wheels on both the nose and main gear. Gear extension is initiated by crew selection of the landing gear "down" switch which energizes the uplock release hydraulic actuators. The main gear is designed with two additional backup uplock release actuators, whereas the nose gear sequences a pyrotechnic uplock release backup (Ref. 5).

In ferry-flight and horizontal flight test configuration, inflight retraction of the gear is possible; however, for orbital missions the retraction hydraulic actuators are less powerful and not designed for inflight operation. They will function on the ground to facilitate ground turn-around operations. Figures 4.7-1

4.7-3

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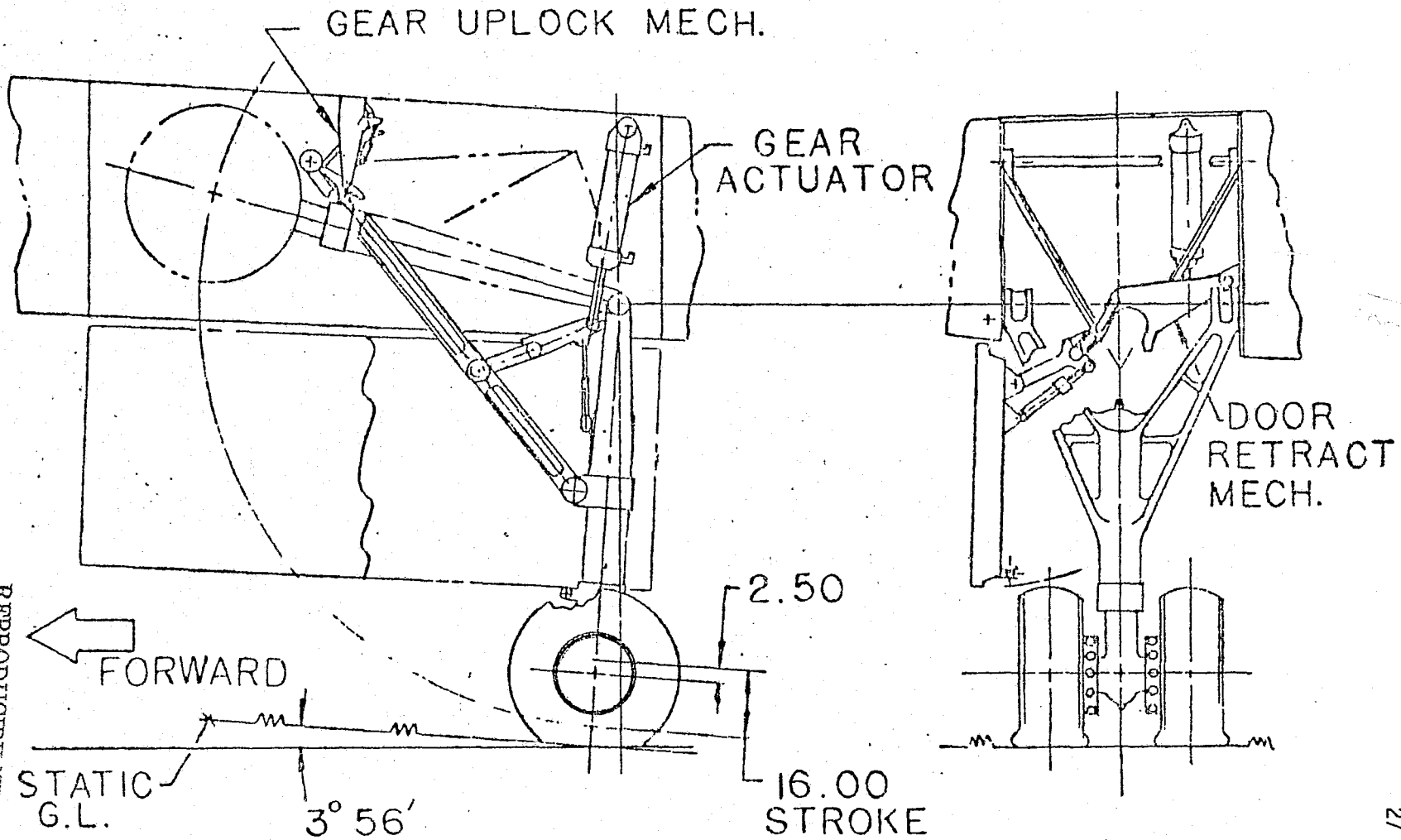


FIGURE 4.7-1 . MAIN LANDING GEAR INSTALLATION

and 4.7-2 (Ref. C) illustrate the forward and up retraction of the main and nose gear into fully enclosed wheel wells. This arrangement enables freefall extension and downlock via airloads in flight.

Nose wheel steering is crew available upon touchdown. Steering "on" selection will normally occur when vehicle velocity is below a "rudder aero-effectiveness" limit. As depicted in Figure 4.7-3, (Ref. 5), steering control is transmitted electrically from the rudder pedals to the hydraulic steering actuator. The steering actuator also functions as a shimmy damper in steering "on" and "off" modes.

Primary deceleration of the Orbiter vehicle during landing rollout is accomplished through the use of the main gear brakes. For maximum efficiency, braking and skid control functions are integrated into a "brake by wire" system as described in Figure 4.7-4, (Ref. 5). Wheel spin-up activates the fully modulated braking/skid control system to prevent premature brake application. Individual wheel lockup is also prevented. This system ensures maximum tire adhesion during deceleration thereby maintaining the optimum braking force on all runway surfaces. Three hydraulic systems are utilized for the braking/skid control functions. Two systems function as backups as any one system is sufficient for braking/skid control operation.

Deceleration is also assisted by drag chute deployment. The drag chute system consists of the main and pilot canopies and risers, deployment mortar, actuation mechanisms, and crew controls. Figure 4.7-5, (Ref. 5) describes the crew activated deployment sequence.

Landing shock attenuation is provided by the landing gear pneudraulic (oil and air/GN₂) shock struts and tires. The tires assist the shock struts in absorbing landing energy and decelerating the landing gear unsprung mass to zero vertical velocity. The shock struts complete Orbiter vehicle deceleration at the required rate.

Hydraulic actuators used in the LDS are supplied power from the Orbiter Hydraulic Power System (HPS) described in Section 4.7.1.6. The individual actuators will be discussed in Section 4.7.1.4.

4.7-5

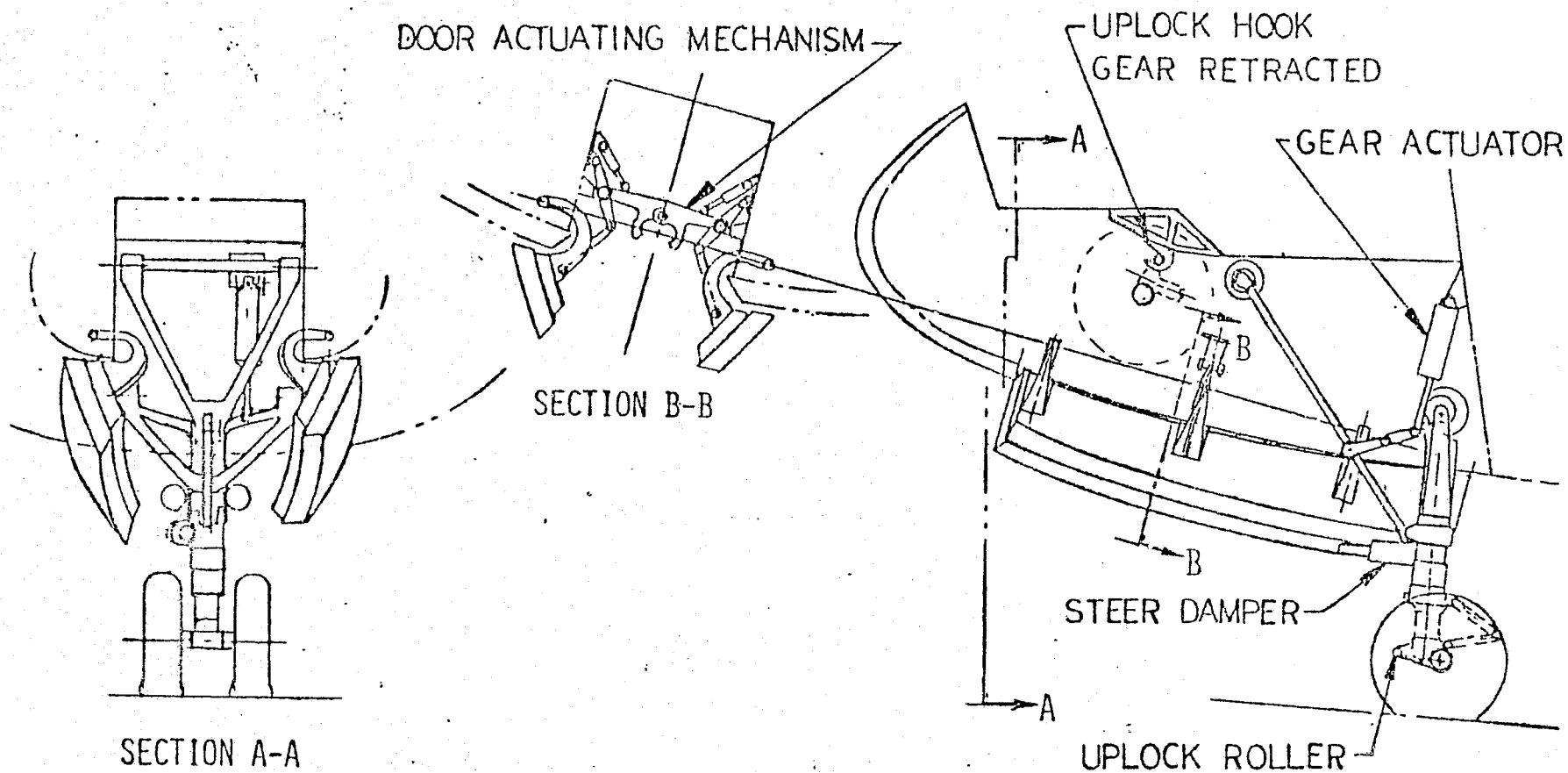
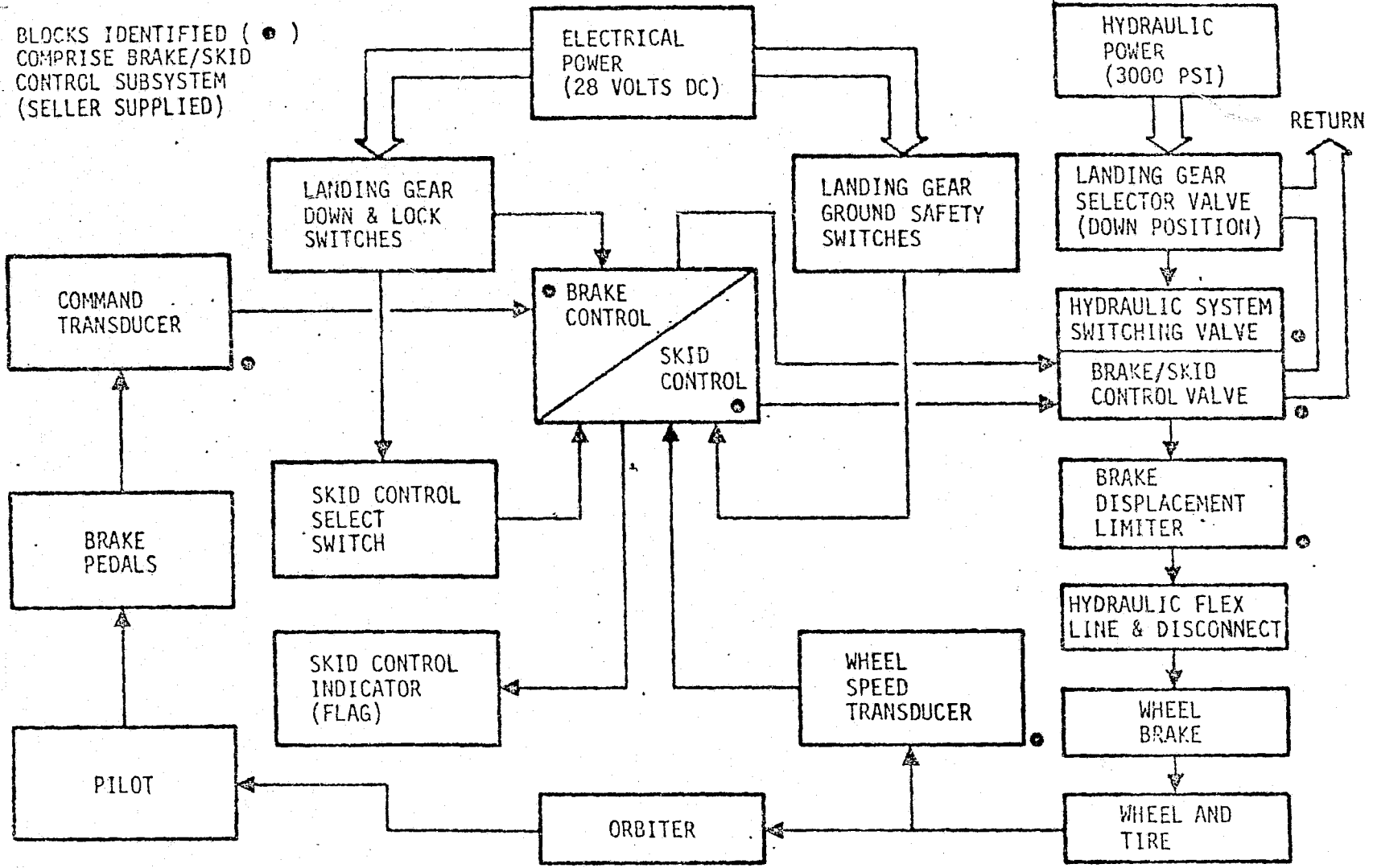


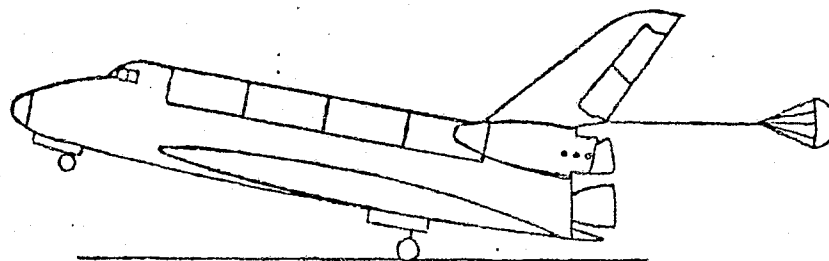
FIGURE 4.7-2 . NOSE GEAR INSTALLATION



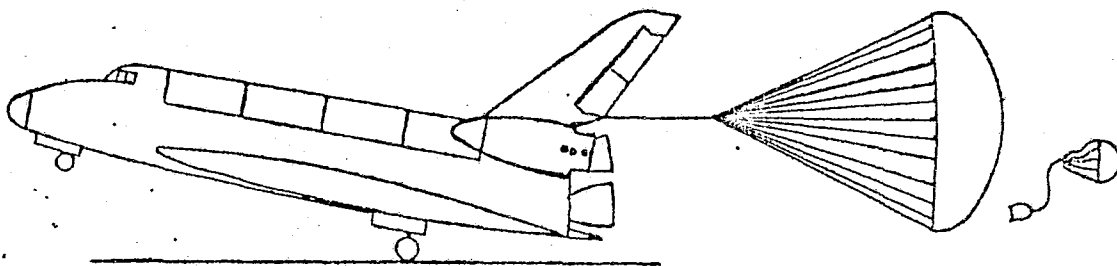
BRAKE/SKID CONTROL SYSTEM ARRANGEMENT

FIGURE 4.7-4 . LDS MAIN GEAR BRAKE ANTI-SKID CONTROL

MAIN GEAR TOUCH DOWN
PILOT SELECT DEPLOY SWITCH
CLOSE RELEASE MECH
OPEN DOORS
FIRE PILOT CHUTE MORTAR



MAIN CHUTE EXTRACTED & INFLATED
PILOT CHUTE RELEASED
DECEL & NOSE GEAR
TOUCH DOWN



DECEL & MAIN CHUTE
JETTISON 20 KTS

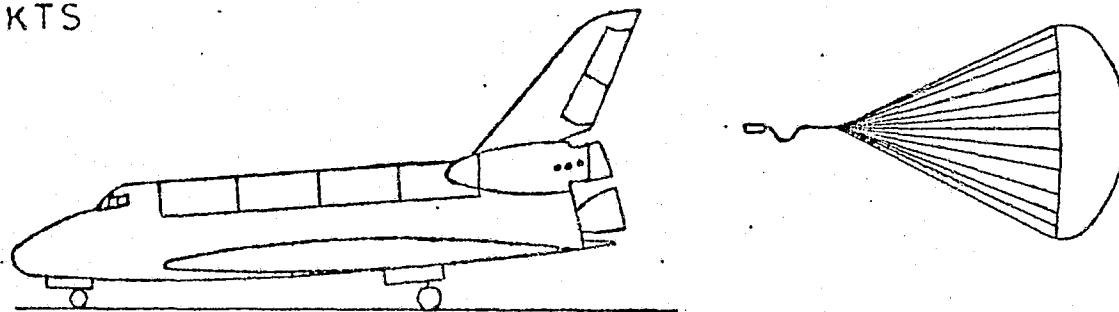


FIGURE 4.7-5 . CHUTE DEPLOYMENT SEQUENCE

LDS Simulation Module Description and Performance Parameters

LDS simulation will incorporate several methods to simulate each subsystem component function to an acceptable level for the training simulator.

The LDS simulation module will use Orbiter geometry, altitude, attitude, vehicle mass, center of mass, groundspeed, and vertical velocity, along with terrain inputs and operator commands, to determine:

- actuator commands
- drag chute and landing gear aerodynamic effects
- crew display signals
- landing (touchdown) forces and moments
- braking and steering forces and moments
- electrical and hydraulic power requirements

All command/response relationships will be simulated using sequential time delay functions based upon actuator response characteristics and electrical power available checks to provide the desired "talkback." This method will be employed for drag chute deployment and jettison, display indicators, and landing gear extension. Dynamics equations combined with control logic loops and spring/damper relationships will be implemented for simulation of the remaining LDS components and subsystems. Spring/damper relationships will be determined from actual test data (Ref. 6). Performance parameters associated with the LDS are shown in Table 4.7-1. Figure 4.7-6 depicts the LDS simulation module interfaces with other simulation modules.

LDS Reference Data Sources and Data Formats

Figure 4.7-7, (Ref. 7) describes a functional math flow which, when combined with a driver, would serve as an LDS reference module. This reference module would provide reference data for verification of the LDS simulation module. The math flow shown primarily simulates the LDS dynamical inputs to the EOM.

A suitable driver routine should be constructed to fully simulate the LDS. The driver would contain crew input response and time delay functions to model those components simulated with "talkback" such as landing gear and drag chute deployment, steering "on" response, etc. Actual hardware simulation results will provide tabular data and curve fits for air/GN₂ spring and shock strut damper characteristics,

TABLE 4.7-1. LDS PERFORMANCE PARAMETERS

PARAMETER	TYPE ^a
NLG and MLG "up/down" command	I
NLG and MLG "unlocked/downlocked" indicator flags	P
NLG and MLG mass	DB
NLG and MLG "up/down" actuator response time	I
Landing gear "down" aerodynamic effects flag	P
NLG and MLG coordinates	DB
Braking forces and moments	CP
Brake pedal displacement and rate	I
Wheel RPM	CP
Brakes "on/off" indicator flag	CP
Tire-to-runway braking force coefficient	DB
Runway terrain function	I
Orbiter landing attitude, attitude rates	I
Orbiter vertical velocity	I
Orbiter groundspeed	I
Orbiter mass	I
Orbiter mass center	I
Orbiter altitude above runway	I
NLG and MLG strut displacement, rate	CP
NLG and MLG GN ₂ spring rate	DB
MLG and MLG damper constant	DB
NLG and MLG tire spring rate	DB
NLG and MLG tire displacement	P
Rudder aero-effectiveness velocity limit	DB
Rudder pedal position	I
NLG steering "on" command and indicator	I, P
NLG steering actuator command	I
NLG steering forces and moments	CP
NLG steering angle and angular rate	I
NLG steering actuator response time	I
Drag chute deploy/jettison command	I
Drag chute deploy/jettison response time	I
Drag chute aero-effects flag	P

^aP - Performance Parameter

CP - Critical Performance Parameter

I - Input

DB - Data Base Input

4.7-11

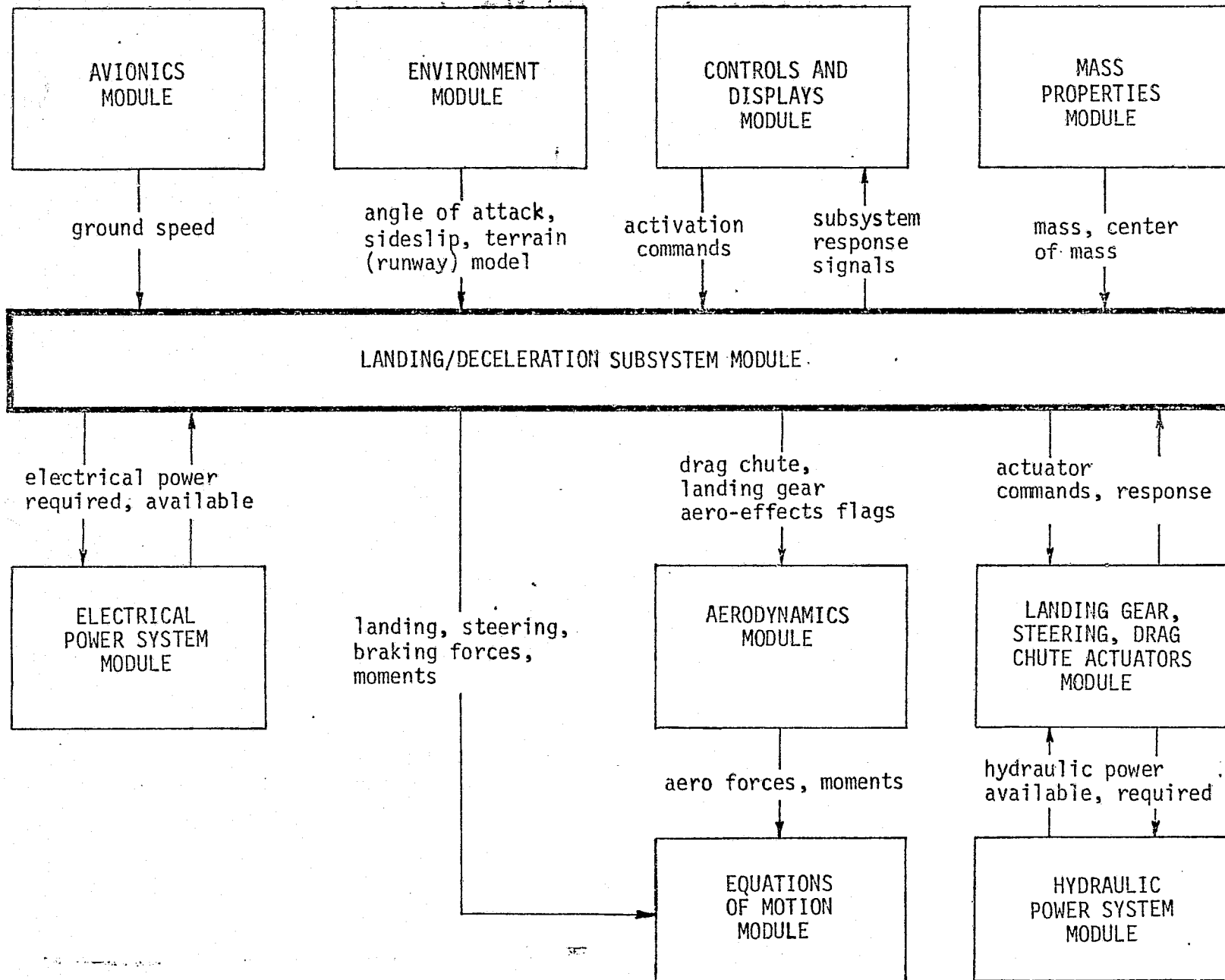


FIGURE 4.7-6 . LDS SIMULATION MODULE INTERFACES

LOOP THRU EQUATIONS FOR :

- J = 1 NOSE GEAR
- J = 2 RIGHT MAIN GEAR
- J = 3 LEFT MAIN GEAR
- J = 4 TAIL TIP
- J = 5 RIGHT WING TIP
- J = 6 LEFT WING TIP

DEFINITION OF MATRIX TRANSFORMATIONS

NORTH-EAST-DOWN TO BODY AXES

$$\begin{bmatrix} C_{xN} (1) & C_{xN} (4) & C_{xN} (7) \\ C_{xN} (2) & C_{xN} (5) & C_{xN} (8) \\ C_{xN} (3) & C_{xN} (6) & C_{xN} (9) \end{bmatrix} = \begin{bmatrix} \cos(\theta) \cos(\psi) & \cos(\theta) \sin(\psi) & -\sin(\theta) \\ \sin(\theta) \sin(\psi) \cos(\psi) - \cos(\theta) \sin(\psi) & \sin(\theta) \sin(\psi) \sin(\psi) + \cos(\theta) \cos(\psi) & \sin(\theta) \cos(\psi) \\ \cos(\theta) \sin(\theta) \cos(\psi) + \sin(\theta) \sin(\psi) & \cos(\theta) \sin(\theta) \sin(\psi) - \sin(\theta) \cos(\psi) & \cos(\theta) \cos(\psi) \end{bmatrix}$$

HORIZONTAL TO BODY AXES

$$\begin{bmatrix} C_{BH} (1) & C_{BH} (4) & C_{BH} (7) \\ C_{BH} (2) & C_{BH} (5) & C_{BH} (8) \\ C_{BH} (3) & C_{BH} (6) & C_{BH} (9) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ \sin(\theta) \sin(\psi) & \cos(\psi) & \cos(\theta) \sin(\psi) \\ \sin(\theta) \cos(\psi) & -\sin(\psi) & \cos(\theta) \cos(\psi) \end{bmatrix}$$

DEFINITION OF SYMBOLS

- \otimes COMPARATOR OR SUMMATION
- \square ENABLE SIGNAL FLOW
- \ominus OFF PAGE CONNECTOR
- ∇ SIGN OF VARIABLE

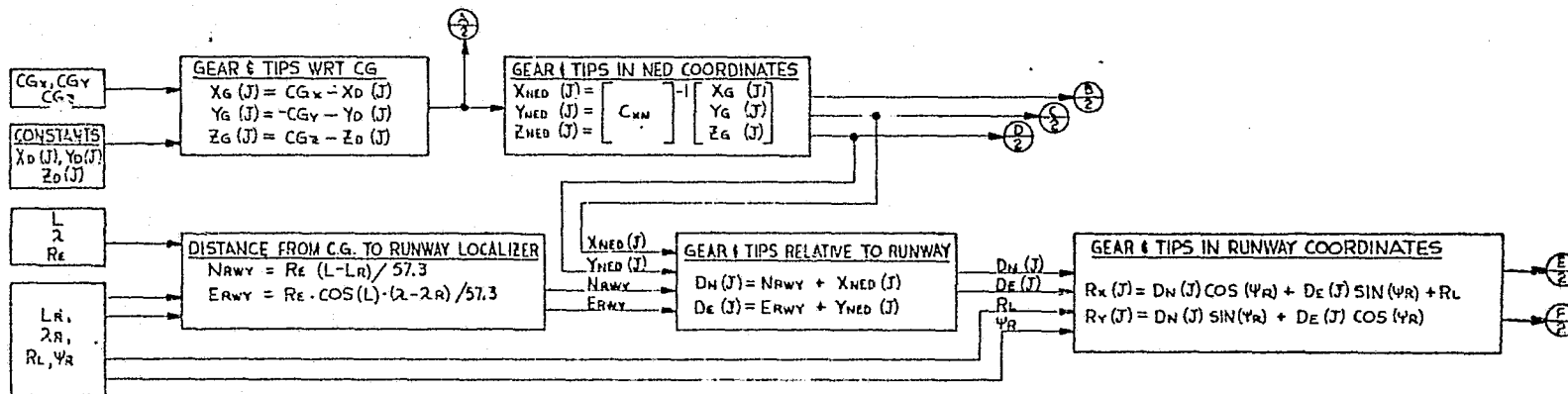


FIGURE 4.7-7 . LDS REFERENCE MODULE MATH FLOW

4.7-13

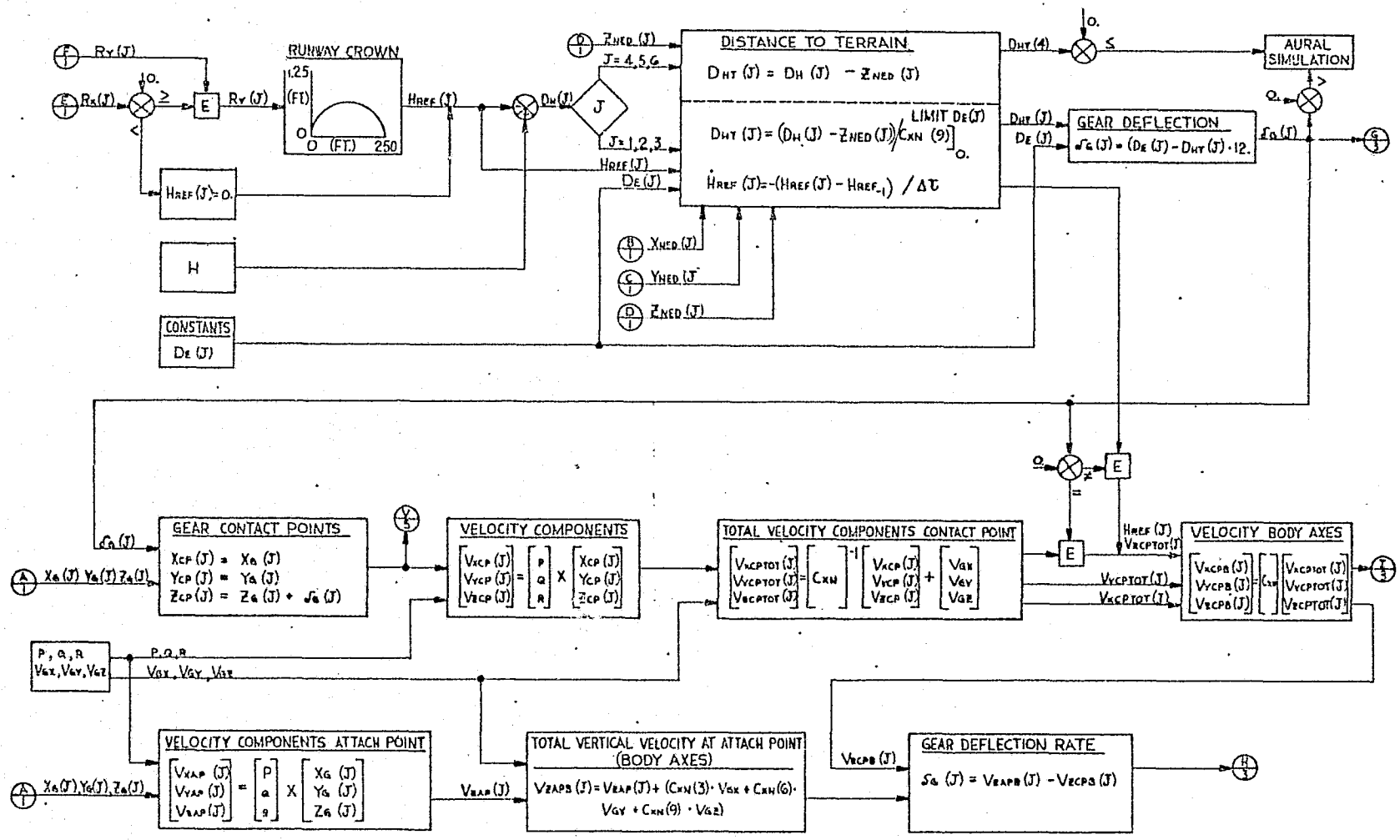


FIGURE 4.7-7 . (CONTINUED)

4.7-14

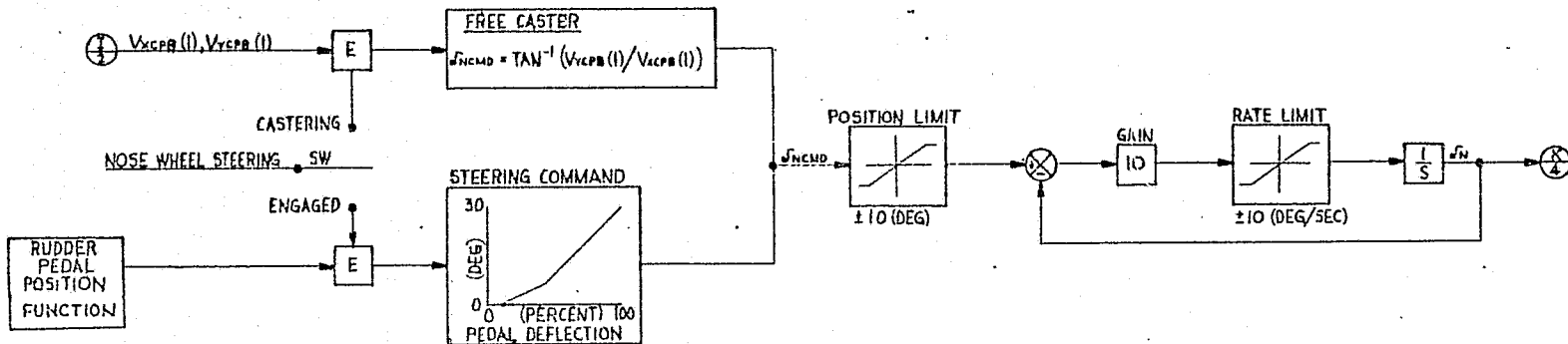
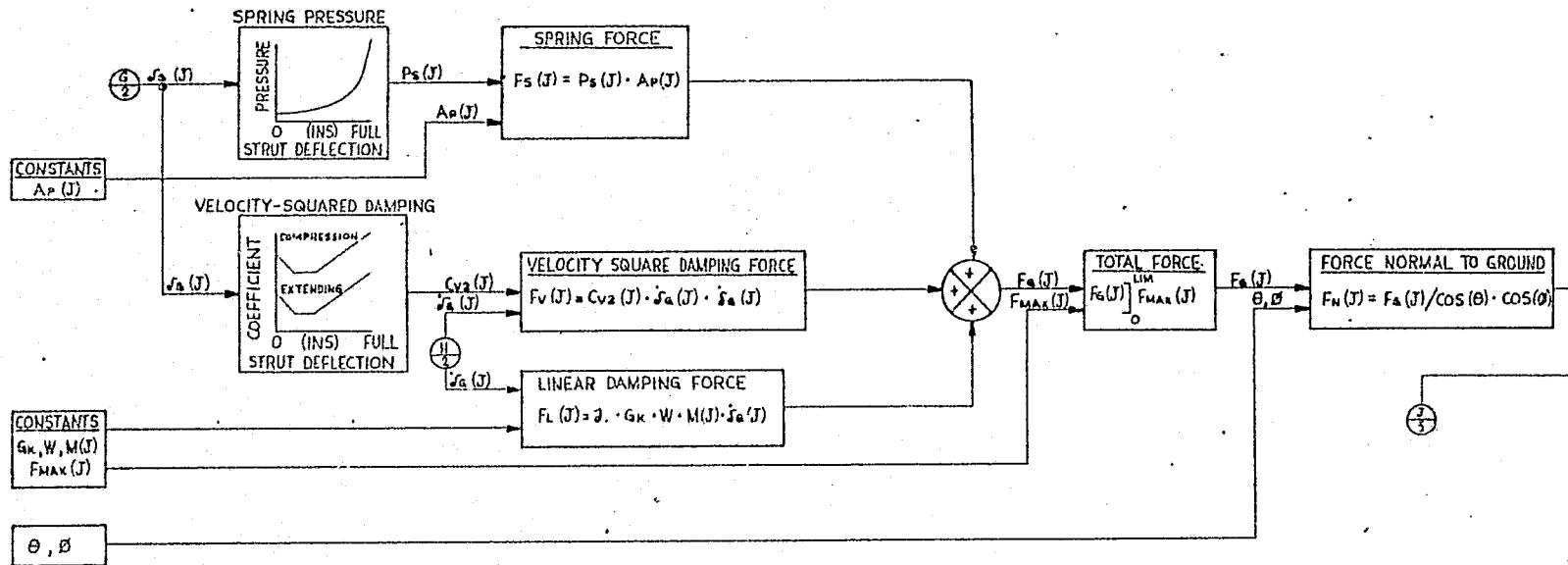


FIGURE 4.7-7 . (CONTINUED)

4.7-15

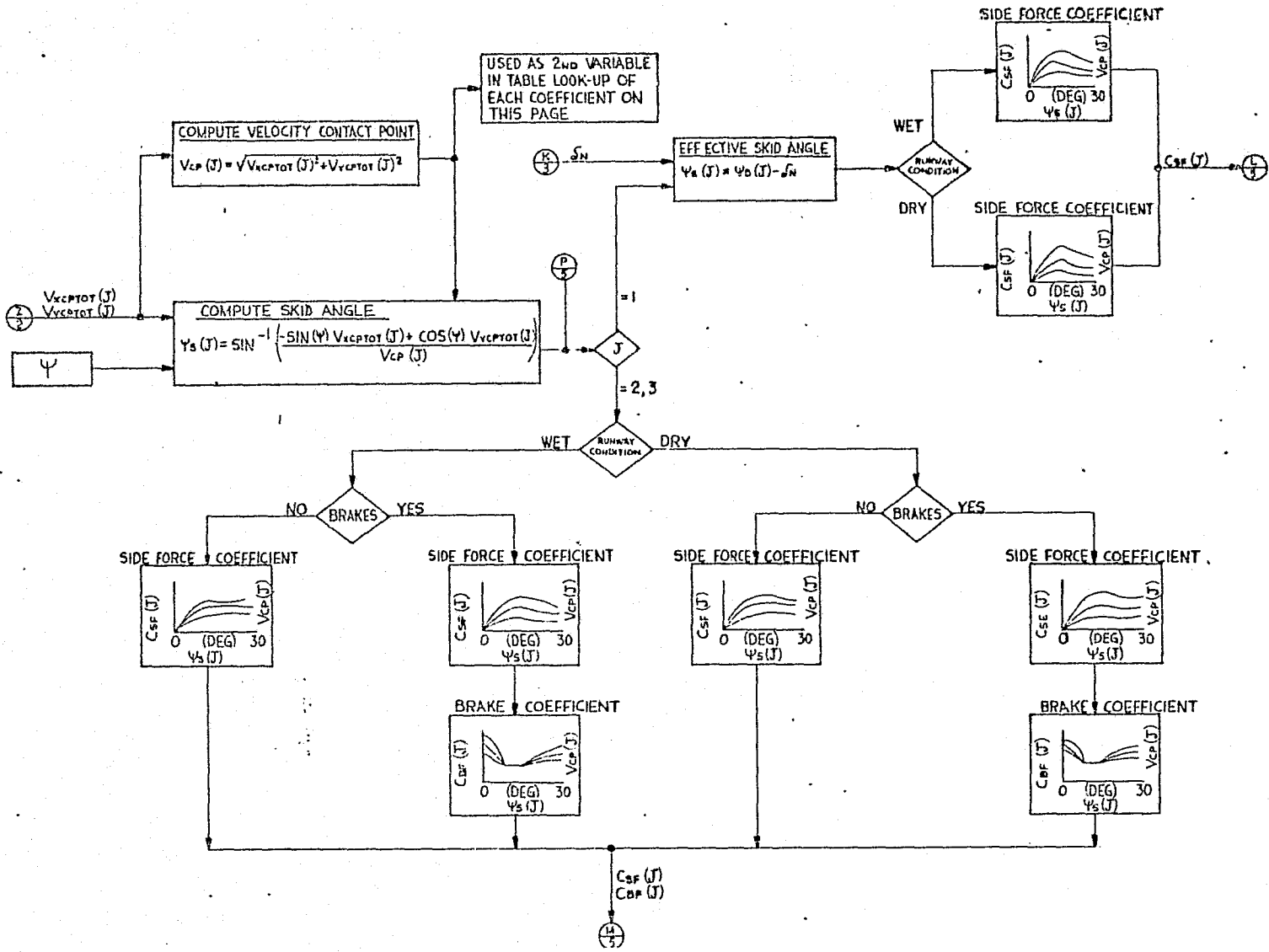


FIGURE 4.7-7. (CONTINUED)

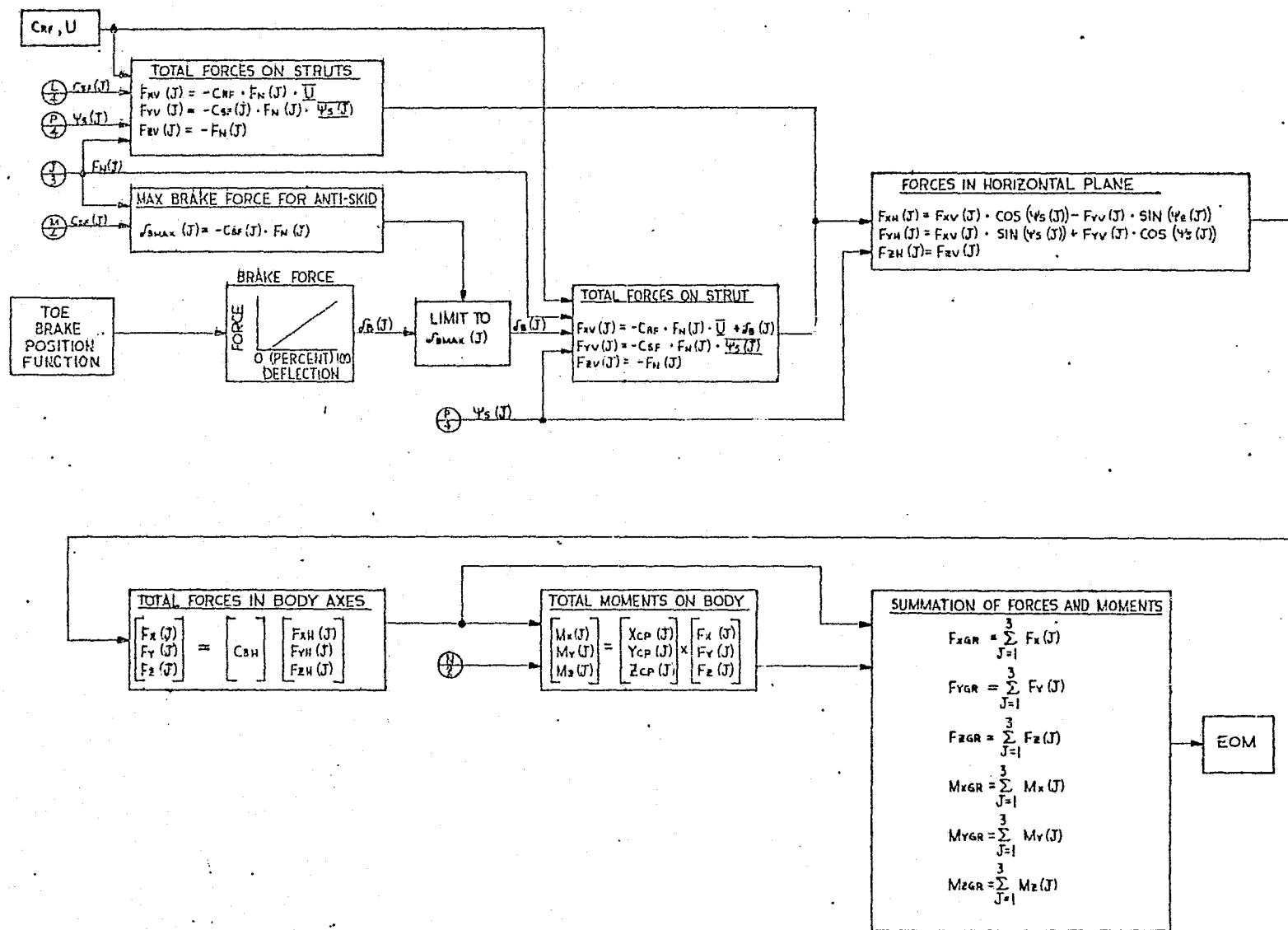


FIGURE 4.7-7 . (CONTINUED)

LEGEND:

CGx CGy CGz	} Orbiter center of gravity coordinates
XD(J) YD(J) ZD(J)	} Gear and tip coordinates with respect to datum
XNED(J) YNED(J) ZNED(J)	} Gear and tip coordinates in North-East-Down system
$\begin{bmatrix} \text{CXN}(i) \\ i=1,9 \end{bmatrix}$	North-East-Down to body axes transformation matrix
$\begin{bmatrix} \text{CBH}(i) \\ i=1,9 \end{bmatrix}$	Horizontal to body axes transformation matrix
L	Orbiter latitude
λ	Orbiter longitude
R_E	Radius of the earth
L_R	Runway localizer latitude
λ_R	Runway localizer longitude
R_L	Local radius of the earth at localizer
ψ_R	Runway azimuth
XG(J) YG(J) ZG(J)	} Gear and tip coordinates from center of gravity
NRWY ERWY	} Components of distance from vehicle center of gravity to runway localizer
DN(J) DE(J)	} Gear and tip locations relative to runway
RX(J) RY(J)	} Gear and tip locations in runway coordinates
HREF(J) HREF(J)	} Runway reference and reference change rate for gear and tips
H	Vehicle altitude
DHT(J)	Distance from gear and tips to runway
SG(J) SG(J)	} Gear deflection and deflection rate

FIGURE 4.7-7 . (CONTINUED)

XCP YCP ZCP	}	Gear contact points
P Q R	}	Body rates about body axes
VGX VGY VGZ	}	Orbiter groundspeed components
VXCP(J) VYCP(J) VZCP(J)	}	Velocity components, gear contact points
VXCPTOT(J) VYCPTOT(J) VZCPTOT(J)	}	Contact point total velocity components
VXCPB(J) VYCPB(J) VZCPB(J)	}	Contact point total velocity components in body axes
VXAP(J) VYAP(J) VZAP(J)	}	Attach point velocity components
VZAPB(J)		Total vertical velocity at attach point in body axes
AP(J)		Shock strut piston area
PS(J)		Shock strut air/GN2 pressure
FS(J)		Shock strut reaction force
CV2(J)		Damper coefficient
FMAX(J) GK W M(J)	}	Linear damping force constants
FL(J)		Landing gear linear damping force
FV(J)		Landing gear velocity squared damping force
FG(J)		Landing gear total damping force
FN(J)		Landing force normal to ground
θ ϕ ψ	}	Orbiter attitude angles

FIGURE 4.7-7 . (CONTINUED)

δ NCMD Steering command
 δ N Steering angle
 $\psi_s(J)$ Tire skid angle
 CSF Side force coefficient
 CBF Braking force coefficient
 CRF Rolling force coefficient
 U Orbiter velocity in the x-direction

$\left. \begin{array}{l} FXV(J) \\ FYV(J) \\ FZV(J) \end{array} \right\}$ Total force on struts (vertical)

$\left. \begin{array}{l} FXH(J) \\ FYH(J) \\ FZH(J) \end{array} \right\}$ Total force on struts (horizontal)

δ BMAX(J) Maximum braking force for anti-skid
 δ B(J) Braking force on each wheel

$\left. \begin{array}{l} FX(J) \\ FY(J) \\ FZ(J) \end{array} \right\}$ Total gear forces in body axes

$\left. \begin{array}{l} MX(J) \\ MY(J) \\ MZ(J) \end{array} \right\}$ Total gear moments on body

$\left. \begin{array}{l} FXGR \\ FYGR \\ FZGR \end{array} \right\}$ Total LDS forces output to EOM

$\left. \begin{array}{l} MXGR \\ MYGR \\ MZGR \end{array} \right\}$ Total LDS moments output to EOM

NOTE: Circled fractions with a letter over a number are cross reference linking equation elements on separate pages. For example, the output point $\frac{A}{2}$ on Sheet 1 refers to the input point $\frac{A}{1}$ on Sheet 2..

FIGURE 4.7-7 . (CONTINUED)

tire skid angles , tire braking, rolling, and side force coefficients, and sequential time delay functions. Note that the nose wheel steering actuator is modeled within the math flow for the reference module. The math flow shown should also be modified to utilize a "flat earth" model for runway proximity/touchdown flight regimes.

LDS Validation Methods and Check Cases

Both static and dynamic check cases should be used for LDS validation data generation. Check cases may include static discrete points or consist of dynamic input functions and vehicle touchdown trajectories.

Static check cases would contain discrete inputs such as static loads on the landing gear spring shock strut. The static deflection can then be calculated. The output data would be plotted as in Figure 4.7-8 (Ref. 7) and the air/GN₂ spring rate verified.

Dynamic inputs would consist of time-dependent functions input to the LDS simulation and reference modules. A step input to the shock strut could be used to validate air/GN₂ spring-hydraulic damper characteristics. Steering reaction forces and tire skid angle could be verified using quasi-steady relationships involving tire load, velocity, tire side force coefficient, and vehicle steering and yaw angle.

Touchdown trajectories and runway profiles could also be used in formulating check cases. For example, a special runway profile could be constructed and the vehicle "rolled" down a given reference trajectory. LDS response could then be evaluated and comparison plots generated for the desired variables.

LDS Data Base Impact

Data base requirements for verification of the LDS consist of an appropriate reference module, check cases, and tables as required for the various tabular lookups of coefficients. When sufficient hardware testing of the LDS has been completed, the maximum sizes for these tables will be determined. Some variation in storage requirements may result until testing is complete.

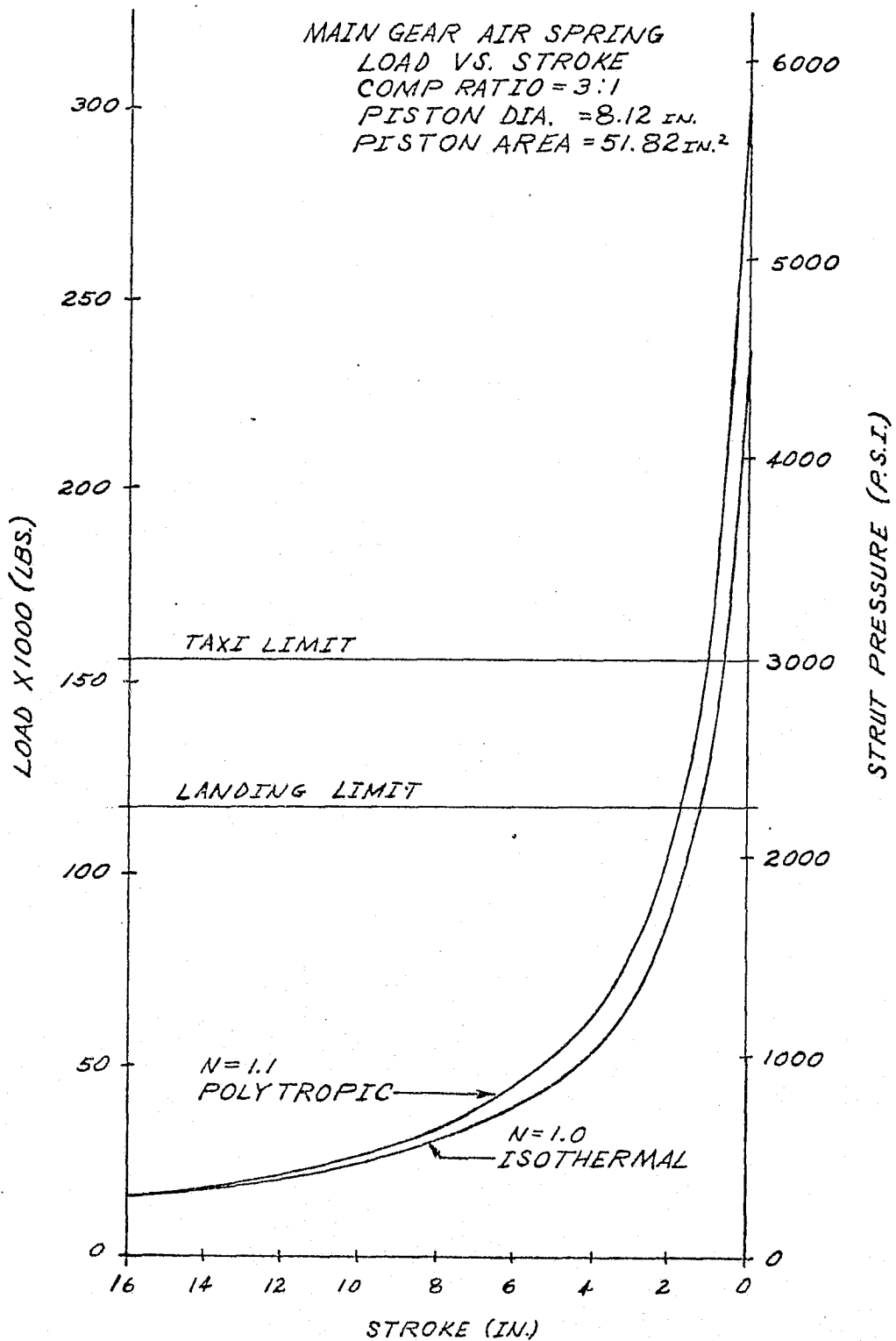


FIGURE 4.7-8 . MAIN GEAR AIR SPRING CHARACTERISTICS

4.7.1.2 Docking Mechanism Subsystem (DMS)

DMS Description

The DMS provides an active or passive interface to effect a satisfactory Orbiter docking/undocking operation with other orbital vehicles. (A passive docking interface is capable of accepting an active docking system; the active docking mechanism can function in either the active or passive mode.) The DMS comprises the actual docking interface as well as the extendible tunnel in the docking module kit. In the event of a DMS failure which would preclude payload door closure, the DMS may be pyrotechnically jettisoned at a separation plane lying below the Orbiter mold line (Ref. 5).

Figure 4.7-9 (Ref. 9) depicts the principal assemblies and systems which compose a typical active and passive DMS. The primary DMS components and assemblies consist of:

- Guide ring assembly
- Capture latch assembly
- Body-mounted latch assembly
- Base and tunnel assembly
- Attenuator assembly
- Retract system
- Structural ring latch assembly
- Electrical components (not shown specifically in Figure 4.7-9)
- DMS jettison assembly (not shown)
- DMS extendible tunnel (not shown)

Initial contact limit conditions for docking are given in Table 4.7-2 (Ref. 8). After vehicle-to-vehicle alignment is attained (via RCS), secondary docking alignment is made using the guide system mounted on the guide rings of the active and passive vehicles. Capture is effected by a series of latches on the extended ring of the active DMS. Following capture and stabilization, the mated vehicles are drawn together by the guide ring extension/retraction system. Hard dock providing a sealed interface is accomplished using the structural latches mounted on the base and tunnel assembly. All extension, retraction and unlatching functions are crew controlled. Undocking is accomplished through sequential unlatching operations.

4.7-23

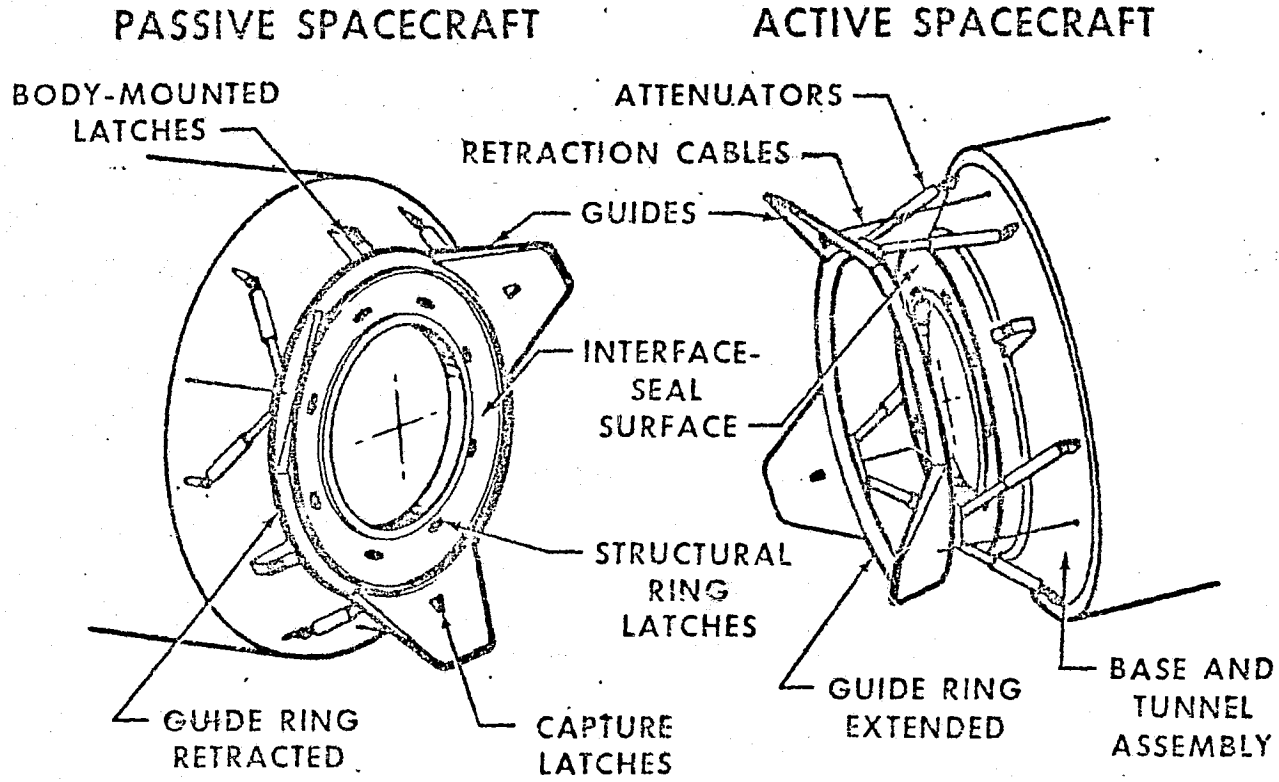


FIGURE 4.7-9. ACTIVE AND PASSIVE DMS

TABLE 4.7-2 . DMS INITIAL CONTACT LIMITS

CONDITION	LIMIT
Closing velocity	0.5 ft./sec.
Lateral velocity	0.1 ft./sec.
Rotational velocity	1.0 deg./sec.
Miss distance	0.5 ft.
Angular misalignment	5.0 deg.

DMS Simulation Module Description and Performance Parameters

The DMS software will simulate the operation of the Orbiter DMS during docking/undocking maneuvers. This software module will be executed 10 times per second in the docking/undocking mission phases.

Inputs to the DMS simulation module consist of (Ref. 11):

- Orbiter vehicle state
- Target vehicle state, relative state
- Crew commands for DMS deployment, jettison, and docking/undocking operations
- Electrical power available
- Orbiter and target mass properties

The DMS simulation module will use these inputs to calculate the docking/undocking reaction forces and moments on the Orbiter and target vehicle. Also output are crew response and status indicators for all docking and undocking operations including DMS deployment and jettison.

Vehicle states and relative states in conjunction with DMS specification will be used to calculate the reaction forces and moments on both vehicles due to the operation of the MDS guide rings, retraction system, and attenuators. DMS deployment, jettison and undocking will be simulated as talkback using time delay functions incorporating power available checks. Latching operations will also be simulated with talkback; however, vehicle alignment checks must be made to respond to latching inputs. The performance parameters associated with the DMS are shown

in Table A.7-3 . Figure A.7-10 depicts the DMS simulation module interfaces with other simulation modules.

DMS Reference Data Sources and Data Formats

Complex docking/undocking operations provide a dynamic environment for the DMS. This environment requires comprehensive reference data for validation of the DMS simulation module. High-fidelity, comprehensive reference data can best be generated by a reference software module similar in function to the Figure 4.7-11 functional flow diagram.

Reference 10 describes, in detail, a well-developed DMS simulation software program which can be implemented as a DMS reference module. The Ring-Finger Docking Dynamics (RFDD) digital program was developed as an engineering/analysis tool for use in determining the docking system loads and attendant vehicular motion resulting from docking two vehicles that have an androgynous, six-hydraulic-attenuator, guide ring, docking interface similar to that designed for the Apollo/Soyuz Test Project (ASTP). Presently the program will analyze either: (1) docking of the Apollo and Soyuz or (2) Shuttle Orbiter to another Orbiter. The RCS subroutine is modified to accommodate the appropriate combination (Ref. 10). It is conceivable that other docking combinations could be simulated with similar program changes (e.g. Soyuz-Orbiter, Space Lab-Orbiter, etc.).

The RFDD program treats the two vehicles and the docking ring as rigid bodies. Each rigid body is modeled with six degrees of freedom. A structurally compliant, hydraulically attenuated docking interface is simulated between the docking ring and the active vehicle. All docking operations except tunnel sealing, hard structural latching, and hard docking dynamics are mathematically simulated (Ref. 10).

Inputs to the RFDD program are defined as (Ref. 10):

- Vehicle (active and passive) mass properties
- Vehicle control systems (active and passive)
- Attenuator locations and design characteristics
- DMS design characteristics and constraints
- Run configuration indicators
- Integration interval controls

TABLE 4.7-3. DMS SIMULATION MODULE PERFORMANCE PARAMETERS

SYMBOL	PARAMETER	TYPE ^a
$I_{=0}$	Orbiter inertia tensor	I
$I_{=t}$	Target inertia tensor	I
M_o	Orbiter mass	I
M_t	Target mass	I
CM_o	Orbiter center of mass	I
CM_t	Target center of mass	I
r, v	Orbiter position, velocity	I
$\delta r, \delta v$	Target relative position and velocity	I
ϕ_o, θ_o, ψ_o $\dot{\phi}_o, \dot{\theta}_o, \dot{\psi}_o$	Orbiter attitude and attitude rates	I
$\delta\phi_t, \delta\theta_t, \delta\psi_t$ $\delta\dot{\phi}_t, \delta\dot{\theta}_t, \delta\dot{\psi}_t$	Target relative attitude and attitude rates	I
δv_c	Orbiter-target closing velocity limit	DB
δv_l	Orbiter-target lateral velocity limit	DB
δv_r	Orbiter-target rotational velocity limit	DB
δl_m	Orbiter-target miss distance limit	DB
δA_m	Orbiter-target angular misalignment limit	DB
$\delta x_{o_d}, \delta y_{o_d}, \delta z_{o_d}$	Relative position of Orbiter DMS	DB
$\delta x_{t_d}, \delta y_{t_d}, \delta z_{t_d}$	Relative (to Orbiter) position of target DMS	CP
	Active DMS geometry	DB
	Passive DMS geometry	DB
C, Rddms	DMS deploy command/response	I/P ^b
C, Rjdms	DMS jettison command/response	I/P
C, Rcdms	DMS capture latch-unlatch command/response	I/P
C, Rrdms	DMS target retract-extend command/response	I/P
C, Rbdms	DMS body-mounted latch-unlatch command/response	I/P
C, Rsdms	DMS structural ring latch-unlatch command/response	I/P
$K_s C_d, l$	DMS attenuator characteristics (spring constant, damping coefficient, travel)	DB
$\delta F_{o, dms}$	Orbiter forces due to DMS	CP
$\delta F_{t, dms}$	Target forces due to DMS	CP
$\delta L_{o, dms}$	Orbiter moment due to DMS	CP

TABLE 4.7-3 . (CONTINUED)

SYMBOL	PARAMETER	TYPE ^a
$S_{L_{t,dms}}$	Target moment due to DMS	CP
P_{dms}	Electrical power load due to DMS	P

^aI - Input

P - Performance Parameter

CP - Critical Performance Parameter

DB - Data Base Input

^b - Denotes 2 parameters - command and response

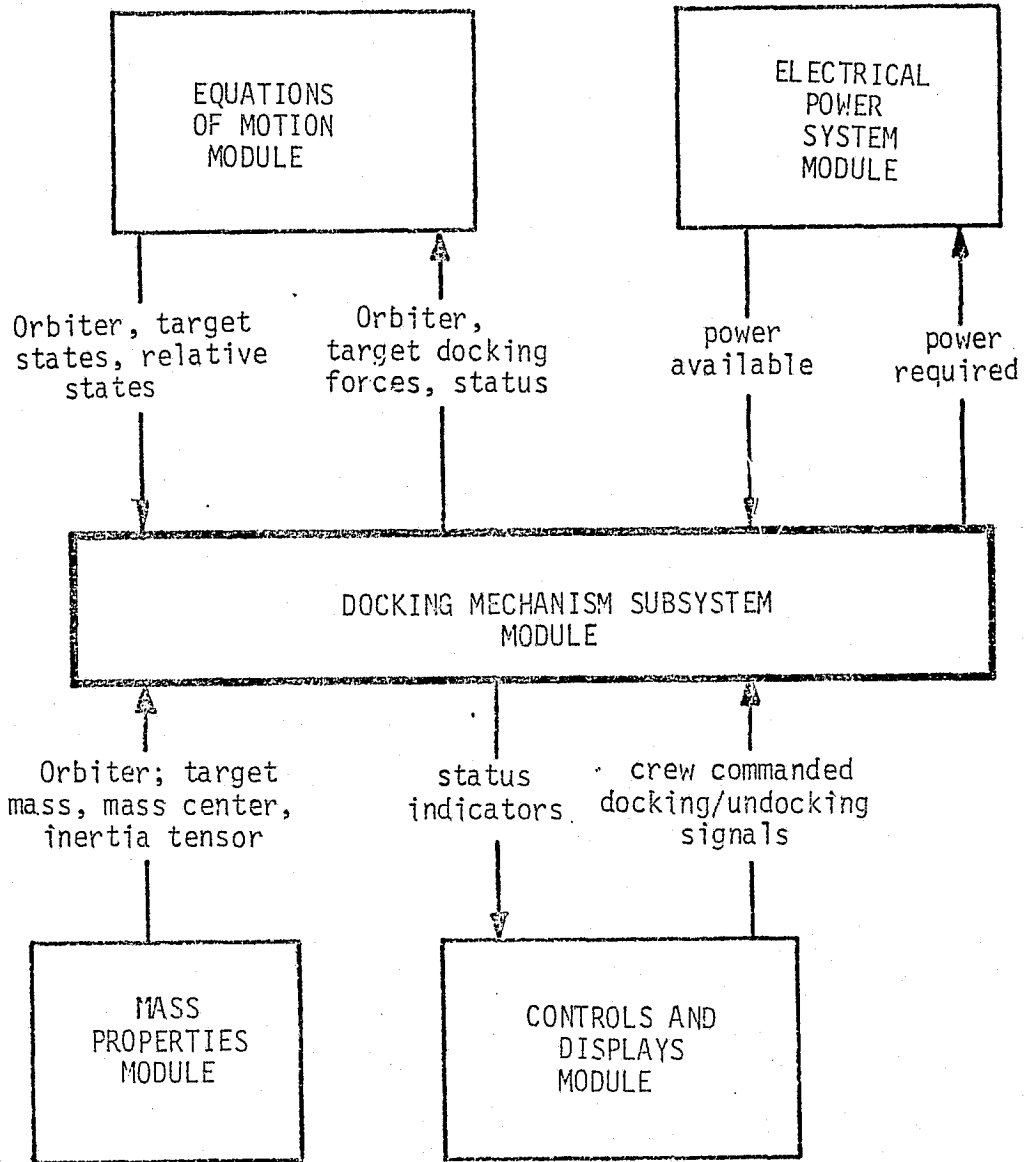


FIGURE 4.7-10 DMS SIMULATION MODULE INTERFACES

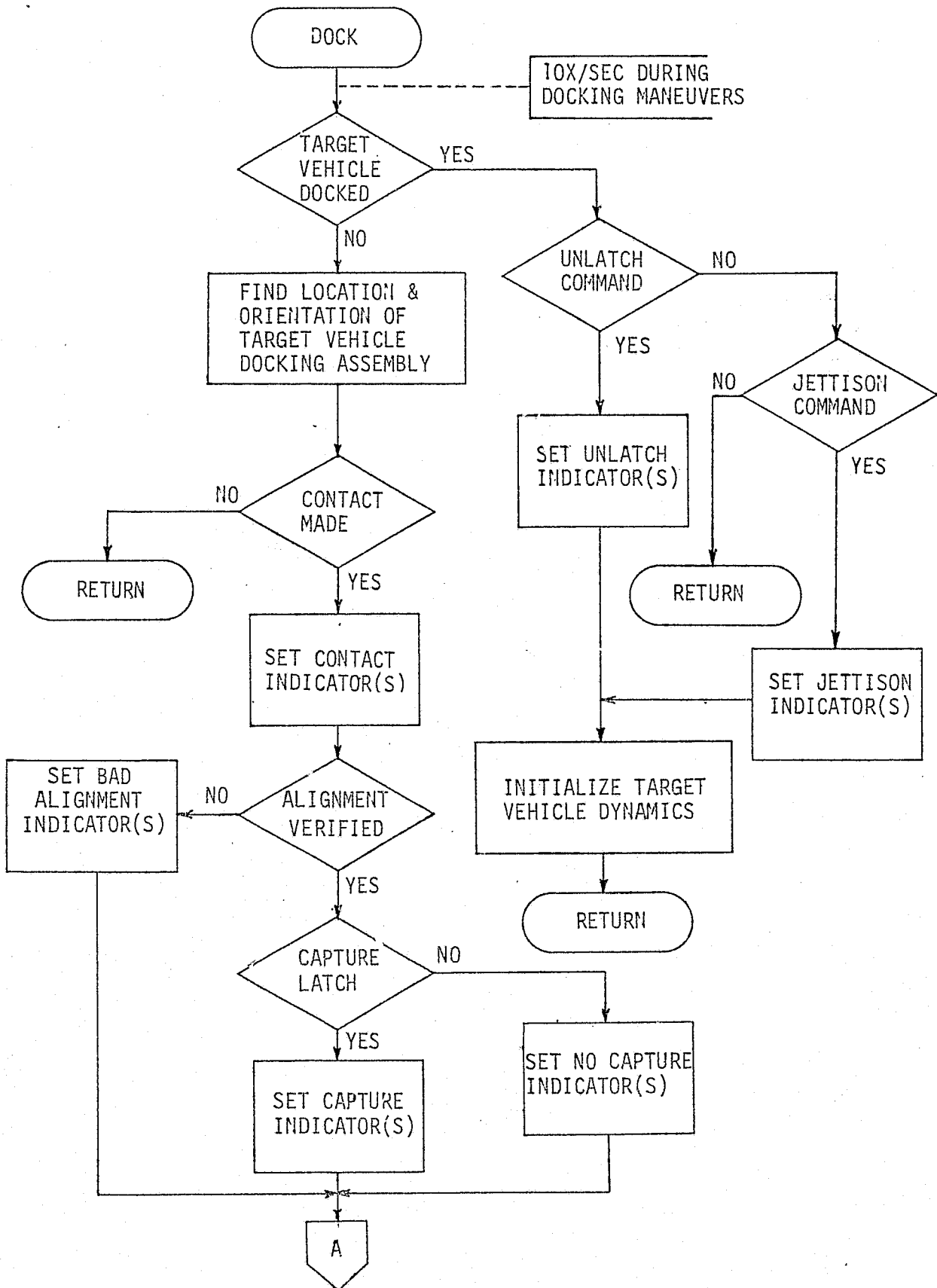


FIGURE 4.7-11. DMS REFERENCE MODULE FUNCTIONAL FLOW DIAGRAM

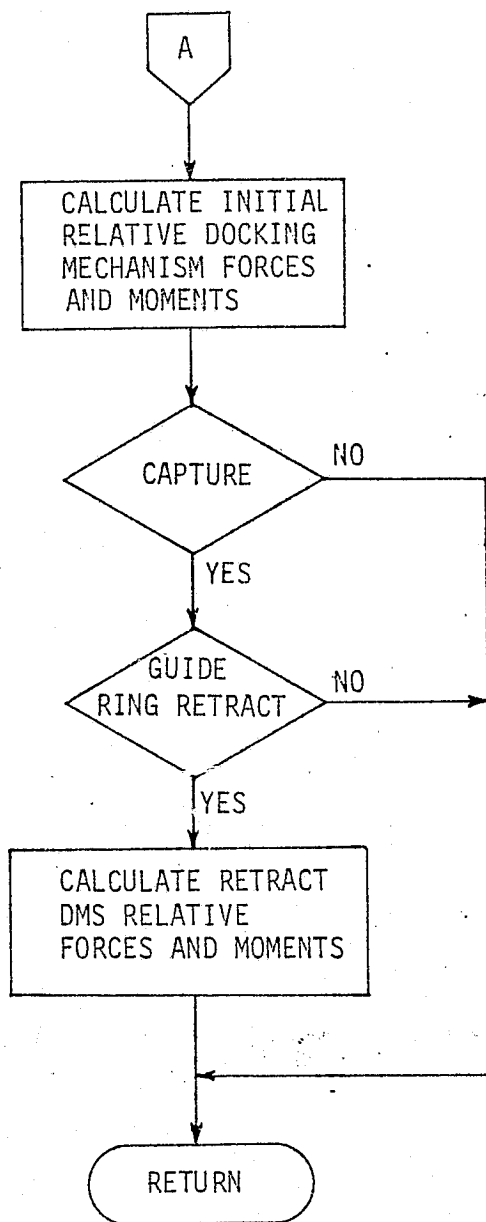


FIGURE 4.7-11. (CONTINUED)

- Print and plot output controls

RFDD program output consists of real-time print and optional time-history plots of DMS and vehicle loads and motions (Ref. 10).

The RFDD program, when used as a reference module, should be combined with a driver which would ensure DMS Simulation Module compatibility and incorporate time-delay talkback functions for DMS tunnel extension, jettison, and undocking operations.

DMS Validation Methods and Check Cases

Check cases for validation of DMS deployment, jettison, and undocking command/response functions can be composed of the required command sequences to verify the proper talkback indicators.

Docking operations should be verified with several check cases containing appropriate velocity and misalignment variations to exercise the docking dynamics reference and simulation modules for each docking target planned. A typical check case should start the two vehicles within the specified miss distance and misalignments, but separated by a relatively large axial distance. The two vehicles are then mathematically positioned axially at some predetermined closing rate. As contact occurs, load computations, vehicle dynamic calculations, and latching simulation continue through draw down. The printed and/or plotted output of both the simulation and reference modules is then analyzed manually or automatically -- as determined by the user.

DMS Data Base Impact

Once the DMS is defined and the appropriate reference module is selected, the primary DMS simulation verification impact upon the verification data base will be in the areas of resident reference data and check cases. Additions to these requirements must be included for each docking target considered.

4.7.1.3 Separation Mechanisms Subsystem

This section discusses those mechanical, pyrotechnic-assisted subsystems which provide for ET/SRB and Orbiter/ET separation during the ascent mission phase.

Separation Mechanisms Description

Shuttle vehicle Orbiter/ET and ET/SRB attach points, umbilical connections and corresponding separation mechanism locations are shown in Figure 4.7-12 (Ref. 12).

ET/SRB Separation - The ET/SRB separation mechanisms provide for efficient, reliable separation of the SRB's (SRB's indicates both solid rocket boosters) from the mated Orbiter/ET vehicle . Included in the ET/SRB separation mechanisms are the fore and aft SRB separation fittings and the SRB boost separation motors (BSM) as shown in Figures 4.7-13, 4.7-14, and 4.7-15 (Ref. 12).

ET/SRB separation commands are generated by Guidance, Navigation, and Control (GN&C) to a sequencer in the Electrical Power Distribution and Control Subsystem (EPDCS). At approximately 125 seconds from launch, pyrotechnic devices in the ET/SRB separation fittings (see Figures 4.7-13 and 4.7-14) are initiated to "guillotine" the SRB's from the ET. The BSM, along with SRM thrust tail-off, direct the SRB's away from the Orbiter/ET. Figure 4.7-16 depicts the nominal separation of an SRB (Ref. 13).

Orbiter/ET Separation - Orbiter/ET separation mechanisms ensure complete separation of the ET from the Orbiter prior to orbital insertion. Structural Orbiter/ET separation occurs at the single forward and 2 aft ET attach points shown in Figure 4.7-12. Figures 4.7-17 and 4.7-18 (Ref. 14) depict typical fore and aft Orbiter/ET separation fittings. Orbiter/ET umbilical disconnect fittings are also included in the separation mechanisms.

Separation sequencing commands from GN&C through the EPDCS, including pyrotechnic initiation, provide structural release of the ET from the Orbiter as shown the Figure 4.7-19 (Ref. 12) separation maneuver.

Separation Mechanisms Simulation Module Description and Performance Parameters

Simulation of both the ET/SRB and Orbiter/ET separation mechanisms will be accomplished using similar techniques involving sequential logic and mechanical

4.7-33

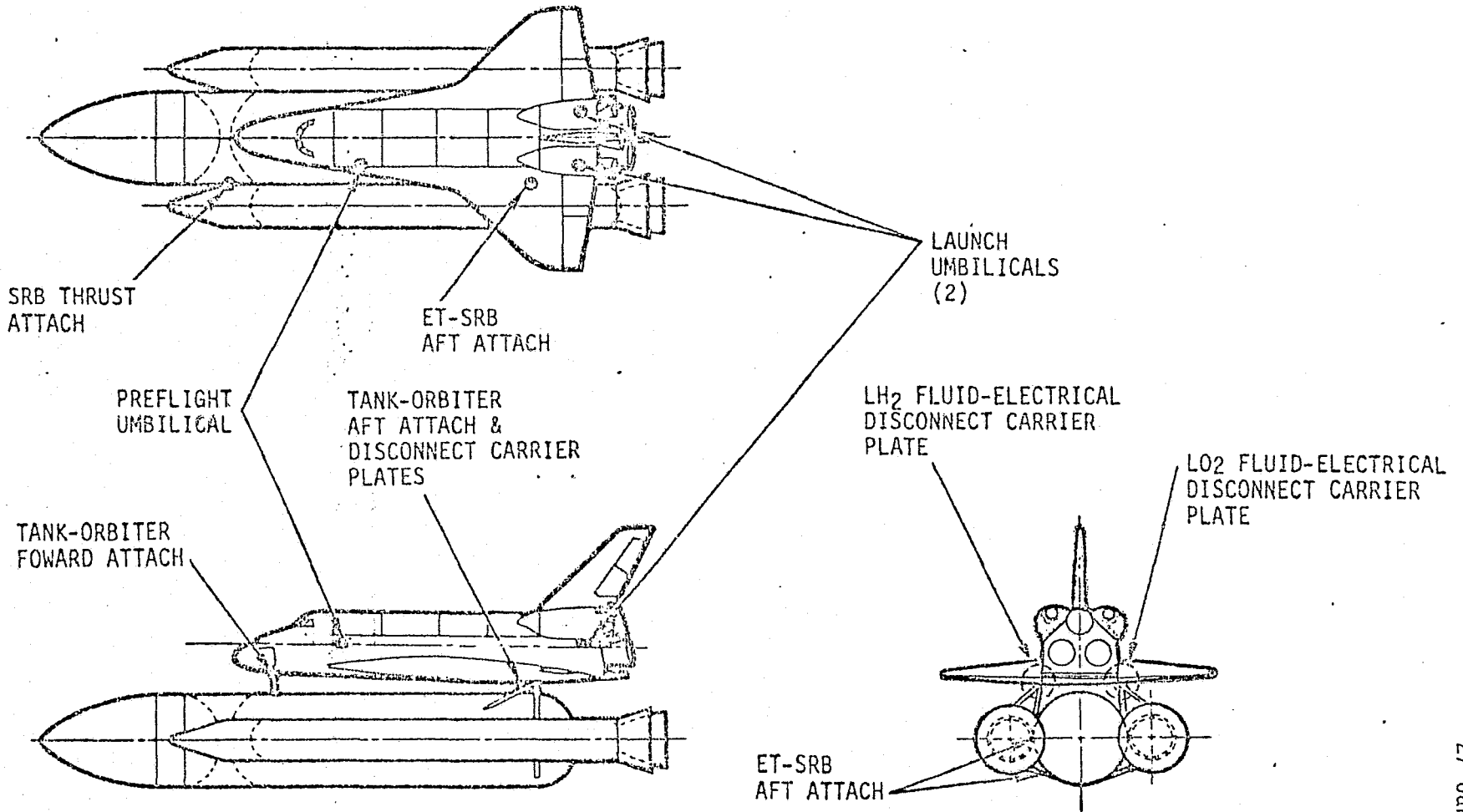


FIGURE 4.7-12. ORBITER/ET AND ET/SRB ATTACH POINTS

4.7-34

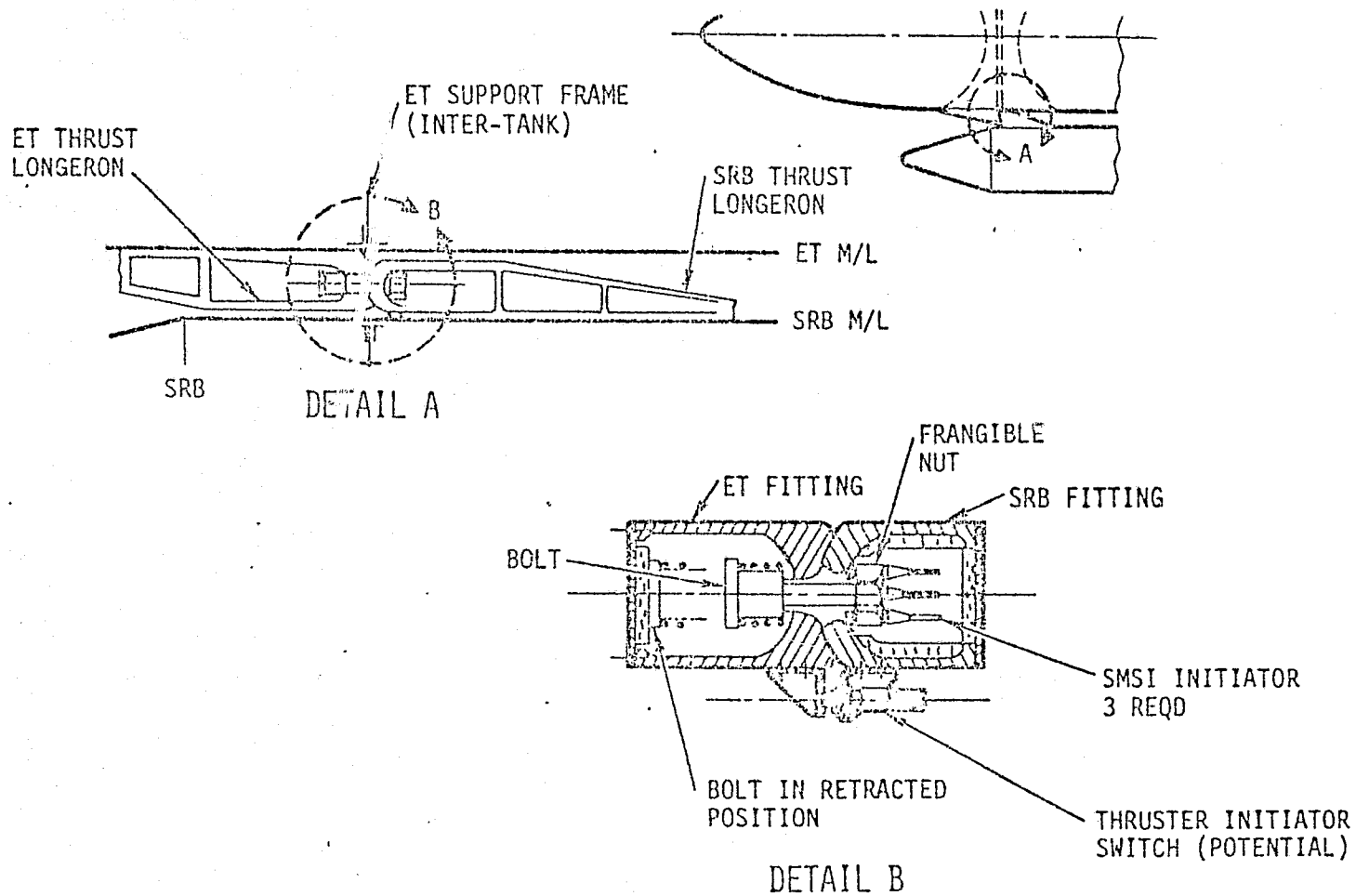


FIGURE 4.7-13. TYPICAL FORWARD ET/SRB SEPARATION FITTING

4.7-35

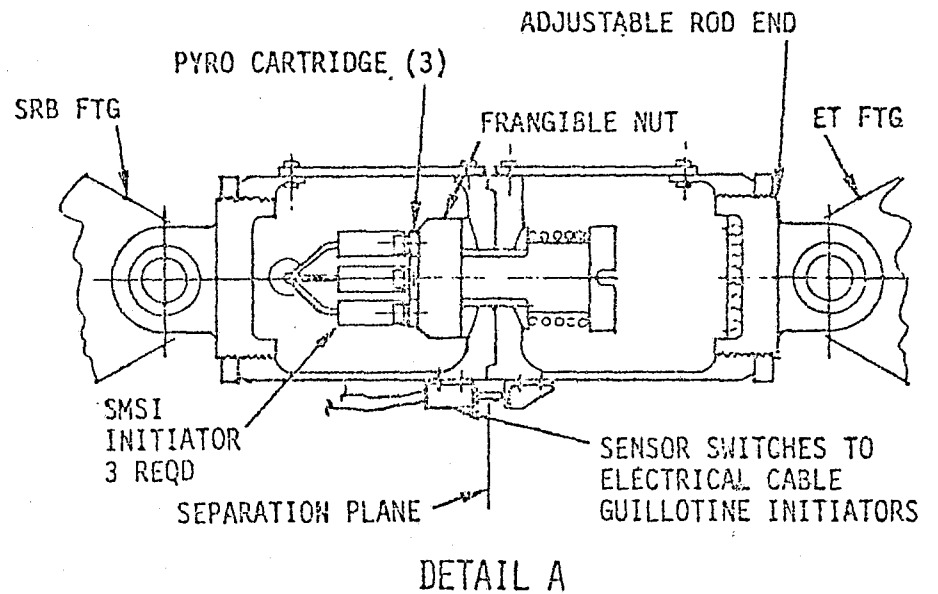
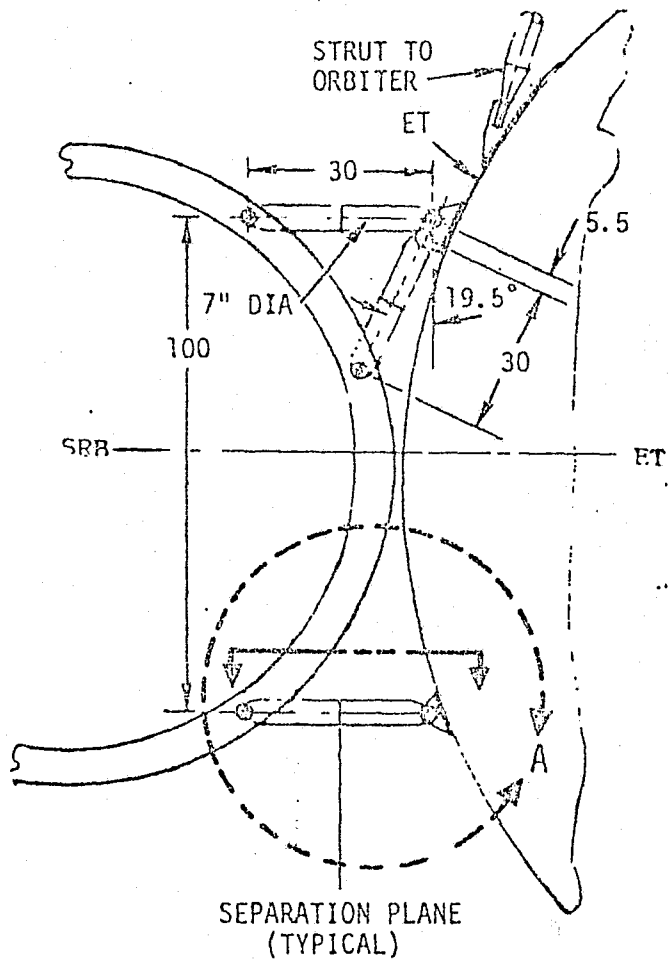


FIGURE 4.7-14. TYPICAL AFT ET/SRB SEPARATION FITTING

4.7-36

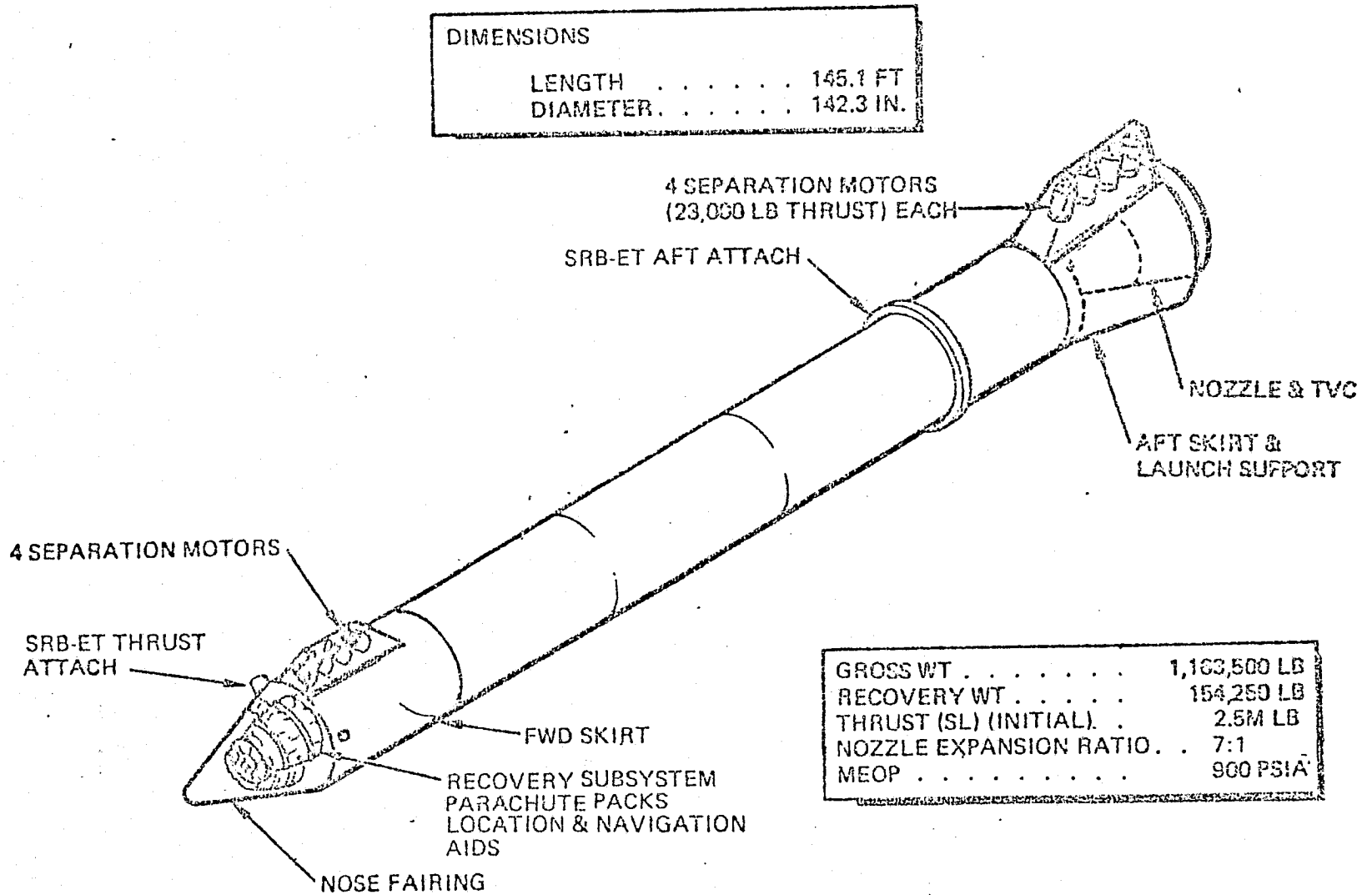


FIGURE 4.7-15. SOLID ROCKET BOOSTER (NOTE SEPARATION MOTORS)

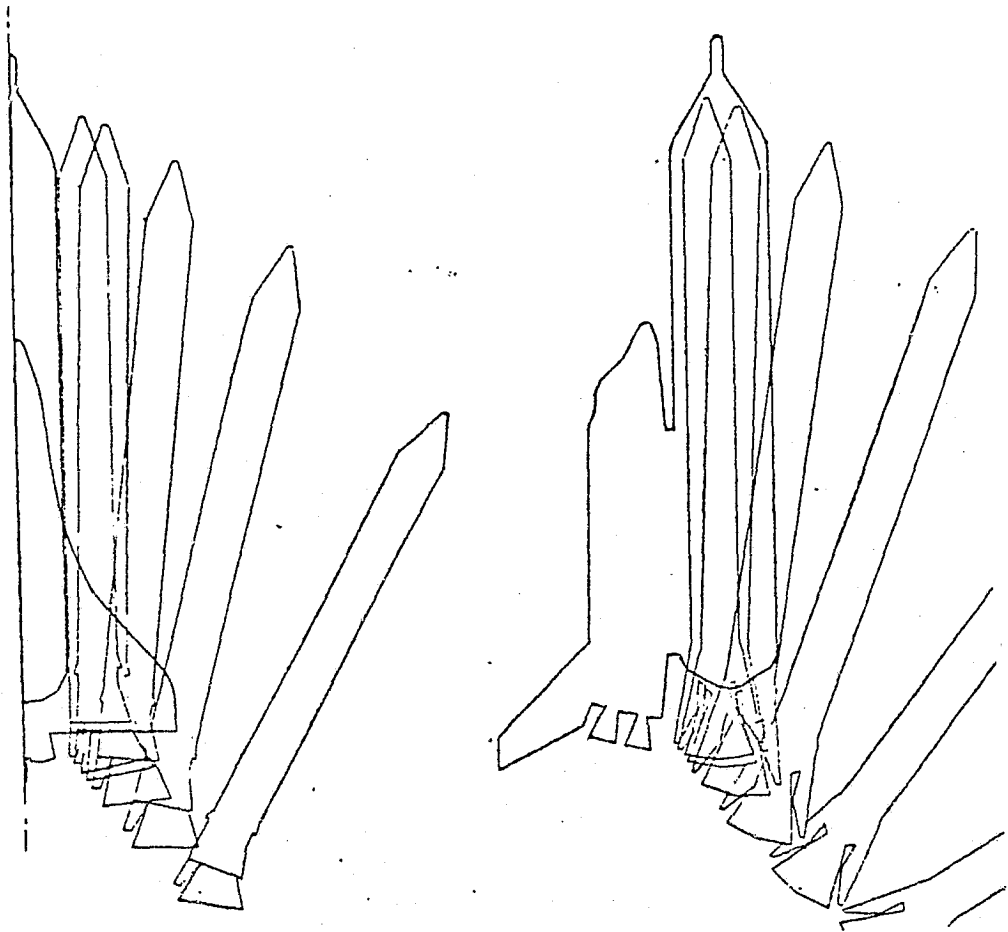
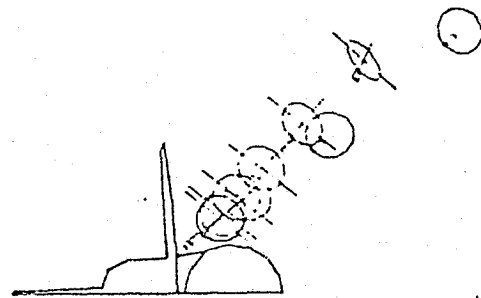


FIGURE 4.7-16. NOMINAL SRB SEPARATION



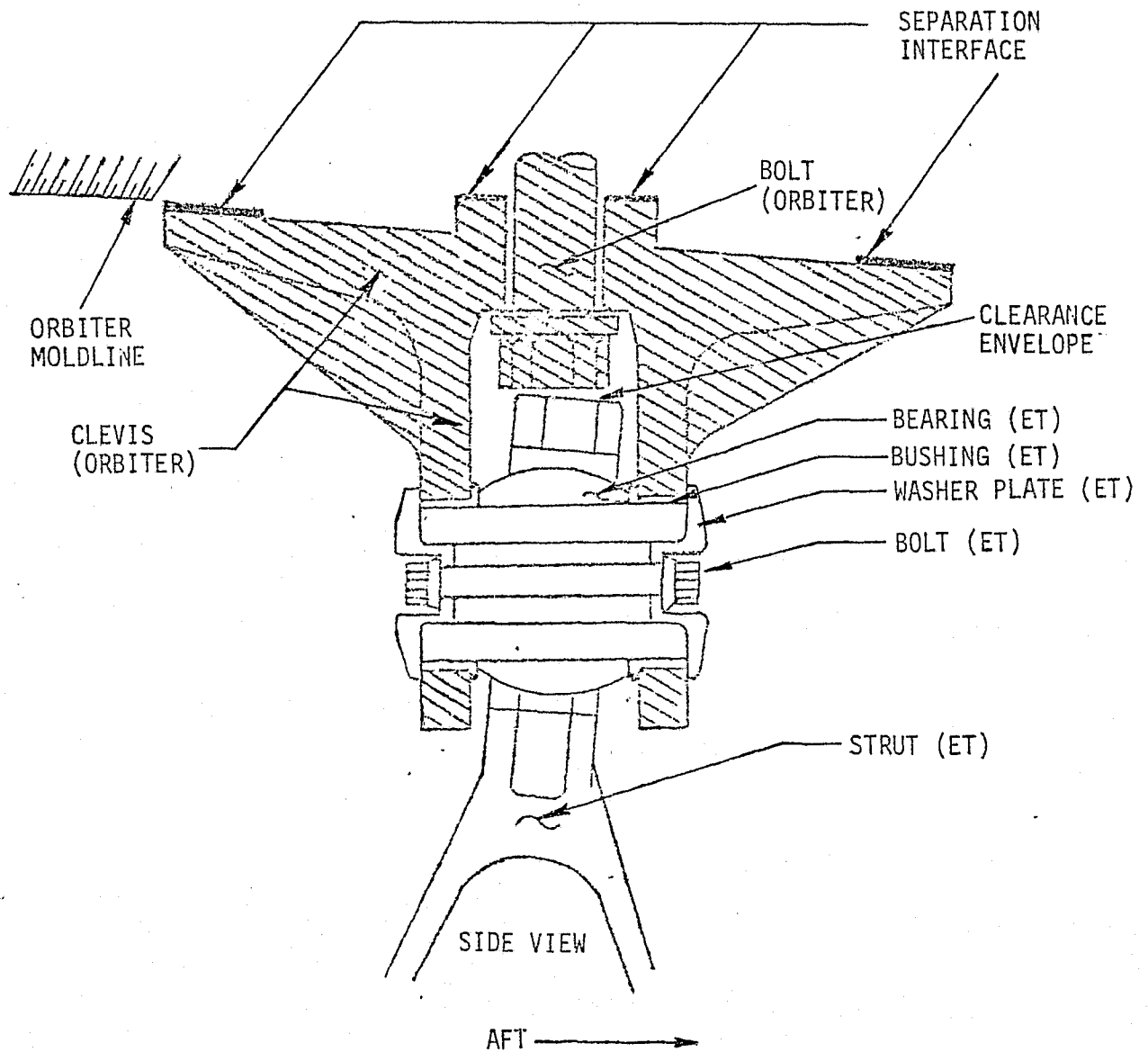


FIGURE 4.7-17. FORWARD ORBITER/ET SEPARATION FITTING

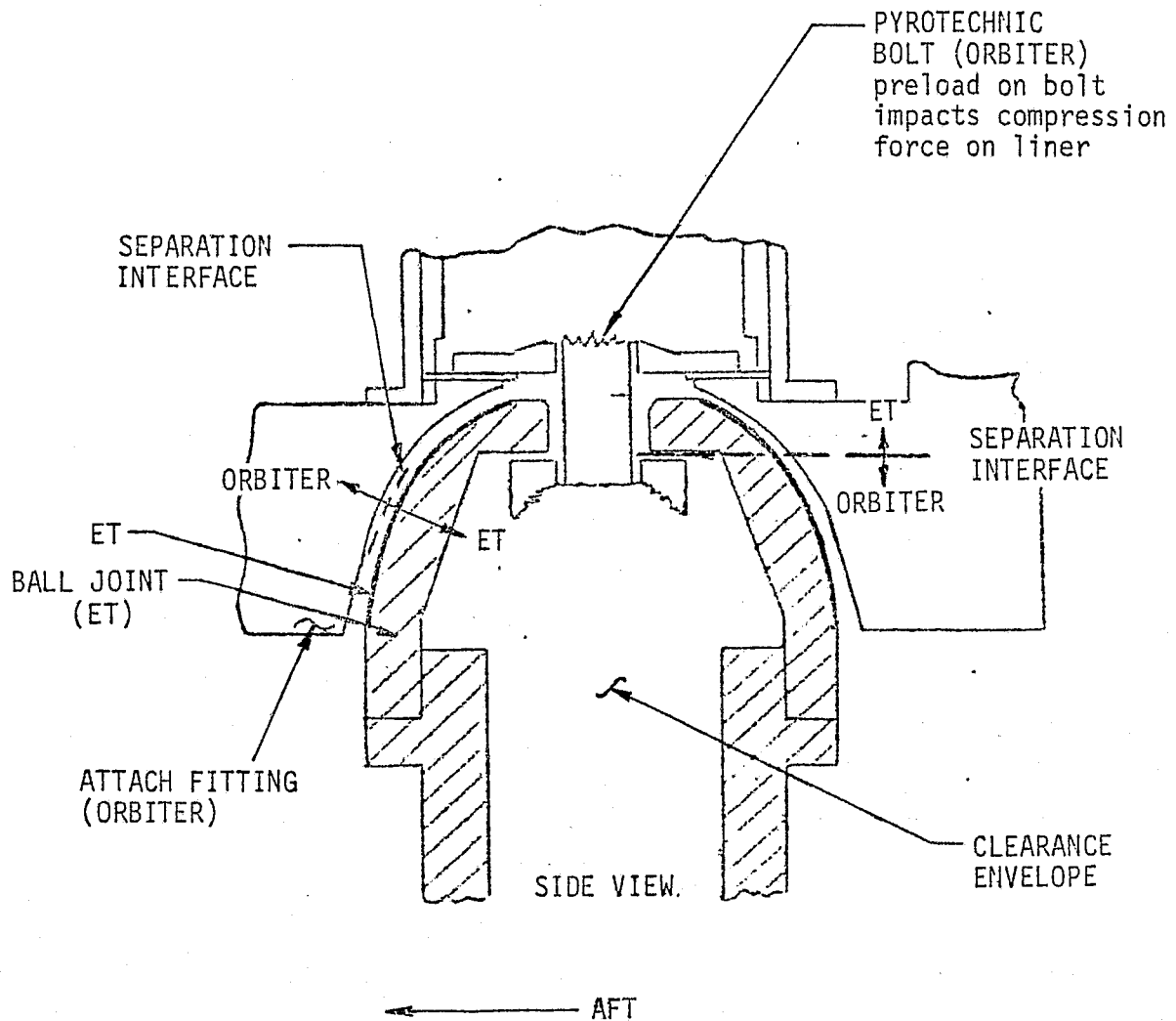


FIGURE 4.7-18. AFT ORBITER/ET SEPARATION FITTING

4.7-40

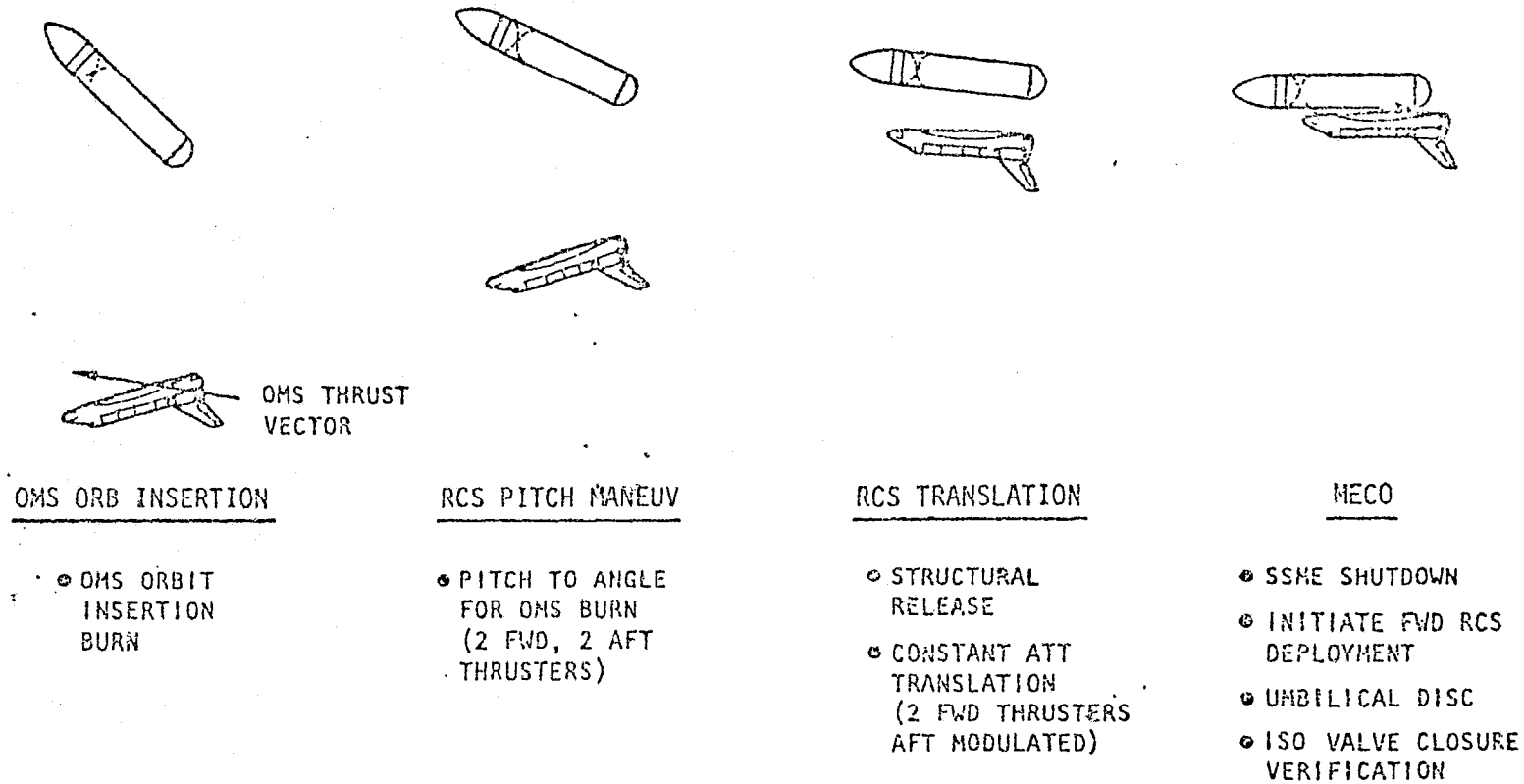


FIGURE 4.7-19. ORBITER/ET NOMINAL SEPARATION MANEUVER

functions to effectively model the actual system (Ref. 11).

Figure 4.7-20 depicts the separation mechanisms subsystem simulation module interfaces. Table 4.7-4 is a listing of the module parameters.

ET/SRB Separation Mechanisms Simulation - The ET/SRB separation mechanisms simulation module will receive pyro-initiate and separation motor ignition commands from GN&C. Response to pyrotechnic SRB separation and BSM will be simulated via "talkback." As BSM burn time is approximately 0.75 seconds, BSM thrust will be simulated with the proper impulsive thrust vector for each rocket motor. SRB separation produces no appreciable forces or moments on the Orbiter/ET vehicle unless a separation failure occurs. Tracking of the separated SRB continues until SRB burnout.

Sequencing of SRB separation will set flags to load new data tables in the Aerodynamics and Mass Properties simulation modules, as shown in Figure 4.7-20.

Orbiter/ET Separation Mechanisms Simulation - Orbiter/ET separation simulation will use sequential time delay functions to provide the "talkback" response for the Orbiter/ET separation mechanism pyrotechnic devices and Orbiter/ET umbilical disconnects. Flags will also be set for aerodynamic and mass properties table re-initializations. Significant separation forces and moments are applied to the Orbiter due to the two rear ball and socket structural attachment designs.

The Orbiter reaction separation forces and moments for the ET rear ball and socket and forward attachments will be computed using simultaneous equation solutions incorporating mechanical functions to effectively model the structural attachment design. Computed forces and moments will be output to the Equations of Motion (EOM) simulation module as shown in Figure 4.7-20.

Separation Mechanisms Subsystem Reference Data Sources and Data Formats

Successful ET/SRB separation has little effect on Orbiter EOM; thus no reference software module is necessary. Verified response to the separation pyrotechnic commands and BSM ignition and corresponding burn time will assure successful simulated ET/SRB separation. Separated SRB relative-state tracking will provide post separation Orbiter/ET-SRB proximity relationships.

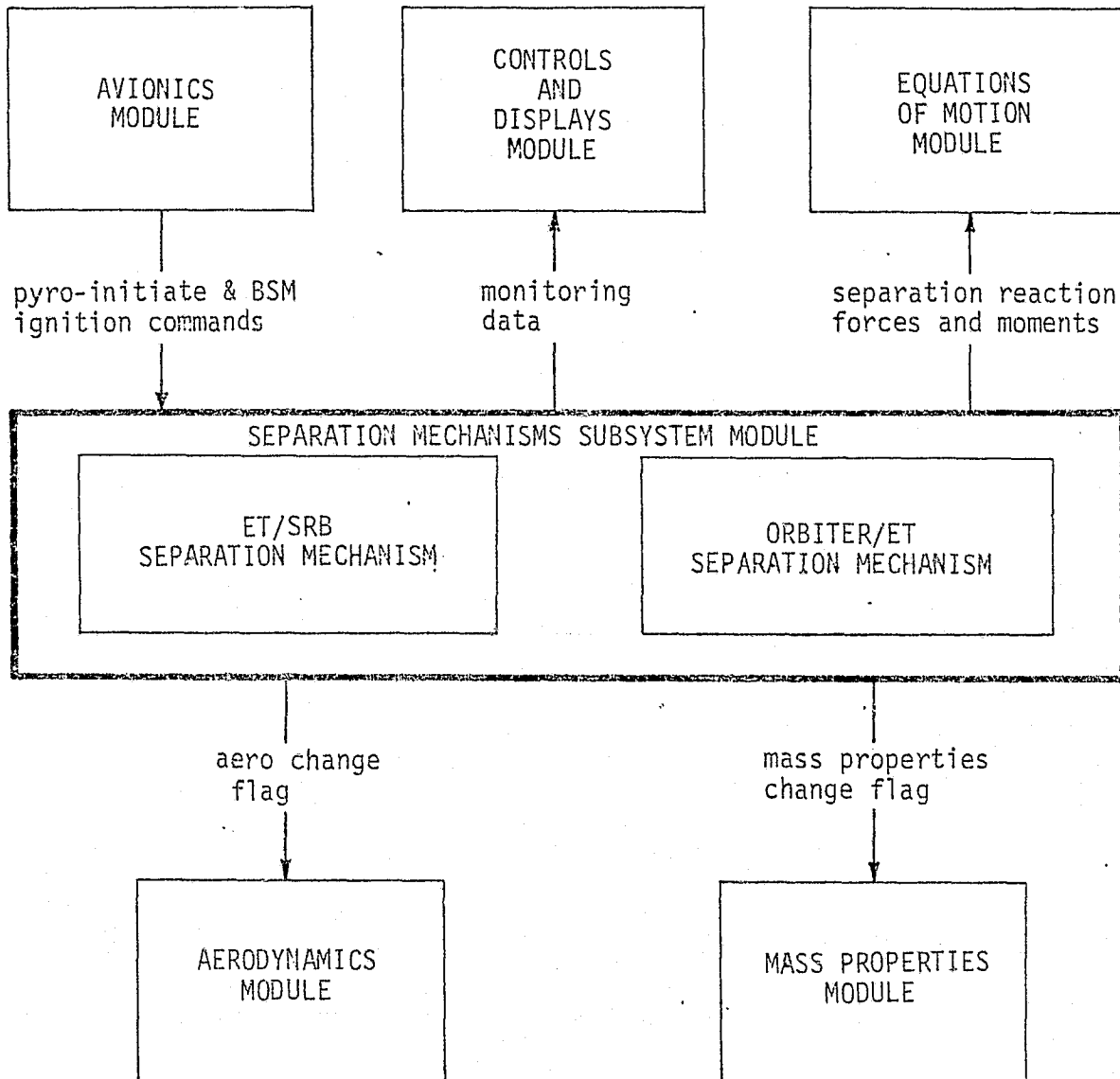


FIGURE 4.7-20. SEPARATION MECHANISMS SUBSYSTEM SIMULATION MODULE INTERFACES

TABLE 4.7-4 . SEPARATION MECHANISM SUBSYSTEM
SIMULATION MODULE PERFORMANCE PARAMETERS

PARAMETER	TYPE ^a
SRB pyro-device separation command/response ^b	I, CP
BSM ignition command/response	I, CP
BSM coordinates	DB
BSM thrust	DB
BSM burn time	DB
SRB tail-off thrust	DB
SRB mass properties	I
SRB relative state vector	I
ET umbilical pyro-disconnect command/response	I, CP
ET separation command/response	I, CP
ET separation forces on Orbiter	CP
ET separation moments on Orbiter	CP
ET mass properties	I
Orbiter mass properties	I
Orbiter/ET forward attach point coordinates	DB
Orbiter/ET forward attach point design constraints	DB
Orbiter/ET aft (2) attach point coordinates	DB
Orbiter/ET aft attachment ball function	DB
Orbiter/ET aft attachment socket function	DB
Ball/socket coefficient of friction	DB
Orbiter state vector	I
Orbiter attitude and attitude rates	I
ET relative state	I
ET relative attitude and attitude rates	I

^aI - Input

P - Performance Parameter

CP - Critical Performance Parameter

DB - Data Base Input

^bIndicates 2 parameters(command and response)

A suitable reference data source for Orbiter/ET separation is described in Figure 4.7-21 math flow. The subroutine shown, ABIND, is used in the SVDS simulation/analysis program. For verification purposes, ABIND would be incorporated into a special driver as described in Section 4.2.

Inputs to ABIND consist of:

- Position vectors to the Orbiter/ET attach points
- Relative position vectors for the Orbiter and ET
- Several transformation matrices (ECI to body coordinates, body coordinates to attach points, etc.)
- Vehicle attitude rates for the Orbiter and ET
- Relative vehicle attitude rates for the Orbiter and ET
- Orbiter and ET mass properties
- Radii of rear attach point ball and socket
- Spring constants, damping coefficients, and coefficients of friction for ball and socket
- A defined region about each socket

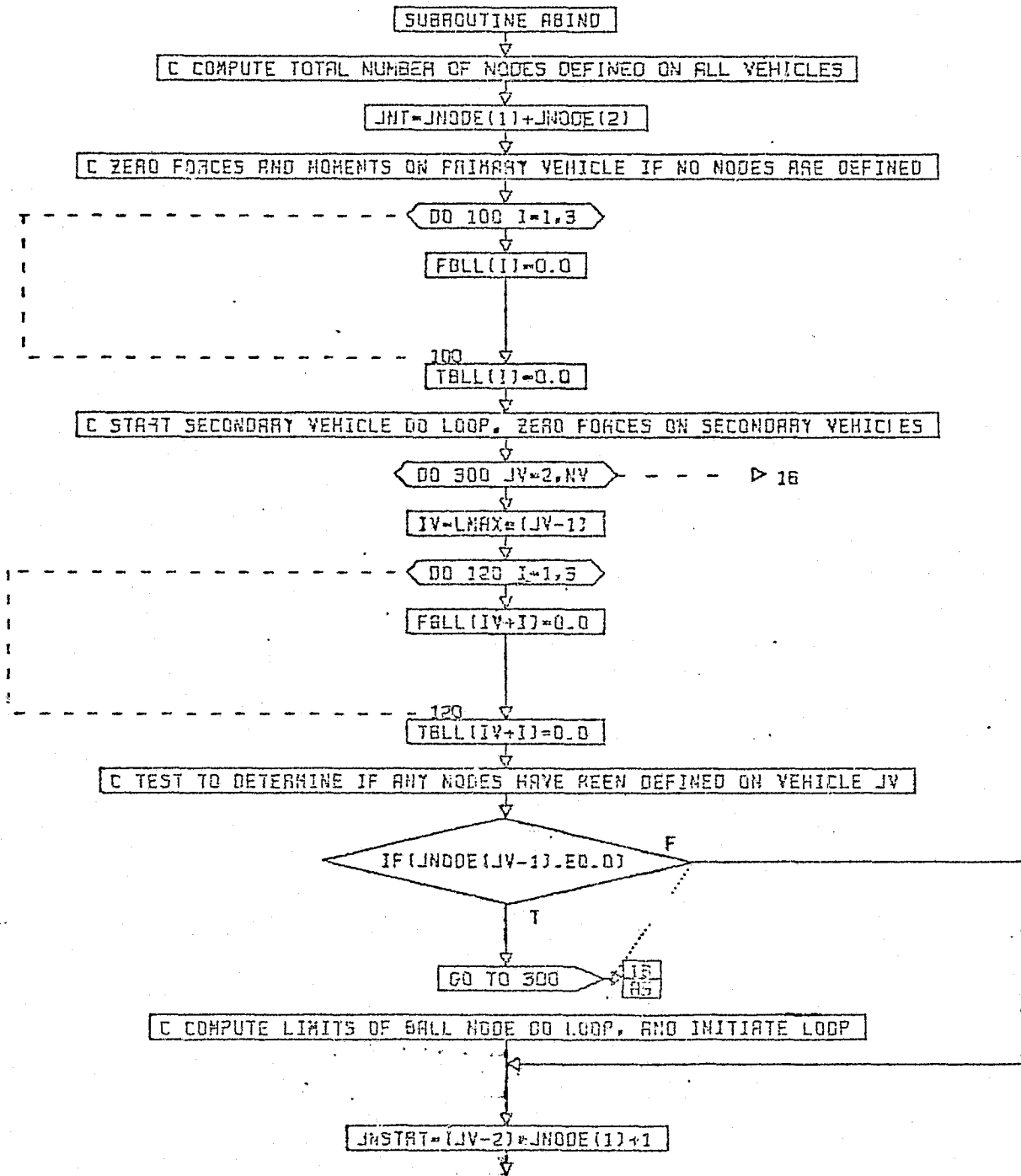
Orbiter reaction forces and moments from the separated ET are computed for output to vehicle EOM.

Separation Mechanisms Subsystem Validation Methods and Check Cases

Since ET/SRB and Orbiter/ET separations are dynamic events, dynamic check cases are required to accurately verify the Separation Mechanisms Subsystems simulation modules.

In the case of the ET/SRB separation mechanisms, verification includes the checkout of; (1) the proper sequencing of pyrotechnic devices and BSM ignition, (2) correct BSM burn time and thrust, (3) SRB tail-off thrust, and (4) tracking of the SRB after separation to monitor Orbiter/ET-SRB proximities. The above parameters can be monitored during an actual simulation run to validate successful SRB separation mechanisms simulation.

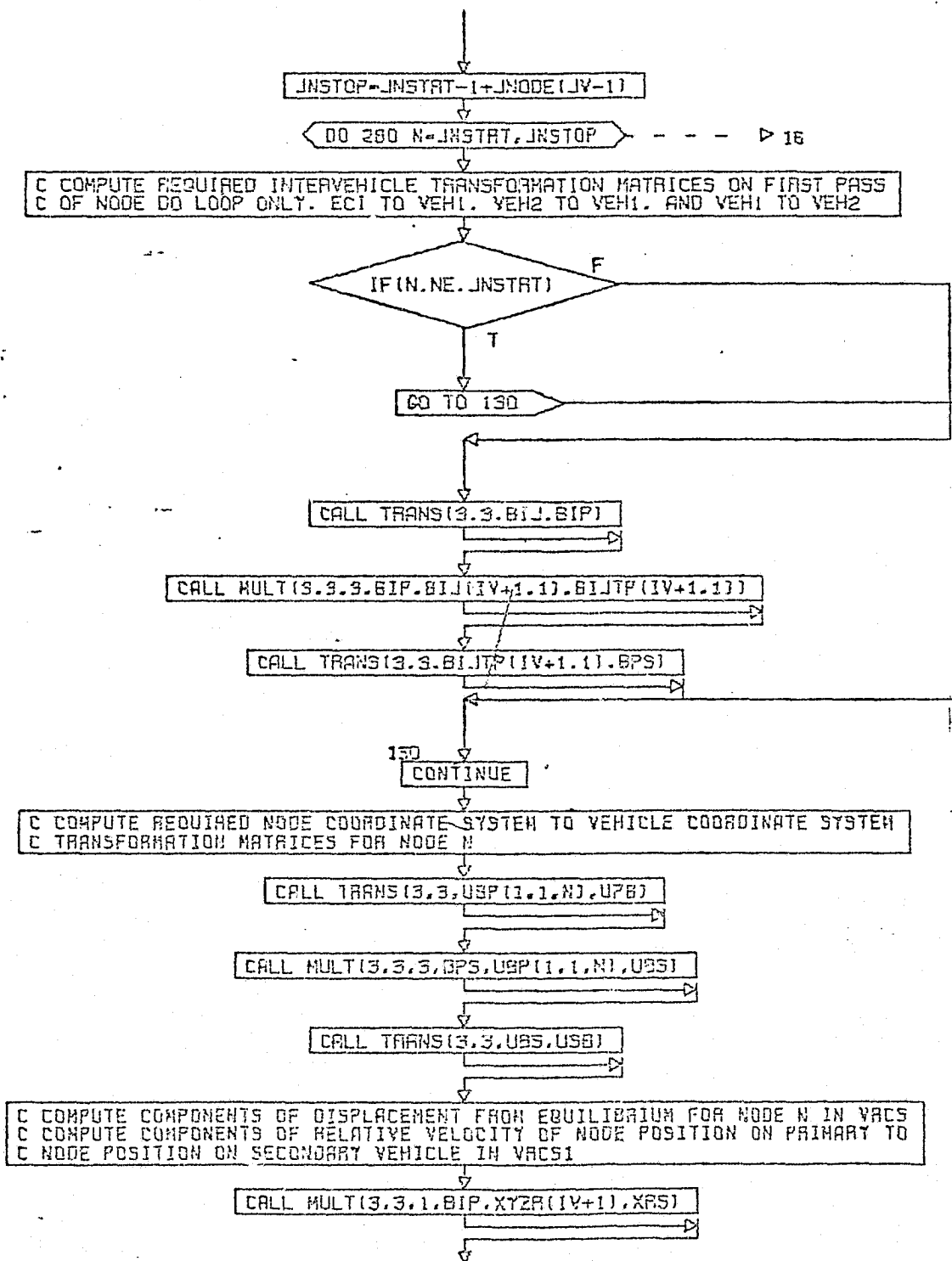
Two parameter types must be verified to accurately check proper Orbiter/ET separation mechanism simulation. The correct pyrotechnic sequencing can be



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ABIND
PG 1 OF 17

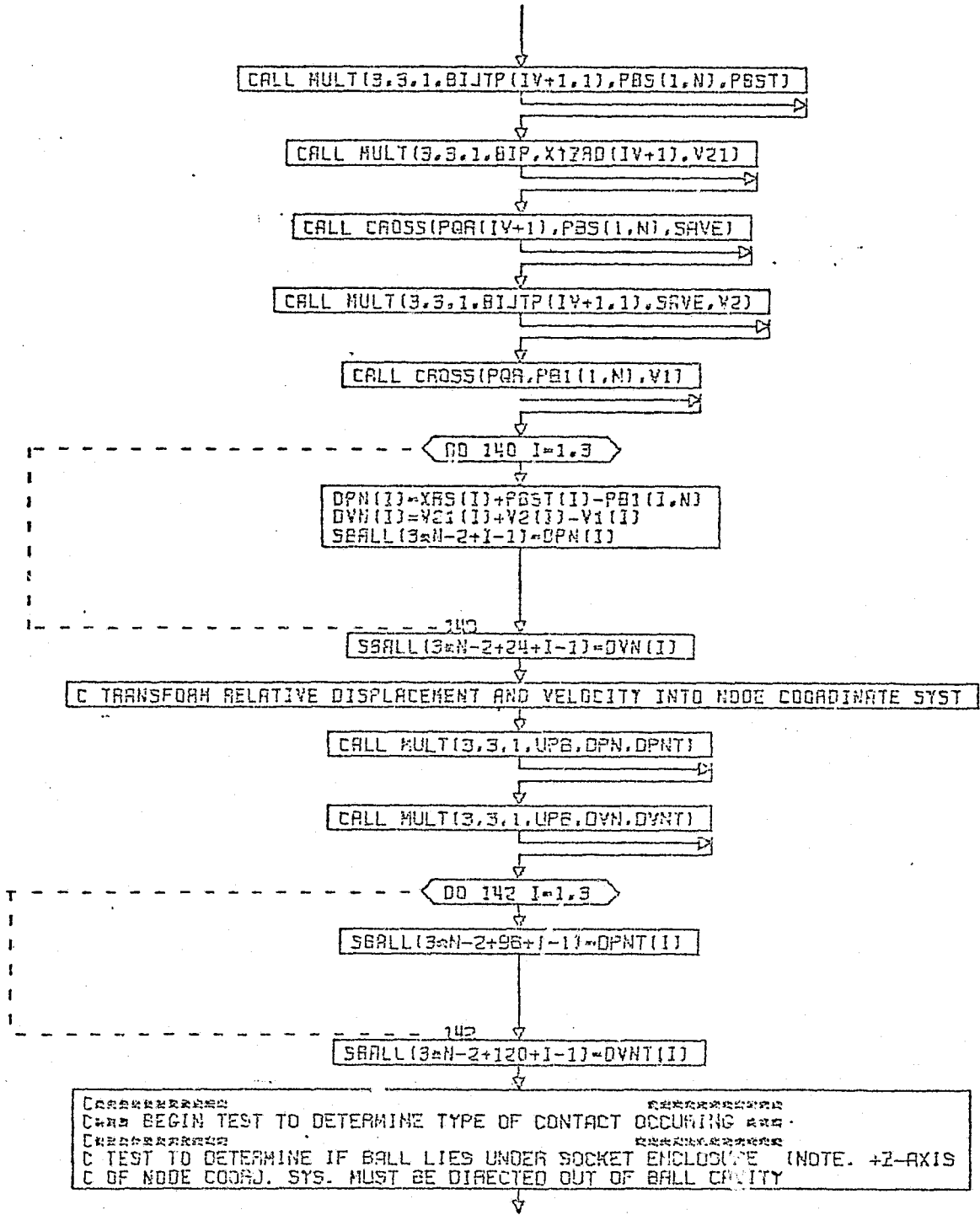
FIGURE 4.7-21. ORBITER/ET AFT SEPARATION MECHANISM REFERENCE MODULE
4.7-45



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ASINO
PG 2 OF 17

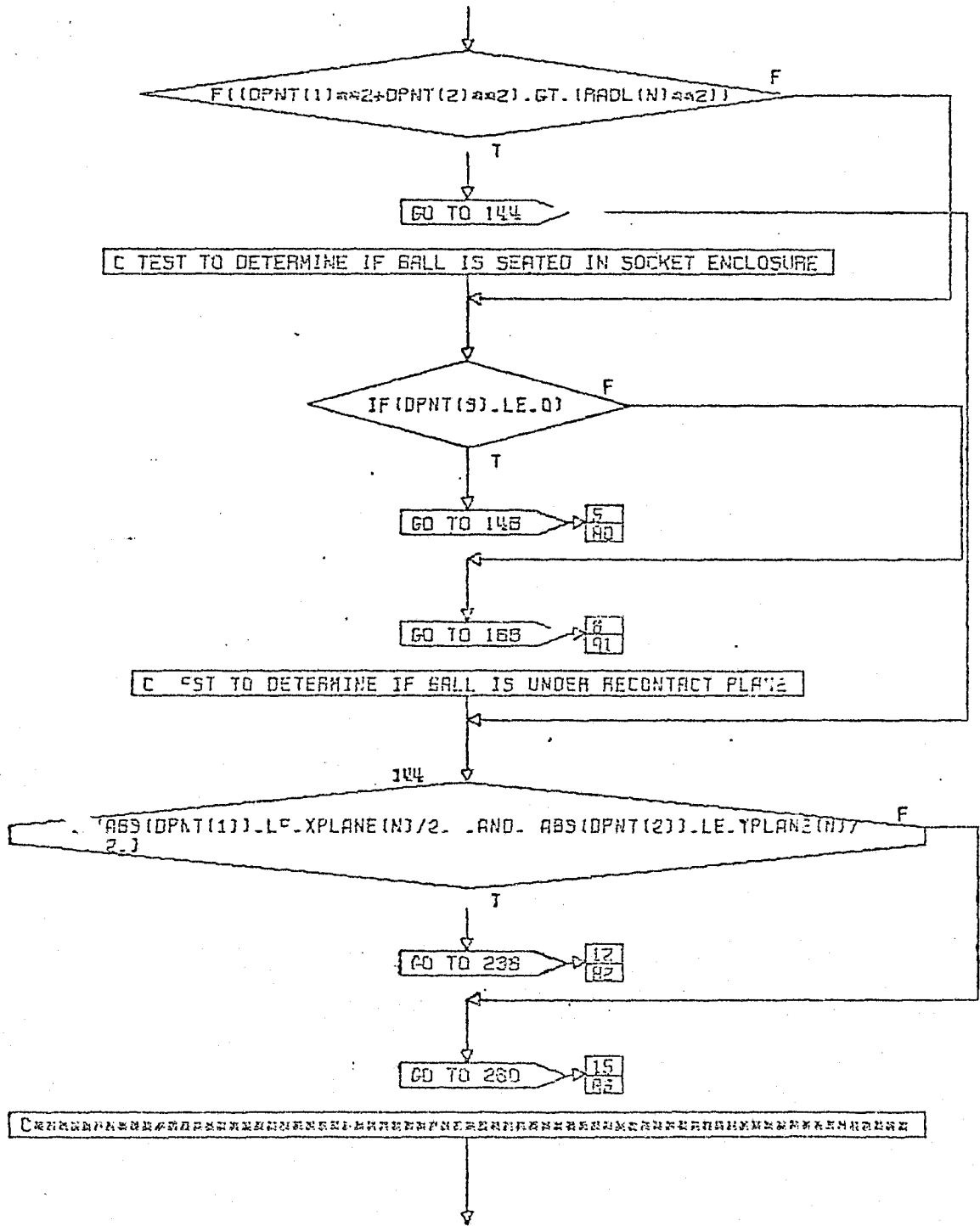
FIGURE 4.7-21. (CONTINUED)



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ABINO
PG 3 OF 17

FIGURE 4.7-21. (CONTINUED)

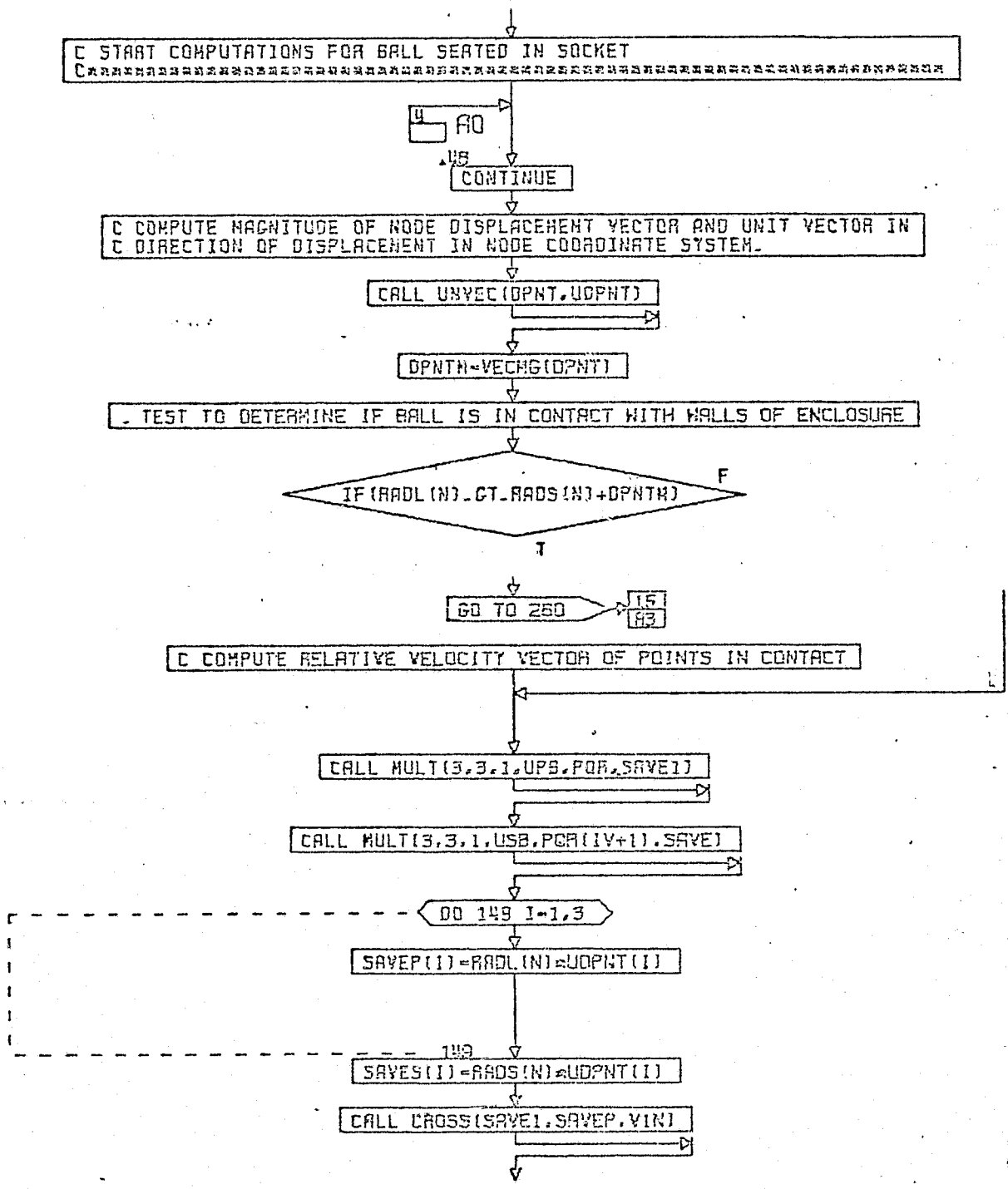


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FIGURE 4.7-21. (CONTINUED)

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PG 4 OF 17

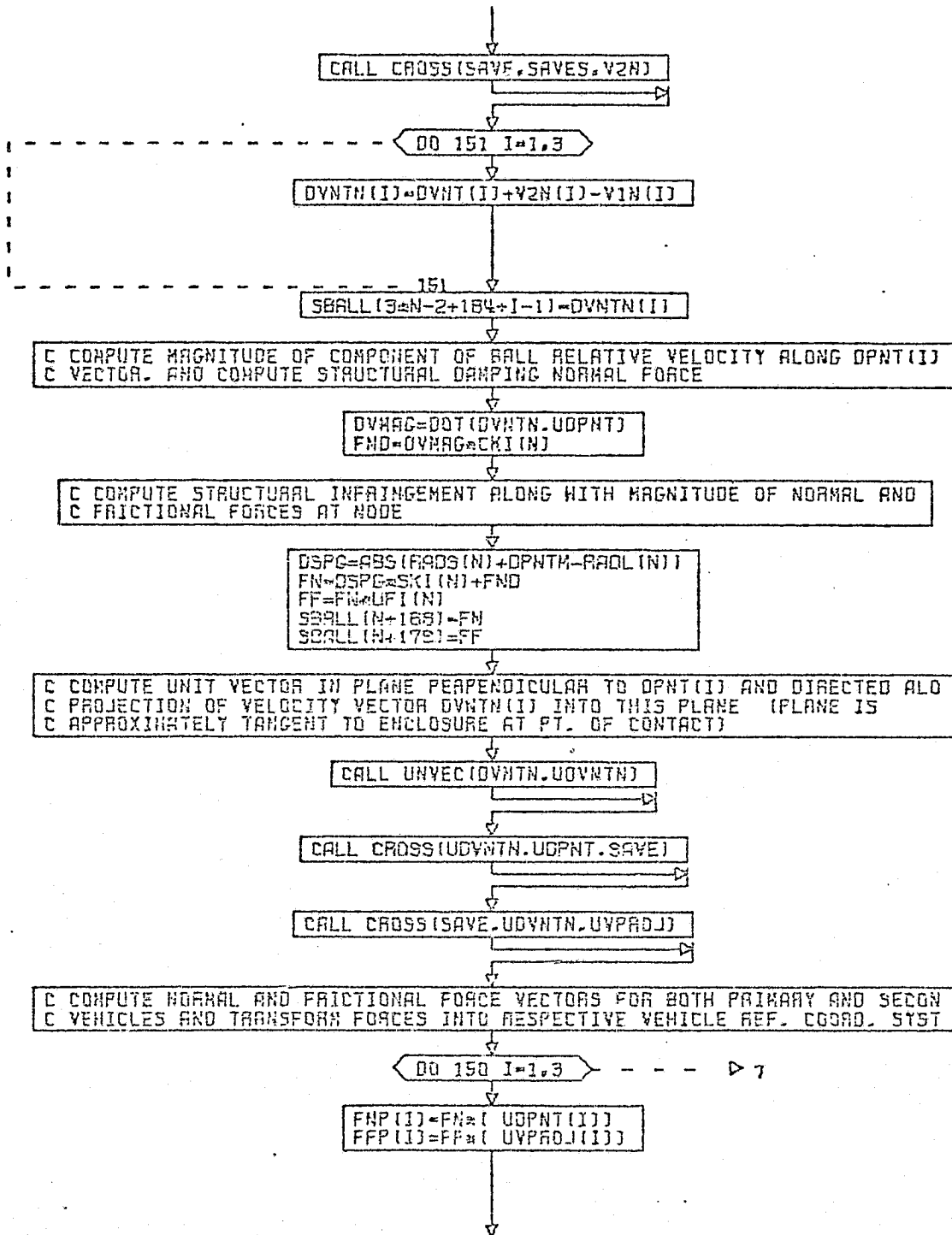
4.7-48



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ABINO
PG 5 OF 17

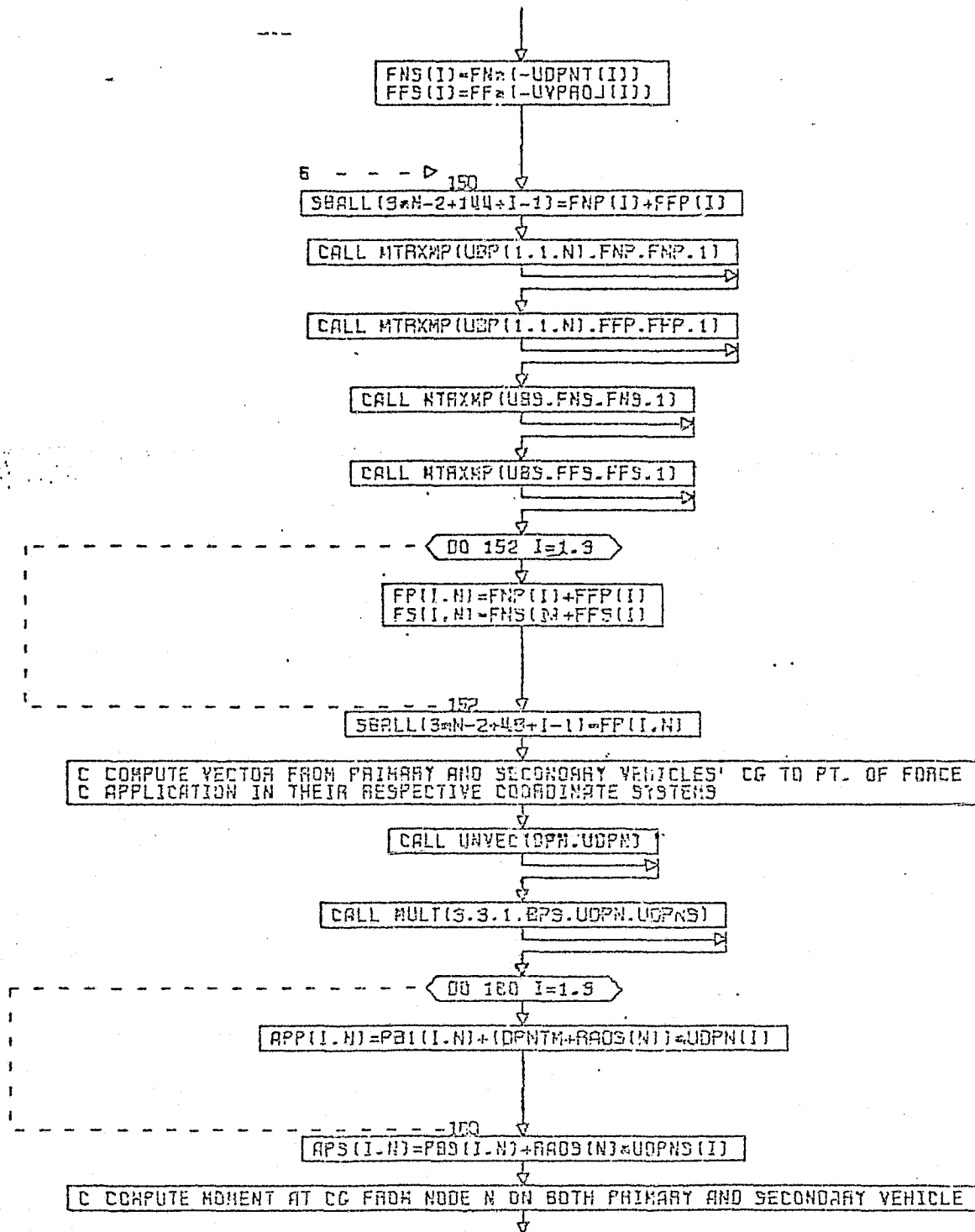
FIGURE 4.7-21. (CONTINUED)



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ASINO
PG 6 OF 17

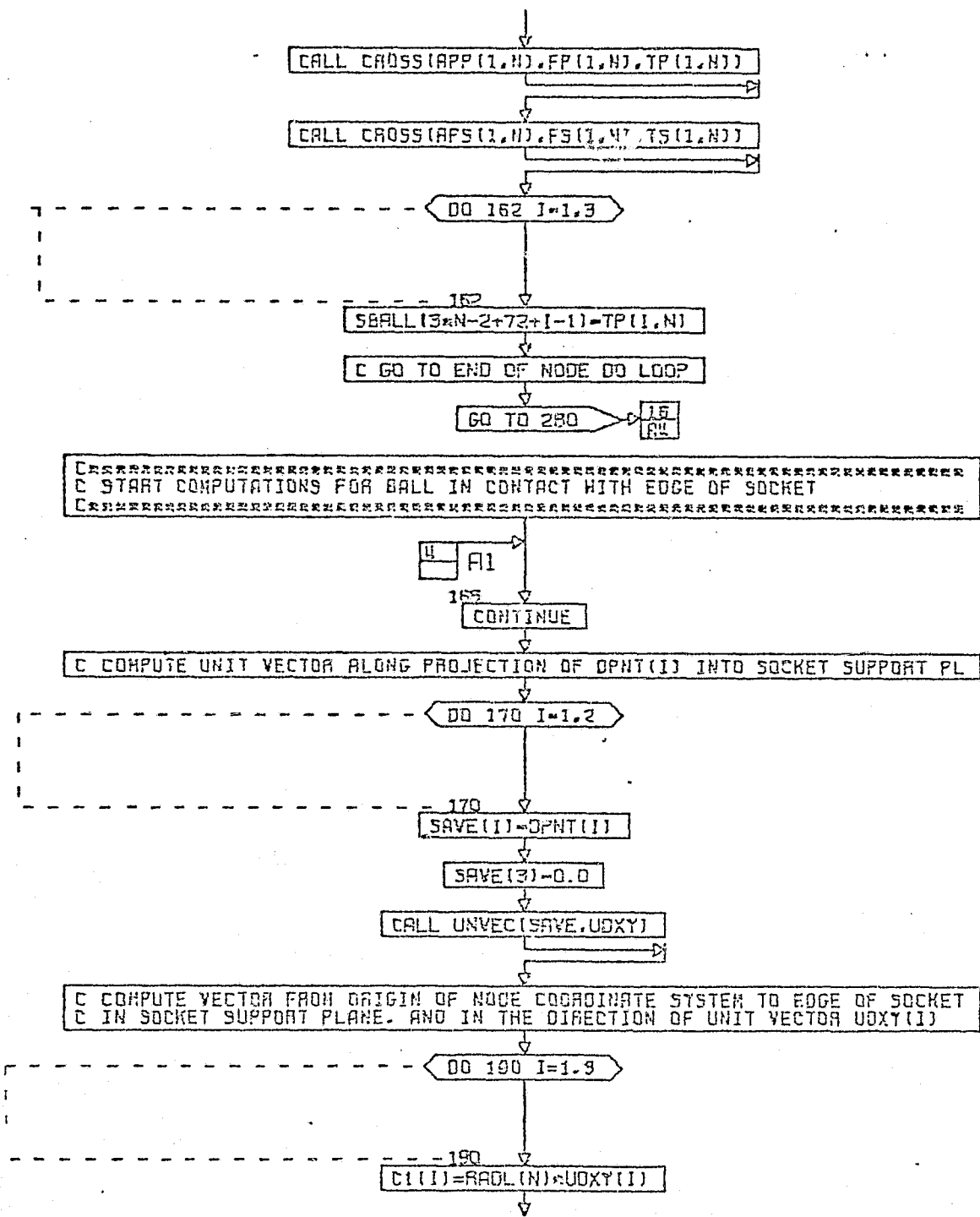
FIGURE 4.7-21. (CONTINUED)



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ASINO
PG 7 OF 17

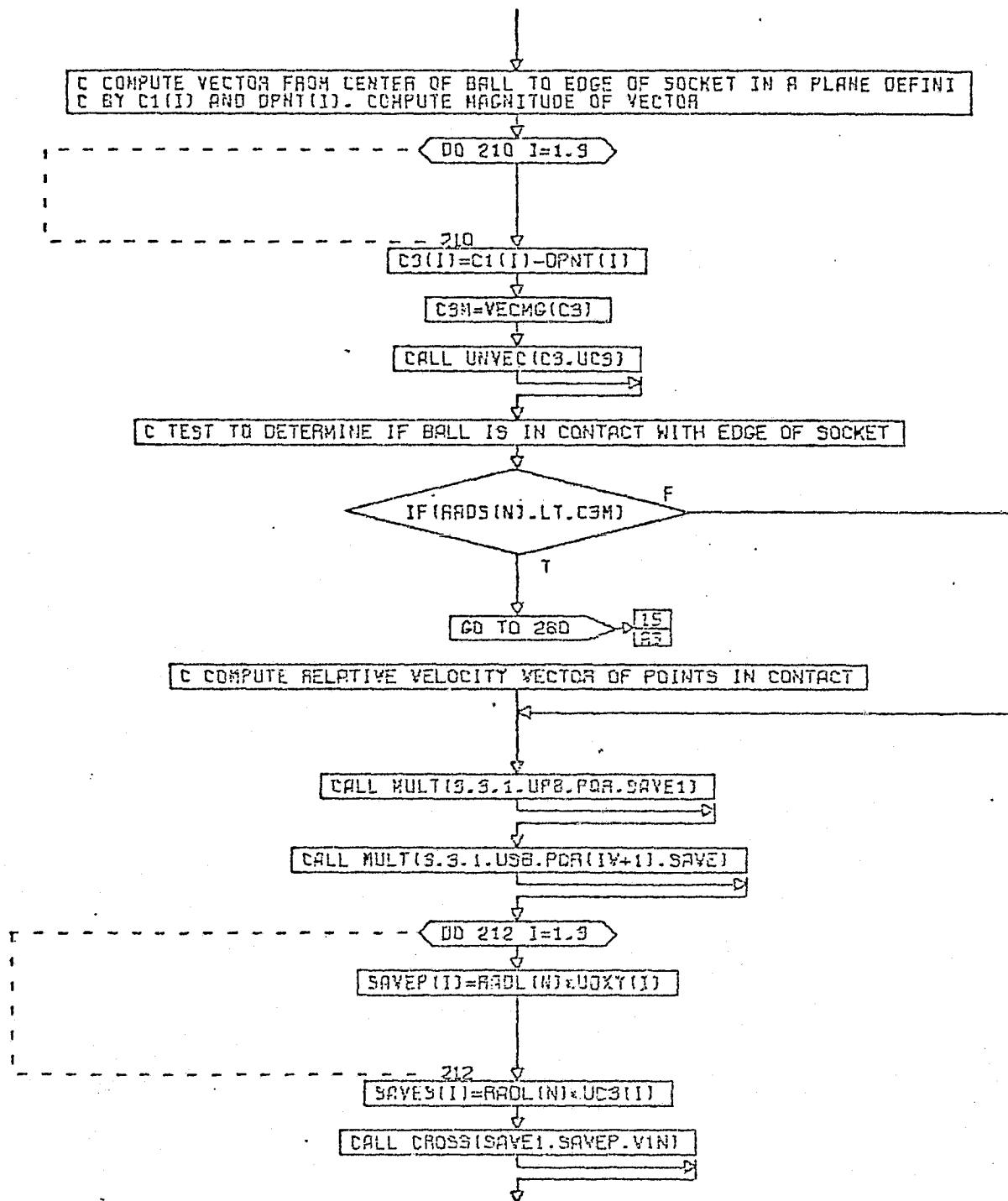
FIGURE 4.7-21. (CONTINUED)



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ASIND
PG 8 OF 17

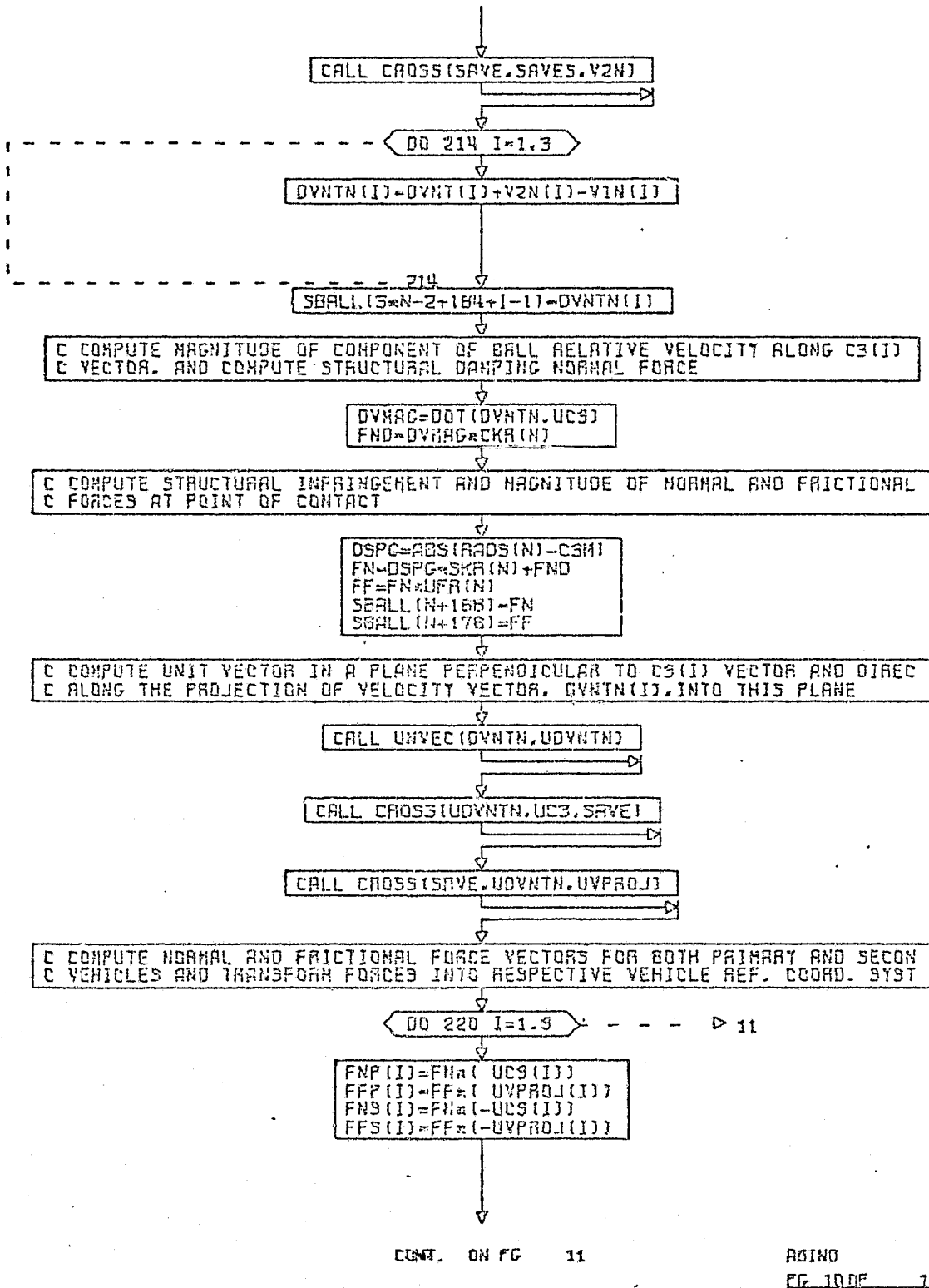
FIGURE 4.7-21. (CONTINUED)



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ABIND
PG 9 OF 17

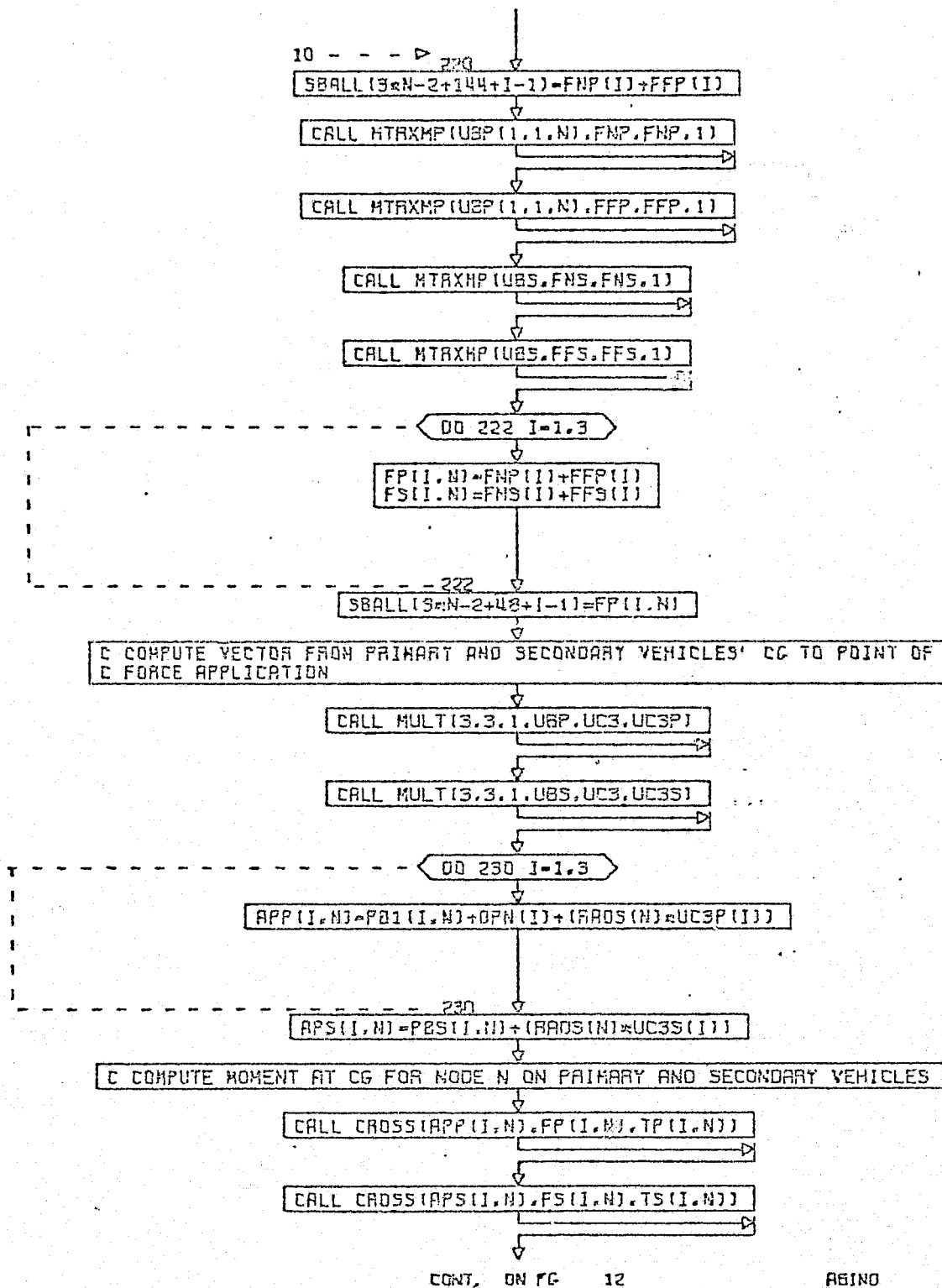
FIGURE 4.7-21. (CONTINUED)



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PG 10DF 17

FIGURE 4.7-21. (CONTINUED)

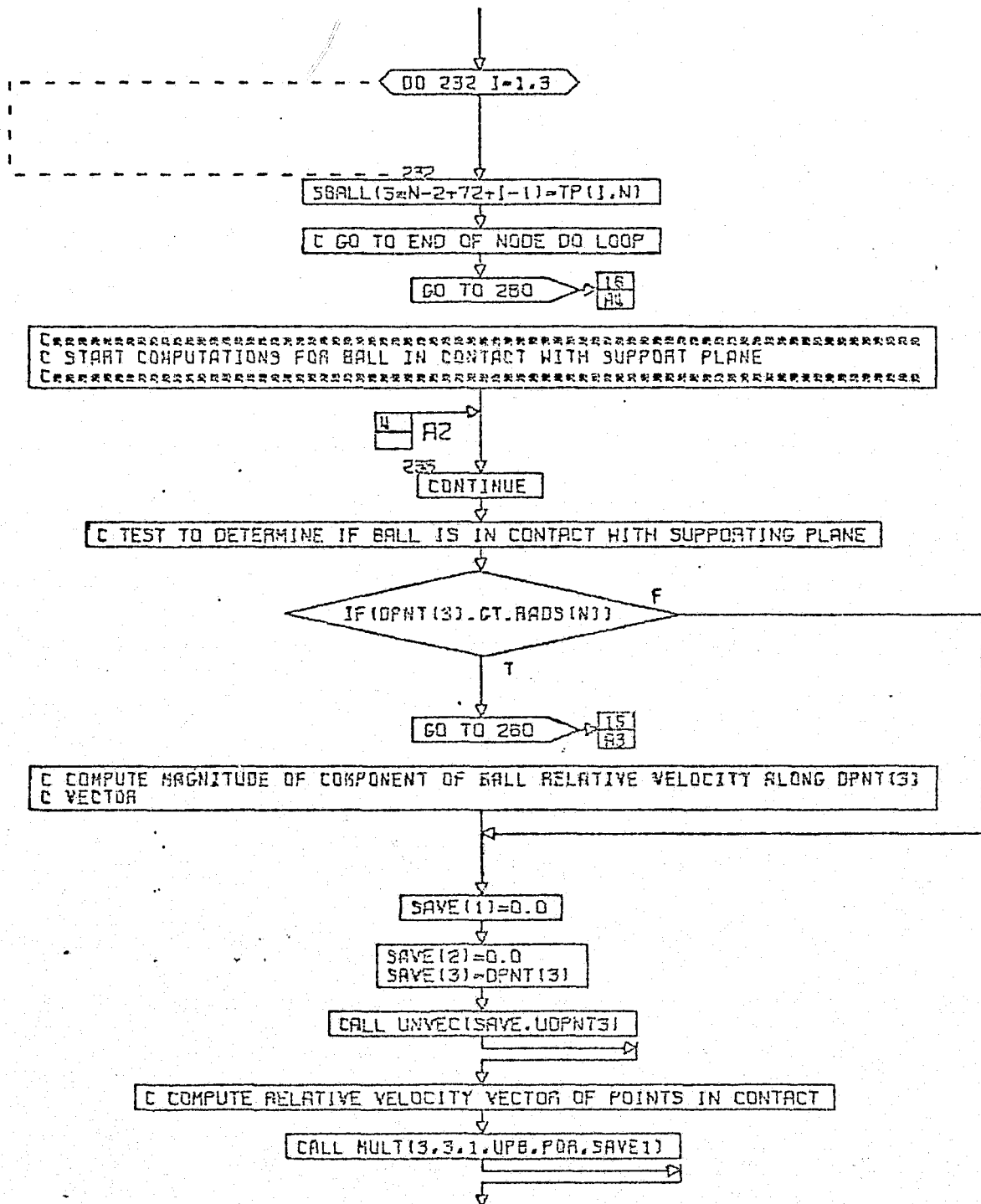


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ABINO
PG 11 OF 17

FIGURE 4.7-21. (CONTINUED)

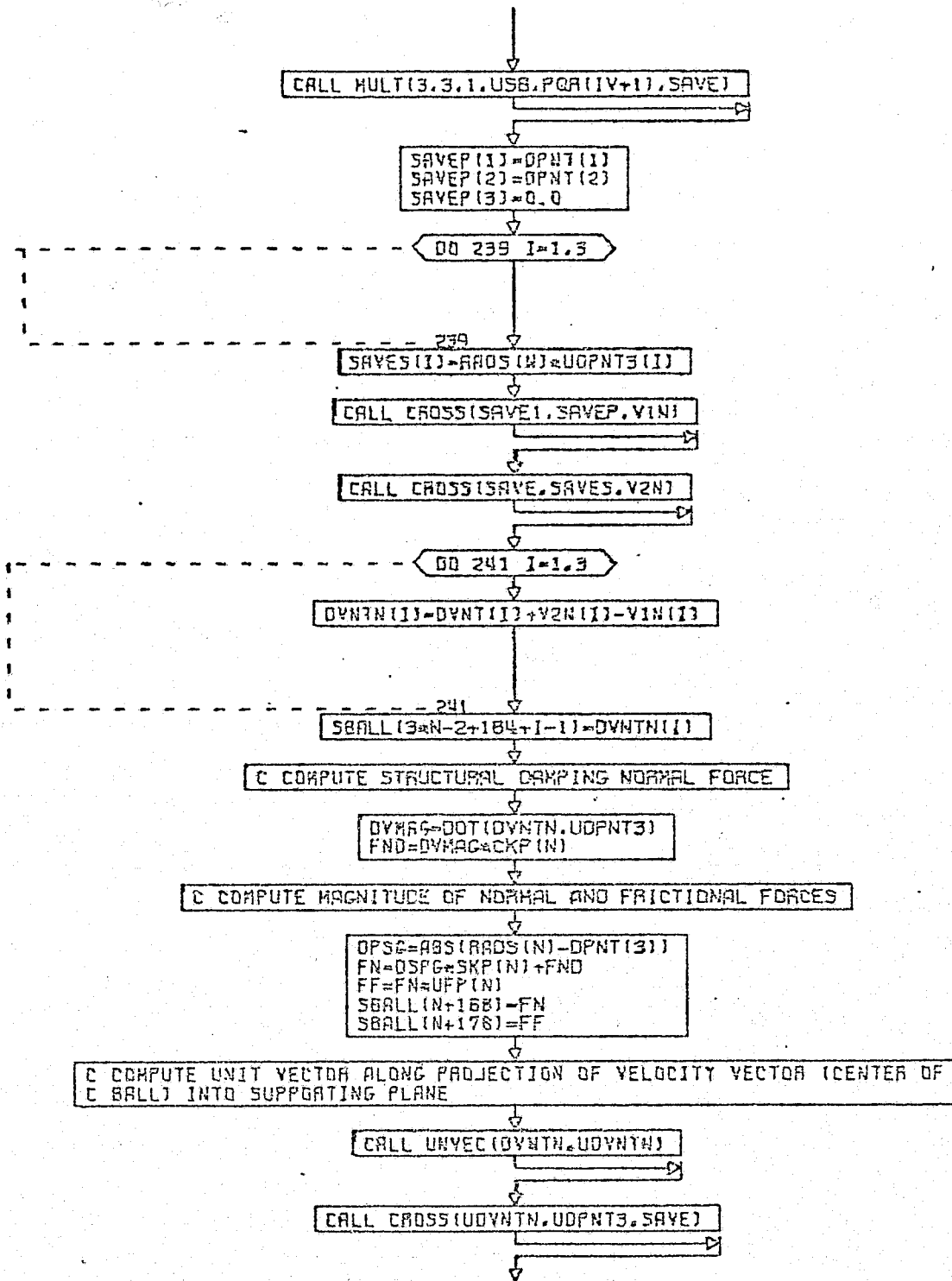
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PG 12 OF 17

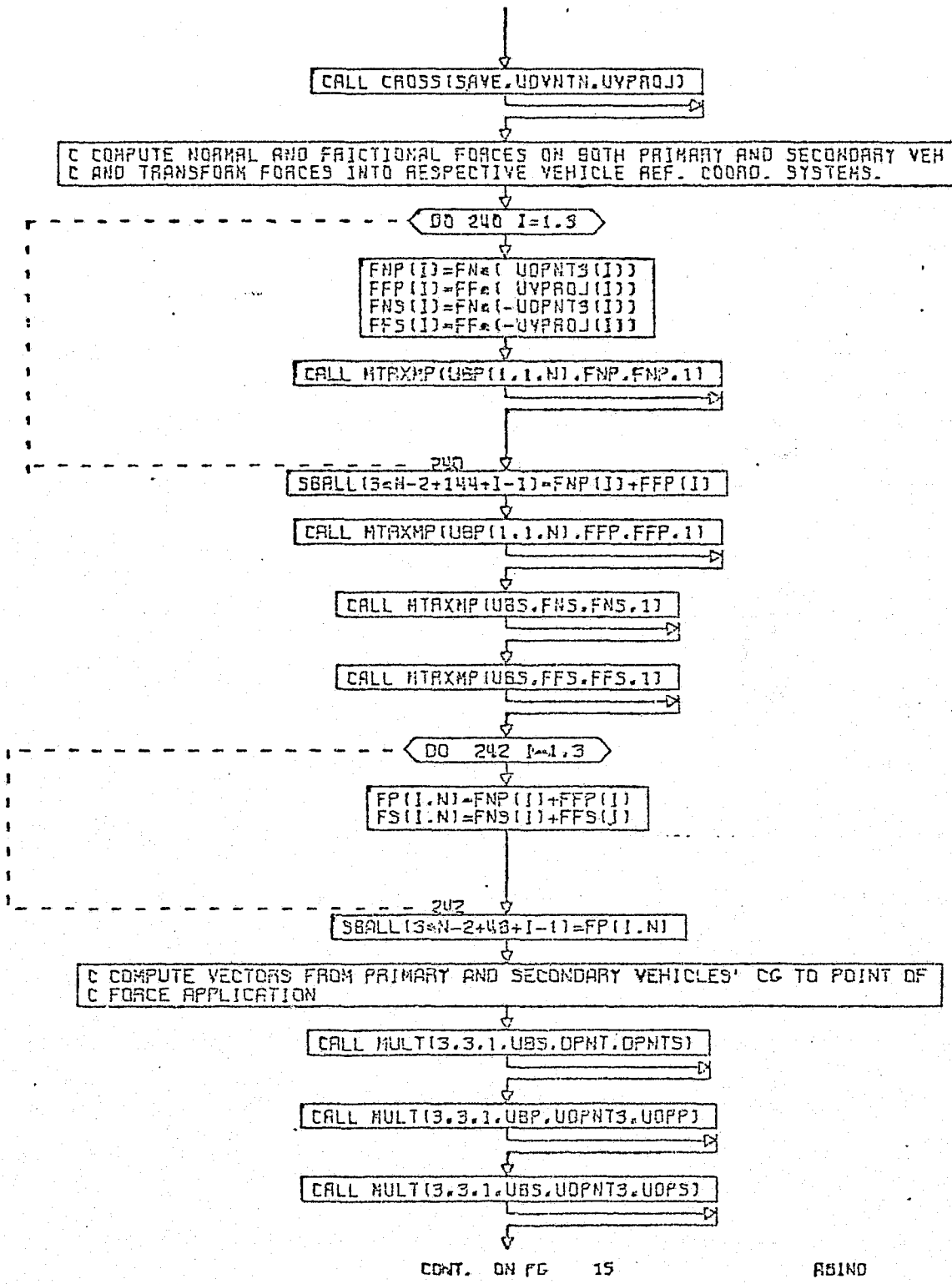
FIGURE 4.7-21. (CONTINUED)



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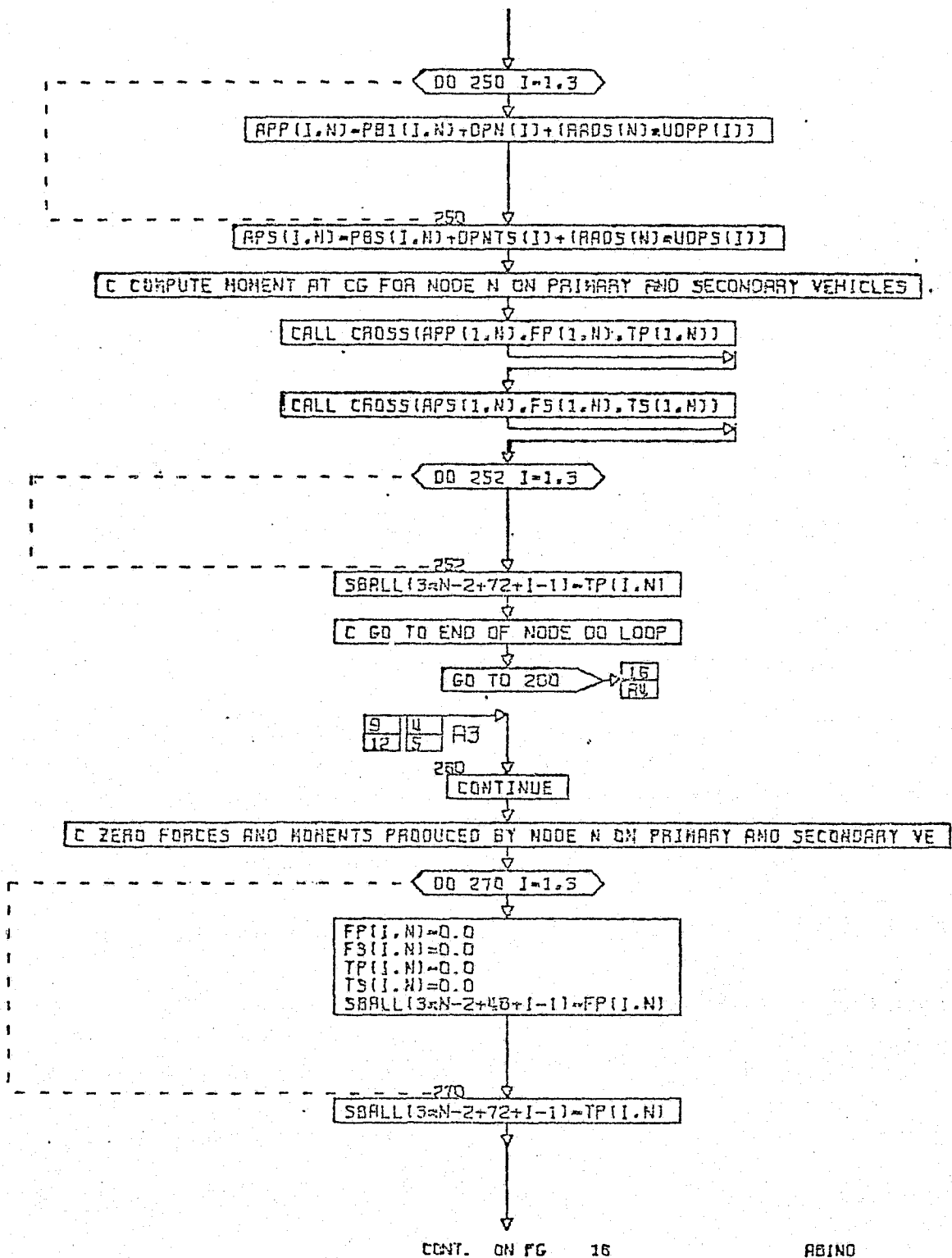
FIGURE 4.7-21. (CONTINUED)



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FIGURE 4.7-21. (CONTINUED)



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FIGURE 4.7-21. (CONTINUED)

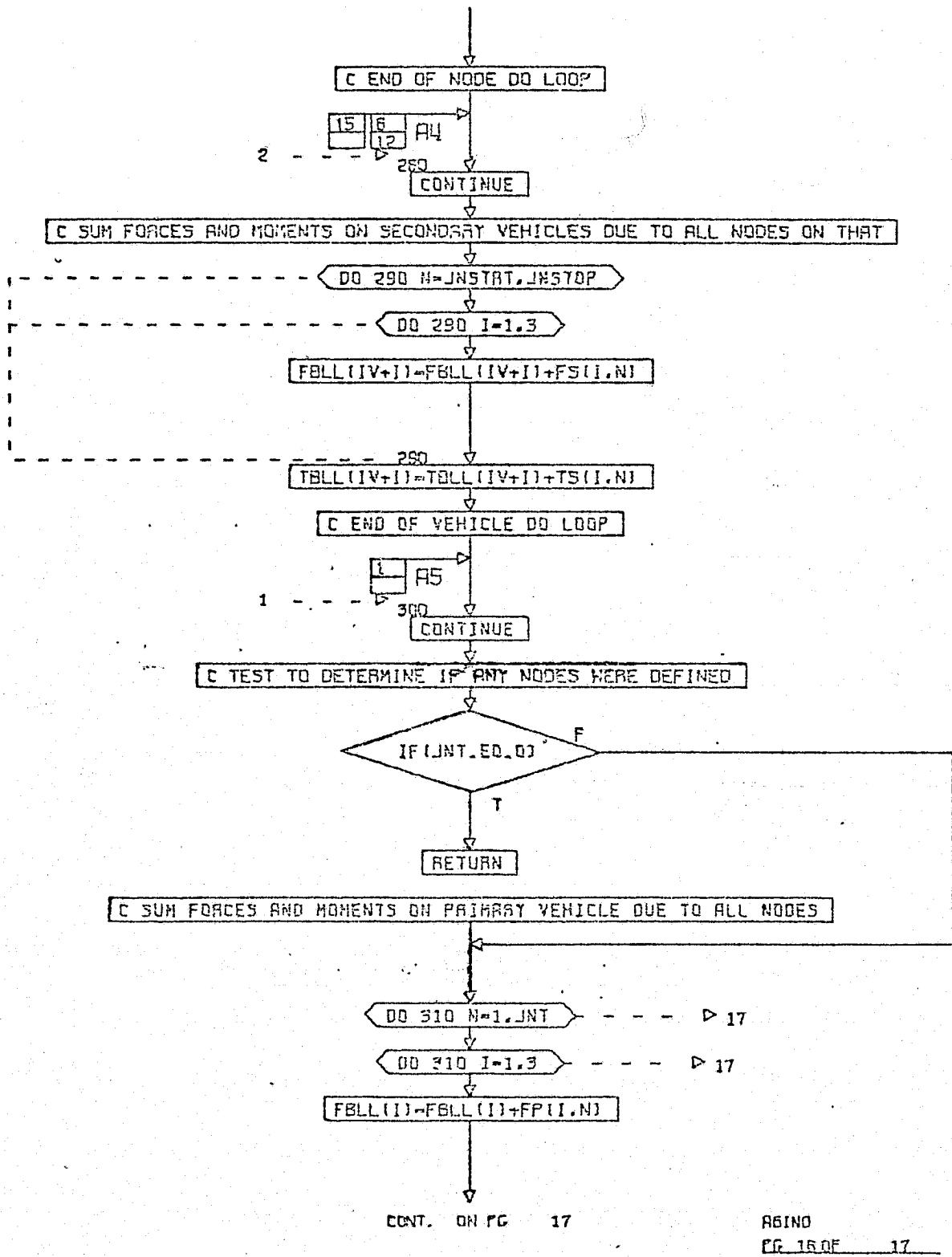


FIGURE 4.7-21. (CONTINUED)

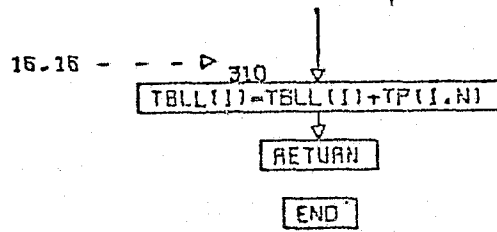


FIGURE 4.7-21. (CONTINUED)

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validated with a simple sequence check of the desired pyrotechnic parameter. After verifying the pyrotechnic sequencing, the actual Orbiter/ET separation forces and moments due to the aft attach points must be verified. These forces and moments can best be validated through the use of a reference module similar to the one previously discussed. A check case incorporating a specific reference trajectory should be developed and exercised with the simulation and reference modules. Analysis of comparison plots of the simulation data and reference data would provide sufficient verification of the simulation module.

Previous simulations of Orbiter/ET separation have shown approximate aft attach point maximum forces of:

Right rear attach point; $F_x = -1092.0$ lbs.

$F_y = -2.0$ lbs.

$F_z = 200.0$ lbs

Left rear attach point; $F_x = -713.0$ lbs.

$F_y = -220.0$ lbs.

$F_z = 40.0$ lbs.

(Note: ET coordinate system)

Separation Mechanisms Subsystem Data Base Impact

Separation Mechanisms Subsystem verification is expected to have a minimal impact upon the verification data base as only various pyrotechnic sequencing checks, a small reference module for the ET aft attachment separation forces and moments, and check cases incorporating resident reference trajectories are required.

4.7.1.4 Actuation Mechanisms Subsystem (AMS)

AMS Description

The Shuttle AMS provides for crew - or computer-initiated control of various mechanical devices. Actuators used on the Shuttle function as servomechanisms (i.e., power-amplifying feedback control systems) in which the controlled variable is mechanical position (Ref. 15). Both electromechanical and hydraulic actuators are included, along with their corresponding valves, switches, servomotors, and linkages.

Electromechanical actuators receive as inputs electronic control signals. A servomotor or electronic switch is then used, along with a feedback loop, to effect the commanded mechanical position. Figure 4.7-22 (Ref. 15) depicts a general block diagram of an electromechanical actuator. Electromechanical actuators are used on the Shuttle for control of:

- Payload bay doors and radiator positions
- The Payload Deployment and Retrieval System (see Section 4.7.1.5, PDRS)
- Docking tunnel extension and docking operations (see Section 4.7.1.2, DMS)
- OMS gimbal position
- Drag chute engagement
- Various other remotely operated doors and latches (star tracker door, ADS and RCS deployment, umbilical doors, etc.)

Hydraulic actuators generally act as mechanical linkages in controlling mechanical position. Hydraulic power from the Orbiter HPS (Section 4.7.1.6) is used in conjunction with servovalves, regulators, and power amplifiers (hydraulic cylinders) to provide the commanded mechanical position. As hydraulic actuators are servomechanisms, a control feedback loop is also used as shown in the Figure 4.7-23 block diagram (Ref. 15). Hydraulic actuators are employed for control of:

- Landing gear uplock release, extension, steering, and "1-G" retraction (see Section 4.7.1.1)
- Orbiter braking and antiskid functions (discussed in Section 4.7.1.1)
- Aero-surface positions (including body flap)
- Main engine gimbal position and shutoff valves
- SRB gimbal position (note: each SRB incorporates a self-contained HPS and therefore does not interface with the Orbiter HPS (Ref. 16)

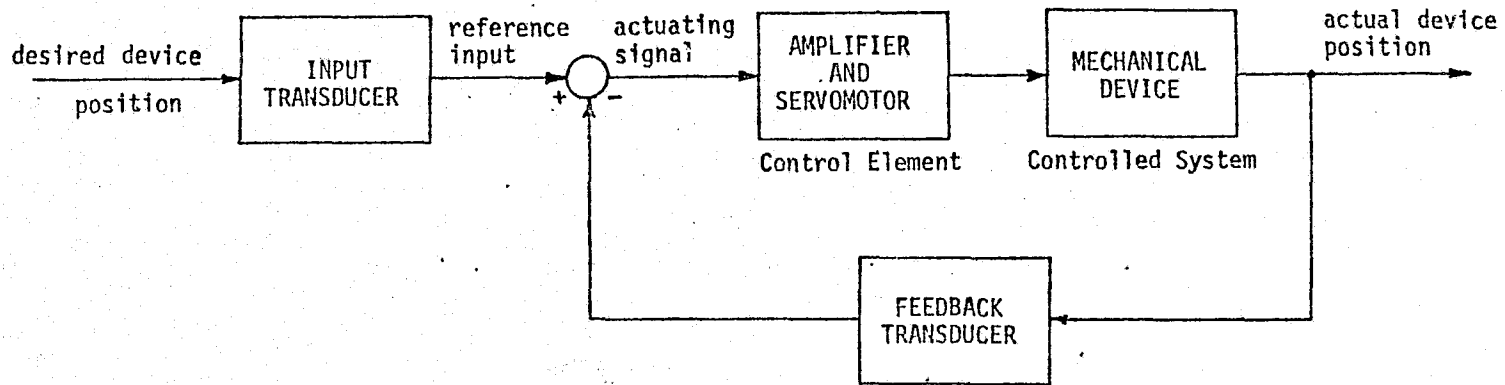


FIGURE 4.7-22. BLOCK DIAGRAM; ELECTROMECHANICAL ACTUATOR (TYP)

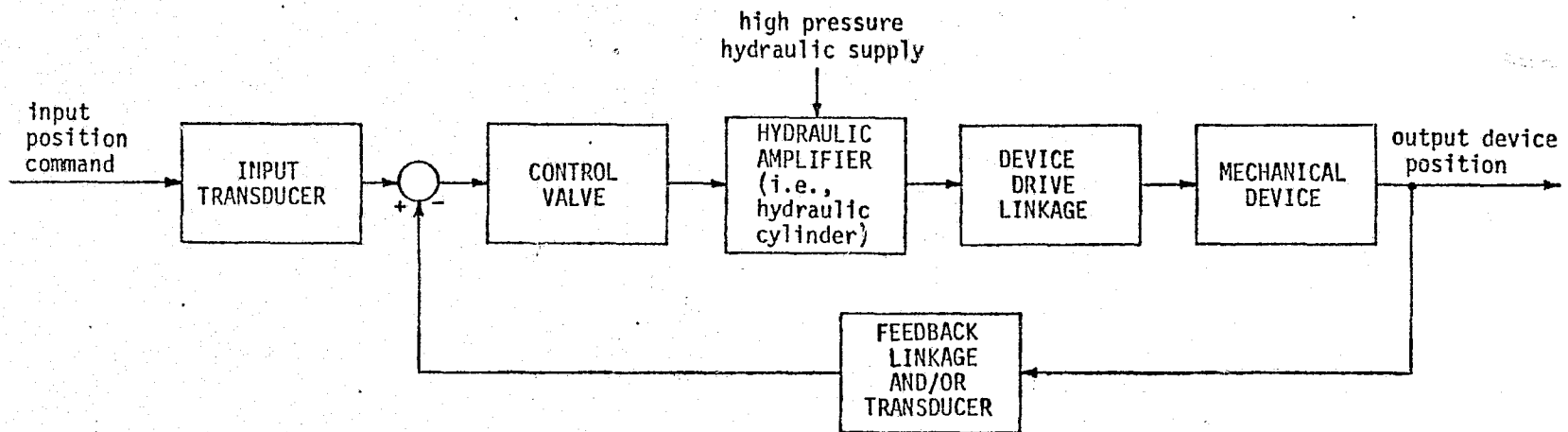


FIGURE 4.7-23. BLOCK DIAGRAM; HYDRAULIC ACTUATOR (TYP)

AMS Simulation Module Description and Performance Parameters

Shuttle AMS simulation is discussed in this section as two submodules; Electromechanical and Hydraulic.

Electromechanical Actuation Simulation Module - Electromechanical actuator simulation will provide the necessary real-world actuator representation desired in a training simulator. Shuttle electromechanical actuators will be modeled using two fidelity-defining methods.

Several electromechanical actuators will be simulated using time-delay functions to effect "talkback" response. Inputs to this type of actuator consist of crew/computer device position signals, switch positions, and electrical power available (from Orbiter EPS). Output will represent the "talkback" response to indicate mechanical position and electrical power required for the desired operation. Actuator functions modeled with this technique consist of:

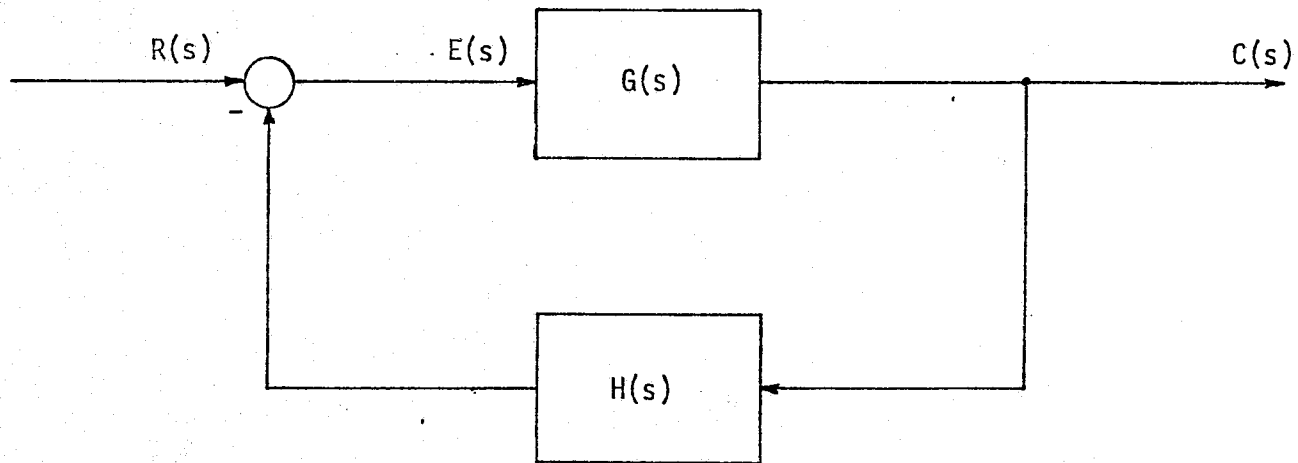
- Docking tunnel extension
- Drag chute engagement
- Operation (open and closure) of various remotely-operated doors and latches

The remaining electromechanical actuators will be simulated with a more complex technique. This technique will use specific transfer functions and control feedback loops similar to the Figure 4.7-24 diagram (Ref. 15). The exact transfer functions and control logic (determined from hardware tests) will simulate non-linear actuator characteristics involving friction, hysteresis, deadband zones, and combined electrical power load effects to model actuator lags, overshoots, and rise time variations (Ref. 11).

Inputs will be similar to those discussed in the "talkback" model; however, outputs will be a dynamic mechanical position, thrust vector, and/or crew/computer responses as indicated in the Figure 4.7-25 diagram of Electromechanical Actuator Mechanisms Simulation Module Interfaces. Performance Parameters associated with electromechanical actuator simulation are given in Table 4.7-5 .

Hydraulic Actuation Mechanisms Simulation Module - Most Shuttle hydraulic actuators will be simulated in a manner similar to that used for complex electromechanical actuator simulation. Only the landing gear uplock release and extension retract

4.7-66



LEGEND:

- $R(s)$ = input command
- $E(s)$ = actuating signal
- $C(s)$ = output command
- $G(s)$ = direct transmission function
- $H(s)$ = feedback transfer function

FIGURE 4.7-24. FEEDBACK CONTROL SYSTEM BLOCK DIAGRAM

4.7-67

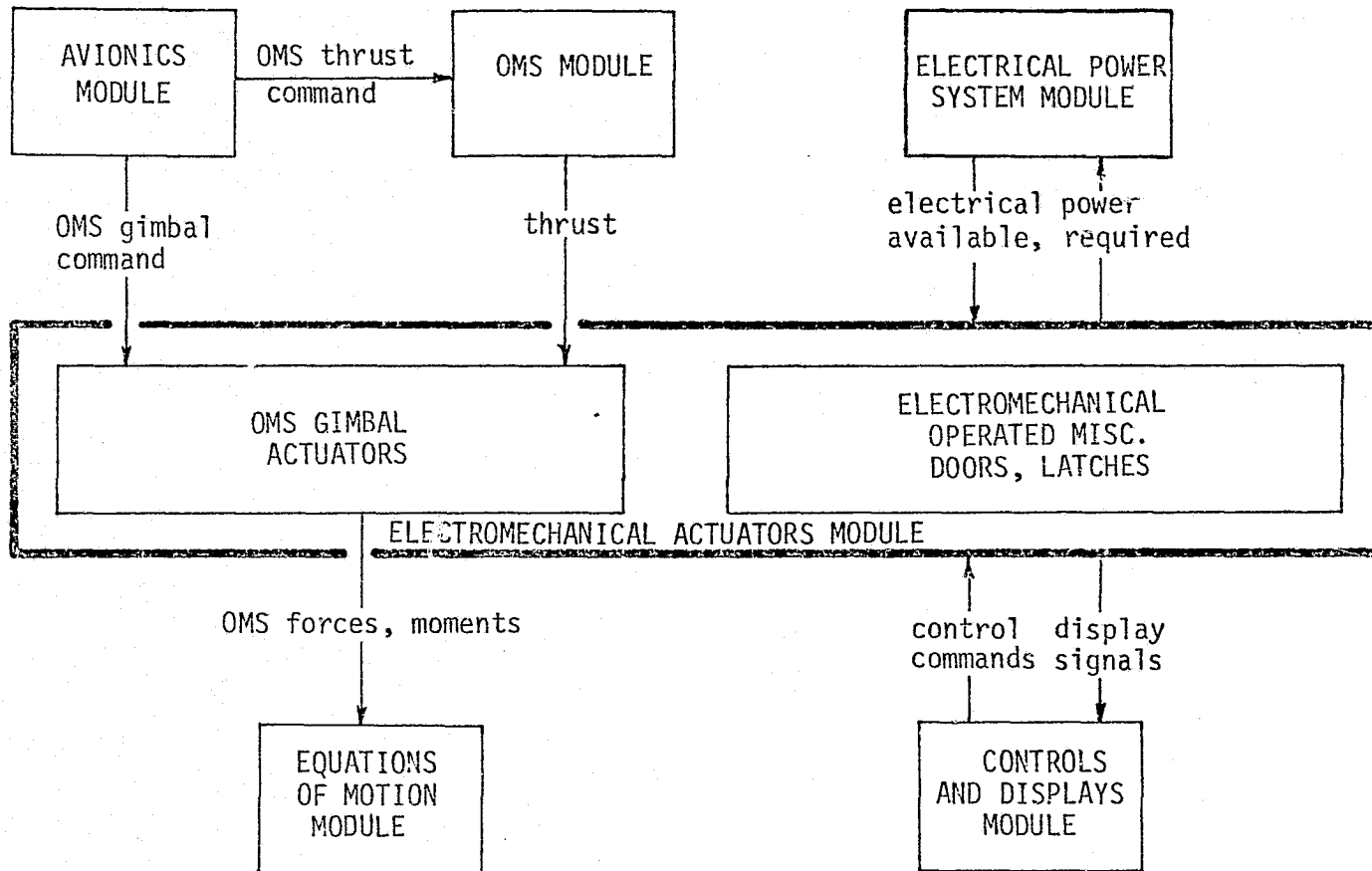


FIGURE 4.7-25. ELECTROMECHANICAL ACTUATION MECHANISMS SIMULATION MODULE INTERFACES

TABLE 4.7-5. AMS SIMULATION MODULES PERFORMANCE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^C
δ_c	Commanded mechanical position	I
δ_{cL}	Limited commanded mechanical position	P
E	Position error command	P
$\{\delta, \dot{\delta}, \ddot{\delta}\}$	Mechanical position deflection, rate, and acceleration	CP
$\{\delta_L, \dot{\delta}_L, \ddot{\delta}_L\}$	Limited mechanical position deflection, rate, and acceleration	P
$\left\{ \begin{matrix} \delta_{max}, \dot{\delta}_{max} \\ \ddot{\delta}_{max} \end{matrix} \right\}$	Maximum mechanical position deflection, rate and acceleration	DB
	Engine thrust	I
	Output thrust vector (where applicable)	CP
K	Forward gain	DB
K_r	Rate feedback gain	DB
K_p	Position feedback gain	DB
$\{f(s)\}$	Actuator transfer functions	DB
E_a	Electrical power available	I
E_r	Electrical power required	P
E_f	Electrical power factor	P
HP_a	Hydraulic power available	I
HP_r	Hydraulic power required	P
HP_f	Hydraulic power factor	P
$\{X_g, Y_g, Z_g\}$	Actuator gimbal coordinates (where applicable)	DB

^CI - Input

DB - Data Base Input

P - Performance Parameter

CP - Critical Performance Parameter

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hydraulic actuators will be simulated with a time-delay "talkback" response combined with a hydraulic power available/required check.

All other Shuttle hydraulic actuators will utilize transfer function - control feedback techniques to accurately model the desired actuator. Actuator transfer functions and control feedback loops will be determined from tests performed in the Flight Control Hydraulic Lab (FCHL). The transfer functions will compensate for actuator friction, hysteresis, and deadzones associated with mechanical linkages as well as hydraulic power load sharing (Ref. 5).

Inputs to the Hydraulic Actuator Mechanisms Simulation Module consist of:

- Crew/computer device position commands (discretes and combinations)
- Hydraulic power available
- Electrical power available

Outputs will include dynamic mechanical positions and rates (e.g., aero-surface deflections), crew/computer response signals and hydraulic power required. In the case of thrusting devices (SSME, SRB gimbals) body-axis thrust forces and moments will also be output. Hydraulic Actuator Mechanisms Simulation Module Interfaces are depicted in Figure 4.7-26. Corresponding module performance parameters are shown in Table 4.7-5 .

AMS Reference Data Sources and Data Formats

Verification of electromechanical and hydraulic actuator mechanism simulation modules can be accomplished through the use of reference data generated with a generalized Actuator Simulation Reference Module as depicted by Figure 4.7-27, (Ref. 17). Only one reference module is necessary for the two types of actuator simulations, as the same general concept applies to both (i.e., both are servo-mechanisms employing transfer functions and control feedback loops). Overall command, acceleration, rate, and position limiting combined with the necessary integrations yield similar results in each case (mechanical position).

Differences will arise, however, in the actual transfer functions, gains and rate limiting curves applicable to each actuator type. These variations will also occur with respect to each individual actuator. Thus, a special driver must be constructed to direct the loading and initializing of tabular data defining each

4.7-70

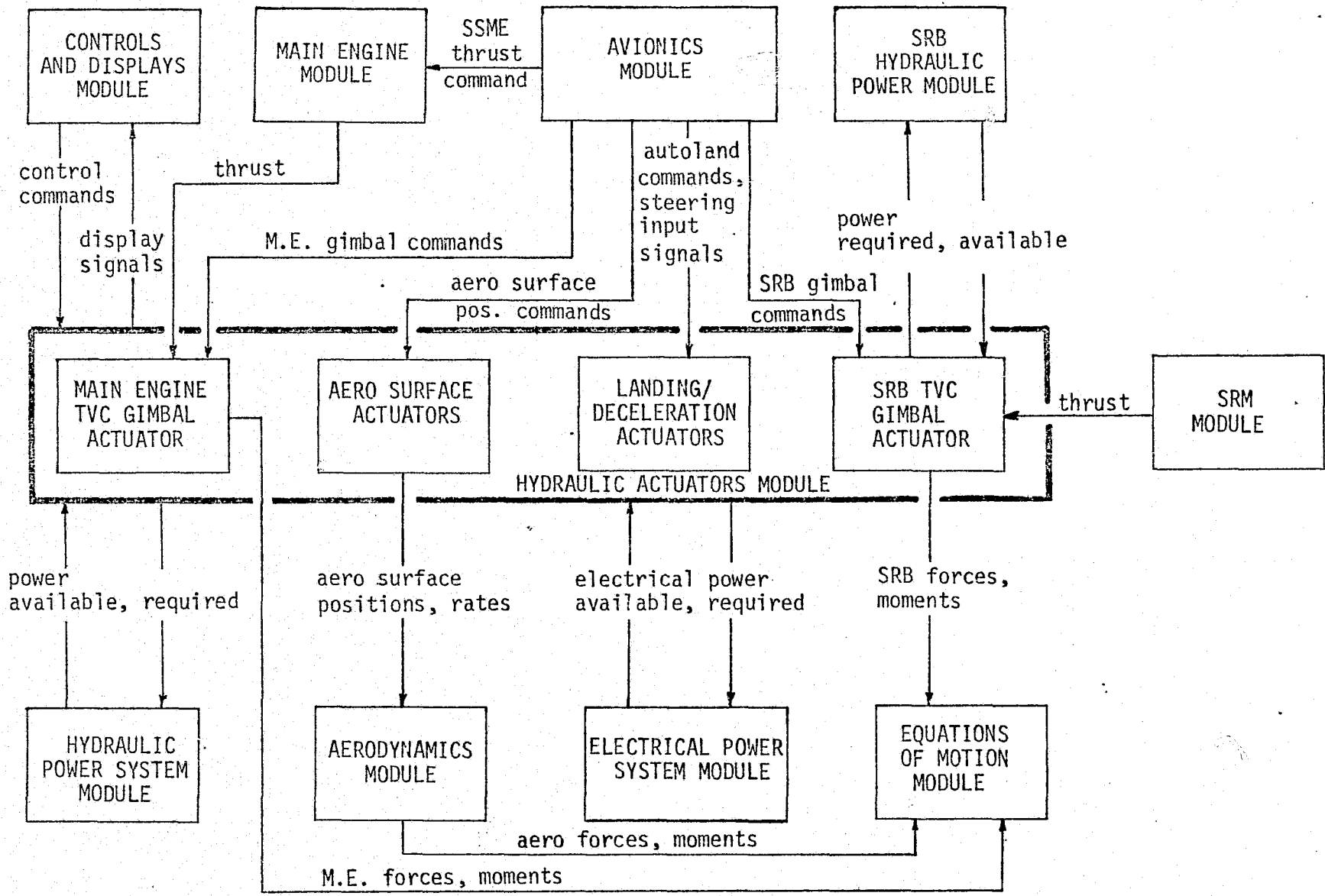


FIGURE 4.7-26. HYDRAULIC ACTUATOR MECHANISMS SIMULATION MODULE INTERFACES

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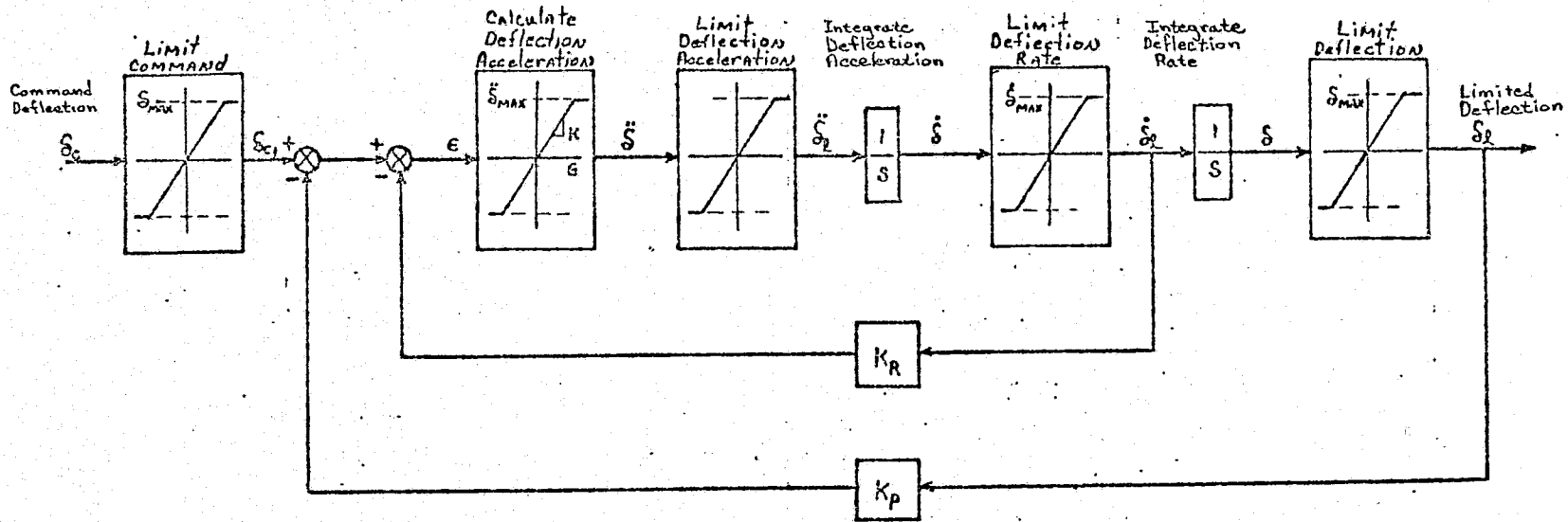


FIGURE 4.7-27. ACTUATOR REFERENCE MODULE FUNCTIONAL FLOW DIAGRAM

actuator. The tabular data will contain information regarding:

- Actuator type (electromechanical or hydraulic)
- Individual actuator transfer functions, gains and limit curves
- Power required computations (electrical, hydraulic or a combination)

Also included in the driver would be the time delay functions required to simulate those actuators which require "talkback" response.

AMS Validation Methods and Check Cases

The AMS Simulation Module should be verified through the use of reference data generated with a suitable reference module, as previously described. In some instances, actual hardware tests might be used as a reference data source (e.g., aero-surface actuators evaluated in the FCHL); however, the use of reference software as a data source is generally more efficient than test data in verification processes (see Section 4.2).

Simple "talkback" response to actuator commands is easily verified using simple check cases involving both parameter sweeps and discretizes to evaluate indicator flags, time-delays, and specific switch logic and sequencing.

More complex actuators must be evaluated using dynamic check cases, which provide the most accurate means of verifying simulated actuator response. Check cases for each actuator (electromechanical or hydraulic) should contain one or more command sequences which exercise the actuator throughout its nominal and maximum operating range. Table 4.7-6 (Ref. 17) describes one such sequence for the aero-surface actuators. Actuator response characteristics can then be plotted as shown in Figures 4.7-28 and 4.7-29 for the OMS engine gimbals (Ref. 17). Selected performance parameters can also be output for verification analysis. The above check case operations can be performed using the simulation module and the reference module, with time-histories of their corresponding performance parameters compared by either manual or automated techniques (see Section 5.3).

AMS Data Base Impact

Data base requirements for verification of the AMS Simulation Module consist of:

- A generalized actuator reference module
- Tabular information for each individual actuator (used in the reference module)

TABLE 4.7-6 . CHECK CASE COMMANDS FOR AERO SURFACE ACTUATOR RESPONSE

t	0.	5.	10.	15.	20.	25.	30.	35.
δ_{eR_c}	20°	-50°	0°	---	---	---	---	---
δ_{eL_c}	20°	-50°	0°	---	---	---	---	---
δ_{e_c}	---	---	---	10°	10°	-40°	-40°	0°
δ_{a_c}	---	---	---	10°	-10°	10°	-10°	0°
δ_{r_c}	30°	-30°	0°	---	---	---	---	---
δ_{SB_c}	105°	---	---	---	-5°	---	---	---
gear _c	1.0	---	---	0.0	---	---	---	---

LEGEND:

- t = time of command issue
- δ_{eR_c} = right elevon position command
- δ_{eL_c} = left elevon position command
- δ_{e_c} = elevator position command
- δ_{a_c} = aileron position command
- δ_{r_c} = rudder position command
- δ_{SB_c} = speed brake position command
- gear_c = gear position command

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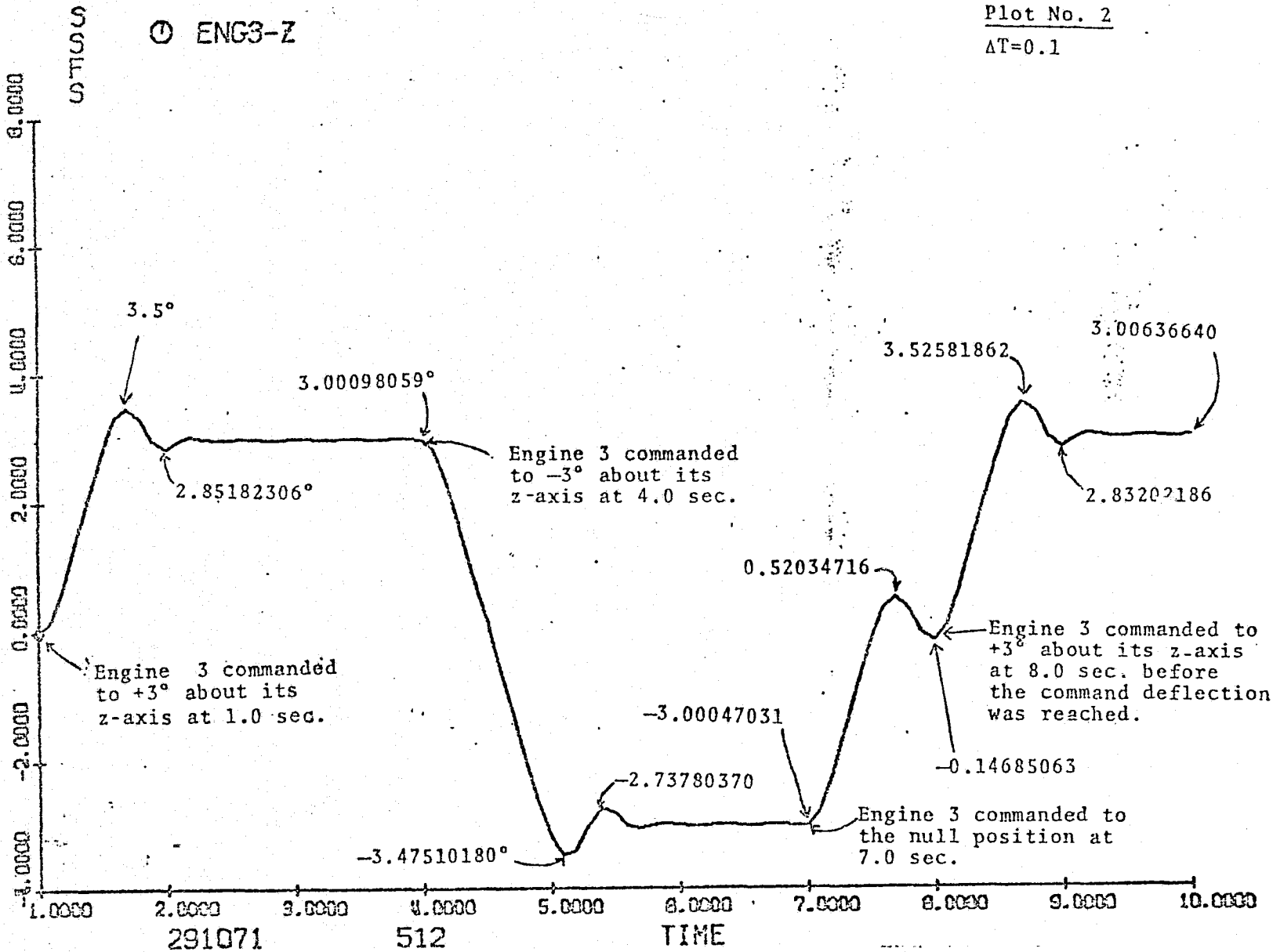


FIGURE 4.7-28. EXAMPLE: REFERENCE DATA OMS GIMBAL ACTUATOR RESPONSE

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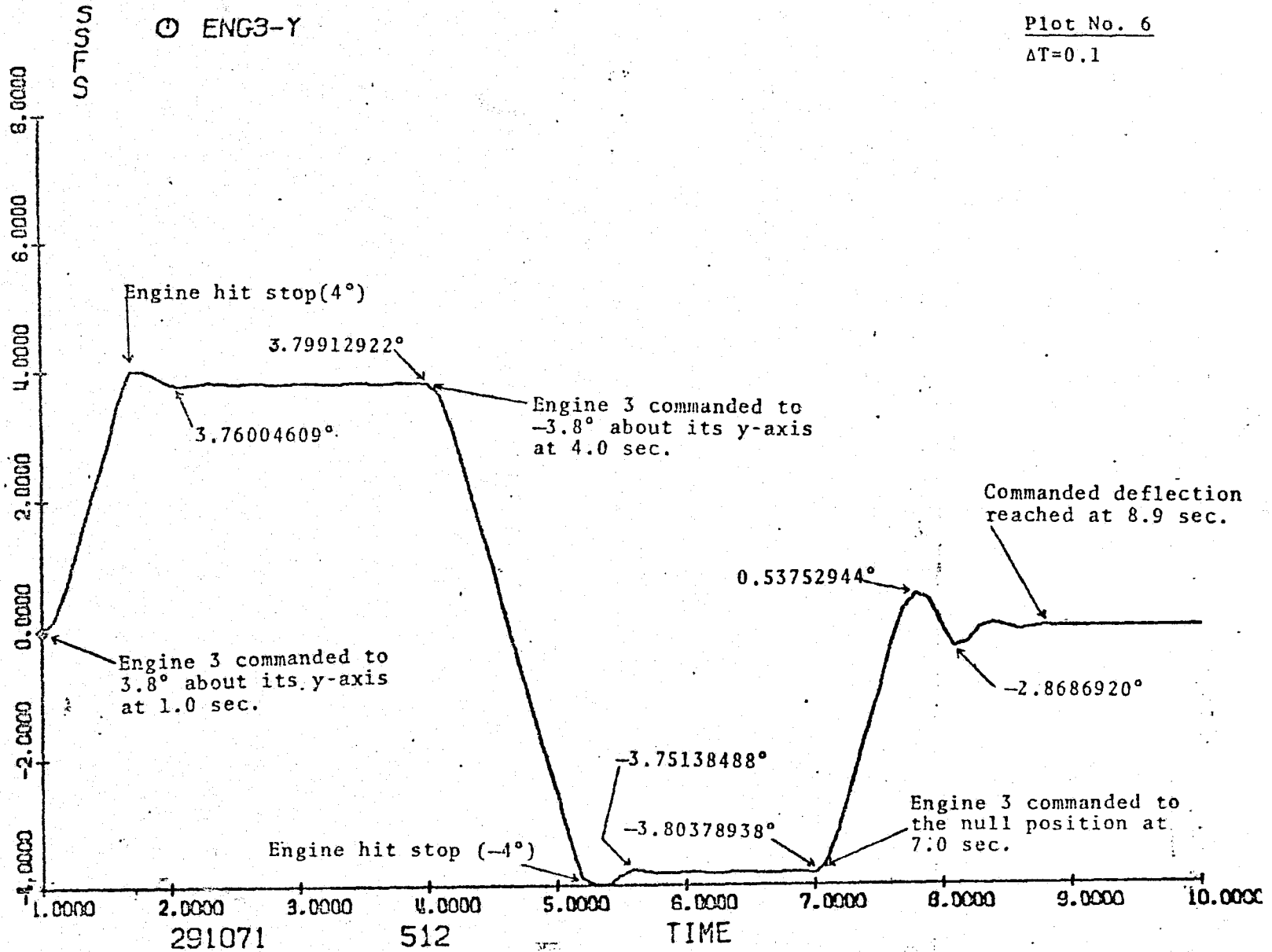


FIGURE 4.7-29. EXAMPLE: REFERENCE DATA OMS GIMBAL ACTUATOR RESPONSE

- Suitable check cases for each actuator
- Reference data generated with the reference module

Overall impact on the verification data base is greatly dependent upon the storage requirements of the tabular information required for each actuator to be verified. After considerable hardware tests have been conducted, these storage areas should remain relatively constant in size. Some variations are expected to occur during Shuttle development and testing.

4.7.1.5 Payload Deployment and Retrieval System (PDRS)

This section describes the components, functions, parameters, and verification of the software module required to simulate the Orbiter Payload Deployment and Retrieval System (PDRS) used in the On-orbit mission phase.

PDRS Description

The PDRS comprises the Payload Retention Mechanism (PRM) and the Payload Deployment and Retrieval Mechanism (PDRM). Functions of the PDRS include payload/target (P/T) manipulation and support services, docking assistance, and inspection capability (Ref. 5).

The PRM consists of a system of guides, latches, and release mechanisms which provide the capabilities for easy and reliable payload installation, removal, or changeout (Ref. 18).

The PDRM is located in the payload bay and on the flight deck of the Orbiter. The components of the PDRM are listed as follows (Ref. 5):

- Manipulator Retention Latches (MRL)
- Manipulator Deployment Mechanism (MDM)
- Manipulator Jettison Subsystem (MJS)
- Shuttle Attached Manipulator Subsystem (SAMS)

The MRL is used to support and lock the manipulator arm in the stowed position. The manipulator arm assembly is deployed and retracted via the MDM. The MJS separates the manipulator and its retention latches from the Orbiter should a failure occur which would preclude the complete stowing of the manipulator assembly.

The SAMS controls and affects actual payload handling using the Control Servo Input (CSI) unit and the Follow Up Output (FUO) unit. The CSI controls the FUO, the manipulator arm assembly, using crew commands to and feedback information from the FUO. Control transfer is accomplished with an electronic interface between the CSI and the FUO containing a resolver.

Only one manipulator arm assembly with its associated MRL, MDM, MJS, and electronics is standard on the Orbiter; however one additional assembly is optional and payload chargeable (Ref. 19). Figure 4.7-30 depicts the mechanical components of the PDRM.

PDRS Simulation Module Description and Performance Parameters

The PDRS simulation software module will simulate those functions performed by each element of the actual Orbiter PDRS. Simulation fidelity of the PDRS elements are; (1) PRM - talkback, (2) MRL - talkback, (3) MDM - low, (4) MJS - talkback, (5) SAMS - high.

Inputs to the PDRS software module consist of:

- Payload bay geometric constraints
- P/T type and placement status
- SAMS operator/control logic commands
- Electrical power available
- Orbiter vehicle translational and rotational states and rates
- P/T translational and rotational states and rates
- Orbiter mass properties
- P/T mass properties

The PDRS software will then provide:

- Manipulator arm retention, deployment, jettison status
- Payload retention status
- Manipulator arm assembly dynamics
- P/T attachment status
- Light, camera, monitor operations signals
- Electrical power system (EPS) loadings
- P/T Orbiter collision status when attached

Simulation of PRM, MRL, MDM, and MJS activation will be accomplished through the use of the following sequence: (1) crew switch set to indicate desired operation; (2) power required/power available check performed; (3) appropriate time delay; (4) crew response indicator set.

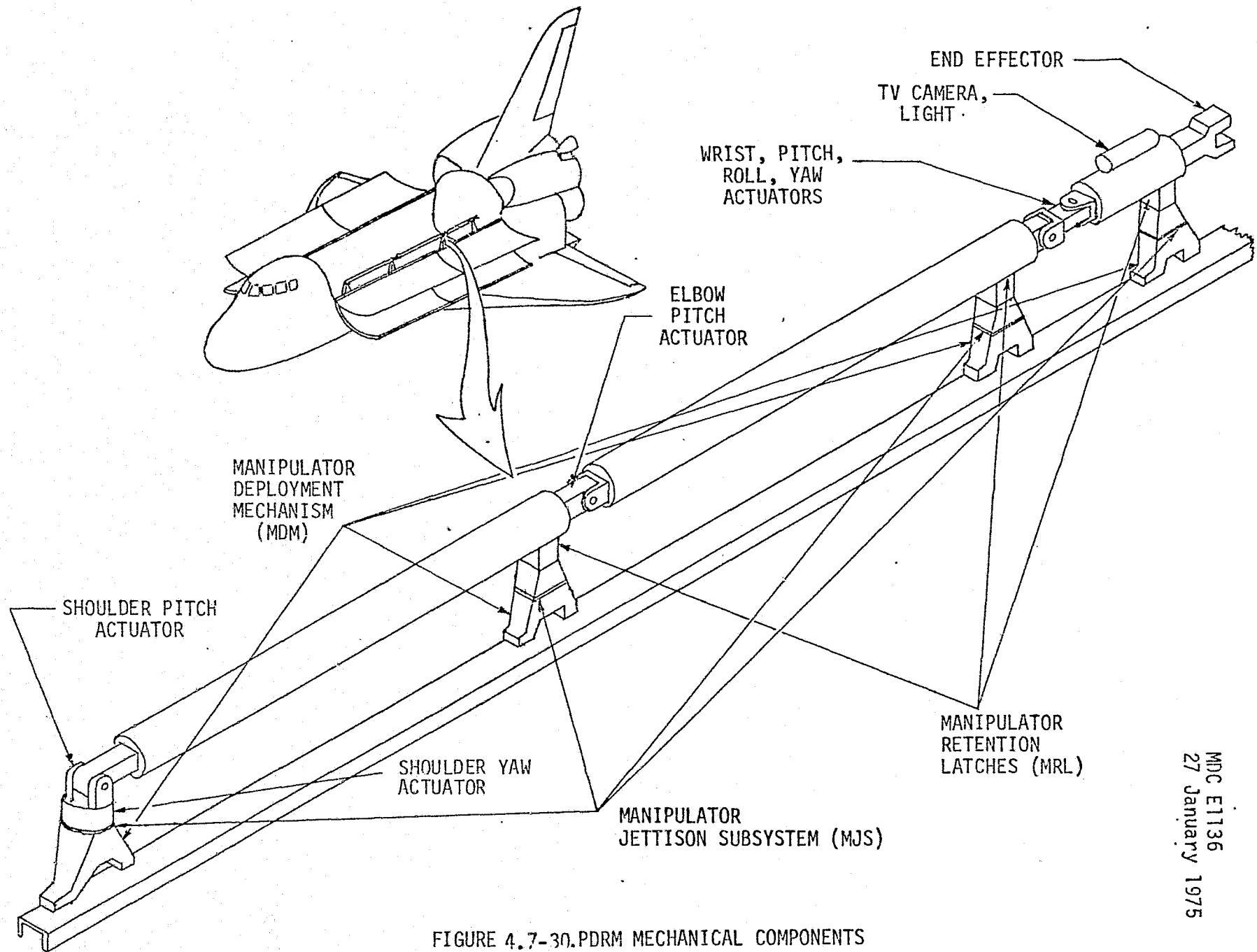


FIGURE 4.7-30. PDRM MECHANICAL COMPONENTS

However, simulation of the SAMS will involve the simulation of the dynamics and interfaces of the manipulator arm assembly. The arm assembly dynamics will be simulated by solving the equations of motion associated with each manipulator arm joint in the Orbiter - manipulator arm - P/T system. Factors affecting the solution of these equations are:

- Manipulator arm instantaneous geometry
- CSI simulation input commands
- Simulated servo motor response to input commands
- Manipulator arm joint geometric limitations
- Reaction forces and torques at each manipulator arm joint due to Orbiter - P/T

A simplified description of one manipulator arm joint depicting the joint reactions is shown in Fig. 4.7-31. Solution of the equations for the Orbiter - manipulator arm - P/T system will enable the software module to determine:

- True manipulator arm joint positions and rates
- Joint potentiometer and tachometer outputs
- Power required for the operation performed
- End effector status (P/T attach/release)

The simulation of the manipulator arm associated visuals will be accomplished utilizing a Computer Generated Image (CGI) technique. The CGI software interface module will receive outputs from the SAMS simulation module describing manipulator arm positions and angles, as well as camera and light operation. Based upon these inputs, the CGI will generate the associated visuals using its data base as described in Section 4.4.1.

The performance parameters described in Table 4.7-7 were selected using the criteria developed in Section 4.1. The execution rate of the PDRS simulation module will be 10 times per second. This will provide an update rate compatible with the mass properties module during attachment/docking as described in Section 4.5.3. PDRS simulation module interfaces with other Orbiter simulation software modules are given in Fig. 4.7-32.

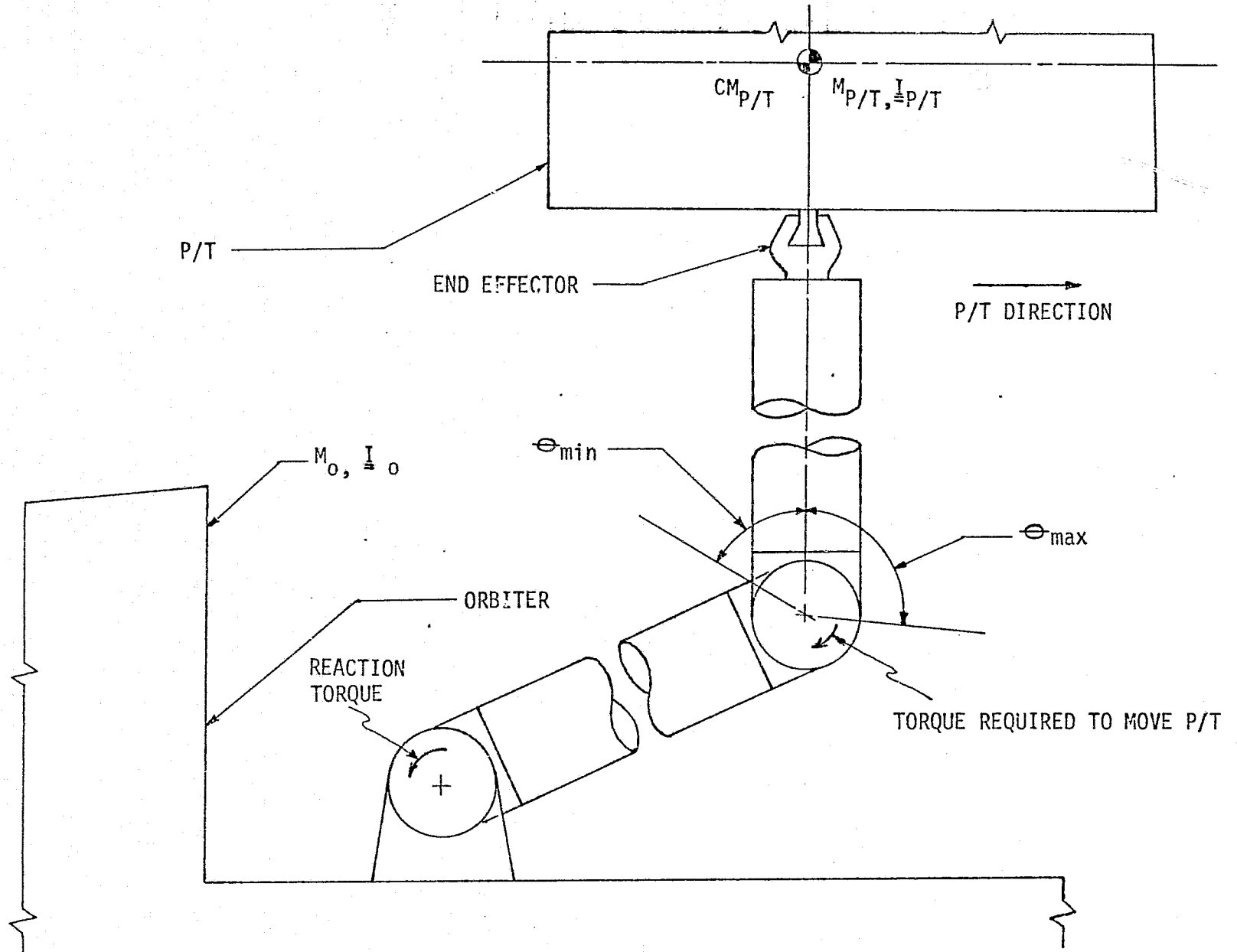


FIGURE 4.7-31. SIMPLIFIED FJO JOINT REACTIONS

TABLE 4.7-7 PDRS PERFORMANCE PARAMETERS

Symbol	Parameter	Type ^c
F_o	Orbiter body forces	I
$F_{P/T}$	P/T ^a body forces	I
I_o	Orbiter inertia tensor	I
$I_{P/T}$	P/T inertia tensor	I
M_o	Orbiter mass	I
$M_{P/T}$	P/T mass	I
CM_o	Orbiter center of mass	I
$CM_{P/T}$	P/T center of mass	I
r, v	Orbiter position, velocity	I
S_r, S_v	P/T relative position and velocity	I
$S_{\phi_{P/T}}, S_{\theta_{P/T}}, S_{\psi_{P/T}}$	P/T relative angular orientation	I
T_{prm}	PRM actuation response time	I
T_{mrl}	MRL actuation response time	I
T_{mdm}	MDM actuation response time	I
T_{mjs}	MJS actuation response time	I
T_{ee}	End effector grasp/release response time	I
$\theta_{min,i}; \theta_{max,i}$	FUO ^b joint geometric limits	I
$l_{ee,max}$	FUO end effector extension limit	I
C_{prm}	PRM command	I
C_{mrl}	MRL command	I
C_{mdm}	MDM command	I
C_{mjs}	MJS command	I
$C_{c,i}$	Camera operation command	I
$C_{l,i}$	Light operation command	I
C_{ee}	End effector grasp/release command	I
S_{r-c}	FUO translational position command	I
S_{r-c}	FUO translational rate command	I

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TABLE 4.7-7 continued

Symbol	Parameter	Type ^c
$\delta\phi_c, \delta\theta_c,$ $\delta\psi_c$	FUO end-point attitude command	I
$\delta\dot{\phi}_c, \delta\dot{\theta}_c,$ $\delta\dot{\psi}_c$	FUO end-point attitude rate command	I
S_c	Camera operation status	P
S_e	Light operation status	P
S_{ee}	End effector status (grasp/release)	CP
S_j	FUO jettison status	P
$\delta r_{fuo,i}$	FUO joint positions in orbiter axes	CP
S_{r_e}	FUO end effector position in orbiter axes	CP
$[\dot{\theta}_{fuo,i};$ $\ddot{\theta}_{fuo,i}]$	FUO joint rates and accelerations	P
$l_{ee}, \dot{l}_{ee}, \ddot{l}_{ee}$	FUO end effector extension, rate and acceleration	P
A_i	FUO joint orientation matrices	CP
$[V_{fuo,i}]$	FUO joint potentiometer outputs	P
$[W_{fuo,i}]$	FUO joint tachometer outputs	P
$[L_{fuo,i}]$	FUO joint torques	CP
$\delta F_{o,prm}$	Orbiter forces due to PRM	P
$\delta F_{o,sams}$	Orbiter forces due to SAMS	CP
$\delta F_{p/T,prm}$	P/T forces due to PRM	P
$\delta F_{p/T,sams}$	P/T forces due to SAMS	CP
L_o	Total moment on orbiter	CP
$L_{p/T}$	Total moment on P/T	CP
$L_{o,pdrs}$	Orbiter moment due to PDRS	CP
$L_{p/T,pdrs}$	P/T moment due to PDRS	CP
P_{pdrs}	Electrical power load due to PDRS	CP

a P/T denotes payload/target
b FUO denotes the manipulator arm

^c I - Input
P - Performance Parameter
CP - Critical Performance Parameter

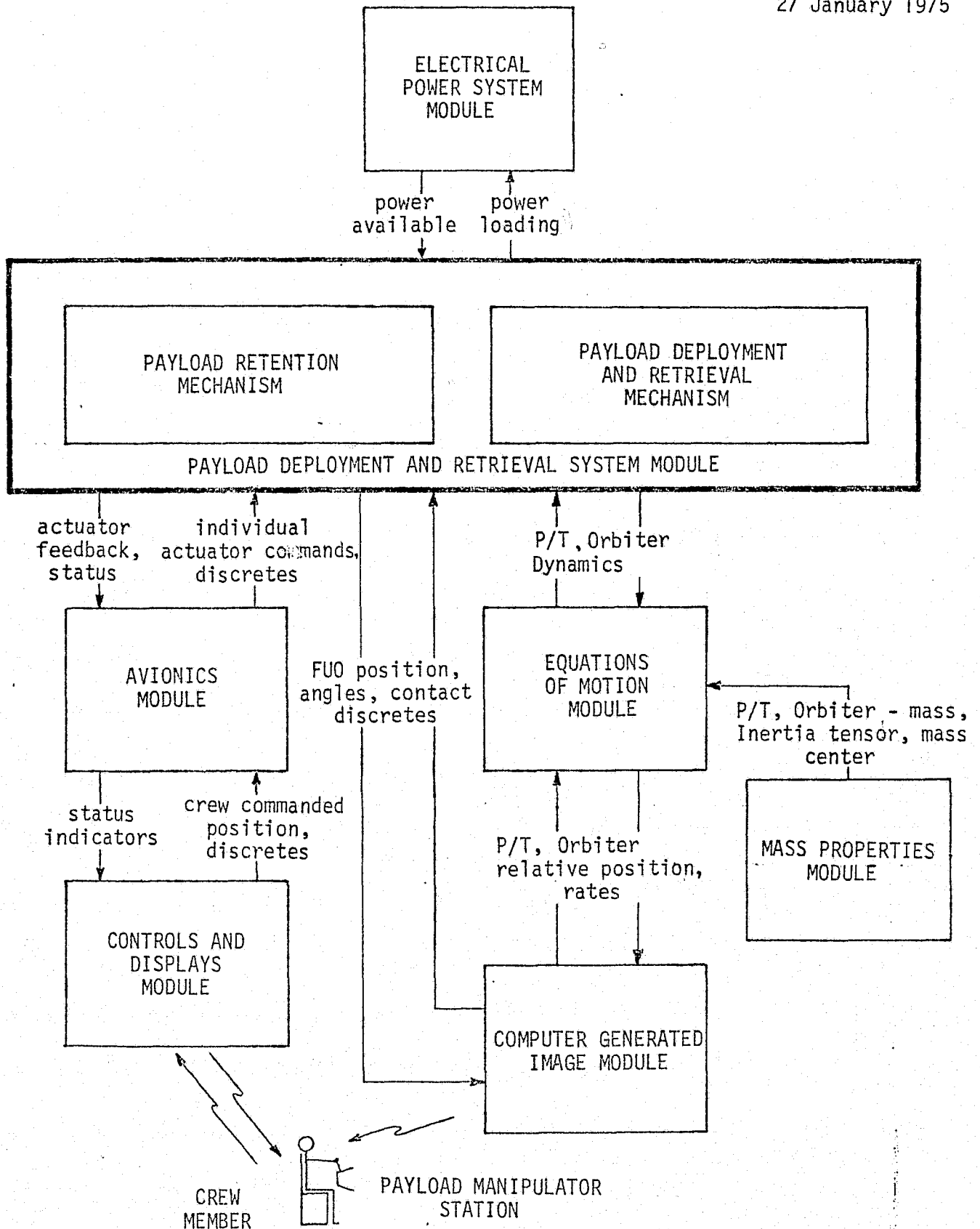


FIGURE 4.7-32 PAYLOAD DEPLOYMENT AND RETRIEVAL SYSTEM MODULE INTERFACES

PDRS Reference Data Sources and Data Formats

The numerous dynamic functions performed by the PDRS Simulation Module require verification reference data over a wide operational range. Test data would not be completely adequate as verification reference data due to actual test limitations. It is then necessary to use a reference software module for reference data generation.

Presently, no readily available math model exists which simulates the Orbiter PDRS. However, Figures 4.7-33a and 4.7-33b depict a conceptual, functional flow diagram of a math model which can be combined with a driver to form a suitable PDRS reference module. This reference module, when implemented and exercised with carefully designed check cases, will supply reference data for the validation of the simulated functions of the PRM, MJS, MDM, MRL, and SAMS.

The reference module driver will control module input/output and ensure PDRS Simulation Module compatibility. Reference module inputs and outputs consist essentially of the corresponding parameters and parameter groups listed in Table 4.7-7 and shown in Figure 4.7-32. Minor variations between simulation and reference module internal parameters may result due to formulation differences, but principal inputs and outputs will be compatible. Other input/output requirements unique to the reference module will be specifically related to the user-designated quantity and fidelity of the desired output verification reference data.

Reference module simulation of the MJS, MDM and MRL response uses a talkback technique. Eventually, as hardware is developed and test data becomes available, time-delay functions should be incorporated simulating the actual time-delay talkback response. The PRM talkback response is also simulated in this manner.

Complete PRM simulation involves a time-delay talkback response function coupled with the appropriate force and moment calculations. PRM reactions forces and moments are used by the Orbiter and P/T equations of motion and based upon:

- PRM design and location(s)
- P/T type
- P/T relative position, velocity, and orientation
- PRM operation commands

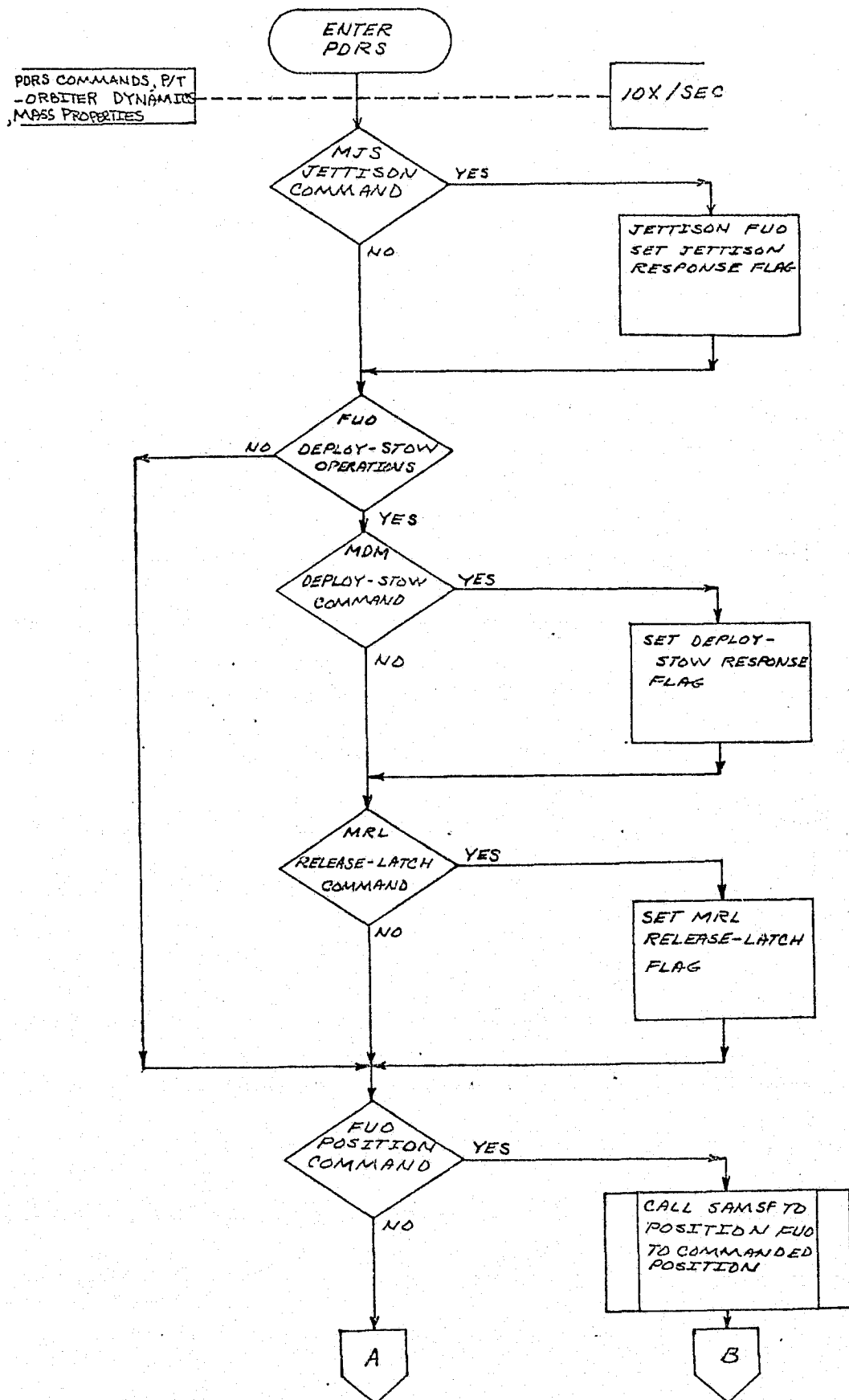


FIGURE 4.7-33a. PDRS REFERENCE MODULE FUNCTIONAL FLOW

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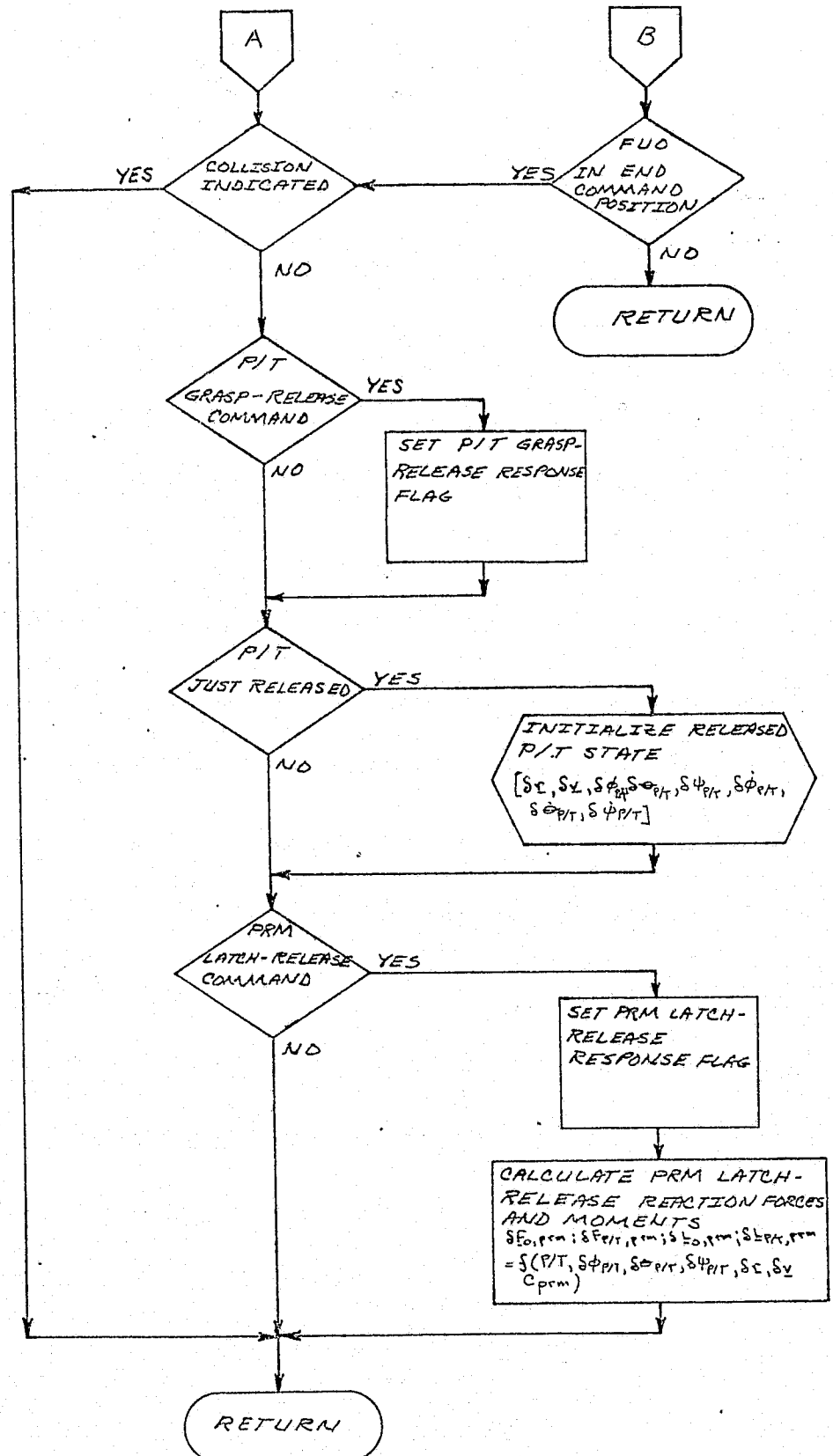


FIGURE 4.7-33a. (CONTINUED)

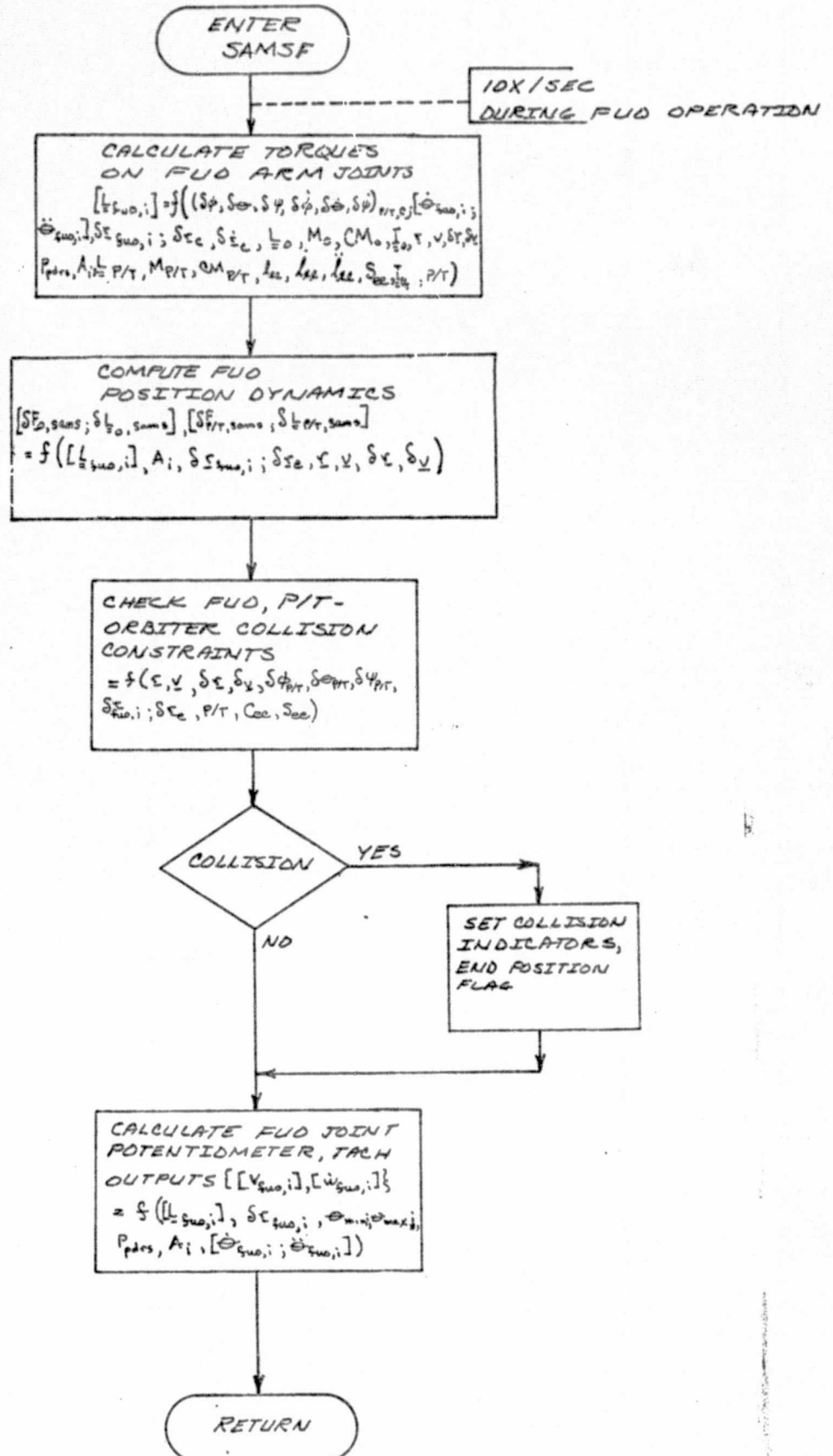


FIGURE 4.7-33b PDRS REFERENCE MODULE FUNCTIONAL FLOW (SAMSF SUBROUTINE)

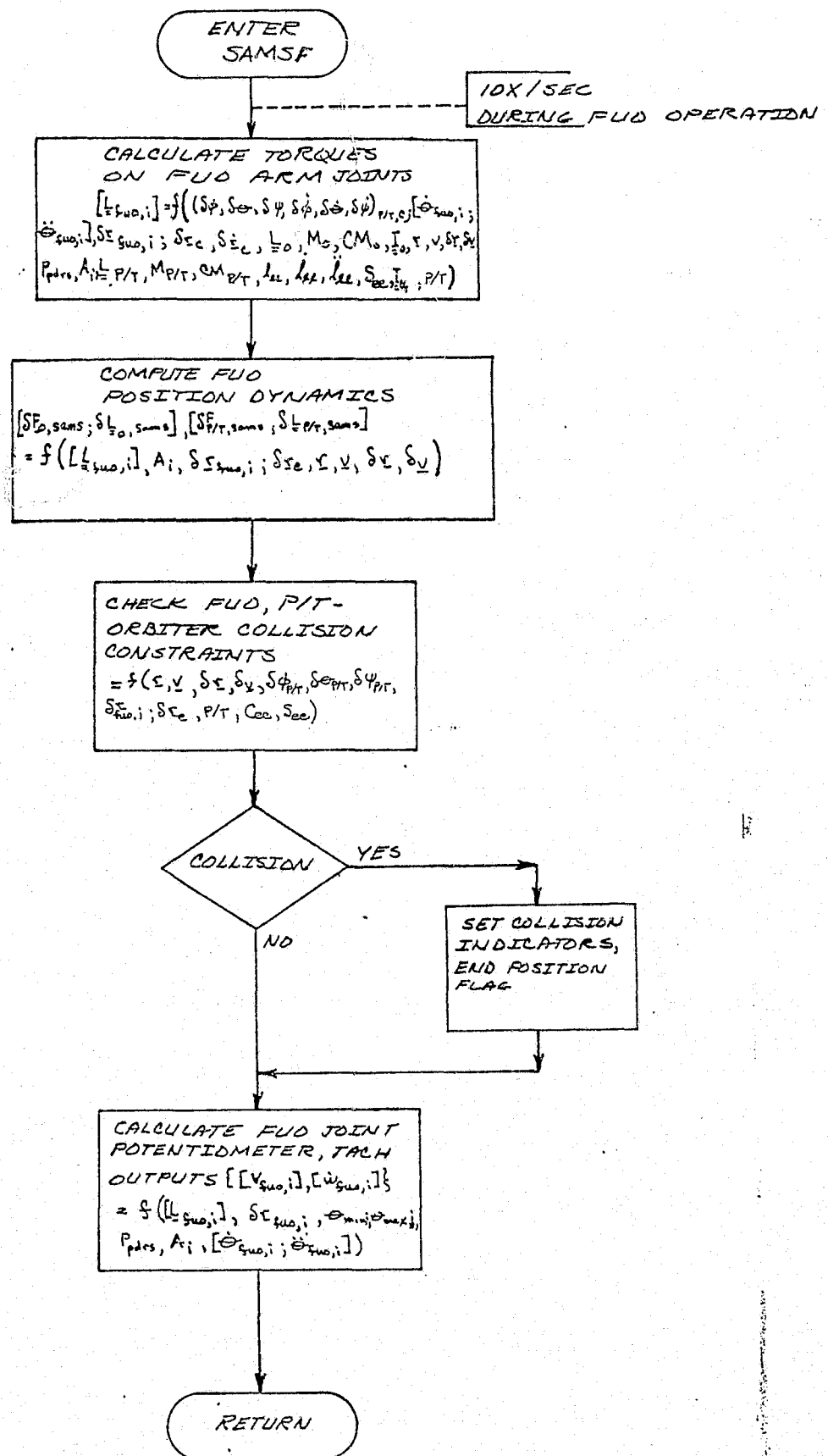


FIGURE 4.7-33b PDRS REFERENCE MODULE FUNCTIONAL FLOW (SAMSF SUBROUTINE)

SAMS simulation verification is concerned chiefly with the dynamics of the FUO. Operator commands to the FUO require that the reference module SAMSF subroutine (Figure 4.7-33b) compute:

- FUO arm joint torques
- FUO position dynamics (SAMS reaction forces and moments)
- FUO-Orbiter-P/T collision constraints
- FUO potentiometer and tachometer outputs

Actual SAMSF formulations and electromechanical actuator transfer functions (see Section 4.7.1.4) will be derived from empirical data obtained from hardware tests of the SAMS, and may experience some modification as the SAMS design evolves. Additional automatic command sequences may also be implemented for standard FUO positioning (less P/T) as required for FUO stowing, deployment, or Shuttle vehicle inspection (Ref. 9).

PDRS Validation Methods and Check Cases

Check case design for verification operation of the MDM, MRL, and MJS should consist of simple discrete command sequences. In sequencing the various commands through the simulation and reference modules, the corresponding talkback response, sequence check flags, and time-delays can be evaluated and analyzed. Low-fidelity (talkback) response of the PRM can also be verified through similar check case design.

Complete verification of the PDRS requires that the PRM and SAMS be verified with dynamic check cases. For both the PRM and SAMS, one or more check cases must be designed for each P/T and/or FUO operation planned. Each check case should verify the complete command sequence and SAMS response for stowing, deployment, retrieval and other manipulations of payloads with appropriate masses and inertias. Other dynamic command sequences should be used to evaluate the response and positioning of the FUO without an attached P/T. Previously discussed command sequences should be similar to the aero-surface command sequence shown in Section 4.7.1.4, although much more complex.

PDRS Data Base Impact

Data base requirements for verification of the PDRS consist of:

- Reference module as described

- Reference data generated with the reference module
- A variety of check cases which exercise all planned PDRS operations
- The necessary tables, tapes, and/or service routines required for PDRS Simulation Module verification

During PDRS simulation development, changes in the PDRS portion of the verification data base will occur. Most of the impact will be minor, unless a significant hardware modification is made. Other changes in the PDRS data base may be required, if payload masses/inertias and operational sequences outside of the previously-validated range are added later in the program.

4.7.1.6 Hydraulic Power Subsystem (HPS)

HPS Description

The hydraulic power system provides power to actuate the aerodynamic flight control surfaces, main engine gimbals and engine controls, main and nose landing gear deployment, speed-brakes, main landing gear brakes, and nose wheel steering. Figure 4.7-34 illustrates the functional configuration of the HPS (Ref. 20). The HPS consists of three main hydraulic pumps, each driven by an auxiliary power unit (APU), connected to the hydraulic system loads.

HPS Simulation Module Description and Performance Parameters

The HPS simulation module will be divided into four main groups of generally related engineering equations. These equations will simulate hydraulic load, stored, accumulator energy, pump-reservoir capability, and hydraulic fluid temperature and heat load.

Signals will also be provided to indicate crew display of hydraulic fluid temperature and quantity as well as caution and warning displays relating high or low fluid temperature and low fluid quantity or pressure (Ref. 11).

Figure 4.7-35 depicts the HPS simulation module interfaces with other simulation modules. An example of module interaction and influence is that of the continuous dynamic loads on the aerodynamic control surfaces affecting HPS pressure and reservoir level. Table 4.7-8 provides a list of the HPS performance parameters (Ref. 21). These parameters are also reflected in Figure 4.7-37.

HPS Reference Data Sources and Data Formats

HPS verification reference data should be generated with a reference module functionally equivalent to the functional HPS reference module flow shown in Figure 4.7-36. Reference 22 describes an existing program which could be effective as a reference data source. As described, the Space Shuttle Hydraulic POWER Program assumes that all design dependent data is available from the Orbiter contractor (Rockwell). User-supplied information consists of output options, mission dependent data, and operational data for each mode to be analyzed. Special care must be exercised in coordinating the specific mission and design-dependent data (Ref. 22).

4.7-92

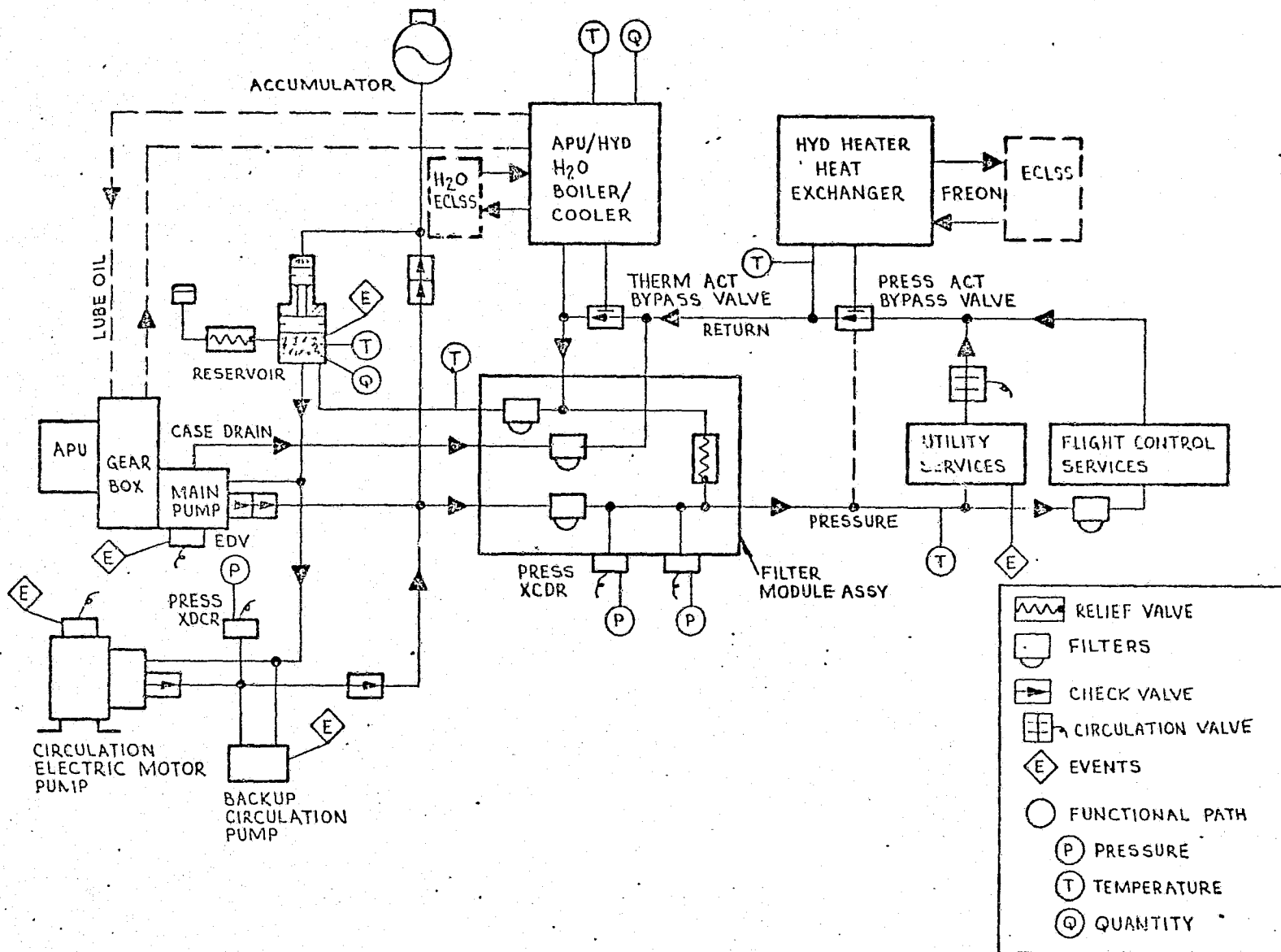


FIGURE 4.7-34. HYDRAULIC POWER SUBSYSTEM (TYP)

MDC E1136
27 January 1975

TABLE 4.7- 8 HYDRAULIC POWER SUBSYSTEM PARAMETERS

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
RESERVOIR FLUID TEMP	-75	+300	DEG F	CP
RESERVOIR FLUID VOLUME	0	+100	PCNT	P
RESERVOIR FLUID LVL LOW	NORM	LOW	EVENT	CP
SUPPLY PRESS A	0	+4000	PSIA	P
SUPPLY PRESS B	0	+4000	PSIA	P
FWD DISTR PRESS LINE TEMP	-75	+300	DEG F	P
FLUID HEATER OUTLET TEMP	-75	+300	DEG F	P
AFT COMPT RTN LINE TEMP	-75	+300	DEG F	P
CIRCULATION PUMP PRESS	0	+500	PSIA	P
CIRCULATION PUMP-ON		ON	EVENT	I
BACK-UP CIRCULATION PUMP ON		ON	EVENT	I
MAIN ENGINE SUPPLY VLV-CLOSE		ON	EVENT	I
READY FOR APU START-ON		READY	EVENT	I
BOILER WATER TEMP	0	+250	DEG F	I
H ₂ O BOILER FLUID VOLUME	0	+100	PCNT	I

^a
P - Performance Parameter
CP - Critical Performance Parameter
I - Input

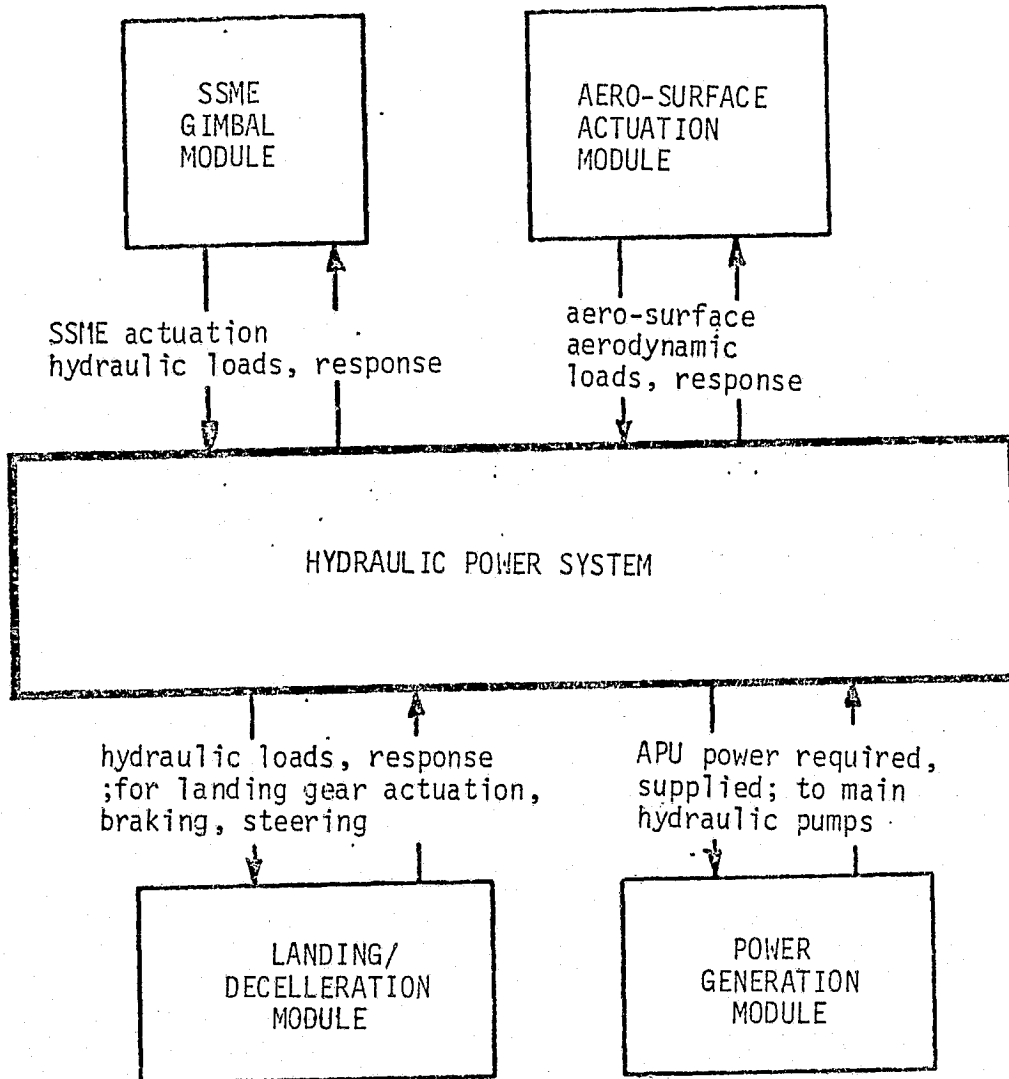


FIGURE 4.7-35 HPS SIMULATION MODULE INTERFACES

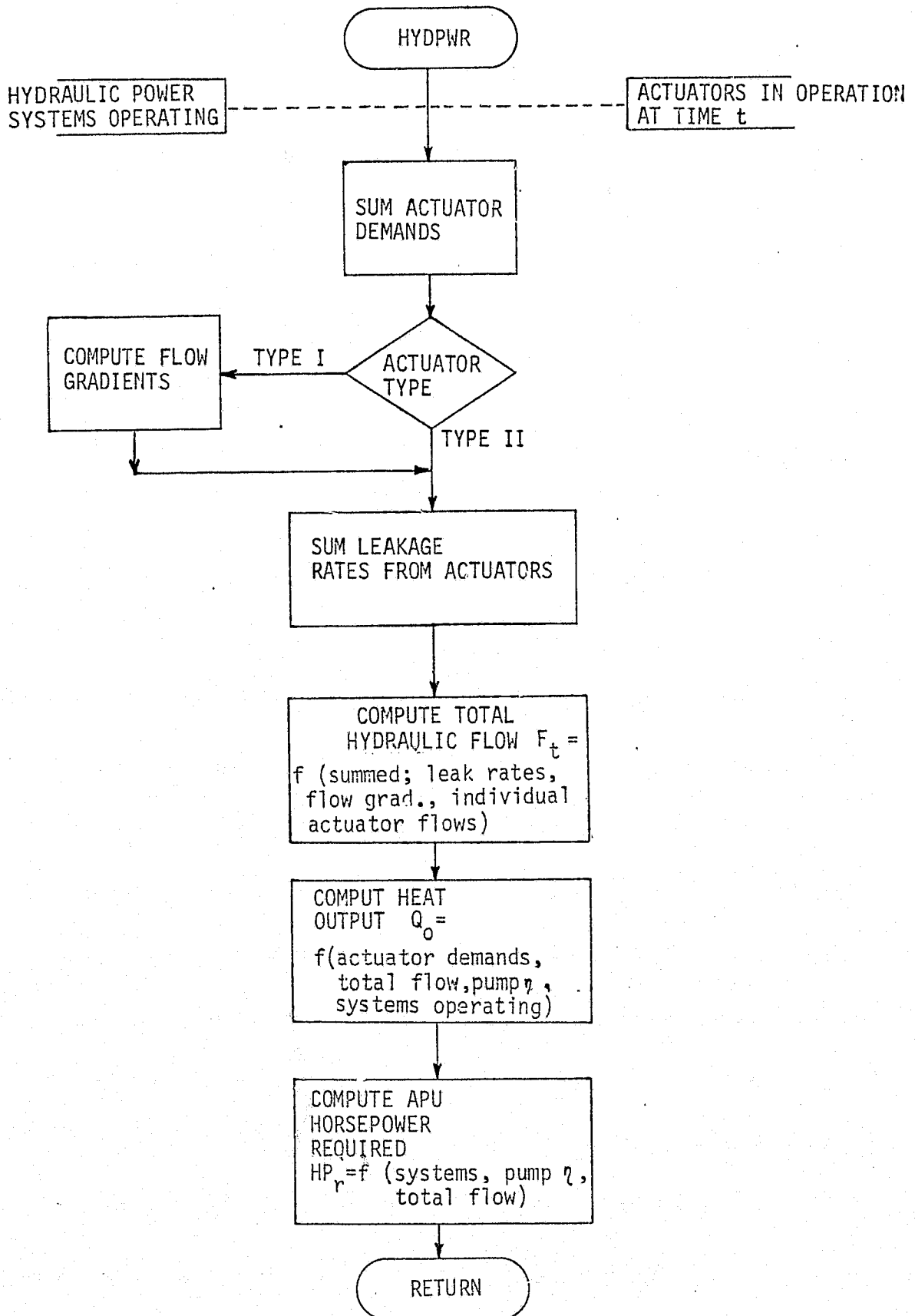


FIGURE 4.7-36. HPS REFERENCE MODULE FUNCTIONAL FLOW DIAGRAM

4.7-95

The POWER program provides an analysis of the flow, power, and thermal characteristics of the Orbiter HPS. Program outputs consist of (Ref. 22):

- Input card images
- Type I actuator data (Type I actuators are variable rate)
- Actuator operational mode status
- Mission flow
- Power and thermal profiles
- Pump characteristics for the mission
- Individual actuator flow
- Individual actuator thermal profiles
- Total mission system power

HPS Validation Methods and Check Cases

Check case construction for verification of the Orbiter HPS should contain the correct inputs (system and module dependent) for both the simulation and reference modules which exercise the complete HPS for the mission phase and/or operating conditions of interest. The ascent and entry mission phase are most important, as the HPS is not used in the on-orbit phase. Either a partial or complete mission phase check case can be executed to generate plots similar to the APU load profile shown in Figure 4.7-37 (Ref. 5). Load profile data -- power, thermal, and flow -- should be generated and output (print, plot, and/or mass storage) for verification analysis. A complete verification requires that HPS load profiles be generated for each Orbiter hydraulic actuator and actuator group as well as the entire HPS.

Data Base Impact

Data base impact for HPS Simulation Module verification will consist of:

- A suitable reference module
- Resident reference data and check cases
- Resident data required by the reference module

Impact to the verification should not expand unless significant changes are made to the HPS.

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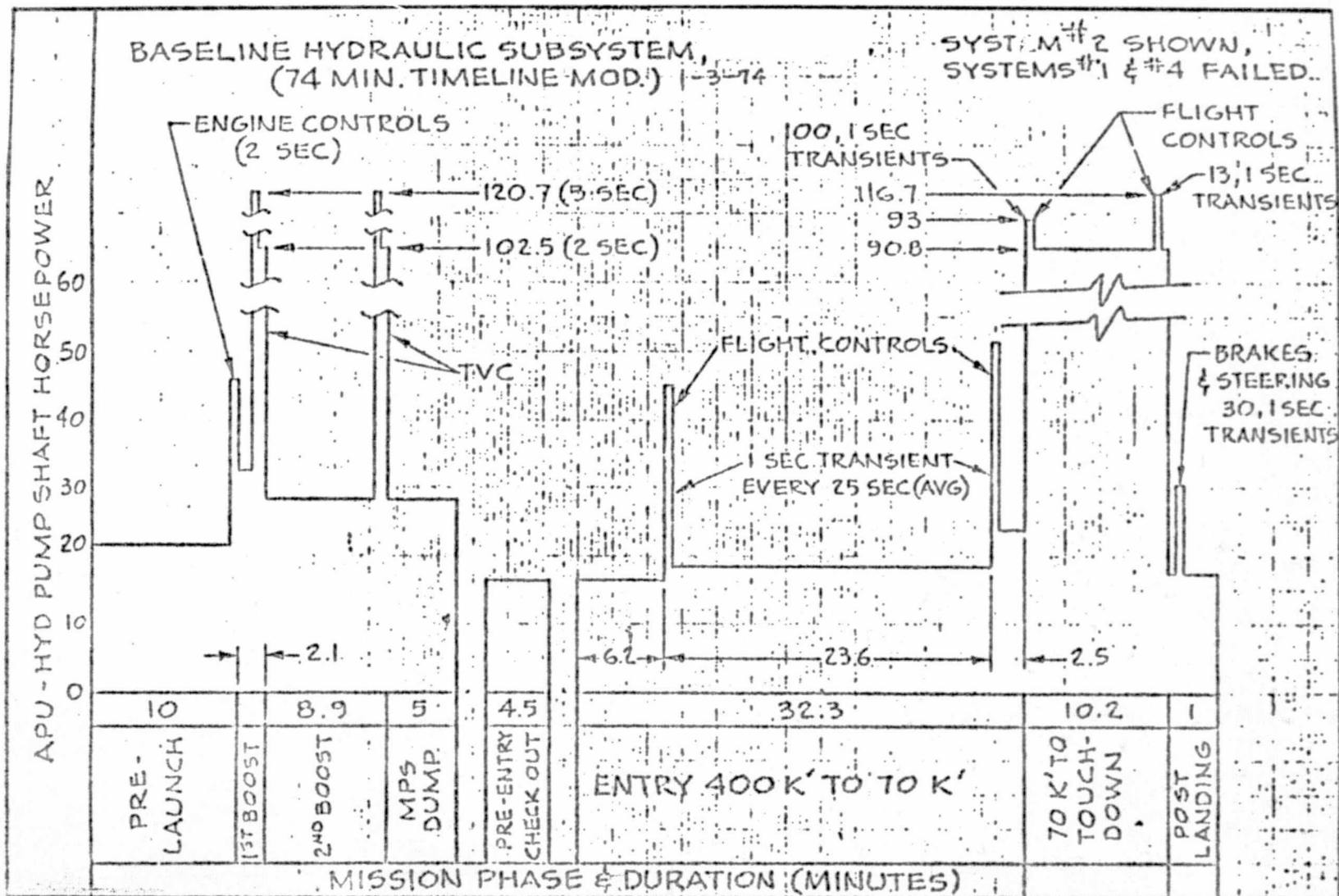


FIGURE 4.7-37. HYDRAULIC POWER SYSTEM #2 LOAD PROFILE (NOTE: ORBITER HPS HAVE BEEN REDUCED TO 3; 4 SHOWN IN THIS FIGURE)

4.7-97

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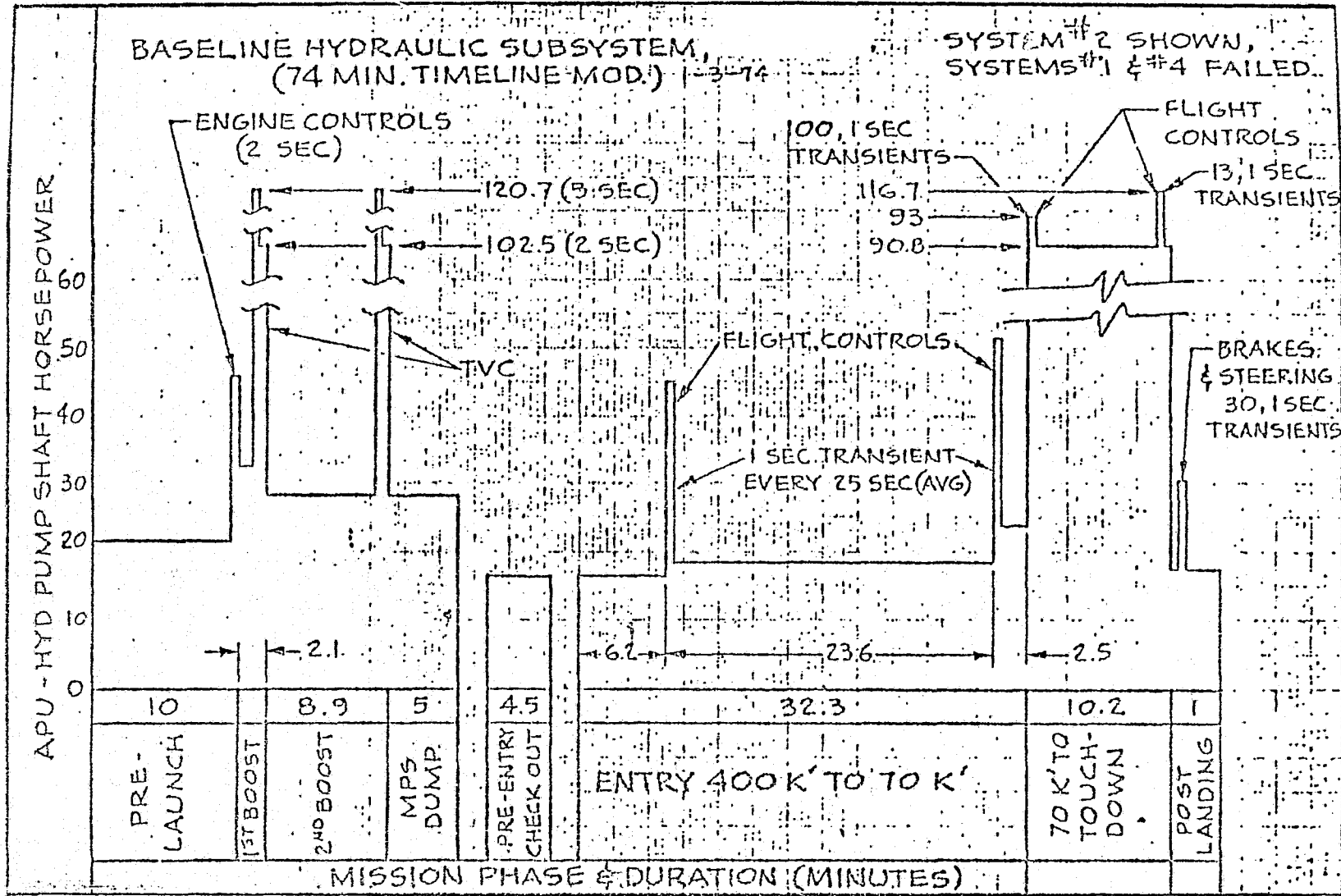


FIGURE 4.7-37. HYDRAULIC POWER SYSTEM #2 LOAD PROFILE (NOTE: ORBITER HPS HAVE BEEN REDUCED TO 3; 4 SHOWN IN THIS FIGURE)

4.7.2 Purge and Vent (P & V) Subsystem

The Orbiter P & V subsystem is very simple in form and function, and little or no simulation requirements exist for this subsystem on any of the simulators of interest to this study. Therefore, this section provides only a brief description of the P & V subsystem and a possible simulation module; validation-oriented subsections are omitted:

4.7.2.1 P & V Subsystem Description

The P & V subsystem performs the following functions:

- purging of various Orbiter cavities and lines using an inert gas (He or N₂)
- venting of various Orbiter cavities to relieve differential pressures and eliminate outgassing products
- detection of hazardous gases (e.g., from leaks in reactant storage systems)
- provision and application of rain repellent for the Orbiter windshield

Figures 4.7-38 and 4.7-39, from Ref.12, provide an overview of the P & V subsystem layout and its GSE interface. Additional layout detail, if needed, is provided by Ref.23. Additional discussion of the GSE interface will be found in Section 4.3.2.3.

As indicated by Figure 4.7-38, the only purging capability self-contained within the orbiter is dry-nitrogen purging of the windshield cavity. This purging is initiated manually by the flight crew whenever necessary (e.g., if fog or ice appears between the windshield panes).

Venting of Orbiter cavities is necessary primarily during periods of rapid external pressure change; e.g., ascent and entry. Both "active" and "passive" vents are provided. Passive vents are simply fixed holes in the Orbiter skin. Active vents consist of valves or doors which are opened and closed at appropriate times -- either manually, cued by the flight crew timeline, or automatically by the onboard sequencing system.

Hazardous-gas detection is apparently a prelaunch function, since no detector outputs are shown by Ref. 21 (see below).

4.7-99

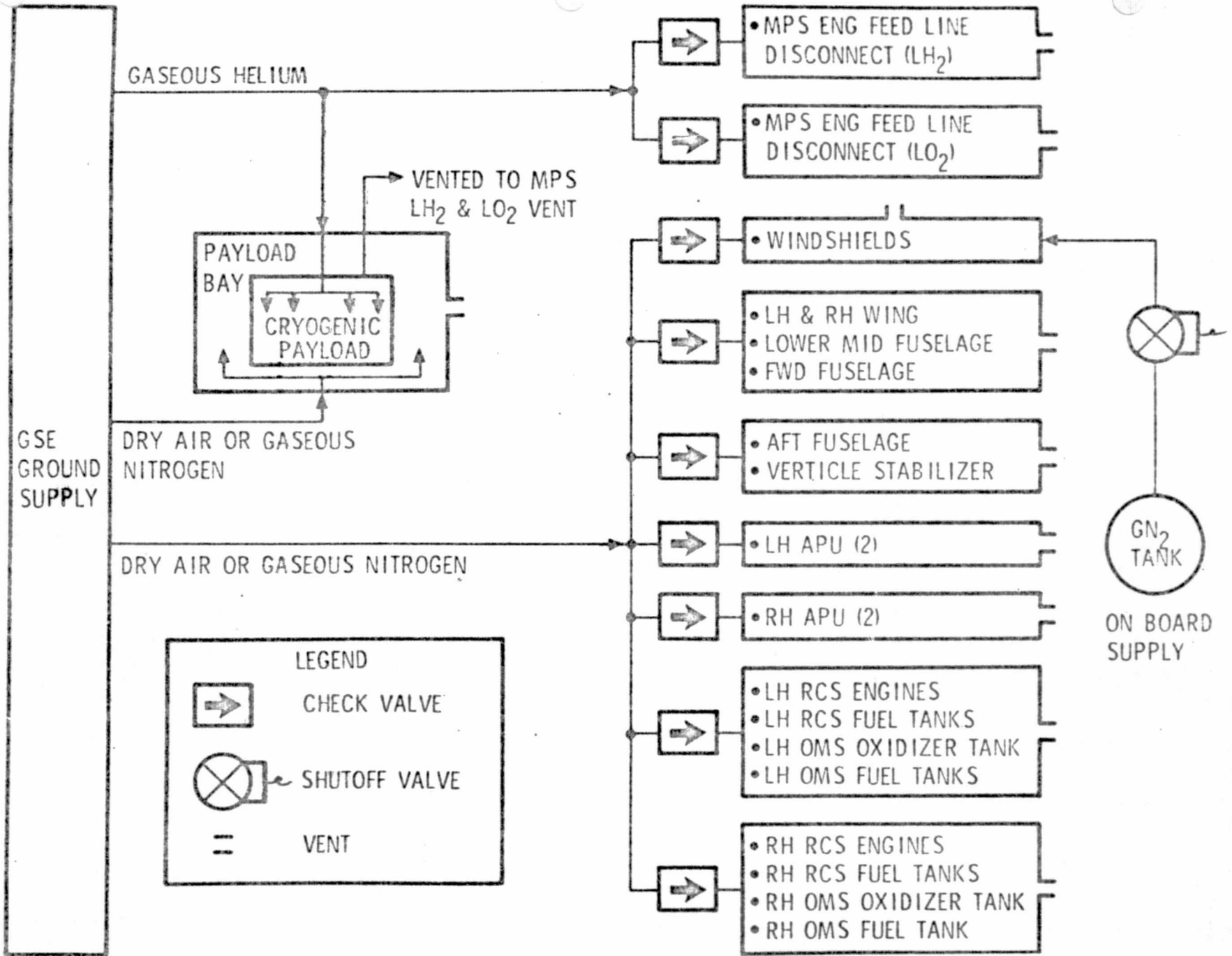


Figure 4.7-38. PURGE SUBSYSTEM FLOW DIAGRAM

4.7-99

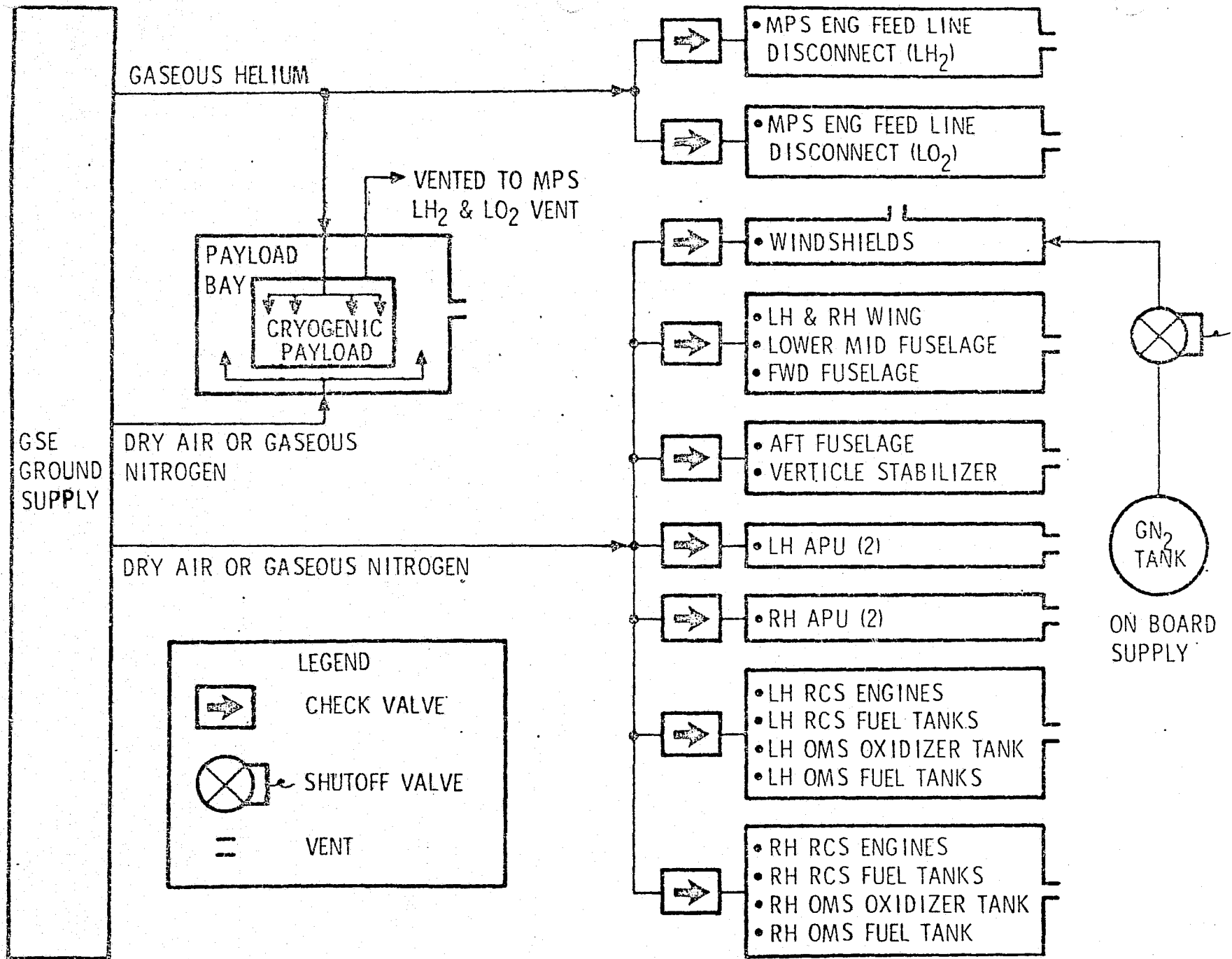


Figure 4.7-38. PURGE SUBSYSTEM FLOW DIAGRAM

4.7-100

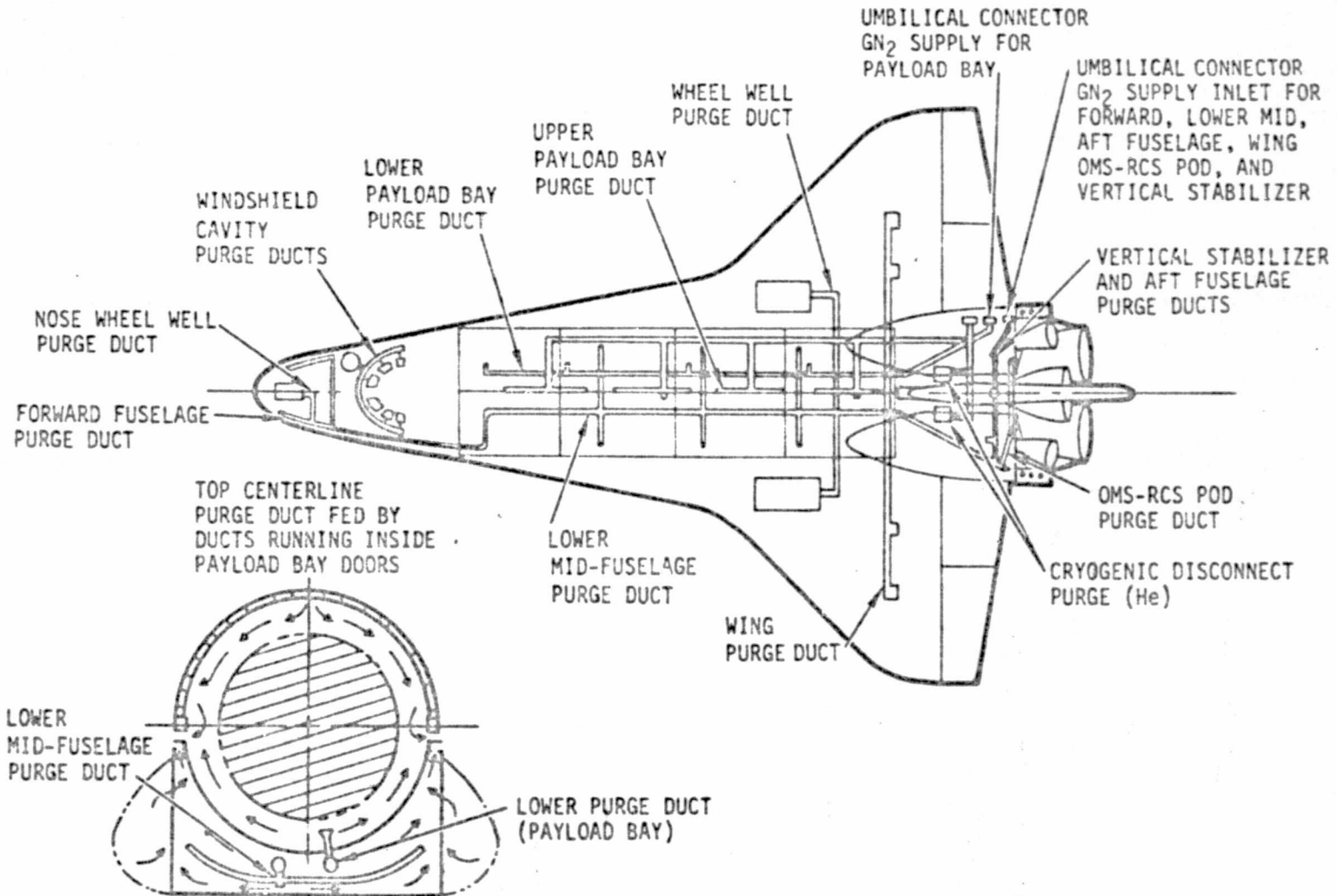


Figure 4.7-39. ORBITER PURGE AND VENT SUBSYSTEM

4.7-100

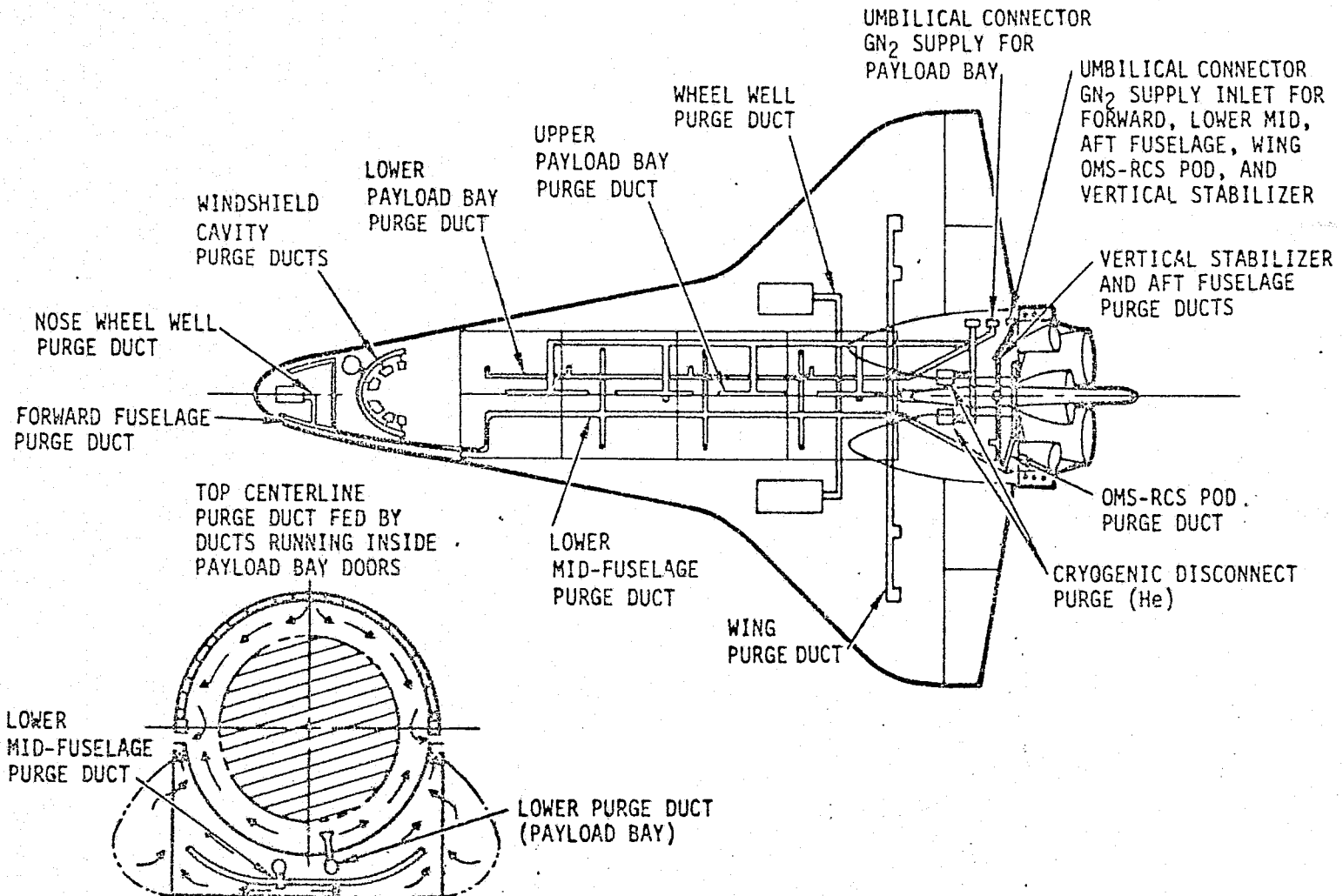


Figure 4.7-39. ORBITER PURGE AND VENT SUBSYSTEM

4.3.2.2 P & V Simulation Module Description and Performance Parameters

Prelaunch purging operations (if simulated) will fall under the Prelaunch/Launch Interface Module, Section 4.3.2.3. The remaining P & V functions, if simulated at all, will probably be implemented only as talkback of manually- or automatically-initiated discrettes. The potential performance parameters are listed in Table 4.7-9; no critical performance parameters are indicated.

Table 4.7-9. P & V Simulation Module Parameters

PARAMETER
Window cavity safety valves (#1,2,3,4,5) open/closed
Window rain repellent tank quality
Orbiter vent doors open/closed
Payload bay vent doors (left, right) open/closed
Forward thruster vent doors (left, right) open/closed
Left forward fuel vent door open/closed
Right forward oxidizer vent door open/closed
Fuselage vent doors (left, right/forward, mid, aft) open/closed
Aft wing vent doors (left, right) open/closed
Left OMS/RCS fuel vent door open/closed
Right OMS/RCS oxidizer vent door open/closed
Fin vent door open/closed

4.7.3 Propulsion and Fuel Systems

The Orbiter Propulsion and Fuel System comprises the Main Propulsion Subsystem (MPS) and External Tank (ET), the Solid Rocket Motors (SRM), the Orbital Maneuvering System (OMS), and the Reaction Control Subsystem (RCS). This section discusses the functions, simulation, and simulation verification of each of these systems and subsystems.

4.7.3.1 Main Propulsion Subsystem and External Tank (MPS/ET)

MPS/ET Subsystem Description

The Orbiter MPS and ET are composed of the three, clustered aft Orbiter main engines, the external propellant tank (which separates from the Orbiter prior to orbital insertion), the Main Engine Controller (MEC), the pneumatic control subsystem, and assorted valves, pumps, and components.

Thrust and gimbal commands are generated by the avionics system (although the Shuttle also has a manual throttling capability) in response to sensed accelerations, computed position and velocity, and intended orbit. The MPS then provides the actual thrust.

MPS thrust is controlled by the MEC. The MEC is an electronic device installed on each main engine which, along with engine sensors, valves, spark igniters, actuators, etc., provides the following SSME functions:

- Sensor excitation and valve/igniter control signals
- Closed-loop control of thrust and propellant mixture ratio
- Engine start and shutdown sequencing
- Engine-ready monitoring
- Engine limit detection
- On-board checkout
- Vehicle/engine interfaces for (1) receiving electrical power and memory data words, and (2) transmission of engine status, performance, and maintenance data.

The MEC provides continuously variable thrust between the Minimum Power Level (MPL) and the Emergency Power Level (EPL) - 50% and 109% of nominal, respectively - as commanded by the vehicle. The thrust control loop contains control logic

to receive thrust level commands from the Orbiter General Purpose Computers (GPC) through the Engine Interface Unit (EIU). The pneumatic control assembly is then directed by the MEC to position the fuel preburner oxidizer valve and oxidizer preburner oxidizer valve to achieve the commanded thrust as indicated by the main combustion chamber combustion pressure measurements (Ref. 26).

Figure 4.7-40 depicts the MPS and ET, showing the separation disconnects as well as the ground servicing interface and the ET pressurization subsystems. Figure 4.7-41 illustrates the MPS and ET Helium subsystem which is utilized for MPS and ET pressurization and the propellant feed system. A more detailed illustration of the plumbing, valves, hydraulic and pneumatic control subsystem, and pressurant subsystem for one typical engine is shown in Figure 4.7-42. Figure 4.7-43 is a sketch of the basic MPS and ET configuration. Figures 4.7-44 and 4.7-45 illustrate the basic onboard displays and controls for the subsystems, which provide the crew interface to the subsystems via the avionics interface (Ref. 20).

MPS/ET Simulation Module Description and Performance Parameters

The MPS and ET simulation module will provide the capability to simulate the MPS and ET and their separation interface throughout the nominal operating ranges of the subsystem, as well as reflecting the influence resulting from other systems and subsystems. (An example of the subsystems interaction and influence is that of the propellant monitoring subsystem interface with the subsystems effecting the propellant usage.) The propellant monitoring subsystem, in conjunction with the MEC, controls the flow rates and mixture ratio of propellants to the engines to deliver the commanded thrust and maintain efficient combustion, while at the same time maintaining the ratio of propellants remaining in the tanks within the proper range.

The fuel and oxidizer volumes will be dynamically simulated for all missions with the associated sensors, control valves, and associated components. The simulation module capabilities will encompass the nominal operational limits, the blue line and red line limits, and the subsystem design limits. The dynamics of the propellant monitoring and control subsystem are also influenced by the burn mixture ratios of the three engines, the flow rates, initial fill quantities, topping characteristics, and the relief characteristics of the fuel and oxidizer valves,

4.7-104

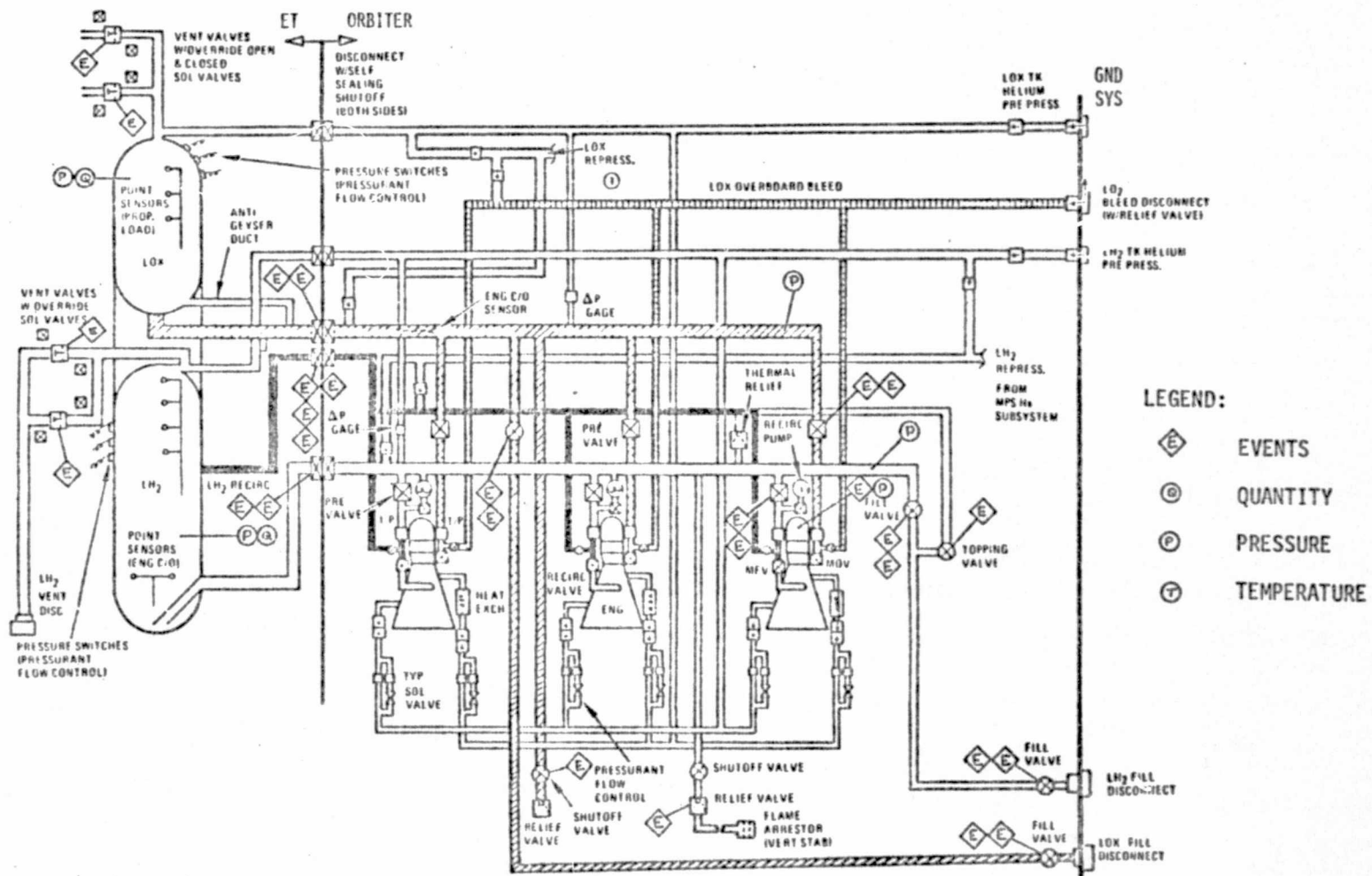


FIGURE 4.7-40 MAIN PROPULSION SUBSYSTEM SCHEMATIC

MDC E1136
27 January 1975

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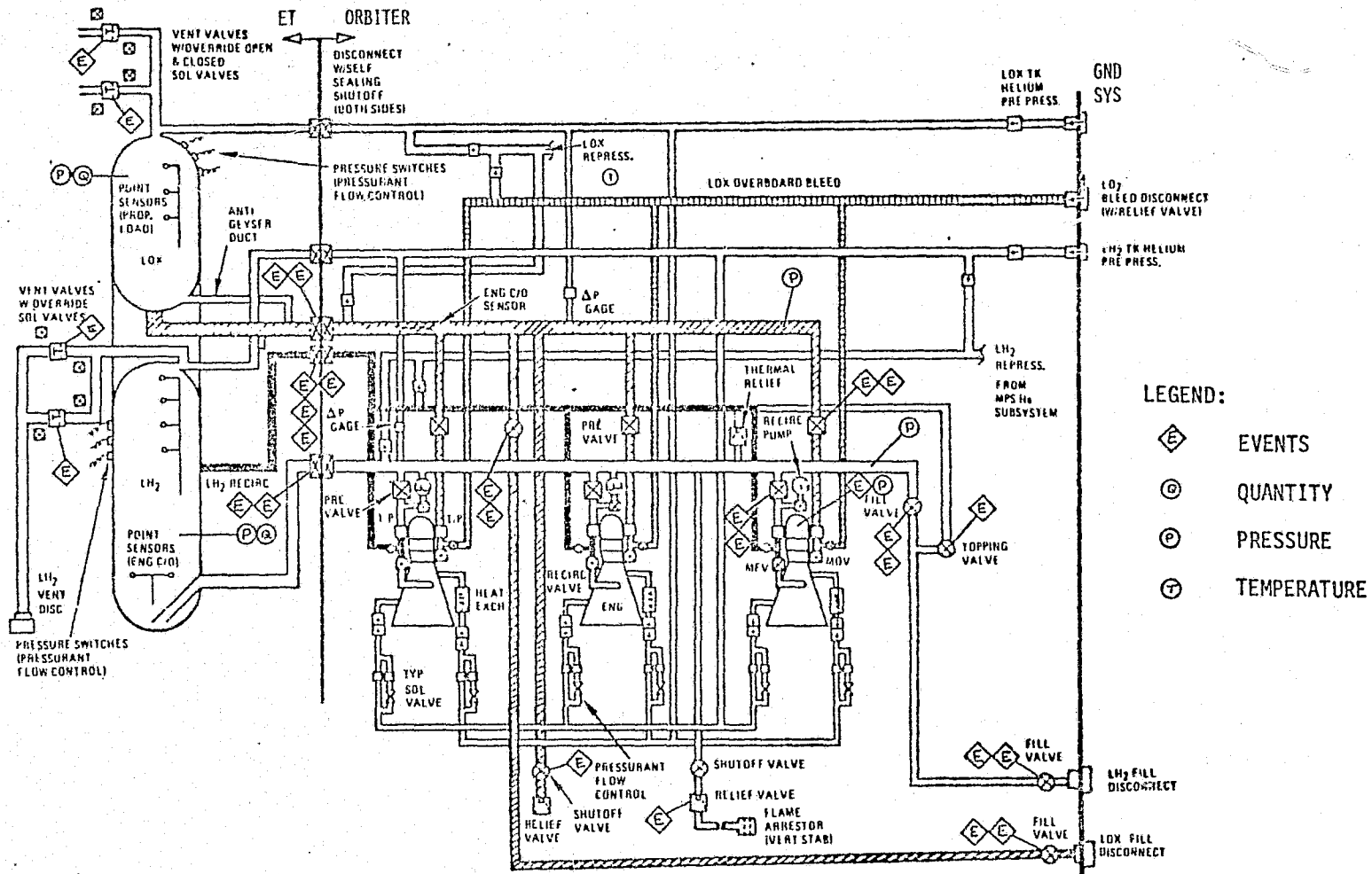


FIGURE 4.7-40 MAIN PROPULSION SUBSYSTEM SCHEMATIC

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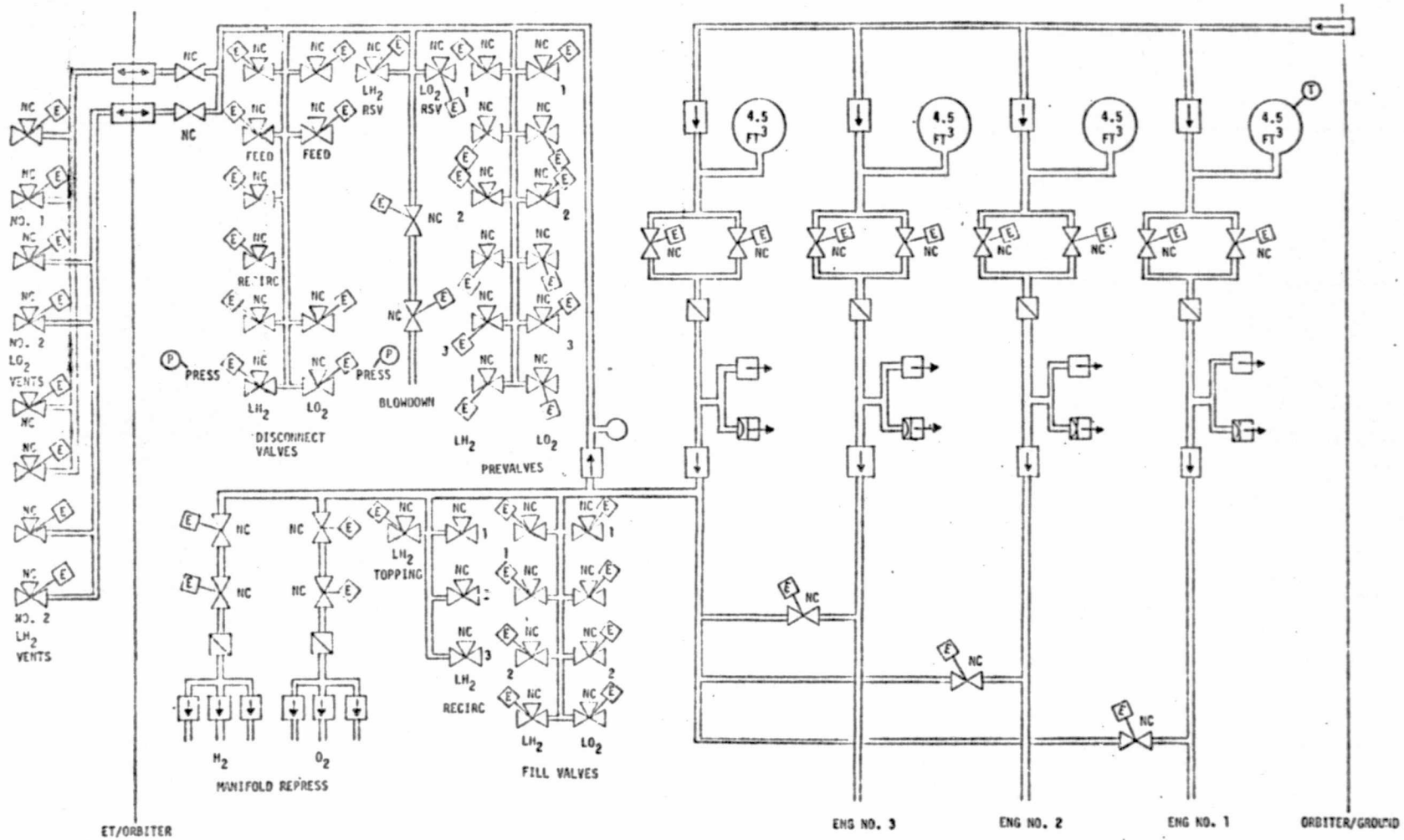


FIGURE 4.7-41 MAIN PROPULSION HELIUM SYSTEM

4.7-105

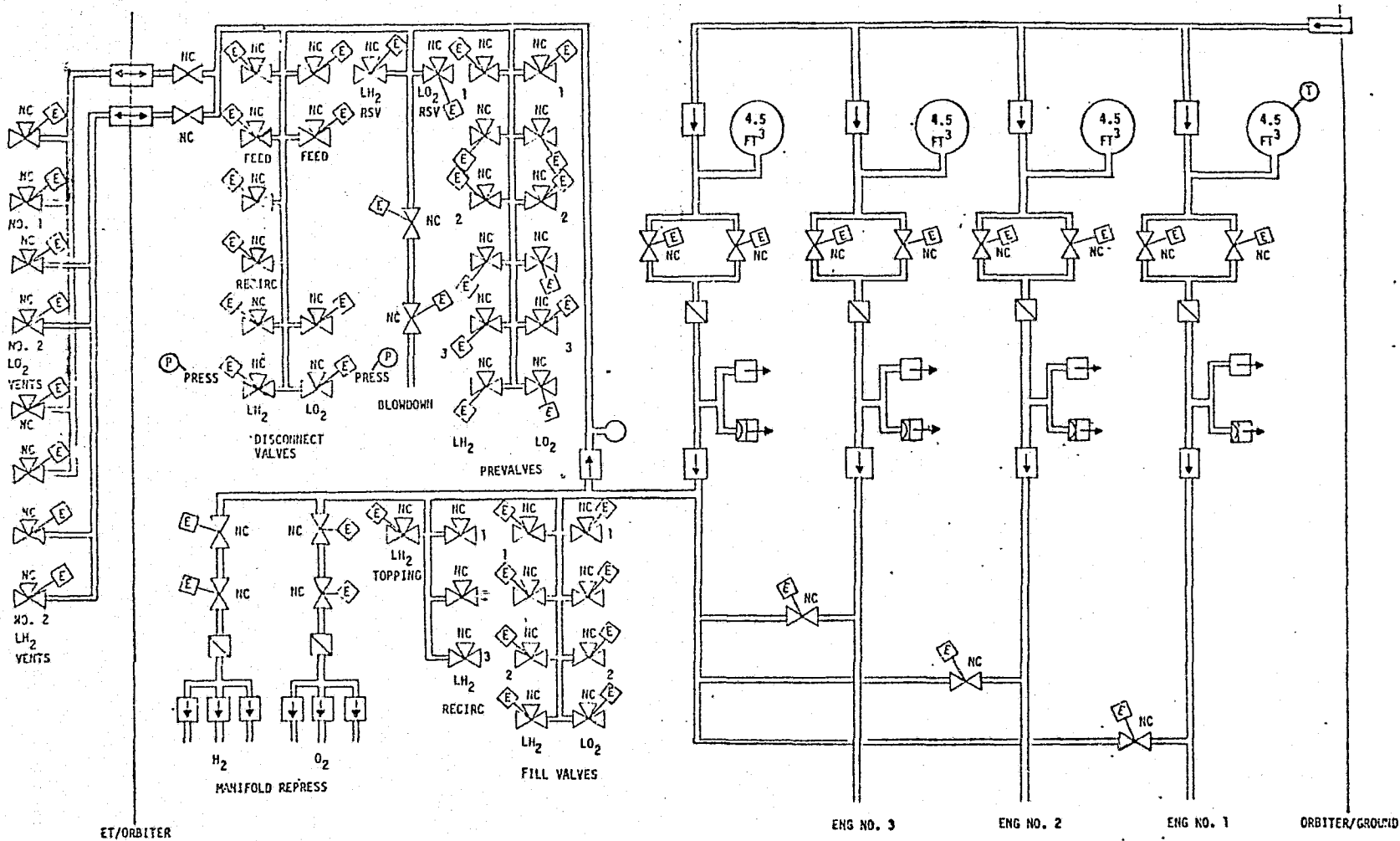


FIGURE 4.7-41 MAIN PROPULSION HELIUM SYSTEM

4.7-106

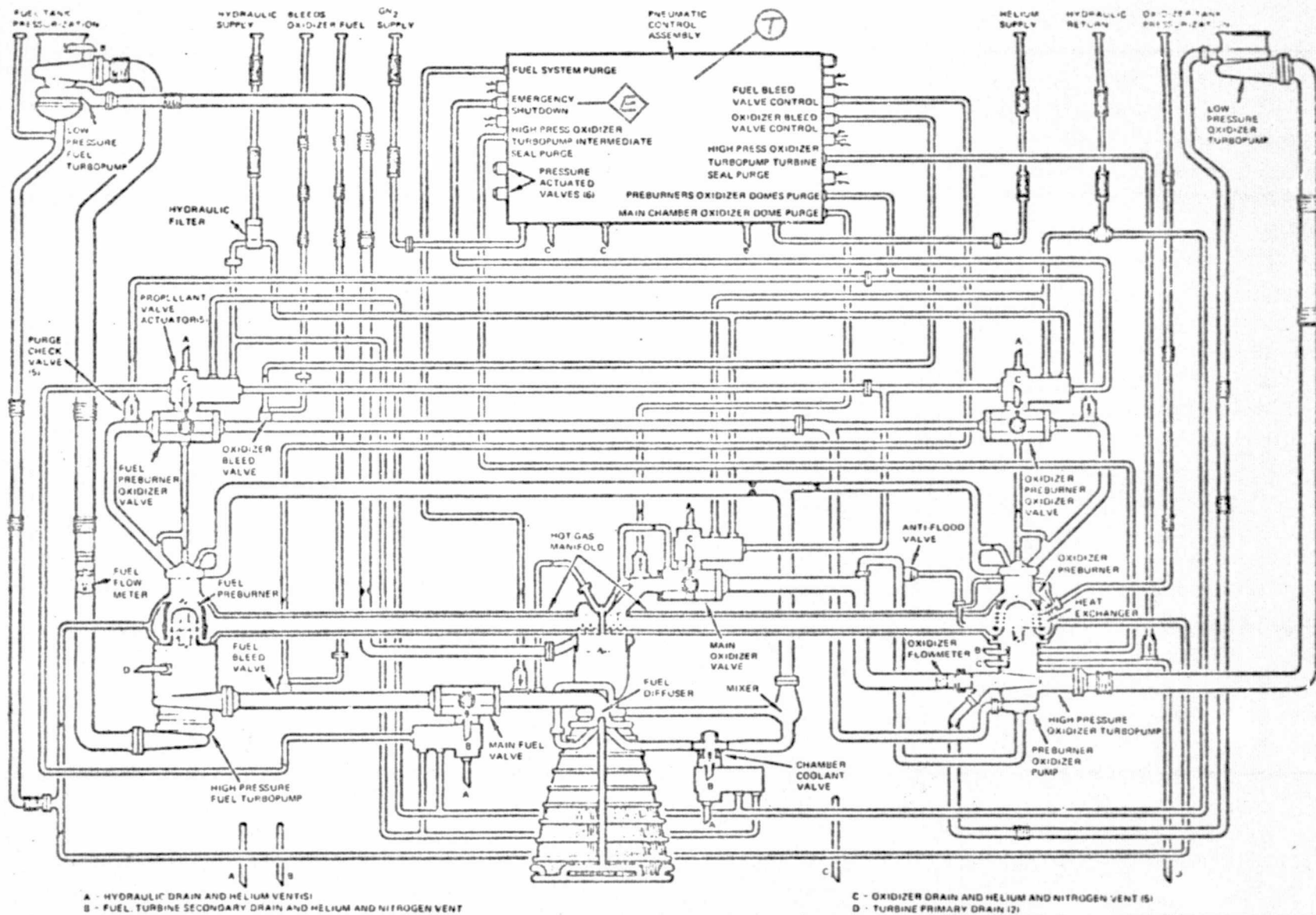


FIGURE 4.7-42 SSME SCHEMATIC

4.7-106

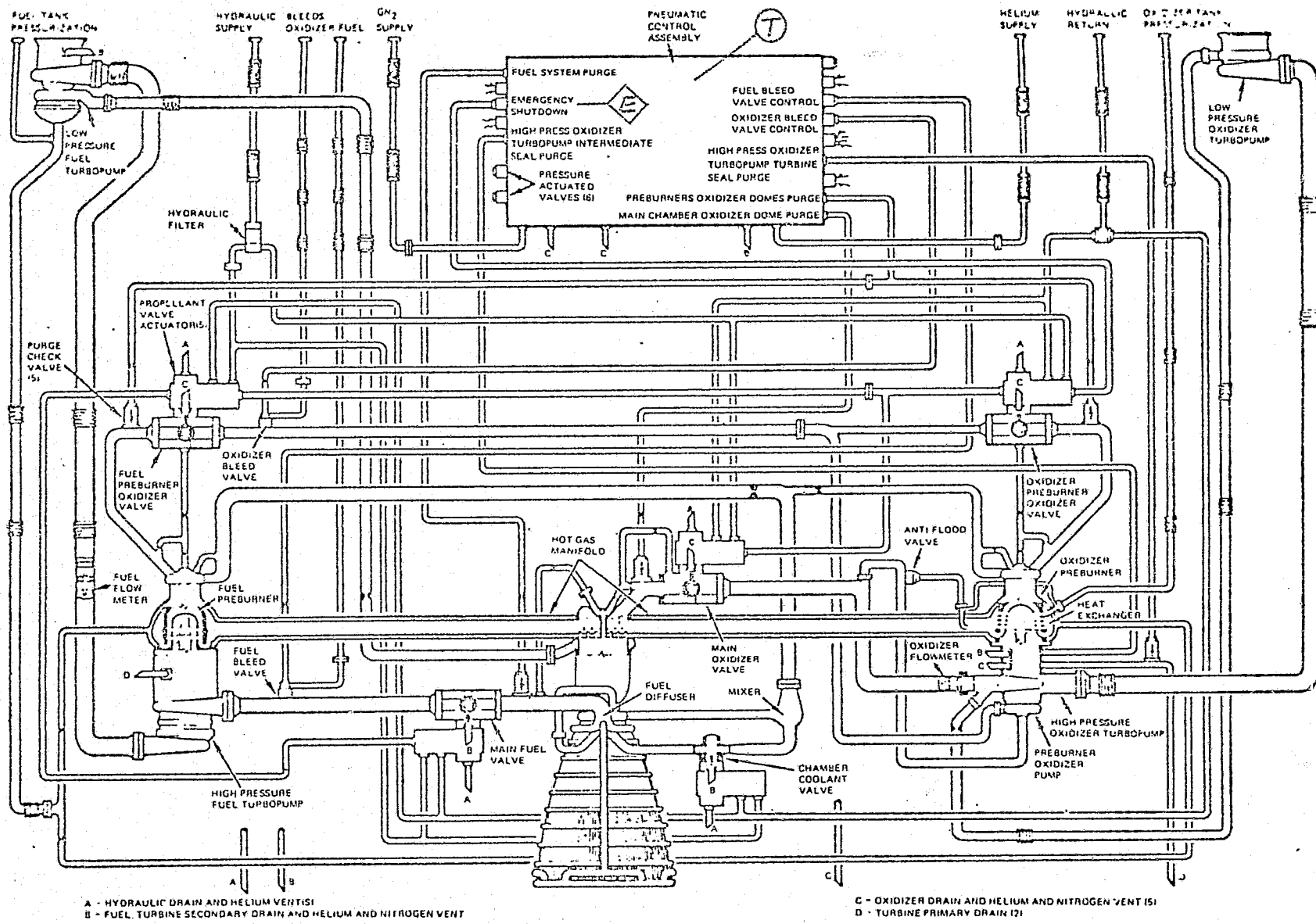


FIGURE 4.7-42 SSME SCHEMATIC

4.7-107

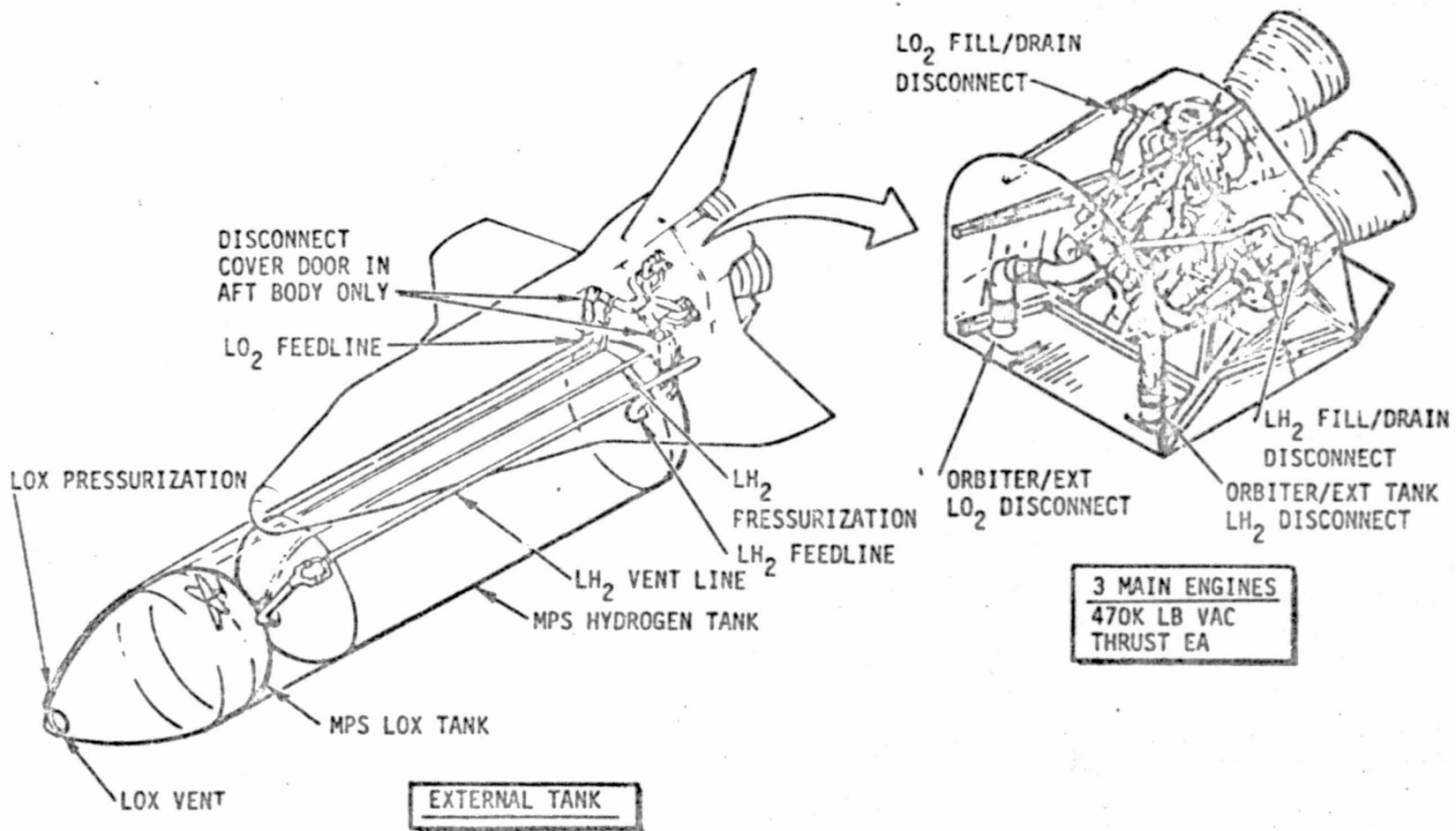


FIGURE 4.7-43 ORBITER MAIN PROPULSION SUBSYSTEM

4.7-107

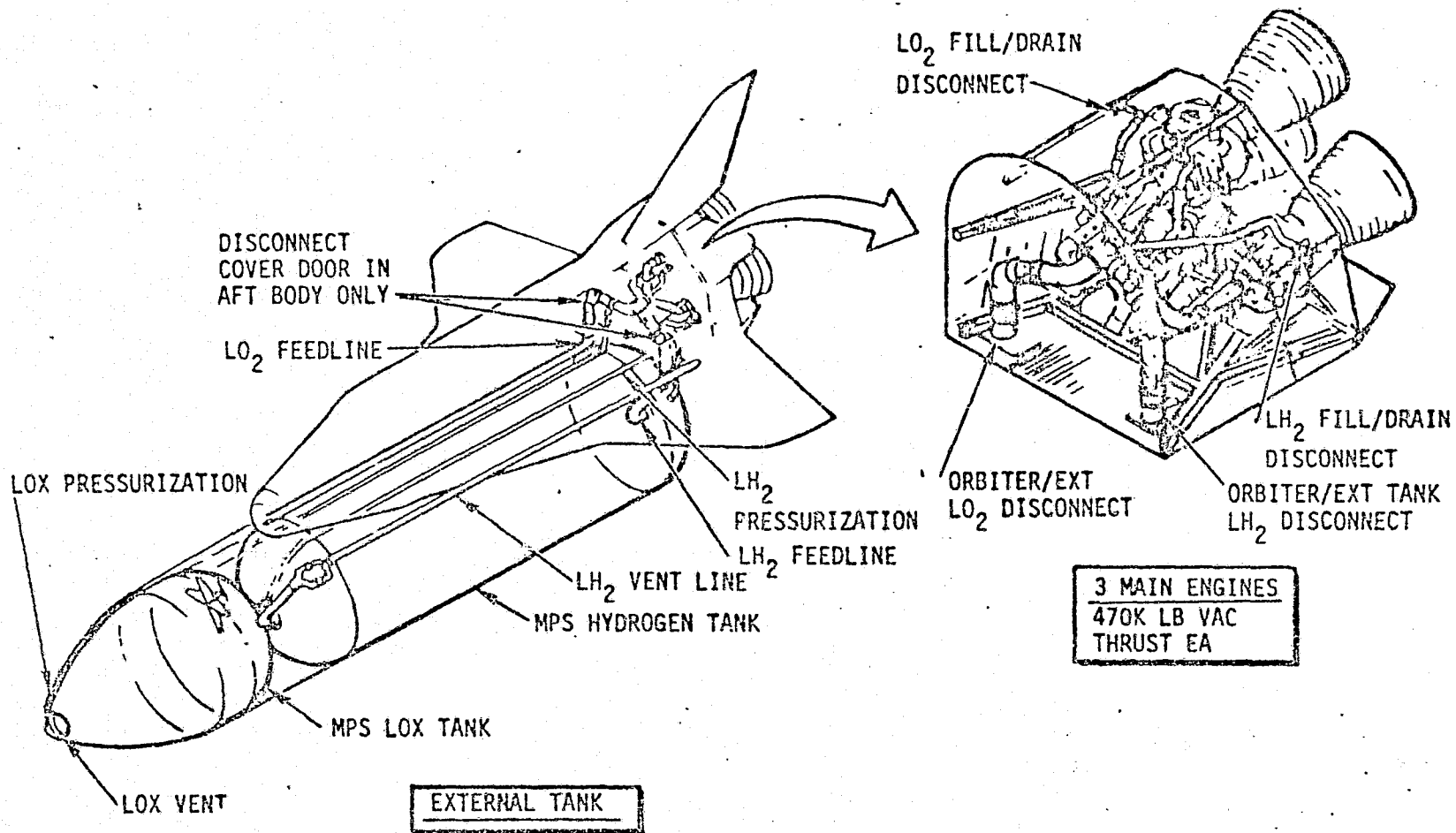


FIGURE 4.7-43 ORBITER MAIN PROPULSION SUBSYSTEM

4.7-108

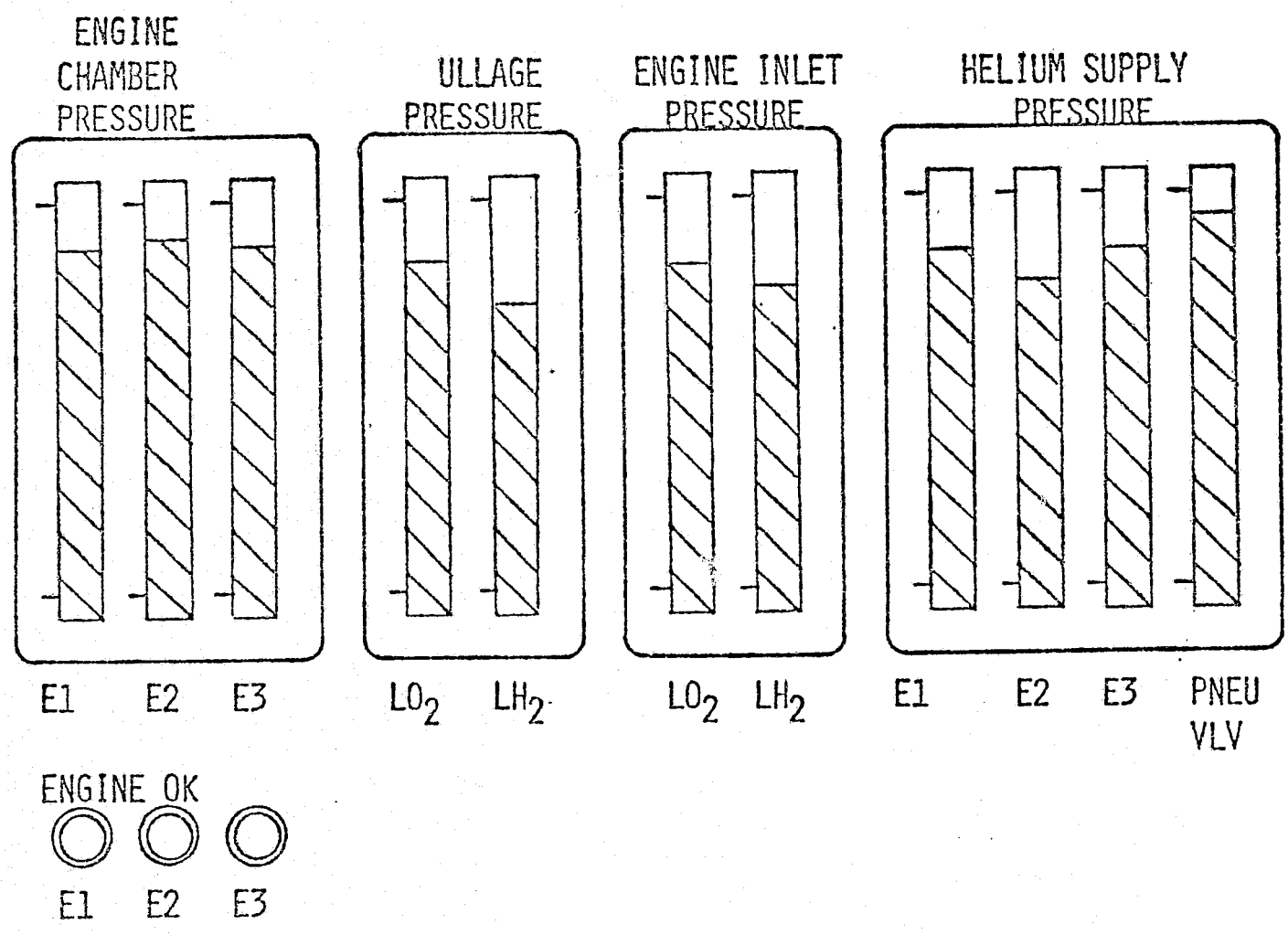


FIGURE 4.7-44 MAIN PROPULSION SUBSYSTEM DEDICATED DISPLAYS

4.7-109

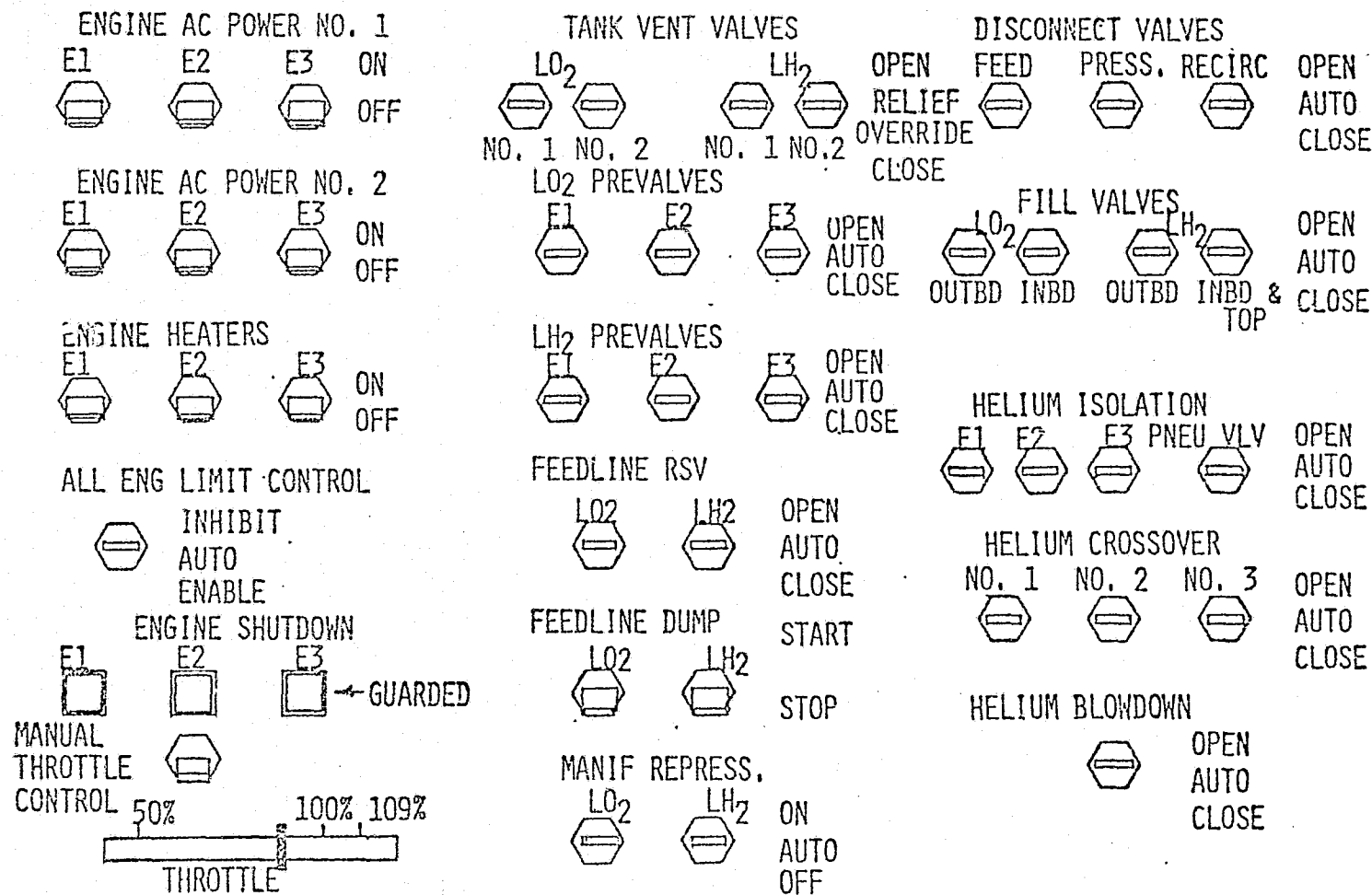


FIGURE 4.7-45 MAIN PROPULSION SUBSYSTEM MANUAL CONTROLS

as well as the burn characteristics of the engines within their design profile boxes and the associated valves, and plumbing configurations for the specific test conditions. Body bending and fuel slosh effects (simulated in the vehicle dynamics module) will be incorporated as appropriate into the MPS/ET simulation module.

The performance parameters associated with each subsystem are located on each illustration and listed in Tables 4.7-10 and 4.7-11. The performance parameters are located on only one engine in detail and are representative of all three. Table 4.7-11 reflects the onboard software parameters. These parameters are transmitted via the engine PCM system and recorded on the maintenance recorder as well as routed to the G&N computer and downlinked via the digital downlink. Reference 21 was used as the prime source for the information in the tables. This system has a high proportion of "critical" performance parameters due to its short operating time, and the critical nature of its functions to vehicle/crew survival and mission success. Figure 4.7-46 depicts the MPS/ET simulation module interfaces with other systems simulation modules.

MPS/ET Reference Data Sources and Data Formats

Reference data from an external source must be generated to verify the MPS/ET simulation module. The specific verification conditions determine the level of reference data fidelity required. This section describes two reference data sources which can be used as reference modules. The first reference module presented is a high-fidelity simulation of the MPS/ET. The second is a lower fidelity representation which provides less detailed reference data. Both models have applications in simulation verification.

MPS/ET High-Fidelity Reference Module - Reference 24 describes a very detailed SSME math model developed by Rocketdyne and designated as the RL00001 model. This digital model is provided for use as a baseline standard to verify other SSME simulation models in the regions of start, throttling, and cutoff operations. Both extended limits and off-nominal operating conditions for the SSME system are simulated. Also modeled in this simulation are SSME turbopump, valve, and propellant feed line dynamics along with MEC functions.

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TABLE 4.7-10 MPS/ET MODULE PARAMETERS

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	INIT	
EMERG SHUTDOWN INHIBIT CMD/RESP ^b		ON	EVENT	I/CP ^b
AC POWER NO 1 ON CMD /RESP		ON	EVENT	I/CP
HEATER POWER ON CMD /RESP		ON	EVENT	I/P
CONTROLLER TEMP	-200	+400	DEG F	P
LH2 PREVALVE OPEN CMD /RESP		ON	EVENT	I/CP
LH2 PREVALVE CLOSE CMD /RESP		ON	EVENT	I/CP
LO2 PREVALVE OPEN CMD /RESP		ON	EVENT	I/CP
LO2 PREVALVE CLOSE CMD /RESP		ON	EVENT	I/CP
HELIUM BOTTLE TEMP	- 65	+500	DEG F	CP
HE ISLN VLV 1 OPEN CMD/RESP		ON	EVENT	I/P
HE ISLN VLV 2 OPEN CMD /RESP		ON	EVENT	I/P
MPS-LH2 INBD FILL VALVE OPEN CMD /RESP		ON	EVENT	I/CP
MPS-LH2 INBD FILL VALVE CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-LH2 OUTBD FILL VALVE OPEN CMD/RESP		ON	EVENT	I/CP
MPS-LH2 OUTBD FILL VALVE CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-LH2 RECIRC DISC VLV OPEN CMD/RESP	ON	OFF	EVENT	I/CP
MPS-LH2 RECIRC DISC VLV CLOSED CMD/RESP	ON	OFF	EVENT	I/CP
MPS-LH2 RECIRC DISC VLV OPEN CMD /RESP		ON	EVENT	I/CP
MPS-LH2 RECIRC DISC VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-LH2 FEED DISC VLV OPEN CMD/RESP		ON	EVENT	I/CP
MPS-LH2 FEED DISC VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-LH2 FLOW RATE			LB/SEC	P
MPS-LH2 MANIF REPRES NO 1 OPEN CMD/RESP		ON	EVENT	I/P
MPS-LH2 MANIF REPRES NO 2 OPEN CMD/RESP		ON	EVENT	I/P
MPS-LH2 FDLN RELIEF SOL CLOSE CMD/RESP		ON	EVENT	I/P
MPS-LH2 TOPPING VLV OPEN CMD/RESP		ON	EVENT	I/P
MPS-LH2 QUANTITY			LB	P
MPS-GH2 DISCONNECT PRESSURE	0	1000	PSIA	CP
MPS-GH2 PRESS DISC VLV OPEN CMD/RESP		ON	EVENT	I/CP
MPS-GH2 PRESS DISC VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-LO2 INBOARD FILL VLV OPEN CMD/RESP		ON	EVENT	I/CP

TABLE 4.7-10 (CONTINUED)

MDC E1136
27 January 1975

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
MPS-L02 INBOARD FILL VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-L02 OUTBD FILL VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-L02 OUTBD FILL VLV OPEN CMD/RESP		ON	EVENT	I/CP
MPS-L02 FEED DISC VLV OPEN CMD/RESP		ON	EVENT	I/CP
MPS-L02 FEED DISC VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-L02 FLOW RATE			LB/SEC	P
MPS-L02 MANIF REPRES NO 1 OPEN CMD/RESP		ON	EVENT	I/CP
MPS-L02 MANIF REPRES NO 2 OPEN CMD/RESP		ON	EVENT	I/CP
MPS-L02 FDLN RELIEF SOL CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-L02 QUANTITY			LB	P
MPS-G0X DISCONNECT PRESSURE	0	1000	PSIA	CP
MPS-G02 PRESS DISC VLV CLOSE CMD/RESP		ON	EVENT	I/CP
MPS-G02 PRESS DISC VLV OPEN CMD/RESP		ON	EVENT	I/CP
MPS-PNEUMATIC VLV HE SUPPLY PRESS	0	5000	PSIA	CP
MPS-PNEUMATIC VLV HE BOTTLE TEMP	-65	+500	DEG F	CP
MPS-PNEU VLV HE RGLTR OUTLET PRESS	0	1000	PSIA	CP
MPS-PNEU VLV HE ISLN NO 1 OPEN CMD/RESP		ON	EVENT	I/P
MPS-PNEU VLV HE ISLN NO 2 OPEN CMD/RESP		ON	EVENT	I/P
MPS-PNEU CROSSOVER NO 1 OPEN CMD/RESP		ON	EVENT	I/P
MPS-PNEU CROSSOVER NO 2 OPEN CMD/RESP		ON	EVENT	I/P
MPS-PNEU CROSSOVER NO 3 OPEN CMD/RESP		ON	EVENT	I/P
MPS-HE SUP BLOWDOWN NO 1 OPEN CMD/RESP		ON	EVENT	I/P
MPS-HE SUP BLOWDOWN NO 2 OPEN CMD/RESP		ON	EVENT	I/P
ET-LH2 ULLAGE PRESS NO 1	0	50	PSIA	P
ET-LH2 ULLAGE PRESS NO 2	0	50	PSIA	P
ET-LH2 ULLAGE PRESS NO 3	0	50	PSIA	P
ET-LH2 VENT VLV NO 1 CLOSE CMD/RESP		ON	EVENT	I/CP
ET-LH2 VENT VLV NO 1 OPEN CMD/RESP		ON	EVENT	I/CP
ET-LH2 VENT VLV NO 2 CLOSE CMD/RESP		ON	EVENT	I/CP
ET-LH2 VENT VLV NO 2 OPEN CMD/RESP		ON	EVENT	I/CP
ET-LOX ULLAGE PRESSURE NO 1	0	30	PSIA	P
ET-LOX ULLAGE PRESSURE NO 2	0	30	PSIA	P
ET-LOX ULLAGE PRESSURE NO 3	0	30	PSIA	P

TABLE 4.7-10 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
ET-LOX VENT VLV NO 1 CLOSE CMD /RESP		ON	EVENT	I/CP
ET-LOX VENT VLV NO 1 OPEN CMD /RESP		ON	EVENT	I/CP
ET-LOX VENT VLV NO 2 CLOSE CMD /RESP		ON	EVENT	I/CP
ET-LOX VENT VLV NO 2 OPEN CMD /RESP		ON	EVENT	I/CP
MPS-MANUAL THROTTLE ENABLED CMD/RESP		ON	EVENT	I/CP
MPS-MANUAL THROTTLE POSITION	50	109	%	I
MPS CHAMBER PRESSURE			PSIA	P
MPS THRUST			LB	CP

^a P - PERFORMANCE PARAMETER

CP - CRITICAL PERFORMANCE
PARAMETER

I - INPUT

^b INDICATES 2 PARAMETERS (COMMAND AND RESPONSE)

TABLE 4.7-11 MPS/ET ON BOARD PROCESSED PARAMETERS

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
FAILURE IDENT DATA WORD-6				P ↑
TEST DATA WORD 6 DATA WORD-7				
THRUST DW-5				
MCC PRESS DW-9-10-11-12				
OX TR PRESURNT PRESS DW-64-65				
HPFTP SHAFT SPEED DW-43				
HPFTP DISCH PRES DW19 THRU-22				
LPFTP DISCH PRESS DW36 THRU-39				
HPOTP SHAFT SPEED DW-57				
HPOTP DISCH TEMP DW-54				
HPOTP DISCH PRESS DW23 THRU-26				
HPOTP TURBO DISCH TEMP DW-59				
HPOTP INTMD SL PGE PRES DW-75				
LPOTP DISCH PRES DW48 THRU-51				
ENGINE STATUS DW-3				
LH2 INLET PRESS	0	200	PSIA	
LH2 INLET TEMP	-430	-379	DEG F	
LH2 PREVALVE OPEN	ON	OFF	EVENT	
LOX INLET PRESS	0	+400	PSIA	
LOX INLET TEMP	-320	-270	DEG F	
LOX PREVALVE OPEN	ON	OFF	EVENT	
HELIUM SUPPLY PRESS	0	5000	PSIA	
HE FGLTR OUTLET PRESS	0	1000	PSIA	
MPS-LH2 INBOARD FILL VLV CLOSED	ON	OFF	EVENT	
MPS-LH2 OUTBD FILL VLV CLOSED	ON	OFF	EVENT	
MPS-LH2 TANK DISC VLV OPEN	ON	OFF	EVENT	
MPS-LH2 FEED DISC VLV OPEN	ON	OFF	EVENT	
MPS-LH2 ENG MANIFOLD PRESSURE	0	200	PSIA	
MPS-LH2 TOPPING VLV CLOSED	ON	OFF	EVENT	
MPS-LOX INBD FILL VLV CLOSED	ON	OFF	EVENT	
MPS-LOX OUTBD FILL VLV CLOSED	ON	OFF	EVENT	
MPS-LOX TANK PRESS DISC VLV OPEN	ON	OFF	EVENT	
LPFTP DISCH TEMP DW-40				↓ P P

TABLE 4.7-11 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
MPS-LOX FEED DISC VLV OPEN	ON	OFF	EVENT	P ↑ ↓ P
MPS-LOX ENGINE MANIFOLD PRESSURE	0	400	PSIA	
MPS-LOX FEEDLINE RELIEF SOV CLOSED	ON	OFF	EVENT	
MPS-LOX LOW LEVEL LIQUID SNSR NO 1	DRY	WET	EVENT	
MPS-LOX LOW LEVEL LIQUID SNSR NO 2	DRY	WET	EVENT	
MPS-LOX LOW LEVEL LIQUID SNSR NO 3	DRY	WET	EVENT	
MPS-LOX LOW LEVEL LIQUID SNSR NO 4	DRY	WET	EVENT	
ET-LH2 LOW LEVEL LIQ SENSOR NO 1	WET	DRY	EVENT	
ET-LH2 LOW LEVEL LIQ SENSOR NO 2	WET	DRY	EVENT	
ET-LH2 LOW LEVEL LIQ SENSOR NO 3	WET	DRY	EVENT	
ET-LH2 LOW LEVEL LIQ SENSOR NO 4	WET	DRY	EVENT	

^a P - PERFORMANCE PARAMETER
CP - CRITICAL PERFORMANCE PARAMETER

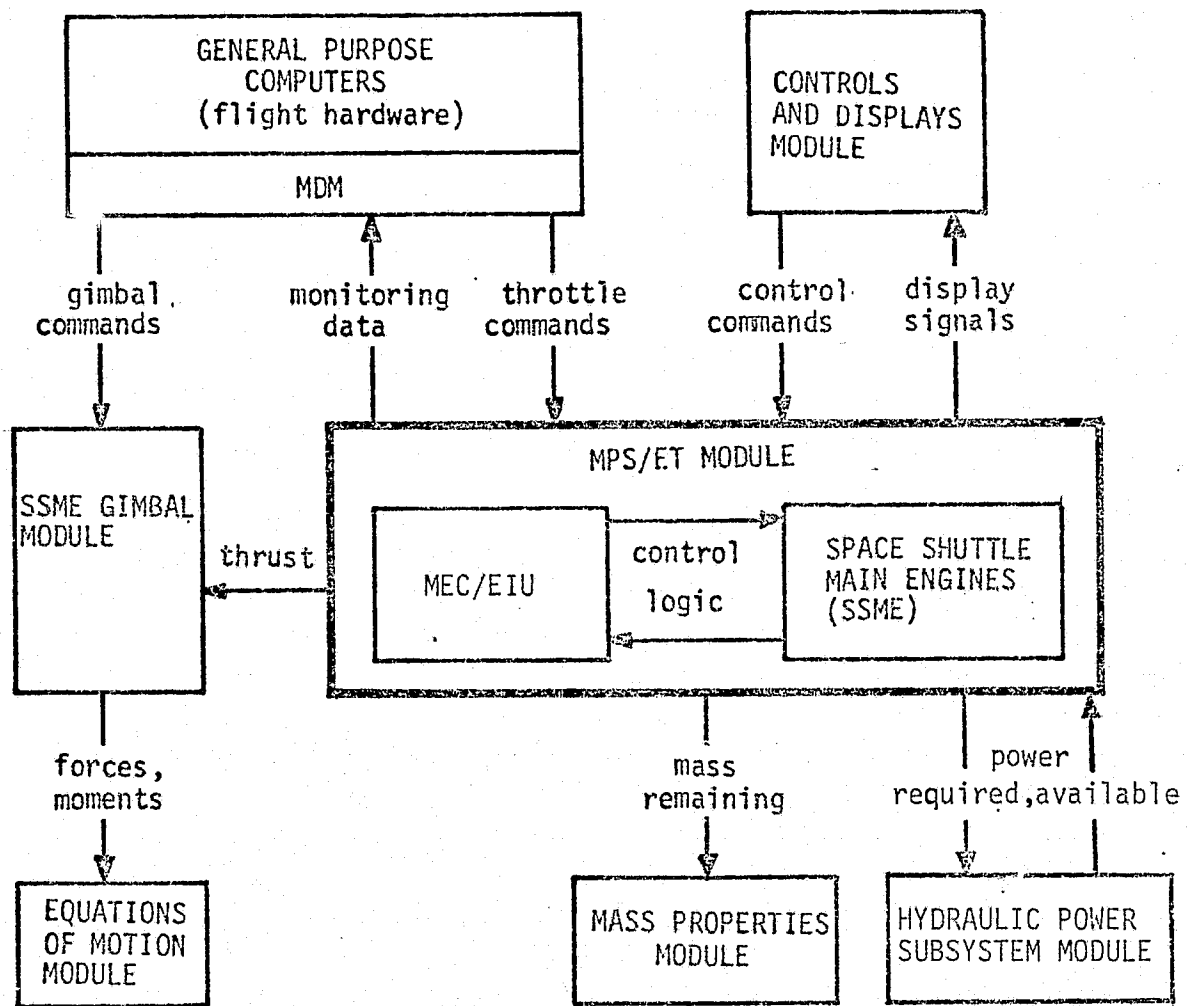


FIGURE 4.7-46 MPS/ET SIMULATION MODULE INTERFACES

Figure 4.7-48 depicts an "intra-module" functional flow diagram for the major subroutines as well as the primary component process elements used in each of the major subroutines. The main program calls all computational subroutines and controls the model input/output. The subroutine names and their functions are listed in Table 4.7-12. Reference 24 provides a program listing and the user information source.

Complete simulation of the MPS/ET with this digital model requires that the ET and helium supply functions be incorporated. These modifications would consist primarily of simple mass decrements from launch conditions based upon fuel and oxidizer flowrates computed in the RL00001 model. Helium supply for the pneumatic control assembly would be similarly decremented.

MPS/ET Low-Fidelity Reference Modules - Figure 4.7-49 (Ref. 25) describes a reference module which would provide low-detailed reference data. This level of fidelity and detail would be adequate for special simulation module verification phases. For example, it would be useful in integrating other simulation verification modules needing only its particular (functional) outputs. It might also be suitable for use with procedures simulators. The lower detailed module would be capable of generating reference data needed to verify corresponding simulation module output in a quick-look verification mode.

Inputs to this reference module consist of:

- throttling commands from guidance
- engine gimbal commands from the Thrust Vector Control System (TVCS)
- nominal vacuum thrust per engine
- atmospheric pressure
- nozzle exit area
- number of engines operating
- oxidizer/fuel mixture ratio

The outputs of this module include:

- the forces and moments acting on the Shuttle from the MPS
- amounts of fuel/oxidizer remaining
- amounts of fuel/oxidizer expended
- fuel mass flow rate

4.7-118

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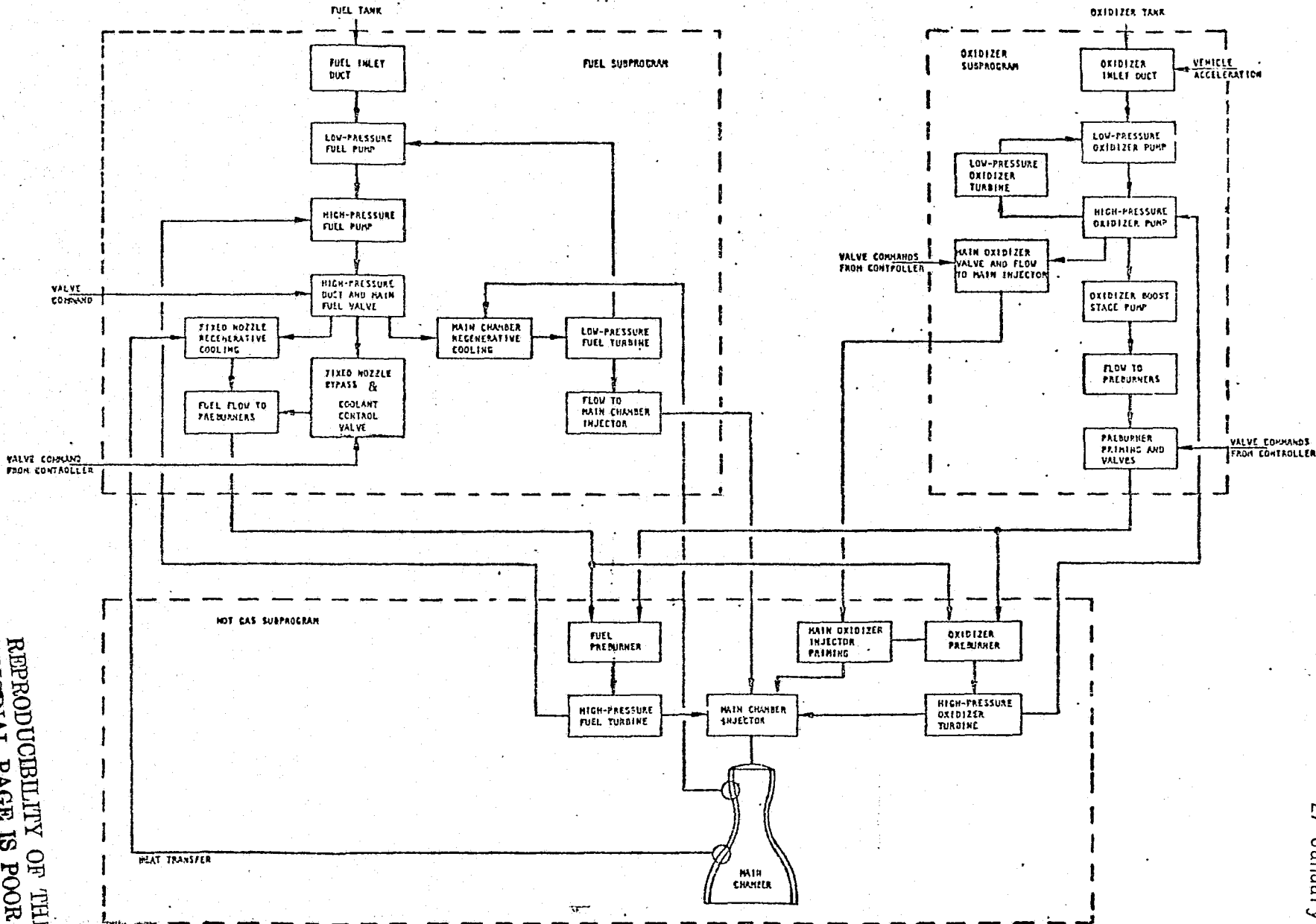
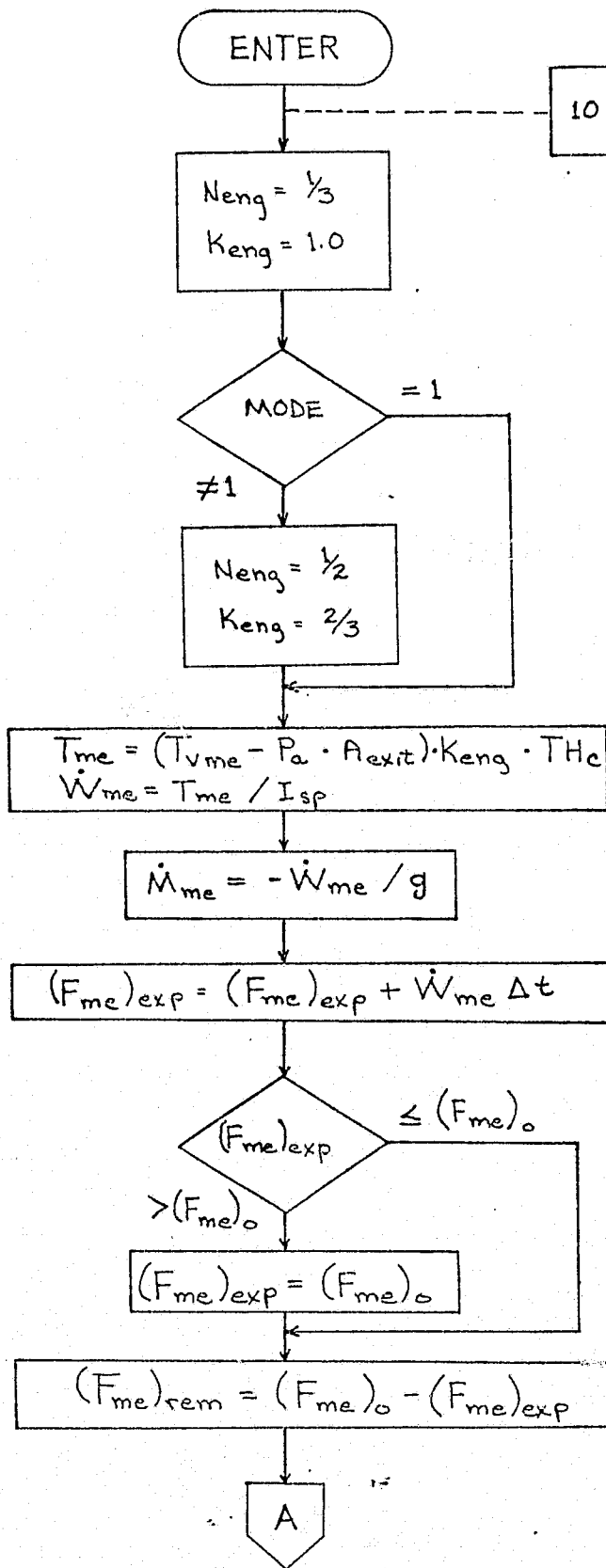


FIGURE 4.7-48. SSME REFERENCE MODULE SUBROUTINES AND ELEMENTS

TABLE 4.7-12. SSME DIGITAL MODEL SUBROUTINES

SUBROUTINE	FUNCTIONS
CNTRØL	Simulates digital controller and hydraulic actuation of engine control valves
DISPL	Generates CRT displays of computed output
EPRØP	Computes error between ideal gas behavior and real hydrogen property map
FGEN	General purpose function generator
FLØW	Computes incompressible fluid flow dynamics
FUELF	Computes fuel feed system flow and pressure dynamics
GFLØW	Computes isentropic gas flow for choked and unchoked orifices
HØTGAS	Computes engine hot gas pressure and flow dynamics
HTF	Computes hot gas side heat transfer coefficient
H2DFPE	Computes hydrogen density as a function of pressure and enthalpy
H2GAMMA	Computes hydrogen specific heat ratio as a function of pressure and temperature
IGN	Simulates ignition system transients
ØXIDF	Computes oxidizer feed system flow and pressure dynamics
PRØP	Computes hydrogen pressure and temperature as a function of density and internal energy
TRBTRQ	Simulates hot gas turbine dynamics
DISPL2	Generates CRT displays of computed output



Set internal constants based on engine mode:
 MODE = 1
 - all engines on
 MODE ≠ 1
 - one engine failed

Compute main engines' throttled thrust and fuel flow

Compute main engine mass flow rates

Compute fuel expended and fuel remaining for main engines

FIGURE 4.7-49. MPS/ET REFERENCE MODULE FLOW DIAGRAM

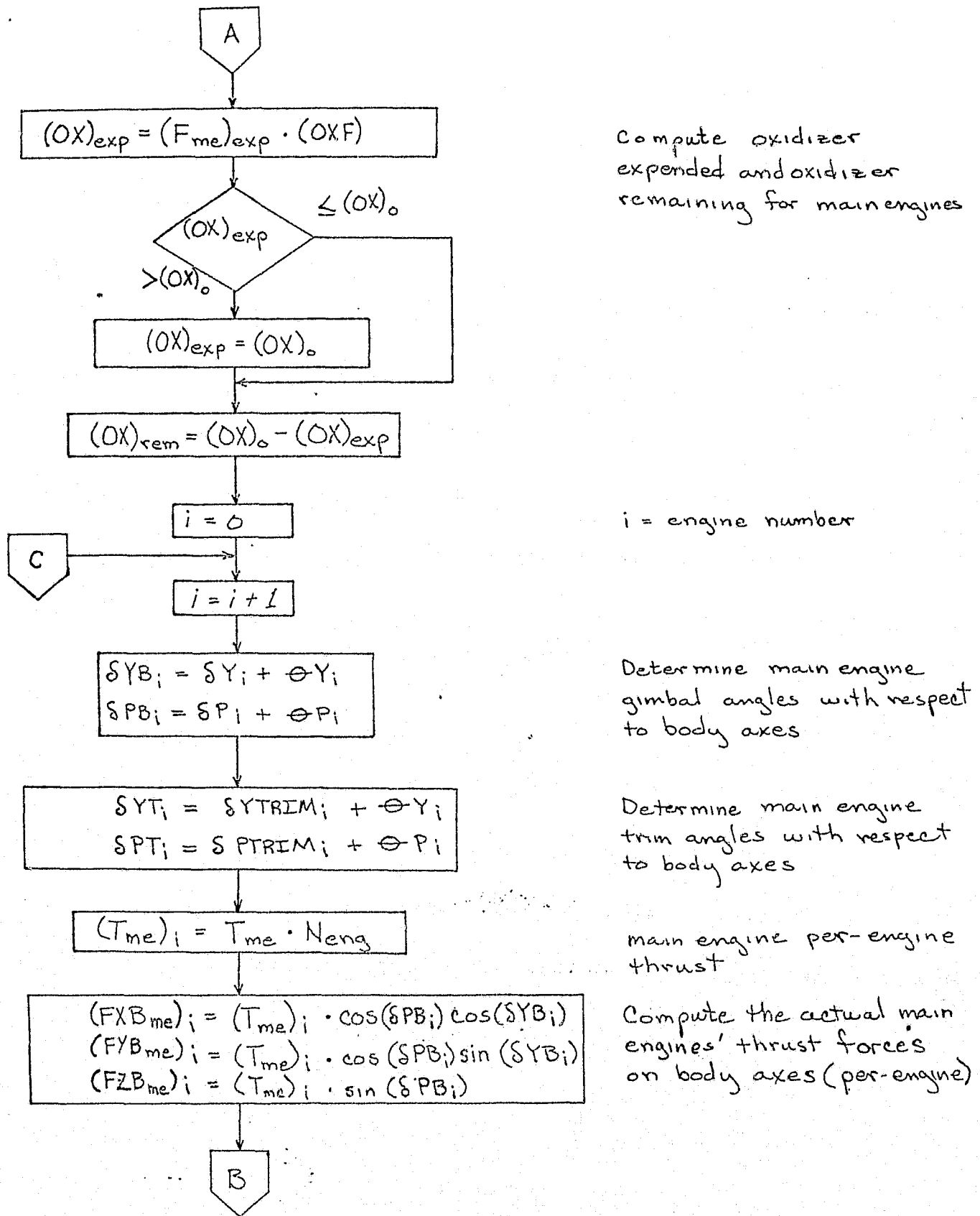


FIGURE 4.7-49. (CONTINUED)

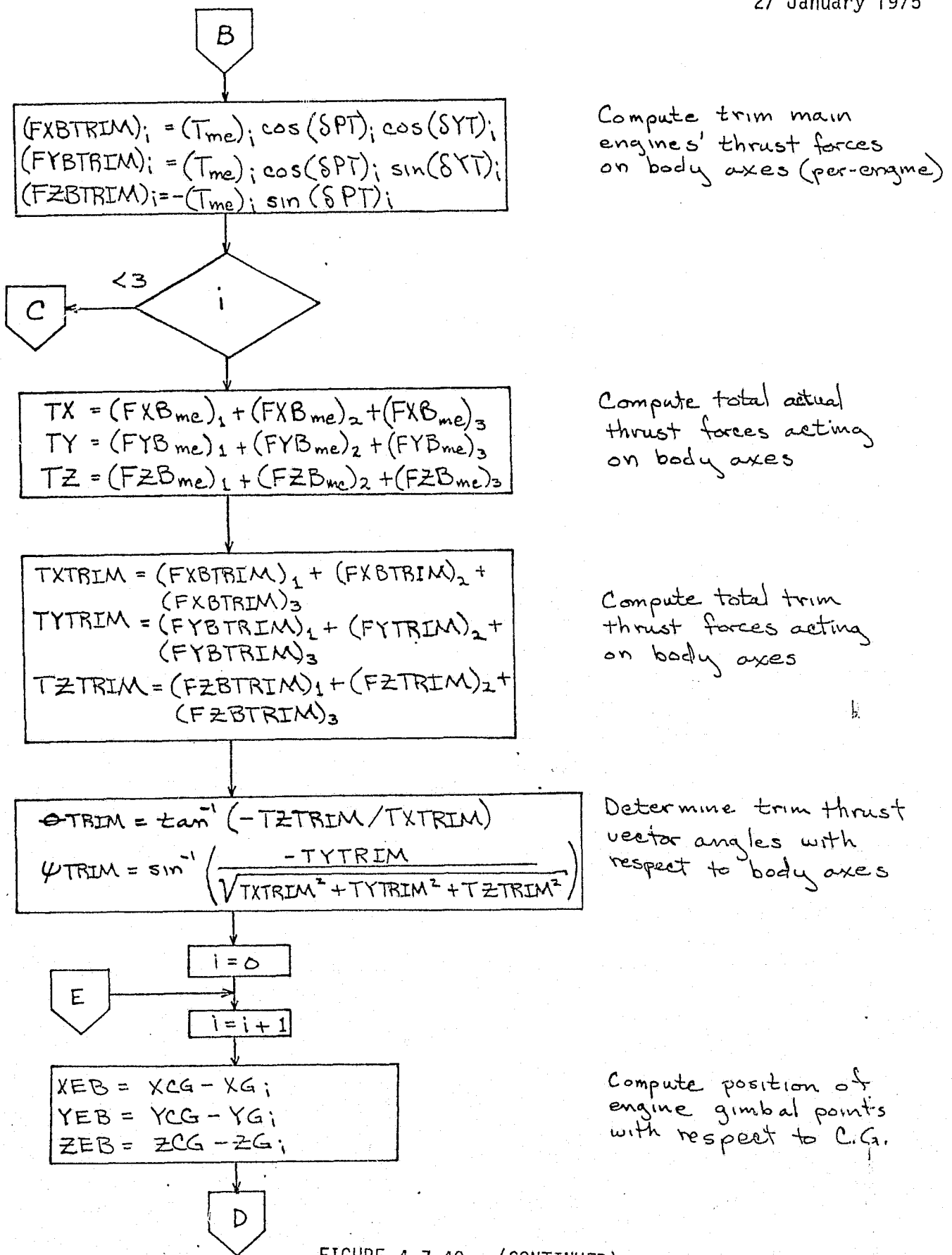
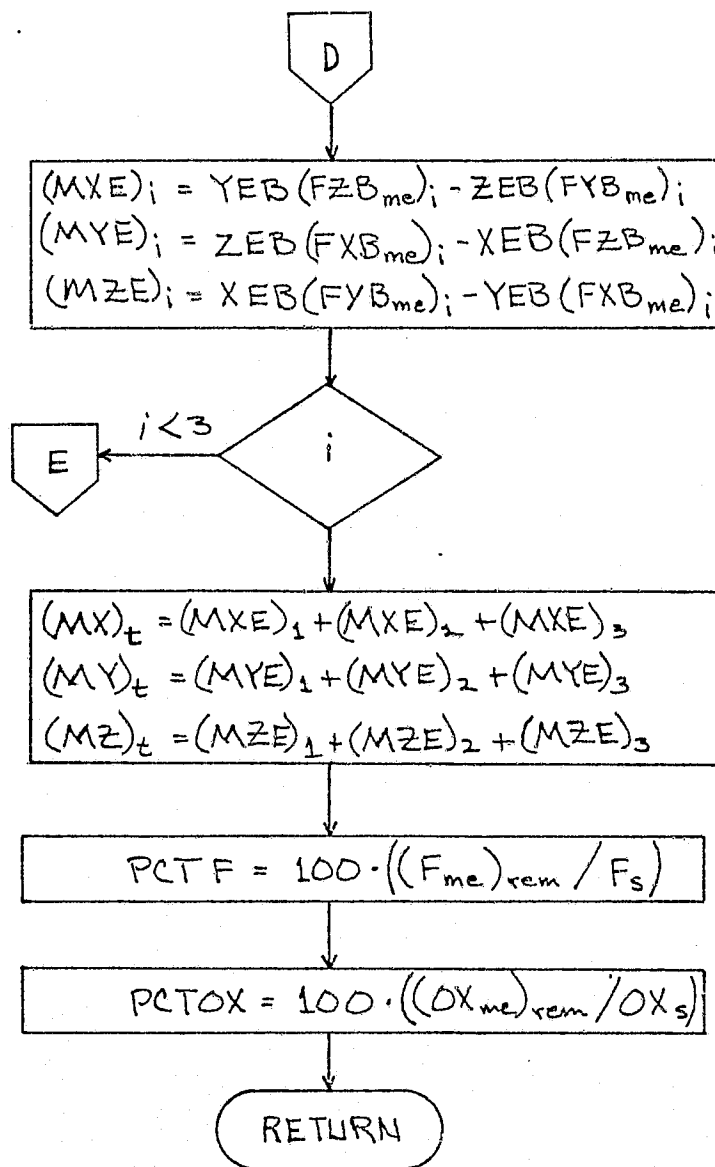


FIGURE 4.7-49. (CONTINUED)



Compute moments on body from each engine

Compute total thrust moments acting on body

Calculate percent main engine fuel remaining

Calculate percent main engine oxidizer remaining

FIGURE 4.7-49. (CONTINUED)

LEGEND

VARIABLE	FUNCTION	TYPE ^a
\dot{M}_{me}	Main engines mass flow rate (slugs/sec)	0
N_{eng}	Internal constant (=1/3 of MODE \neq 1; = 1/2 if MODE = 1)	
P_a	Ambient pressure (psf)	I
TH_c	Throttle command	I
T_{me}	Main engine thrust (lbs)	
$(T_{me})_i$	Main engine thrust for engine i (lbs)	
T_{vme}	Main engine vacuum thrust (lbs)	DATA
$\left. \begin{matrix} TX \\ TY \\ TZ \end{matrix} \right\}$	Total thrust forces on body axes (lbs)	0
$\left. \begin{matrix} TXTRIM \\ TYTRIM \\ TZTRIM \end{matrix} \right\}$	Total trim thrust forces acting on body (lbs)	
\dot{W}_{me}	Main engine fuel flow (lbs/sec)	I
$\left. \begin{matrix} XCG \\ YCG \\ ZCG \end{matrix} \right\}$	C.G. position in Orbiter data reference plane (ft)	I
$\left. \begin{matrix} XEB \\ YEB \\ ZEB \end{matrix} \right\}$	Position of engine gimbals with respect to C.G. in body axes (ft)	
$\left. \begin{matrix} XG_i \\ YG_i \\ ZG_i \end{matrix} \right\}$	Gimbal position of engine i in Orbiter data reference planes (ft)	DATA
PCTF	Percent main engine fuel remaining	0
PCTOX	Percent main engine oxidizer remaining	0
Δt	Subroutine internal integration interval (sec)	I
δP_i	Pitch gimbal angle of engine i with respect to null (rad)	I
δPB_i	Pitch gimbal angle of engine i with respect to body axis (rad)	
δPT_i	Pitch gimbal trim angle of engine i with respect to body axis (rad)	
A_{exit}	Main engine nozzle exit area (ft ²)	I
$(F_{me})_{exp}$	Main engine fuel expended (lbs)	0
$(F_{me})_{rem}$	Main engine fuel remaining (lbs)	I
$(F_{me})_0$	Main engine fuel onboard at time = 0 (lbs)	I
F_s	Main engine fuel onboard at launch (lbs)	I

FIGURE 4.7-49. (CONTINUED)

LEGEND

VARIABLE	FUNCTION	TYPE ^a
$(OX)_{exp}$	Main engine oxidizer expended (lbs)	0
$(OX)_{rem}$	Main engine oxidizer remaining (lbs)	0
$(OX)_0$	Main engine oxidizer onboard at time = 0 (lbs)	I
OX_s	Main engine oxidizer onboard at launch (lbs)	I
$\left. \begin{matrix} (FXB_{me})_i \\ (FYB_{me})_i \\ (FZB_{me})_i \end{matrix} \right\}$	Main engine thrust forces on body axes for engine i (lbs)	0
$\left. \begin{matrix} (FXBTRIM)_i \\ (FYBTRIM)_i \\ (FZBTRIM)_i \end{matrix} \right\}$	Main engine trim thrust forces on body axes for engine i (lbs)	I
g_i	gravitational acceleration (ft/sec ²)	I
i	Main engine number = 1-upper; = 2-lower left; = 3-lower right	
I_{sp}	Specific impulse	I
K_{eng}	Ratio of number of main engines on to total	
MODE	Main engine operating mode = 1-all operating = 2-upper engine failed = 3-left engine failed = 4-right engine failed	I
$\left. \begin{matrix} (MXE)_i \\ (MYE)_i \\ (MZE)_i \end{matrix} \right\}$	Moments about body axes due to engine i (ft/lbs)	0
$\left. \begin{matrix} (MX)_t \\ (MY)_t \\ (MZ)_t \end{matrix} \right\}$	Total engine moments on body axes (ft/lbs)	0
$SPTRIM_i$	Pitch gimbal trim angle of engine i with respect to null (rad)	
SY_i	yaw gimbal angle of engine i with respect to null (rad)	I
SYB_i	yaw gimbal angle of engine i with respect to body axis (rad)	
$SYTRIM_i$	Yaw gimbal trim angle of engine i with respect to null (rad)	
$\ominus P_i$	Pitch null angle of engine i with respect to body axis (rad)	DATA
$\ominus TRIM$	Pitch angle of trim thrust vector with respect to body axes (rad)	0

FIGURE 4.7-49. (CONTINUED)

LEGEND

VARIABLE	FUNCTION	TYPE ^a
ΘY_i	Yaw null angle of engine i with respect to body axis (rad)	DATA
ψ_{TRIM}	Yaw angle of trim thrust vector with respect to body axes (rad)	0

^aI - Input

0 - Output

DATA - Data resident in program

FIGURE 4.7-49. (CONTINUED)

4.7-126

- trim thrust vector angles with respect to body axes

In developing this model it was assumed that throttling commands are generated by guidance (no manual throttle capability), no engine internal dynamics are simulated (instantaneous throttle response), and no internal SSME subsystems simulation (plumbing and valve dynamics, turbopump dynamics, internal thermodynamics). Thrust is decayed instantaneously at SSME cutoff.

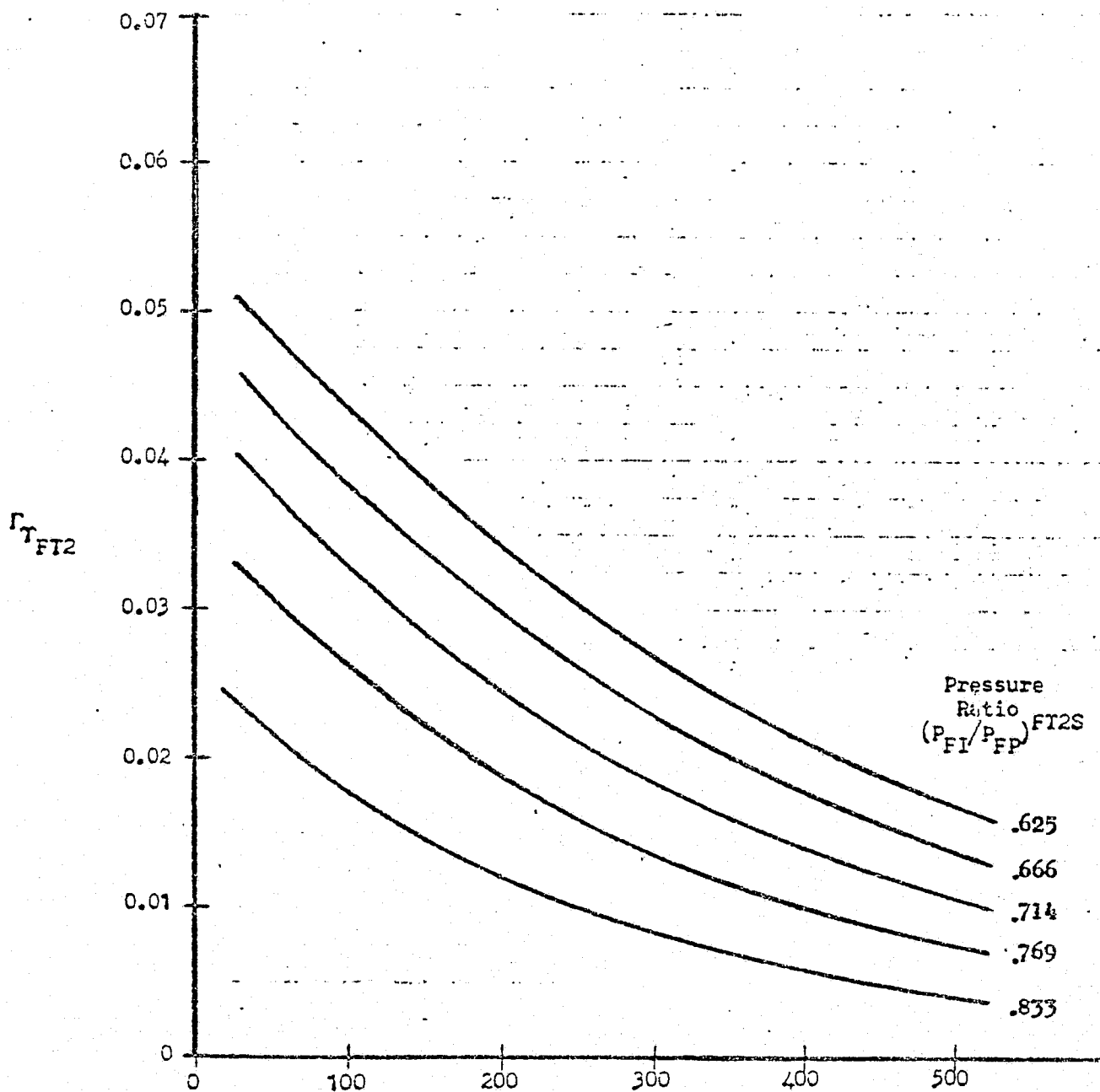
MPS/ET Validation Methods and Check Cases

Complete simulation module verification requires exercising the MPS/ET simulation software through the extremes of the various subsystem inputs to verify proper response to the influencing subsystem stimuli. Comparison of the reference module response to that of the simulation module will determine simulation module validity. Actual verification will be performed in an off-line or batch test mode using special check cases.

Check case design will incorporate functions to exercise the simulation and reference modules throughout the Minimum Power Level (MPL), the Nominal Power Level (NPL), and the Emergency Power Level (EPL). The level of detail employed in the reference module and the specific verification conditions will determine the type of check case used.

High-Fidelity Check Cases - High-fidelity, dynamic verification of the simulation module requires check cases which evaluate the MPS/ET simulation module in the regions of start, throttling, and engine cutoff operations. Through each of these regions, performance parameters for each subsystem would be output and compared with the reference module results. Subsystem transient behavior and steady-state values must be checked. Comparisons would be made using plot output similar to the Figure 4.7-50 description of the SSME high-pressure fuel turbine torque characteristics. This detailed plot represents internal SSME functions. Automated techniques, discussed in Section 5.3, can also be used in evaluating the check case results.

Low-Fidelity Check Cases - Low-level check cases, employed with the corresponding reference module, may also be required. Check cases composed of static conditions would be used. For example, discrete throttling levels evaluated with respect to



LEGEND:

η_{FT2} = high pressure fuel turbine speed parameter

$\Gamma_{T_{FT2}}$ = torque function (in-lbs); high pressure fuel turbine

FT2S = fraction of pressure ratio available for fuel turbine power (dimensionless)

P_{FI} = main fuel injector pressure

P_{FP} = fuel preburner pressure

FIGURE 4.7-50. HIGH-PRESSURE FUEL TURBINE TORQUE CHARACTERISTICS

thrust and consumables usage (fuel and oxidizer) would be needed to check simulation module outputs to Vehicle Dynamics and Mass Properties modules.

MPS/ET Data Base Impact

Data base requirements for verification of the MPS/ET simulation module consist of the reference module(s), the reference module generated data, check cases, and various service routines as necessary. A high-fidelity module verification will require a complex reference module and corresponding check cases. Impact upon the verification data base will increase in accordance with reference module complexity.

4.7.3.2 Reaction Control Subsystem (RCS)

RCS Description

The RCS provides maneuvering capabilities for the Orbiter during Insertion, On-orbit, and Entry phases. The RCS provides additional capabilities for attitude changes and small translational accelerations.

As defined in Reference 20 , the RCS is composed of one forward and two aft RCS modules. The forward module consists of two thruster clusters, a left side and a right side cluster. Each cluster contains eight main thrusters and three vernier thrusters. The fuel and oxidizer propellant tankage is shared by the two clusters. The aft RCS consists of two modules, a left and a right module. Each aft module is independent, consisting of twelve main thrusters, fuel and oxidizer tanks with separate propellant pressurant systems and the associated plumbing and components. However, the fuel and oxidizer sources for each aft RCS module can be inter-shared, as well as with the sources for each of the two OMS pods and the OMS payload bay kit (when carried for extended mission capabilities).

Figure 4.7-51 (from Reference 20) depicts the plumbing and thruster system of a typical forward RCS module indicating the cluster grouping. A typical aft RCS module is depicted in Figure 4.7-52, including the OMS and other aft RCS module interconnects. Figure 4.7-53 provides a more comprehensive indication of the propellant sharing capability by the valves and interconnects between the aft RCS modules, the OMS pods, and the OMS payload bay kit forming the auxiliary propulsion subsystem.

RCS Simulation Module Description and Performance Parameters

The RCS simulation module provides the capability to simulate the RCS throughout the design operating ranges of the subsystem and interfacing systems.

An example of the subsystems interaction and influence is that of the propellant subsystem interface with the crossover plumbing subsystem to provide crossfeed or sharing of propellant sources between the appropriate auxiliary propulsion subsystems. Each individual propellant source will be simulated for a defined mission or mission phase. These capabilities will encompass the subsystems nominal operational limits, the blueline and redline limits, and the design limits

4.7-133

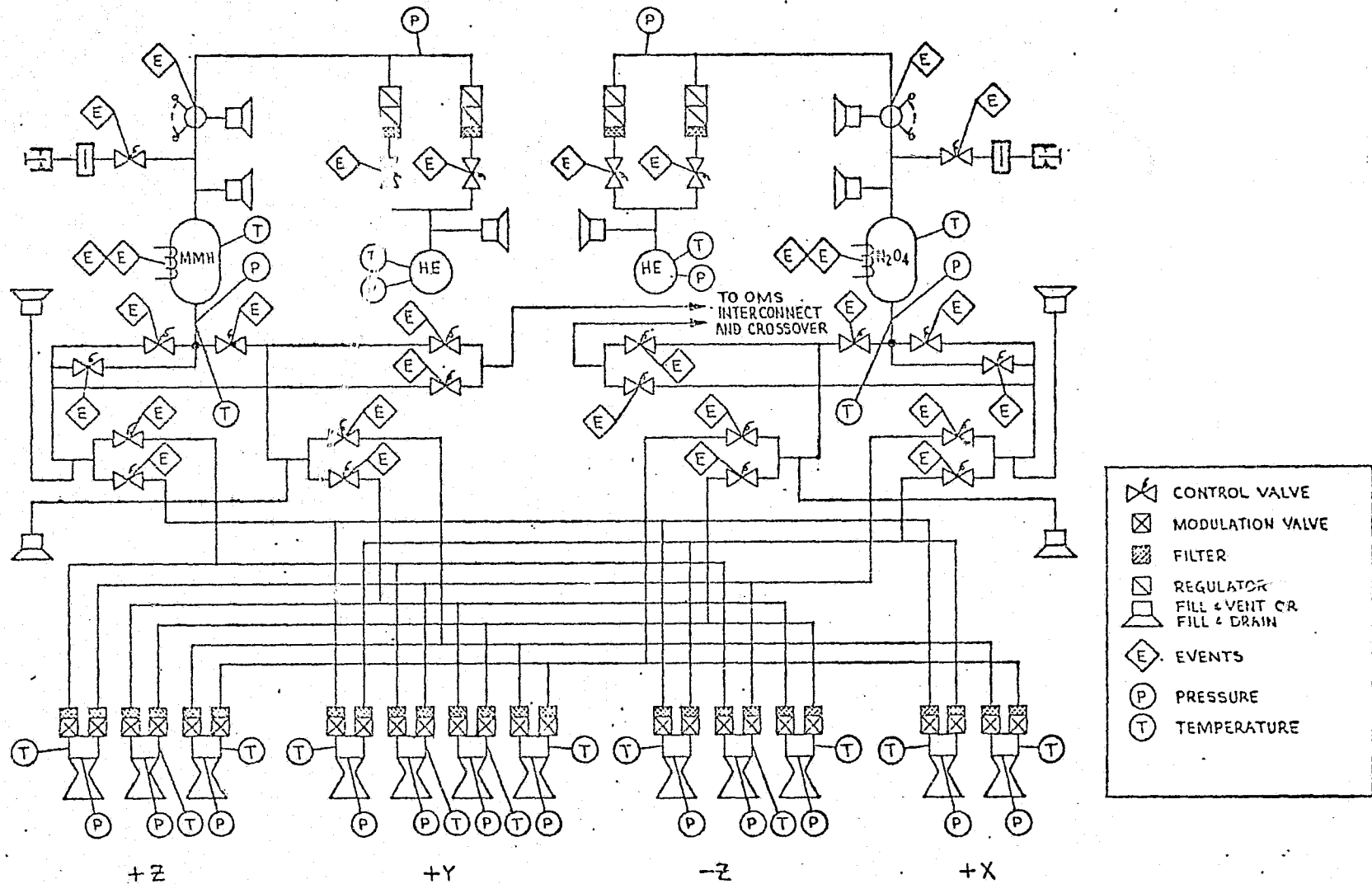


FIGURE 4.7-51 RCS BIPOPELLANT FORWARD MODULE ONLY LEFT-SIDE THRUSTERS SHOWN

4.7-132

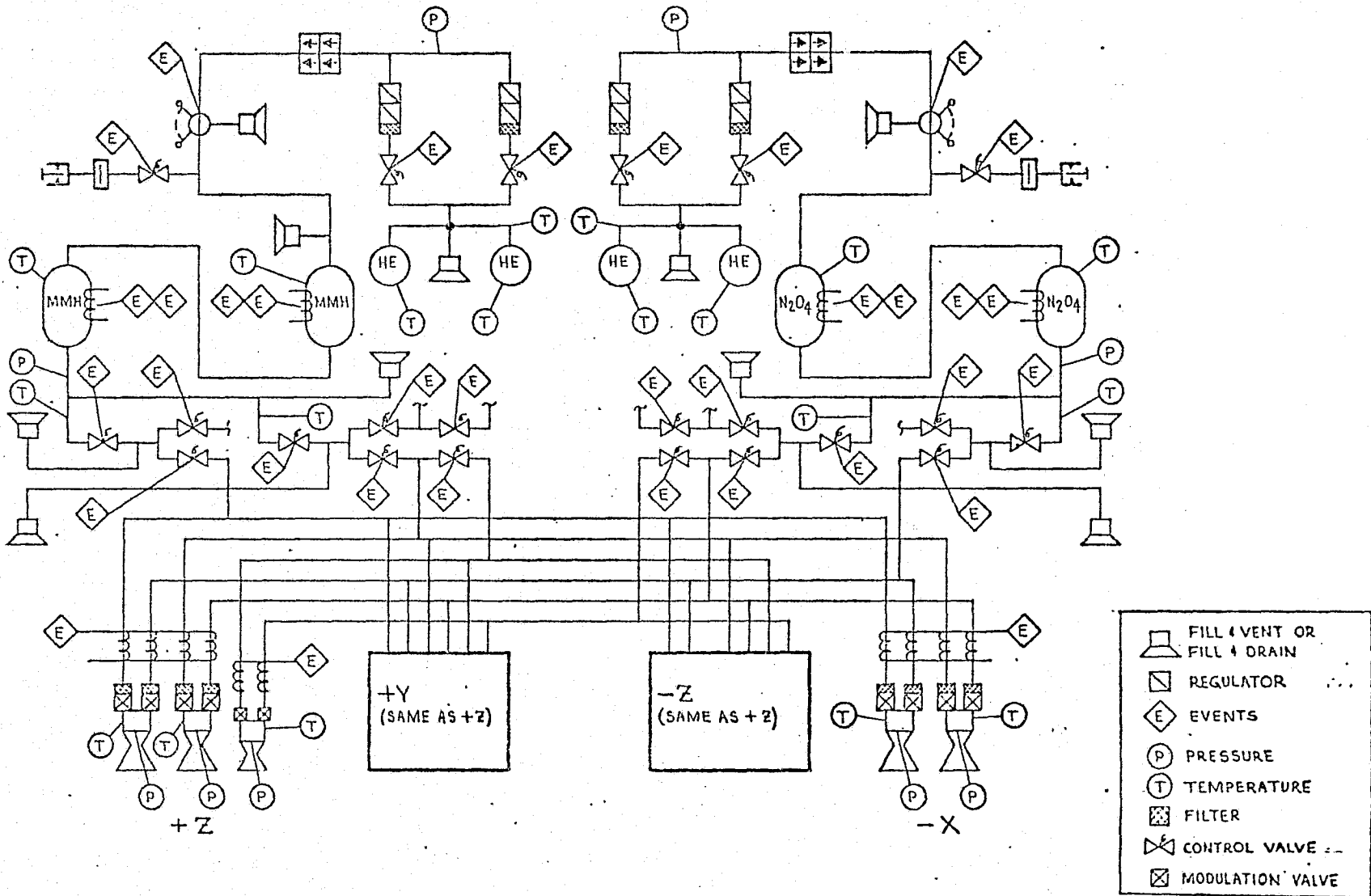


FIGURE 4.7-52 RCS BIPOPELLANT AFT MODULE (LEFT SIDE)

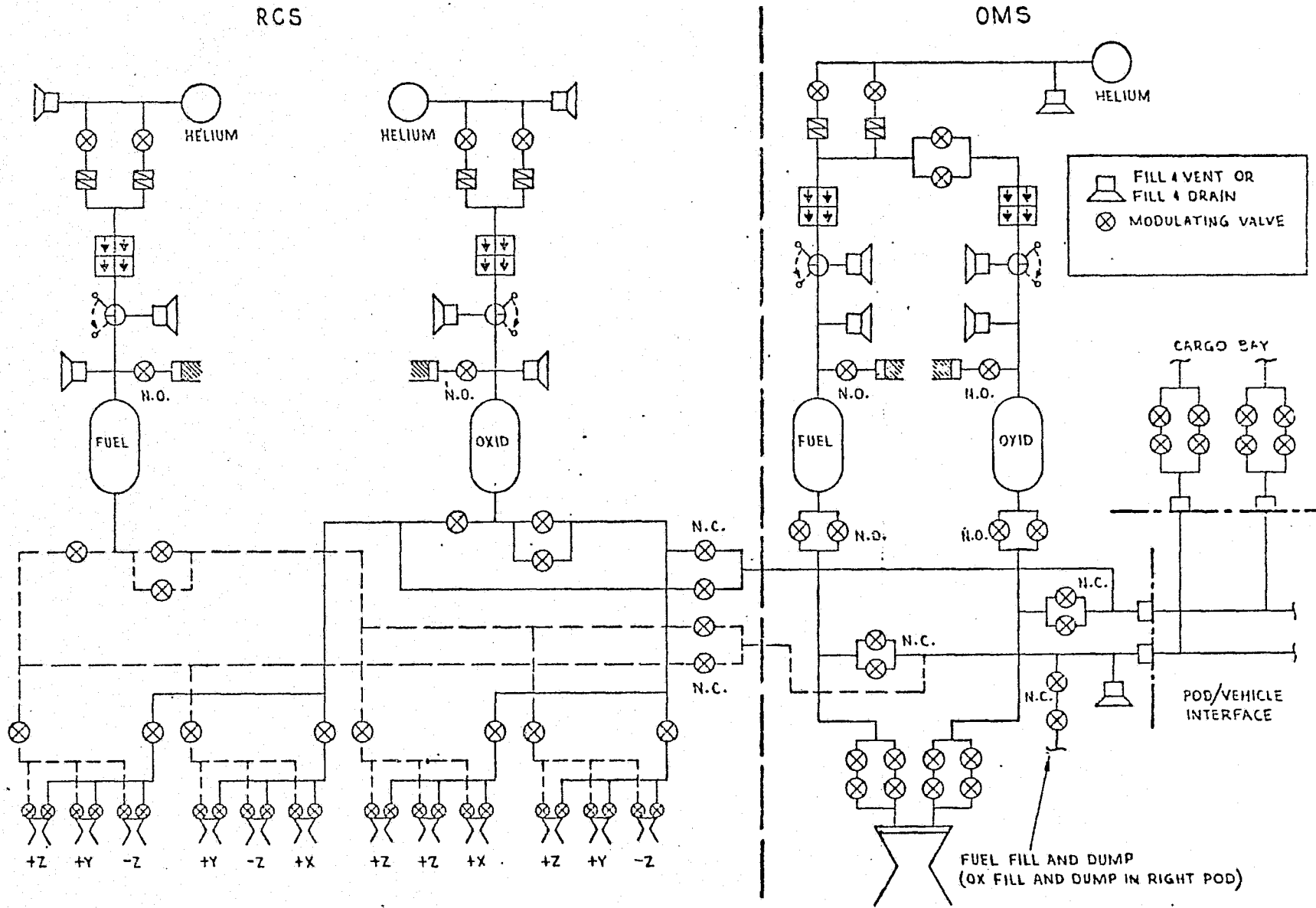


FIGURE 4.7-53 AUXILIARY PROPULSION SUBSYSTEM SCHEMATIC INTERCONNECTED OMS & RCS POD SHOWN

to simulate the proper response and capability of the RCS simulation module. The dynamics of the propellant sources usage are also influenced by the propellant pressurant sources, pressurant depletion rates, pressurant fill pressures, temperature, and volume, the propellant flow rates, the propellant initial fill quantities, the insertion accuracy, OMS usage, and the plumbing and associated valve configuration for the normal and crossfeed lines for the specific simulated conditions.

RCS thruster firing signals interface with the avionics module with inputs initiated by automated systems and hand controllers. The RCS simulation module interfaces with other simulation modules are depicted in Figure 4.7-54. Tables 4.7-13 and 4.7-14 list the performance parameters for the respective forward and aft RCS modules, in the RCS simulation module (Ref. 21).

RCS Reference Data Sources and Data Formats

Figure 4.7-55 (Ref. 27) describes a subroutine, RCSENG, from the SVDS simulation/analysis program (Ref. 28). RCSENG can be combined with a driver to form a reference module which would serve as an adequate data source for RCS verification reference data.

RCSENG computes the thrust of up to 35 user specified RCS jets on the Orbiter. Hardware on and off thruster firing delays are simulated using an "equivalent square wave" technique. Within the integration interval in which the thrust is acting, this square wave is averaged to produce a constant thrust over the entire interval with the total impulse remaining unchanged. A jet status table enables simulation of manual on-off control and jet system failures (Ref. 27). RCS forces and torques in Orbiter body axis coordinates are computed-both individually (each jet) and collectively (summed).

RCSENG inputs consist of (Ref. 28):

- Number and location of RCS jets simulated
- RCS thrust vectors (directions and magnitudes)
- Turn on-off time delays
- RCS jet minimum electrical on-time
- Manual on-off jet control flag.

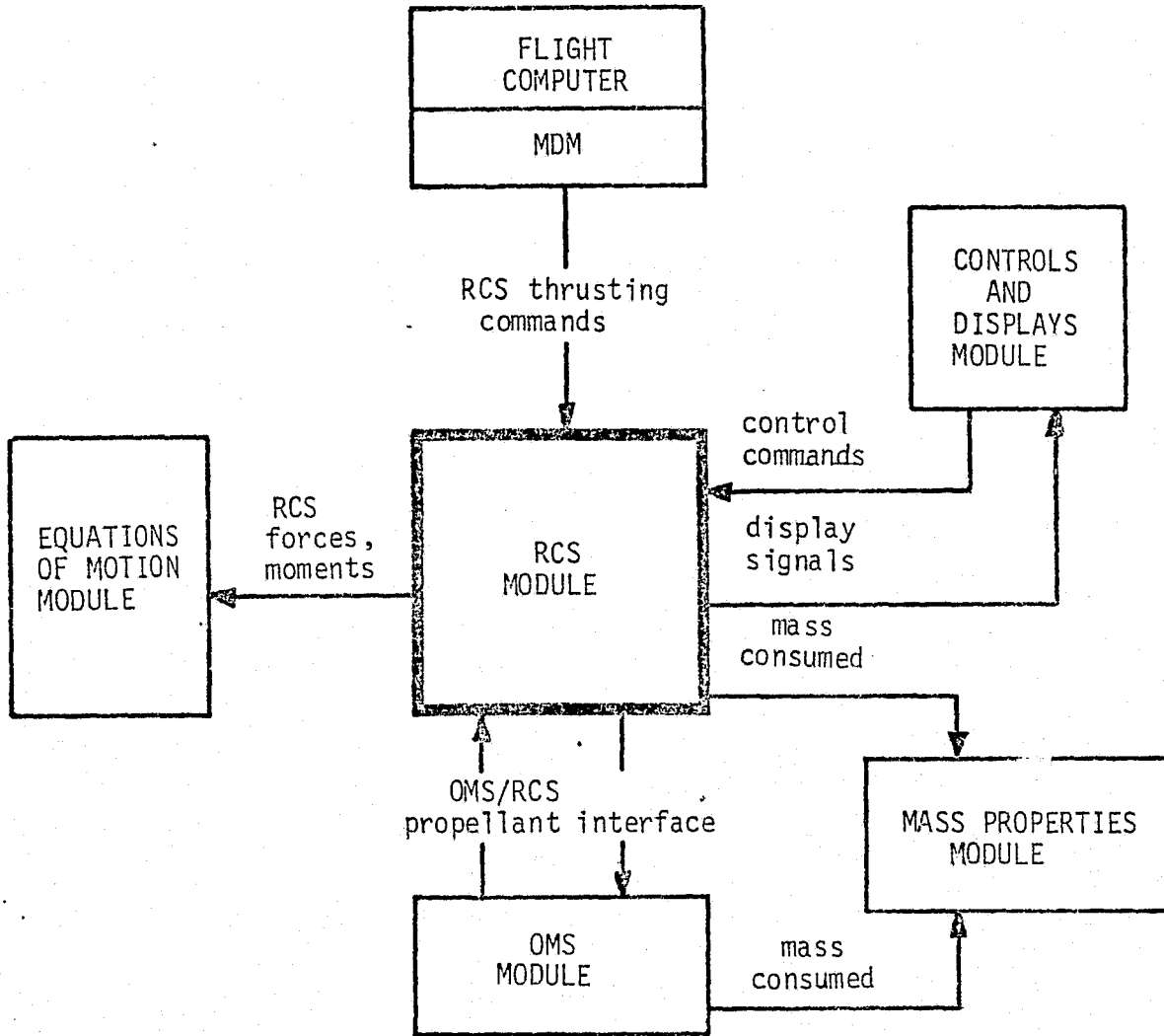


FIGURE 4.7-54 RCS SIMULATION MODULE INTERFACES

TABLE 4.7-13 RCS MODULE FORWARD PARAMETERS

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Helium Oxidizer Tank Pressure	0	+5000	PSIA	CP
Helium Fuel Tank Pressure	0	+5000	PSIA	CP
Helium Oxidizer Purge Valve No. 1 CMD/RESP ^b		CLOSE	EVENT	I/P ^b
Helium Oxidizer Purge Valve No. 2 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Valve No. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Valve No. 2 CMD/RESP		CLOSE	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 1 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 2 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 3 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Relief Isolation Valve-A CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Relief Isolation Valve-B CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Relief Isolation Valve-A CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Relief Isolation Valve-B CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Purge Manual Isln. Vlv. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Oxidizer Purge Manual Isln. Vlv. 2 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Manual Isolation Vlv. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Manual Isolation Vlv. 2 CMD/RESP		CLOSE	EVENT	I/P
Oxidizer Thruster Isolation Valve-E CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-F CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-E CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-F CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-A CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-B CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-C CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-D CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-A CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-B CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-C CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-D CMD/RESP		OPEN	EVENT	I/CP
Sump Fuel Heater Primary CMD/RESP		ON	EVENT	I/P
Sump Oxidizer Heater Primary CMD/RESP		ON	EVENT	I/P
Storage Fuel Heater Primary CMD/RESP		ON	EVENT	I/P
Storage Oxidizer Heater Primary CMD/RESP		ON	EVENT	I/P

TABLE 4.7-13 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Helium Fuel Regulator Isolation Valve No. 1 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Regulator Isolation Valve No. 2 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Regulator Isolation Valve No. 3 CMD/RESP		OPEN	EVENT	I/P
Thruster Injector Temperature No. 1	0	+500	DEG F	CP
Thruster Injector Temperature No. 3	0	+500	DEG F	CP
Thruster Injector Temperature No. 5	0	+500	DEG F	CP
Thruster Injector Temperature No. 7	0	+500	DEG F	CP
Thruster Injector Temperature No. 9	0	+500	DEG F	CP
Thruster Injector Temperature No. 11	0	+500	DEG F	CP
Thruster Injector Temperature No. 13	0	+500	DEG F	CP
Thruster Injector Temperature No. 15	0	+500	DEG F	CP
Thruster Injector Temperature No. 101	0	+500	DEG F	CP
Thruster Injector Temperature No. 103	0	+500	DEG F	CP
Thruster Injector Temperature No. 105	0	+500	DEG F	CP
Thruster Chamber Pressure-1	0	+200	PSIA	CP
Thruster Chamber Pressure-3	0	+200	PSIA	CP
Thruster Chamber Pressure-5	0	+200	PSIA	CP
Thruster Chamber Pressure-7	0	+200	PSIA	CP
Thruster Chamber Pressure-9	0	+200	PSIA	CP
Thruster Chamber Pressure-11	0	+200	PSIA	CP
Thruster Chamber Pressure-13	0	+200	PSIA	CP
Thruster Chamber Pressure-15	0	+200	PSIA	CP
Oxidizer Storage Tank Shell Temperature	-50	+300	DEG F	P
Oxidizer Sump Tank Shell Temperature	-50	+300	DEG F	P
Fuel Storage Tank Shell Temperature	-50	+300	DEG F	P
Fuel Sump Tank Shell Temperature	-50	+300	DEG F	P
Fuel Regulator Outlet Pressure	0	+300	PSIA	CP
Fuel Propellant Manifold Pressure	0	+300	PSIA	CP
Oxidizer Regulator Outlet Pressure	0	+300	PSIA	CP
Oxidizer Propellant Manifold Pressure	0	+300	PSIA	CP
Fuel Manifold Temperature No. 1	-50	+300	DEG F	P
Fuel Manifold Temperature No. 2	-50	+300	DEG F	P

TABLE 4.7-13 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Oxidizer Manifold Temperature No. 1	-50	+300	DEG F	P
Oxidizer Manifold Temperature No. 2	-50	+300	DEG F	P
Helium Oxidizer Tank Temperature No. 1	-50	+300	DEG F	P
Helium Oxidizer Tank Temperature No. 2	-50	+300	DEG F	P
Helium Fuel Tank Temperature No. 1	-50	+300	DEG F	P
Helium Fuel Tank Temperature No. 2	-50	+300	DEG F	P
Sump Oxidizer Heater Secondary CMD/RESP		ON	EVENT	I/P
Storage Fuel Heater Secondary CMD/RESP		ON	EVENT	I/P
Storage Oxidizer Heater Secondary CMD/RESP		ON	EVENT	I/P
Vernier Thruster Heaters ON CMD/RESP		ON	EVENT	I/P
Thruster Heaters A ON CMD/RESP		ON	EVENT	I/P
Thruster Heaters B ON CMD/RESP		ON	EVENT	I/P
Thruster Heaters C ON CMD/RESP		ON	EVENT	I/P
Thruster Heaters D ON CMD/RESP		ON	EVENT	I/P
Sump Fuel Heater Secondary CMD/RESP		ON	EVENT	I/P
Thruster Chamber Pressure-101	0	+200	PSIA	CP
Thruster Chamber Pressure-103	0	+200	PSIA	CP
Thruster Chamber Pressure-105	0	+200	PSIA	CP

^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

^b indicates 2 parameters (command and response)

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TABLE 4.7-14 RCS MODULE AFT PARAMETERS

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Helium Oxidizer Relief Isolation Vlv. No. 1 CMD/RESP ^b		OPEN	EVENT	I/P ^b
Helium Oxidizer Relief Isolation Vlv. No. 2 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Relief Isolation Valve No. 1 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Relief Isolation Valve No. 2 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Manual Purge Isolation Vlv.1 CMD/RESP		CLOSE	EVENT	I/P
Helium Oxidizer Manual Purge Isolation Vlv.2 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Manual Purge Isolation Vlv. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Manual Purge Isolation Vlv. 2 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Regulator Isolation Valve 1 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Regulator Isolation Valve 2 CMD/RESP		OPEN	EVENT	I/P
Helium Fuel Regulator Isolation Valve 3 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 1 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 2 CMD/RESP		OPEN	EVENT	I/P
Helium Oxidizer Regulator Isolation Vlv. 3 CMD/RESP		OPEN	EVENT	I/P
Oxidizer Thruster Isolation Valve-A CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-B CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-C CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Thruster Isolation Valve-D CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-A CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-B CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-C CMD/RESP		OPEN	EVENT	I/CP
Fuel Thruster Isolation Valve-D CMD/RESP		OPEN	EVENT	I/CP
Oxidizer Regulator Outlet Pressure	0	+300	PSIA	CP
Oxidizer Propellant Manifold Pressure	0	+300	PSIA	CP
Fuel Regulator Outlet Pressure	0	+300	PSIA	CP
Fuel Propellant Manifold Pressure	0	+300	PSIA	CP
Oxidizer Manifold Temperature	-50	+300	DEG F	P
Fuel Manifold Temperature	-50	+300	DEG F	P
Thruster Chamber Pressure-17	0	+200	PSIA	CP
Thruster Chamber Pressure-19	0	+200	PSIA	CP
Thruster Chamber Pressure-21	0	+200	PSIA	CP
Thruster Chamber Pressure-23	0	+200	PSIA	CP
Thruster Chamber Pressure-25	0	+200	PSIA	CP
Thruster Chamber Pressure-27	0	+200	PSIA	CP

TABLE 4.7-14 (CONTINUED)

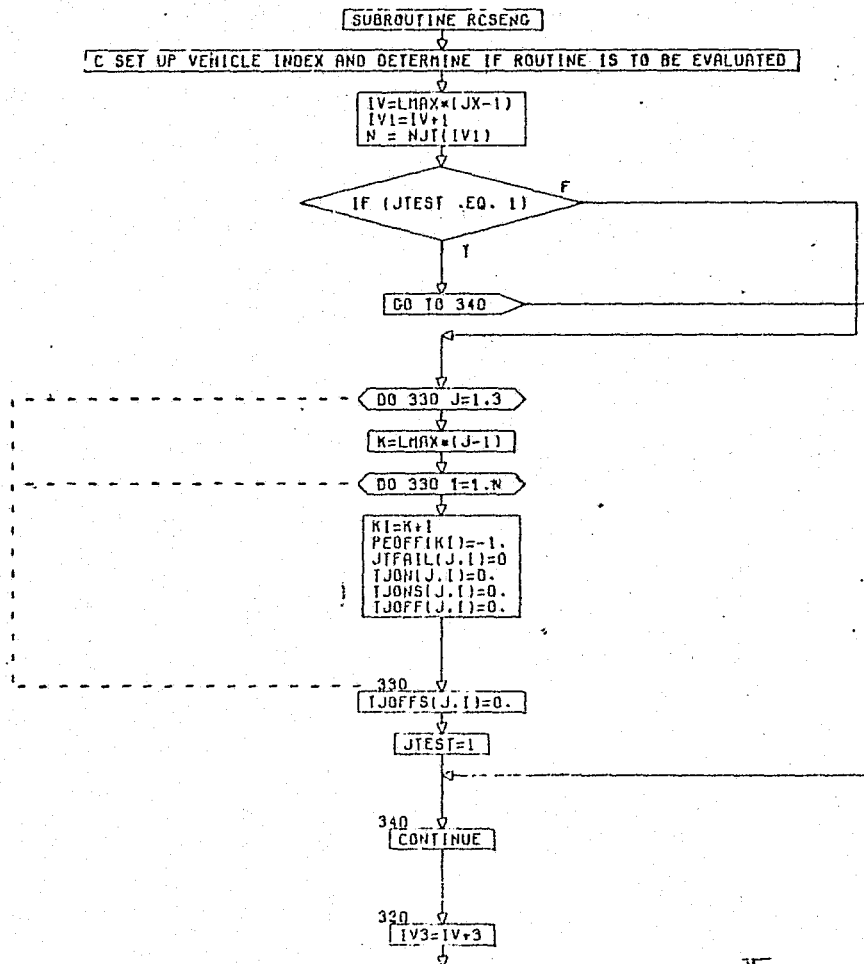
MDC E1136
27 January 1975

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Thruster Chamber Pressure-29	0	+200	PSIA	CP
Thruster Chamber Pressure-31	0	+200	PSIA	CP
Thruster Chamber Pressure-33	0	+200	PSIA	CP
Thruster Chamber Pressure-35	0	+200	PSIA	CP
Thruster Chamber Pressure-37	0	+200	PSIA	CP
Thruster Chamber Pressure-39	0	+200	PSIA	CP
Helium Oxidizer Tank Temperature	-50	+300	DEG F	I
Helium Fuel Tank Temperature	-50	+300	DEG F	I
Thruster Injector Temperature No. 17	0	+500	DEG F	CP
Thruster Injector Temperature No. 19	0	+500	DEG F	CP
Thruster Injector Temperature No. 21	0	+500	DEG F	CP
Thruster Injector Temperature No. 23	0	+500	DEG F	CP
Thruster Injector Temperature No. 25	0	+500	DEG F	CP
Thruster Injector Temperature No. 27	0	+500	DEG F	CP
Thruster Injector Temperature No. 29	0	+500	DEG F	CP
Thruster Injector Temperature No. 31	0	+500	DEG F	CP
Thruster Injector Temperature No. 33	0	+500	DEG F	CP
Helium Oxidizer Tank Pressure	0	+5000	PSIA	CP
Helium Fuel Tank Pressure	0	+5000	PSIA	CP
Helium Oxidizer Purge Valve No. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Oxidizer Purge Valve No. 2 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Valve No. 1 CMD/RESP		CLOSE	EVENT	I/P
Helium Fuel Purge Valve No. 2 CMD/RESP		CLOSE	EVENT	I/P
Fuel Heater Secondary CMD/RESP		ON	EVENT	I/P
Oxidizer Heater Secondary CMD/RESP		ON	EVENT	I/P
Thruster Injector Temperature No. 35	0	+500	DEG F	CP
Thruster Injector Temperature No. 37	0	+500	DEG F	CP
Thruster Injector Temperature No. 39	0	+500	DEG F	CP
Oxidizer Tank Shell Temperature	-50	+300	DEG F	P
Fuel Tank Shell Temperature	-50	+300	DEG F	P
Fuel Heater Primary CMD/RESP		ON	EVENT	I/P
Oxidizer Heater Primary CMD/RESP		ON	EVENT	I/P

^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

^b indicates 2 parameters
 (command and response)

4.7-141



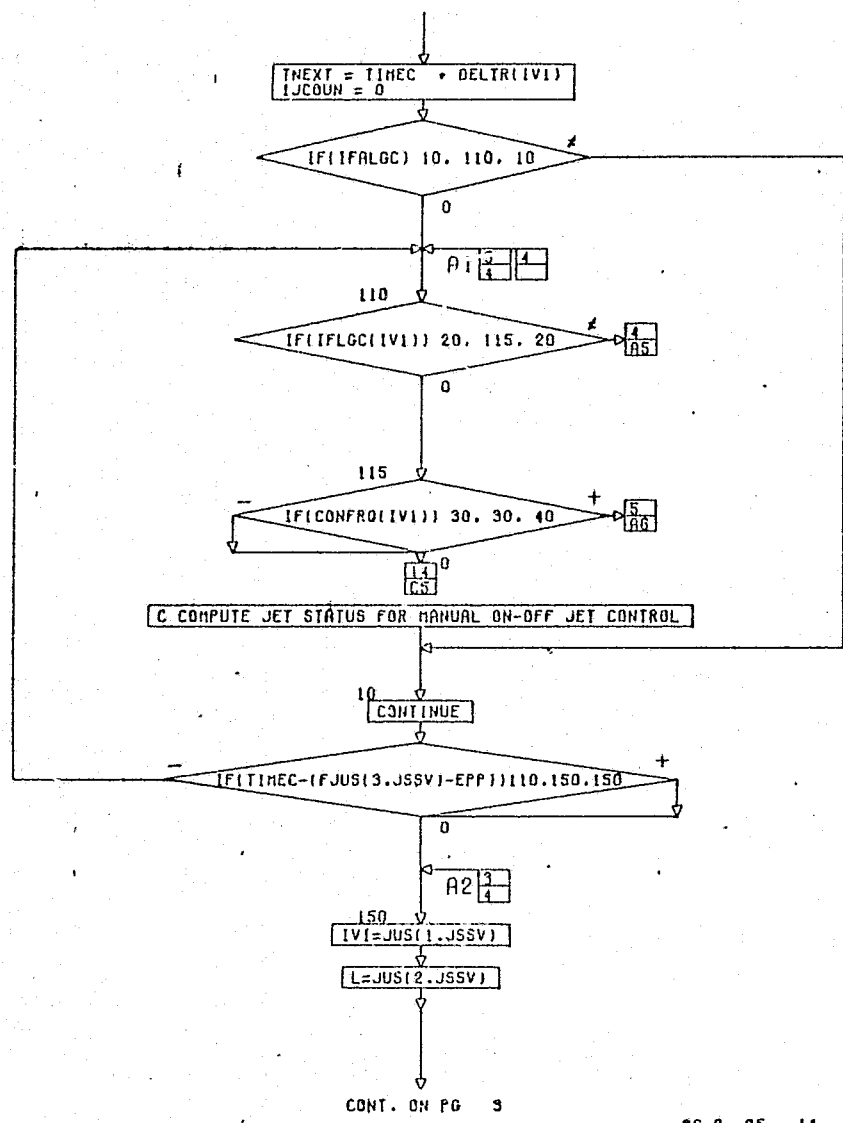
CONT. ON PG 2

PG 1 OF 14

- Vehicle index are computed and the number of RCS jets is assigned a temporary location.
- If it is the program initialization (JTEST#1) control proceeds as follows:
 - Vehicle dependent index is computed.
 - RCS jet parameter is for all jets of all vehicles are zeroed.
 - Initialization flag is set to one.
 - However if JTEST=1 the aforementioned computations are bypassed.
 - Vehicle index computed.

FIGURE 4.7-55. RCSENG SUBROUTINE FLOW CHART

4.7-142



• The electrical time variable is computed and jet status table interrogation counter is set to zero.

$$T_{HX} = T_C + \Delta T_R$$

IJCOUN=0

• If the jet status table is not used (IFALGC=0) the next test is performed on the status of the specific vehicle table, otherwise control is advanced to the jet status for manual on-off jet control computations.

• If the inputs are made to jet status tables (IFLGC=0) then control is advanced to compute jet on and off times for open loop steering, otherwise control continues.

• If the control frequency computation interval is less than or equal to zero ($\Delta t \leq 0$), RCSENG is exit and control is returned to main program, otherwise control is advanced to zeroing the total body torques and forces.

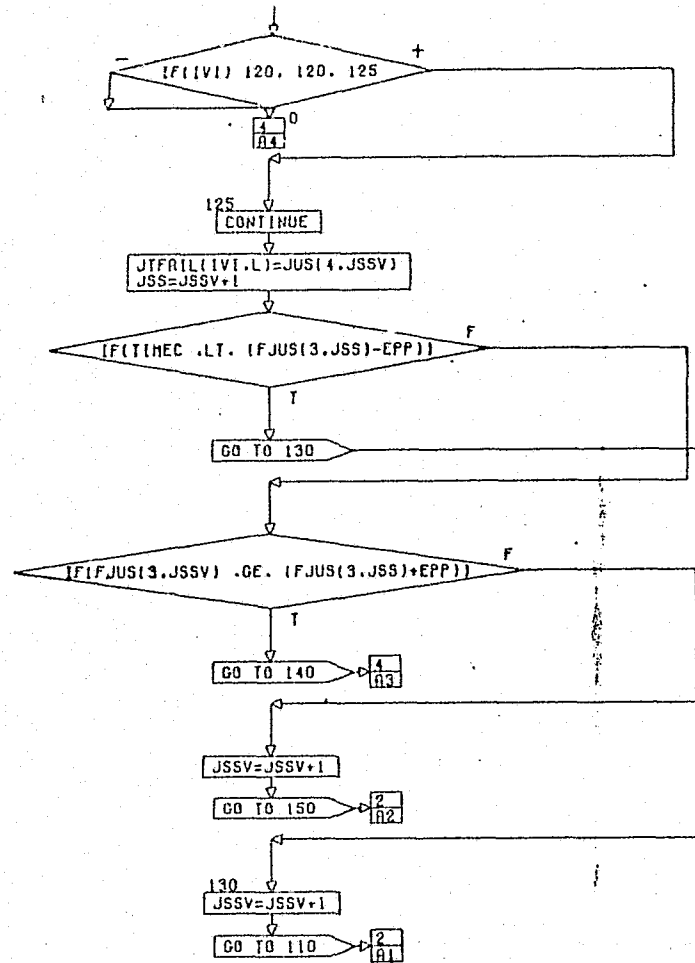
• The jet status for manual on-off jet control is computed if the sum of the appropriate jet status table value and the tolerance on current time is less than the current time (t_C), otherwise control is returned back to the test of the jet status input flag.

• Indices used to locate proper RCS jet status flag is computed.

PG 2 OF 14

FIGURE 4.7-55. (CONTINUED)

4.7-143



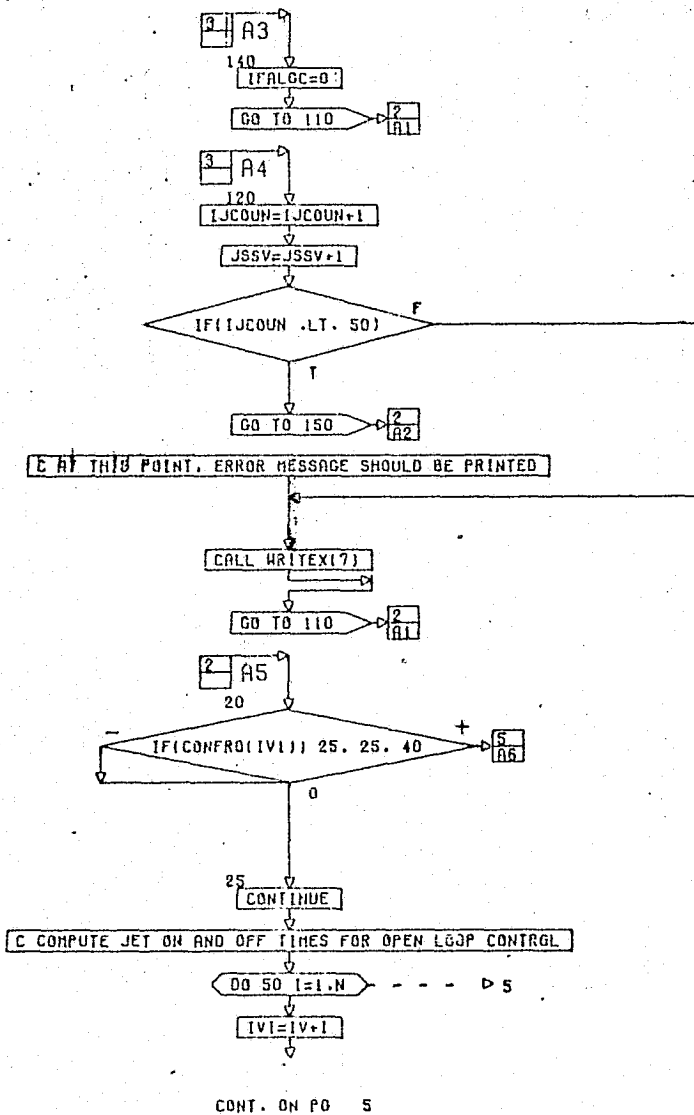
CONT. ON PG 4

PG 3 OF 14

- A test made on the index value to assure that a value is input in the jet status table that was specified by IVALG. If no value is present control advances to an error message print out, otherwise control continues.
- The RCS jet status flag is set equal to the appropriate value of the manual on-off control of the RCS jet.
- The subscript for the jet status table is set equal to the subscript for the jet status table which indicates the next location plus one.
- If the difference in the manual on-off control of the RCS jet and the tolerance on current time is less than or equal to current time (t_c) then control is advanced to the update of the jet status table index and recycled back to the computation of the RCS jet indices, otherwise logic flow continues.
- If the i th value of the manual on-off controls is greater than or equal to the i th plus one value plus the tolerance on current time then the jet status flag is set to zero (IFALG=0) indicating no inputs were made to the table for that vehicle. If the test is false the jet status table index is updated and control recycled back to the rest of the jet status input flag.

FIGURE 4.7-55. (CONTINUED)

4.7-14A



- Interrogation counter is advanced by one.
- The jet status table index is updated by one.
- A test is made to determine if the jet status table has been interrogated fifty times. If the fifty passes are made then an error message is printed which states that the "jet status table" flag (IFLGC) was input as one and no values were input to the jet status table, control is then returned to test the next table flag. If IJCOUN is less than fifty interrogation logic is recycled.

• If open loop control is being used (CONFRQ=0) logic continues, otherwise control advance to the zeroing of the RCS force and moment.

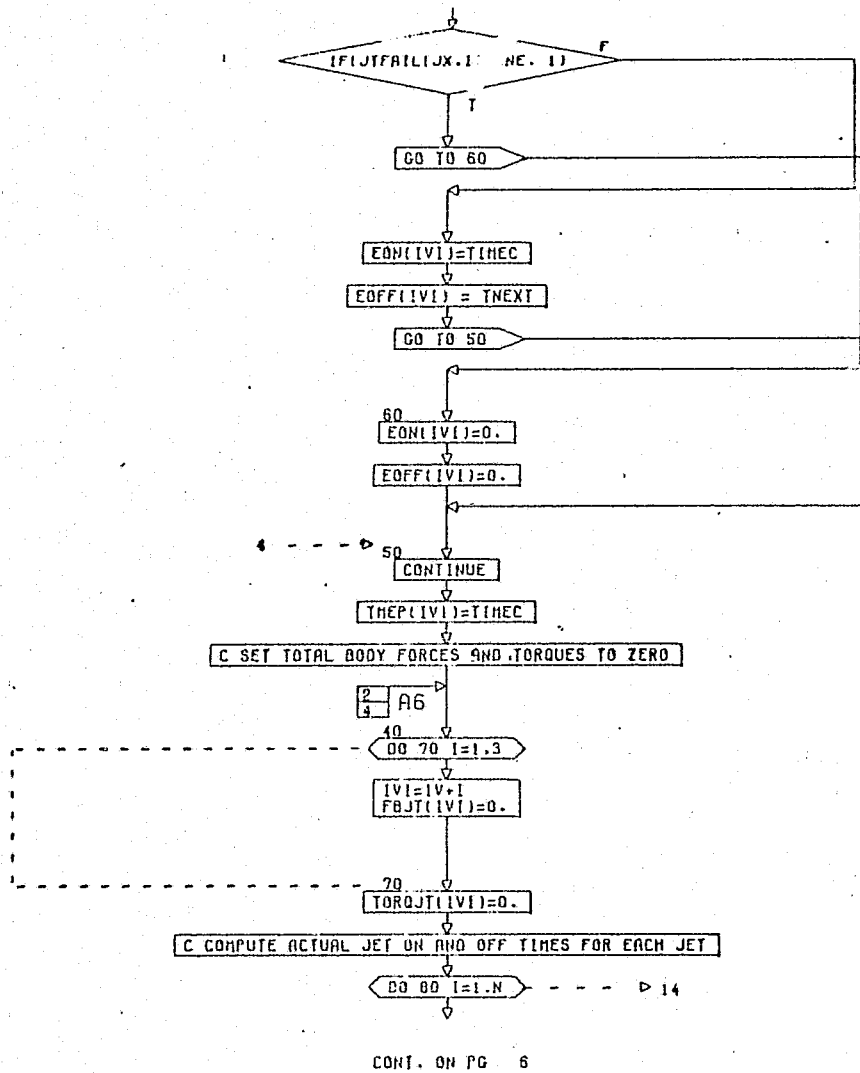
• Vehicle data index is computed.

CONT. ON PG 5

PG 4 OF 14

FIGURE 4.7-55. (CONTINUED)

4.7-145



- If a given jet fail is on (JTFALL=0), then the electrical on time (E_{ON}) is set equal to the current time (t_C), and the electrical off time (E_{OFF}) is set equal to electrical time variable;

$$E_{ON} = t_C$$

$$E_{OFF} = t_{NX}$$

- or if jet is not failed (JTFALL=1), then E_{ON} and E_{OFF} are zeroed.

$$E_{ON} = 0$$

$$E_{OFF} = 0$$

- The time at which the control system or jet status table was evaluated is equal to current time.

$$t_{TP} = t_C$$

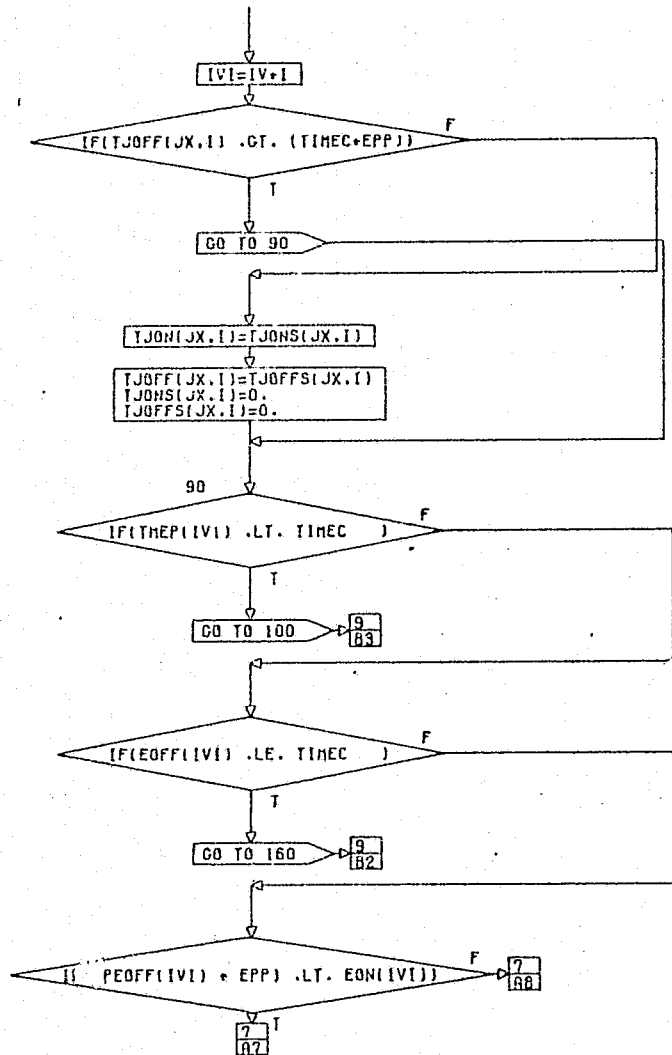
- Vehicle data index is computed.
- Vehicle RCS forces and moments are zeroed.

$$\bar{F}_{ST} = 0$$

$$\bar{H}_{JT} = 0$$

FIGURE 4.7-55 (CONTINUED)

4.7-146



CONT. ON PG 7

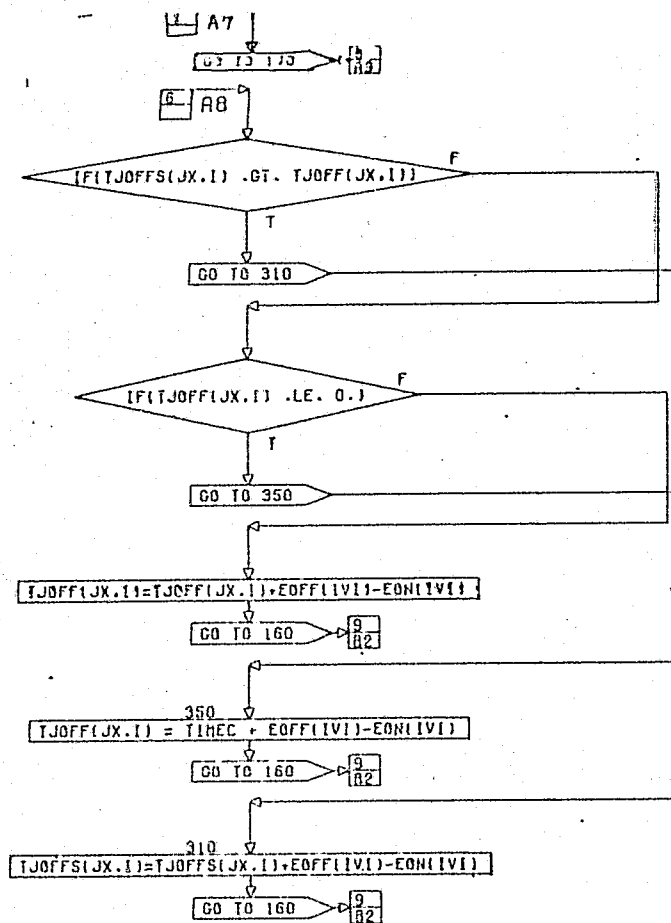
PG 6 OF 14

FIGURE 4.7-55. (CONTINUED)

- Vehicle data index is computed.
- If the time at which the thrust goes on (t_{JON}) is greater than the current time t_c , logic advances to the test of t_{TP} , otherwise logic flow continues.
- The time at which the thrust goes on (t_{JON}), and the time at which the thrust goes off (t_{JOFF}) are set equal to the square wave on and off times which were saved from the previous evaluation of the routine, in the event that the jet was issued an electrical on signal before t_{OFF} or t_{JOFF} had occurred. The previous times are then reloaded.

$$\begin{aligned} t_{JON} &= t'_{JON} & \text{then: } t'_{JON} &= 0 \\ t_{JOFF} &= t'_{JOFF} & t'_{JOFF} &= 0 \end{aligned}$$
- If t_{TP} is less than the current time (t_c) the logic which computes the square wave on and off is bypassed (meaning no electrical on and off signals have been issued) and control is transferred to the computation of the thrust, otherwise logic continues.
- If the electrical off signal (E_{OFF}) is less than or equal to the current time, it is assumed that no electrical signal has been issued for the jet and the square wave logic is bypassed, however, if the test is false logic flow continues.
- If the save value of the electrical off time (E'_{OFF}) plus the tolerance on current time (E_{PP}) is less than the electrical on time (E_{ON}) control is transferred to the computation of the next portion of the square wave. If the test is false, logic flow continues.

A.7-1A7



CONT. ON PG 2

PG 7 OF 14

- If the past value of the time at which the thrust goes off (t'_{OFF}) is less than or equal to the present value (t_{OFF}) the logic flow continues, otherwise control is advanced to the calculation of t'_{OFF} .

- If t_{JOFF} is greater than zero then it is updated by;

$$t_{JOFF} = t_{JOFF} + t_{PP} - E_{ON}$$

Control is then advanced to the calculation of E'_{OFF} .

- If t_{JOFF} is less than or equal to zero then it is updated by

$$t_{TOFF} = t_C + E_{OFF} - E_{ON}$$

Control is then advanced to the calculation of E'_{OFF} .

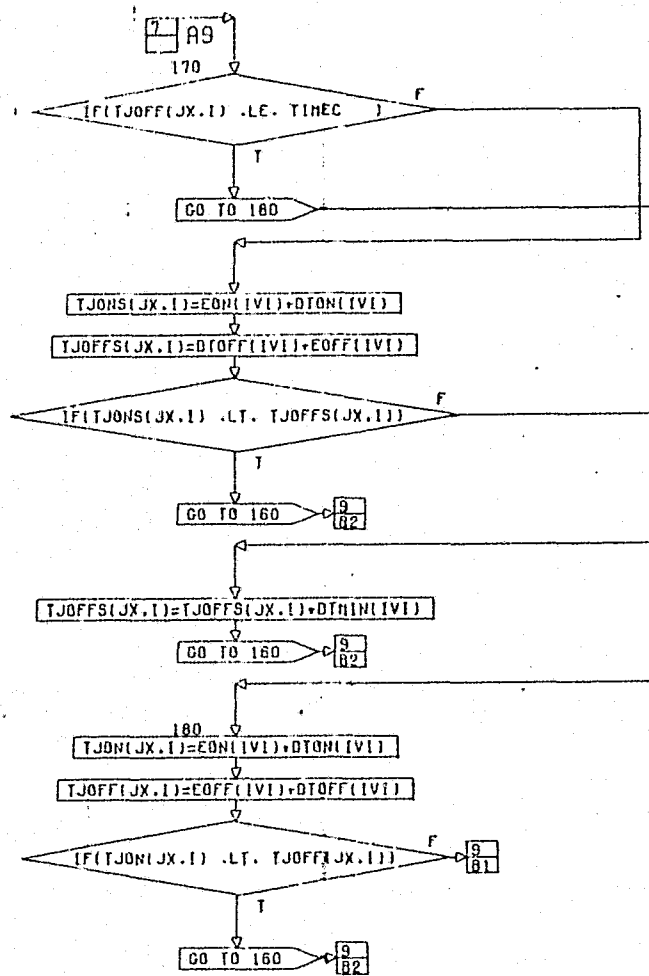
- The past time at which the thrust cuts off (t'_{OFF}) is updated as;

$$t'_{OFF} = t'_{OFF} - E_{ON}$$

Control is then advanced to the calculation of E'_{OFF} .

FIGURE 4.7-55. (CONTINUED)

4.7-148



CONT. ON PG 9

CG. B. DE. 14

- If t_{JOFF} is greater than current time, the new "square wave" on and off times must be solved because t_{JOFF} is still required in computing the current thrust, otherwise control is transferred to the calculation of t_{JON} and t_{JOFF} .

- The new "square wave" times are computed.

$$t'_{JON} = E_{ON} + \Delta t_{ON}$$

$$t'_{OFF} = E_{OFF} + \Delta t_{OFF}$$

- If the thrust on time (t_{JON}) is less than past value of the thrust off time (t'_{JOFF}) control is advanced to the calculation of E'_{OFF} . If the test is false then t'_{JOFF} is updated.

$$t'_{OFF} = t'_{OFF} + \Delta t_{MIN}$$

Control is then advanced to the calculation of E'_{OFF} .

- The thrust on and off times are computed for the new "square wave" with engine time delays.

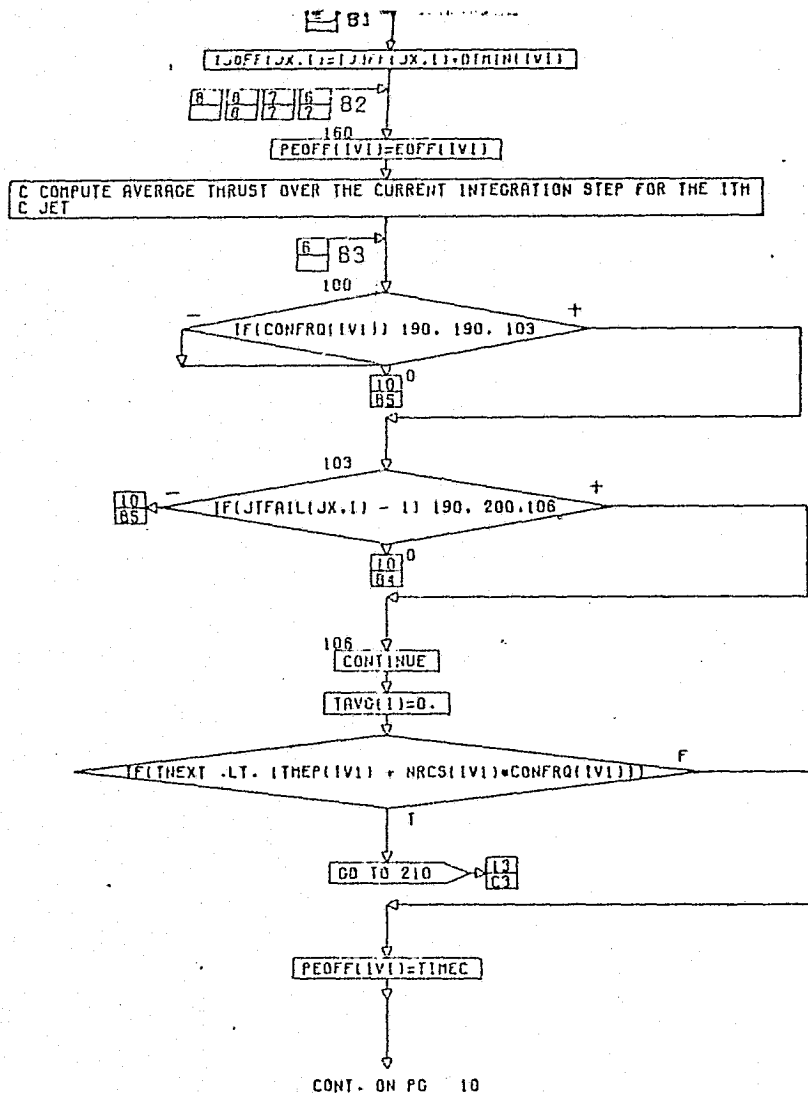
$$t_{JON} = E_{ON} + \Delta t_{ON}$$

$$t_{JOFF} = E_{OFF} + \Delta t_{OFF}$$

- If the thrust on time (t_{JON}) is less than the thrust off time (t_{JOFF}) then control is advanced to the calculation of E'_{OFF} , otherwise t_{JOFF} is recomputed as

$$t_{JOFF} = t_{JOFF} + \Delta t_{MIN}$$

FIGURE 4.7-55. (CONTINUED)



• The past value of the electrical cut off time (t_{OFF}^i) is computed.

$$E_{OFF}^i = E_{OFF}$$

• If the control frequency step size is less than or equal to zero (open loop steering option), control is advanced to bypass computing the thrust on the "square wave," otherwise control continues.

• If the jet fail flag is less than zero again control bypasses computing the thrust based on the square wave, if the flag is equal to zero (jet failed) the average thrust is set equal to the thrust magnitude, if the jet does not fail (flag greater than zero) then the average thrust is set to zero.

$$T_{AVG} = 0$$

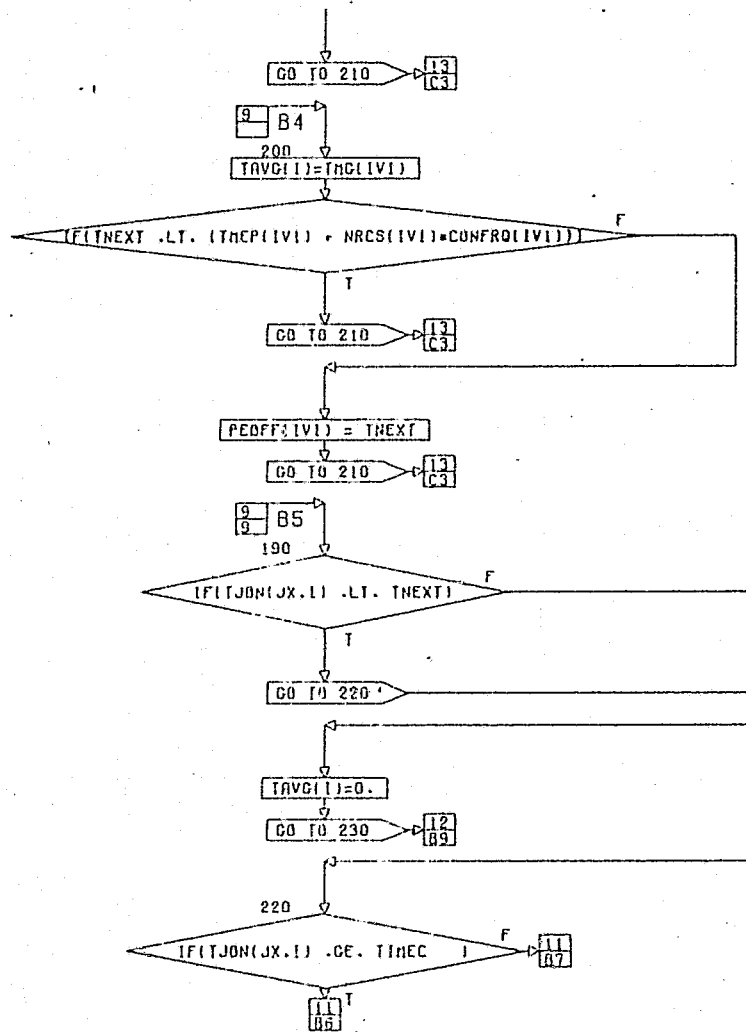
• If the control system is to be evaluated at the next integration step (the test is false) the electrical off time is set equal to current time;

$$E_{OFF}^i = t_C$$

and the logic advances to the computation of the RCS forces and torques. Likewise if the test is true control also advances to the computation of RCS forces and torques.

FIGURE 4.7-55. (CONTINUED)

4.7-150



CONT. ON PG 11

PG 10 OF 14

FIGURE 4.7-55. (CONTINUED)

- The average thrust is set equal to the thrust magnitude.

$$T_{AVG} = T_{MAG}$$

- If the control system is to be evaluated at the next integration step (test is false), the past value of the electrical off time is set equal to the current time plus Δt_R .

$$E_{OFF} = t_{HX}$$

If the test is true and after the preceding operation control is advanced to the calculation of the RCS force and torques.

- Entry into this point of logic denotes that there is no jet fail and the following logic computes the square wave to denote the thrust interval.

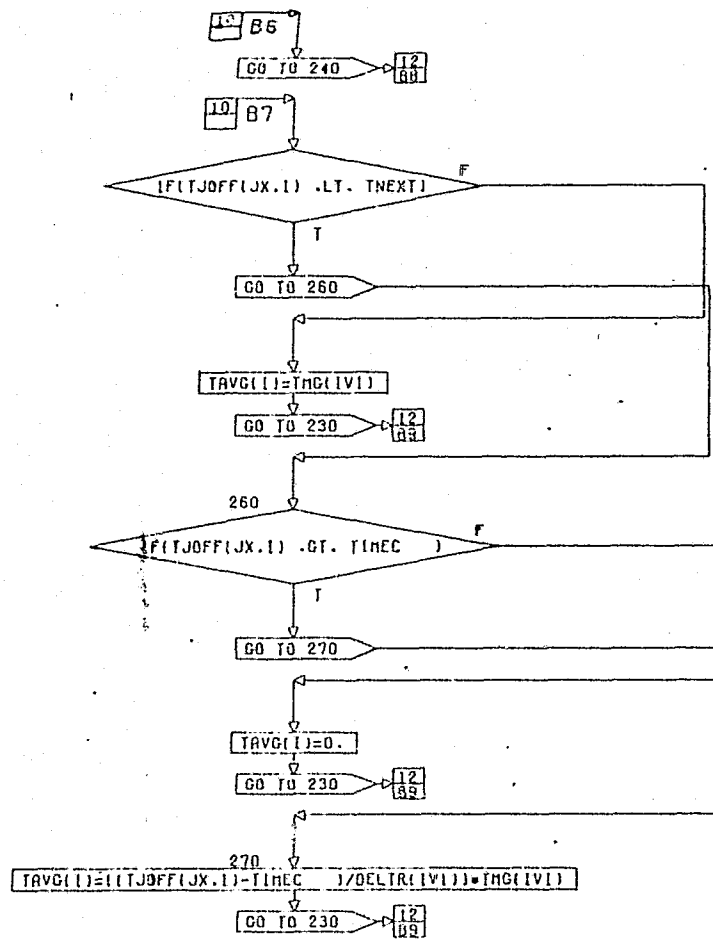
- If the jet on time is greater than or equal to current time plus Δt_R , then the average thrust is zeroed;

$$T_{AVG} = 0.0$$

and control is advanced to further test to determine square wave configuration, however, if the test is true, logic flow continues.

- If the jet on time is greater than or equal to the current time logic flow is advanced to the test of jet off time with t_{HX} , otherwise logic flow continues.

4.7-151



- If the thrust off time is greater than or equal to the current time plus Δt_R , then average thrust is set equal to the thrust magnitude;

$$T_{AVG} = T_{MAG}$$

and from here logic flow is advanced to further test to determine the square wave configuration. However, if the test is true, logic flow continues.

- If the thrust off time is less than or equal to the current time the average thrust is set equal to zero;

$$T_{AVG} = 0.0$$

and the control is advanced to further test to determine the square wave configuration. However, if the test is true the average thrust is set equal to;

$$T_{AVG} = ((t_{JOFF} - t_C) / \Delta t_R) T_{MAG}$$

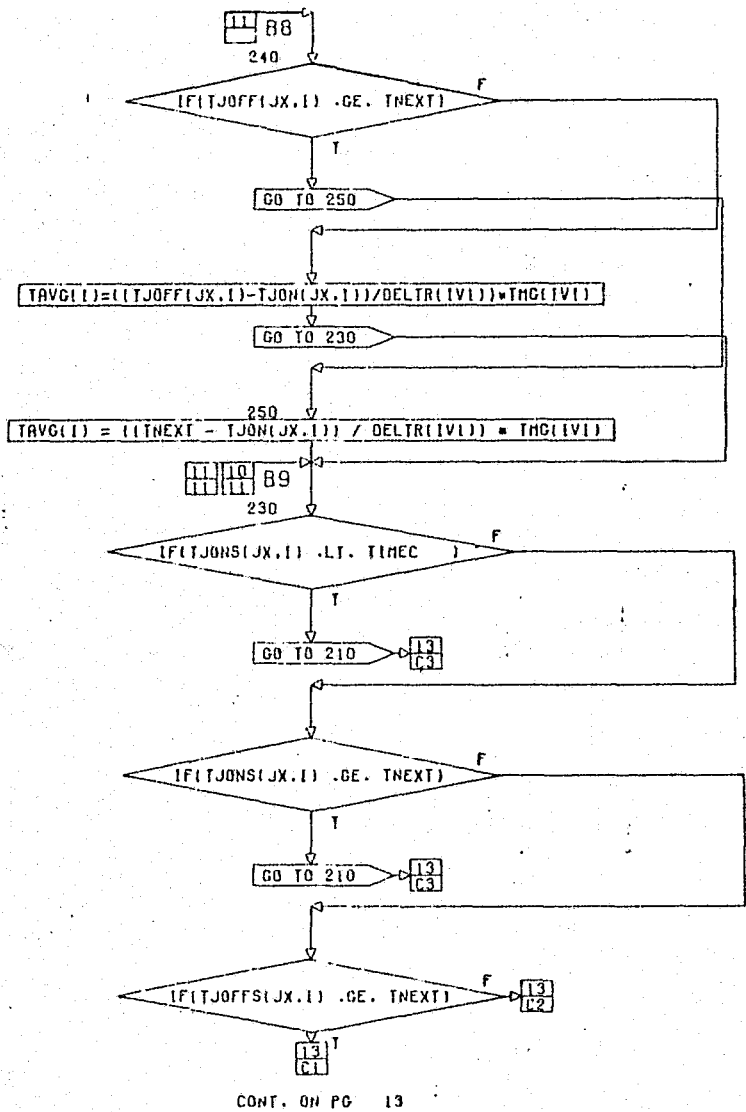
then the flow advances to further test to determine the square wave configuration.

CONT. ON PG 12

PG 11 OF 14

FIGURE 4.7-55. (CONTINUED)

4.7-152



- If the jet off time is less than the current time plus Δt_R , the average thrust is defined as;

$$T_{AVG} = ((t_{JOFF} - t_{JON}) / \Delta t_R) T_{MAG}$$

otherwise the average thrust is defined as:

$$T_{AVG} = ((t_{NX} - t_{JON}) / \Delta t_R) T_{MAG}$$

- At this point further tests are made to determine the square wave configuration.
- If the thrust on time is less than the current time or greater than or equal to current time plus Δt_R , then proceed to compute the RCS forces. Otherwise, the logic continues.

- If the thrust off time is less than the current time plus Δt_R , then the average thrust is redefined as:

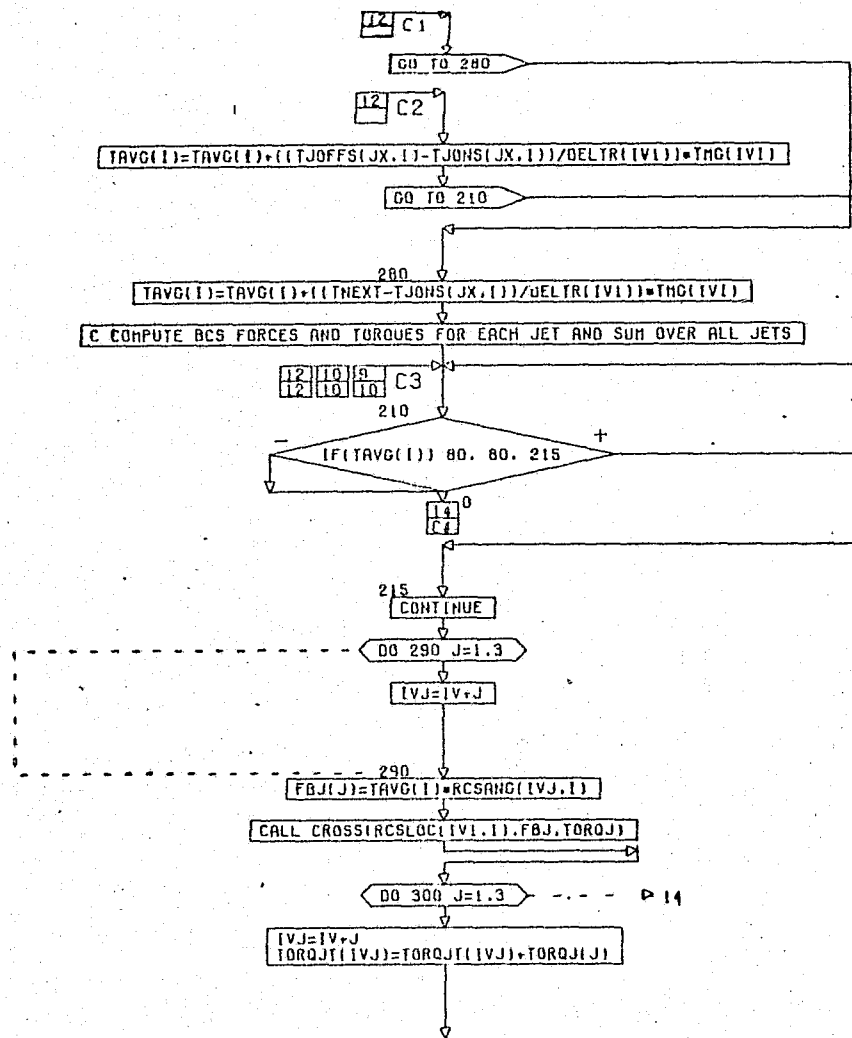
$$T_{AVG} = T_{AVG} + ((t'_{OFF} - t'_{JON}) / \Delta t_R) T_{MAG}$$

CONT. ON PG 13

PG 12 OF 14

FIGURE 4.7-55. (CONTINUED)

4.7-153



CONT. ON PG 14

PG 13 OF 14

- If the previous test is true then the average thrust is

$$T_{AVG} = T_{AVG} + ((t_{HX} - t_{JON}) / \Delta t_R) T_{HAG}$$

- At this point the computed thrust is used to calculate the forces and moments for each jet and sum overall jets.
- If the average thrust is zero the RCS jet logic is recycled, if it is not then the logic flow continues.

- Vehicle dependent index to locate data in the RCSANG array is computed.

- The force due to a particular jet is computed from the average thrust and the direction cosines between the RCS jets thrust vector and the vehicle's BCS axes.

$$\vec{F} = T_{AVG} \begin{Bmatrix} RCS_X \\ RCS_Y \\ RCS_Z \end{Bmatrix} \text{ for each jet}$$

- The torque due the RCS jet is computed as:

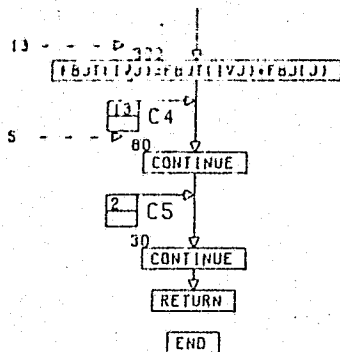
$$\vec{H} = \begin{Bmatrix} X_{RCS} \\ Y_{RCS} \\ Z_{RCS} \end{Bmatrix} \times \vec{F}$$

- The total torque is then

$$\vec{H}_{JT} = \sum_{I=1}^{NJT} \vec{H}_I \text{ for jet } I$$

FIGURE 4.7-55. (CONTINUED)

4.7-154



- The total force per vehicle is then
- $$\bar{F}_{JT} = \sum_{i=1}^{NJT} \bar{F}_i$$
- The RCS logic is recycled until all jets are evaluated.
 - Control is returned to the main program.

LEGEND:

RCS/ENG COMMON VARIABLE DESCRIPTION TABLE

CODE	MATH	USE	DIMENSION	COMMON ARRAY	DEFINITION OF VARIABLE
CONFRC		U	1	DAPI (1)	RCS/JVC DAP CONTROL SYSTEM MODEL COMPUTATION INTERVAL (SEC)
DELTR	Δt_R	U	1	GNDAT1(2)	ROTATIONAL INTEGRATION STEP SIZE (SEC)
DTMIN	Δt_{MIN}	U	25	RJDAT1(252)	RCS JET MINIMUM ELECTRICAL ON TIME ONCE THE ELECTRICAL ON SIGNAL HAS BEEN ACTIVATED (SEC)
DTOFF		U	25	RJDAT1(227)	TIME DELAY IN TURNING OFF EACH RCS JET AFTER THE ELECTRICAL OFF SIGNAL HAS BEEN ISSUED (SEC)
DTON		U	25	RJDAT1(202)	TIME DELAY IN TURNING ON EACH RCS JET AFTER THE ELECTRICAL ON SIGNAL HAS BEEN ISSUED (SEC)
E _{OFF}	E_{OFF}	C/U	25	RJDAT1(278)	TIME AT WHICH RCS JET ELECTRICAL ON SIGNAL IS TO BE TURNED OFF (SEC)
E _{ON}	E_{ON}	C/U	25	RJDAT1(303)	TIME AT WHICH RCS JET ELECTRICAL ON SIGNAL IS TURNED ON (SEC)
E _{PP}	E_{PP}	U		RJDAT2(206)	TOLERANCE ON CURRENT TIME FOR EVALUATION OF JET STATUS TABLE (SEC)
FBJT	F_{JT}	C/U	3	RJDAT1(328)	TOTAL THRUST FORCE FROM ALL JETS IN VEHICLE BCS (LBS)
FJUS		C/U	4,51	RJDAT2(2)	JET STATUS TABLE
IFALGC		C/U		RJDAT2(1)	JET STATUS TABLE FLAG =0 JET STATUS TABLE IS NOT USED =1 JET STATUS TABLE IS USED
IFLGC		U	1	RJDAT1(277)	JET STATUS TABLE FLAG =0 VALUES ARE NOT INPUT TO JET STATUS TABLE FOR VEHICLE CONSIDERED =1 VALUES ARE INPUT TO JET STATUS TABLE FOR VEHICLE CONSIDERED
JSSV		C/U		RJDAT2(207)	INDEX FOR JET STATUS TABLE WHICH INDICATES NEXT LOCATION TO BE USED

FIGURE 4.7-55. (CONTINUED)

4.7-155

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

CODE	MATH	USE	DIMENSION	COMMON ARRAY	DEFINITION OF VARIABLE
NRCS		U	1	DAPI (35)	INTEGER NUMBER OF TVC SAMPLE PERIOD INTERVALS CYCLED FOR EACH RCS ROLL CONTROL LOOP CYCLED
PEOFF	E'_{OFF}	C/U	25	RJDAT1(331)	SAVED VALUE OF EOFF FROM PREVIOUS CONTROL SYSTEM EVALUATION (SEC)
RCSANG	RCS_x, RCS_y, RCS_z	U	3,25	RJDAT1(77)	DIRECTION COSINES OF THRUST VECTOR OF THE RCS JET
RCSLOC	XYZ	U	3,25	RJDAT1(2)	VRCS LOCATION OF THE RCS JETS (FT)
TIMEC	t_c	U		GNDAT2(183)	CURRENT TRAJECTORY TIME (SEC)
TIMEP	t_{TP}	C/U	1	RJDAT1(356)	LATEST TRAJECTORY TIME THAT THE RCS DAP CONTROL SYSTEM WAS EVALUATED (SEC)
TMG	T_{MAG}	U	25	RJDAT1(177)	THRUST MAGNITUDE OF EACH RCS JET (LBS)
TORQJT	M_{JT}	C/U	3	RJDAT1(357)	TOTAL MOMENT ABOUT VEHICLE CG IN VEHICLE RCS (FT-LBS)
JTEST		C/U		RJDAT2(208)	RCS ENGINE MODEL INITIALIZATION FLAG =0 INITIALIZATION PASS OF RCS ENGINE MODEL =1 EXECUTE RCS ENGINE MODEL LOGIC (INITIALIZATION COMPLETED)
JX		U		GNDAT2(169)	INTERNAL VEHICLE NUMBER
LMAX		U		GNDAT2(174)	MAXIMUM LENGTH OF VEHICLE COMMON
NJT		U	1	RJDAT1(1)	NUMBER OF RCS JETS BEING SIMULATED

RCSNG INTERNAL VARIABLE DESCRIPTION TABLE

CODE	MATH	DEFINITION OF VARIABLE
FBJ	F	RCS COMPONENTS OF THE FORCE VECTOR PRODUCED BY A SINGLE RCS JET. (LBS)
IJCOUN		INTERNAL COUNTER.
IV		VEHICLE INDEX.
JSS		SUBSCRIPT FOR THE JET STATUS TABLE.
JTFAIL		RCS JET STATUS FLAG. =0 NO MANUAL COMMAND TO JET. =1 JET COMMANDED ON. =2 JET COMMANDED OFF.
N		NUMBER OF JETS.
TJOFF	t_{JOFF}	TIME AT WHICH JET IS ACTUALLY TURNED OFF. (SEC)
TJOFFS	t_{JOFF}	SAVED VALUE OF TJOFF IN THE EVENT THAT EON IS ISSUED BEFORE TJOFF OCCURS. (SEC)
TJON	t_{ON}	TIME AT WHICH RCS JET IS ACTUALLY TURNED ON. (SEC)
TJONS	t_{ON}	SAVED VALUE OF TJON IN THE EVENT THAT EON IS ISSUED BEFORE TJOFF OCCURS. (SEC)
TNEXT	t_{NX}	TEMPORARY VARIABLE EQUIVALENT TO CURRENT TIME PLUS THE ROTATIONAL INTEGRATION STEP SIZE. (SEC)
TORQJ	M	RCS COMPONENTS OF THE TORQUE VECTOR PRODUCED BY A SINGLE RCS JET. (FT-LBS)

FIGURE 4.7-55. (CONTINUED)

Outputs of RCSENG are the individual and summed RCS thrust forces and torques on the Orbiter. RCS mass properties information is not computed in RCSENG.

A driver must be constructed to ensure a complete RCS reference module. In addition to providing input/output simulation module compatibility, the RCS reference module driver must provide accurate simulation of: (1) fuel and oxidizer mass consumed during RCS activation (including turn on-off losses) and (2) RCS/OMS propellant sharing interface functions. These calculation and logic sequences should not be difficult to implement.

RCS Validation Methods and Check Cases

Check cases for RCS simulation module verification should consist of static and dynamic command sequences to exercise both the simulation and reference modules.

In the static check cases, each RCS jet could be fired and its effects on Orbiter body axis forces and moments analyzed. Individual jet thrust and consumables usage can be similarly evaluated. Static firing check cases for groups of RCS jets should be developed to check collective jet performance.

Dynamic check cases would be composed of integrated jet firing command sequences which simulate actual Orbiter maneuvers or manual and automatic control systems. Dynamic maneuvers include:

- Orbiter/ET separation
- Docking/payload handling
- Entry attitude control

Data Base Impact

RCS Simulation Module verification data base requirements consist of:

- RCS reference module
- Resident reference data and check cases
- Any additional routines, jet tables, etc. as needed for verification

The reference module, once developed, should not expand significantly; however, vehicle design changes involving the placement and thrust of individual and groups of RCS jets and various control system modifications will require the construction of additional check cases.

4.7.3.3 Orbital Maneuvering System (OMS)

OMS Description

The OMS provides maneuvering capabilities for the Orbiter during orbital insertion, on-orbit, and de-orbit mission phases. The OMS is contained in two semi-independent pods located on the aft portion of the Orbiter. The prime components of each OMS pod are the OMS engine, fuel tank, oxidizer tank, propellant pressurant system, and the associated plumbing and components. However, the fuel and oxidizer sources can be inter-shared between pods, as well as the sources for the aft RCS pods.

Figure 4.7-56 illustrates the propellant sharing capability, by use of manifold tanks and isolation valves, between the two OMS pods and the aft RCS modules. Figures 4.7-57, 4.7-58, and 4.7-59 depict the tankage, engine, optional OMS payload bay kit, and respective associated hardware for one OMS pod (Ref. 20).

OMS Simulation Module Description and Performance Parameters

Simulation of the OMS will utilize a combination of logical, functional, and explicit engineering equations to calculate the required parameters. For simulation purposes, the OMS module will provide the OMS thrust as well as crew displays of fuel, oxidizer, helium, and engine chamber pressure, and for oxidizer and fuel quantities (Ref. 11).

Included in the simulation module will be subsystem simulation and interaction. An example of the subsystems interaction and influence is that of the propellant subsystem interface with the pressure subsystem which maintains proper propellant flow in a non-gravity environment. The dynamics of the pressurant subsystem are also influenced by the depletion, the flow rates, the burn mixture ratio, and initial fill quantities of the fuel and oxidizer as well as the burn characteristics of the engine within its design profile box and the associated valves, and plumbing configurations.

Figure 4.7-60 depicts the OMS simulation module interfaces with other simulation modules. The performance parameters associated with the OMS module are described in Table 4.7-15(Ref. 21).

4.7-158

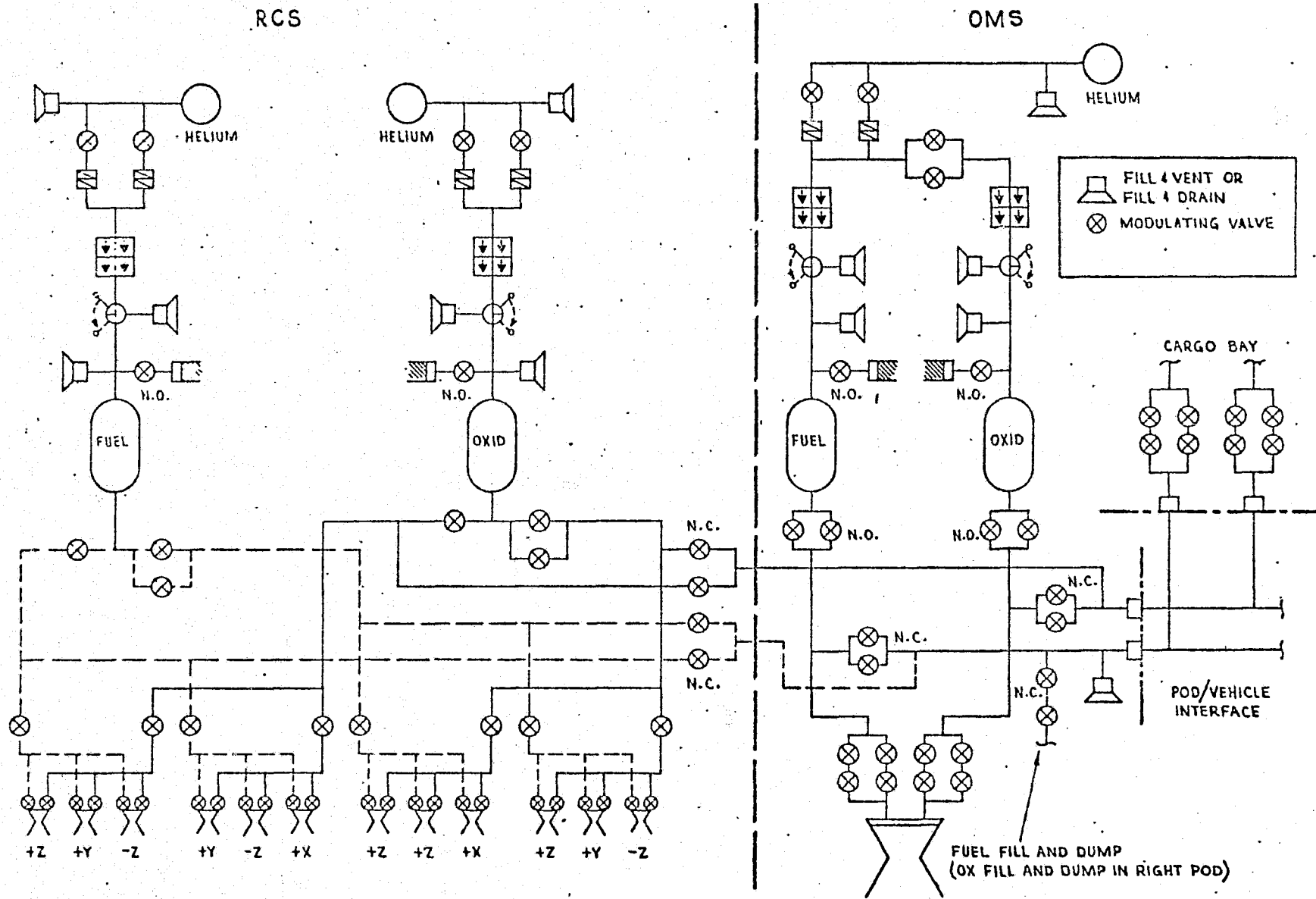


FIGURE 4.7-56. AUXILIARY PROPULSION SUBSYSTEM SCHEMATIC INTERCONNECTED OMS & RCS LEFT POD SHOWN

4.7-159

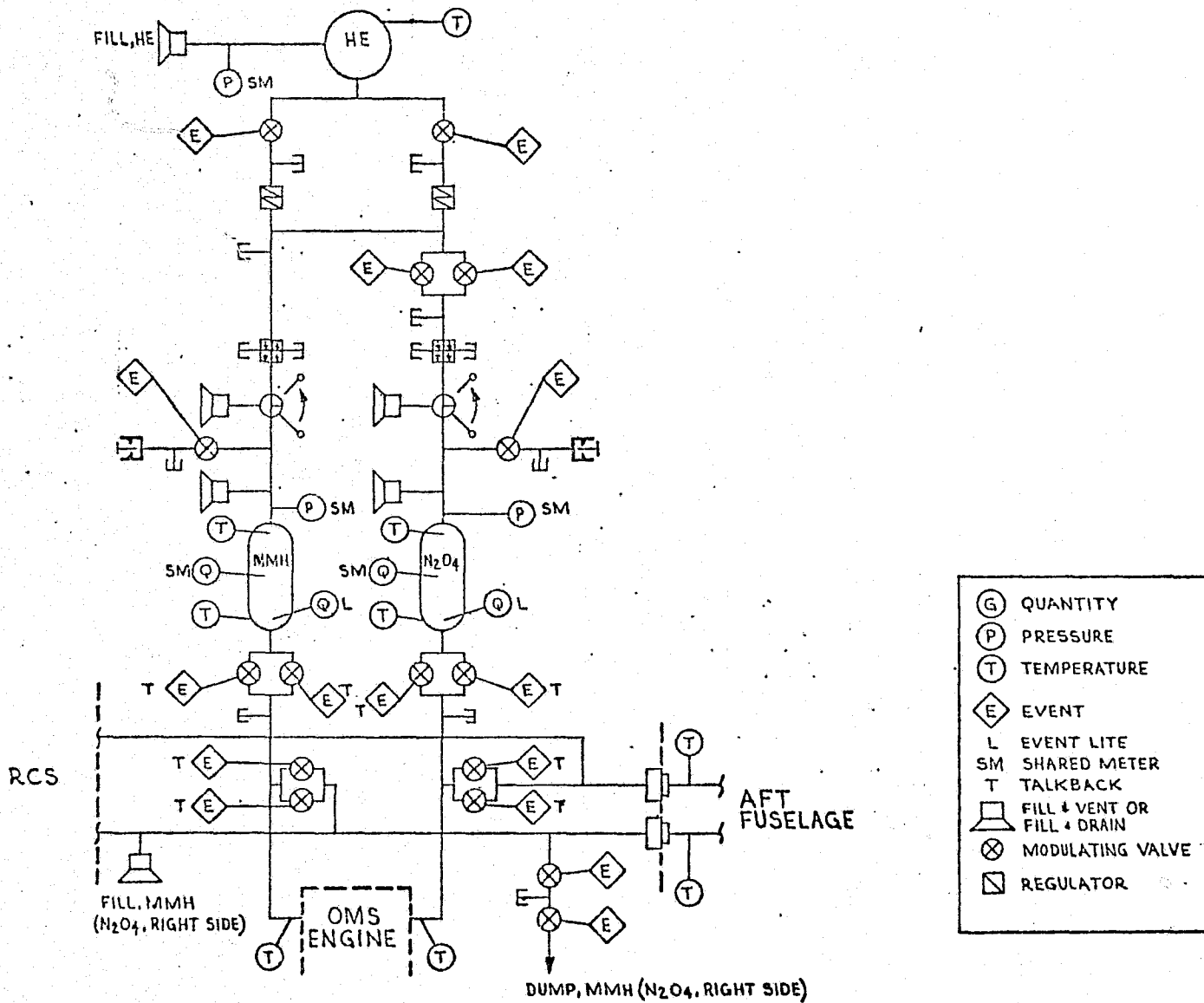
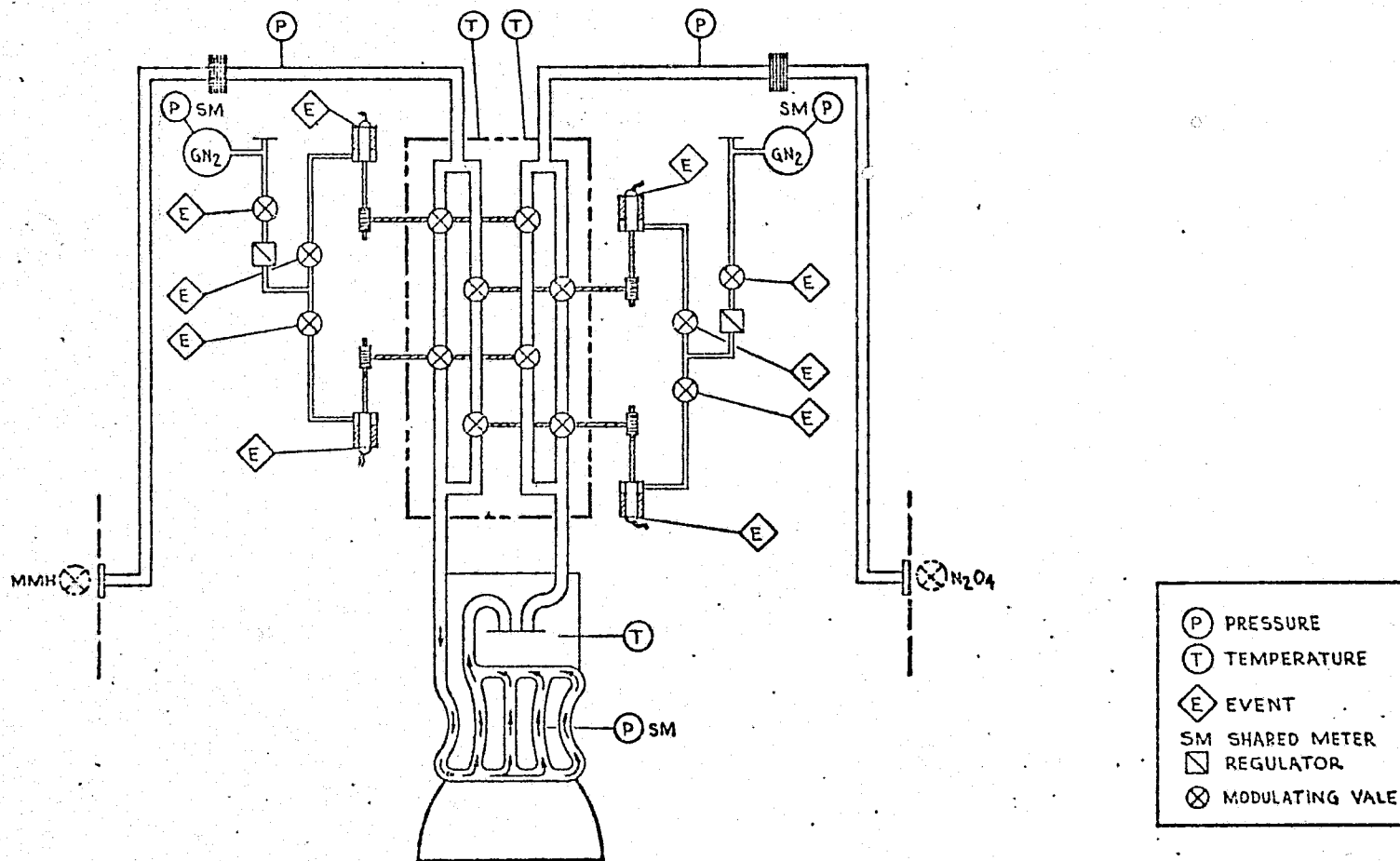


FIGURE 4.7-57 OMS LEFT POD OPERATIONAL INSTRUMENTATION MEASUREMENTS

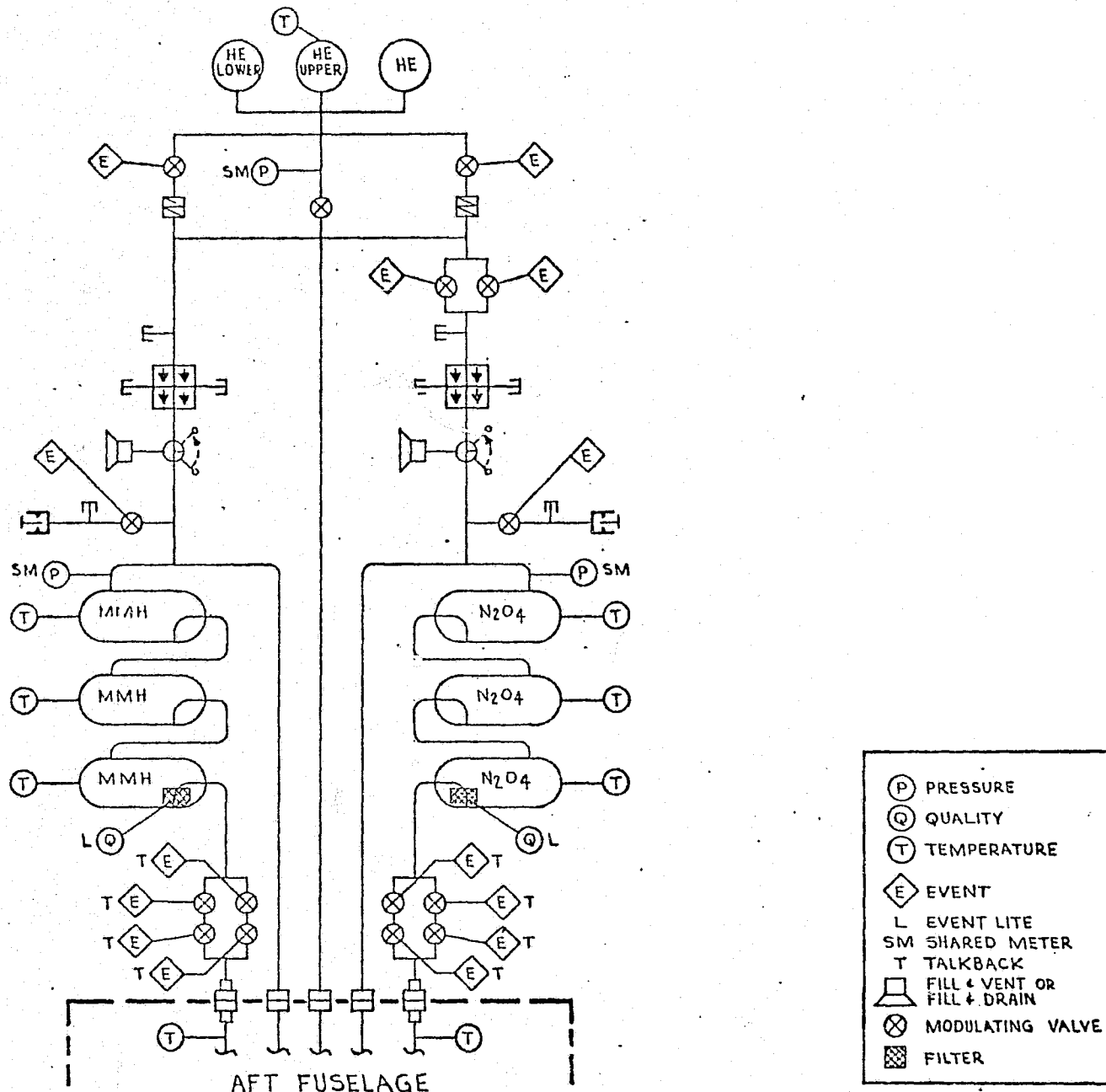
4.7-160



- | | |
|-----|-----------------|
| (P) | PRESSURE |
| (T) | TEMPERATURE |
| (E) | EVENT |
| SM | SHARED METER |
| □ | REGULATOR |
| ⊗ | MODULATING VALE |

FIGURE 4.7-58 OMS ENGINE OPERATIONAL INSTRUMENTATION MEASUREMENTS

4.7-161



AFT FUSELAGE
 FIGURE 4.7-59 OMS PAYLOAD BAY KIT OPERATIONAL INSTRUMENTATION MEASUREMENTS

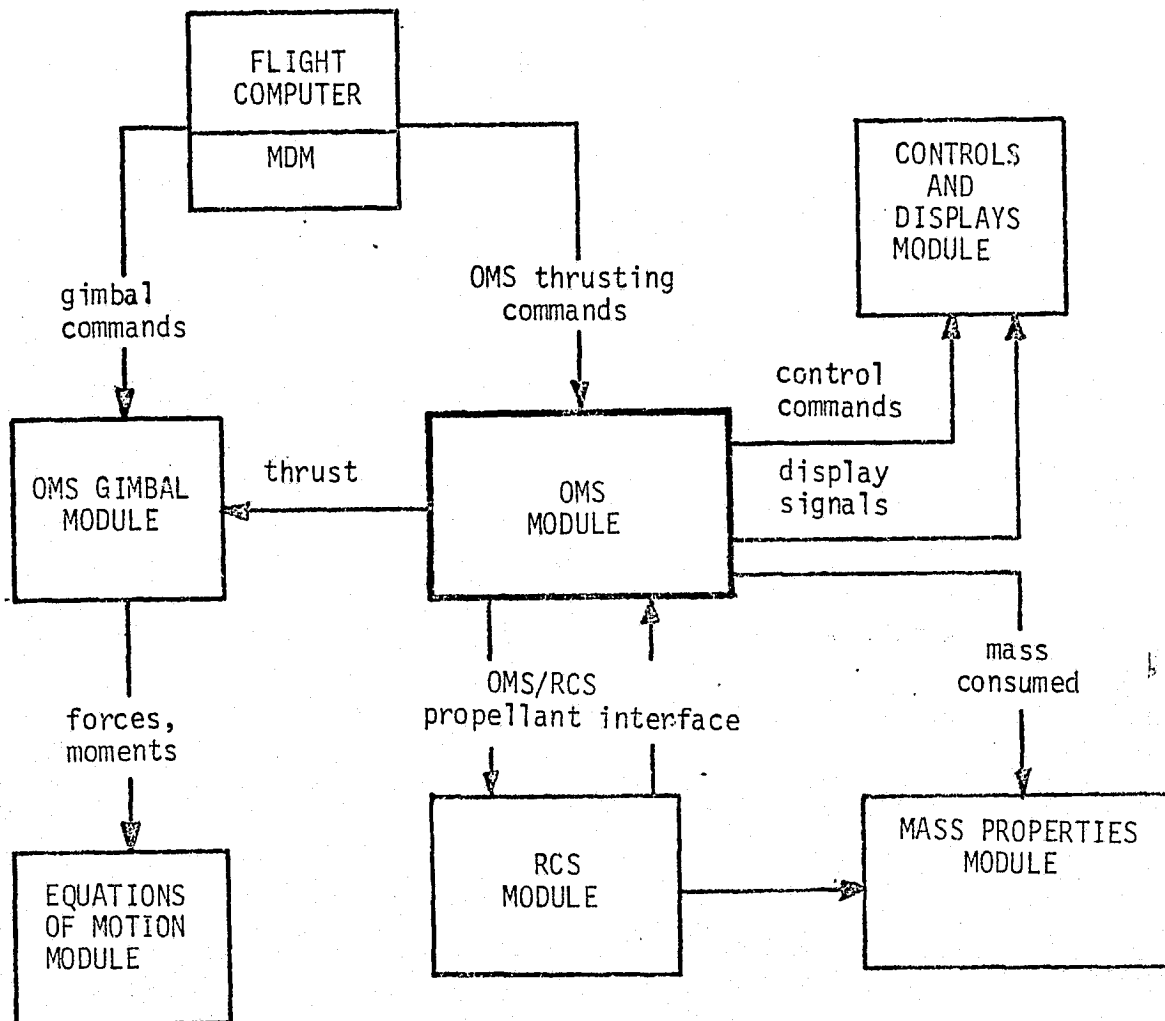


FIGURE 4.7-60, OMS SIMULATION MODULE INTERFACES

TABLE 4.7-15 OMS MODULE PARAMETER LIST

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	Low	High	Unit	
FIGURE 2, PROPELLANT SUBSYSTEMS				
Engine Fuel Crossfeed Line Temperature	0	+200	Deg F	P
Engine Fuel Crossfeed Valve No. 1 Position	Close	Open	Event	P
Engine Fuel Crossfeed Valve No. 2 Position	Close	Open	Event	P
Engine Fuel Tank Quantity	0	+100	PCT	CP
Engine Fuel Tank Level Low		Low	Event	CP
Engine Fuel Tank Temperature - Lower	0	+200	Deg F	P
Engine Fuel Tank Ullage Pressure	0	+300	PSIA	P
Engine Fuel Tank Ullage Temperature	0	+200	Deg F	P
Helium Fuel Isolation Valve Open		On	Event	P
Engine Fuel Tank Relief Isolation Valve Position	Close	Open	Event	CP
Engine Helium Tank Pressure	0	5000	PSIA	CP
Engine Helium Tank Temperature - Upper	-200	+200	Deg F	P
Engine Helium Fuel Isolation Valve Position	Close	Open	Event	P
Vapor Isolation Valve No. 1 Position	Close	Open	Event	P
Vapor Isolation Valve No. 2 Position	Close	Open	Event	P
Engine Fuel Dump Valve Position	Close	Open	Event	CP
Engine Fuel Feed/Dump Valve Position	Close	Open	Event	CP
Engine Oxidizer Inlet Temperature	0	+200	Deg F	CP
Engine Oxidizer Inlet Pressure	0	+300	PSIA	CP
Engine Oxidizer Isolation Valve Position	Close	Open	Event	CP
Engine Oxidizer Bi-Propellant Valve Temperature	-50	+500	Deg F	CP
Engine Oxidizer Crossfeed Line Temperature	-65	+500	Deg F	P
Engine Oxidizer Crossfeed Valve No. 1 Position	Close	Open	Event	P
Engine Oxidizer Crossfeed Valve No. 2 Position	Close	Open	Event	P
Engine Oxidizer Tank Quantity	0	+100	PCT	CP
Engine Oxidizer Tank Level Low		Low	Event	CP
Engine Oxidizer Tank Temperature - Lower	0	+200	Deg F	P
Engine Oxidizer Tank Ullage Pressure	0	+300	PSIA	P

TABLE 4.7-15 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	Low	High	Unit	
FIGURE 2, PROPELLANT SUBSYSTEMS (continued)				
Engine Oxidizer Tank Ullage Temperature	0	+200	Deg F	P
Helium Oxidizer Isolation Valve Open		On	Event	P
Engine Oxidizer Tank Relief Isolation Valve Position	Close	Open	Event	CP
Engine Helium Oxidizer Isolation Valve Position	Close	Open	Event	P
Engine Oxidizer Dump Valve Position	Close	Open	Event	CP
Engine Oxidizer Feed/Dump Valve Position	Close	Open	Event	CP
FIGURE 3, ENGINE				
Engine Chamber Pressure	0	+200	PSIA	CP
Engine Injector Temperature	-65	+500	Deg F	CP
Engine Fuel Inlet Temperature	0	+200	Deg F	CP
Engine Fuel Inlet Pressure	0	+300	PSIA	CP
Engine Fuel Isolation Valve Position	Close	Open	Event	CP
Engine Bi-Propellant Valve 1 Bank A Position	Close	Open	Event	P
Engine Bi-Propellant Valve 2 Bank A Position	Close	Open	Event	P
Engine Bi-Propellant Valve 1 Bank B Position	Close	Open	Event	P
Engine Bi-Propellant Valve 2 Bank B Position	Close	Open	Event	P
Engine Bi-Propellant Fuel - Valve Temperature	-65	+500	Deg F	CP
Engine Pneumatic Pressure Supply A	0	+300	PSIA	P
Engine Pneumatic Pressure Supply B	0	+300	PSIA	P
Engine Delta V Thrust Bank A Open		On	Event	P
Engine Delta V Thrust Bank B Open		On	Event	P
FIGURE 4, PAYLOAD BAY KIT				
Fuel Isolation Valve Position - Auxiliary	Close	Open	Event	P
Fuel Transfer Line Temperature Aft Fuselage - Aux.	0	+200	Deg F	P
Fuel Tank No. 1 Level Low - Auxiliary		Low	Event	I
Fuel Tank No. 1 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Fuel Tank No. 2 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Fuel Tank No. 3 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Fuel Tank No. 3 Ullage Temperature - Auxiliary	0	+200	Deg F	P

TABLE 4.7-15 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	Low	High	Unit	
FIGURE 4, PAYLOAD BAY KIT (continued)				
Helium Fuel Isolation Valve Open - Auxiliary		On	Event	CP
Fuel Tank Isolation Relief Valve Position - Aux.	Close	Open	Event	P
Helium Tank Pressure - Auxiliary	0	5000	PSIA	CP
Helium Tank Temperature Upper - Auxiliary	-200	+200	Deg F	P
Helium Fuel Isolation Valve Position - Auxiliary	Close	Open	Event	P
Helium Oxidizer Isolation Valve Open - Auxiliary		On	Event	P
Oxidizer Isolation Valve Position - Auxiliary	Close	Open	Event	P
Oxidizer Transfer Inlet Temp. Aft Fuselage - Aux.	0	+200	Deg F	P
Oxidizer Tank No. 1 Level Low - Auxiliary		Low	Event	I
Oxidizer Tank No. 1 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Oxidizer Tank No. 2 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Oxidizer Tank No. 3 Bulk Temperature - Auxiliary	0	+200	Deg F	P
Oxidizer Tank No. 3 Ullage Temperature - Auxiliary	0	+200	Deg F	P
Oxidizer Tank Isolation Relief Valve Position - Aux.	Close	Open	Event	P
Helium Oxidizer Isolation Valve Position - Auxiliary	Close	Open	Event	CP
Vapor Isolation Valve No. 1 Position - Auxiliary	Close	Open	Event	P
Vapor Isolation Valve No. 2 Position - Auxiliary	Close	Open	Event	P

- ^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

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OMS Reference Data Sources and Data Formats

The Figure 4.7-61 math flow describes the subroutine THR2, from the SSFS simulation/analysis program (Ref. 17), which can be modified slightly and combined with a main program driver to form a reference module capable of generating OMS verification reference data.

THR2 models OMS thrust for a maximum of three equivalent thrust Orbiter OMS engine (currently there are only two). The model assumes that each engine is independently gimballed and that the engine deflections are input from an OMS actuator model. THR2 computes and outputs OMS thrust forces and torques in the Orbiter body axis coordinate system.

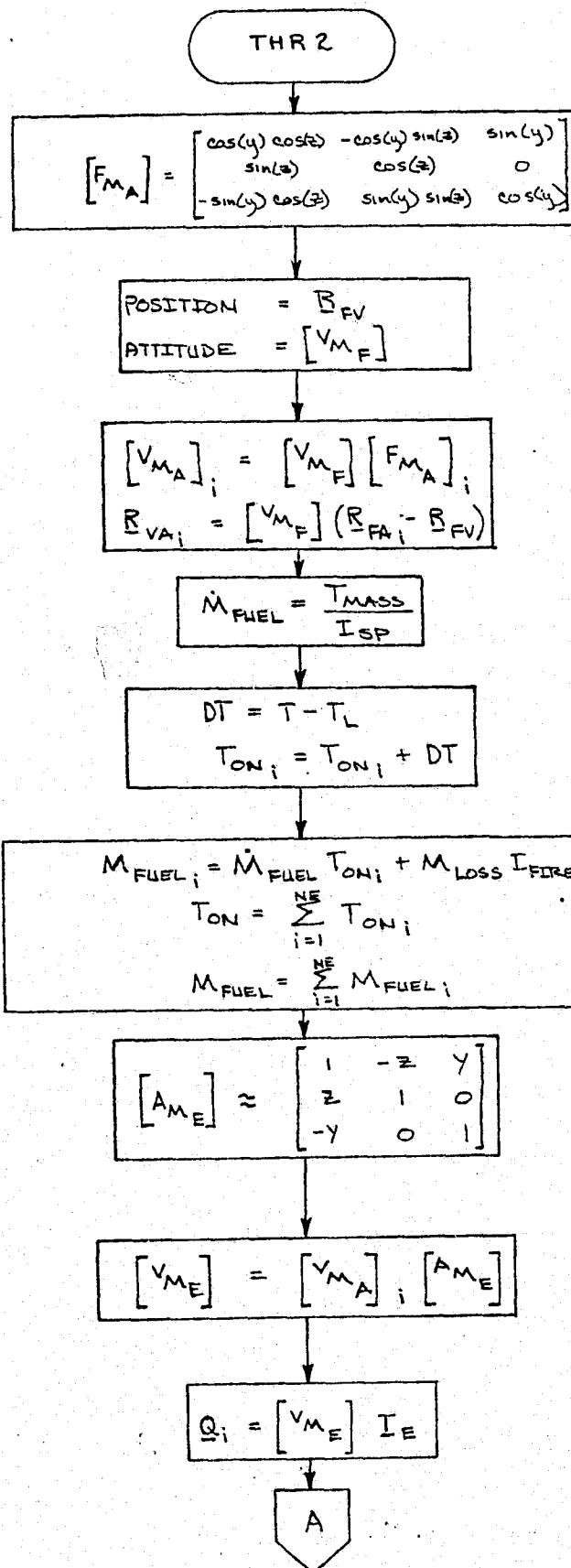
The direction of output thrust force, Q , depends upon engine location and deflection. Engine locations are initially specified in the Fabrication (F) frame. An engine coordinate system (E) and an actuator coordinate system (A) are also defined for each engine. Figure 4.7-62 depicts the various coordinate system relationships used in THR2.

Inputs to THR2 consist of:

- Location of vehicle mass center in body axis system
- Fabrication to vehicle body axis transformation matrix
- Engine actuator locations and mounting angles
- Engine thrust and gimbal deflections
- Fuel loss per OMS firing
- Specific impulse
- Number of OMS engines
- Thrust command on-off delays and minimum impulse time

Outputs are the computed OMS forces and torques in body axis coordinates along with fuel mass consumed.

To function adequately as a reference data source, THR2 must be modified to include calculation of OMS oxidizer consumed. Fuel and oxidizer consumption are then output. A main program (driver) should also be incorporated to control and maintain input/output compatibility with the simulation module. This includes the OMS/RCS propellant sharing interface and propellant pressurant calculations.



SET UP ATTITUDE MATRIX CONV.
FROM (A) FRAME TO (F) FRAME
(y & z ARE ACTUATOR ENGINE MOUNT
ANGLES)

LOOK UP POSITION AND ATTITUDE
RELATIONSHIPS BETWEEN (F) AND
(V) FRAMES

COMPUTE ATTITUDE AND POSITION
OF ACTUATOR SYSTEMS RELATIVE
TO THE VEHICLE FRAME

COMPUTE FUEL MASS FLOW RATE

CALCULATE ENGINE ON TIME

CALCULATE TOTAL ENGINE ON
TIME AND FUEL CONSUMED

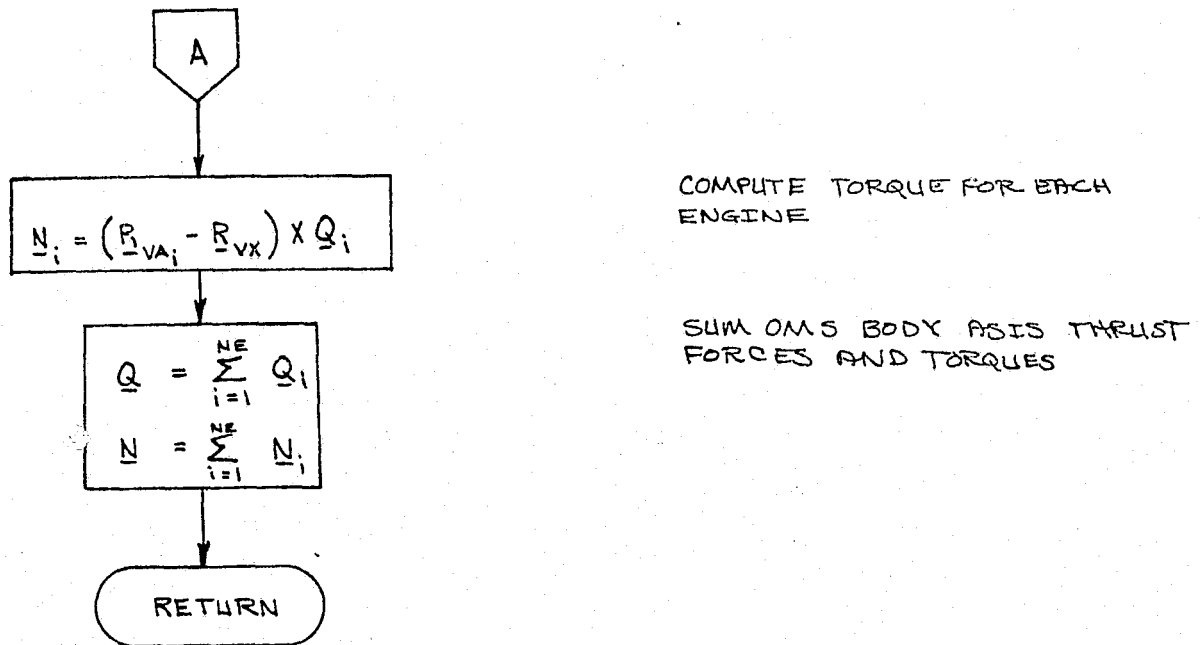
DEFINE ATTITUDE RELATIONSHIPS
BETWEEN (E) SYSTEMS AND (A)
SYSTEMS (ASSUME SMALL ($\pm 4^\circ$)
TVC ANGLES)

COMPUTE (E) FRAME TO (V) FRAME
MATRIX

COMPUTE ENGINE THRUST FORCE
FOR EACH ENGINE

FIGURE 4.7-61. THR2 SUBROUTINE MATH FLOW

4.7-167



LEGEND:

X_V, Y_V, Z_V Axes of the vehicle (V) body frame.

X_F, Y_F, Z_F Axes of the fabrication (F) frame.

$X_{E_i}, Y_{E_i}, Z_{E_i}$ Axes of the i th engine (E) frame.

$X_{A_i}, Y_{A_i}, Z_{A_i}$ Axes of the i th Actuator (A) frame.

R_{FV} Position of the vehicle's (V) body frame in the fabrication (F) frame. meters

R_{FA_i} Position of the i th engine actuator (A) in the fabrication (F) frame. meters

R_{VA_i} Position of the i th engine actuator (A) in the vehicle (V) body frame. meters

$[F_{MA}]_i$ Attitude matrix to go from the i th actuator (A) frame to the fabrication (F) frame.

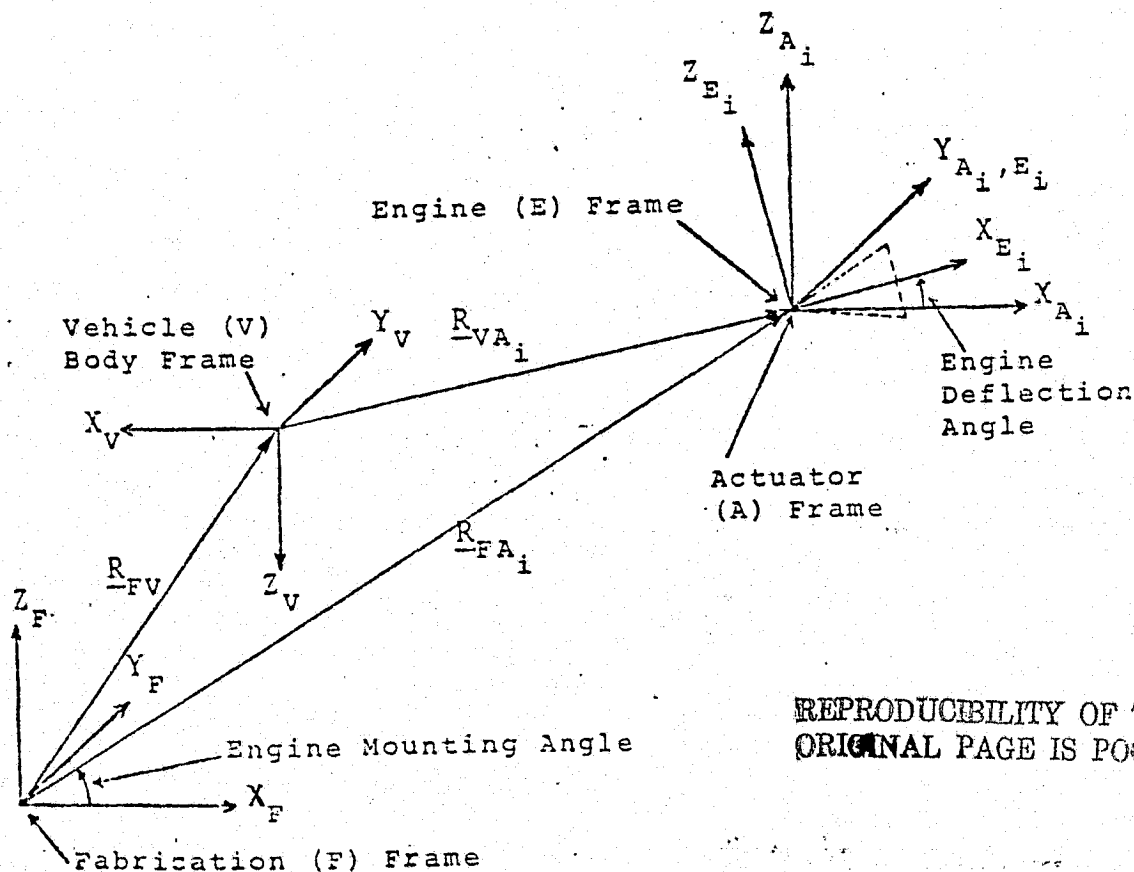
FIGURE 4.7-6] (CONTINUED)

$[M_F^V]$	Attitude matrix to go from the fabrication (F) frame to the vehicle (V) body frame.	
$[M_A^V]_i$	Attitude matrix to go from the <i>i</i> th actuator (A) frame to the vehicle (V) body frame.	
T_{MASS}	Thrust magnitude divided by the gravitational acceleration.	kg
I_{SP}	Specific impulse	sec
DT	Delta time since last update	sec
T	Present time	sec
T_L	Time of the last THR2 update	sec
T_{ON_i}	Time <i>i</i> th OMS engine has been on.	sec
M_{LOSS}	Fuel lost per OMS engine firing.	kg
I_{FIRE_i}	Number of times <i>i</i> th OMS engine has been fired.	
\dot{M}_{FUEL}	Mass flow rate.	kg/sec
M_{FUEL_i}	Mass of the fuel used by the <i>i</i> th OMS engine.	kg
M_{FUEL}	Total fuel mass use by all the OMS engines.	kg
T_{ON}	Total on-time for all OMS engines.	sec
$[M_E^A]$	Attitude matrix to go from the engine (E) frame to the actuator (A) frame.	

FIGURE 4.7-61. (CONTINUED)

- $[V_{M_E}]$ Attitude matrix to go from the engine (E) frame to the vehicle (V) body frame.
- \underline{T}_E Thrust vector for all the OMS engines. nt
- \underline{Q}_i Force vector of the i th OMS engine. nt
- \underline{N}_i Torque vector of the i th OMS engine. nt-m
- \underline{R}_{VX} Position of the vehicle's center of mass (X) in the vehicle (V) body frame. meters
- \underline{Q} Total force vector nt
- \underline{N} Total torque vector nt-m
- NE Number of gimbalable engines

FIGURE 4.7-61. (CONTINUED)



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FIGURE 4.7-62. THR2 COORDINATE SYSTEMS RELATIONSHIPS

OMS Validation Methods and Check Cases

Check case design for OMS Simulation Module verification should consist of closed-loop command sequences to evaluate proper execution sequence and the calculated forces, torques, and mass properties information. A brief check case example is shown in Table 4.7-16 (Ref. 17). In this case, engines 1 and 3 were turned on with their engines in the null position. Both engines were then commanded to their indicated stops. The corresponding forces and moments are given in the figure. Check cases of this type should cover both the static design end-points (as shown) and intermediate values. Dynamic sequences should also be designed for OMS thrust transient effects analyses.

OMS Data Base Impact

Data base impact should be minimal for OMS Simulation Module verification, as the reference module and check cases can be simple in design and construction, thus reducing the overall OMS verification data base requirements.

TABLE 4.7-16. OMS CHECK CASE EXAMPLE

Engine	Engines in Null Position		A X I S	Engines 1 & 3 Commanded to Stops	
	Forces	Torques		Forces	Torques
1	43244.537	1927.814	X	43620.685	-13549.384
	-4263.431	20443.561	Y	-7354.579	-34151.602
	9507.928	398.718	Z	6411.012	53012.341
2	0.0	0.0	X	0.0	0.0
	0.0	0.0	Y	0.0	0.0
	0.0	0.0	Z	0.0	0.0
3	43244.537	-1203.340	X	43620.685	14037.903
	4263.431	20443.561	Y	7354.579	-34151.602
	9507.928	-3693.951	Z	6411.012	-56336.236
TOTALS	86489.074	724.504	X	87241.370	488.519
	0.0	40887.121	Y	0.0	-68303.203
	19015.856	-3295.233	Z	12822.024	-3323.896

4.7-172

4.7.3.4 Solid Rocket Motors (SRM)

SRM System Description

The SRM represents the engine and propellant portion of the Solid Rocket Boosters (SRB's). One SRM and its associated propellant is contained in each SRB. Each SRB contains, in addition to the SRM subsystem, an avionics subsystem, a recovery subsystem, a thrust control (TVC) subsystem, and a structures subsystem.

In general, solid rocket propulsion depends on 1) the grain composition, geometry, and mean temperature at ignition, 2) the combustion chamber conditions, and 3) the nozzle characteristics. The grain geometry of the SRM propellant consists of a truncated cone for the first 75 percent followed by a star in the latter 25 percent. The mean grain temperature at ignition and combustion chamber are limited under normal operation. The nozzle characteristics are fixed by design. Each SRM has the same overall propulsion characteristics; however, minor deviations are expected due to variations in initial mean grain temperature and grain irregularities.

SRM Simulation Module Description and Performance Parameters

The simulation module is based upon the SRM as defined for the SRB's used on the Space shuttle vehicle. The SRM simulation module will utilize tabular data and table lookup techniques to calculate the SRM total thrust, the body axis thrust forces and moments, the propellant mass, and mass flow rate (Ref. 11).

SRM simulation module interfaces are shown in Figure 4.7-63. Table 4.7-17 lists the performance parameters associated with the SRM simulation module. These parameters were established using the criteria developed in Section 4.1.

SRM Reference Data Sources and Data Formats

A reference software module will provide reference data to be used to verify the SRM simulation module. Reference modeling is only to a detail necessary to provide reference data for normal operation of the SRM (i.e., no failure considerations are provided and the model does not provide for thrust termination other than the nominal burning to depletion). By normal operation it is meant that the operating status remains within the operational design specifications.

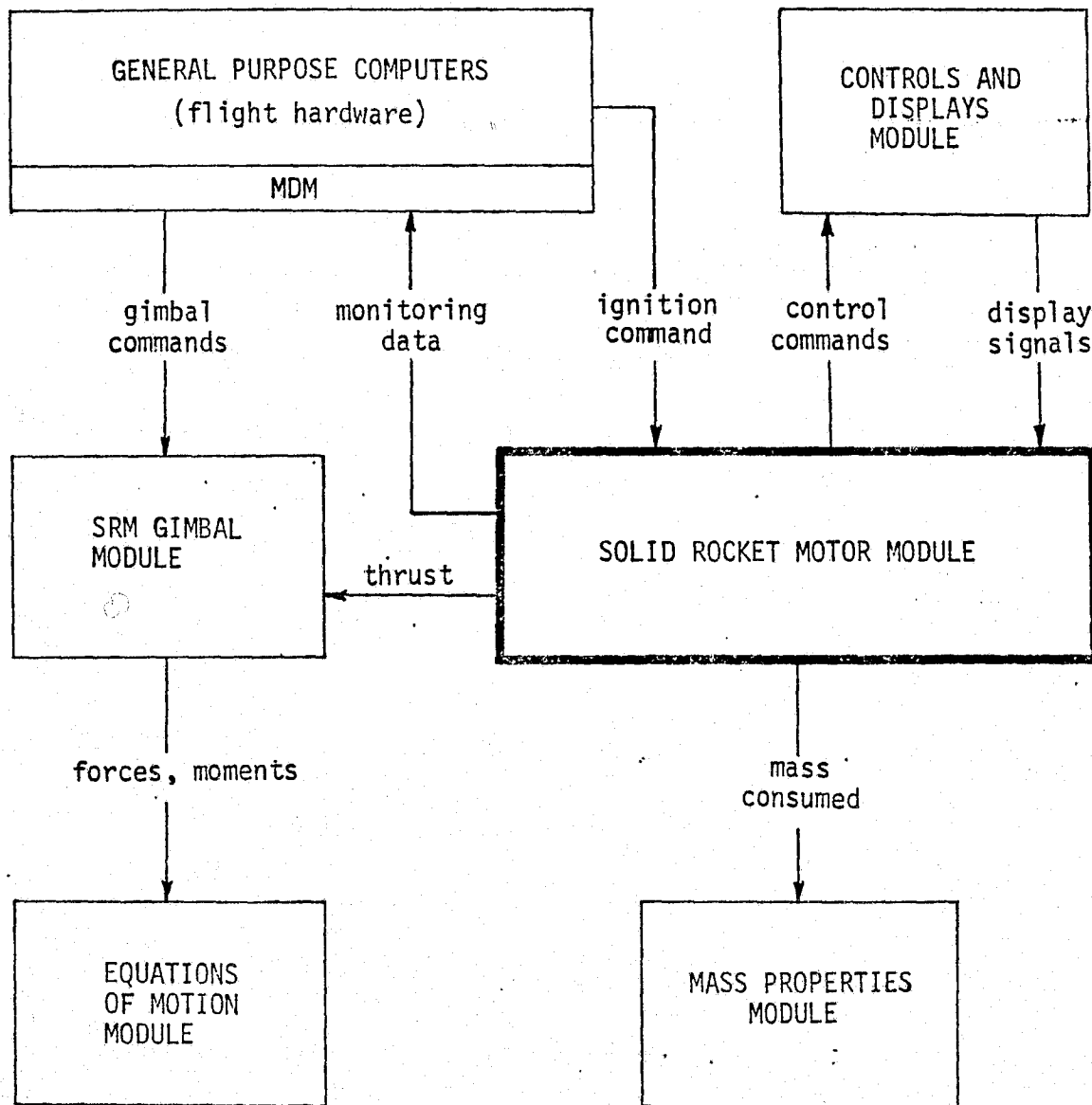


FIGURE 4.7-63. SRM SIMULATION MODULE INTERFACES

TABLE 4.7-17 SOLID ROCKET MOTOR MODULE PARAMETER LIST

PARAMETER	DEFINITION	TYPE ^a
DT	INTEGRATION TIME STEP	I
P ₀	ATMOSPHERIC PRESSURE	I
δP, δY	δP - PITCH GIMBAL ANGLE, δY - YAW GIMBAL ANGLE	I
T _G	MEAN GRAIN TEMPERATURE AT IGNITION	I
IFM	INDICATOR FLAG TO SPECIFY TRANSFORMATION OF THRUST INTO BODY-AXIS FORCES AND MOMENTS	I
i	SRM INDICATOR INDEX (SPECIFIES LEFT OR RIGHT SRM)	I
M	MASS OF THE GRAIN (USED INTERNALLY AND UPDATED FOR OUTPUT)	P
P _c , T _c	P _c - COMBUSTION CHAMBER PRESSURE, T _c - COMBUSTION CHAMBER TEMPERATURE	CP
\dot{M}	MASS FLOW RATE	CP
TH _v	VACUUM THRUST	P
TH	ALTITUDE THRUST	CP
A _E	EFFECTIVE EXHAUST AREA	DB
θ _i , ψ _i	THE TWO ANGLES THAT DEFINE THE GIMBAL NULL POSITION WRT THE BODY AXES (ONE SET FOR EACH SRB)	DB
TX, TY, TZ	THRUST FORCES IN THE TIME INVARIANT BODY AXES	CP
LX, LY, LZ	THRUST MOMENTS IN THE TIME INVARIANT BODY AXES	CP
XG _i , YG _i , ZG _i	GIMBAL LOCATION IN THE TIME INVARIANT BODY AXES SYSTEM (ONE SET FOR EACH SRB)	DB

- ^a
P - PERFORMANCE PARAMETER
CP - CRITICAL PERFORMANCE PARAMETER
I - INPUT
DB - DATA BASE INPUT

As described in the Figure 4.7-64 math flow, the reference module model consists primarily of the reference performance characteristics tabulated as a function of grain mass remaining (M) and mean grain temperature at ignition (T_G). Specifically, the combustion chamber pressure, the vacuum thrust, and the mass flow rate are stored as functions of M and T_G , and the combustion chamber temperature is stored as a function of M . (Chamber temperature is not characteristically highly dependent on chamber pressure variations or the initial grain temperature; however, if SRM performance data indicates the contrary, then it should be modeled accordingly.) For each time step during simulated burning, the mass flow rate is used to decrement the mass remaining.

Due to standardization, reference propulsion characteristics are the same for both SRM's being simulated, and a single model can represent the propulsion for both (separately). In the reference module, the only difference in the left and right SRM computations are associated changes in relative geometry (i.e., the gimbal location and the gimbal null angles). These changes are handled by the pick-up of the appropriate value through an associated input index (i).

The propulsion parameters are computed by table interpolations and are indicated by the functions f_1 , f_2 , f_3 , and f_4 of Figure 4.7-64. The total altitude thrust is computed by correcting the vacuum thrust for the loss due to atmospheric pressure. If desired, the thrust is then resolved into the time invariant body axis components with the corresponding thrust moments.

The indicated operations for resolving the thrust into the body axis components are presented as two successive transformations. The inner transformation (f_6) represents the resolution of the total thrust (assumed to be along a single line of action represented by the first component of a triad axis system) into thrust along the gimbal null axes (representing a zero deflection of gimbal actuators). The outer transformation (f_5) represents the transformation of these null axis thrust components into thrust components along the time invariant body axes. The two functions, f_5 and f_6 , are dependent on the appropriate coordinate system definitions as well as baseline vehicle characteristics.

The moment computations indicated are the standard moment equations in terms

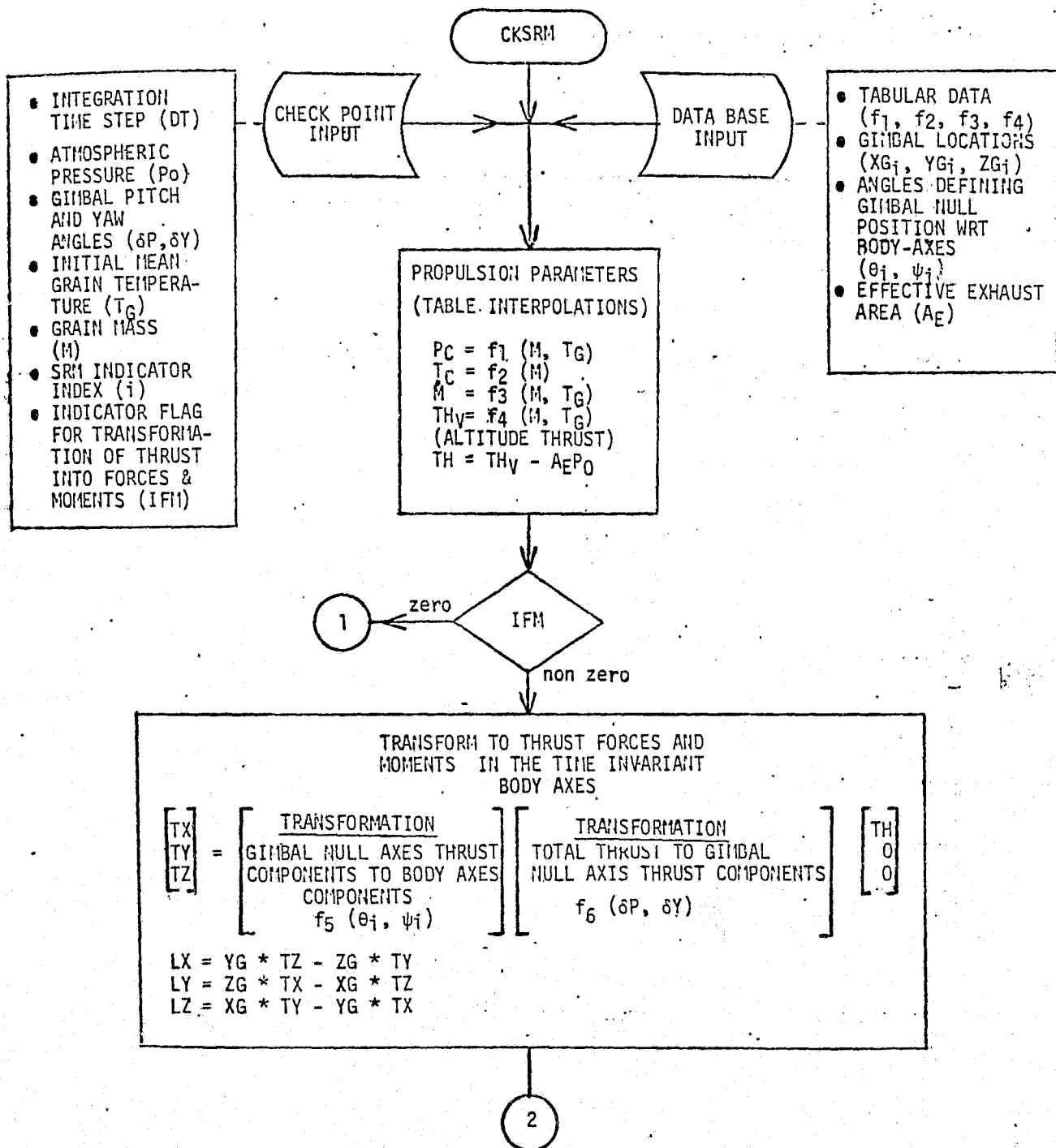


FIGURE 4.7-64 SRM REFERENCE MODULE MATH FLOW

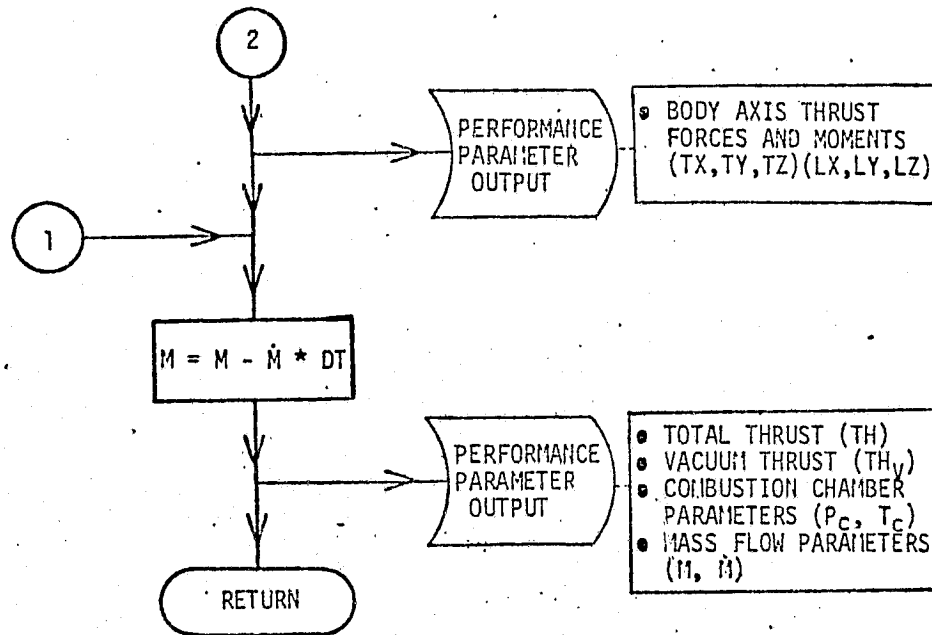


FIGURE 4.7-64 (CONTINUED)

of the forces (TX, TY, TZ) and the moment arms (XG, YG, ZG) with the appropriate sign convention consistent with a right hand coordinate system definition. Performance parameters are then output and a mass update is performed. Additional outputs are also made as necessary for simulation module verification.

SRM Validation Methods and Check Cases

Validation methods used to verify the simulation module utilize the data generated with the reference module for comparison purposes. That is, the reference module and simulation module would both be accessed by a driver routine supplying check point data and the resulting performance parameters would be output and stored for post-processing applicable to the verification task.

One check point should be established to reproduce the reference sea level propulsion characteristics (i.e., M should be initialized to a reference value, T_G should be assigned a reference temperature (e.g., 60°F), P_0 should be sea level atmospheric pressure, and DT as appropriate for the mass integration). (NOTE: that when generating propulsion characteristics for the complete SRM action time, the sequential check points use the mass (M) as updated in the previous check point.)

Additional check points should reproduce the propulsion characteristics for non-reference initial mean grain temperatures (i.e., $T_G \neq 60^{\circ}\text{F}$, but within the operational range of 40°F to 90°F).

The remaining check points should exercise the modules through the full range of nominal use. These check points can be generated with off-line digital analysis programs and can be representative of realistic states along typical trajectories (including the gimbals deflections providing realistic TVC). These cases are required to provide verification data for the altitude dependency of the thrust and the calculations necessary to compute the thrust related forces and moments.

The actual verification can be made by direct comparison of output (plots and single case situations) and by the use of the plotting techniques discussed in Section 5.3.

In addition to the check point capability, the reference module is structured

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so as to be easily driven by data generated in previous simulation runs. This provides the capability to verify the simulation for particular situations suspected of inaccuracies.

SRM Data Base Impact

The reference module and the associated verification technique as presented require certain data to be available for the reference module data base. The data base requirements are presented with an indication of the likely source in Table 4.7-18.

It should be noted that the tabular data represents the expected performance characteristics and not the design requirement characteristics. However, the design requirements may be used prior to availability of the SRM reference characteristics. In addition, some form of configuration control protection should be employed with respect to data base items for the reference module, since it is anticipated that changes will occur as the program progresses.

TABLE 4.7-18 SRM REFERENCE MODULE DATA BASE REQUIREMENTS

ITEM DESCRIPTION	SOURCE
a PROPULSION CHARACTERISTICS (P_C , T_C , \dot{M} , TH_V) AS APPROPRIATE FOR REDUCTION TO TABULAR FORM	a SRM SUBSYSTEM CONTRACTOR
b GIMBAL LOCATION (XG_i , YG_i , ZG_i) IN BODY AXES	b VEHICLE CONTRACTOR
c ANGLES DEFINING GIMBAL NULL AXES WRT THE BODY AXES (θ_i , ψ_i)	c VEHICLE CONTRACTOR
d EFFECTIVE EXHAUST AREA (A_E)	d VEHICLE CONTRACTOR

4.7.4 Power Generation Subsystems

This section discusses the Electrical Power Generation and Auxiliary Power Generation.

4.7.4.1 Electrical Power Generation

The Electrical Power Generation (EPG) portion of the Electrical Power System includes three H_2/O_2 fuel cells with associated water cooling loops; and the Power Reactant Storage and Distribution subsystem (PRSD). (The battery subsystem has been deleted.) The distribution and control of electrical power is accomplished by the Avionics Subsystem.

EPG System Description

Each of the three fuel cells contains subsystems which provide the following functions:

- Heating and pressure regulation of the H_2 and O_2 .
- Coolant circulation and control for proper temperature control.
- H_2/O_2 circulation to remove product water from the fuel cell.

Reference 20 provided Figure 4.7-65, a schematic of the fuel cell interfaces with other systems. Figure 4.7-66 (also from Reference 20) illustrates the fuel cell internal operations and functions, which are discussed below.

Fuel Cell

The H_2 and O_2 from the PRSD are passed through pre-heaters (heat exchangers) which warm the gases prior to flow through coupled pressure regulators which maintain the proper operational gas pressures for purges and normal fuel power generation.

The fuel cell coolant loop circulates a cooling fluid through the fuel cell. This fluid transfers heat from the fuel cell to the active Thermal Control System. The system includes coolant pump, flow control valve, condenser (heat exchanger), startup heaters, fuel cell coldplates, O_2/H_2 pre-heaters (heat exchangers), and coolant accumulator.

The H_2/O_2 circulation is accomplished by a combination pump/ H_2O separator. The flow is through the fuel cell, condenser, and the water separator. The fuel

4.7-183

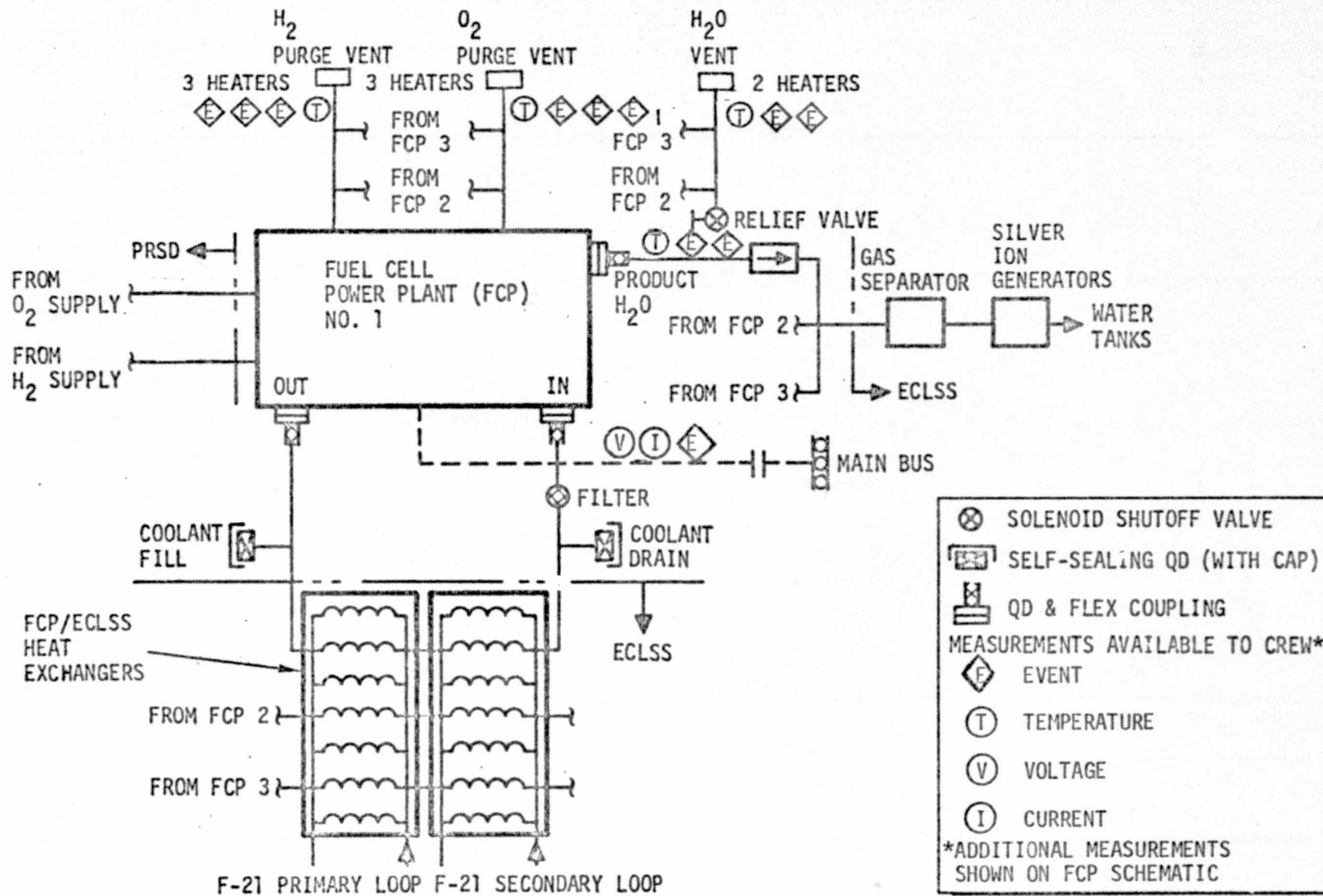


FIGURE 4.7-65 ELECTRICAL POWER GENERATION
(EPG) DESCRIPTION
FCP SUBSYSTEM SCHEMATIC

4.7-184

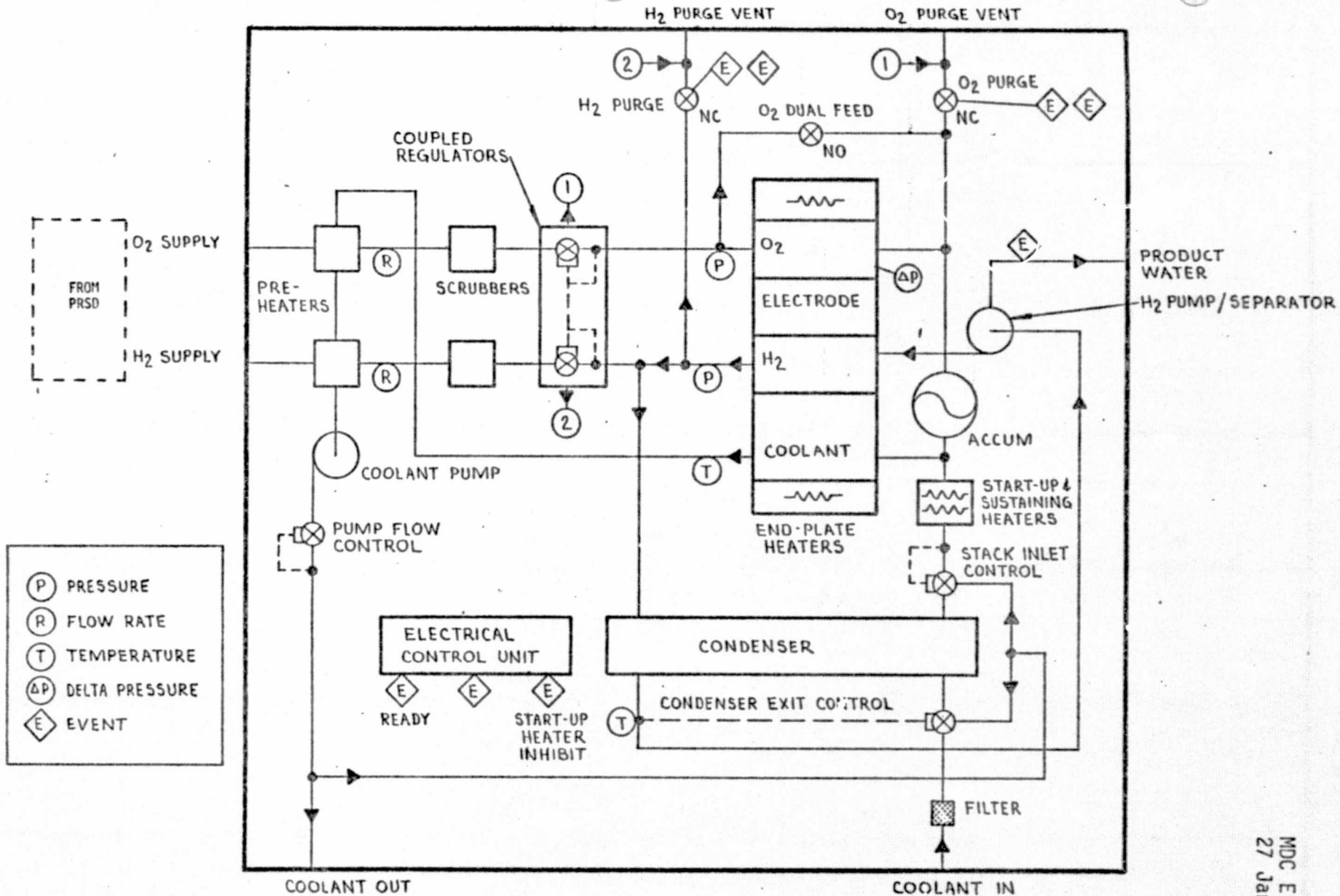


FIGURE 4.7-66, EPG DESCRIPTION, FUEL CELL POWER PLANT SCHEMATIC

MDC E1136
27 January 1975

cell product water is output to the ECLSS for storage and use.

PRSD

The Power Reactant Storage and Distribution (PRSD) subsystem comprises cryogenic storage tanks, control valves and distribution manifold. The Shuttle subsystem has two tank assemblies for O_2 and two tank assemblies for the H_2 . However, provisions of the manifolds allow the addition of cryogenic O_2 and H_2 tank assemblies in the payload bay. Each tank assembly has two heaters, burst diaphragm and relief valve. The subsystem schematic from Reference 20 is shown in Figure 4.7-67.

EPG Module Description and Performance Parameters

The EPG module functions are to provide the calculations related to the fuel cell operations and the PRSD performance. Figure 4.7-68 is an illustration of the EPG module functional elements and their interfaces with other modules. The functions of each functional element are discussed in the following paragraphs. The module performance parameters for the fuel cell and PRSD are identified in Tables 4.7-19 and 4.7-20.

Fuel Cell Pressure Control - The following calculations are provided by this element:

- Electrode pressure - a function of temperature, gas quantity, gas volume.
- Gas Usage rates - a function of electrical load, inlet pressure, electrode pressure, temperature, purge mode selection, and electrode differential pressures.
- Electrode Gas Quantities - functions of regulator flow characteristics and gas usage rates.
- H_2O quantity - function of electrical load and electrode pressures.

Fuel Cell Coolant Loop - This element makes the following calculations:

- Pump flow rate - a function of loop configuration selection, fluid temperature, input voltage.
- Pump outlet temperature - a function of inlet temperature, flow rate, input electrical power, and output hydraulic power.

4.7-186

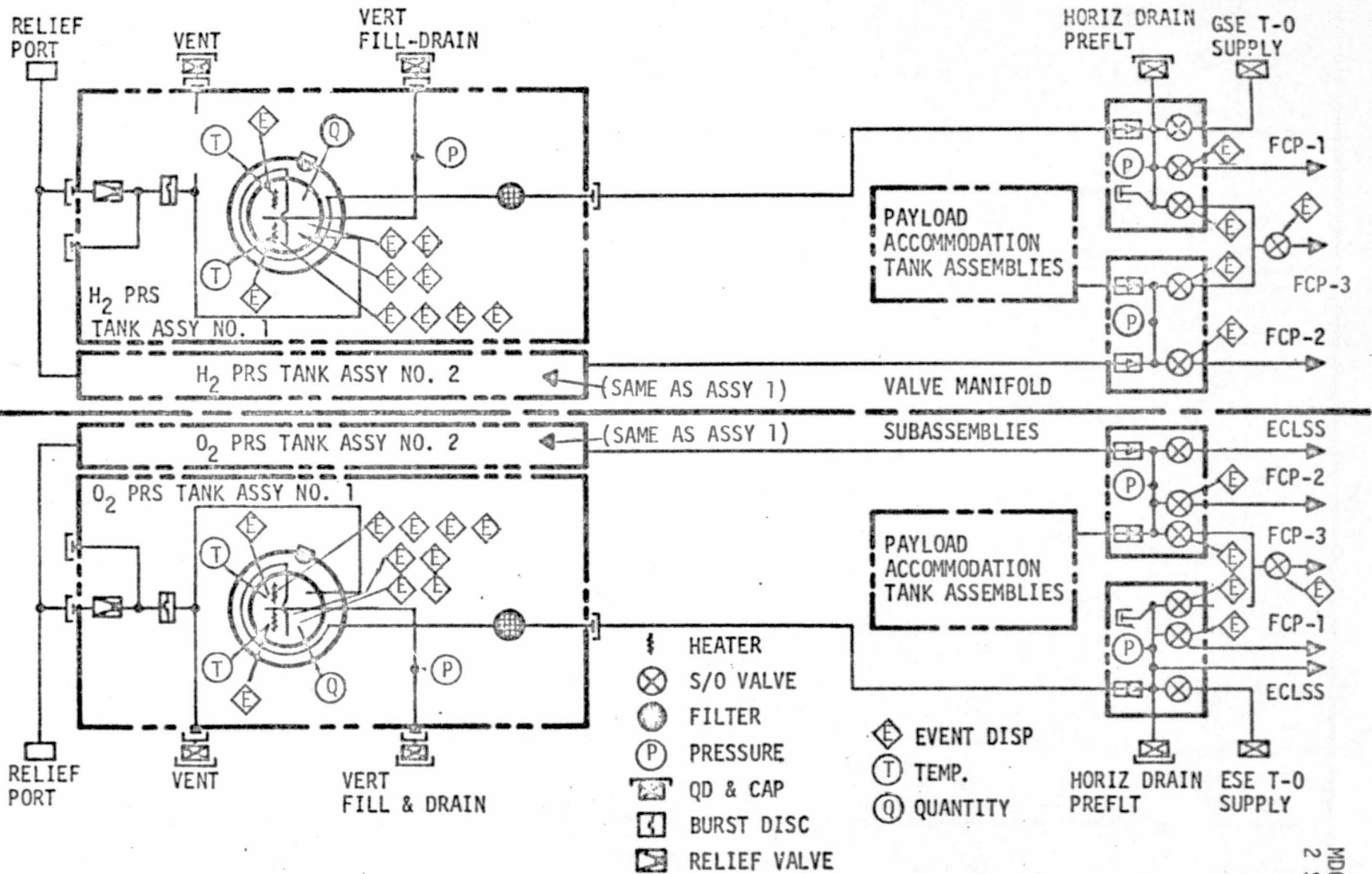


FIGURE 4.7-67 POWER REACTANT STORAGE AND DISTRIBUTION (PRSD) SUBSYSTEM SCHEMATIC

4.7-187

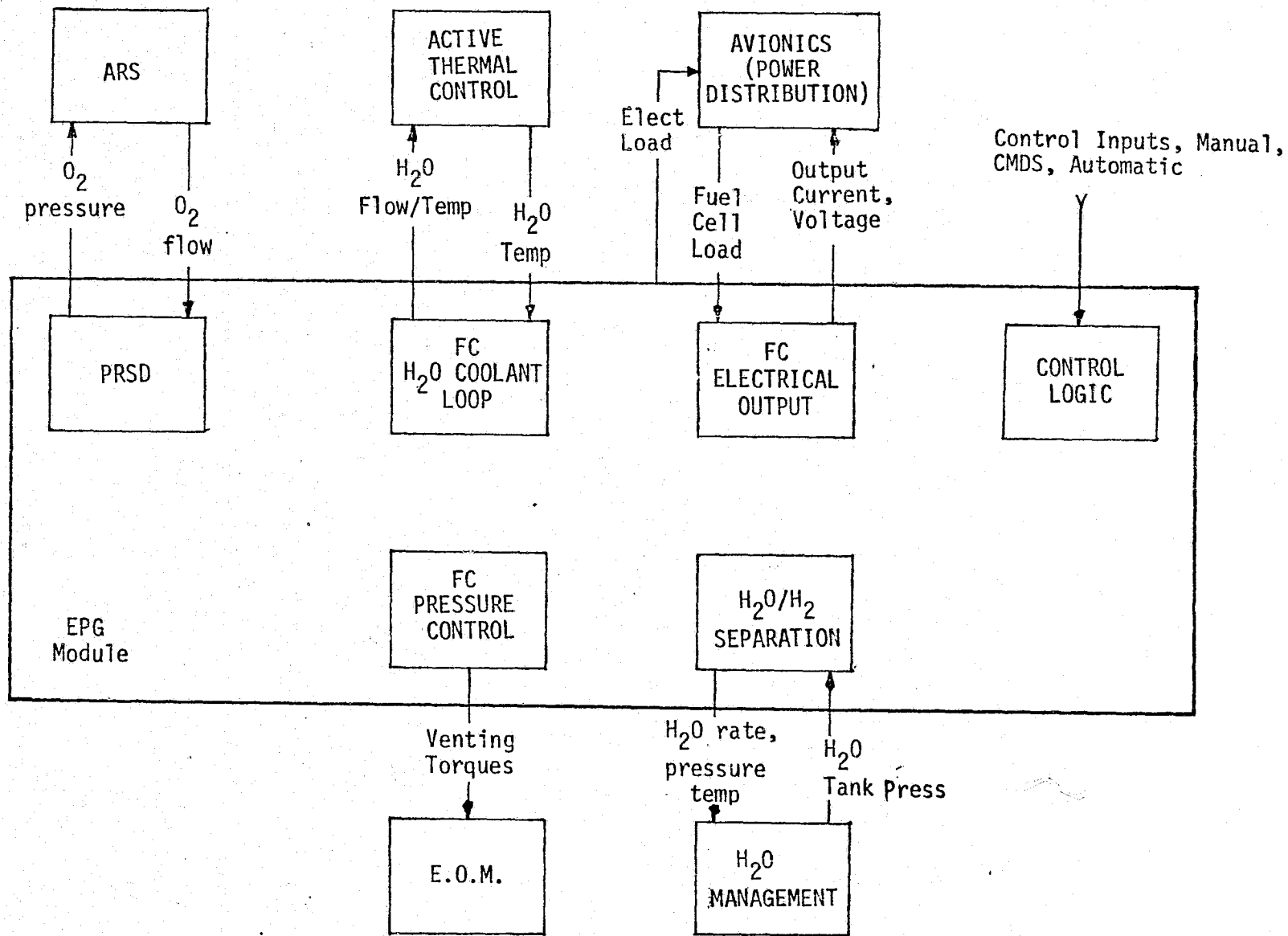


FIGURE 4.7-68. ELECTRICAL POWER GENERATION MODULE ELEMENTS AND INTERFACE WITH OTHER MODULES.

TABLE 4.7-19 EPS FUEL CELL PARAMETERS (TYP 3)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
H2 Regulator Pressure	0	+100	PSIA	CP
Voltage	0	+40	VDC	P
Current	0	+500	AMP DC	P
Cell Current Low	LOW		EVENT	P
Ready	OFF	ON	EVENT	I
Start Up Heater	OFF	ON	EVENT	I
Startup Heater - OFF		ON	EVENT	I
Stack Cool Out Temperature	-50	+300	DEG F	CP
Condenser Exit Temperature	0	+250	DEG F	CP
O2 Flow	0	25	LB/HR	CP
O2 Regulator Pressure	0	+100	PSIA	CP
H2 Flow	0	4.5	LB/HR	CP
O2 Purge Valve Automatic		ON	EVENT	I
H2O Condition	ON	OFF	EVENT	I
H2O Outlet Valve Position	OPEN	CLOSE	EVENT	I
Product H2O Line Temperature	0	+200	DEG F	CP
H2O Line Heater Active		ON	EVENT	I
H2O Line Heater ON		ON	EVENT	I
O2 Pressure Over H2O	0	+10	PSID	P
H2 Purge Valve OPEN		ON	EVENT	I
H2 Purge Valve - Automatic		ON	EVENT	I
O2 Purge Valve OPEN		ON	EVENT	I

^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

TABLE 4.7-20 EPS POWER REACTANT STORAGE AND DISTRIBUTION PARAMETERS
(COMMON 3 FUEL CELLS)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
H2 Circulation Isolation Valve 1A OPEN	CLOSE	OPEN	EVENT	P
H2 Circulation Isolation Valve 1B OPEN	CLOSE	OPEN	EVENT	P
H2 Circulation Pump 1A ON		ON	EVENT	P
H2 Circulation Pump 1A Automatic		ON	EVENT	P
H2 Circulation Pump 1B ON		ON	EVENT	P
H2 Circulation Pump 1B Automatic		ON	EVENT	P
H2 Circulation Line Heater No. 1A-Active		ON	EVENT	P
H2 Circulation Line Heater No. 1B-Active		ON	EVENT	P
H2 Manifold 1 Pressure	0	+400	PSIA	CP
H2 Manifold 1 Isolation Valve Closed	OPEN	CLOSE	EVENT	P
H2 Manifold 2 Pressure	0	+400	PSIA	CP
H2 Manifold 2 Isolation Valve Closed	OPEN	CLOSE	EVENT	P
H2 FCP 1 Supply Valve Closed	OPEN	CLOSE	EVENT	P
H2 FCP 2 Supply Valve Closed	OPEN	CLOSE	EVENT	P
H2 FCP 3 Supply Valve Closed	OPEN	CLOSE	EVENT	P
H2 Pressure	0	+400	PSIA	CP
H2 Quantity	0	100	PCNT	P
H2 Heater 1A ON	OFF	ON	EVENT	P
H2 Heater 1A Temperature	-425	+200	DEG F	CP
H2 Heater 1B ON	OFF	ON	EVENT	P
H2 Heater 1B Temperature	-425	+200	DEG F	CP
H2 Purge Vent Temperature	0	+250	DEG F	CP
H2 Relief Vent Heater 1 Active		ON	EVENT	P
H2 Relief Vent Heater 2 Active		ON	EVENT	P
H2 Relief Vent Heater 3 Active		ON	EVENT	P
O2 Pressure	0	+1500	PSIA	CP
O2 Quantity	0	100	PCNT	P

TABLE 4.7-20 (CONTINUED)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
02 Heater 1A ON	OFF	ON	EVENT	P
02 Heater 1A Temperature	-325	+300	DEG F	CP
02 Heater 1B ON	OFF	ON	EVENT	P
02 Heater 1B Temperature	-325	+300	DEG F	CP
02 Circulation Isolation Valve 1A OPEN	CLOSE	OPEN	EVENT	P
02 Circulation Isolation Valve 1B OPEN	CLOSE	OPEN	EVENT	P
02 Circulation Pump 1A ON		ON	EVENT	P
02 Circulation Pump 1A Automatic		ON	EVENT	P
02 Circulation Pump 1B ON		ON	EVENT	P
02 Circulation Pump 1B Automatic		ON	EVENT	P
02 Circulation Line Heater No. 1A-Active		ON	EVENT	P
02 Circulation Line Heater No. 1B-Active		ON	EVENT	P
02 Manifold 1 Pressure	0	+1500	PSIA	CP
02 Manifold 1 Isolation Valve Closed	OPEN	CLOSE	EVENT	P
02 Manifold 2 Pressure	0	+1500	PSIA	CP
02 Manifold 2 Isolation Valve Close	OPEN	CLOSE	EVENT	P
FC 1 02 Supply Valve Closed	OPEN	CLOSE	EVENT	P
FC 2 02 Supply Valve Closed	OPEN	CLOSE	EVENT	P
FC 3 02 Supply Valve Closed	OPEN	CLOSE	EVENT	P
H2O Relief Vent Temperature	0	+250	DEG F	CP
FC H2O Relief Vent Heater 1 Active		ON	EVENT	P
FC H2O Relief Vent Heater 2 Active		ON	EVENT	P
02 Purge Vent Temperature	0	+250	DEG F	CP
02 Relief Vent Heater 1 Active		ON	EVENT	P
02 Relief Vent Heater 2 Active		ON	EVENT	P
02 Relief Vent Heater 3 Active		ON	EVENT	P

^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

- Coolant flow to ATCS - a function of condenser H_2O/H_2 outlet temperature, pump flow rate, startup heater inlet temperature, and condenser fluid outlet temperature.
- Fluid temperature to ATCS - a function of pump outlet temperature.
- Coolant flow to condenser - a function of coolant flow to ATCS, condenser H_2O/H_2 outlet temperature, startup heater inlet temperature, and condenser fluid outlet temperature.
- Condenser fluid inlet temperature - a function of condenser fluid flow rate, pump outlet temperature, condenser H_2/H_2O outlet temperature, ATCS fluid flow, and ATCS fluid return temperature.
- Condenser fluid outlet temperature - a function of condenser fluid flow, H_2/H_2O flow, H_2/H_2O inlet temperature, and condenser fluid inlet temperature.
- Startup heater inlet temperature - a function of stack inlet control valve characteristics, pump fluid outlet temperature, condenser fluid outlet temperature, condenser flow rate, and pump flow rate.
- Startup heater temperature - functions of heater electrical power, inlet fluid temperature, and fluid flow rate.
- Startup heater outlet temperature - a function of fluid flow, heater temperature, and inlet fluid temperature.
- Fuel cell outlet temperature - a function of the fuel cell temperature, pump flow rate, and startup heater outlet temperature.
- O_2 Pre-heater fluid outlet temperature - a function of inlet fluid temperature, inlet O_2 temperature, O_2 flow rate, pump flow rate.
- O_2 Pre-heater outlet O_2 temperature - a function of inlet O_2 temperature, inlet fluid temperature, and O_2 and fluid flow rates.
- H_2 Pre-heater outlet fluid temperature - a function of O_2 pre-heater fluid outlet temperature, H_2 inlet temperature, H_2 flow rate, and fluid flow rate.
- H_2 Pre-heater outlet H_2 temperature - a function of O_2 Pre-heater fluid outlet temperature, H_2 inlet temperature, H_2 flow rate, and fluid flow rate.
- Fuel cell temperature - a function of electrical load, end plate heater power, O_2/H_2 flow rates, coolant flow rate, H_2/H_2O flow rate, coolant inlet temperature, and H_2/H_2O inlet temperature.

H_2/H_2O Circulation - This element calculates the following:

- H_2/H_2O pump flow - a function of electrical input voltage, H_2/H_2O temperature,

rpm, and output power.

- Separator H₂O flow - a function of separator efficiency and H₂O quantity inlet.
- Separator H₂O pressure - a function of H₂O tank pressure, and H₂O flow.
- Separator outlet H₂O temperature - a function of inlet H₂/H₂O temperature, input electrical power, and output hydraulic power.
- H₂ pump outlet temperature - a function of the inlet H₂/H₂O temperature, input electrical power, and output hydraulic power.
- H₂ pump outlet pressure - a function of H₂ temperature, and pump flow rate.
- Condenser inlet H₂/H₂O temperature - a function of inlet H₂ temperature, inlet H₂ flow, H₂/H₂O pump flow, fuel cell outlet H₂/H₂O temperature, and H₂/H₂O pressure.

Fuel Cell Electrical Output - This element generates the following:

- Output voltage level - a function of reactant quantities at electrodes, output current, and fuel cell temperature.
- Output current - a function of load impedance, and fuel cell output voltage.

PRSD - The calculations performed by this element are:

- Reactant Quantities - functions of ECLSS usage, fuel cell usage, and relief venting.
- Tank temperatures - functions of input heater power, heat leakage, reactant flow rates, and pressures.
- Tank pressures - functions of reactant quantities, temperatures, and volumes.
- Burst diaphragm rupture (discrete) - a function of diaphragm characteristics and pressure.
- Relief flow rate - a function of tank pressure, ambient pressure, reactant temperature, and relief valve characteristics (only after burst diaphragm rupture).
- Manifold temperature - a function of inlet and outlet flow rates, and temperatures.
- Manifold pressure - a function of inlet flow, outlet flow, and manifold temperature.

- Manifold flow rates - functions of inlet pressure, inlet temperature, and outlet pressure.

EPG Reference Data Sources and Data Formats

Several sources of data exist for use for developing reference modules or making direct comparison with simulator results. The system and component design performance requirements, analysis/performance predictions, test results, and flight performance data are a few. Figure 4.7-69 is an overview flow chart of methods of using these sources in a direct comparison with the results of a simulator run. In brief, the method is to establish the design requirement, analysis, etc. as input conditions on the simulation module to be verified. The simulation module is allowed to reach a stabilized response and the resulting data output for manual comparison with the spec requirements, analysis results, etc. This method is discussed in Section 4.2.1.4. The method of section 5.1 can be used with the reference models for verification.

Fuel Cell

The fuel cell requirements are provided by Reference 30. The requirements, analysis and predictions can be determined from Reference 31, design or analysis groups, and MPAD. Many of the test results can be acquired from individual acceptance tests and integrated-systems checkout. Reference 29 discusses a computer program for simulation of the CSM fuel cells for the Skylab mission. The Shuttle fuel cell system is very similar to the one described by this reference; thus, the subject program should be easily converted for Shuttle simulation verification.

PRSD - The basic flow for the PRSD O_2 reference module is shown in Figure 4.7-70. This approach utilizes the basic flow charts shown in Figures 4.7-71 and 4.7-72. The approach for PRSD- H_2 parameters would be identical to the O_2 except for the fluid characteristics. Reference 32 can be used as a source of O_2 characteristics while Reference 33 provides the H_2 characteristics. Reference 31 provides many of the component characteristics of interest.

EPG Validation Methods and Check Cases

The reference module is utilized by the method of Section 5-1, while the systems performance data is used by the technique of Section 4.2 is validating the EPG simulation module. Drivers required to generate and maintain interfacing

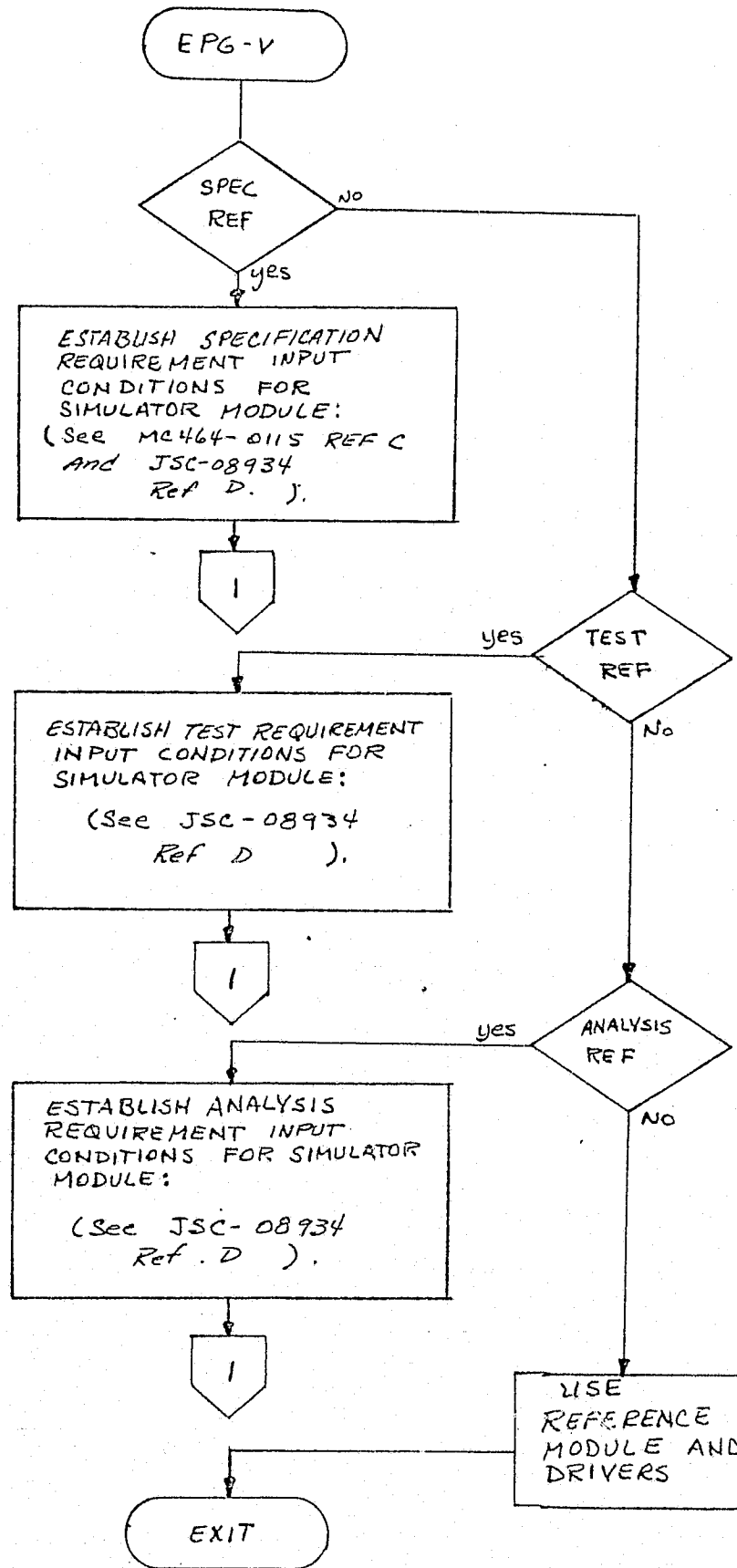


FIGURE 4.7-69. BASIC EPG VERIFICATION DATA SOURCE FLOW CHART

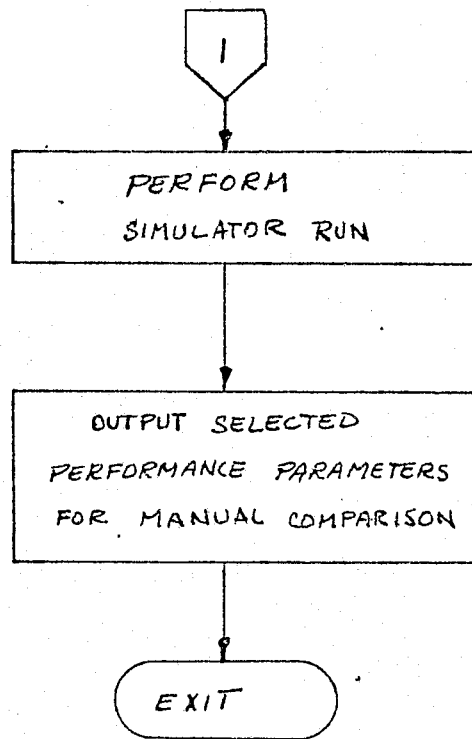


FIGURE 4.7-69. (CONTINUED)

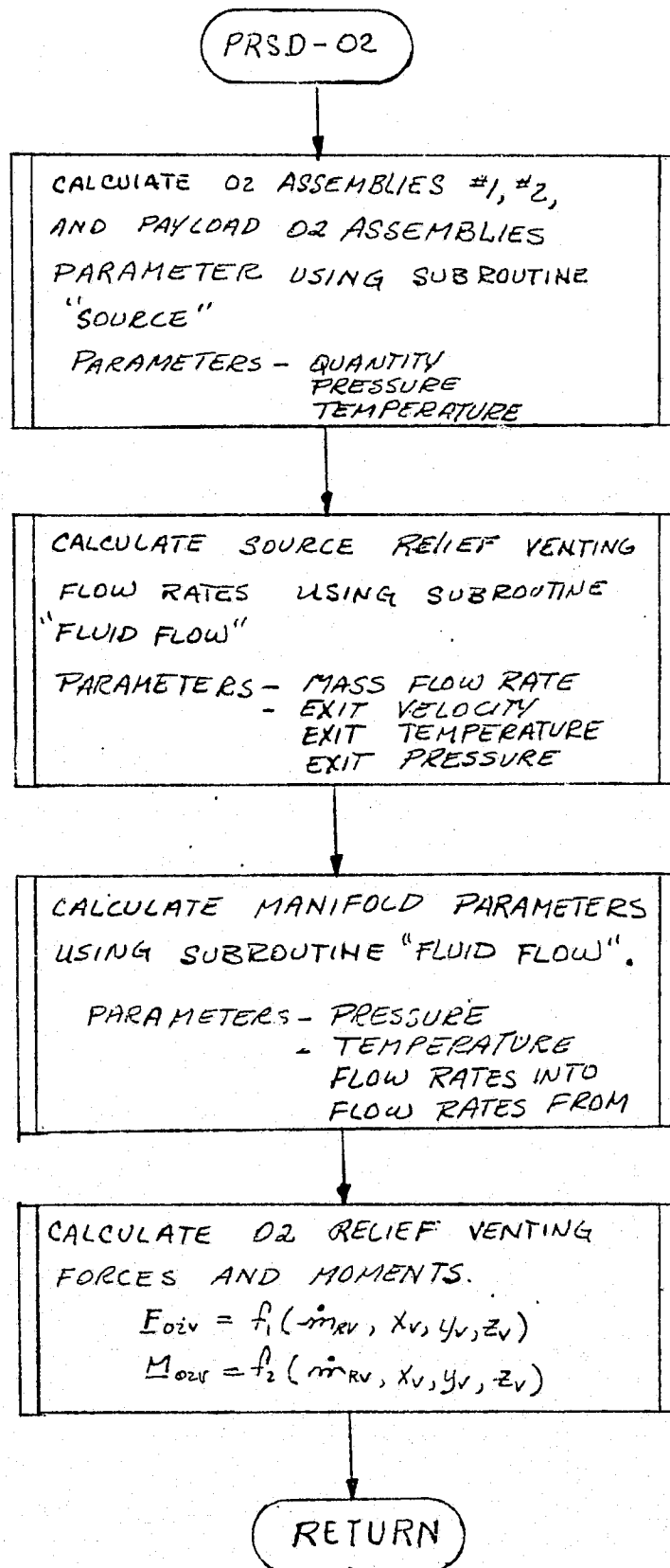
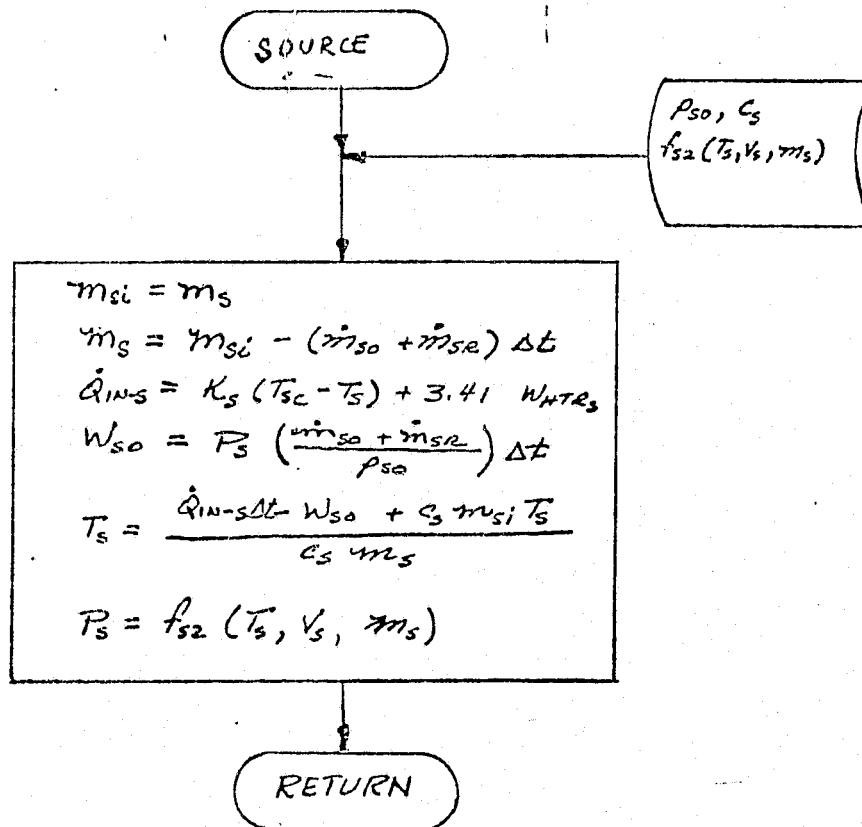


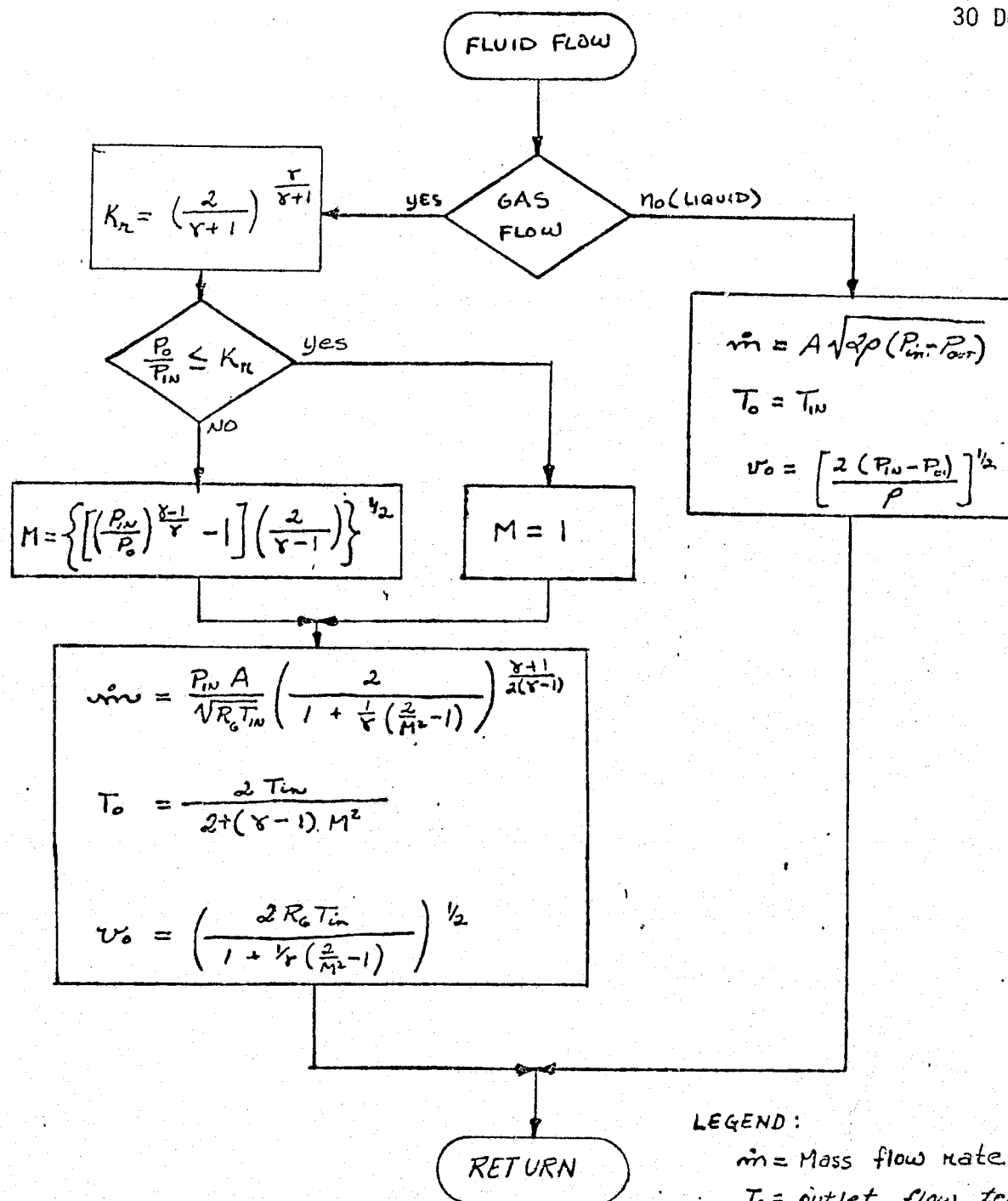
FIGURE 4.7-70. PRSD REFERENCE MODULE OVERALL MATH FLOW



LEGEND

- m_s = FLUID MASS IN TANK
- \dot{m}_{so} = FLUID FLOW RATE IN OUTLET LINE
- \dot{m}_{sr} = FLUID FLOW RATE VIA RELIEF LINE
- T_s = TANK FLUID TEMPERATURE
- P_s = TANK FLUID PRESSURE
- ρ_{s0} = FLUID DENSITY
- c_s = FLUID SPECIFIC HEAT
- T_{sc} = TANK COMPARTMENT TEMPERATURE
- W_{HTRS} = TANK ELECTRICAL HEATER POWER
- \dot{Q}_{in-s} = HEAT LEAK INTO TANK
- W_{so} = WORK DONE BY FLUID IN EXPANSION
- Δt = TIME INCREMENT
- V_s = TANK VOLUME

FIGURE 4.7-71. PRSD SOURCE TANK REFERENCE MODULE MATH FLOW



K_r = critical Pressure Ratio
 M = Mach number

LEGEND:

\dot{m} = Mass flow rate.
 T_o = outlet flow temperature
 P_o = outlet Pressure
 T_{in} = inlet Temperature
 P_{in} = inlet Pressure
 R_g = Gas constant
 γ = Specific heat ratio
 A = Effective flow Area.
 ρ = density

FIGURE 4.7-72. MATH FLOW FOR FLUID FLOW CALCULATIONS

module input parameters include:

- Atmosphere Revitalization
- Active Thermal Control
- Avionics (Electrical Power distribution)
- H₂O Management
- Control Logic Inputs

The check cases should include minimum, intermediate, and maximum electrical power load requirements, transient power switching loads, and projected mission load profiles.

EPG Data Base Impact

The impact of the EPG validation on the simulator data base is in four forms. These forms are the reference module, required drivers, processing subroutines, and data files. The most significant impact is the reference module. The reference module includes the fuel cell and the power reactants systems. The drivers would have the next most significant impact. The drivers would be required for both the reference module method and the systems performance data method.

The processing subroutines would include the data output routines (tables, plots, etc.) and any comparisons or data manipulations. The output routines would be required for the reference module and the systems performance data methods. Most processing routines would be common to all modules validated, however.

Data files are required for the power load profiles, O₂/H₂ cryogenic tables, and output data tables.

4.7.4.2 Auxiliary Power Generation (APG)

The APG consists of three Auxiliary Power Units (APU's) which provide power to the hydraulic pumps in the three hydraulic power systems. The three APU's are identical with each driving only one hydraulic system. APU's are identical with each driving only one hydraulic system.

APG System Description

Figure 4.7-73 (taken from Reference 20) is a schematic of the APU used for the Shuttle Orbiter. The fuel (N₂H₄) is expelled from the fuel tank by a fixed quantity of nitrogen used as a pressurant. A turbine-driven fuel pump feeds the

4.7-200

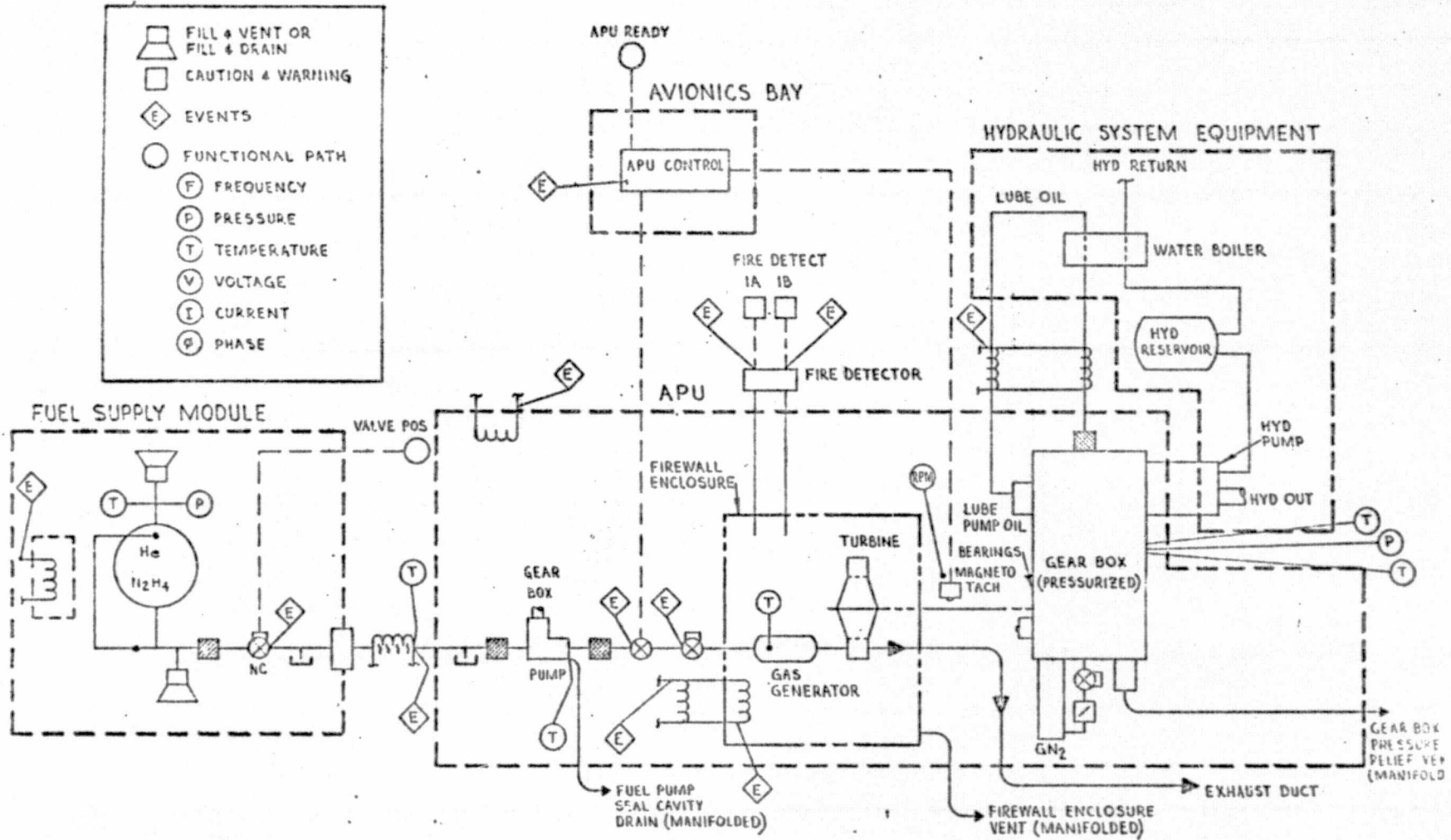


FIGURE 4.7-73 APU SUBSYSTEM OPERATIONAL MEASUREMENTS (TYP-4)

fuel through control valves into the gas generator. The gas generator is a heated catalytic bed which causes decomposition of the fuel into a hot gas. The hot, high pressure gas is then used to drive the turbine and exhausted overboard. A gearbox provides torque and angular velocity transformation to drive the fuel pump, AC generator (if any), oil pump and hydraulic fluid pump. The oil pump circulates the gearbox lubricant through the gearbox and the water boiler for cooling. The lubricant in the gearbox is pressurized by a tank of GN_2 via a pressure regulator. An electronic APU controller provides fuel flow modulation to allow startup, shutdown, and maintain normal turbine run speed.

APG Module Description and Performance Parameters

Figure 4.7-74 is a schematic showing the APG module functional elements and their interfaces with other modules. Table 4.7-21 is a listing of the APU parameters. The functions performed by each element are discussed below:

Fuel Source

- N_2 pressure - function of temperature, Helium quantity, and N_2H_4 quantity remaining.
- Tank (fuel) temperature - function of heater power, input, and N_2H_4 usage.
- N_2H_4 quantity - function of initial quantity and fuel usage rate.

Fuel Pump

- Pump flow rate - function of turbine speed and fuel density.
- Pump bypass rate - function of fuel delivered to the gas generator, pump flow rate, and control mode.
- Fuel source flow rate - function of fuel delivered to the gas generator and control mode.
- Fuel pump torque - function of friction, speed, flow, differential pressure, and moment of inertia.

Gas Generator

- Pressure - function of temperature, fuel inlet flow, gas flow out, and gas quantity.
- Temperature - function of fuel decomposition rate, heater power, exhaust temperature, and turbine flow rate.
- Gas quantity - function of turbine flow, fuel inlet rates, and decomposition rate.

4.7-202

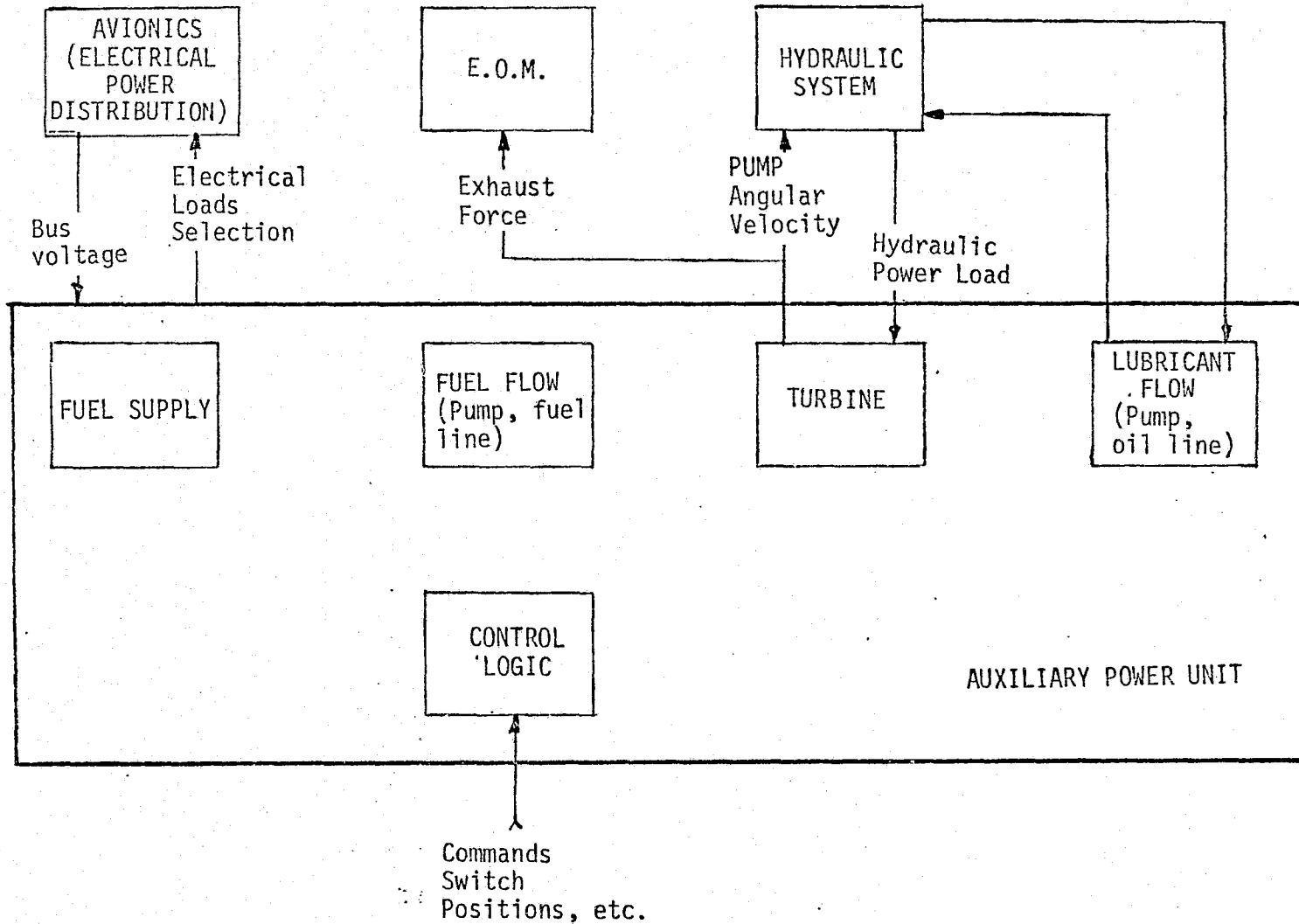


FIGURE 4.7-74. APU REFERENCE MODULE FUNCTIONAL ELEMENTS AND INTERFACES WITH OTHER MODULES

TABLE 4.7-21 APU REFERENCE MODULE PARAMETER LIST (From Ref. 27)

PARAMETER NOMENCLATURE	DATA RANGE			TYPE ^a
	LOW	HIGH	UNIT	
Shutdown inhibit command		ON	EVENT	P
Propellant tank pressure	0	600	PSIA	CP
Propellant tank temperature	0	+160	DEG F	P
Tank heater-element A-B ON		ON	EVENT	P
Discharge line temperature	0	+160	DEG F	P
Line heater-element A-B ON		ON	EVENT	P
Fuel pump discharge temperature	0	250	DEG F	P
Package heater-element A-B ON		ON	EVENT	P
Fuel isolation valve-open command		ON	EVENT	P
Fuel isolation valve position	Open	CLD	EVENT	CP
Lube oil heater-element A-B ON		ON	EVENT	P
Thermal bed heater A ON		ON	EVENT	P
Thermal bed heater B ON		ON	EVENT	P
Gas generator bed temperature	0	2500	DEG F	CP
Controller power-on command		ON	EVENT	P
Status light - ready	OFF	ON	EVENT	P
Start command	.	ON	EVENT	P
Turbine speed	0	100K	RPM	CP
Gearbox lube oil temperature	0	400	DEG F	CP
Gearbox lube oil pressure	0	+100	PSIA	P
Gearbox bearing temperature no. 1	0	500	DEG F	CP

- ^a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

Turbine

- Turbine speed - function of turbine torque, gear box lubricant temperature, hydraulic pump load, system friction, system moments of inertia, fuel pump rate, and AC generator output power.
- Turbine input power - function of turbine polytropic efficiency, gas inlet temperature, gas inlet pressure, and gas outlet pressure.
- Discharge temperature - function of inlet temperature, turbine power.
- Turbine fuel flow - function of inlet pressure, temperature, outlet pressure, and effective turbine flow area.

Gearbox

- Oil pump pressure - function of pump speed, oil temperature, and line resistance.
- Oil pump flow rate - function of pump speed.
- Oil pump torque load - function of oil temperature, flow rate, and line resistance.
- Oil temperature - function of oil pump flow, return oil temperature, oil quantity.
- Rate heat input - a function of friction and rotation (rpm).

APU Control

- Valve control(s) - function of input commands, turbine speed, temperatures.

APG Reference Data Sources and Data Formats

The APG module can be verified by use of reference module(s) or system performance data. The reference module(s) should have incorporated the most accurate systems performance data in order to achieve a high degree of fidelity. The systems performance data would include design requirements, analysis results, test results, and vehicle flight data.

Figure 4.7-75 is a flow chart utilizing the reference data sources for verification. The sources of the systems performance data include:

- MC201-0001 (Reference 34.) - provides system and component design perfor-

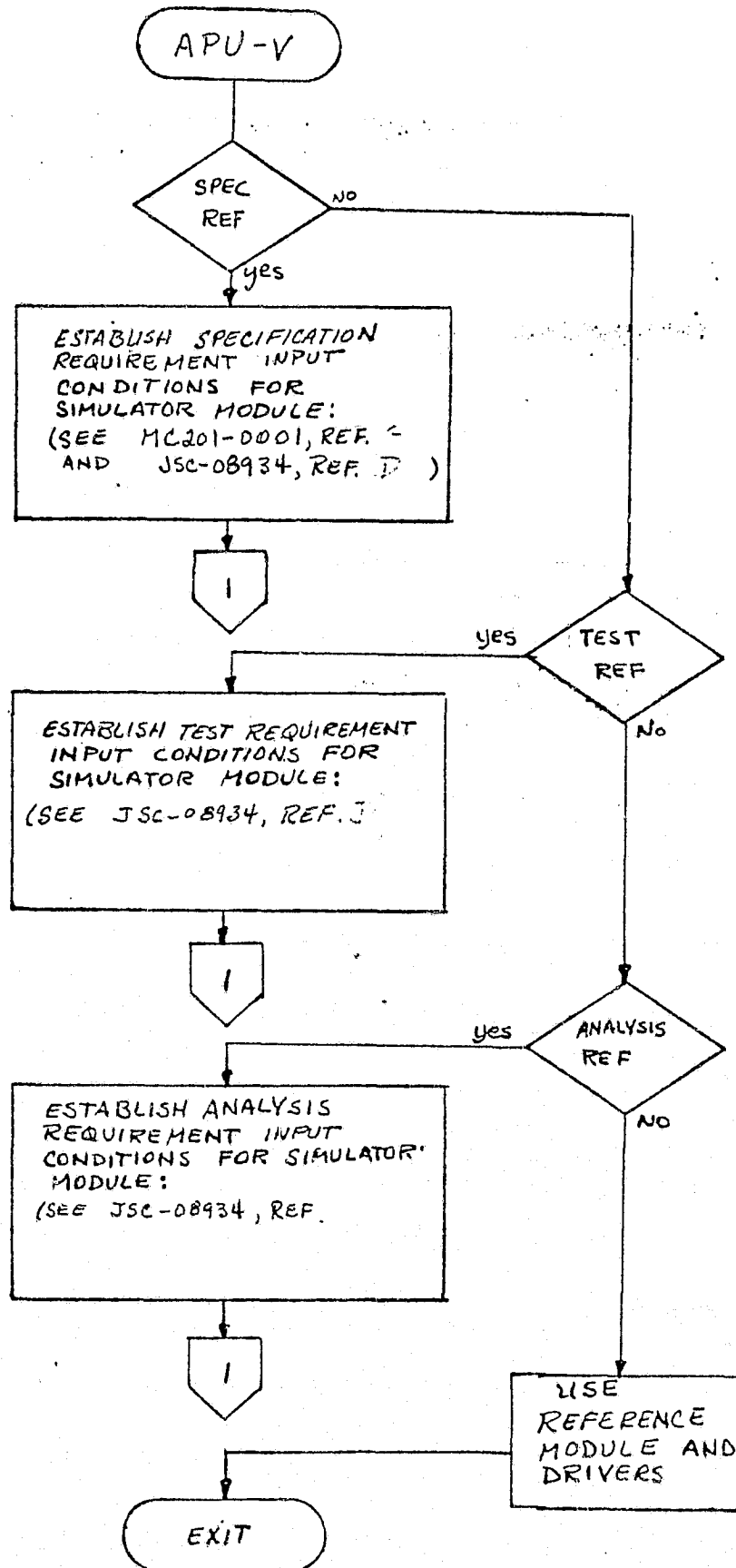


FIGURE 4.7-75. FLOW CHART FOR APU VERIFICATION
4.7-205
MCDONNELL DOUGLAS AERONAUTICS COMPANY - EAST

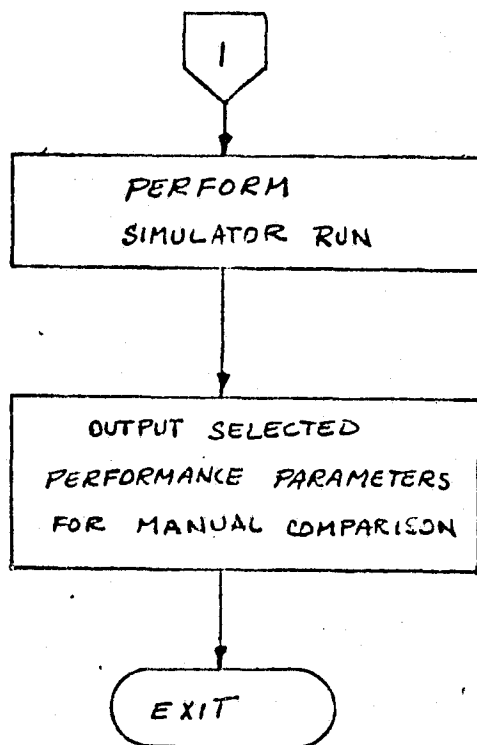


FIGURE 4.7-75. (CONTINUED)

mance requirements.

- JSC-08934, Vol. I (Reference 31) - provides a compilation of design requirements, analysis results, test results, and performance predictions for various Shuttle systems.
- SAPUCM (Reference ---) - the Simplified Auxiliary Power Unit Consumables Model allows the conduct of full consumable analysis for comparison with the simulation module.

A reference module for the APU is shown in Figure 4.7-76.

APG Validation Methods and Check Cases

The method of Section 5.1 and the selected reference module on the technique presented in Section 4.2.1.4 with the system performance data can be used for verification of the APG module. When utilizing the reference module, the following interface module drivers are required:

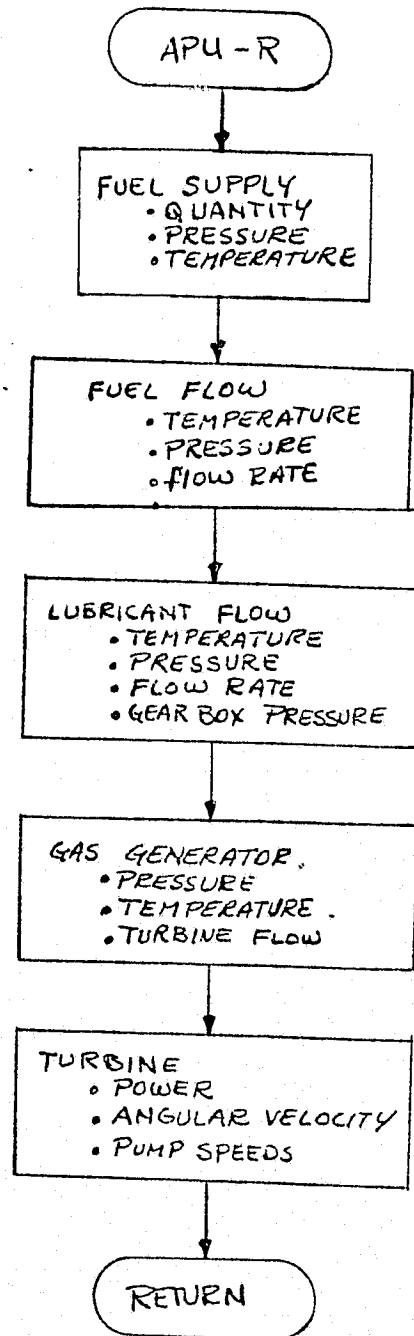
- Hydraulic power - system functions, power load, and lubricating oil (Gearbox) cooling
- Electrical power bus voltages
- Control logic inputs

Check cases should include startup, shutdown, steady-state maximum hydraulic load, steady state minimum hydraulic load, mission hydraulic load profiles, and hydraulic load switching.

APG Data Base Impact

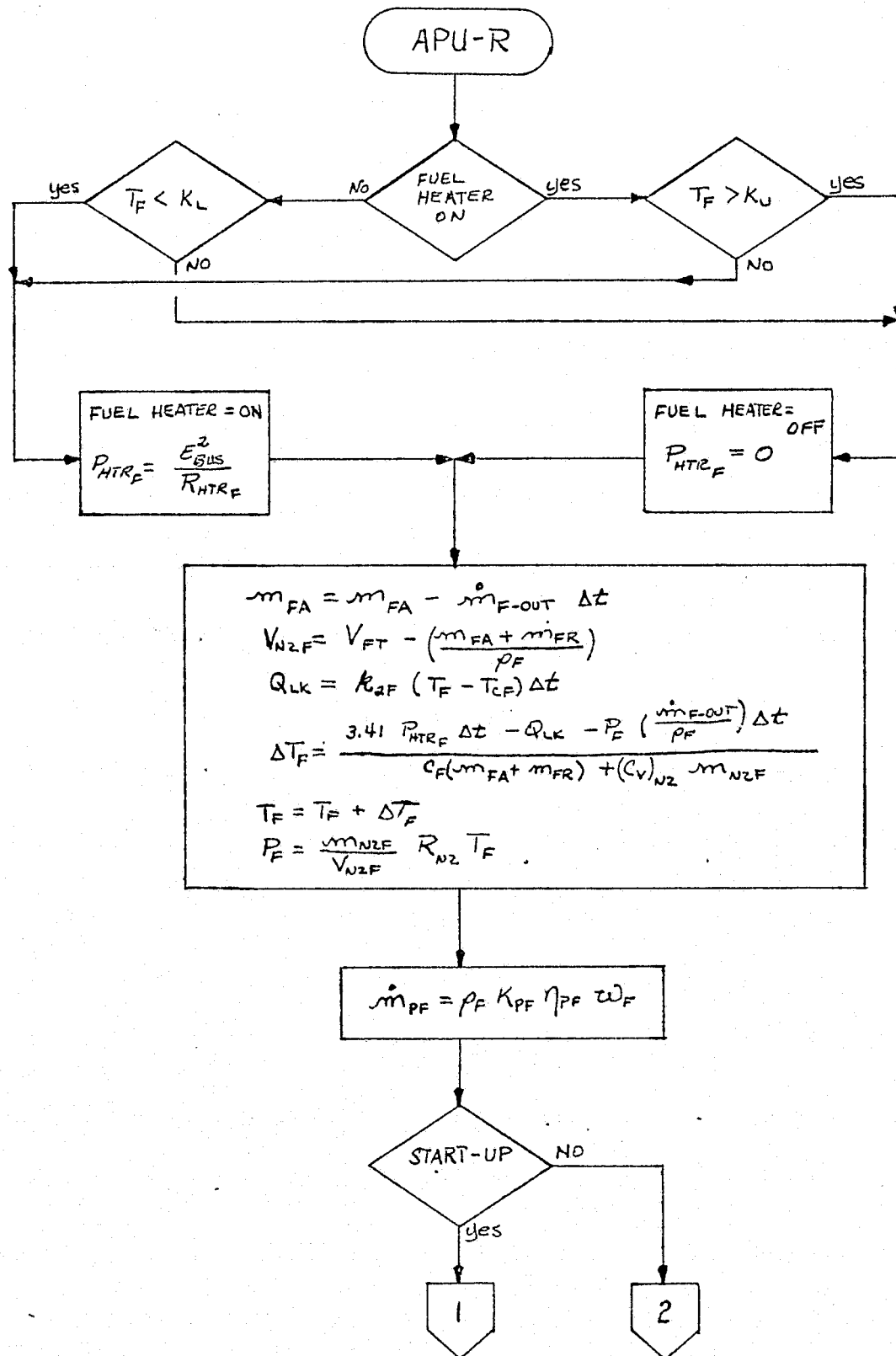
The impacts on the simulator data base are associated with the reference module, special drivers and check case data files. The selected APG reference module will have a large impact. The development of Figure 4.7-76 into a reference module (or the use of some detailed model) will be the bulk of the impact.

Special drivers will also be required for the simulation module and reference modules. These drivers would include the hydraulic power subsystem, electrical power system, and control logic inputs. The hydraulic power subsystem driver would provide hydraulic pump loads and cooling for the gearbox lubricating oil. The electrical power driver provides appropriate bus voltage levels for the heaters, control logic, and valve actuation. Switch positions, command inputs, and automatic inputs are provided by the control logic input driver.



(a) overview

FIGURE 4.7-76. APU REFERENCE MODULE MATH FLOW.



(b) detailed math

FIGURE 4.7-76. (CONTINUED)

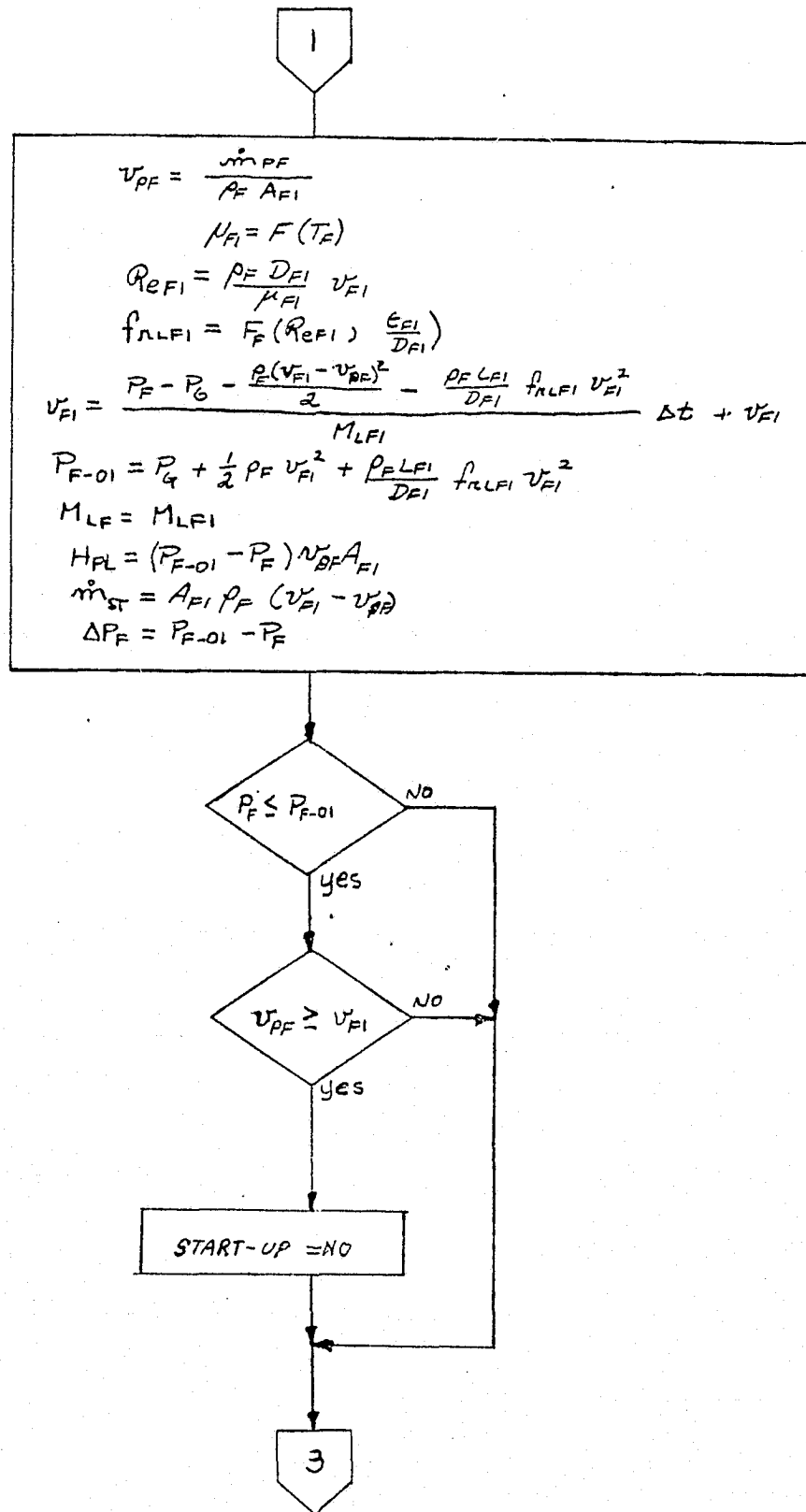


FIGURE 4.7-76. (CONTINUED)

4.7-210

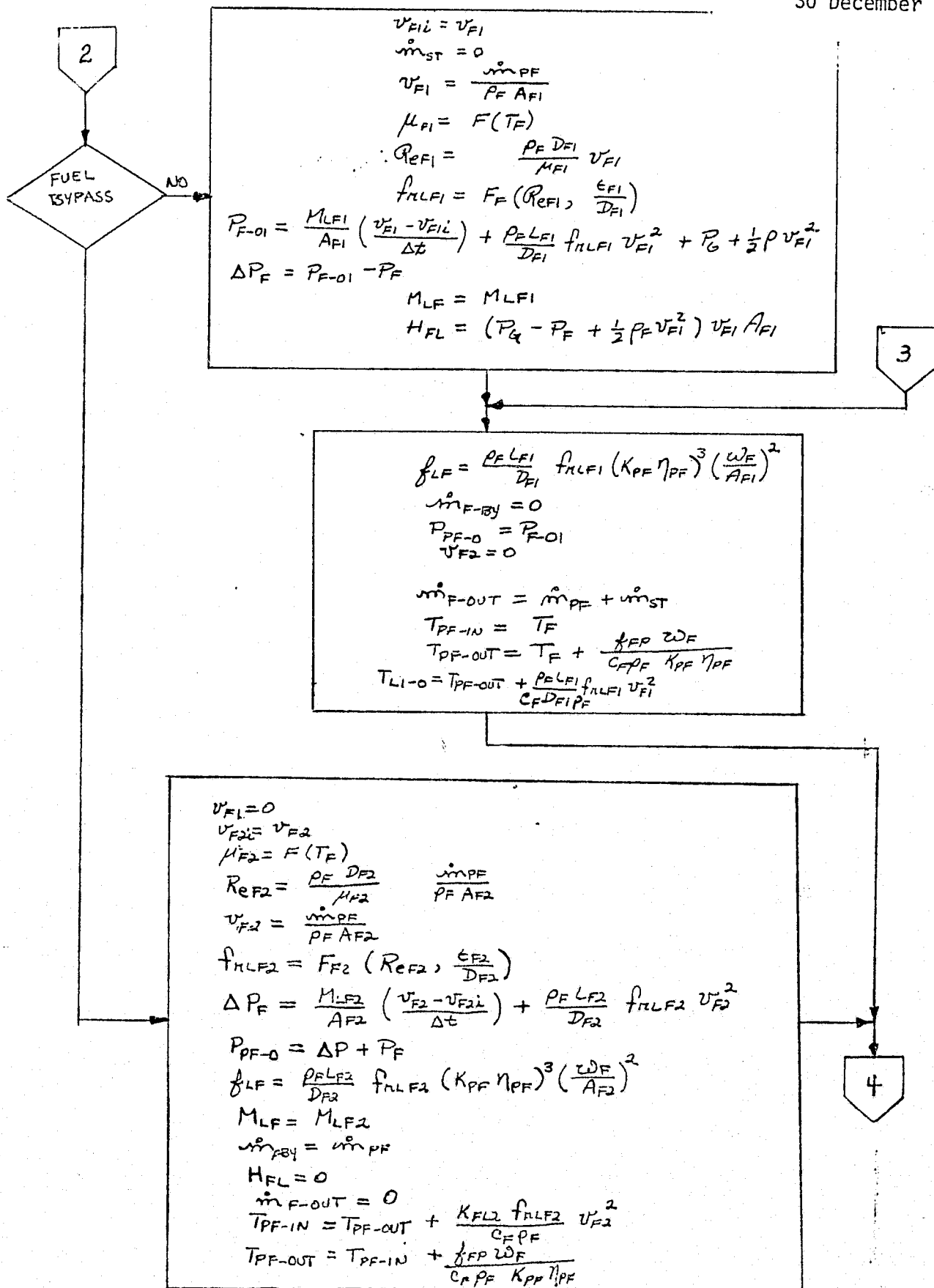


FIGURE 4.7-76. (CONTINUED)



$$J_F = J_{FP} + \eta_{PF}^2 K_{PF}^2 M_{LF}$$

$$f_F = f_{FP} + f_{LF}$$

$$\dot{m}_{FI} = v_{FI} \rho_F A_{FI}$$

$$\dot{m}_{PO} = \rho_o K_{PO} \eta_{PO} \omega_o$$

$$T_{PO-O} = T_{TGB} + \frac{f_{OP} \omega_o}{C_o \rho_o K_{PO} \eta_{PO}}$$

$$v_{oi} = v_o$$

$$K_{OL} = \frac{\rho_o L_o}{D_o}$$

$$\mu_o = F(T_{GB})$$

$$v_o = \frac{\dot{m}_{PO}}{\rho_o A_{OL}}$$

$$R_{EO} = \frac{\rho_o D_o}{\mu_o} v_o$$

$$f_{NLO} = F(R_{EO}, \frac{L_o}{D_o})$$

$$\Delta P_o = \frac{M_{LO}}{A_{OL}} \left(\frac{v_o - v_{oi}}{\Delta t} \right) - \frac{\rho_o L_o}{D_o} f_{NLO} v_o^2 - \frac{1}{2} \rho_o v_o^2$$

$$P_{OP-OUT} = P_{GB} + \Delta P_o$$

$$f_o = f_{OP} + K_{OL} f_{NLO} (K_{PO} \eta_{PO})^3 \left(\frac{\omega_o}{A_{OL}} \right)^2$$

$$J_o = J_{OP} + (\eta_{PO} K_{PO})^2 M_{LO}$$

$$T_{OL-OUT} = T_{OEO} + \frac{K_{OL} f_{NLO} v_o^2}{C_o \rho_o}$$

$$H_{OL} = \frac{1}{2} \rho_o v_o^3 A_o$$

$$\dot{Q}_{GB-IN} = \frac{f_{GB} \omega_T^2}{2} + \frac{1}{2} \dot{m}_{PO} v_o^2$$

$$\dot{Q}_{GB-OUT} = C_o \dot{m}_{PO} (T_{GB} - T_{OL-OUT}) - C_{VN2} \dot{m}_{VN2} (T_{GB} - T_{SN2})$$

$$T_{GB} = \Delta t \left(\frac{\dot{Q}_{GB-IN} - \dot{Q}_{GB-OUT}}{C_o M_{OR} + C_{VN2} M_{ORN2} + C_{GB} M_{GB}} \right) + T_{GB}$$

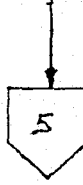


FIGURE 4.7-76. (CONTINUED)

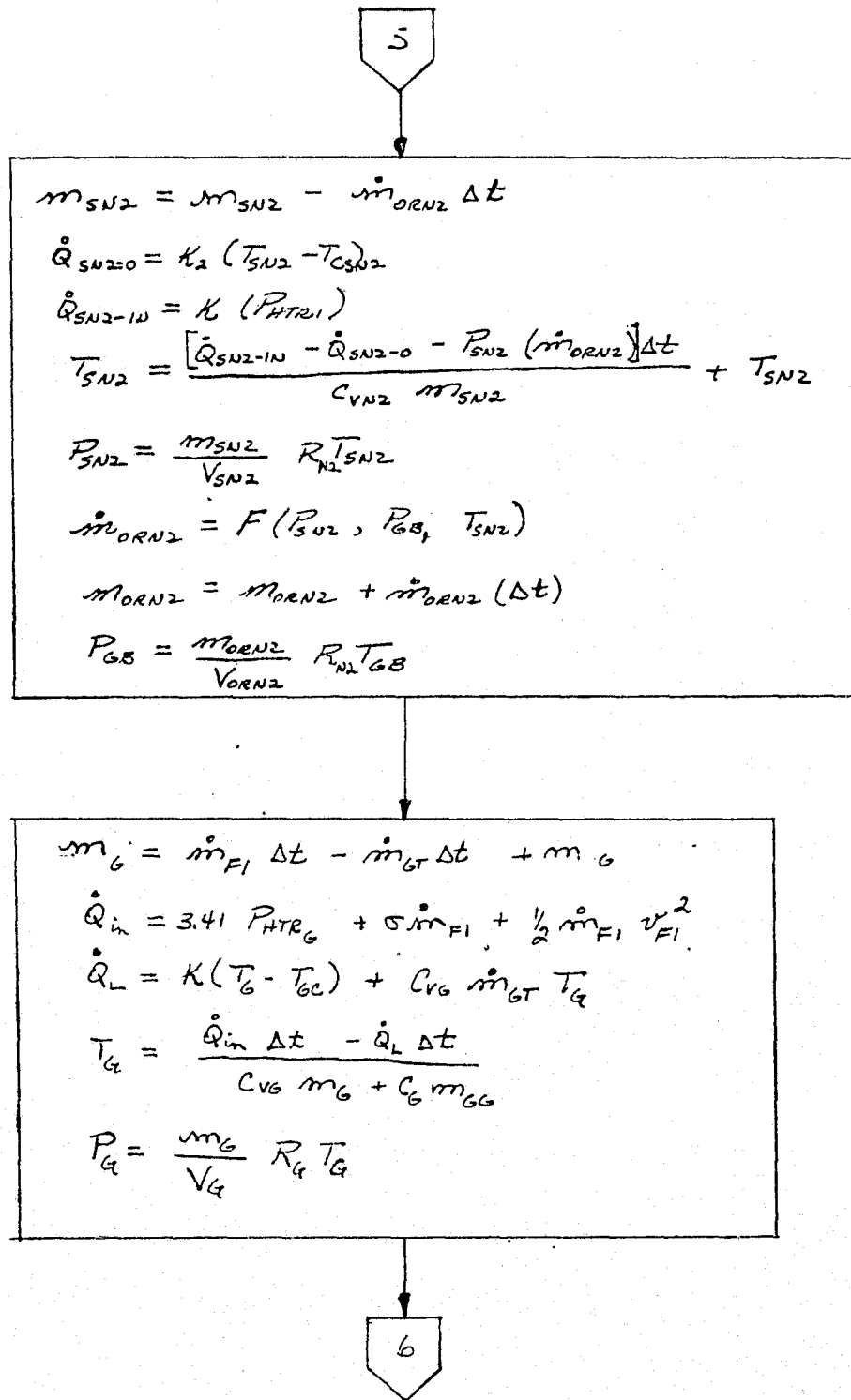


FIGURE 4.7-76. (CONTINUED)

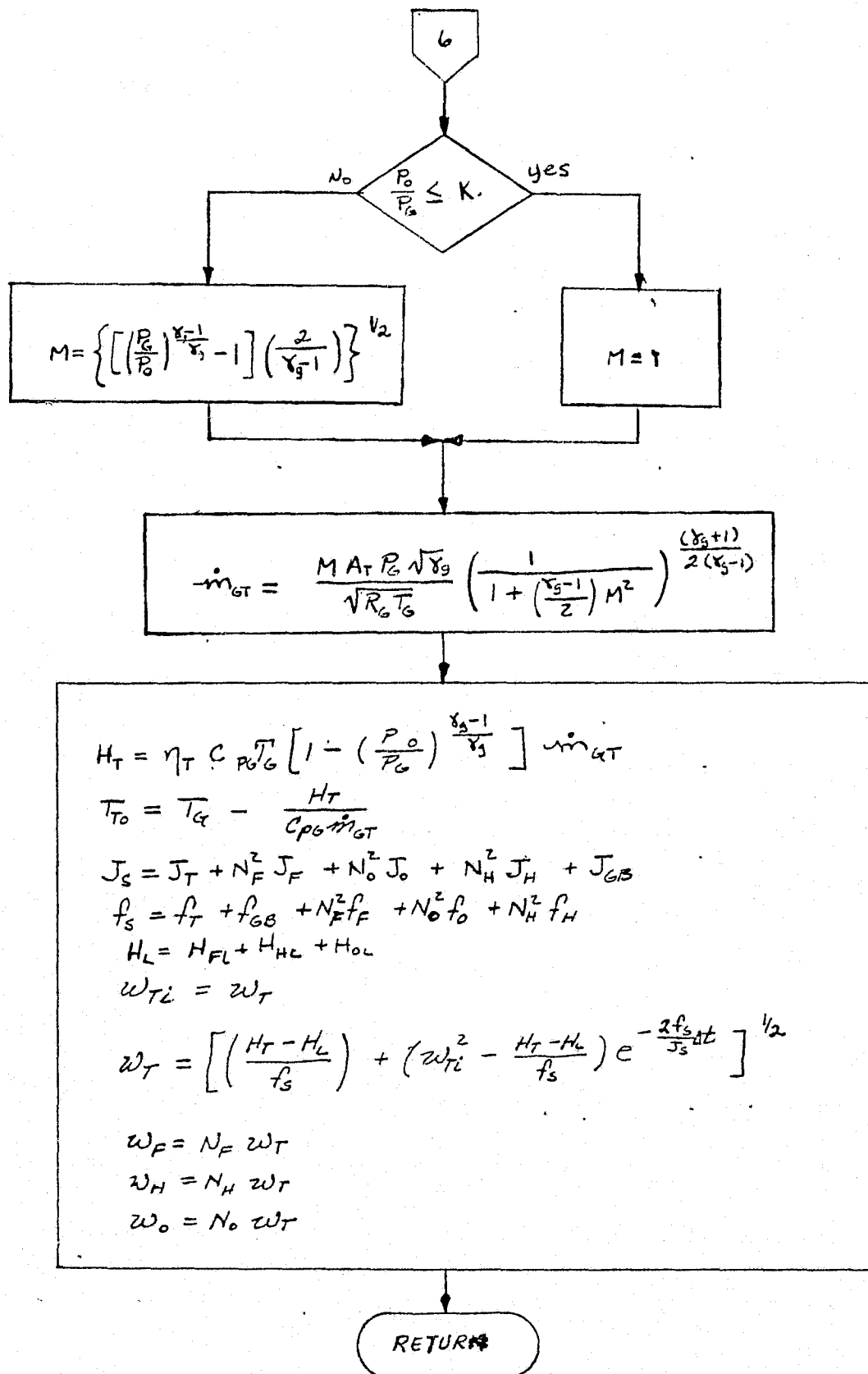


FIGURE 4.7-76. (CONTINUED)

LEGEND:

- m_{GB} - Gear Box mass
- m_{GG} - Mass of Gas Generator
- m_{FA} - Fuel mass available
- m_{FR} - Residual fuel mass
- m_{N_2F} - Fuel tank N_2 mass
- m_{ORN_2} - N_2 mass in Gear Box pressure bellows
- m_{OR} - Lubricant mass in Gear Box
- m_{SN_2} - Gear Box - N_2 source tank N_2 mass
- m_G - Gas mass in Gas Generator
- M_{LF1} - Mass of fuel in fuel line 1 (Run)
- M_{LF2} - Mass of fuel in fuel line 2 (Bypass)
- M_{LF} - Mass of fuel in fuel pump line
- M_{LD} - Mass of lubricant in oil base
- M - Mach number of turbine flow
- V_{N_2F} - Volume of N_2 in fuel tank
- V_{FT} - Fuel tank volume
- V_{SN_2} - Gear Box N_2 source tank volume
- V_{ORN_2} - Gear Box N_2 bellows volume
- V_G - Gas volume of Gas Generator

- T_F - Fuel tank and fuel temperature
- T_{CF} - Fuel tank compartment temperature
- T_{PF-IN} - Fuel pump inlet fuel temperature
- T_{PF-OUT} - Fuel pump outlet temperature
- T_{LI-O} - Gas Generator inlet fuel temperature
- T_{PO-O} - Lubricant pump outlet temperature
- T_{GB} - Gear Box lubricant temperature
- T_{GR-OUT} - Gear Box lubricant return temperature
- T_{OEO} - Lubricant temperature out of Hydraulic Boiler
- T_{SN_2} - Gear Box N_2 source tank temperature
- T_{CSN_2} - Gear Box N_2 tank compartment temperature
- T_G - Gas Generator temperature
- T_{GC} - Gas Generator compartment temperature
- T_{TO} - Turbine outlet gas temperature

- σ - Fuel heat of formation

FIGURE 4.7-76. (CONTINUED)

4.7-215

- \dot{m}_{FOI} - Mass flow rate of fuel from fuel tank
 \dot{m}_{PF} - Fuel pump mass flow rate
 \dot{m}_{st} - Fuel flow rate through startup line
 \dot{m}_{F-BY} - Bypass line fuel flow rate
 \dot{m}_{PO} - Lubricant pump mass flow rate
 \dot{m}_{ORN_2} - N_2 flow rate to Gear Box pressure bellows
 \dot{m}_{GT} - Gas flow rate through turbine
 ρ_F - Fuel density
 ρ_o - Lubricant density
 Δt - Time increment
- C_F - Specific heat of fuel
 $(C_V)_{N_2}$ - Specific heat at constant volume of N_2
 C_o - Specific heat of lubricant
 C_{GB} - Specific heat of Gear Box
 C_{VG} - Specific heat of fuel gases at constant volume
 C_G - Specific heat of gas generator
 C_{PG} - Specific heat of fuel gases at constant pressure
 γ_g - Fuel gases specific heat ratio
- R_{N_2} - N_2 gas constant
 R_g - Fuel gas constant
- η_{PF} - Fuel pump volume displacement per cycle
 η_{PO} - Lubricant pump volume displacement per cycle
 K_{PF} - Fuel pump efficiency factor
 K_{PO} - Lubricant pump efficiency factor
- ω_F - Fuel pump angular velocity
 ω_H - Hydraulic pump angular velocity
 ω_o - Lubrication pump angular velocity
 ω_T - Turbine angular velocity
 N_F - Gear ratio of fuel pump to turbine
 N_o - Gear ratio of oil pump to turbine
 N_H - Gear ratio of hydraulic pump to turbine

FIGURE 4.7-76. (CONTINUED)

4.7-216

- f_s - System friction at turbine
- f_{ILO} - Oil line friction factor
- f_{NLEI} - Fuel delivery line friction factor
- f_{NLEZ} - Fuel bypass line friction factor
- f_{LF} - Fuel friction due to line related to pump shaft
- f_{LOP} - Friction losses of oil pump
- f_{FP} - Friction losses of fuel pump
- f_{HP} - Friction losses of hydraulic pump
- f_o - Oil pump and line friction losses
- f_F - Fuel pump and line friction losses
- J_{FP} - Fuel pump moment of inertia
- J_{OP} - Oil pump moment of inertia
- J_{HP} - Hydraulic pump moment of inertia
- J_F - Summation of pump and fuel inertias
- J_o - Summation of pump and oil inertia
- J_s - System moment of inertia at turbine
- J_{GB} - Gear Box moment of inertia at turbine
- H_{OL} - Oil pump hydraulic power load
- H_{FL} - Fuel pump hydraulic power load
- H_{HL} - Hydraulic pump hydraulic power load
- H_T - Turbine power
- H_L - Hydraulic power load for turbine
- η_T - Turbine efficiency

FIGURE 4.7-76. (CONTINUED)

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The use of analysis/test/design requirements reference data requires the use of special drivers. These drivers establish and maintain proper conditions in the module which correspond to the analysis/test/design requirements conditions. The plotting or outputting of the simulation data would also require special subroutines. However, the total impact of the analysis/test/design requirements is small.

The use of input/output files for special check case profiles may be required. The profiles would include hydraulic power profiles for launch and reentry-through-landing.

4.7.5 Avionics

Avionics subsystems are involved in sensing, communications, information handling, and control. The following subsections discuss avionics modules under the categories of Guidance, Navigation and Control; Communications and Tracking; Displays and Controls; Operational Instrumentation; and EPS Distribution and Control. Data Processing and Software functions are performed by flight hardware and software in the simulators of interest to this study.

4.7.5.1 Guidance, Navigation and Control

Guidance, Navigation and Control subsystems and components are used for sensing vehicle-related observables, using these sensor data to estimate vehicle state variables, and defining and executing desired vehicle maneuvers. The subsystems and components in this category include inertial measurement units, strapdown gyros and accelerometers, propulsion systems interfaces, optical trackers, and the aeroflight control system.

4.7.5.1.1 Inertial Measurement Unit (IMU) - The IMU is used to sense the inertial orientation and acceleration of the vehicle.

IMU System Description

Generally, three types of IMU's are employed in spacecraft:

- three-gimbal platform - as used in the Apollo Command Module.
- four-gimbal platform - as used in the Gemini spacecraft and currently baselined for Shuttle (see Refs. 20, 35).
- strap-down platform - similar to the backup attitude reference system on Apollo; considered as an alternate attitude reference system for Shuttle.

Regardless of the type, the IMU outputs directly perceivable by the crew consist of three angular readouts which describe the orientation of the spacecraft with respect to an inertial reference. In addition, accelerometer outputs are input to the onboard computer for processing. In the case of the four-gimbal platform, the output of a redundant inner roll gimbal is also input to the onboard computer. This gimbal provides the capability of preserving the stable member attitude reference during "gimbal lock" conditions. The output of this gimbal is used by the flight computer to prevent gimbal lock, but is not normally displayed to the crew.

The performance verification methods presented in this section are particularly suited to the four-gimbal arrangement, since this design has all-attitude capabilities under normal conditions of body rates. Additional development would be required to verify IMU simulation in and around the gimbal-lock regions characteristic of the other two types of IMU design.

IMU Module Functions and Performance Parameters

Figure 4.7-77 depicts the interfaces between the IMU module and the rest of the simulation. Inputs come from four basic sources:

- o MDM (Multiplexer/Demultiplexer), which provides the "operate" discrete and the flight software torquing and slew commands.

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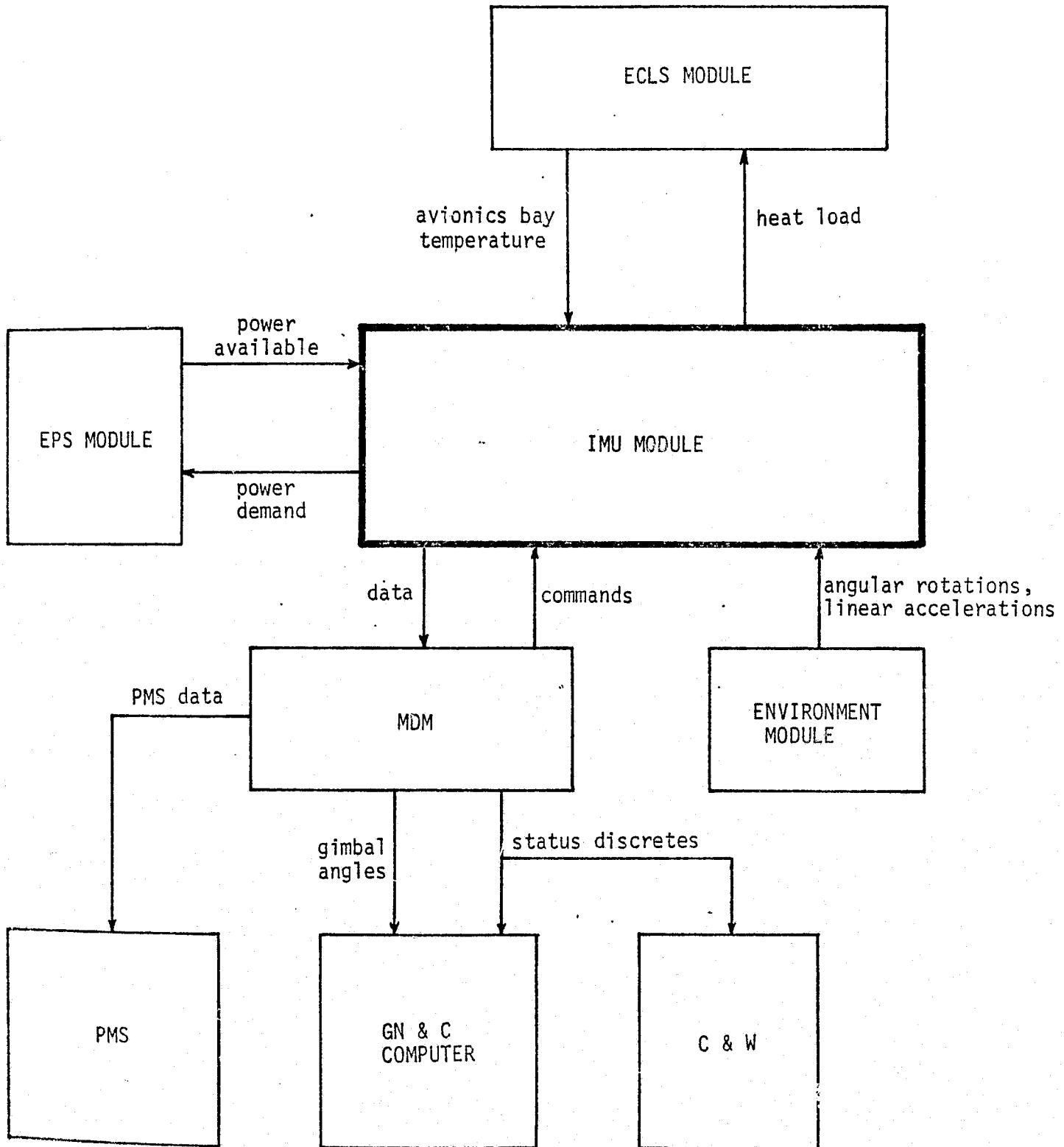


FIGURE 4.7-77 . IMU MODULE INTERFACES

- EPS (Electrical Power System), which provides the 28 Vdc operating power.
- ECLS (Environment Control and Life Support) system, which provides the thermal control.
- Environment, which provides the vehicle dynamics sensed by the platform: angular rotation and inertial acceleration.

Outputs of the IMU fall into four categories:

- Status discretes which are used by the flight software and the Caution and Warning (C & W) system.
- PMS (Performance Monitor System) Data, which are used by the flight software performance monitor system for its redundancy management function.
- Gimbal angle resolver data, which consists of sine and cosine data from the coarse (1X) and fine (8X) resolvers attached to the individual gimbals and is used by the flight software and the FDAI for determining the orientation of the vehicle with respect to the stable member of the platform.
- Accelerometer Data, which consists of the ΔV accumulator outputs and is used by the flight software to determine the total inertial acceleration acting on the vehicle.

Using the current Shuttle baselined four-gimbal platform as a reference, the performance parameters as defined in Ref. 20 are summarized in Table 4.7-22.

Note on this table that the three primary gimbal angles (not the resolver sine and cosine outputs) have been chosen as critical performance parameters. The fourth gimbal is a redundant roll gimbal which is forced by the stabilization loop to remain at or near zero. It only has a non-zero value during the time that the platform is in the condition that would result in gimbal-lock in a three gimbal platform. Since the stabilization loop of the IMU is not expected to be part of the simulation software (Reference 11), the role of this redundant gimbal in the simulation is unknown. Some empirically-determined "kluge" simulation may be incorporated to provide a "wobble" in the FDAI during these conditions; however, verification of this implementation would be dependent on the manner of its simulation, and is therefore not addressed in this newsletter.

TABLE 4.7-22 . IMU MODULE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
ω $\dot{\omega}$ φ, θ, ψ V_x, V_y, V_z \underline{a}_{imu}	"Operate" discrete	I
	Electrical power	I
	Avionics Bay temperature	I
	Gyro torquing and gimbal slew commands	I
	Body angular rate vector	I
	Body sensed acceleration vector	I
	Status discretes (IMU ready, operate mode, overtemperature, IMU fail)	O
	PMS data (redundant sensed angular rate, overtemperature, IMU mode/BITE status)	O
	Gimbal angle resolvers:	
	• outer roll (coarse/fine)	P
	• pitch (coarse/fine)	P
	• yaw (coarse/fine)	P
	• inner roll (fine only)	P
Gimbal angles (roll, pitch, yaw)	CP	
ΔV accumulator outputs	P	
Instantaneous accelerometer outputs	CP	

LEGEND:

- I = input
- O = output
- P = performance parameter
- CP = critical performance parameter

IMU Reference Data Sources and Data Formats

Two methods are presented in this section to provide ideal (closed-form solution) IMU angular information in response to selected vehicle body rate inputs. The first method, the "constant rate input method", employs constant body rates or stable member drift rates as inputs, and computes the resultant gimbal angle time histories. The second method, the "closed-form gimbal angle input method", computes the body rate time history which must be input to produce a pre-selected gimbal angle time history.

These methods apply only to the nominal operation of an IMU. Failure modes, effects of off-nominal temperature or power conditions, and control logic are not considered. In the design of these IMU reference math models, only rate and acceleration inputs and gimbal angle and accelerometer outputs are considered. Generation of status discrettes and PMS data would require a high-fidelity representation of actual hardware operational logic, which is best obtained from test data. Similarly, determination of IMU responses to input voltages and temperatures will require test results from the actual flight hardware. Generation of the IMU responses to slew commands and gyro torquing commands would involve a high fidelity simulation of the flight hardware stabilization loop. Approximate data for the response to gyro torquing commands can be generated by equating the torquing commands to the gyro drift rates in the reference module presented in this section.

Constant Rate Input Method - By holding the rate input to an IMU constant, the total angular displacement can be determined as a linear function of time. The corresponding IMU gimbal angles can be easily determined by first defining the total angular response in terms of quaternion elements. Once the time history of quaternion element variation is determined, the individual gimbal angles can be extracted from the body/IMU direction cosine matrix, which is a function of the quaternion elements.

Two types of rate inputs are considered:

- body rates (p, q, r) - three components of angular velocity about the body axes.
- drift rates (D_x, D_y, D_z) - three components of angular velocity about the stable member reference axes. (These rates can also be interpreted as gyro torquing commands from the flight software.)

Both types may be input in a single run. Other input data required are: the iteration rate (Δt) at which the resultant gimbal angles are to be printed out; the initial gimbal angles ($\varphi_0, \theta_0, \psi_0$); the body-axis referenced accelerations (A_x, A_y, A_z), to check the IMU accelerometer computations; and the time (t_{max}) at which the run is to stop.

Figure 4.7-78 presents a math flow of this technique. An initialization path is incorporated, to allow the capability to preset the gimbal angles to any value prior to initiating the input rates. Additional data is computed (including an initial direction-cosine matrix, C) concerning the orientation of the angular velocity vector with respect to the initial stable member orientation, which serves as the inertial reference for the remainder of the computations.

After the initialization pass, the gimbal angles at each time increment (Δt) are computed. This computation progresses as follows:

- 1) Time is incremented by Δt .
- 2) The total angular displacements of the body (Ω_r) and of the stable member (Ω_d) from their initial orientations are computed as linear functions of time.
- 3) The quaternion elements (d_1, d_2, d_3, d_4) defining the angular displacement of the stable member are computed as a function of total drift angle Ω_d and the orientation of the drift vector.
- 4) The direction cosine matrix (D) defining the orientation of the stable member with respect to its initial position is computed.
- 5) The quaternion elements (r_1, r_2, r_3, r_4) defining the angular displacement of the vehicle are computed as a function of the total displacement Ω_r , and the orientation of the rate vector.

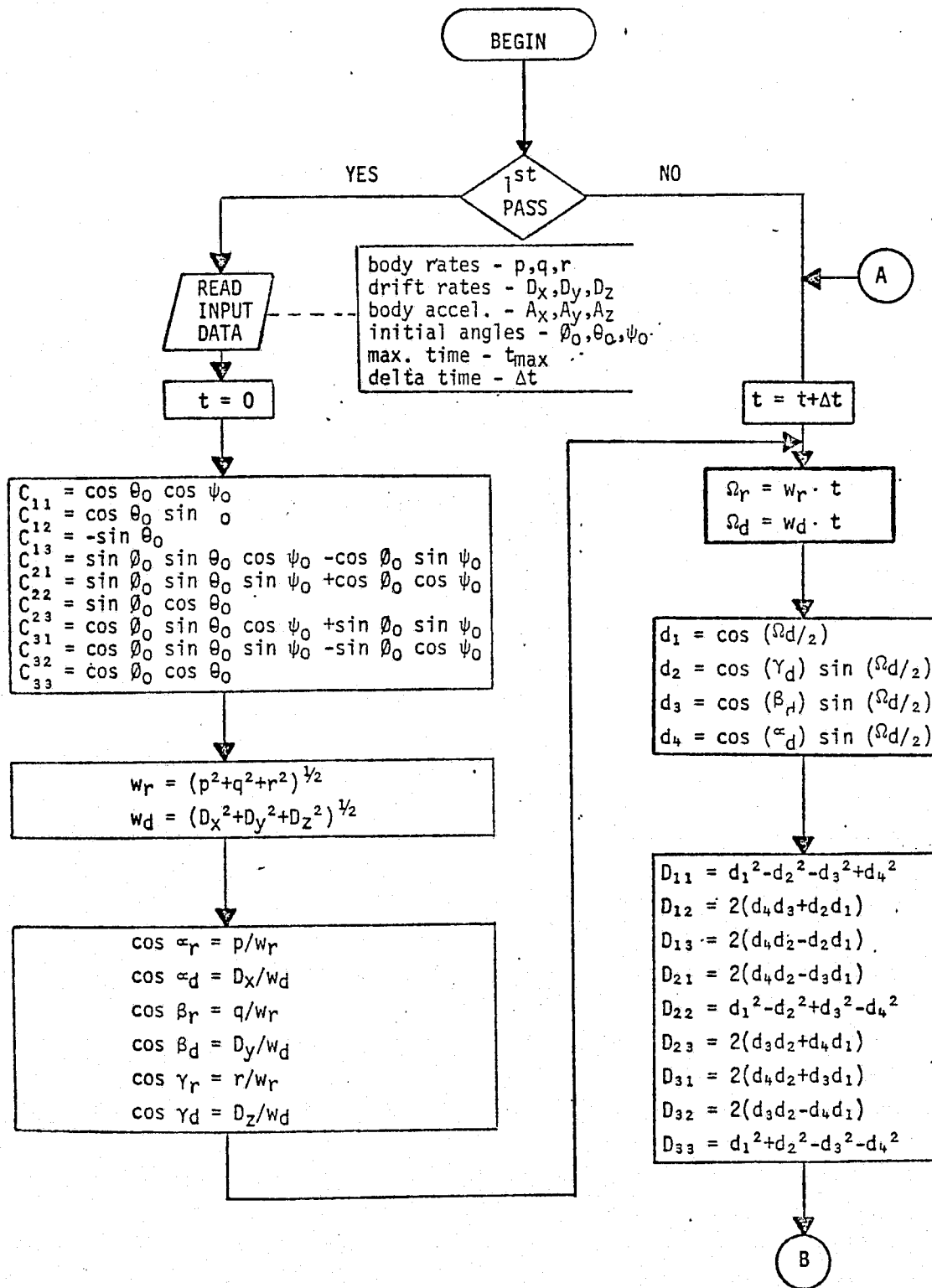


FIGURE 4.7-78 CONSTANT RATE INPUT METHOD
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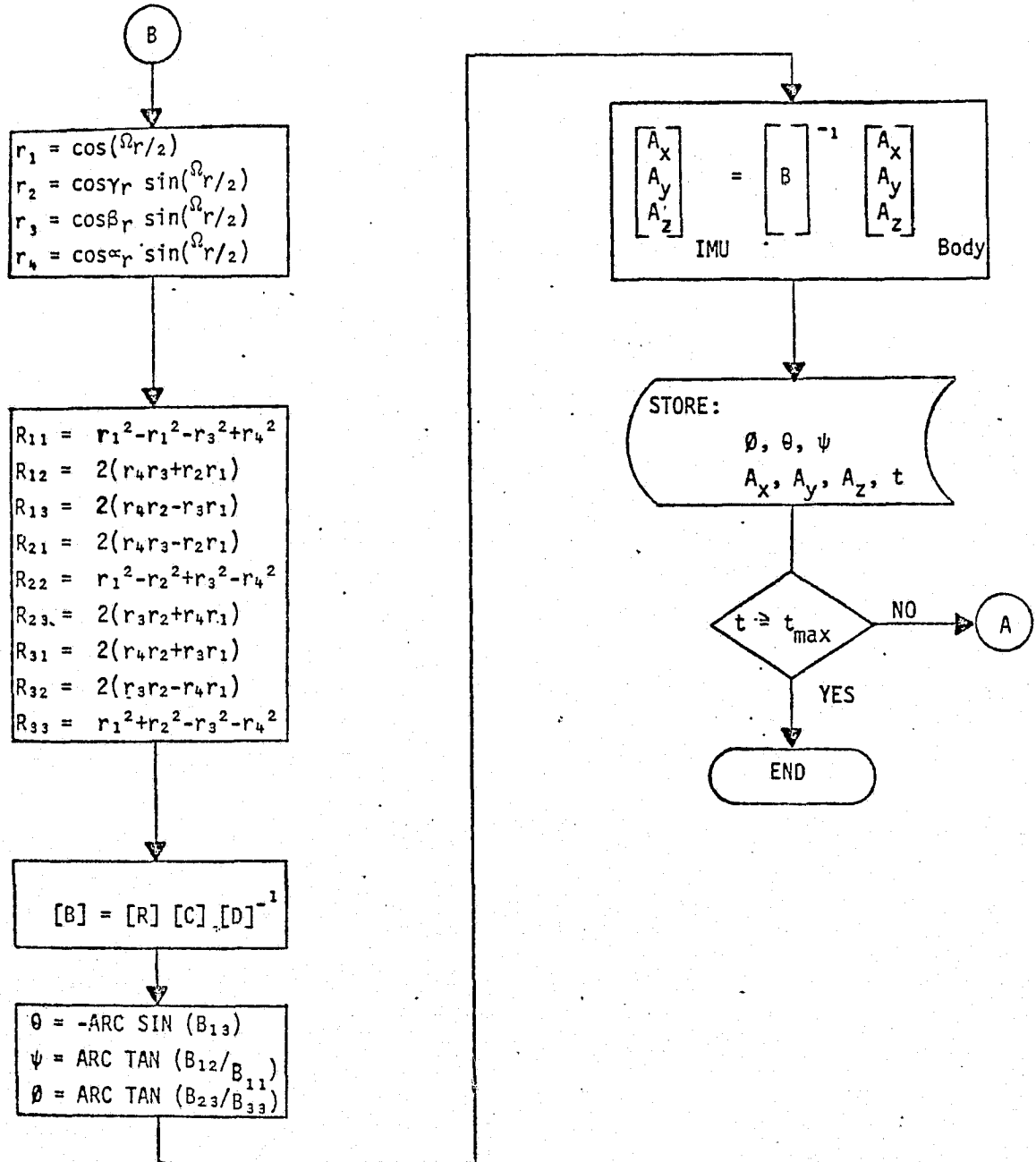


FIGURE 4.7-78 (CONTINUED)

- 6) The direction cosine matrix (R) defining the orientation of the vehicle with respect to its initial position is computed from the quaternion elements.
- 7) The direction cosine matrix (B) defining the orientation of the vehicle with respect to the stable member is computed as a function of the three previously defined matrices.
- 8) The gimbal angles describing this orientation are extracted from the B matrix. The equations presented are valid for a gimbal sequence of yaw (ψ), pitch (θ), roll (ϕ); other sequences can be treated in a similar manner.
- 9) The ideal IMU accelerometer outputs are computed using the B matrix and the input body-referenced accelerations.
- 10) The gimbal angles and accelerometer outputs are stored for comparison with simulation software outputs.

Closed Form Gimbal Angle Input Method - The previous method is primarily suited to verifying the IMU performance during orbital conditions, where the body rates tend to be constant for considerable periods of time. It is also necessary to verify the IMU performance for variable body rates such as encountered during entry conditions. The math flow shown in Figure 4.7-79 describes a method for establishing a closed-form relationship between variable body rates and IMU gimbal angles.

This reference module, given a desired IMU output time history, "inverts" the IMU transformation to generate the body-rate time history which must be input to the IMU. To do this, it is necessary to restrict the form of the input. Each gimbal angle time-history must be an analytic function of time; thus the time derivative of the function (i.e., gimbal angle rate) is precisely computable.

Three typical examples are:

$$\phi = A \sin w_1 t \rightarrow \dot{\phi} = A w_1 \cos w_1 t$$

$$\theta = \frac{B}{C} \tan^{-1} \left(\frac{t-D}{C} \right) \rightarrow \dot{\theta} = \frac{B}{C^2 + (t^2 - D^2)}$$

$$\psi = E [\cos w_2 t + (w_2^2 t) \sin w_2 t] \rightarrow \dot{\psi} = E (w_2 t) \cos w_2 t$$

With the gimbal angle rates thus defined, the corresponding body rates are determined by standard Euler transformations. The body rate data is then written

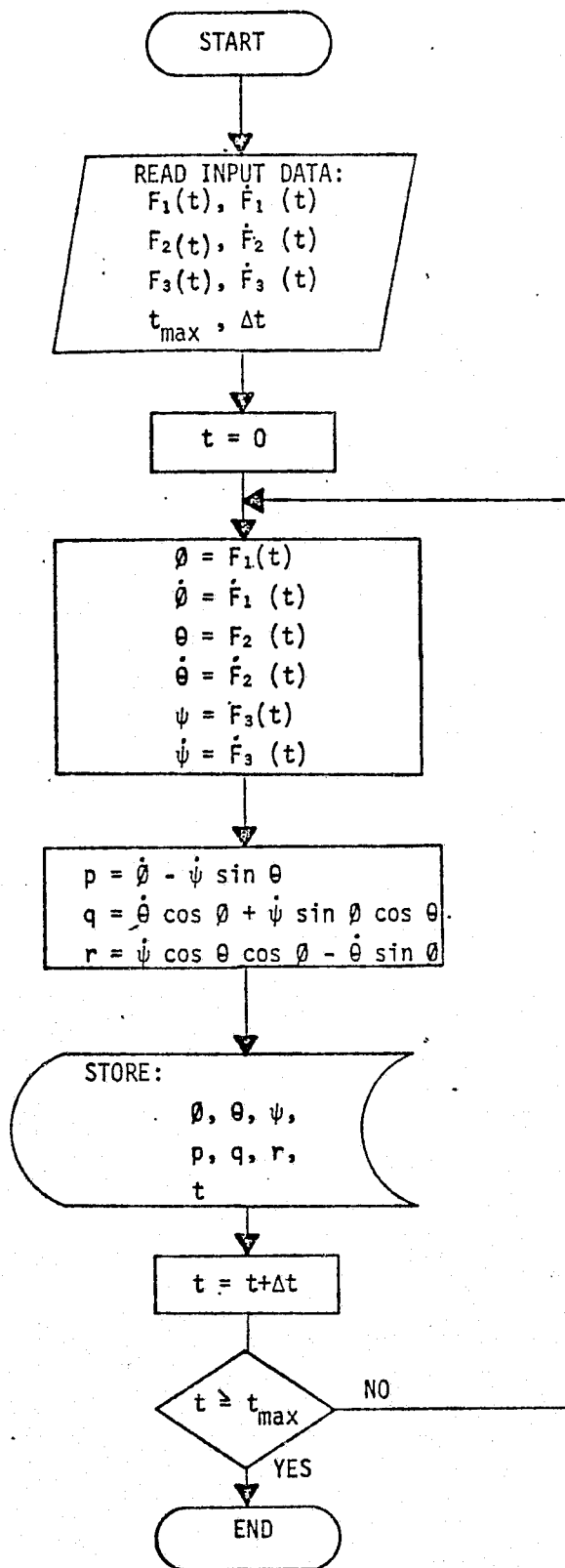


FIGURE 4.7-79 CLOSED FORM GIMBAL ANGLE METHOD

on an output tape for each computation interval required by the simulation software.

IMU Data Base Impact

Data base impact for initial IMU dynamical validation is very minor; only the above reference modules and a few mathematical subroutines are required. Revalidation of the basic IMU dynamics should be required rarely, if at all. Validation of subsidiary IMU outputs will require a certain amount of hardware test data.

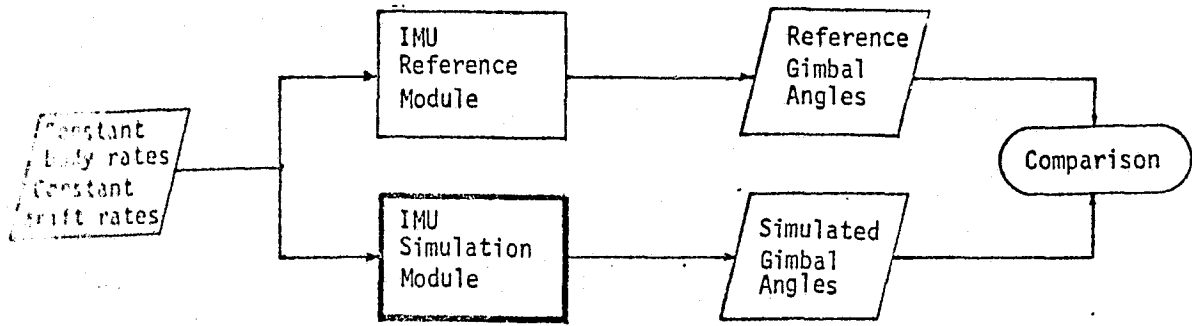
IMU Validation Methods and Check Cases

Verification software structures employing the closed-form-solution reference modules previously described are shown in Figure 4.7-80 .

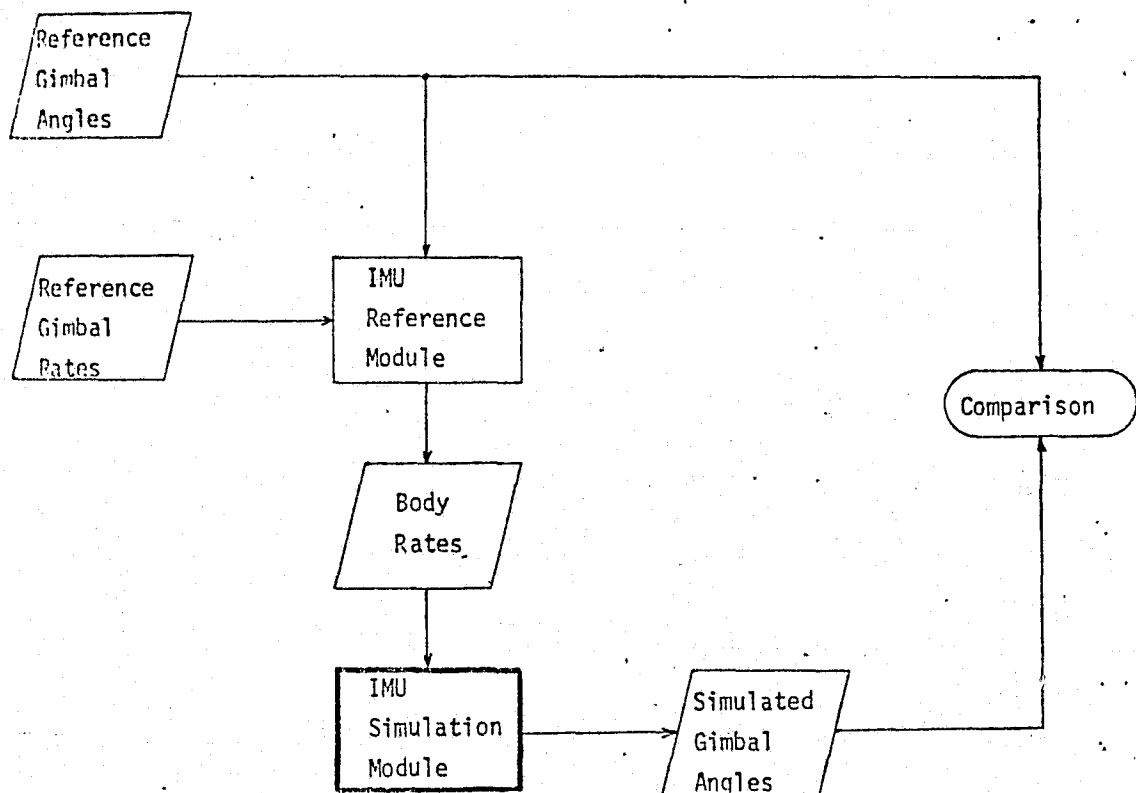
To use the constant rate input method, Figure 4.7-80 (a), input constant body rates and/or drift rates to the IMU reference module and the IMU simulation module, thus obtaining comparable gimbal-angle time histories.

To use the closed-form gimbal angle input technique, Figure 4.7-80 (b), select analytic functions of time to be used as inputs (see preceding examples). These time-histories and their derivatives are input to the reference module, which generates body-rate time-histories to be input to the IMU simulation module. The outputs of the IMU simulation module should then match the original gimbal-angle time histories.

A set of check cases applying different combinations of magnitude and frequency inputs to the various IMU axes should be used for thorough validation of individual-axis responses and their interactions. Due to the analytical nature of the reference data, a highly-accurate match with simulation data should be demanded; e.g., one percent or better over time spans up to a hundred seconds.



(a) CONSTANT RATE INPUT TECHNIQUE



(b) CLOSED-FORM GIMBAL ANGLE INPUT TECHNIQUE

Figure 4.7-80. IMU SIMULATION VERIFICATION
TECHNIQUES

4.7.5.1.2 Strapdown Inertial Sensors - This section concerns those inertial sensors which are "strapped down"; i.e., rigidly mounted to the vehicle structure, rather than on a stable element.

SIS System Description

The SIS subsystem, as described in Refs. 20, 37, consists of five identical sensor packages - three at various locations in the Orbiter, and one in each SRB. Each package contains a normal and lateral accelerometer, and orthogonal rate gyros to sense body roll, pitch and yaw rates. These sensors provide data for use in the vehicle attitude control loops. The SIS has also been considered for use as a backup navigation data source in the event of multiple IMU failures. This application would require the addition of longitudinal accelerometers.

SIS Simulation Module Description and Performance Parameters

The input/output interfaces of the SIS module are shown in Fig. 4.7-81. Primary inputs are of course the body angular rates, the body-axis sensed accelerations of the center of mass, and the current c.g. position. The primary outputs are the simulated rate gyro and accelerometer outputs, which include the effects of sensor location, axis misalignment, and possibly hardware error characteristics. (Hardware error modelling may not be required, unless the SIS is used as a backup navigation reference.) Body bending and fuel slosh contributions to SIS outputs are discussed in Section 4.6. Subsidiary inputs and outputs include electrical power, avionics bay temperature, and various status and failure discrettes. Table 4.7-23 provides a parameter list for the SIS simulation module.

SIS Reference Data Sources and Data Formats

Figure 4.7-82 provides the math flow for a reference module which provides data for nominal SIS operation only. Off-nominal operation due to failures and voltage variations and temperature variations is not considered in this study.

Two separate flow paths are shown on Figure 4.7-82: an error-free computation path, and a measurement-error path. On the error-free path, Equation (1) calculates sensed vehicle accelerations at the sensor-package location, in ideal

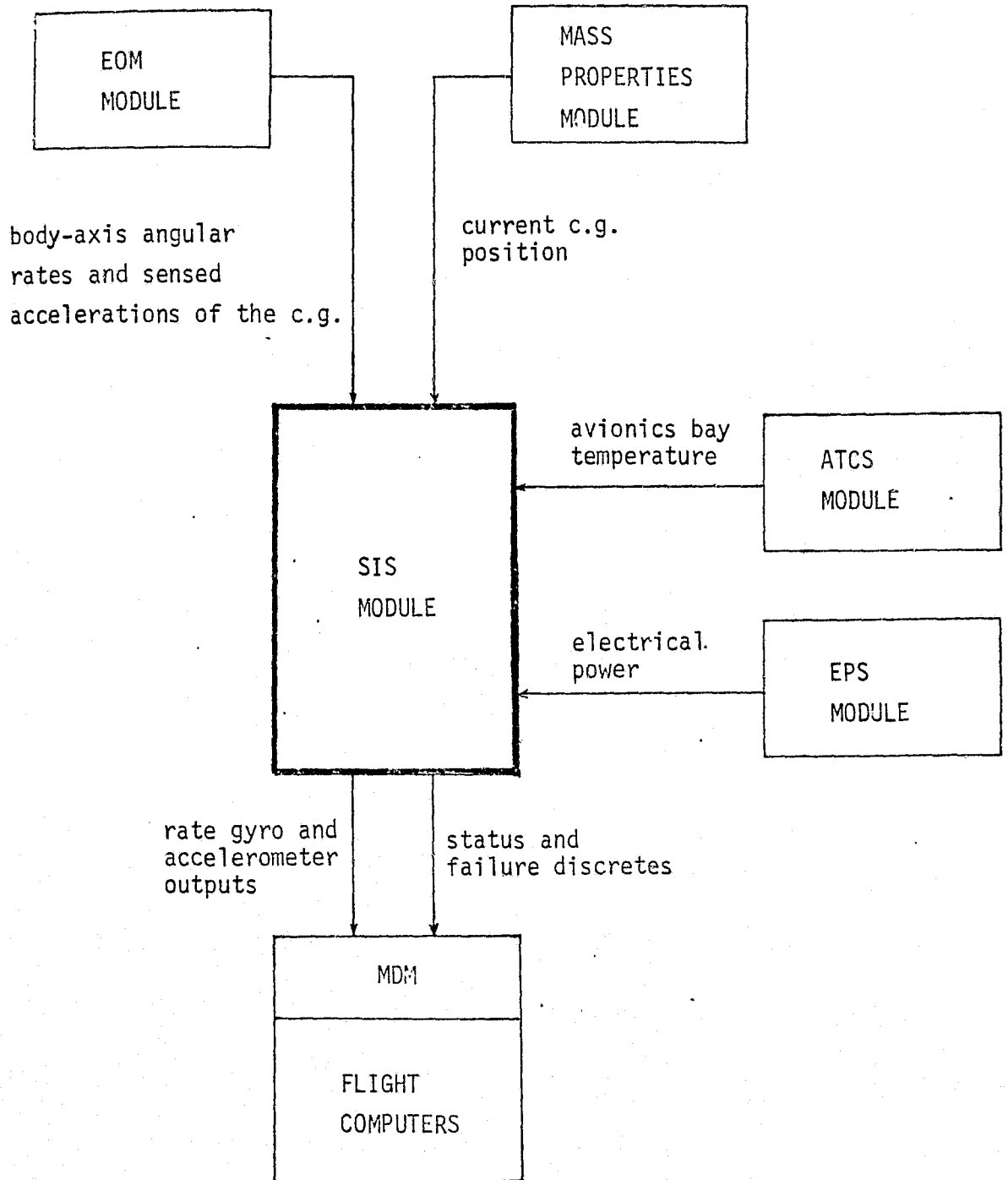
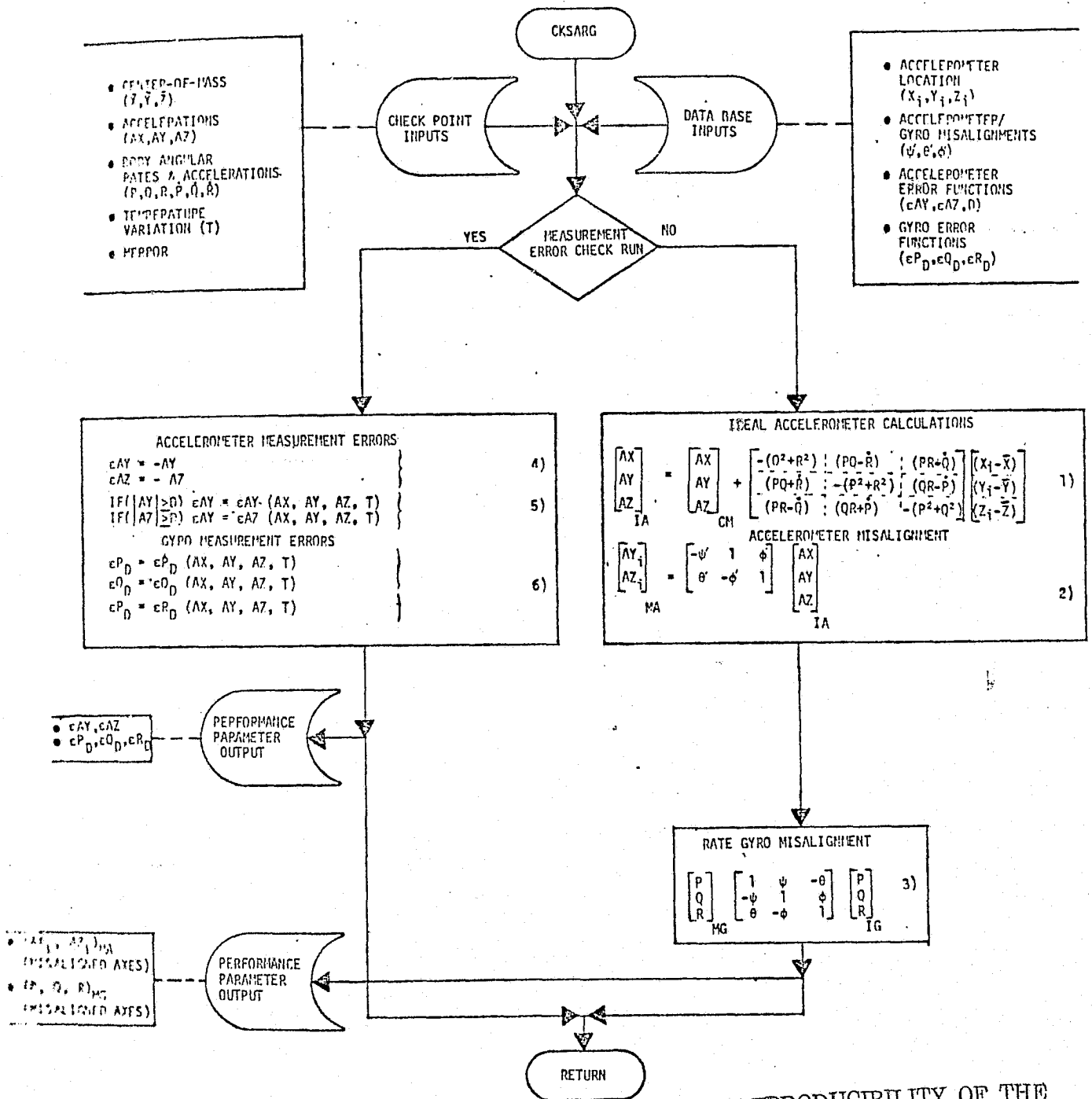


FIGURE 4.7-81. STRAPDOWN INERTIAL SENSOR MODULE INTERFACES.

4.7-23. STRAPDOWN INERTIAL SENSOR MODULE PARAMETERS

SYMBOL	DEFINITION	TYPE ^a
x, y, z	Body coordinates of center of gravity	I
\underline{a}	Vehicle sensed acceleration	I
p, q, r ; $\dot{p}, \dot{q}, \dot{r}$	Vehicle angular rate and acceleration in body axes	I
ΔT	Difference between operating temperature and calibration temperature of the SIS	I
x_i, y_i, z_i	Typical sensor locations (in body coordinates)	DB
ψ', θ', ϕ'	Accelerometer/rate gyro misalignments (ψ' = misalignment in X-Y plane, θ' = misalignment in X-Z plane, ϕ' = misalignment in Y-Z plane)	DB
D	Accelerometer dead zone	DB
$\epsilon a_y, \epsilon a_z$	Accelerometer measurement errors	DB
$\epsilon p_d, \epsilon q_d, \epsilon r_d$	Rate gyro measurement errors (roll, pitch, yaw drift rates respectively)	DB
\underline{a}_{-ia}	Accelerations at the accelerometer, in ideal axes	P
\underline{a}_{-ma}	Accelerations at the accelerometer, in misaligned axes	CP
p_{ma}, q_{ma}, r_{ma}	Vehicle angular rates, in misaligned axes	CP

^a LEGEND: DB = data base input
I = input
P = performance parameter
CP = critical performance parameter



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FIGURE 4.7-82. STRAPDOWN INERTIAL SENSOR REFERENCE MODULE MATH FLOW.

sensor axes. Equations (2) and (3) then transform the ideal-axis accelerations and angular rates into true sensor-axis outputs, using small-angle relationships for axis misalignments. A single misalignment transformation is used for both accelerometer and gyro outputs, since the use of a typical misalignment provides all the generality required for a complete verification.

The measurement-error computations are provided on the assumption that some or all of the simulations of interest will require sensor error modelling. The measurement-error path is taken only when an input flag is set.

The accelerometer measurement error reference data is generated using Equations (4) and (5) of Fig. 4.7-82, where D is from the data base and represents a typical dead zone or threshold below which no acceleration is sensed, and the functions ϵAY and ϵAZ are generalized representations of the measurement errors that would be added to the true axis accelerations. Equation (7) presents an expansion for the accelerometer error function ϵA of Equation (5), using a standard modelling algorithm for typical accelerometer measurement errors.

$$A_1 = B_a + C_1 A_1 + C_2 A_1^2 + \dots + C_{12} A_2 + C_{13} A_3 + C_{14} T + \dots \quad (7)$$

The parameters in Equation (7) are defined as follows:

- B_a = accelerometer total bias (mean + random)
- A_1, A_2, A_3 = acceleration components along the input axis and the cross-axes, respectively
- C_1 = linear scale factor error
- C_2 = non-linearity error coefficient
- C_{12}, C_{13} = cross-axis sensitivity error coefficients
- ΔT = difference between calibration temperature and operating temperature
- C_{14} = linear temperature error coefficient

It may not be necessary to model all the terms shown in Equation (7), depending upon the fidelity required. In addition, Equation (7) does not represent the most general case; for example, we could include higher order non-linearity terms, error terms proportional to acceleration products, and non-linear temperature variations. The necessary terms in the error model can be determined using vendor-supplied design and test data for individual errors, the real-world sensor use, and the simulator's functional requirements. Typically, bias, linear scale factor, second order non-linearity and linear temperature error terms would be all that is required for sensors involved in a navigation function.

Equation (6) provides rate gyro measurement error reference data, where the functions ϵP_D , ϵQ_D , and ϵR_D are generalized representations of measurement errors based on sensor design and test data. The error values output would normally be added to the true rate outputs as drift rates. Equation (8) presents an expansion for gyro drift rate, using a standard modeling algorithm:

$$\begin{aligned} \epsilon_D = & B_g + K_i A_i + K_o A_o + K_s A_s + \dots + K_{io} A_i A_o + K_{os} A_o A_s \\ & + K_{is} A_i A_s + K_t \Delta T + \dots \end{aligned} \quad (8)$$

where the individual parameters are defined as follows:

B_g	= gyro total bias drift (mean + random).
A_i, A_o, A_s	= case accelerations along the input, output, and spin axes respectively.
K_i, K_o, K_s	= anisoelastic drift coefficients
ΔT	= difference between calibration temperature and operating temperature
K_t	= linear temperature coefficient

It may not be necessary to model all the terms of Equation (8), or it might be necessary to model additional terms; for example, drifts proportional to acceleration squared or possibly drift due to external magnetic fields. As with the accelerometer error modeling, gyro error model fidelity should be determined using vendor-supplied design and test data on individual errors, the real-world sensor use, and the simulator's functional requirements.

The gyro case accelerations shown as variables in the error functions of Equation (8) are the same as the body accelerations for the accelerometer error functions. The transformation of AX, AY, and AZ into gyro input, output, and spin axis accelerations depends on the individual gyro orientations. As a result the individual drift rate equations for ϵP_D , ϵQ_D , and ϵR_D will have different body acceleration components as the respective gyro axis accelerations. Since the error model is not affected by the preceding generalizations, there is no loss in the validity of the verification.

The data required for validation will normally be in hard-copy format. Basic information, such as sensor package locations and typical misalignments, should be found in Ref. 36. Hardware error coefficients may have to be obtained from test reports or other less-accessible sources.

SIS Validation Methods and Check Cases

In general, checkpoint data will be required for both error-free and measurement-error modes of operation of the SIS module. Although reference-trajectory segments may be used to provide input data, selected discrete checkpoints will be simpler to implement, and actually give better results.

For reference data not containing measurement errors, the inputs include sensor location in the body reference system, the center-of-mass accelerations, body angular rates and angular accelerations, and a zero value for the measurement-error flag. Only a relatively small number of independent input check points are required for a complete verification for this mode, since the equations involved are relatively simple. Sets of three widely-spaced linearly-independent vectors in linear acceleration, angular rate, angular acceleration and axis misalignments will provide a thorough validation exercise. Several sensor-package locations should be tested, including fore/aft, left/right, and up/down displacements relative to the c.g. Agreement between reference and simulation data should be close to machine accuracy (e.g., five to six significant figures).

When generating reference data for the error model verifications, the required inputs are the accelerations at the sensor in the sensor true axes (assumed the

... for both accelerometers and rate gyros), the operating temperature variation from that for calibration, and a positive value for the measurement-error flag. Data can be generated by varying the inputs selectively to magnify effects of different error terms. Comparisons can then be made which are identifiable with individual error components. Agreement should be within a few percent.

When driving the simulator models to generate the corresponding data, we anticipate that some action will have to be taken to provide compatibility with the reference module execution mode. For example, contributions due to flexible body dynamics must be zeroed; simulation-module measurement-error models must be deactivated for non-measurement error check points. For the measurement error check points, sensor locations should be set to the center of gravity, with zeroed misalignments. Since the simulator software has not yet been developed, only the preceding generalizations are made with respect to interface initializations and input identifications required for the simulator module.

SIS Validation Data Base Impact

Data base impact for SIS module initial validation is very minor. The reference module is rather simple, and the use of discrete checkpoints obviates handling of large data files. Revalidation would only be required if significant changes were made in the measurement-error model.

4.7.5.1.3 Propulsion Systems Interface Units (PSIU's) - These units, which transfer data between the propulsion subsystems and flight computers and/or crew controls and displays, include the Main Engine Controller/Engine Interface Unit (MEC/EIU), the Solid Rocket Booster (SRB) interface, the Orbital Maneuvering System Thrust Vector Control (OMS TVC) interface, and the Reaction Control System (RCS) interface.

Except for the MEC/EIU, these are rather simple hardware units, and we assume that their functional simulation, data-word generation/interpretation capabilities and malfunction-insertion provisions will be "embedded" in the module which simulates the corresponding propulsion subsystem. Only the MEC/EIU will be described in any detail in this section; the other PSIU's perform the same general functions.

PSIU Subsystem Descriptions

The MEC hardware and functions are described by Ref. 26, the MEC software by Ref. 38. The EIU is described by Ref. 39. Specifications for the other PSIU's have apparently not been issued yet.

The MEC and EIU together perform the following functions:

- Accept discrete (e.g., start, shutdown) and variable (e.g., thrust level) commands from the Orbiter avionics.
- Control SSME sequencing, thrust, and mixture ratio.
- Perform engine checkout and monitoring.
- Transmit SSME checkout/monitoring data back to the Orbiter avionics
- Perform self-test.

Figure 4.7-83 (after Ref. 26) shows the control and data interfaces of the MEC/EIU. The EIU's role in control/data interchange is simply code conversion and formatting. Other PSIU's perform similar functions, except for thrust variation.

PSIU Module Description and Performance Parameters

PSIU simulation has two aspects: functional simulation, and data-word generation/interpretation. From the functional viewpoint, we assume that each PSIU simulation is "embedded" in the module which simulates the associated

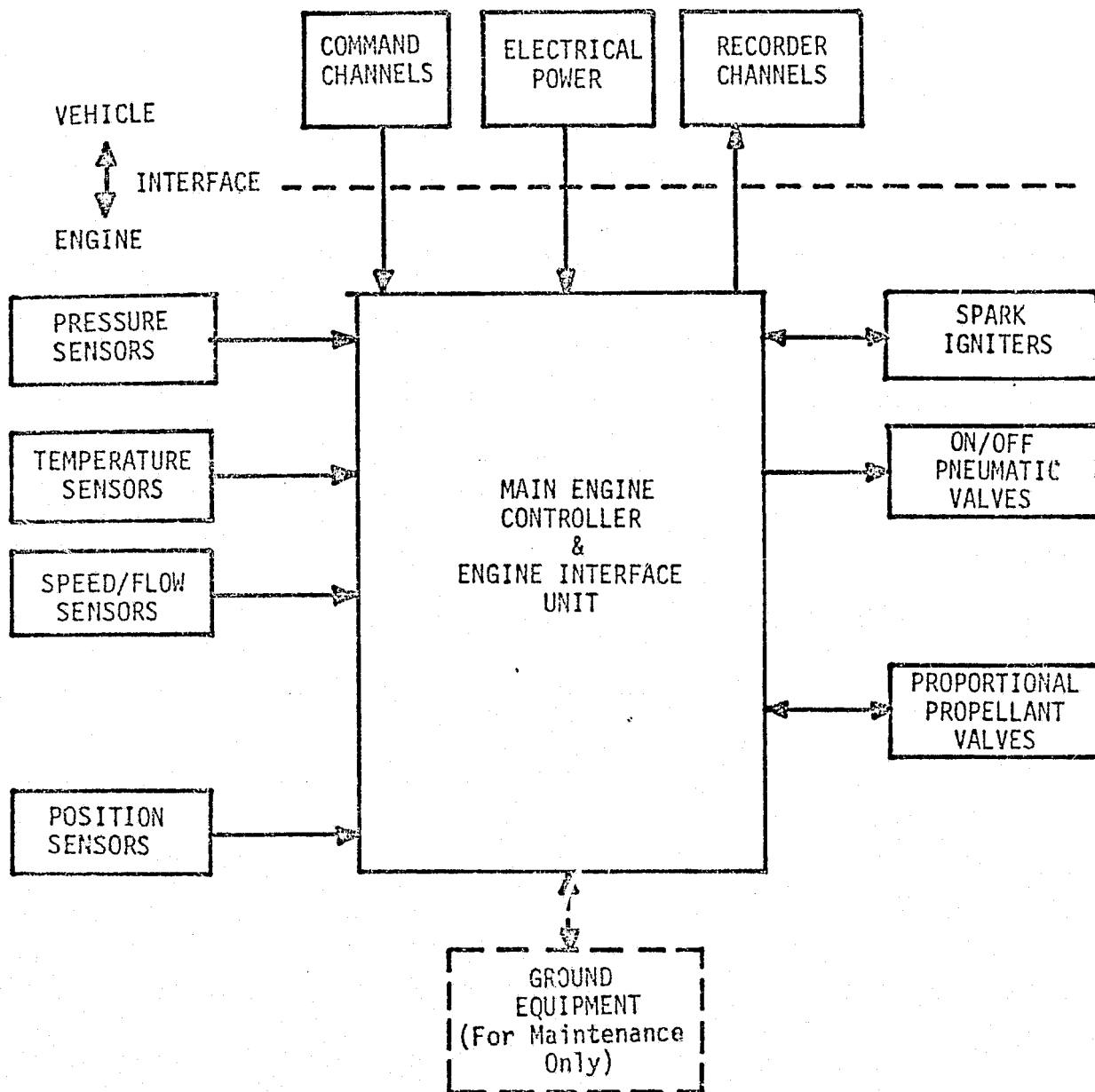


FIGURE 4.7-83 . MEC/EIU HARDWARE INTERFACES

propulsion subsystem. Thus the overall command/response characteristics of each propulsion module will be a composite of (a) the internal processing of the PSIU and (b) the response of the propulsion hardware - pumps, valves, combustion chamber and nozzle. Startup/shutdown sequencing will probably be simulated as empirical time functions for thrust buildup/tailoff.

The other basic function of the PSIU modules is the handling of digital data-words, including interpretation of command words received from the flight computers, and generation and formatting of monitoring and status words for transmission to the flight computers. These functions must be implemented precisely to satisfy the flight software; however, they will be shared with or entirely absorbed by the Flight Hardware Interface Device (FHID), thus simplifying the simulation software.

Each PSIU module will also require some failure-insertion provisions; simulated failures may affect either the functional simulation, the data-word handling, or both.

No performance-parameter tables are provided for PSIU simulation modules. Since PSIU simulation is embedded in the propulsion subsystem simulation module, the performance parameters for each such module will include both functional-simulation parameters and avionics-related command and status words. For example, see Section 4.7.3.1 for the SSME/MEC/EIU parameter table and simulation-module interface diagram.

PSIU Reference Data Sources and Data Formats

The functional performance of each PSIU simulation will be implicitly validated by end-to-end command/response validation of the associated propulsion module. This will include static thrust levels, thrust buildup/tailoff, and (for the SSME only) throttle response.

The basic source of functional-simulation reference data will be engineering simulations of each propulsion subsystem. Later in the program, engineering data will be refined using static-firing data; these data will be corrected for atmospheric pressure in the case of the larger engines, but vacuum-chamber firing data will be available for the smaller engines. These considerations are discussed in Section 4.7.3.

Command/status data-word formats must be verified bit-by-bit for each nominal and off-nominal case, the basic source of reference data being the most current version of each PSIU specification.

Due to the complexity of the MEC/EIU, it may be necessary to verify this submodule in isolation, before integration with the basic SSME module. The hardware/software MEC simulation described by Ref. 40 may be a suitable source of reference data for such an exercise.

PSIU Validation Methods and Check Cases

Each composite PSIU/propulsion-subsystem module must be exercised over its overall operating range, including startup, constant thrust, and tailoff. Additional check cases will be necessary for the variable-thrust SSME. These will include static-thrust levels from MPL to EPL, as well as dynamic throttle response to both increase and decrease commands over the operational static-thrust range. For simulators which use functional simulation of the flight software, the command inputs will be in the normal internal floating-point format of the host computer.

For simulators using flight-computer hardware, inputs must be in the format in which they will be received from the flight computer/FHID. The set of check cases must then be sufficient to verify that each PSIU module properly interprets all valid flight-computer command words, and returns the correct status/monitoring words for all self-test modes, nominal and off-nominal operational modes.

PSIU Validation Data Base Impact

In the functional-simulation area, validation of the PSIU's contributes no data base impact, since PSIU functions are implicit in the end-to-end validation of the propulsion modules.

Validation of digital data-word handling will require a command/response data-word "dictionary" covering the operational regime of the simulator of interest. For the MEC/EIU, this dictionary will be fairly extensive (several hundred entries); for other PSIU's, the dictionaries will be short (perhaps a few dozen entries).

4.7.5.1.4 Star Tracker (ST) - Unlike previous manned space vehicles, the Orbiter provides fully automatic star/target tracking, without crew viewing of the tracker field. This section discusses the ST hardware and its flight-computer interface, as well as the functions and validation of the associated simulation module.

ST Subsystem Description

The ST is a strapdown, wide field-of-view ($10 \times 10^\circ$) image-dissector device. It provides automatic acquisition and tracking, under flight-computer control, of a selected star or sun-illuminated rendezvous target. While tracking, it outputs the apparent magnitude and position in the field of the object being tracked. Its sensitivity (acquisition threshold) is variable on command; the maximum sensitivity is sufficient to acquire and track the 153 brightest stars (S-20 magnitude), or a sunlit target whose apparent brightness is at least equivalent to an S-20 magnitude of +3 at a range of 300 nm.

Despite the stray-light protection afforded by its light shade (LS), the ST may fail to acquire, or lose track on, stars or targets which are in the vicinity of other bright objects; e.g., the sun, moon, earth, or a brighter star. To protect the tracker from damage due to excessive input brightness, it is provided with a shutter, activated by a separate bright source sensor. Field of view and response time of this subsystem are sufficient to prevent damage due to a bright object approaching at a rate of 10 deg/sec.

The physical arrangement of the three ST/LS assemblies, mounted on the nav base for maximum accuracy, is shown in Figure 4.7-84 (from Ref. 41); additional detail may be found in Ref. 42. Note that #1 and #2 star trackers provide overlapping coverage.

Star tracker operational modes, internal signal processing, and command/data interfaces are indicated by Figure 4.7-85. The modes of interest are:

- Open/close door
- Self test
- Search/acquire star or target
- Track star or target
- Break track
- Close shutter (bright source protection)

4.7-247

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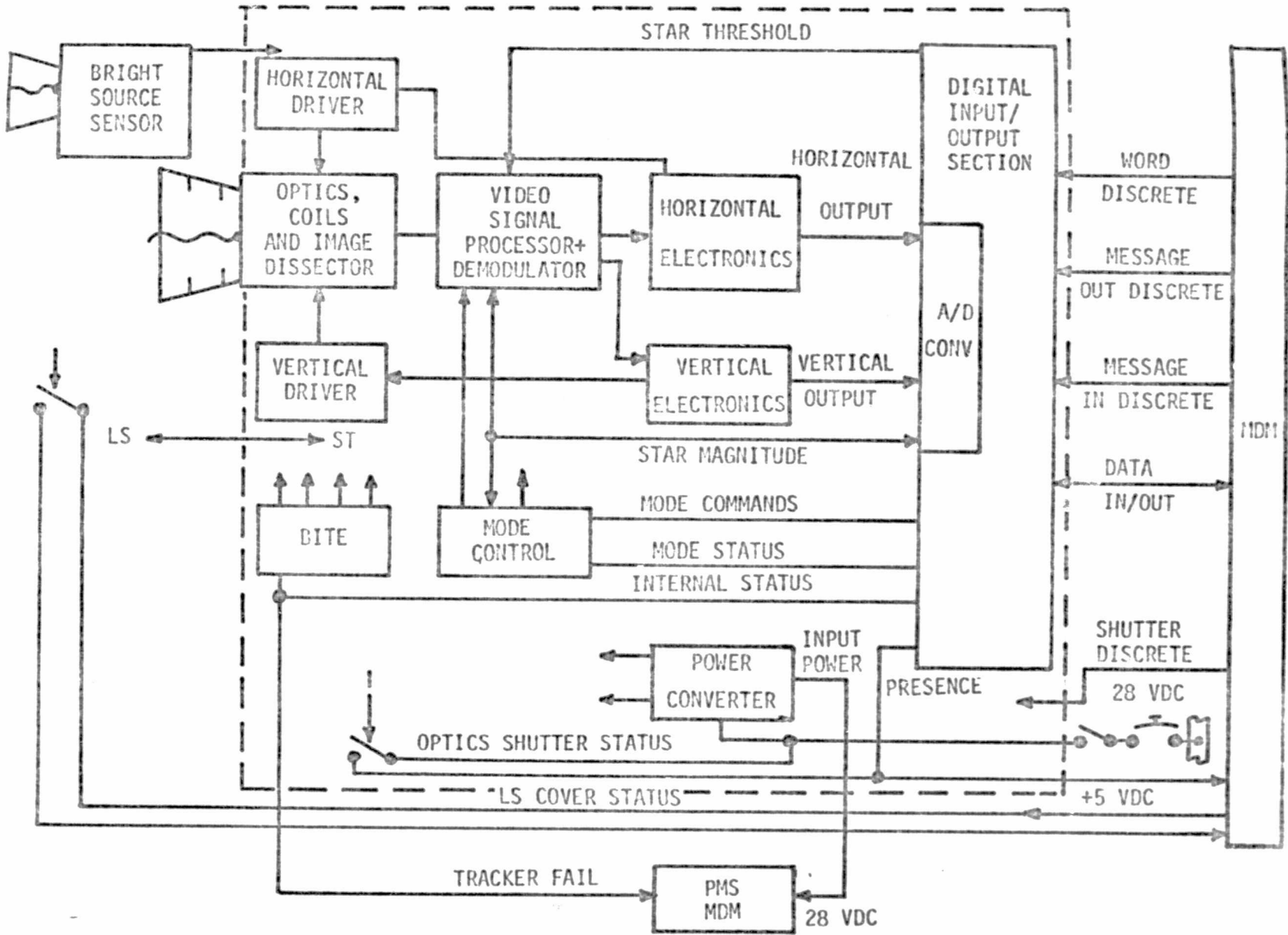


FIGURE 4.7-85. STAR TRACKER FUNCTIONAL BLOCK DIAGRAM (REFERENCE)

The star tracker door, in the left side of the Orbiter fuselage, is closed during ascent and entry, and opened on orbit. The self-test mode activates ST BITE, causing the ST to return a discrete indicating either operable or failed status.

In initiating a search, the flight computer sets the acquisition threshold, and may also provide horizontal and vertical position offset coordinates. In the absence of offset coordinates, the ST searches its entire field, locking onto either the first catalog star acquired, or to the brightest object in the field. If given an initial offset, it searches a reduced field centered on the offset point. In either case, a rectangular raster-scan search pattern is used, the search time will not exceed ten seconds, and the ST falls into the track mode.

The ST remains in the track mode until given a "break-track" command, the object passes out of the field of view, or it loses lock due to excessive vehicle rates or bright-source interference. Since the ST's are strapped-down, it may be necessary for Orbiter attitude maneuvers to be executed to maintain tracking. (Note that Ref. 41 does not presently define ST discrettes for search failure or loss of target during track.)

ST Module Description and Performance Parameters

Star tracker functions will be simulated at varying levels of detail. Door opening and closing will be simulated as talkback, with time delay and allowance for malfunction insertion. Self-test operation can be simulated with a small command/response dictionary which allows for nominal status and a repertoire of inserted malfunctions.

To obtain realistic star selection and timing results, the search/acquire mode simulation will have to be rather detailed. For all stars which are not blocked by the sun, moon, or earth, and satisfy the magnitude criterion defined by the current threshold selection setting, coordinate transformation and gating operations will determine whether they fall in the range of the scan pattern. To determine the first star acquired, a "lexicographic ordering" operation (see Ref. 43) will be required to determine which of the candidate stars is "nearest" to the starting corner (shown as the bottom-left corner in Figure 4.7-86, in terms of scan-pattern coordinates. Hardware scan-rate parameters can then be used to compute the acquisition time.

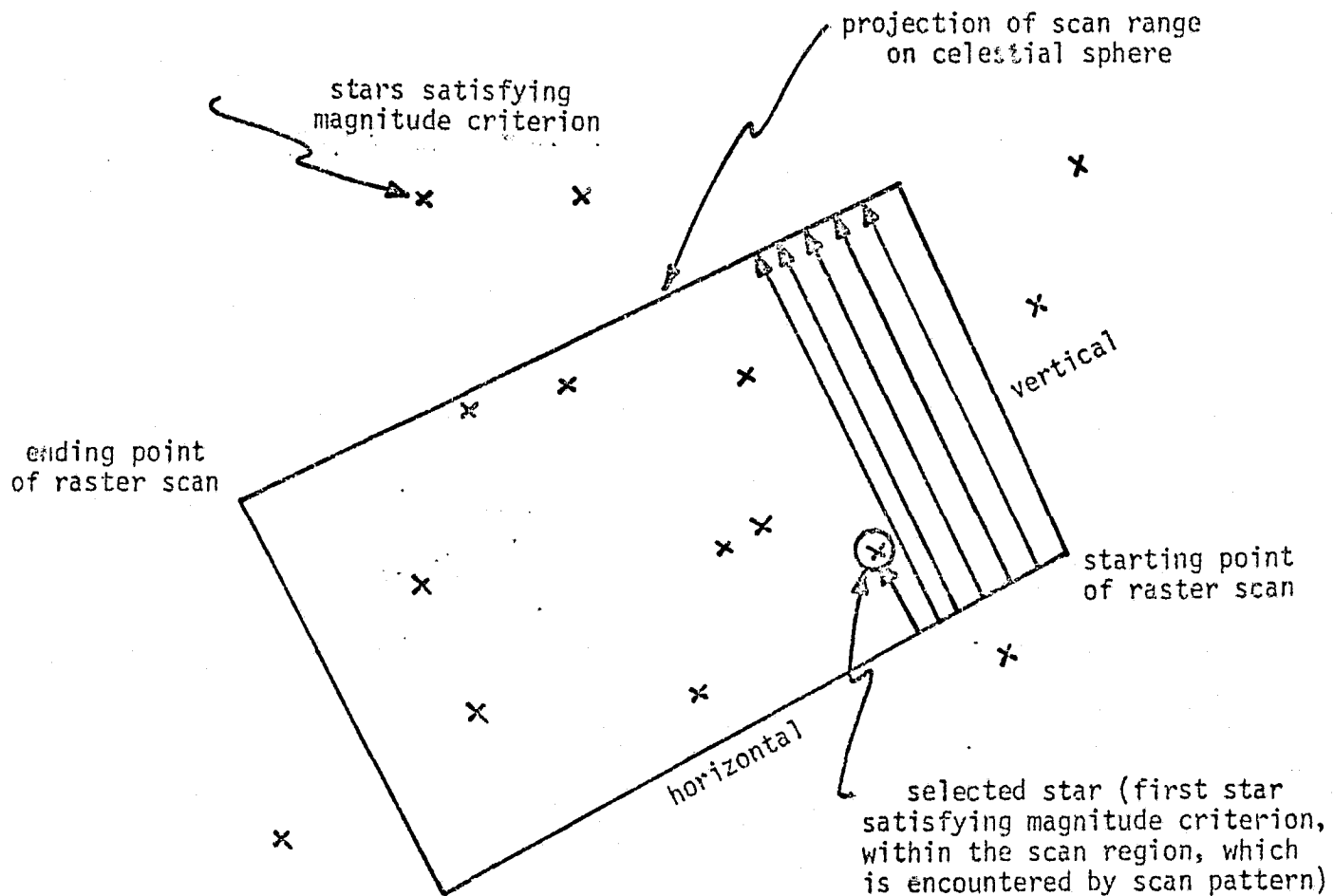


FIGURE 4.7-86. TYPICAL SCAN-PATTERN RELATIONSHIPS

The scan computations per se will be simpler for target acquisition, or for the search mode in which the brightest object in the field is selected. However, computation of target brightness will require determination of terminator position, range to target, and target viewing aspect (e.g., broadside vs. end-on).

Simulation of tracking outputs requires only a simple coordinate transformation, plus logic for loss of tracking due to excessive vehicle rates, movement of the object out of the field, and inserted malfunctions. Hardware error sources (bias and random) and stellar aberration due to Orbiter inertial velocity will also be simulated.

Bright-source relative positions and closure rates must be simulated at all times that any star tracker is operational.

Star tracker simulation module parameters are listed in Table 4.7-24, and module interfaces are shown in Figure 4.7-87.

ST Reference Data Sources and Data Formats

Initial validation of the track mode is best supported using closed-form solutions, for several special orientations of the ST axes relative to the point targets used for testing.

For more complete validation (all operational modes, interface with environment and dynamics), a detailed reference module will be required. Two candidate reference modules have been identified. One of these was developed, checked out, and used for the study described in Ref. 44. However, we recommend the module now being developed and checked out for inclusion in SVDS, the math flow of which (Ref. 45) is presented in Figure 4.7-88. Note that the search-mode simulation in this module only simulates the brightest-object selection criterion. Modifications will be necessary if the first-object-acquired criterion of Ref. 41 is actually implemented in the flight system.

ST Data Base Impact

The reference module for ST simulation validation is quite detailed; it will be of the same order of size as the ST simulation module for the SMS, larger than the one for the SPS. In addition, a driver routine will be required to generate Orbiter and target states and rates. Initially, these should be just synthetic

C-4

TABLE 4.7-24. STAR TRACKER MODULE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
	Door-open discrete	I
	Search-mode command discrete	I
	Initial search position commands (horizontal and vertical displacement)	I
	Self-test mode command	I
	Threshold-set command	I
	Break-track command	I
	Bus voltage	I
$\underline{r}, \underline{v}$	Orbiter position & velocity (ECI axes)	I
$\underline{\delta r}$	Target relative position (Orbital axes)	I
ϕ, θ, ψ	Orbiter attitude	I
$\underline{\omega}$	Orbiter angular rate vector	I
	Star catalog (magnitudes, unit vectors in ECI)	I
	Sun & moon positions (unit vectors in ECI)	I
	Earth horizon altitude	I
	Tracker alignment angles	DB
	Horizontal & vertical scan rates	DB
	Tracker hardware errors (bias, scale factor, and random)	DB
	Shutter-closed discrete	CP
	Self-test data	P
	Track-mode engaged discrete	P
	Star/target tracking position (horizontal & vertical displacement)	CP
	Star/target apparent magnitude	CP

^aI = input

DB = data base input

P = performance parameter

CP = critical performance parameter

4.7-252

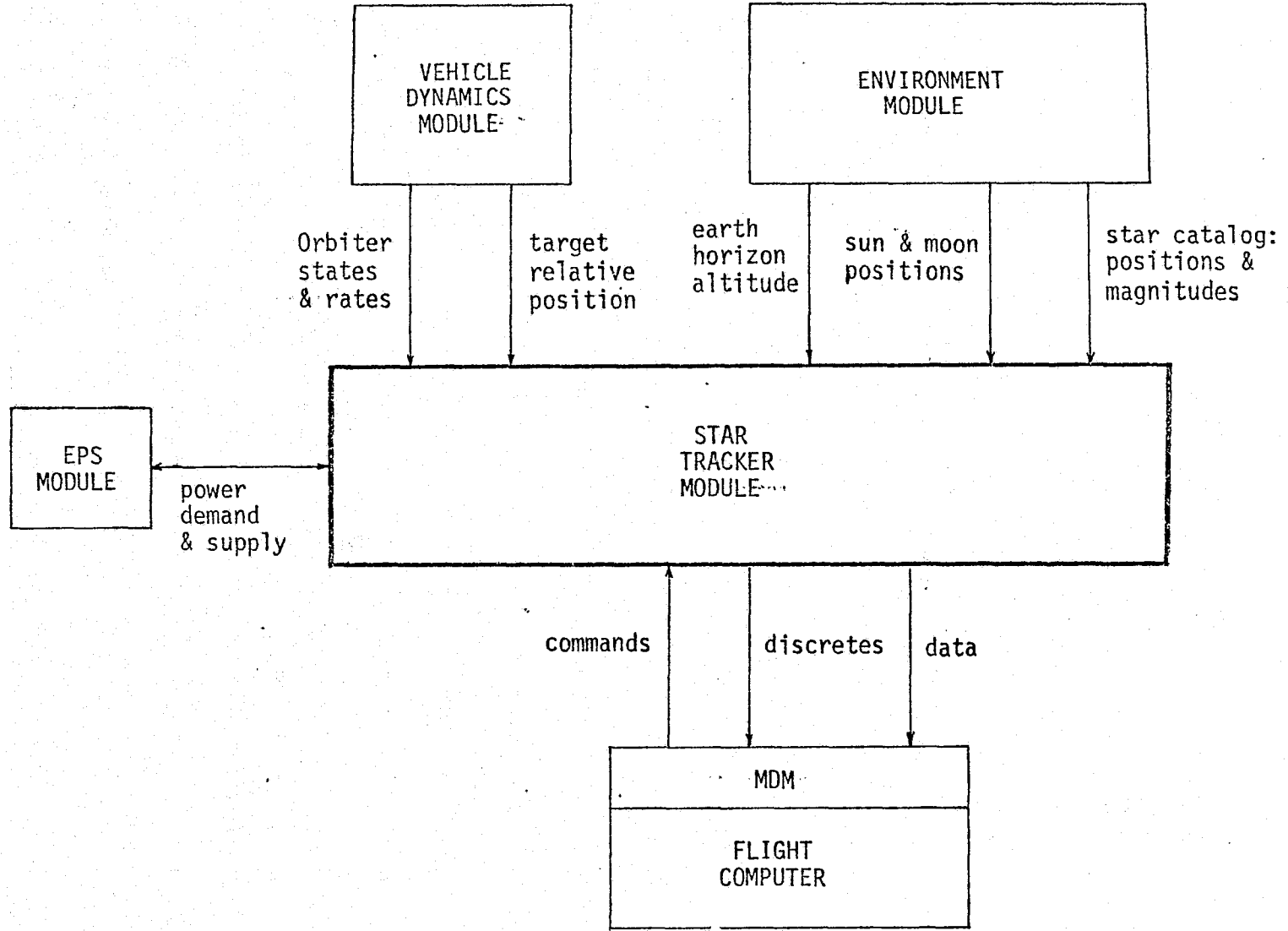


FIGURE 4.7-87. STAR TRACKER SIMULATION MODULE INTERFACES

Program STTR

Purpose: To generate simulated star tracker measurements from vehicle trajectory and attitude information.

Inputs:

n(3,3) angular rotations defining star tracker coordinate frames with respect to the shuttle body frame

DEL(3) angular factor to account for celestial body brightness

RB(3) average radii of the earth, sun, and moon

KATM angular factor for the earth's atmosphere

RE effective radius of the earth for sun occultation

MRZV rendezvous tracking flag

FOV star tracker raster field of view (one half of the side of the square)

AFOV auto-optics field of view

NSTAR number of stars in the star table

CFOV half-angle of the circular field of view enclosing the star tracker square raster field

RMAX maximum range for beacon tracking

BMAG beacon visual magnitude

TMAG sun-illuminated target visual magnitude

T elapsed time since the clock epoch

R(3) vehicle position vector

RT(3) target vehicle position vector

ITK(3) star tracker activation flags

MAUTOP(3) auto-optics flags

MBCON(3) beacon tracking flags

PSICOM(2,3) auto-optics angular commands

TIB(3,3) ECI-to-body transformation matrix

IABERR
INOISE
IHISAL
ISCALE
IQUANT

error option flags

CNOIS

constant for computing tracker noise standard deviation

PHI(3,3)

tracker misalignment vectors

SF(3,2,3)

tracker scale factor nonlinearities

QUANT

deflection output quantization level

Outputs:

ITRAC(3)

tracking flags

PSI(2,3)

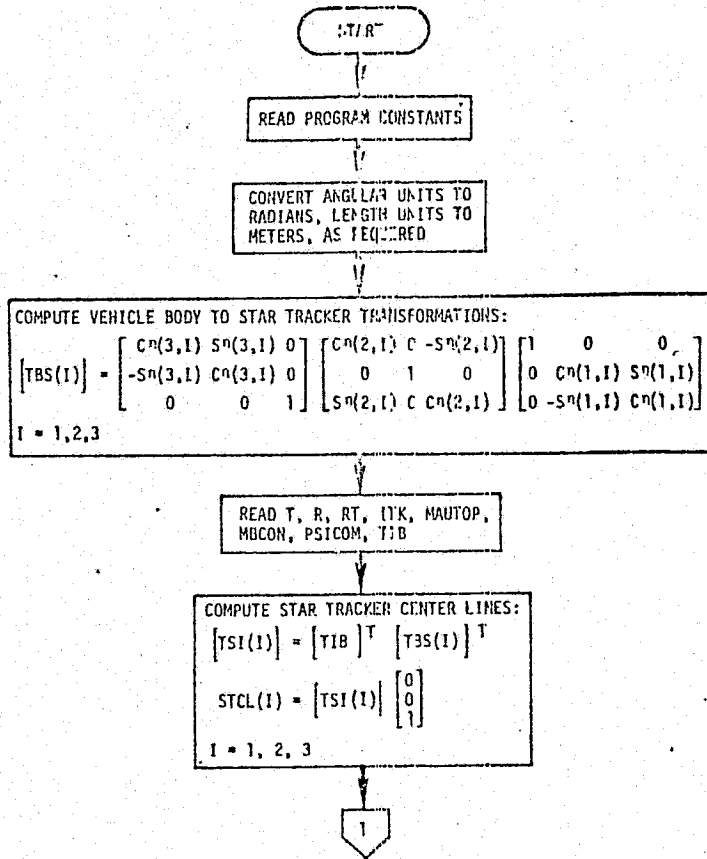
ideal star tracker deflection angles

PSIOB(2,3)

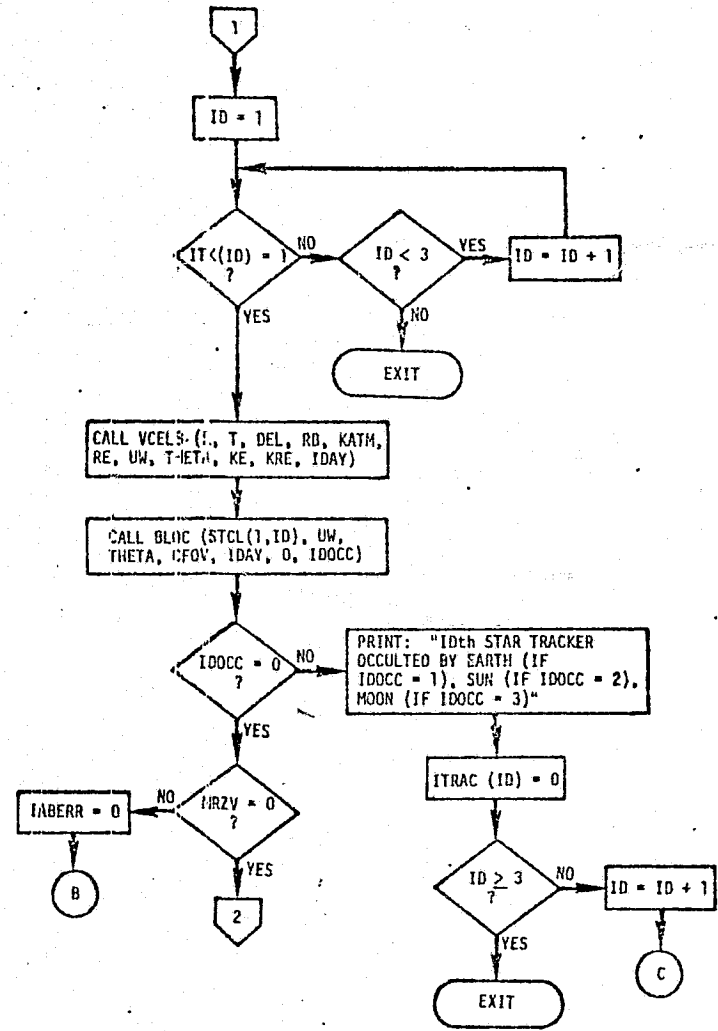
simulated star tracker angles

FIGURE 4.7-88. STAR TRACKER REFERENCE MODULE MATH FLOW

4.7-254



STRAK-1



STRAKR-2

FIGURE 4.7-88. (CONTINUED)

4.7-255

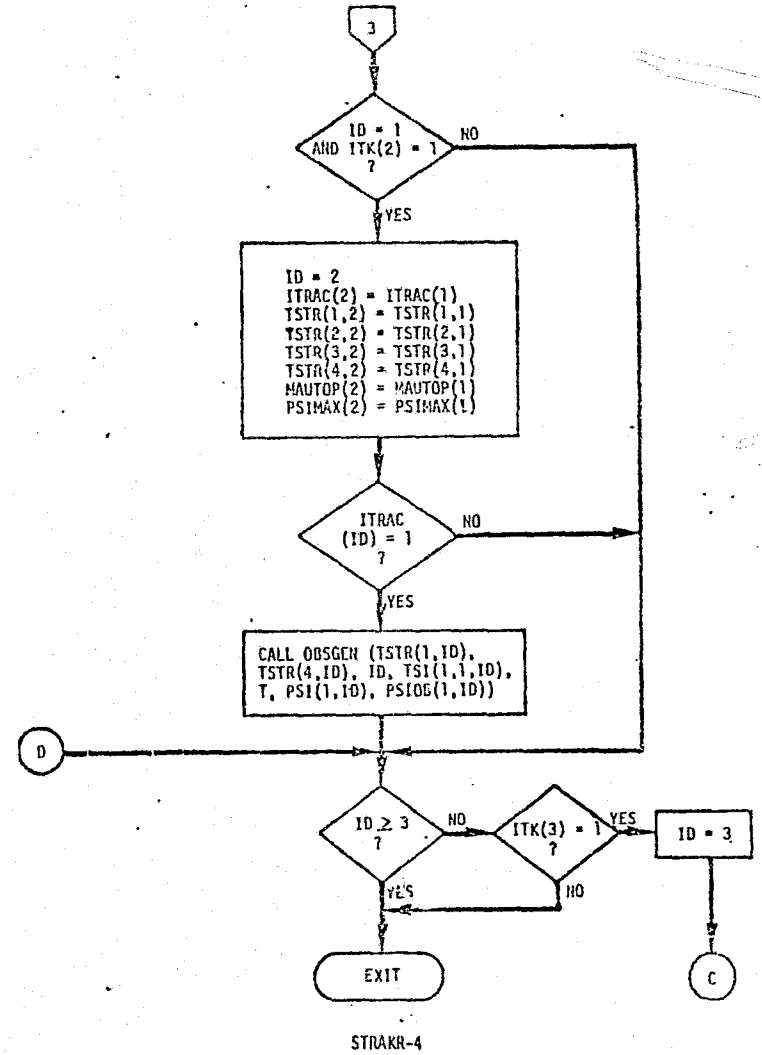
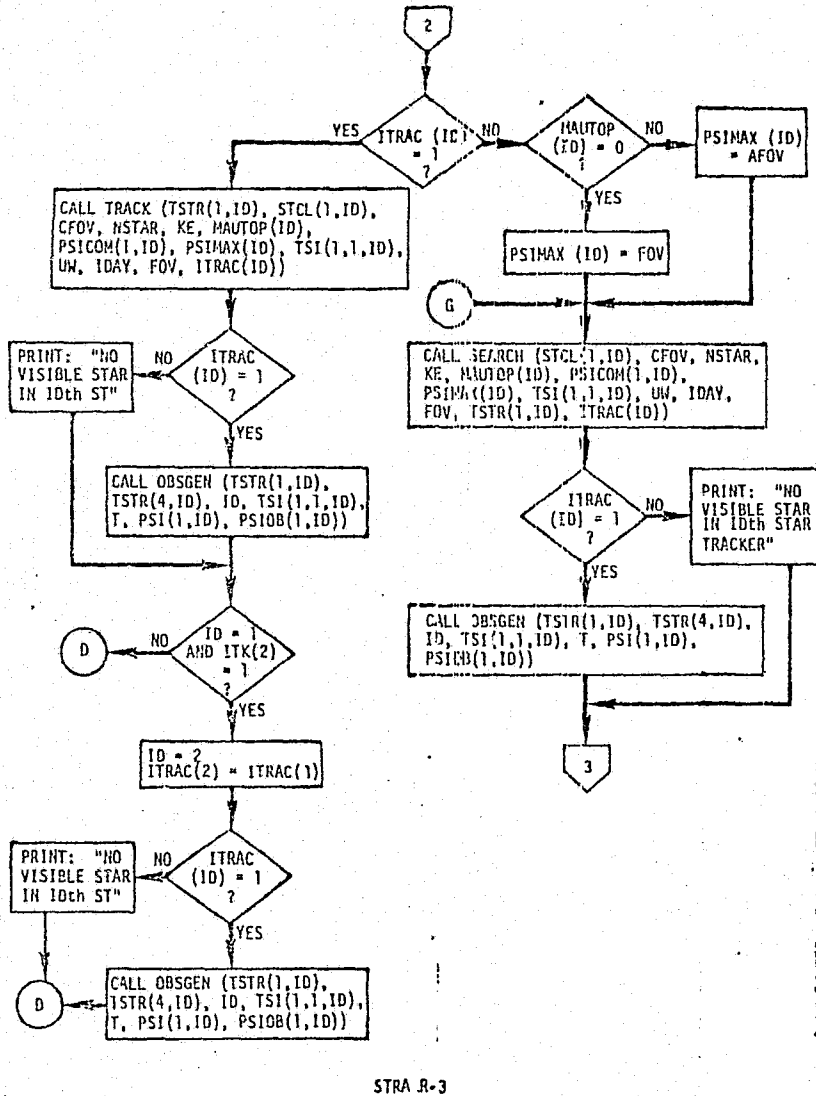


FIGURE 4.7-38. (CONTINUED)

4.7-256

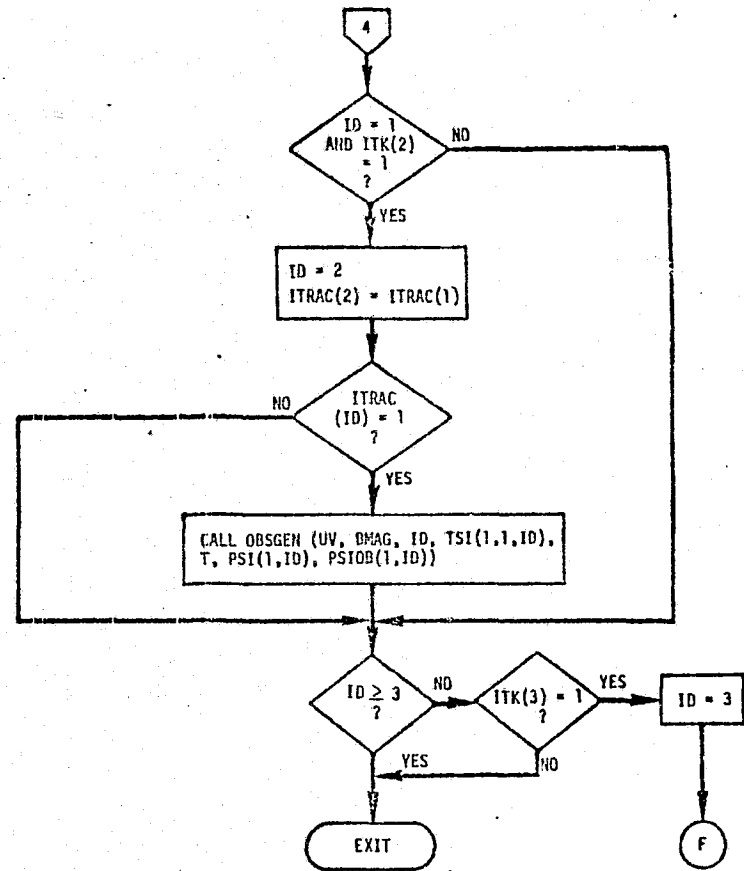
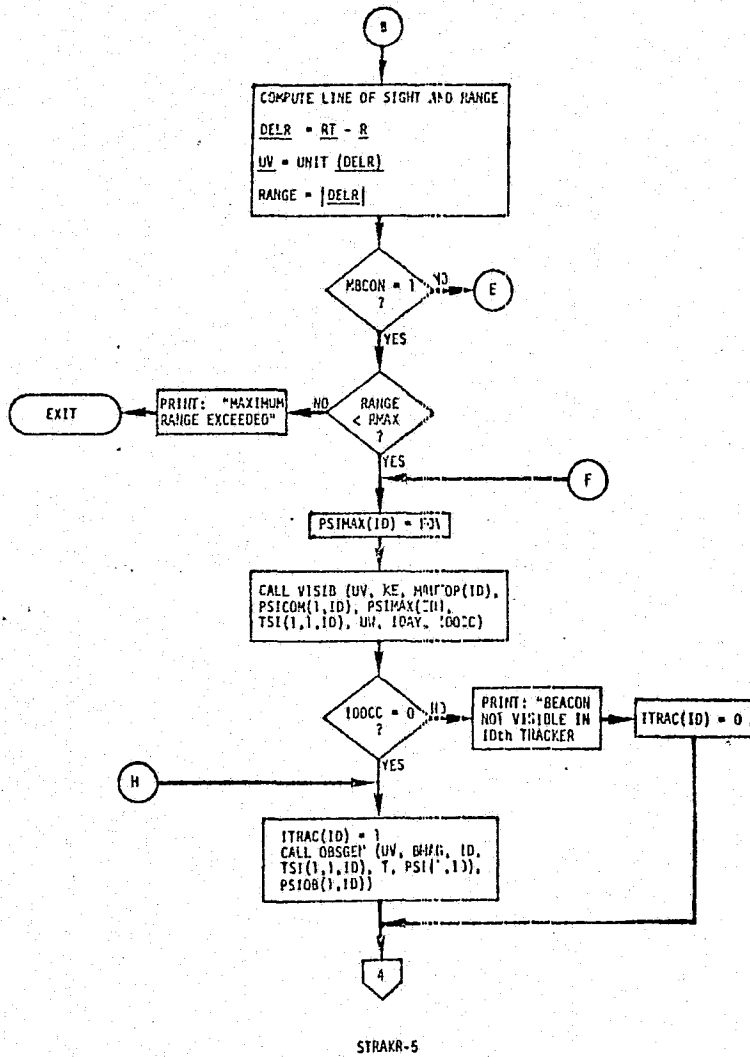
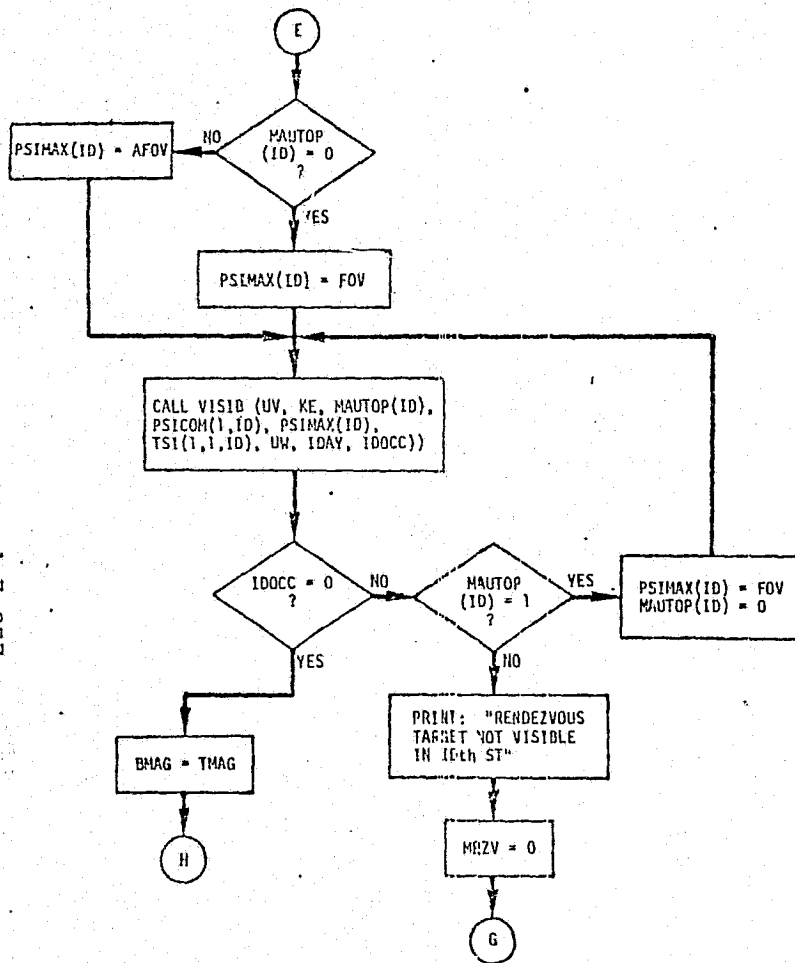


FIGURE 4.7-88. (CONTINUED)

A 7-257



STAKR-7

Subroutine AST-4 (F, U, USTAR)

Purpose: To compute the shift in the apparent line of sight to a star due to motion of the observing vehicle about the sun.

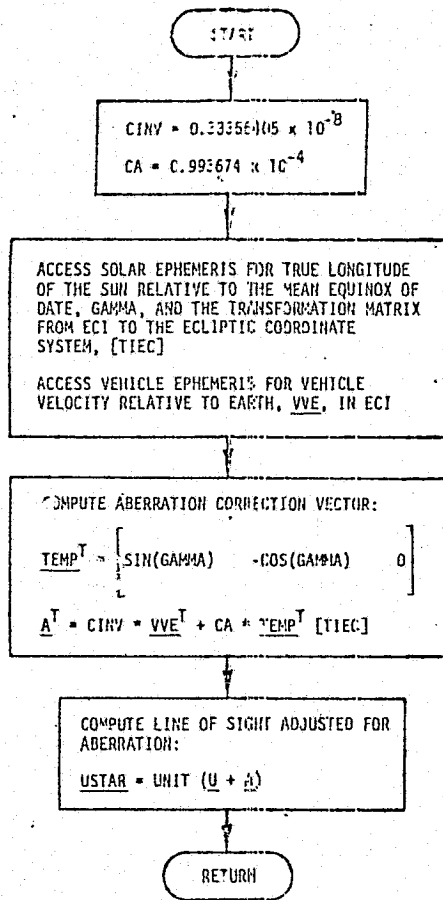
Inputs:

T elapsed time from the clock epoch
U(3) geometrical line of sight to star

Output:

USTAR(3) line-of-sight vector corrected for aberration

FIGURE 4.7-88. (CONTINUED)



ABERR-1

Subroutine ELOC (V, LW, THETA, CFOV, IOAY, EEARTH, IDOCC)

Purpose: To test FOV interference by the earth, sun, or moon

Inputs:

- V(3) target line of sight or ST centerline
- LW(3,3) unit vectors from the vehicle to the earth, sun, or moon
- THETA(3) effective half-angles of the earth, sun, and moon subtended at the vehicle
- CFOV half-cone angle of the circular field-of-view encompassing the ST search raster pattern
- IOAY orbital phase (day/night) flag
- EEARTH earth only flag

Output:

- IDOCC identity of the occulting body
 - IDOCC = 1: earth
 - = 2: sun
 - = 3: moon

FIGURE 4.7-88. (CONTINUED)

4.7-259

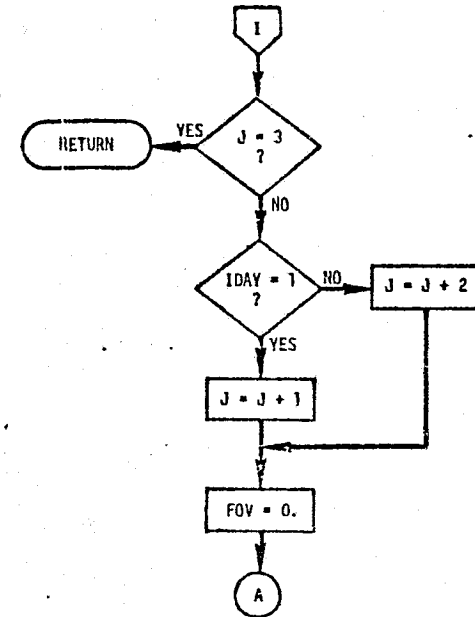
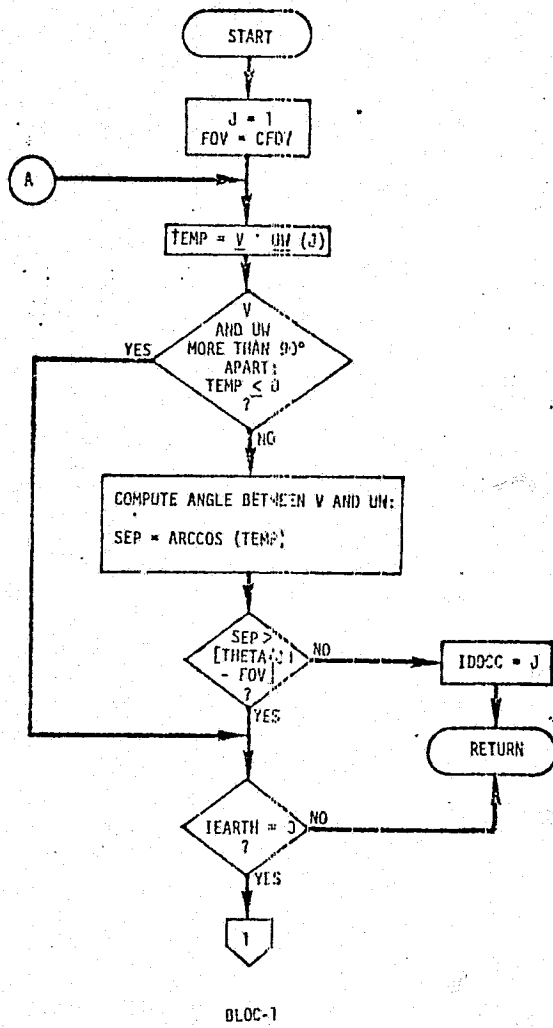


FIGURE 4.7-88. (CONTINUED)

Subroutine OBSGEN (SI, VMAG, ITRKR, TSI, T, PSI, PSIOB)

Purpose: To compute simulated star tracker deflection angles

Inputs:

- SI(3) geometrical line of sight to the target
- VMAG visual magnitude of target
- ITRKR identity of tracker
- TSI(3,3) star tracker-to-EI1 transformation matrix
- T elapsed time since the clock epoch
- LABERR } error option flags: (input via COMMON)
- INOISE }
- INISAL }
- ISCALE }
- IQUANT }
- CHOIS constant for computing tracker noise standard deviation (via COMMON)
- PHI(3,3) tracker misalignment vectors (via COMMON)
- SF(3,2,3) tracker scale factor nonlinearities (via COMMON)
- QUANT deflection output quantization level (via COMMON)

Outputs:

- PSI(2) ideal star tracker deflection angles
- PSIOB(2) simulated star tracker angles

4.7-26f

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

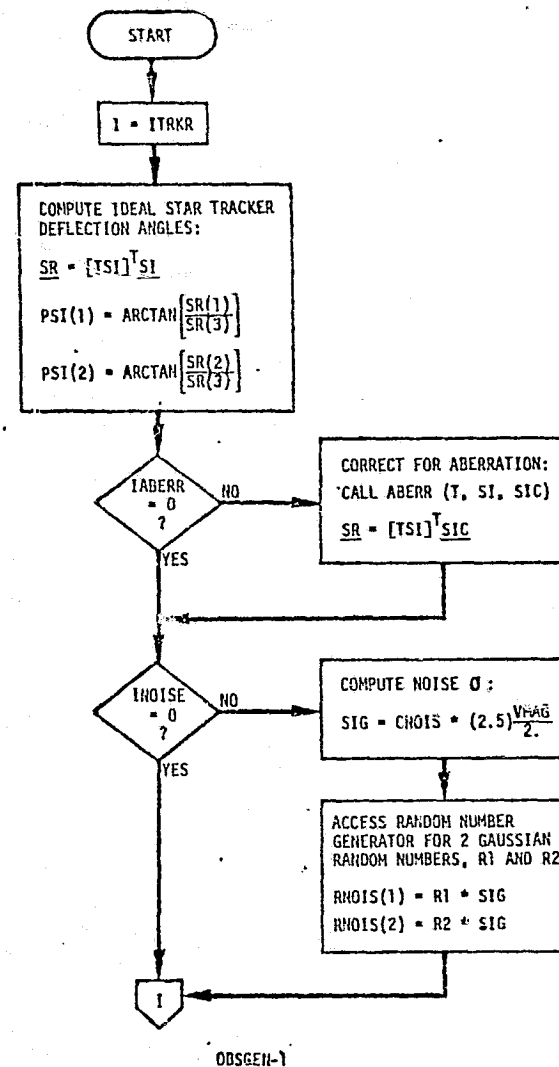
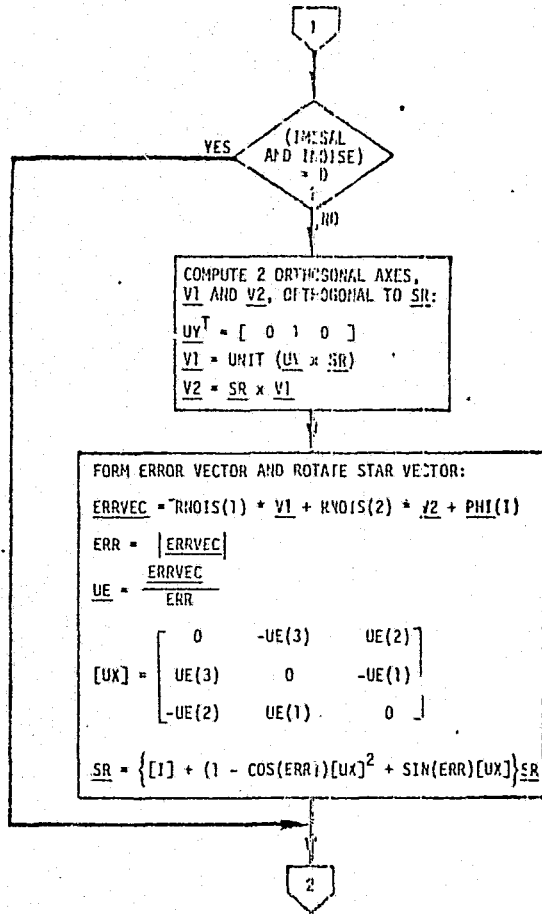
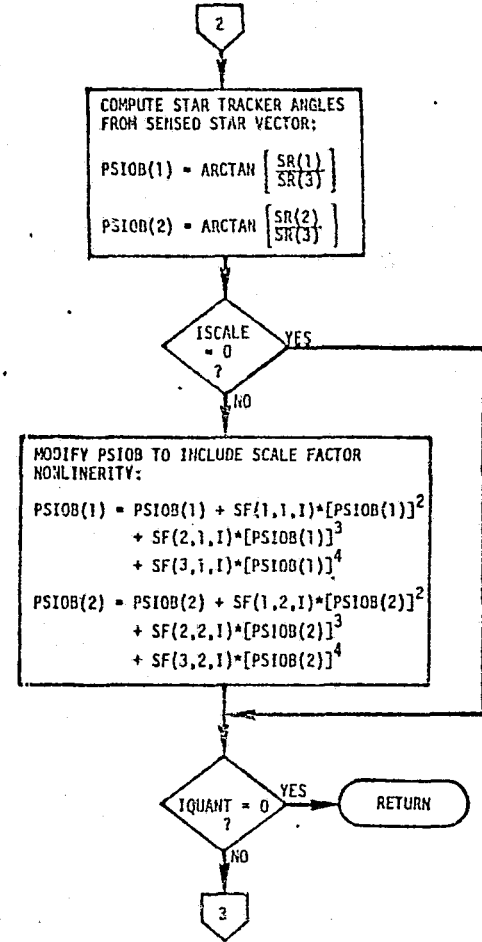


FIGURE 4.7-88. (CONTINUED)

4.7-261



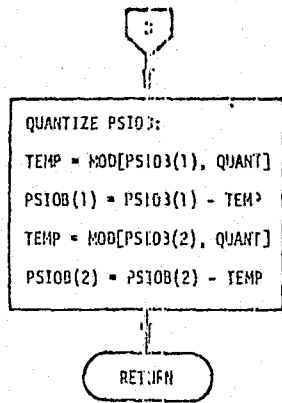
OBSSE-1-2



OBSGEN-3

FIGURE 4.7-88. (CONTINUED)

4.7-262



0155E4-4

Subroutine SCREEN (STCL, CFOV, NSTAR, STRDAT, NS)

Purpose: To sort out navigation stars which fall within the circular field of view encompassing the ST search raster pattern

Inputs:

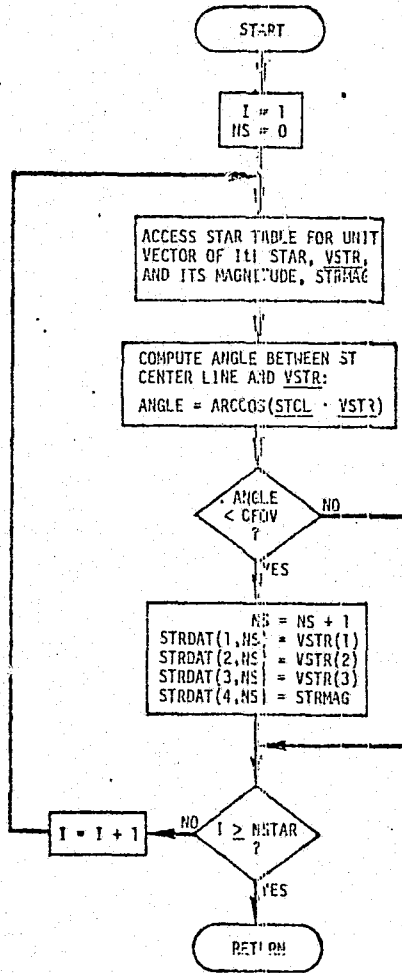
STCL(3)	ST centerline in ECI coordinates
CFOV	half-angle of the circular field of view encompassing the ST search raster pattern
NSTAR	number of stars in the star table

Outputs:

STRDAT(10,4)	star data (unit vectors and magnitudes) of candidate stars
NS	number of candidate stars

FIGURE 4.7-88. (CONTINUED)

4.7-263



SCREEN-1

Subroutine SEARCH (STCL, CFOV, NSTAR, KE, MAUTOP, PSICOM, PSIMAX, TSI, UW, IDAY, FOV, TSTR, ITRAC)

Purpose: To detect a target star for tracking

Inputs:

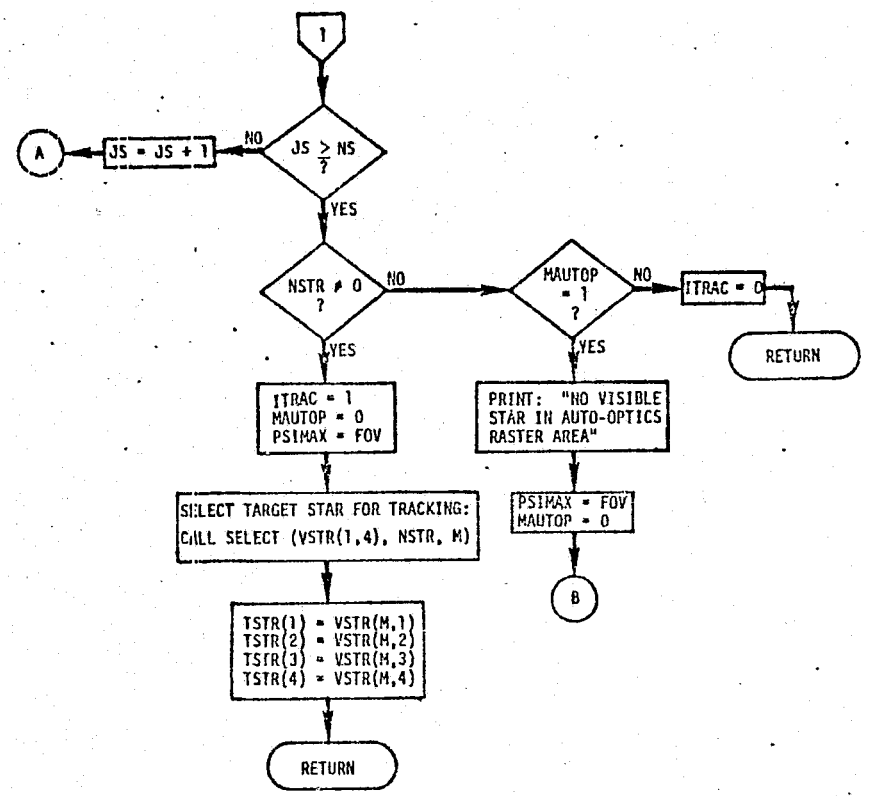
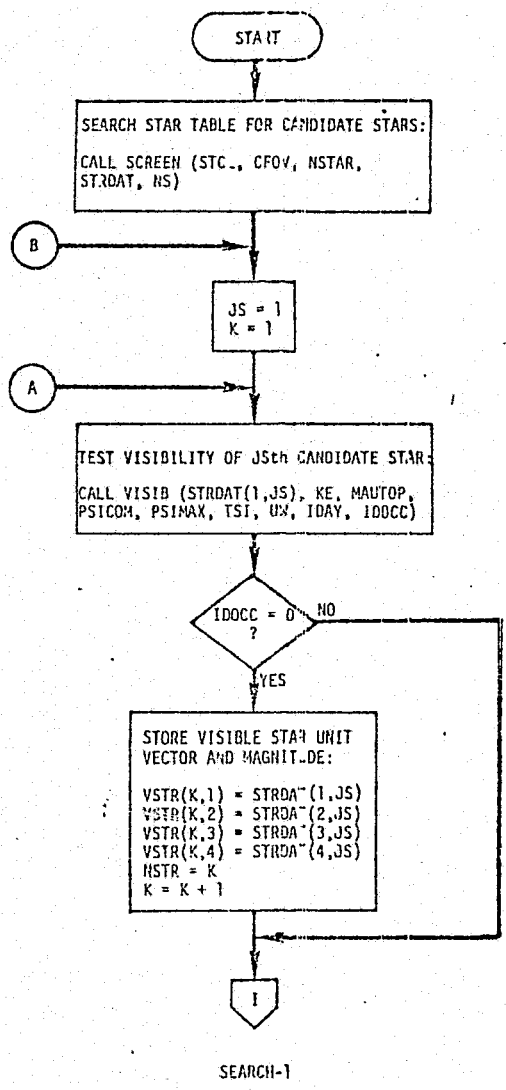
STCL(3)	star tracker centerline
CFOV	half-angle of circular field of view enclosing the tracker search raster pattern
NSTAR	number of stars in the star table
KE	effective half-angle of the earth
MAUTOP	auto-optics mode flag
PSICOM(2)	auto-optics deflection commands
PSIMAX	raster limit
TSI(3,3)	ST-to-ECI transformation matrix
UW(3,3)	unit vectors from vehicle to the earth, sun, and moon
IDAY	orbital phase (day/night) flag
FOV	tracker search raster size

Outputs:

TSTR(4)	target star unit vector and magnitude
ITRAC	tracking flag

FIGURE 4.7-88. (CONTINUED)

4.7-264



SEARCH-2

FIGURE 4.7-88. (CONTINUED)

Subroutine SELECT (SMAG, NSTR, MIN)

Purpose: To select the brightest star in the ST field of view

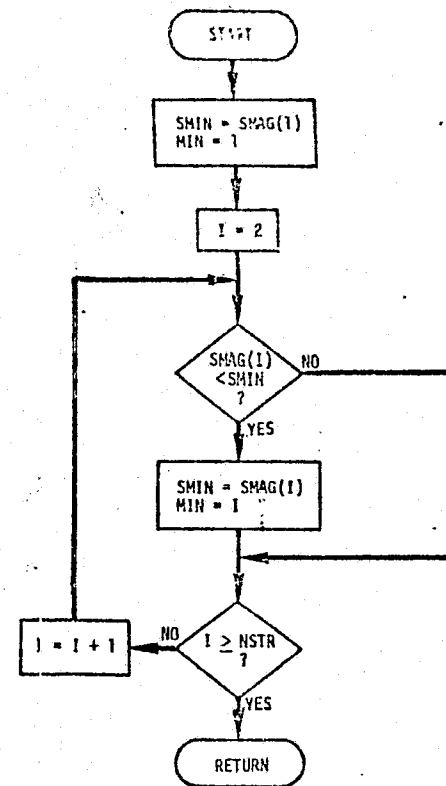
Inputs:

SMAG(NSTR) magnitudes of visible stars

NSTR number of visible stars

Outputs:

MIN Index of the brightest star



SELECT-1

FIGURE 4.7-88. (CONTINUED)

Subroutine TRACK (TSTR, STCL, CFOV, NSTAR, KE, MAUTOP,
PSICOM, PSIMAX, TSI, UW, IDAY, FOV, ITRAC)

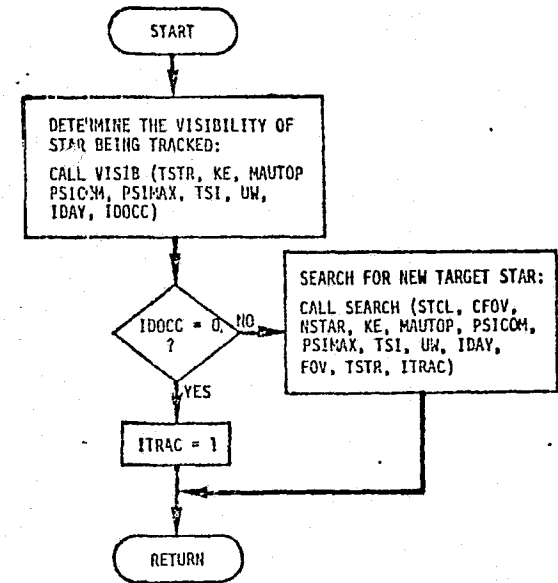
Purpose: To test the visibility of the star being tracked and to search for a new target star if the visibility test is failed.

Inputs:

TSTR(4)	target star unit vector and magnitude
STCL(3)	star tracker centerline
CFOV	half-angle of circular field of view enclosing the tracker search raster pattern
NSTAR	number of stars in the star table
KE	effective half-angle of the earth
MAUTOP	auto-optics mode flag
PSICOM(2)	auto-optics deflection commands
PSIMAX	raster limit
TSI(3,3)	ST-to-ECI transformation matrix
UW(3,3)	unit vectors from vehicle to the earth, sun, and moon
IDAY	orbital phase (day/night) flag
FOV	tracker search raster size

Outputs:

TSTR(4)	target star unit vector and magnitude
ITRAC	tracking flag



TRACK-1

FIGURE 4.7-88. (CONTINUED)

Subroutine VECELB (R, T, DEL, RB, KATH, RE, UW, THETA, KE, KRE, IDAY)

Purpose: To compute vehicle-to-celestial body (the earth, sun, and moon) unit vectors, half-angles of celestial bodies, and orbital phase.

Inputs:

R(3) vehicle position vector
 T elapsed time from the clock epoch
 DEL(3) angular factors to account for celestial body brightness
 RB(3) average radii of the earth, sun, and moon
 KATH angular factor for the earth's atmosphere
 RE effective radius of the earth for sun occultation

Outputs:

UW(3,3) vehicle-to-celestial body unit vectors
 THETA(3) effective half-angles of celestial bodies including glow
 KE effective half-angles of the earth including the atmosphere
 KRE effective half-angle of the earth for sun occultation
 IDAY day phase flag

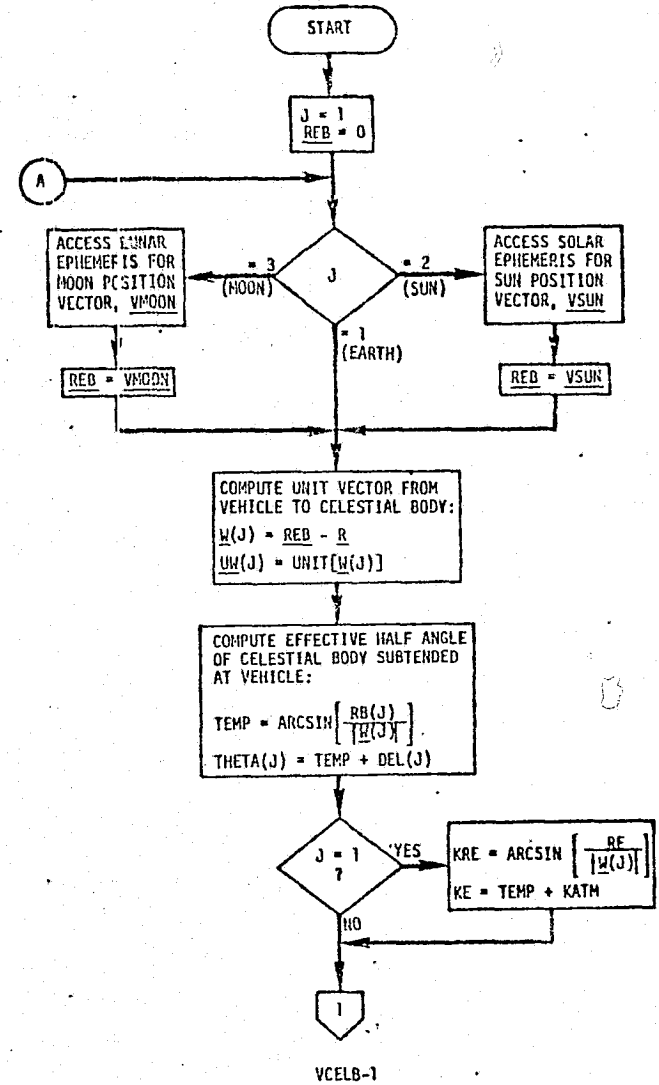
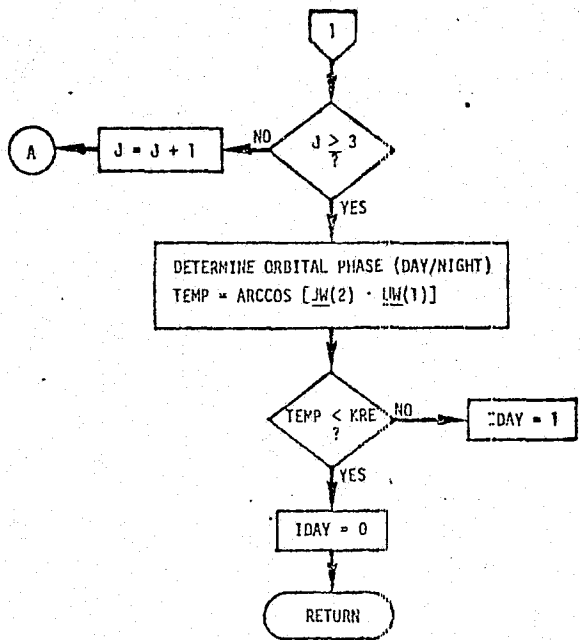


FIGURE 4.7-88. (CONTINUED)



VCEL8-2

Subroutine VISIB (V, KE, MAUTOP, PSICOM, PSIMAX, TSI, UN, IDAY, ISOCC)

Purpose: To test the visibility of a target within a specified raster area (search or auto-optics).

Inputs:

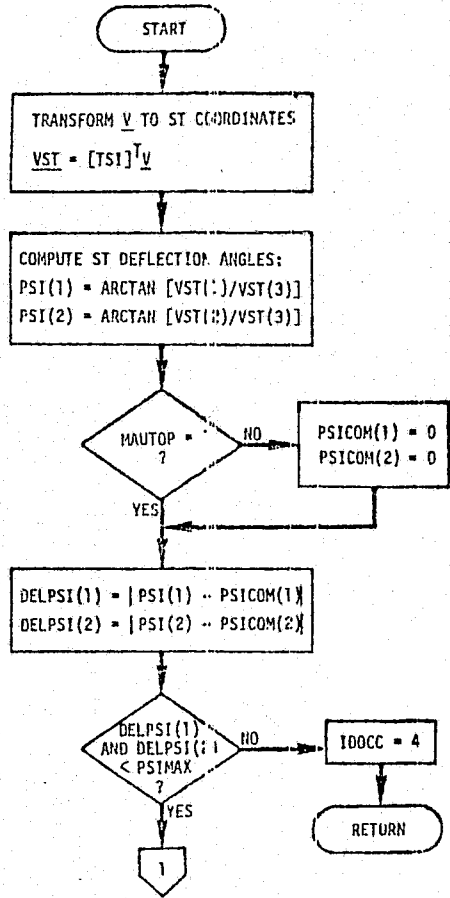
V(3)	target line of sight in ECI
KE	effective half-angle of the earth subtended at the vehicle
MAUTOP	auto-optics mode flag
PSICOM(2)	auto-optics angular commands
PSIMAX	raster limit
TSI(3,3)	ST-to-ECI transformation matrix
UW(3,3)	unit vectors from vehicle to the earth, sun, and moon
IDAY	orbital phase (day/night) flag

Outputs:

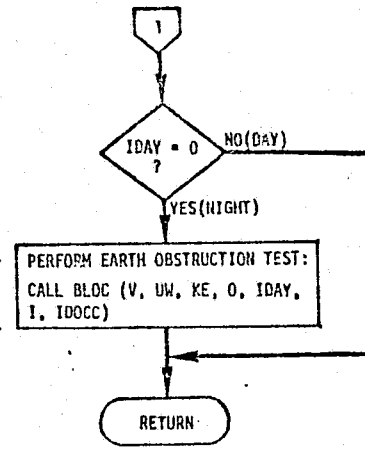
ISOCC	visibility flag
	ISOCC = 0: target visible
	= 1: earth occultation
	= 4: target outside specified raster area

FIGURE 4.7-88. (CONTINUED)

4.7-269



VISIB-1



VISIB-2

FIGURE 4.7-88. (CONCLUDED)

states and rates; later, realistic vehicle dynamics can be provided by an EOM module. Hardware data (error sources and scan-rate parameters) and a star catalog complete the ST validation data base requirements.

4.7.5.1.5 Aero-Flight Control System (FCS) - The FCS, which is used during approach and landing, TAEM, and part of entry, is described in Ref. 46. This is a "fly by wire" system, with data handling and control functions performed by the flight software resident in redundant digital computers. The backup FCS is another digital computer (with identical CPU hardware and simplified software).

Of the flight hardware involved in flight control, most modules -- e.g., IMU, rate gyros, TACAN receivers -- are covered in other sections of this report. The flight hardware modules which we have assigned exclusively to FCS are:

- Aerosurface Actuator Interface Units
- Air Data System

4.7.5.1.5.1 Aerosurface Actuator Interface Units (ASAIU's) - These are rather simple hardware units, with very limited simulation and validation requirements. Therefore, the discussion which follows is rather brief. Additional information relating to somewhat similar hardware units (PSIU's) may be found in Section 4.7.5.1.3.

ASAIU Description

Like the PSIU's described in Section 4.7.5.1.3, the ASAIU's provide interfacing between controlled hardware units (in this case, aerosurface actuators) and manual controls and flight computers, performing signal processing and checkout functions. When the control channels and aerosurface actuators are performing properly, the primary function of the ASAIU's is formatting and conversion of signals from and to the flight computers, to implement closed-loop vehicle control.

The ASAIU's also implement "voting" of redundant commands and feedback signals, enabling command equalization as well as malfunction detection, isolation, switch-out and annunciation. Switchout of a malfunctioning actuator can be overridden by crew command. In the case of the quad-redundant hydraulic actuators used on the fast-response surfaces -- elevons and rudder/speedbrake -- these monitoring functions are implemented with rather complex and as yet ill-defined algorithms involving position feedbacks and hydraulic pressures sensed at multiple ports. For the dual-redundant hydraulic actuators used on the body flap, the implementation is similar, albeit simpler.

Specifications and study reports defining command/response word formats, malfunction-handling algorithms, etc., have not yet been identified.

ASAIU Module Description and Performance Parameters

Again like the PSIU's, it seems reasonable to assume that the functions of the ASAIU's will be "embedded" in the associated actuator simulation modules. This is particularly true in view of the fact that the level of detail of actuator simulation will probably not be adequate to directly simulate the equalization and monitoring functions in high fidelity. That is, the actuators will be simulated basically as transfer functions with appropriate nonlinearities (see Section 4.7.1.4); thus the physical quantities used in the monitoring process will simply not exist in the simulation. It may be possible to translate these physical parameters into their equivalent transfer-function variables. More likely, however, the simulation module will simply talkback inserted malfunctions.

4.7.5.1.5.2 Air Data System (ADS) -- The air data system is used to sense the velocity and orientation of the Orbiter relative wind, providing data used for aeroflight control.

ADS System Description

Figure 4.7-89 shows an overview of the air data system and its hardware interfaces. The total system consists of: a set of dual-redundant probes, with associated deploy/retract mechanisms and heaters; dual/dual-redundant air data transducer assemblies (ADTA); and electronics interfaces. The probes are deployed during the transition phase of entry, and air data outputs are used from then until landing. (See Refs. 20, 48.)

Figure 4.7-90 is an expansion of an ADTA, identifying the individual transducers, calibration memories, and miscellaneous electronics. The ADTA has self-test and operate modes. Self-test data is evaluated by the GN&C computers to determine the status of each ADTA. In the operate mode, the ADTA responds to probe inputs to generate static pressure, total pressure, total temperature and differential pressure outputs. These are processed by the GN&C computer to compute airspeed, angles of attack, etc.

ADS Simulation Module Description and Performance Parameters

We assume that the ADS simulation module will provide a high-fidelity simulation of ADTA self-test and operate mode outputs and a time-delay simulation of probe deployment and retraction, will allow for various internal failure modes, and will respond properly to variations in simulated bus voltages.

Figure 4.7-91 is an overview of ADS simulation module interfaces. Table 4.7-25 provides an ADS module parameter list.

ADS Reference Data Sources and Data Formats

The ADS reference module discussed in this section provides a simulation of the nominal operation of the air data probes and the ADTA, and sets discrettes for probe deploy/retract and heaters without any detail simulation. The individual hardware elements of the air data system are not modelled in this reference module.

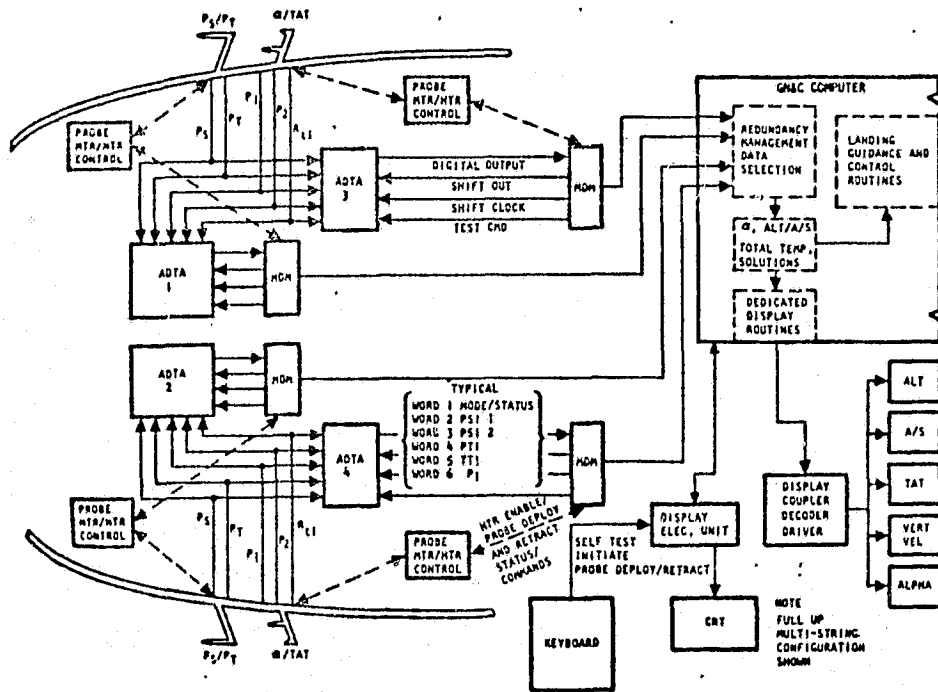


FIGURE 4.7-89 AIR DATA SYSTEM FUNCTIONAL CONFIGURATION (ORBITER 103)

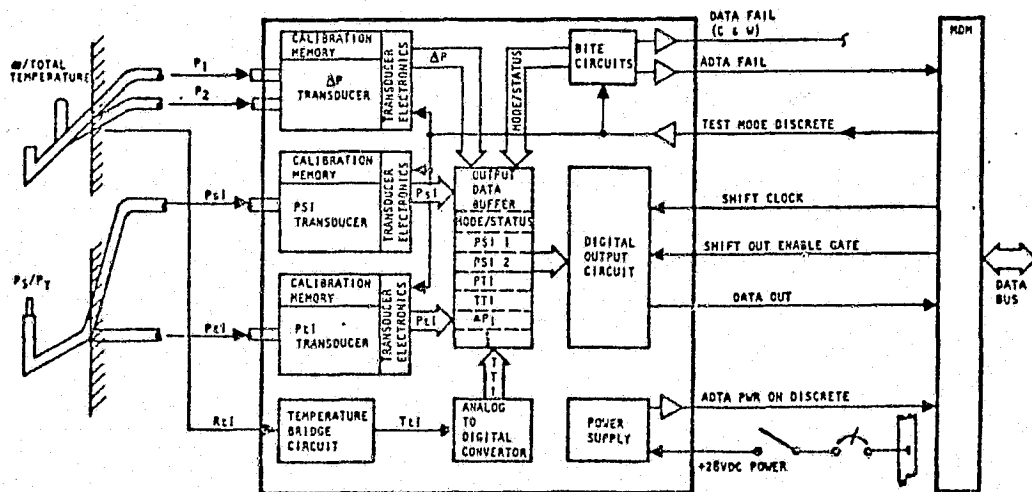


FIGURE 4.7-90 INTERNAL ADTA FUNCTIONAL CONFIGURATION

TABLE 4.7-25 AIR DATA SYSTEM MODULE PARAMETER LIST

SYMBOL	DEFINITION	TYPE ^a
--	Command for self-test mode or operation mode	I
T_o, P_o	Ambient air temperature and pressure	I
M	Mach number	I
α, β, V_a	Angle-of-attack angle-of-sideslip and airspeed	I
--	ADTA self-test values for $P_{si}, P_{ti}, T_{ti}, \Delta P_i$, and mode/status	DB
η	Temperature sensor recovery factor	DB
γ	Specific heat ratio for air	DB
P_{so}, P_{to}, T_{to}	Ideal probe values of static pressure, total pressure and total temperature	P
ΔP	Ideal probe differential pressure (function of vehicle aerodynamics)	P
$\delta P_{so}, \delta P_{to}, \delta T_{to}$	Changes in ideal probe values due to vehicle dynamics	P
$\epsilon P_{si}, \epsilon P_{ti}, \epsilon T_{ti}, \epsilon \Delta P_i$	ADTA hardware errors	P
P_{si}	Indicated static pressure (divided into most significant and least significant words)	CP
P_{ti}	Indicated total pressure	CP
T_{ti}	Indicated total temperature	CP
ΔP_i	Indicated pressure differential	CP
--	ADTA Operational Mode and Status flag	O
--	Power-on discrete from ADTA	O
--	Probe heater status discrete	O
--	Probe deploy/retract status discrete	O

^aLEGEND:

- I = input
- DB = data base input
- O = output
- P = performance parameter
- CP = critical performance parameter

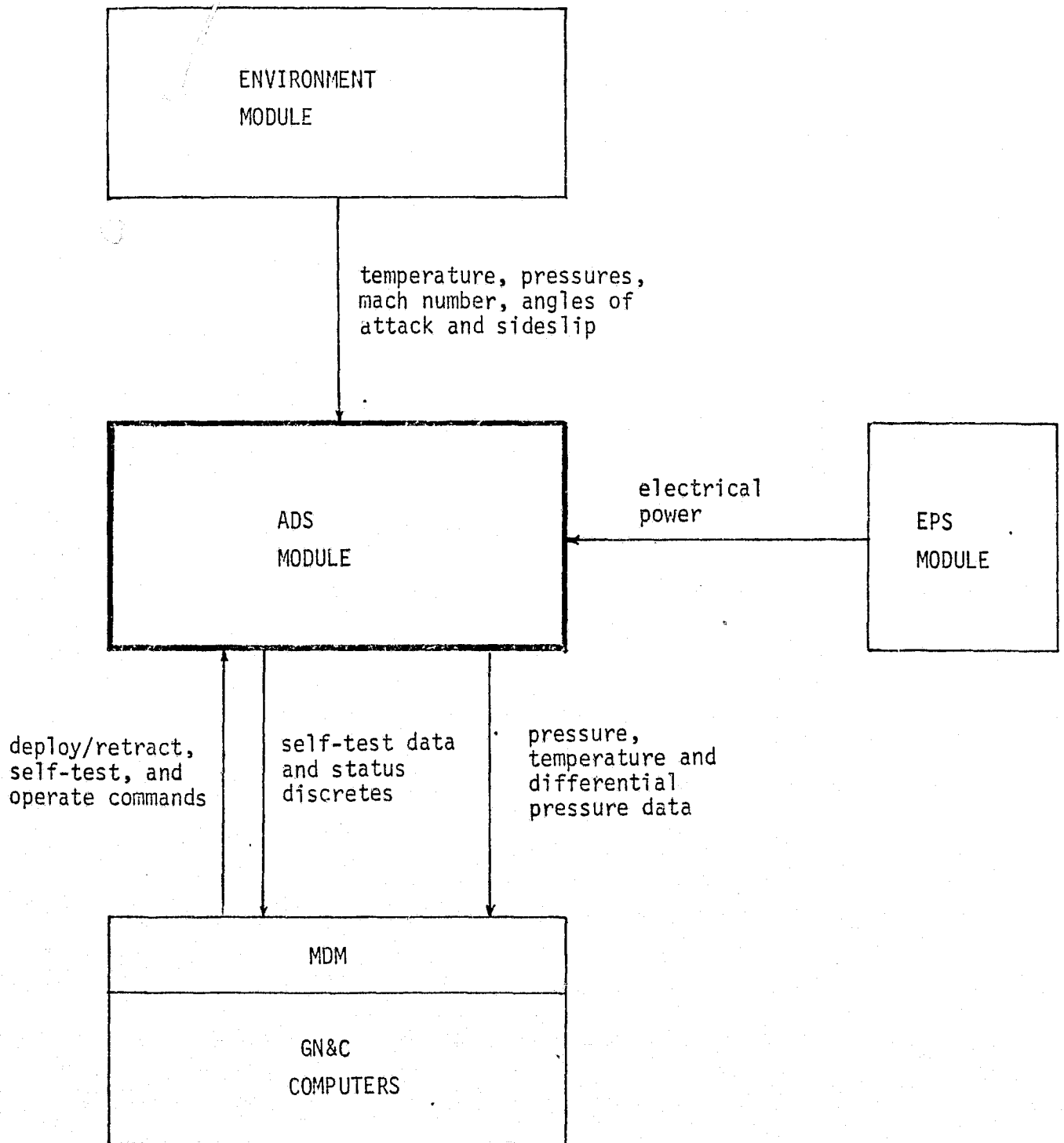


FIGURE 4.7-91. ADS MODULE INTERFACES

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... of hardware errors is to be accomplished by means of "generalized functions" (table lookups, polynomials, etc.), based upon hardware test data.

The math flow for module CKADS, as shown in Fig. 4.7-38, is initialized with constant parameters from the data base, and driven by checkpoint data provided either by an on-line driver routine or accessed from a predefined data file. It has two basic paths: one for the self-test mode, and one for the operate mode.

Self-Test Mode - The ADS reference module simulates the ADTA self-test mode, normally initiated by the GN&C computer. Generation of reference verification data for the self-test mode is accomplished by simply setting the ADTA output to the values expected by the GN&C computer for a nominal status.

Operate Mode - The operate mode simulates the functional situation in which dynamic sensor data is supplied to the GN&C computer for processing. Generation of the ADTA output during this mode is accomplished by exercising Equations (1) through (9) of Figure 4.7-92, discussed in the following paragraph.

Equations (10), (11), and (12) provide the ideal values for total temperature (T_t), static pressure (P_s), and total pressure (P_t), as measured by the air data probes. The equations presented are developed, using fundamental dynamics and thermodynamics of air, in Reference 47.

$$T_t = T_o \left(1.0 + \frac{\gamma-1.0}{2.0} \eta M^2\right) \quad (10)$$

$$P_s = P_o \quad (11)$$

$$P_t = P_o \left(1.0 + \frac{\gamma-1.0}{2.0} M^2\right)^{\frac{1}{\gamma-1}} \quad \text{for } M \leq 1$$

$$P_t = P_o \left(1.0 + \frac{1.0+\gamma}{2.0} M^2\right) \left[\frac{(1.0+\gamma)^2 M^2}{4\gamma M^2 - 2(\gamma-1.0)}\right]^{\frac{1}{\gamma-1}} \quad \text{for } M \geq 1 \quad (12)$$

Note that the probes are assumed to be located in the free stream ahead of any shock wave, and the temperature sensor is assumed to measure full adiabatic temperature increase within the recovery factor η . Equations (10), (11), and (12) are for airflow axial along the probes, and will not provide the correct measurement when the incident flow is not axial. They are typical calibration equations; by addition of correction terms dependent on vehicle parameters such as angle of attack, angle of sideslip, and airspeed, representative ideal values for P_s , P_t , and T_t can be achieved for all vehicle states. The additive

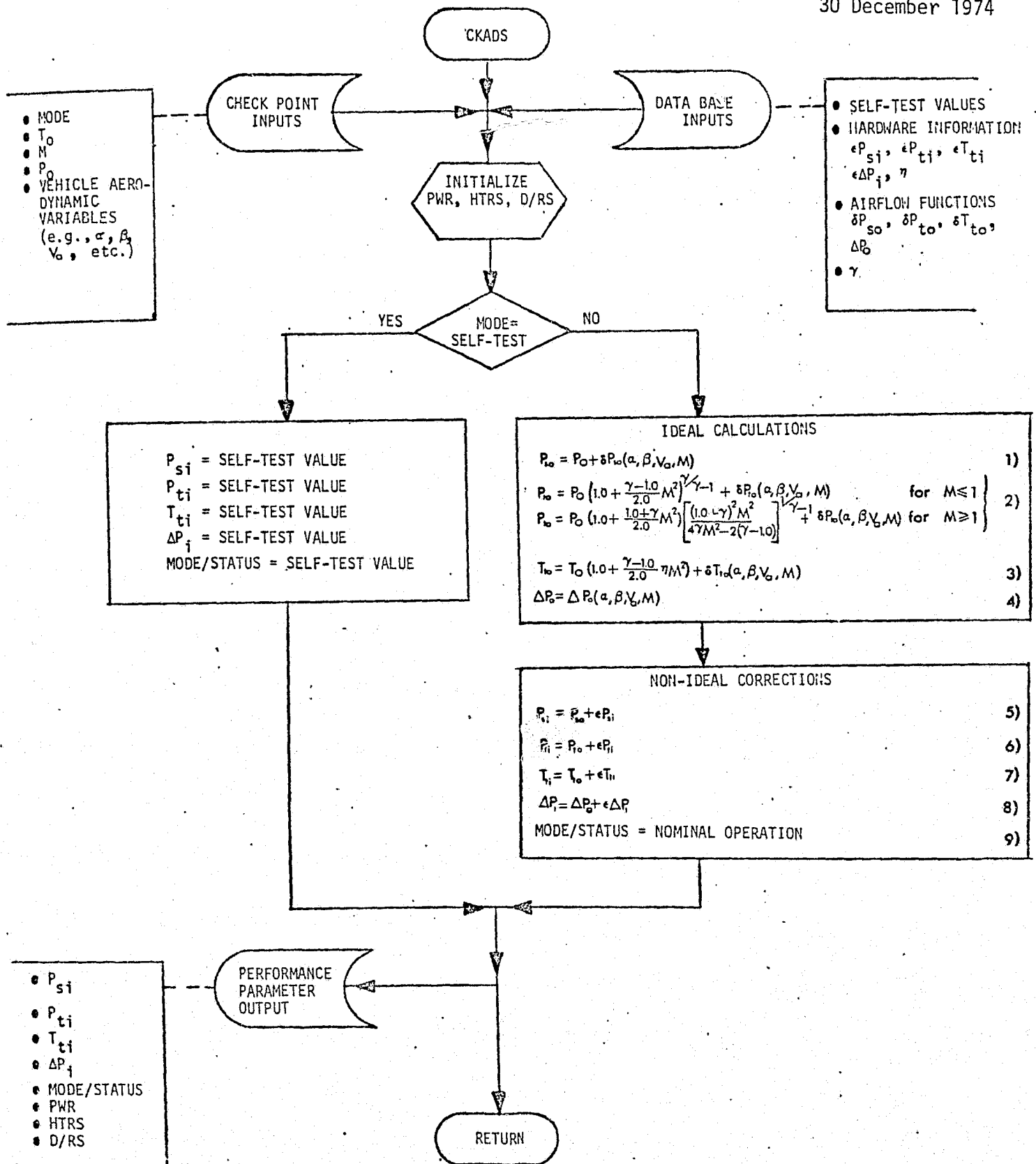


FIGURE 4.7-92 AIR DATA SYSTEM REFERENCE DATA MODULE

Corrections indicated by δ in Equations (1), (2), and (3) of Figure 4.7-92 are derived from test data.

The differential pressure parameter (ΔP), is a function of vehicle dynamics and airflow around the probe, with the functional form heavily dependent on probe design and location on the vehicle. For the reference module, the ideal ΔP is modeled using design and test data. (The flight software will contain an algorithm for converting ΔP_i into sensed angles of attack; this algorithm will be essentially the inverse of the reference module algorithm.)

The ideal inputs to the ADTA thus obtained are then degraded due to non-ideal operation of the hardware. Typically, hardware errors can be divided into two classes: those which are compensated for in the software accepting the data, and those not compensated for and thereby introduced into the system. Since the GN&C flight software will likely perform compensation for certain hardware characteristics, both types should be introduced to the ideal data. The reference module discussed here provides all hardware errors as additive terms (ϵ) to the ideal values. The hardware error functions are determined using design and test data.

The final output performance parameter, the mode/status flag, is assigned the appropriate value for nominal system operation. Since operate and self-test values may differ, the parameter appears in both paths of Figure 4.7-92.

ADS Module Validation Methods and Check Cases

ADS module validation is performed by driving both the simulation module and the reference module with corresponding input data. Check-case data required by the reference module are as follows:

- Power-off Data Check - The power off checkpoint is to verify that the power-off condition for the ADTA results in proper power-off output data. This single check point need not be built in to the reference module.

- Self-Test Data Check - The self-test check point is to verify the ADTA output in response to self-test commands. The reference output for this check point will consist of stored test words identical to those existing in the GN&C computer for verification of the ADTA status. The reference module input needs only the mode parameter to specify the self-test condition.
- Operate Data Check - This check consists of a series of check points chosen to verify the system output over its normal range of use. The reference data for this check is generated by a parametric variation of the inputs (P, T, α, β , etc.) used in the calculation of the performance parameters. The appropriate parameter variations are selected based on performance specifications for the air data system and the vehicle.

The simulation module, being more directly hardware-oriented, will require additional input data (see Table 4.7-25) for proper operation.

In addition to the discrete check points, the appropriate input values to the reference module may be stored along with resulting simulation module outputs from a simulation run. The verification executor can then access the data to drive the reference module and generate data for comparison with the stored simulation data. However, care should be used in utilizing this option. Since the reference module does not simulate all the air data system hardware-related effects (e.g., malfunctions, voltage and temperature variations), the simulation data must be in the nominal operational regime to be directly comparable.

For nominal operation, reference/simulation data agreement should be within a few percent for moderate mach numbers and angles of attack, during steady flight. Discrepancies of ten percent or greater would not be unreasonable at high mach numbers or high angles of attack, during turbulence or high-g maneuvers.

ADS Data Base Impact

The parameters and functions indicated on Figure 4.7-92 as input through the data base must be available to the reference module from mass storage. Table 4.7-26 presents the individual data base items, with an indication of the data source and added comments on the type of data.

TABLE 4.7-26 REFERENCE MODULE DATA BASE SOURCE LIST

ITEM	SOURCE	COMMENT
Self-test values	Air Data Subsystem Vendor	Nominal Values indicating a "GO" status
γ	Reference Simulation Standards	Assigned Reference Value (e.g., 1.40 for air)
"	Air Data Subsystem Vendor	From Design or Test Data
$\epsilon P_{si}, \epsilon P_{ti}$ $\epsilon T_{ti}, \epsilon \Delta P_i$	Air Data Subsystem Vendor	Predicted static error data from design studies
$\delta P_{si}, \delta P_{ti}$ $\delta T_{ti}, \Delta P_i$	Vehicle Vendor	From Wind Tunnel or Flight Test Data

The complicated nature of the airflow functions δP_{si} , δP_{ti} , and ΔP warrants the use of flight test data when available. Wind tunnel data or predicted values will in general provide only trend data, but should be used until flight test data becomes available. However initially obtained, the airflow functions should be updated upon the availability of flight test data to ensure a valid simulation.

For all test data items, it is important that configuration control procedures be utilized to maintain up-to-date data base information. Reference module data base updates would result from system modifications and from the availability of more reliable data through program advances. When such updates are incorporated into the reference module, a reverification of the simulator air data module would be undertaken. If it is found that the simulator module is no longer valid with respect to the updated data, simulator management would then be informed.

4.7.5.2 Communications and Tracking (C&T) Subsystem

The C&T subsystem provides capabilities for transmission of information and/or commands and determination of relative state variables between the Orbiter and (a) ground-based facilities (see Section 4.3.2.1) and (b) payloads and rendezvous targets (see Section 4.3.2.2). Orbiter/payload communication and tracking is performed during the on-orbit mission phase; Orbiter/ground communication and tracking may be performed during any mission phase - except for a short period of communications "blackout" during entry.

C&T Subsystem Description

The block diagram of Figure 4.7-93 (Ref. 36) provides an overview of the C&T subsystem. This subsystem includes several types of components:

- receivers, transmitters and transponders
- record/playback equipment
- data handling and distribution equipment (e.g., signal processors, coders, data interleavers, switching systems)
- antennas
- manual control and display interfaces
- flight computer interfaces

Component specifications (Refs. 49 through 58) provide detailed information relating to many of these components; specifications for other components have not yet been identified.

C&T Module Description and Performance Parameters

The C&T subsystem simulation module will consist of a number of submodules. Each such submodule will provide the operational modes and performance parameters of one of the basic hardware components of the C&T subsystem, model appropriate hardware errors, and allow for the insertion of simulated malfunctions. Table 4.7-27 gives a list of performance parameters for the C&T simulation module.

Figure 4.7-94 shows the C&T module interfaces. Definition of the interface with the artificial environment module requires some assumptions about the software design. We have assumed that, for maximum module independence, each of these modules will require a minimum of information about the other. For example, the ground nav/comm module will compute the line-of-sight (LOS) to the Orbiter (as seen from the ground), in its own axis set, and use the ground-antenna gain pattern to compute its transmitted signal strength along that LOS. The onboard C&T

TABLE 4.7-27. COMMUNICATIONS AND TRACKING SIMULATION MODULE PARAMETERS

SYMBOL	DESCRIPTION	TYPE ^a
R_{SE}	Ground station coordinates (earth-fixed axes)	I
	Ground station identification tags	I
	Ground station transmitting frequencies	I
	Line-of-sight contact flags	I
r, v	Orbiter position and velocity (ECI axes)	I
$\delta r, \delta v$	Target relative position and velocity (ECI or orbital axes)	I
ϕ, θ, ψ	Orbiter attitude	I
h	Orbiter altitude (above local terrain)	I
r_s, \dot{r}_s	Station range and range rate	I
A_{ZS}, E_S	Station azimuth, elevation	I
r_T, \dot{r}_T	Target range and range rate	I
S_{ST}, S_{TT}	Transmitted signal strength from ground station, target	I
	Incoming and outgoing data/command streams	I
	Onboard antenna gain patterns	DB
u_s, u_T	Line-of-sight to station, target (body axes)	P
S_{SR}, S_{TR}	Received signal strength from station, target	P
S_T	Transmitted signal strength to ground station or target	P
D_c	Measured doppler counts	CP
h_{ra}	Measured radar altitude	CP
\hat{r}_s, \hat{r}_T	Measured range to station, target	CP
\hat{A}_{ZS}, \hat{E}_S	Measured station-referenced azimuth, elevation	CP
$\hat{\phi}_T, \hat{\dot{\phi}}_T$	Measured target angle and angular rate	CP

^aTYPE: I = input
 DB = data base input
 P = performance parameter
 CP = critical performance parameter

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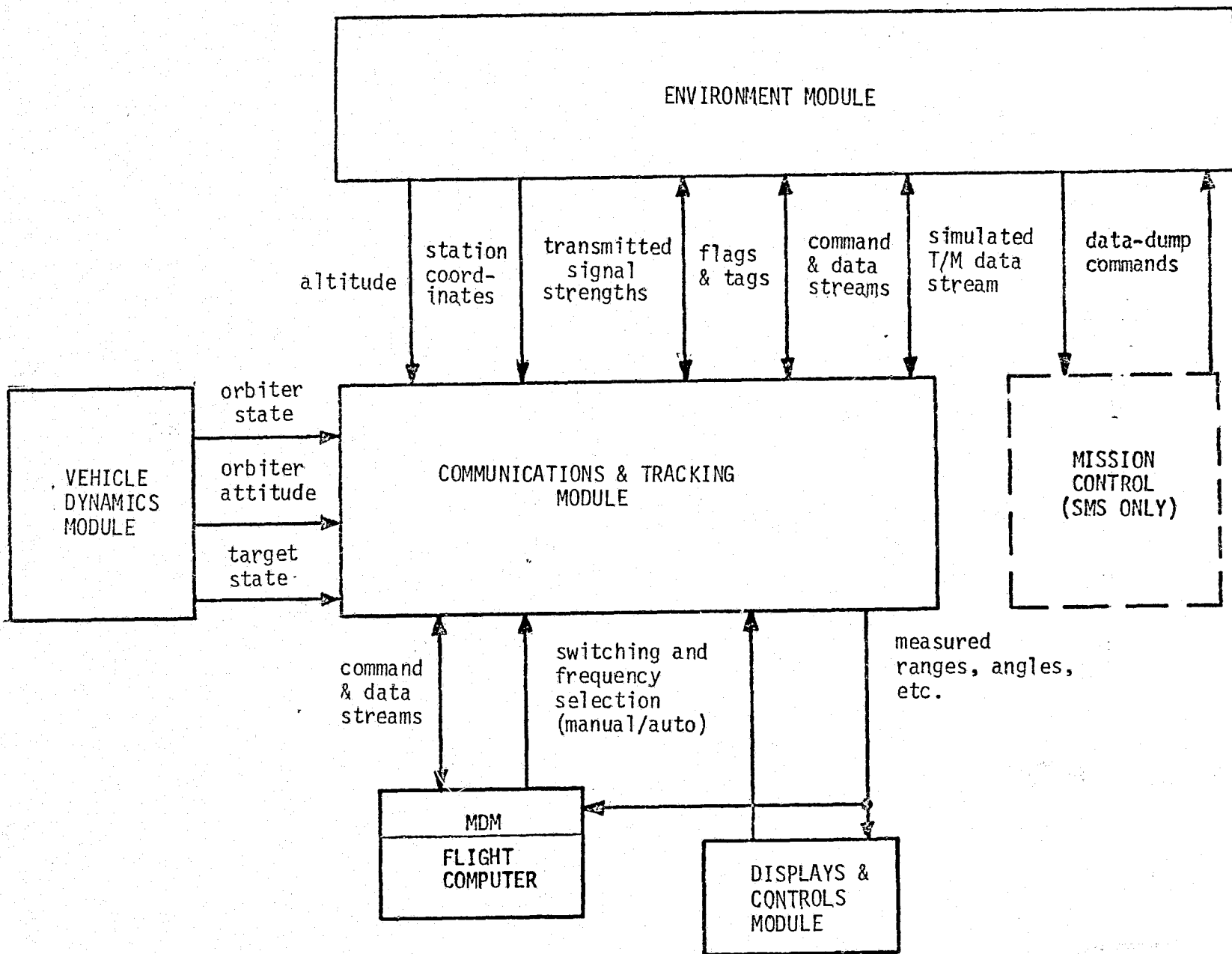


FIGURE 4.7-94. COMMUNICATIONS & TRACKING MODULE INTERFACES

module will compute the LOS to the ground antenna (as seen from the Orbiter), in its body-axis set, and then use the onboard antenna gain pattern and the transmitted signal strength to compute its received signal strength along that LOS. Thus, each module will need to know its own antenna patterns, but neither module will need to know the other's antenna patterns. In addition, each module will need to output various flags and tags to inform the other which ground facilities are active and in view, which onboard subsystems are active, etc.

The Shuttle Mission Simulator, which is sometimes used in integrated operations with Mission Control, must provide the capability to provide a simulated telemetry stream -- realtime and/or recorder data-dump. This will require the C&T module to have telemetry simulation modes, in which properly-formatted mass-storage files are generated during simulator operation, then dumped over an appropriate communication channel upon commands received via the Mission Control communication link.

C&T Reference Data Sources and Data Formats

Figure 4.7-95 shows the math flow and variable definition for a module (CHKCMT) to generate reference data for validation of the C&T simulation module. The equations shown in this figure are derived in Ref. 59. Geometry calculations necessary to compute range, range rate, bearing, etc. are performed in terms of coordinate systems as shown in Figure 4.7-96; (see Ref. 60). In some cases, complete information required for equation development is not yet available, and computations are shown as generalized functions. These generalized functions may be implemented in computational form, or via table lookup, polynomial fit, etc., as the required data becomes available during the course of the Shuttle program. Status discrettes and other secondary parameters are assumed set to their nominal operational values, and are not represented on the math flow.

Note that this reference module is designed for initial validation of the C&T module, and includes computations which will actually be performed by the artificial environment module. A simpler reference module will be appropriate for integrated validation of the C&T and artificial environment modules.

Command parameters (e.g., switching, data-dump) normally generated by manual controls, flight computers, or ground command must be provided by an external driver and/or manual data input to the reference module, in a format matching their

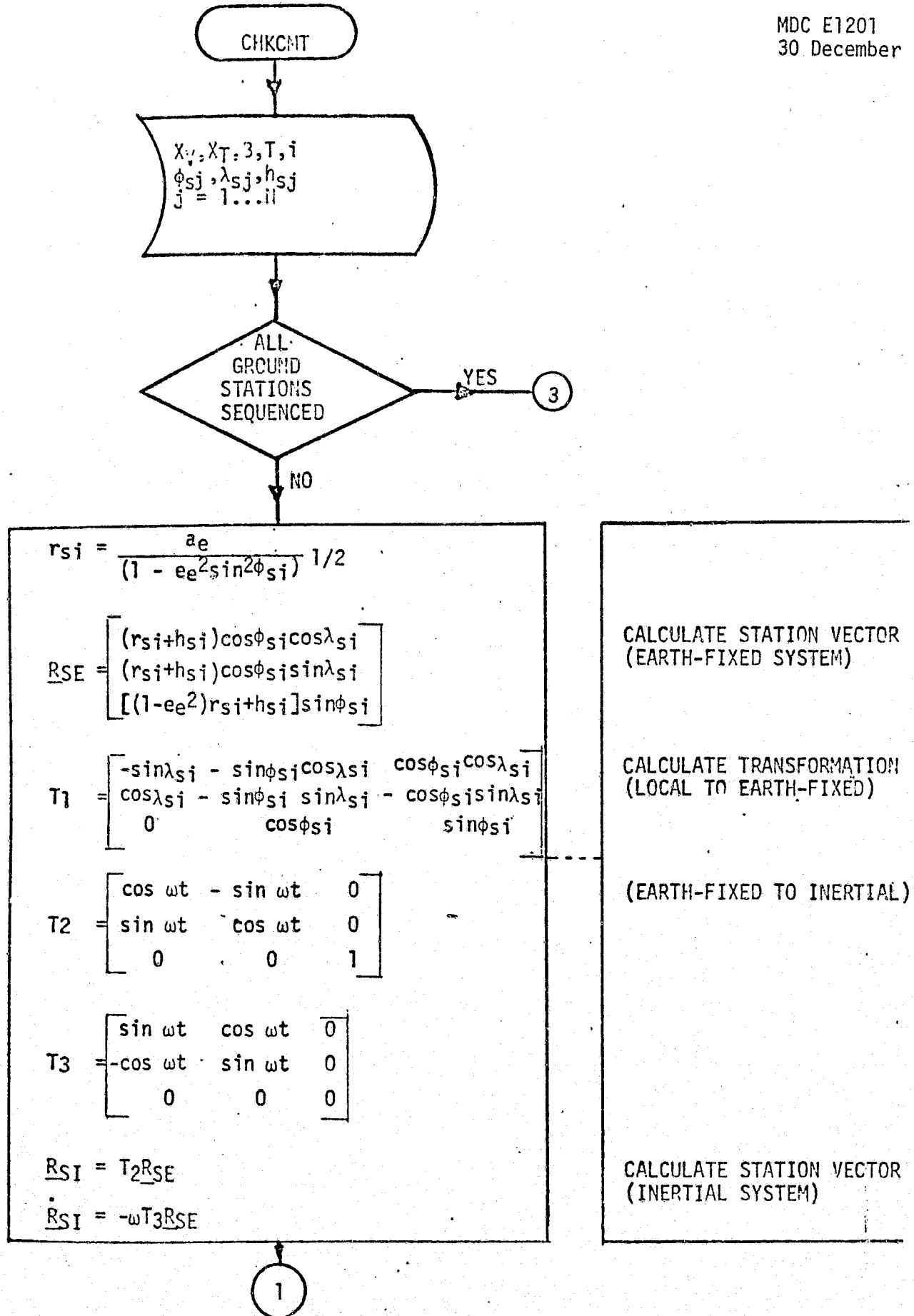


FIGURE 4.7-95 COMMUNICATIONS AND TRACKING REFERENCE MODULE MATH FLOW.

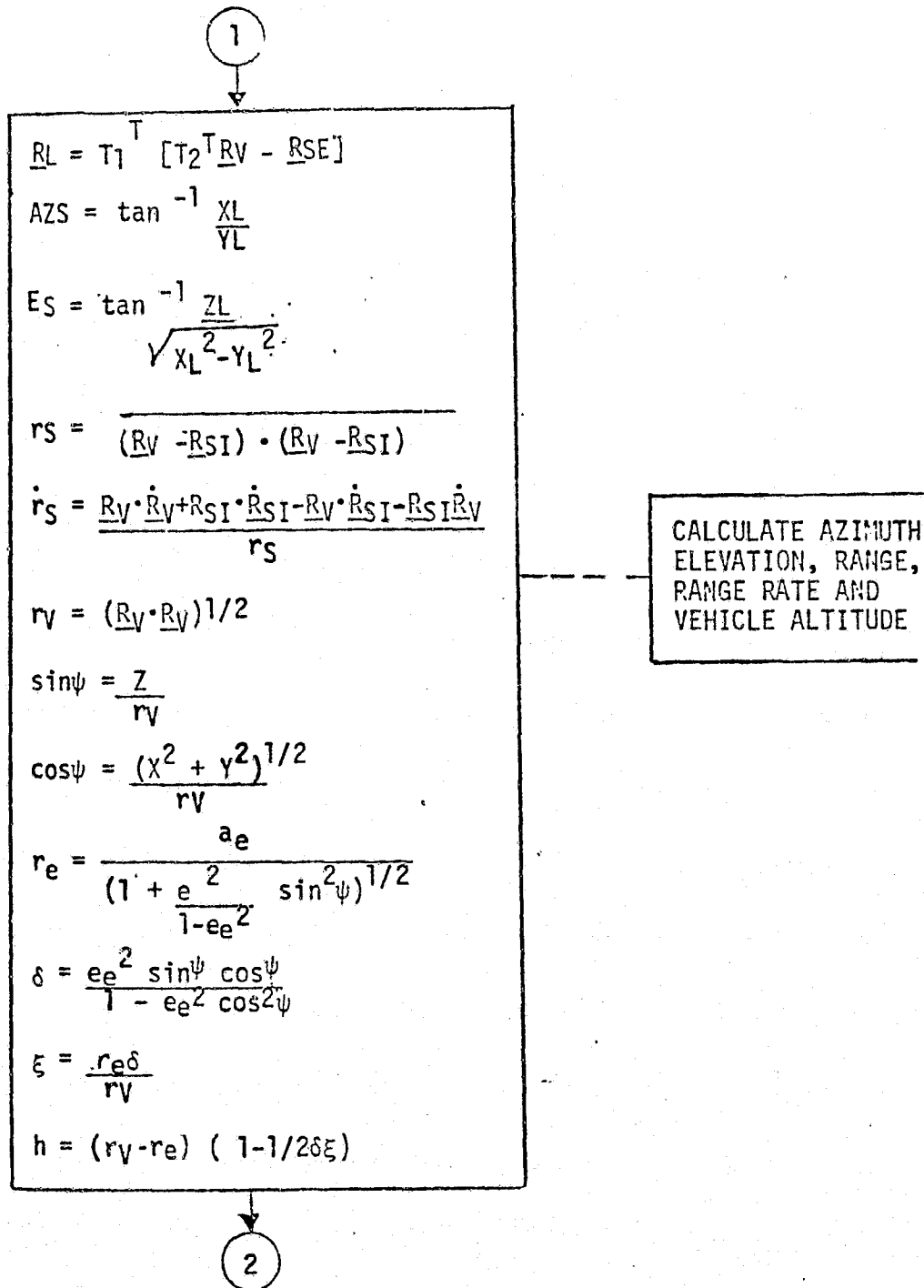


FIGURE 4.7-95 (CONTINUED)

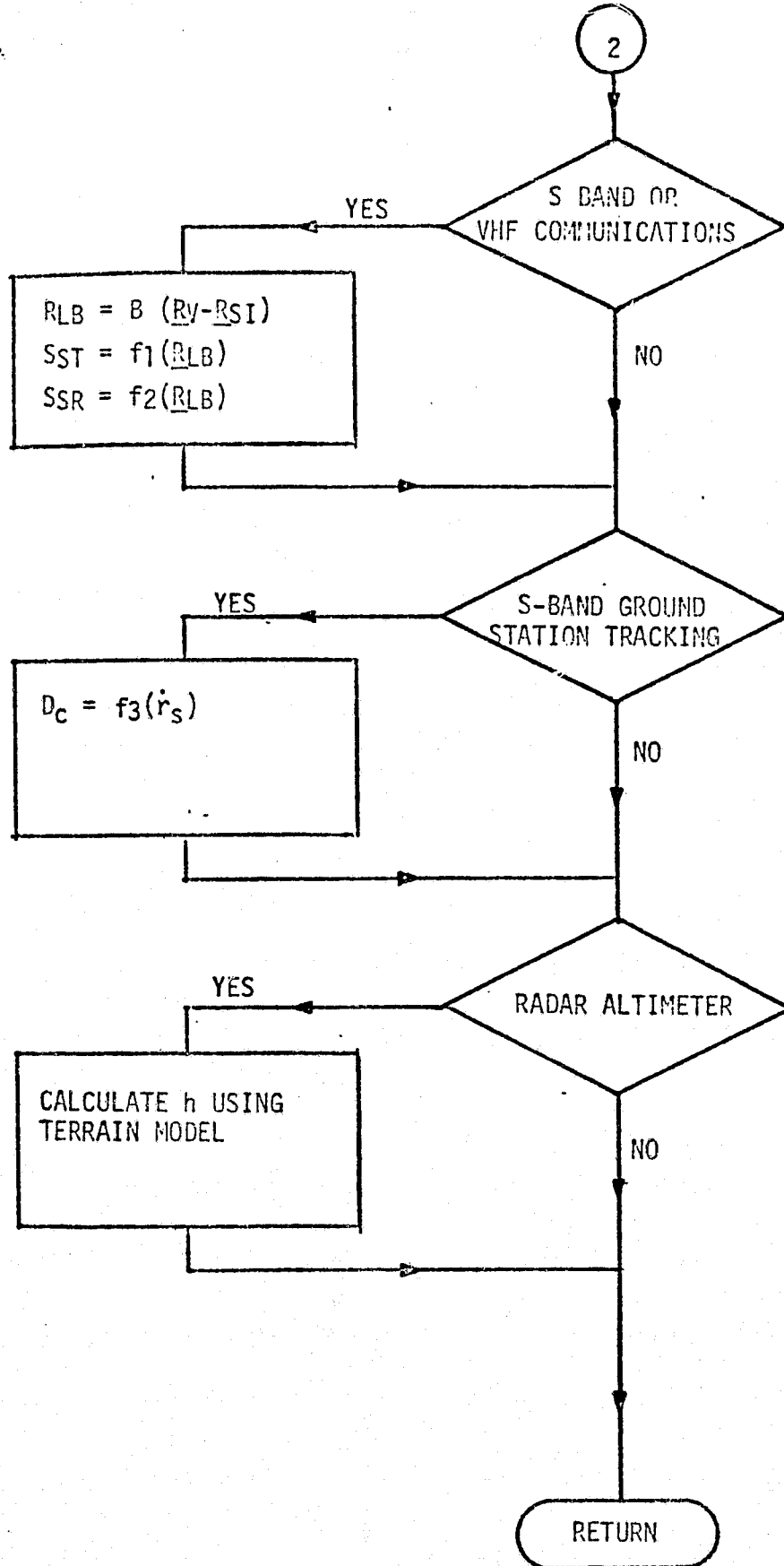


FIGURE 4.7-95 (CONTINUED)

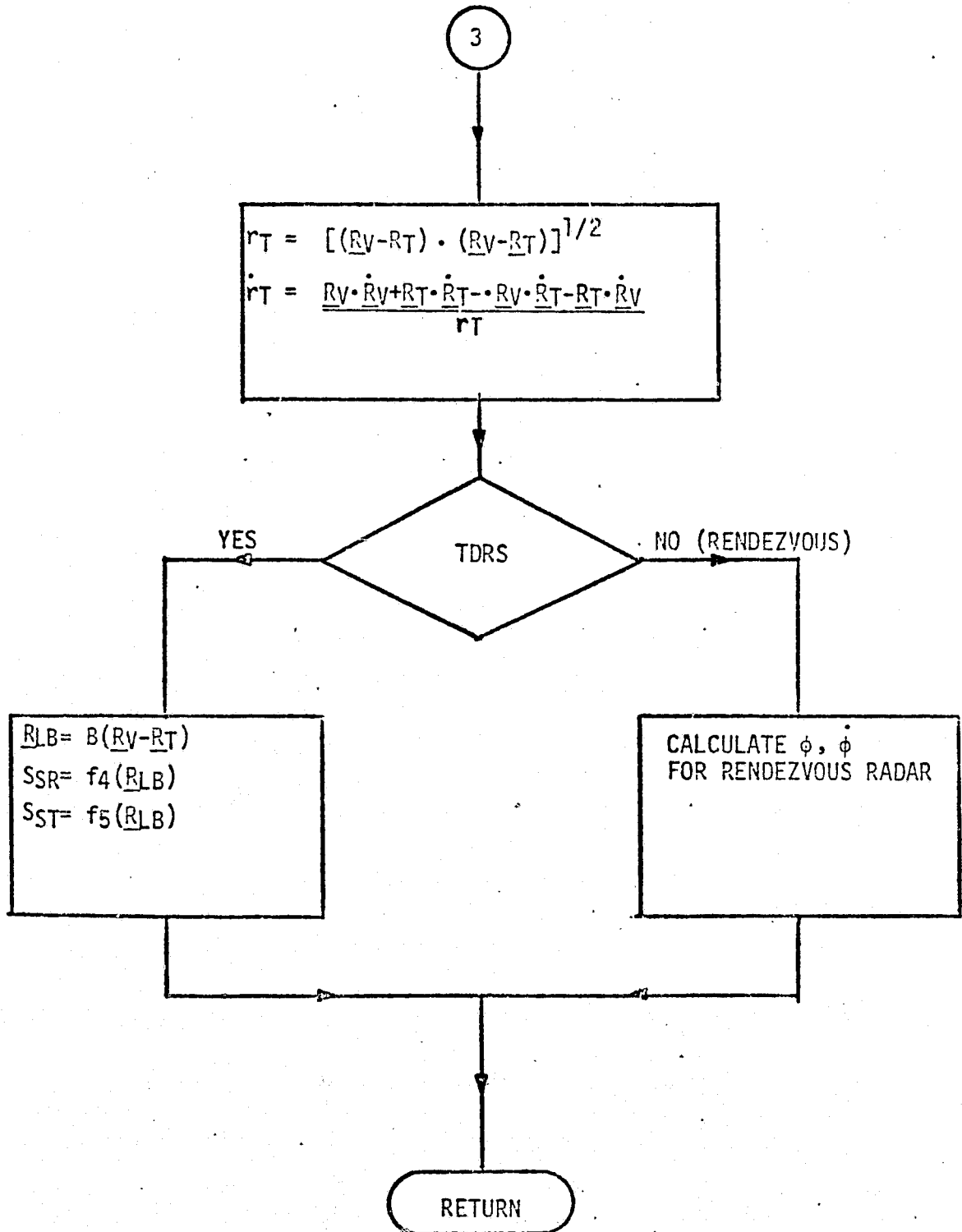


FIGURE 4.7-95 (CONTINUED)

LEGEND

SYMBOL	DEFINITION
i	Pass number
ϕ_{si}	Ground station latitude
λ_{si}	Ground station longitude
h_{si}	Ground station altitude
N	Number of Ground stations to be verified
a_e	Earth semimajor axis
e_e	Earth eccentricity
ωt	Angle between vernal equinox and Greenwich Meridian (Note t depends on time of reference frame initialization)
ω	Earth rotation rate
f_1	Function relating Doppler counts to range rate (Ground Transmission)
f_2	Function relating antenna transmitted signal strength to line of sight (vehicle to ground station)
f_3	Function relating antenna received signal strength to line of sight (ground station to vehicle)
f_4	Function relating antenna transmitted signal strength to line of sight (vehicle to TDRS)
f_5	Function relating antenna received signal strength to line of sight (TDRS to vehicle)

FIGURE 4.7-95 (CONCLUDED).

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intended operational format in the eventual integrated-simulator environment. A pseudo-data stream should also be provided to verify proper transfer of telemetry data.

Note that, to simplify the reference module logic, values for azimuth, elevation, range and range rate are computed for all ground station types, even though not needed in every case; e.g., elevation angle and range rate are not used for TACAN stations.

C&T Validation Methods and Check Cases

In accordance with the basic validation software structure described in Section 5.1, Figure 4.7-97 provides the math flow for a checkpoint-generation routine to be used in C&T module validation. This routine will provide, in addition to discretizes for selection of operational modes, ground stations and TDRS satellites, the following vehicle-dynamics-related data:

$\underline{X} = (X, Y, Z, \dot{X}, \dot{Y}, \dot{Z}) =$ shuttle state vector

$\underline{X}_t = (X_t, Y_t, Z_t, \dot{X}_t, \dot{Y}_t, \dot{Z}_t) =$ rendezvous-target state vector

B = 3 X 3 coordinate transformation matrix

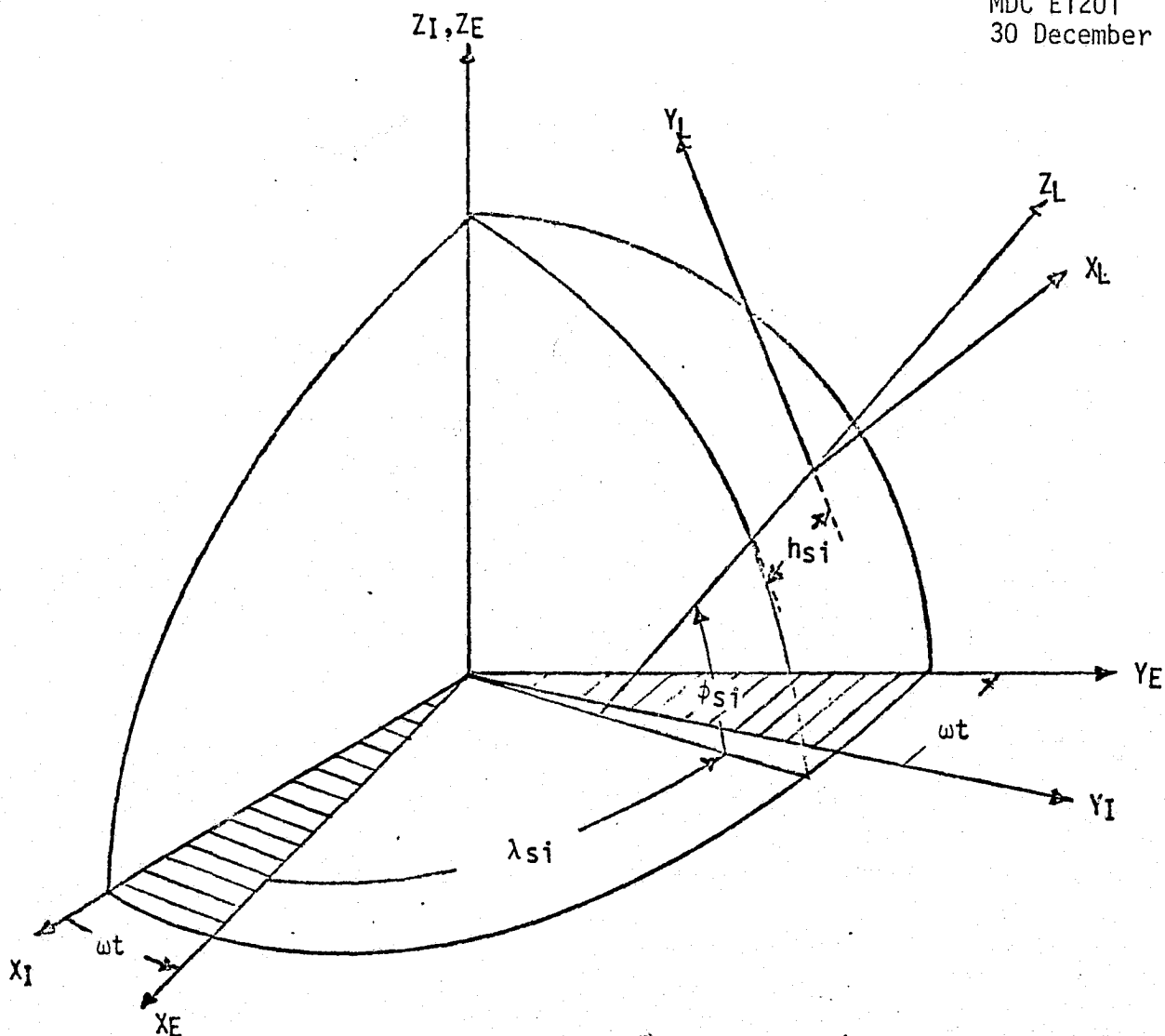
T = universal time

The logic of this driver routine provides for exercising the linkage between the Orbiter and every ground facility, as well as varying the relative position and velocity over the entire range of operational interest. For initial validation, synthetic state vectors will be used. Later, when a vehicle dynamics module becomes available, integrated validation will make use of realistic trajectories which pass into and through the regions of ground-station and payload contact.

C&T Validation Data Base Impact

The data base contributions for C&T module validation will include the reference module, the checkpoint-generation routine, ground-station tables, antenna-pattern functions or tables, and temporary files of checkpoint inputs and outputs.

The reference module and checkpoint-generation module are both fairly simple, and will impose little storage load. The ground-station table will may be fairly extensive (dozens or hundreds of stations, depending upon Shuttle operational rules), but will be common to the simulator data base rather than in addition to



- X_I - Through the Vernal Equinox of Reference
- Y_Z - 90° East in the Equatorial plane
- Z_I - Through the North Pole
- X_E - Through the Greenwich Meridian
- Y_E - 90° East in the Equatorial plane
- Z_E - Through the North Pole
- X_L - East through the station location in the Earth tangential plane
- Y_L - North through the station location in the Earth tangential plane
- Z_L - Up through the station location along the geodetic vertical

FIGURE 4.7-96 COORDINATE SYSTEMS FOR COMMUNICATIONS AND TRACKING MODULE.

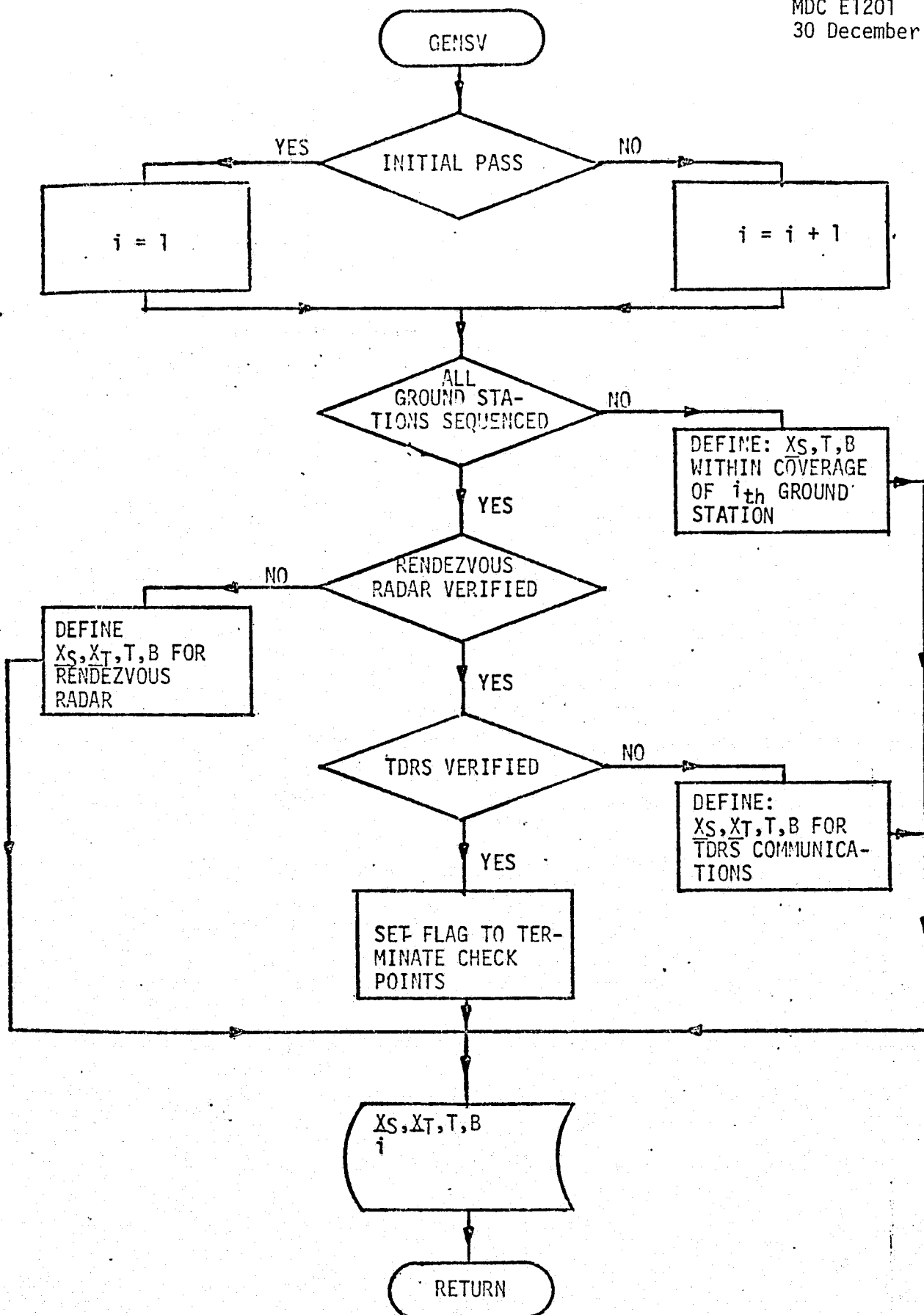


FIGURE 4.7-97 COMMUNICATIONS AND TRACKING CHECKPOINT-GENERATION MATH FLOW.

it. The antenna-pattern data, if maintained in tabular rather than functional form, will also be extensive, but should also be common to the simulator. The extent of the checkpoint files will vary with the resolution desired for comparison plots, and in any event, these files need not be maintained after initial validation is completed. Overall, the data base impact for C&T module validation should be minor.

4.7.5.3 Controls and Displays (C&D)

The controls and displays group includes subsystems and components involved in the presentation of information to the flight crew and flight crew control of the Shuttle vehicle and its various onboard systems. It also includes the Master Events Controller (MEC), which transfers discrete commands from the flight computer to various pyrotechnic devices.

Controls and displays will be discussed in four categories: timers (including the MEC), artificial feel system, miscellaneous display interfaces, and miscellaneous control interfaces. Flight-computer CRT/keyboard units are excluded from this discussion, on the assumption that they will be implemented using flight hardware on the simulators of interest.

This discussion will be brief, since C&D software requirements are minor, and much of their validation will be done in an integrated rather than isolated-module configuration:

C&D Subsystem Description

Timers and MEC - This category includes the Master Timing Unit (MTU), the event timer, and the MEC.

The MTU (Ref. 61), based on a crystal-controlled oscillator, provides (a) stable frequency outputs for use by various Orbiter subsystems and payloads, and (b) serial time code outputs for subsystems including computers, data acquisition systems, recorders, displays and attached payloads. It includes separate time accumulators for Greenwich Mean Time and Mission Elapsed Time, which can be set or updated by external control.

The Event Timer (Ref. 62) is used by the crew in execution of maneuvers and other onboard procedures. It accepts and counts timing pulses from the MTU (or a backup internal source), and generates a numeric display. Operational modes are count-up, count-down, reset, preset, and override.

The MEC (Ref. 63) recognizes two types of discrete commands output by the flight computer: critical and non-critical. Critical command words must be

transmitted by all four computers to be acted upon; non-critical words may be received from any individual flight computer. Command words are then decoded and addressed to the proper pyro initiator controller (PIC), to perform such actions as SRB initiation, SRB or ME separation, etc.

Artificial Feel System - The artificial feel used on Orbiter manual controls consists of simple spring resistance and no software input is required.

Miscellaneous Display Interfaces - The Orbiter crew station panels include a great number of displays, some of which are described in Refs. 64 - 66. These displays provide visual and/or aural information of a discrete (events, anomalies) or continuous nature (range, altitude, air-speed, etc.) to the crew. Some of this information comes directly from onboard sensors, some is generated by flight computers. In some cases, the display interface simply buffers and formats the raw data; in other cases, software compensation for sensor and display calibration is provided.

The caution and warning (C&W) status display incorporates crew-settable switches to select channels, change alarm limits, suppress alarm indications, etc.

Miscellaneous Control Interfaces - Orbiter crew station panels also incorporate a number of controls -- hand controllers, switches, circuit breakers, etc. These controls enable the crew to input discrete (e.g., arm drag chute) and continuous (e.g., aerosurface, thruster) commands to control the vehicle. The control interface hardware and software merely buffers and decodes these control inputs for use by the flight computer.

C&D Module Description and Performance Parameters

Timers and MEC - Timer functions will be simulated using the basic simulator central clock (either within the host computer or external hardware) as a timing source. The event timer will require a simple software module, which will accept mode-select commands from the crew panel. The MEC software module will just provide delayed-time talkback of non-critical discretets; its method of voting critical discretets will depend upon how flight-computer redundancy is implemented in the various simulators.

Miscellaneous Display Interfaces - The display interface software will perform simple buffering, formatting and scaling of signals from the host computer. Some meters may require compensation-curve processing, based upon periodic calibration data.

The caution and warning status display, if flight hardware, will interface directly with the flight computer. If implemented as simulator hardware, it will require flight-computer data conversion by means of software in the host and/or the FEID. An interface with the aural simulation hardware will also be required to generate tone, klaxon and siren outputs, used to indicate mission-critical anomalies.

Miscellaneous Control Interfaces - The control interface software will simply buffer, format and scale discrete and continuous control inputs for the host and/or FC/FEID.

Summary - Figure 4.7-98 depicts the C&D simulation module interfaces. Table 4.7-28 lists the C&D simulation module parameters.

C&D Reference Data Sources and Data Formats

The basic sources of reference data are the specifications of the onboard systems, and of the simulator hardware and software for the particular simulator of interest. The simple C&D software modules just perform a simulator-peculiar mapping of inputs to outputs -- e.g., discrete input #xxx is delayed for ttt seconds and becomes discrete output #yyy; so much controller motion maps into so many degrees of aerosurface deflection.

C&D Validation Methods and Check Cases

The bulk of the C&D validation is performed on the integrated simulator. Preliminary validation of discrete-data handling would be done by means of an external driver and a command/response "dictionary." Preliminary validation of continuous-data handling would be performed by providing sampled inputs over the specified range (e.g., the input to a particular meter), generating a data plot to be compared to the meter calibration curve.

4.7-299

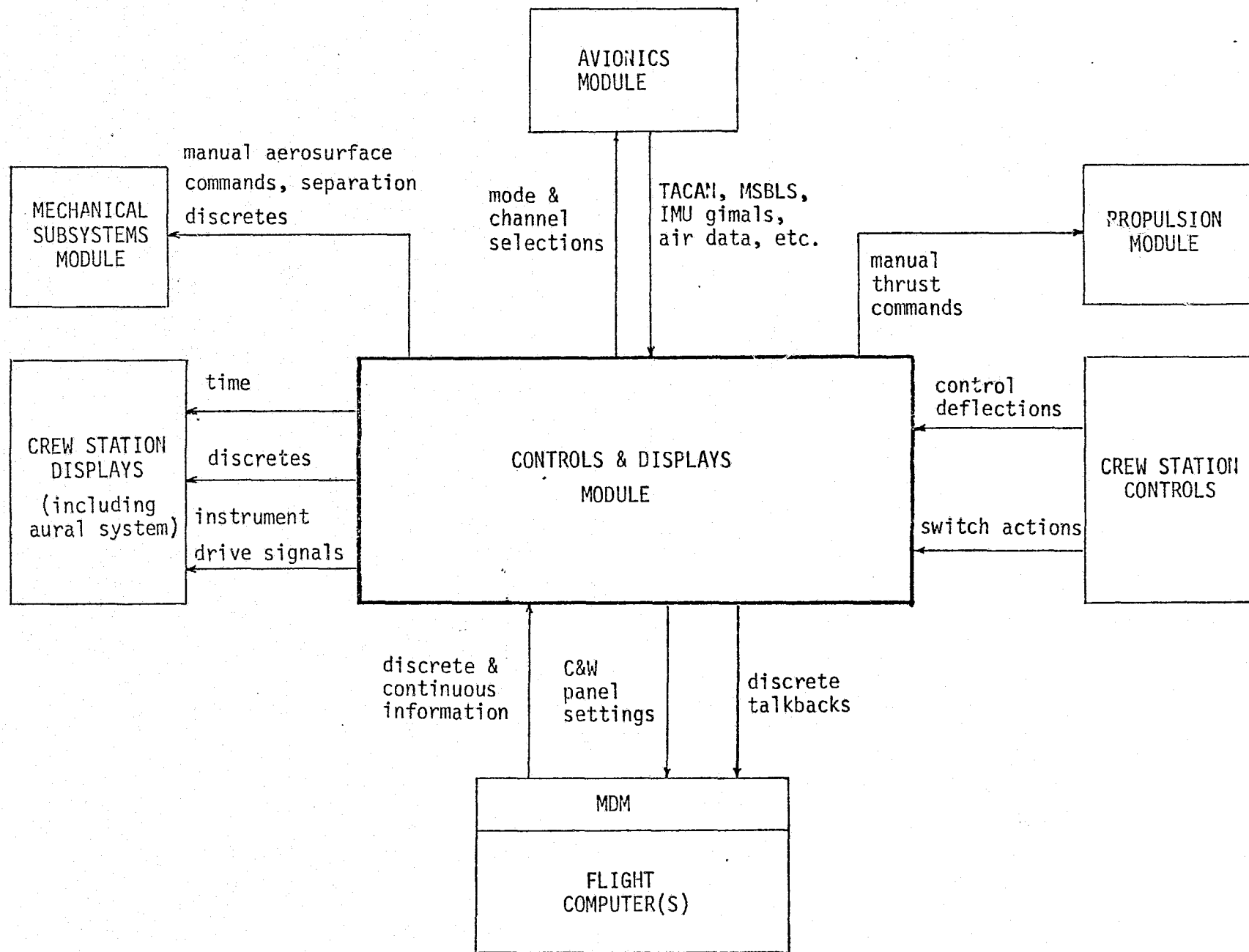


FIGURE 4.7-98. CONTROLS AND DISPLAYS MODULE INTERFACES

TABLE 4.7-28. CONTROL AND DISPLAY MODULE PARAMETERS

DESCRIPTION	TYPE ^a
Hand-controller and rudder pedal deflections	I
Manual switch actions	I
Flight computer discretes	I
Flight computer continuous data	I
Avionics data: MSBLS, TACAN, IMU gimbals, etc.	I
Aerodynamic and runway velocities	I
Sensor and instrument scaling and calibration data	DB
Aerosurface deflection commands (manual)	P
Avionics mode and channel-select commands	P
Thrust commands (manual)	P
Displayed times: GMT, MET, event	P
Display discretes: C&W, channel set, etc.	P
Instrument drive signals	P
C&W panel settings: inhibits, limits, etc.	P
Discrete talkbacks	P

^aTYPE - I = input

DB = data base input

P = performance parameter

C&D Validation Data Base Impact

Very little on-line storage is required for validation of the C&D module, which requires no reference module as such. The on-line data base will consist of some short command/response dictionaries, a few calibration curves, and a simple external driver module.

4.7.5.4 Operational Instrumentation (OI)

The OI subsystem provides the telemetry processing and caution and warning (C&W) functions on the Shuttle Orbiter. The telemetry processing function consists of data buffering, scaling and formatting, and control of onboard recording, recorder dumping, and real-time telemetry to the ground network. The caution and warning function consists of buffering, filtering and gating data, and generating display messages in response to detected anomalies.

These functions are all implemented in flight software in the Orbiter flight computers, and will thus require no simulation software in the simulators of interest, which will incorporate flight computer hardware. In the SMS, which simulates most onboard subsystems in high fidelity, OI implementation will require the subsystem simulations to provide realistic values for such performance-correlated variables as temperatures, voltages, and various operational discretes -- over and above a correct representation of subsystem functions. In the SPS and OAS, we expect little or no implementation of OI functions, and much-simplified representation of most onboard subsystems.

The telemetry and maintenance recorders are discussed under C&T (Section 4.7.5.2), and the C&W displays under Controls and Displays (Section 4.7.5.3).

4.7.5.5 Electrical Power Distribution and Control

The Electrical Power Distribution and Control (EPD&C) subsystem provides the means of conditioning and transfer of electrical energy from the fuel cells or ground support equipment (GSE) umbilicals to the various systems electrical equipment. In addition, the subsystem includes external vehicle illumination. This section provides a discussion of the subsystem components, module performance parameters, reference data sources, validation methods, and impact to the simulation data base.

EPD&C Subsystem Description

Figure 4.7-99 is a schematic of the EPD&C subsystem. The means of energy transfer is a network of bus bars which are connected by electrical cables, power relays, solid state power controllers, fuses, etc. This network of buses includes:

- 3 main buses
- 3 essential (critical) control buses
- 3 forward local buses
- 3 midsection local buses
- 3 aft section local buses
- 3 AC 3-phase buses (powered by 3 inverters)

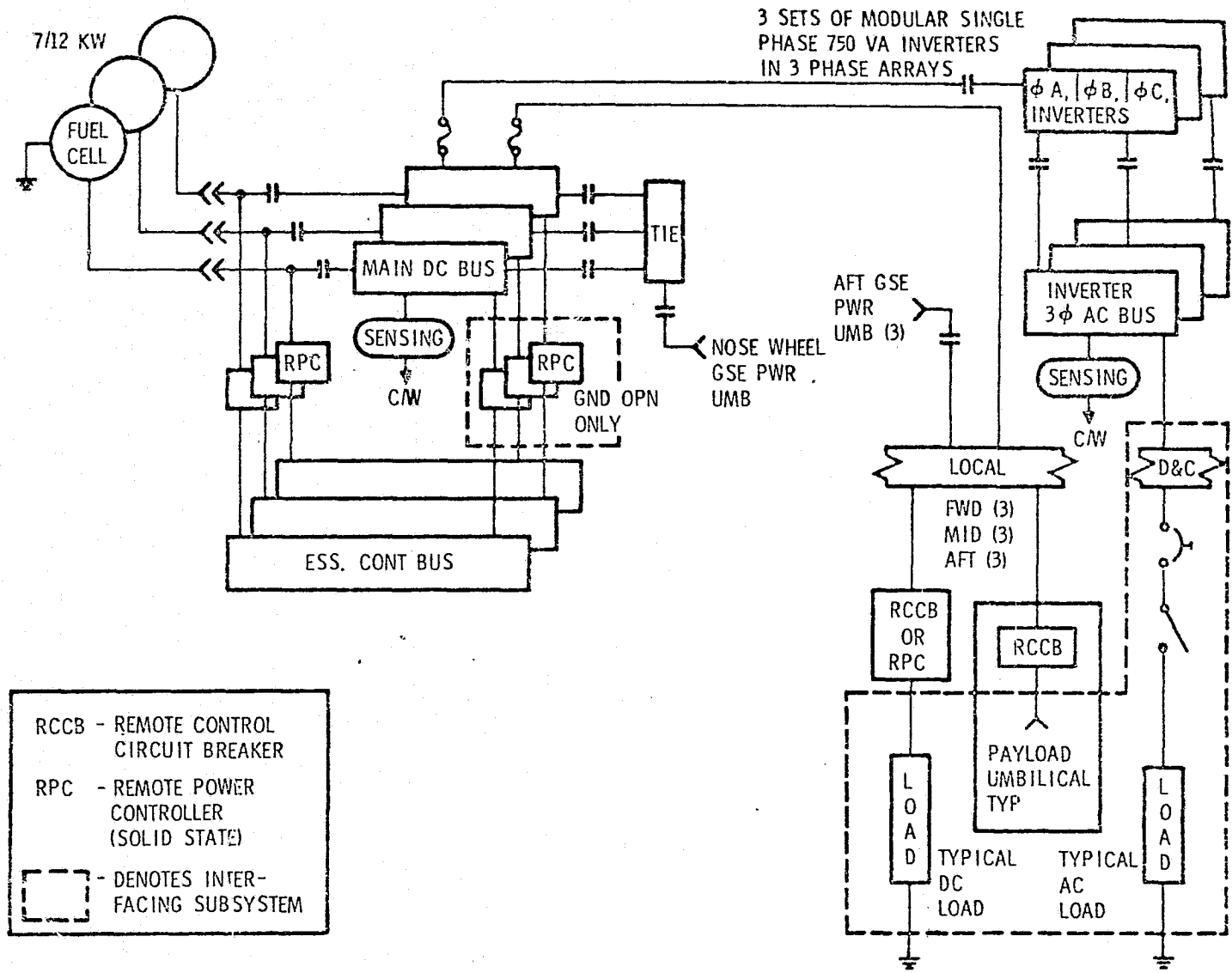
The three main buses can be individually interconnected by a tie bar which also allows connection of the tie bar to GSE power via the nose-wheel umbilical. The three aft local buses can be individually connected to GSE power via the aft GSE power umbilical. The three aft local buses can also be connected together via a tie bar. The 3-phase AC buses can also be electrically connected by tie bars.

The illumination system block diagram is presented in Figure 4.7-100. The exterior lighting is controlled by manual switching. The lighting includes landing, navigational, anti-collision, rendezvous, docking, manipulator, payload and camera lights.

EPD&C Module Description and Performance Parameters

The Figure 4.7-101 schematic illustrates the EPD&C module interfaces with the other modules and shows the functional elements within the module. The performance parameters of the module are listed in Table 4.7-29. The module functional elements provide the following calculations:

4.7-304



RCCB - REMOTE CONTROL
CIRCUIT BREAKER

RPC - REMOTE POWER
CONTROLLER
(SOLID STATE)

--- DENOTES INTER-
FACING SUBSYSTEM

FIGURE 4.7-99. ELECTRICAL POWER DISTRIBUTION AND CONTROL SUBSYSTEM SCHEMATIC

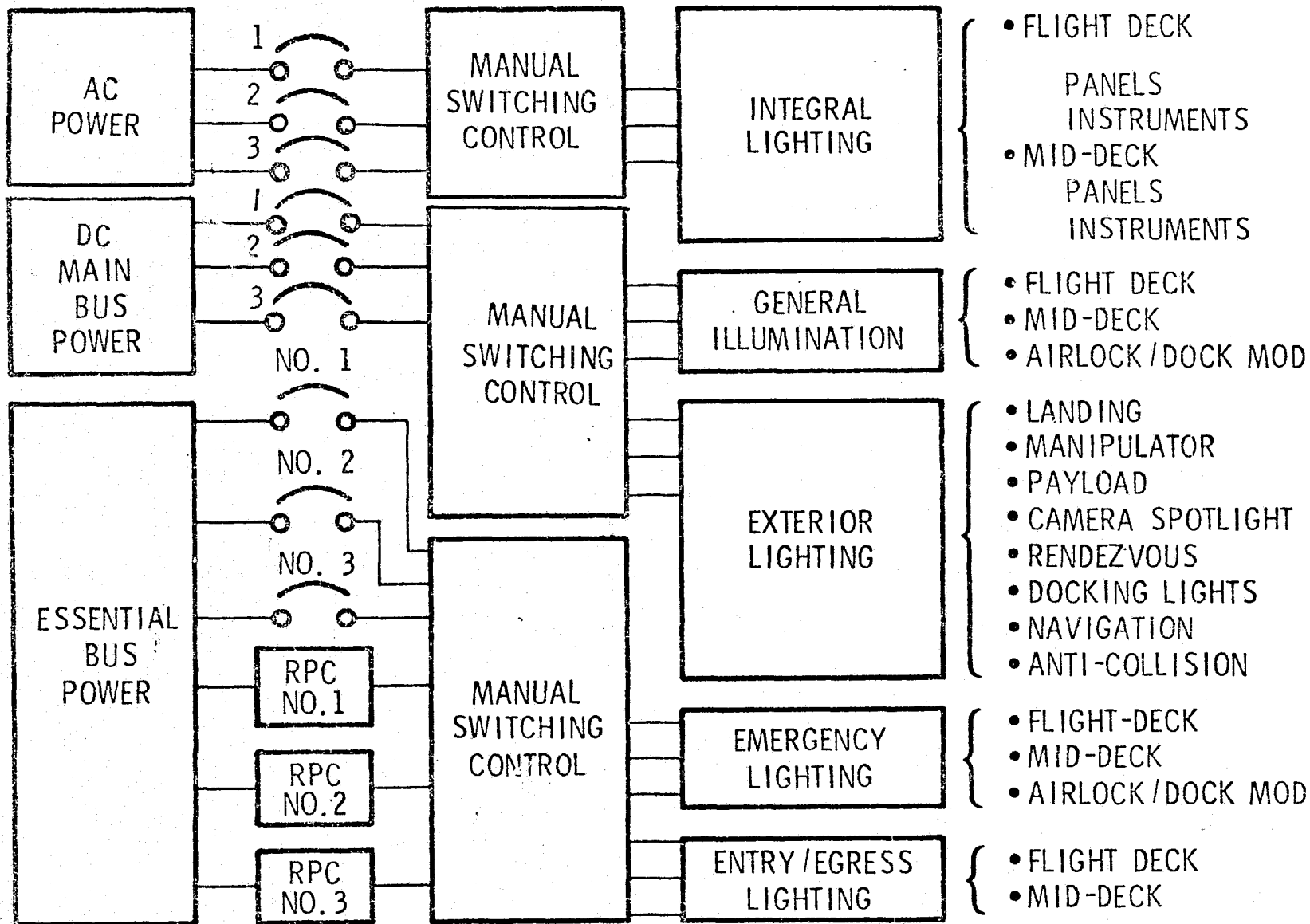


FIGURE 4.7-100. ILLUMINATION SUBSYSTEM SCHEMATIC

4.7-306

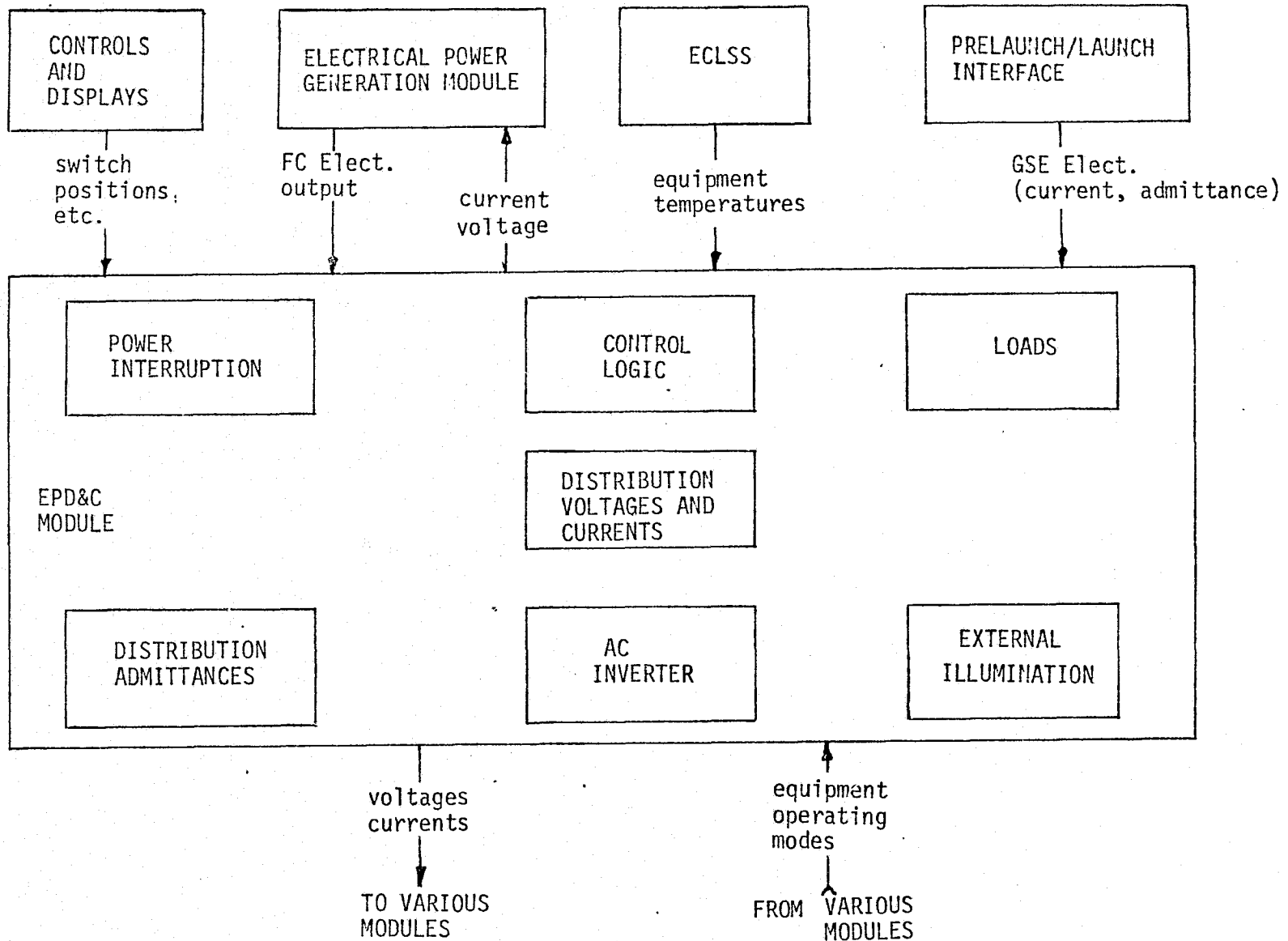


FIGURE 4.7-101. ELECTRICAL POWER DISTRIBUTION AND CONTROL MODULE ELEMENTS AND INTERFACES.

- Loads - determine the admittance values of each load as functions of operating mode, input voltage, and temperature.
- Control logic - determines enabling/disabling selection logic from the control inputs.
- AC inverter - calculates:
 - Inverter AC load - determines inverter load-phase as functions of AC voltage, mode selected temperatures.
 - Inverter efficiency - this is a function of inverter temperature, AC load, and input DC voltage.
 - Equivalent DC load - a function of inverter efficiency and inverter AC load.
- Distribution resistances - calculates the bus network distribution resistances as functions of the control logic, and bus voltages.
- Distribution voltages and currents - calculates bus and load voltages and currents as functions of the fuel cell current/admittance, load admittances, and distribution network resistances.
- Power interruption - sums current through the power interruption devices, determines overload conditions, integrates overload time, and sets logic indicating power line open.
- External illumination - determines light operating mode and on/off condition from control logic and bus voltages.

EPD&C Reference Data Sources and Formats

The component design performance requirements, performance predictions, test results, and flight vehicle performance results can be used as reference data for direct comparison with simulation results. Reference 31 is specifically intended to provide data of this type. Component design requirements are defined in the following Rockwell International documents:

<u>COMPONENT</u>	<u>SPECIFICATION</u>
Fuses	MC451-0010
Thermal circuit breakers	MC454-0026
Remote control circuit breakers	MC454-0027
Remote power controller	MC450-0017
AC inverters	MC495-0012

Various analysis computer programs are available for use in providing reference data. One such program is the Shuttle Electric Power System Analysis Computer Program (SEPS) developed by TRW for the consumables analysis section of the Mission Planning and Analysis Division (see Ref. 67). The subroutines used in the SEPS can be easily developed into an adequate reference module. The complete development of a suitable module would be a relatively simple and straightforward task. Figure 4.7-102 is a generalized overview of the module operations.

Figure 4.7-103 provides an equivalent DC circuit for the Shuttle EPD&C. It also shows the defining matrices for the circuit assuming the switches are all closed and the diodes are forward-biased. The defining matrix equation is:

$$[I] = [G] [E]$$

where $[I]$ = column matrix for the node input current sources

$[G]$ = square admittance matrix of the circuit

$[E]$ = column matrix of the node voltages

The node voltages can be determined from the following equation:

$$E_x = \frac{\Delta_x}{\Delta_o}$$

E_x = x-node voltage

Δ_o = value of the determinant of $[G]$

Δ_x = value of the determinant of the matrix resulting by replacing the x column of the $[G]$ with $[I]$

The analysis of the circuit with all switches open is similar with the resulting matrices being less complex.

EPD&C Validation Methods and Checkcases

The methods of Sections 5.1 and 4.2 can be used in validating the EPD&C simulation module. A comparison of the parameters listed in Table 4.7-29 and bus power, load power, fuel cell input power, fuel cell input watt hours, and ampere hours, should provide adequate checks. During the module runs, interface drivers will be required to provide the input parameters from the interfacing modules. It will also be necessary to provide drivers to initialize or hold static the intermodule parameters and conditions. Drivers required are:

- FC electrical outputs
- Equipment operating mode, etc.

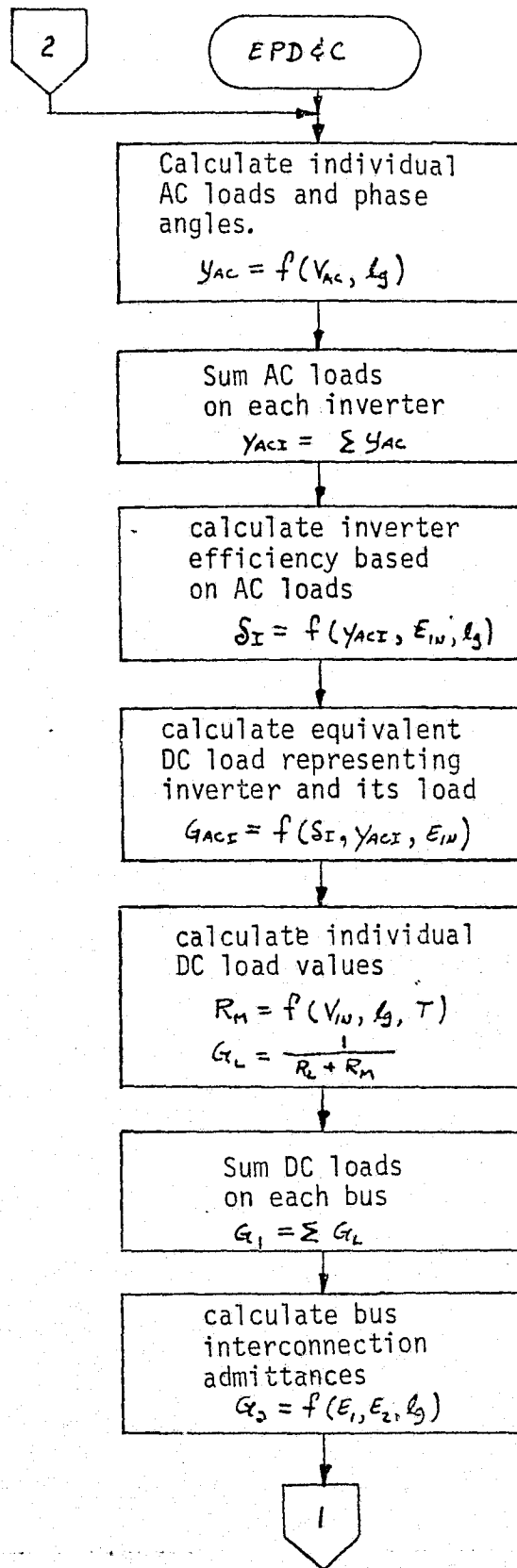


FIGURE 4.7-102 ELECTRIC POWER DISTRIBUTION AND CONTROL SUBSYSTEM REFERENCE MODULE MATH FLOW.

4.7-310

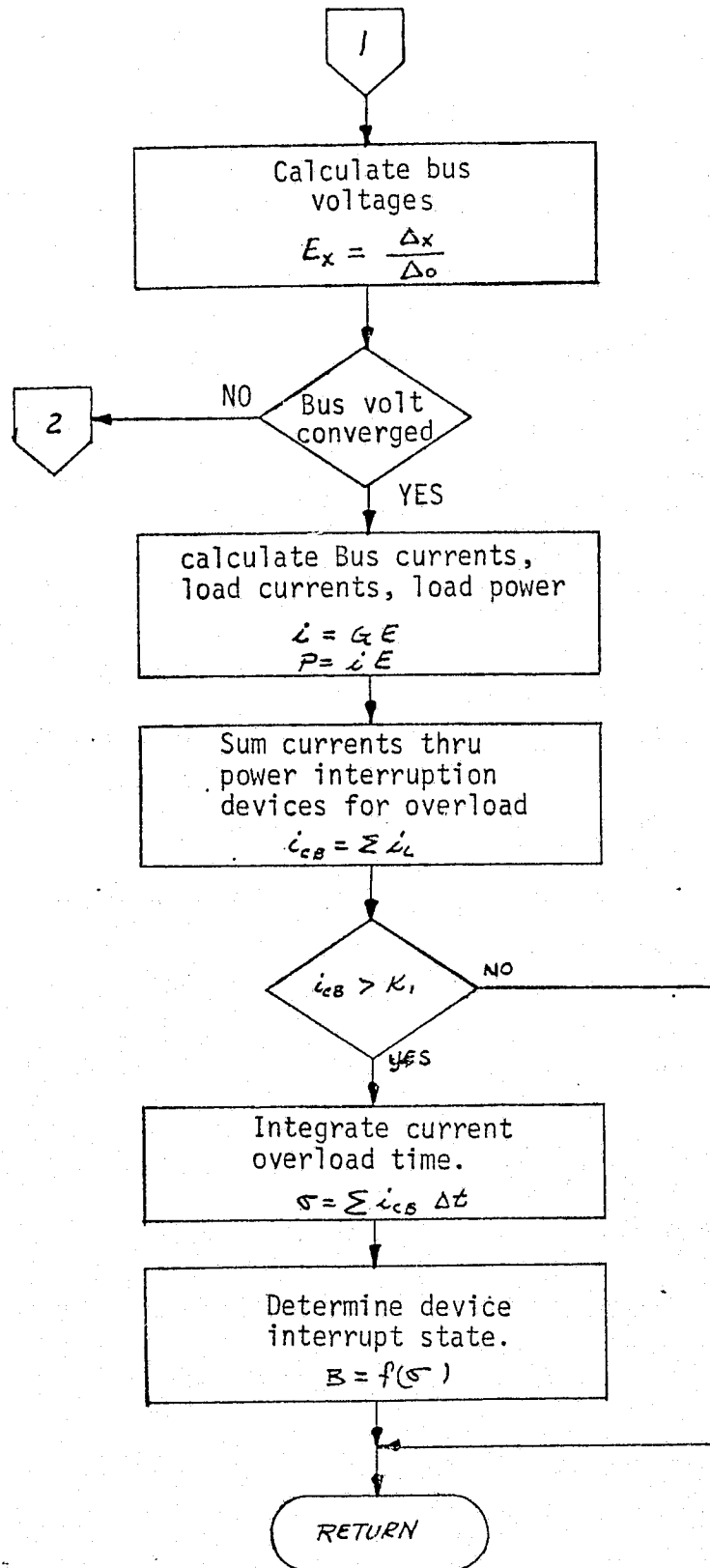
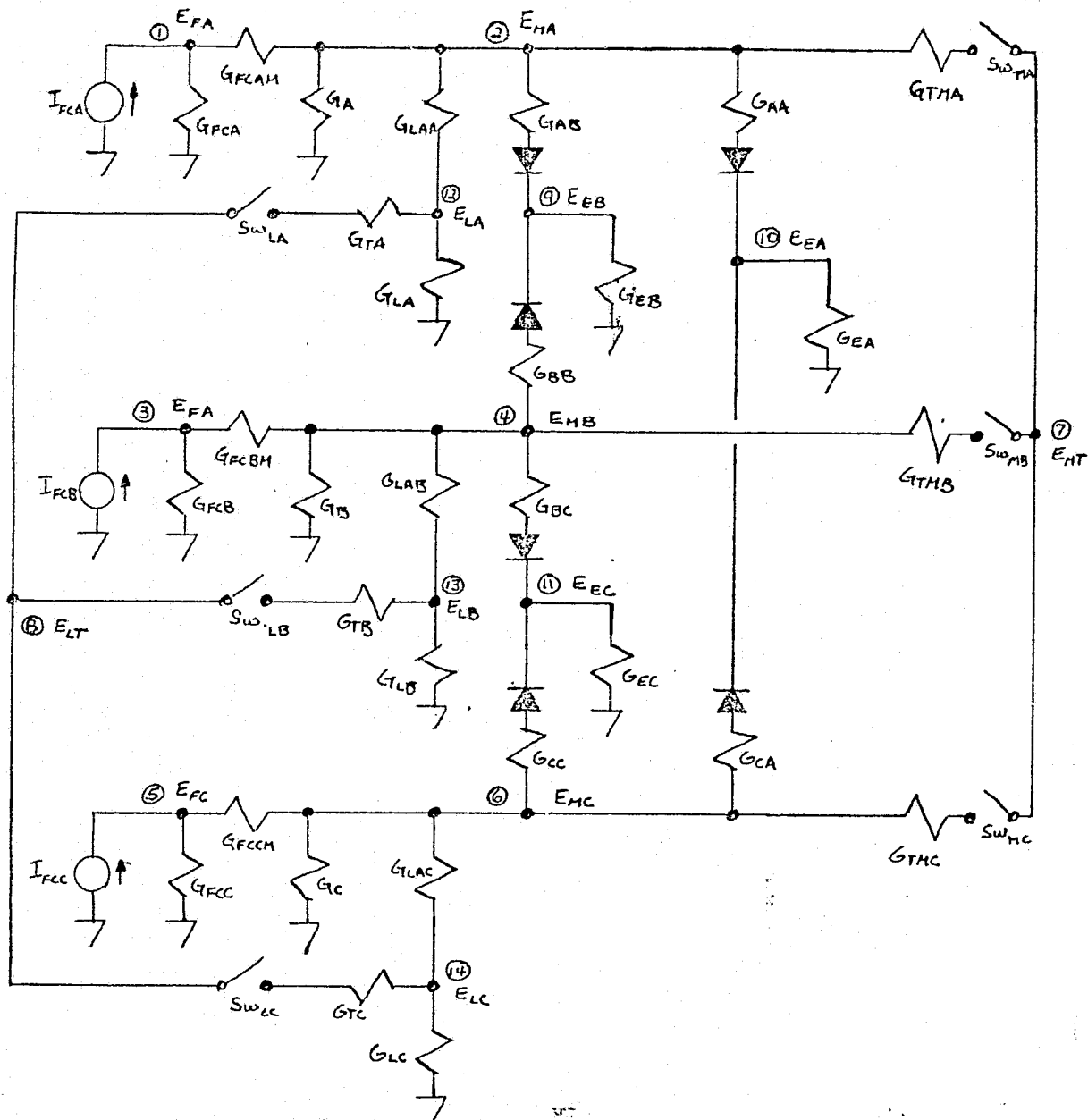


FIGURE 4.7-102 (CONTINUED)

LEGEND:

Y_{AC}	= AC load admittance
V_{AC}	= AC bus voltage
I_g	= logic inputs
Y_{ACI}	= Sum of AC loads on AC inverter
S_I	= Inverter electrical efficiency
G_{ACI}	= Equivalent DC load representing inverter and its AC loads
R_M	= Individual DC load resistances
R_L	= Line resistance from load to bus
G_I	= Sum of bus load admittances
G_2	= Bus interconnection admittance (DC)
E_x	= Bus voltage
Δ_x	= Value of determinant of the admittance matrix with x-column replaced by current matrix
Δ_0	= Value of the determinant of the admittance matrix
i	= Current
E	= voltage
P	= Power (electrical)
B	= Interruption state of power interrupt devices (fuses, circuit breakers, etc.)
Δt	= Time increment
T	= Temperature

FIGURE 4.7-102 (CONTINUED)



$$[I] = [G][E]$$

$$[I] = \begin{bmatrix} I_{FCA} \\ 0 \\ I_{FCB} \\ 0 \\ I_{FCC} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$[E] = \begin{bmatrix} E_{FA} \\ E_{HA} \\ E_{FB} \\ E_{HB} \\ E_{FC} \\ E_{HC} \\ E_{HT} \\ E_{LT} \\ E_{EB} \\ E_{EA} \\ E_{EC} \\ E_{LA} \\ E_{LB} \\ E_{LC} \end{bmatrix}$$

FIGURE 4.7-103. ELECTRICAL POWER DISTRIBUTION AND CONTROL EQUIVALENT CIRCUIT AND MATRIX DEFINITIONS

MOONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

4.7-313

$$\begin{bmatrix} G \end{bmatrix}$$

$$\equiv$$

G_{11}	$-G_{FCAM}$	0	0	0	0	0	0	0	0	0	0	0	0	0
$-G_{FCAM}$	G_{22}	0	0	0	0	$-G_{TMA}$	0	$-G_{AB}$	$-G_{AA}$	0	$-G_{LAA}$	0	0	0
0	0	G_{33}	$-G_{FCBM}$	0	0	0	0	0	0	0	0	0	0	0
0	0	$-G_{FCBM}$	G_{44}	0	0	$-G_{TMB}$	0	$-G_{BB}$	0	$-G_{BC}$	0	0	0	0
0	0	0	0	G_{55}	$-G_{FCCM}$	0	0	0	0	0	0	0	0	0
0	0	0	0	$-G_{FCCM}$	G_{66}	G_{TMC}	0	0	$-G_{CA}$	$-G_{CC}$	0	0	0	$-G_{LAC}$
0	$-G_{TMA}$	0	$-G_{TMB}$	0	$-G_{TMC}$	G_{77}	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	G_{88}	0	0	0	$-G_{TA}$	$-G_{TB}$	$-G_{TC}$	0
0	$-G_{AB}$	0	$-G_{BB}$	0	0	0	0	G_{99}	0	0	0	0	0	0
0	$-G_{AA}$	0	0	0	$-G_{CA}$	0	0	0	$G_{10 10}$	0	0	0	0	0
0	0	0	$-G_{BC}$	0	$-G_{CC}$	0	0	0	0	$G_{11 11}$	0	0	0	0
0	$-G_{LAA}$	0	0	0	0	0	0	0	0	0	$G_{12 12}$	0	0	0
0	0	0	$-G_{LAB}$	0	0	0	0	$-G_{TB}$	0	0	0	0	$G_{13 13}$	0
0	0	0	0	0	$-G_{LAC}$	0	$-G_{TC}$	0	0	0	0	0	0	$G_{14 14}$

NOTES: 1. ALL MATRICES SHOWN ARE WITH ALL SWITCHES CLOSED.

2.

$$G_{11} = G_{FCA} + G_{FCAM}$$

$$G_{22} = G_{FCAM} + G_A + G_{LAA} + G_{AB} + G_{AA} + G_{TMA}$$

$$G_{33} = G_{FCB} + G_{FCBM}$$

$$G_{44} = G_{FCBM} + G_B + G_{LAB} + G_{BB} + G_{BC} + G_{TMB}$$

$$G_{55} = G_{FCC} + G_{FCCM}$$

$$G_{66} = G_{FCBM} + G_C + G_{LAC} + G_{CC} + G_{CA} + G_{TMC}$$

$$G_{77} = G_{TMA} + G_{TMB} + G_{TMC}$$

$$G_{88} = G_{TA} + G_{TB} + G_{TC}$$

$$G_{99} = G_{AB} + G_{BB} + G_{BB}$$

$$G_{10 10} = G_{CA} + G_{EA} + G_{AA}$$

$$G_{11 11} = G_{BC} + G_{CC} + G_{CC}$$

$$G_{12 12} = G_{LAA} + G_{TA} + G_{LA}$$

$$G_{13 13} = G_{LAB} + G_{TB} + G_{LB}$$

$$G_{14 14} = G_{LAC} + G_{TC} + G_{LC}$$

FIGURE 4.7-103. (CONTINUED)

LEGEND:

I_{FCA}
 I_{FLB}
 I_{FLC} } = Norton's equivalent current sources representing the fuel cell A, B, C outputs.

G_{FCA}
 G_{FCB}
 G_{FCC} } = Norton's equivalent admittance for the fuel cells A, B, C.

$G_{FC()}M$ = Admittances connecting fuel cell output to main buses.

G_A
 G_B
 G_C } = Equivalent loads on main buses A, B, C including forward local/middle local/AC bus loads and wiring losses.

G_{LAA}
 G_{LAB}
 G_{LAC} } = Admittance between main buses and AFT local buses A, B, C.

G_{LA}
 G_{LB}
 G_{LC} } = Admittance loads on AFT local buses A, B, C.

G_{TA}
 G_{TB}
 G_{TC} } = Admittance between AFT local buses A, B, C and AFT Bus Tie.

G_{TMA}
 G_{TMB}
 G_{TMC} } = Admittances between main buses A, B, C and main Bus Tie.

G_{AA}
 G_{CA} } = Admittance between main buses A, C and essential bus A.

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FIGURE 4.7-103. (CONTINUED)

G_{AB}	}	= Admittances between main buses A, B and essential bus B.
G_{BB}		
G_{BC}	}	= Admittances between main buses A, B and essential bus C.
G_{CC}		
G_{EA}	}	= Admittance loads on essential buses A, B, C.
G_{EB}		
G_{EC}		
E_{FCA}	}	= Fuel cell output voltages.
E_{FCB}		
E_{FCC}		
E_{FCA}	}	= Fuel cell A, B, C input voltages.
E_{FCB}		
E_{FCC}		
E_{MA}	}	= Main buses A, B, C voltages.
E_{MB}		
E_{MC}		
E_{MT}		= Main bus tie-bar voltage.
E_{LT}		= AFT local tie-bar voltage.
E_{EA}	}	= Essential buses A, B, C voltages.
E_{EB}		
E_{EC}		
E_{LA}	}	= AFT local buses A, B, C voltages.
E_{LB}		
E_{LC}		
Δ_o		= Value of the determinant of the G-matrix ([G])
Δ_x		= Value of the determinant of the matrix resulting by replacing the x-column of the G-matrix with the I-matrix.
Sw		= Switch.

FIGURE 4.7-103, (CONTINUED)

4.7-316

- Equipment temperature
- Control logic (switch positions)
- Prelaunch/launch interface - GSE electrical inputs parameters

The check cases implemented should include step changes in loads, bus switching, maximum equipment powered, minimum equipment powered, and expected mission load profiles (equipment powered time-line). System checkout or test sequence results can be input as check cases with simulation results compared directly to the test results.

EPD&C Data Base Impact

The EPD&C reference module and drivers are of moderate impact to the simulation data base. The majority of the processing subroutines (data comparison, read, write, etc.) would be common to all modules requiring validation. The equipment power profiles (time-lines) would be required but represent a minor impact. Data files would also be required for the input and output data tables.

4.7.6 Environmental Control/Life Support System

This section includes the discussion of the Atmosphere Revitalization System; the Active Thermal Control System; and the Food, Water, and Waste Management System.

4.7.6.1 Atmosphere Revitalization System (ARS)

The ARS includes the Atmosphere Revitalization Pressure Control Subsystem (ARPCS), and the ARS Cabin Atmosphere Control Subsystem (ARS-CACS). These two subsystems are discussed in the following sections.

4.7.6.1.1 Atmosphere Revitalization Pressure Control System Description

The Atmosphere Revitalization Pressure Control Subsystem (ARPCS) provides three basic functions for the Shuttle Orbiter. The functions provided are:

- 1) N_2 and O_2 storage (gas)
- 2) distribution of gaseous O_2 and N_2 , at proper pressures, to the user equipment, system, etc.
- 3) ensuring proper O_2 and N_2 mixture while controlling cabin (crew quarters) pressure.

These functions are accomplished via interconnecting manual valves, solenoid valves, pressure regulators, pressure sensors, electronic controls and relief valves. This interconnection was determined from schematic VL70-000214 (Reference 79), specification MC250-0002 (Reference 71), and a Preliminary Design Review (PDR) handout on the Power Reactant Storage and Distribution System. The resulting representative plumbing schematic is shown in Figure 4.7-104 and 4.7-105. Although these figures are not totally accurate, they should suffice for the current verification study purposes.

N_2 Supply and Distribution - The N_2 gas is stored in 3000 psi bottles containing approximately 50 pounds of N_2 in each. The primary source of N_2 is one (1) bottle, with the auxiliary source comprised of three (3) bottles. Additional bottles can be carried in the payload area and connected to the system if desired. Either the primary, auxiliary, or payload supply can be selected to deliver gas to either of the two N_2 distribution networks.

The N_2 distribution networks are each comprised of various control valves (manual and solenoid) and two (2) N_2 pressure regulators. A 175 psi outlet regulator provides the proper pressure level to the O_2/N_2 cabin pressure controller and to the potable H_2O bottle regulators. This 175 psi regulator also provides outlet pressure relief (at approximately 200 psi) to prevent over pressurizing the downstream distribution network. The pressure relief is vented overboard resulting in possible vehicle attitude and rate disturbance torques. Potable water bottle regulators maintain pressurization of the three (3) potable water tanks. Pressure is regulated 8 to 12 psi above the cabin pressure. This higher pressure ensures the expulsion of the water from the tanks. It should be noted that the N_2 side

27 January 1975

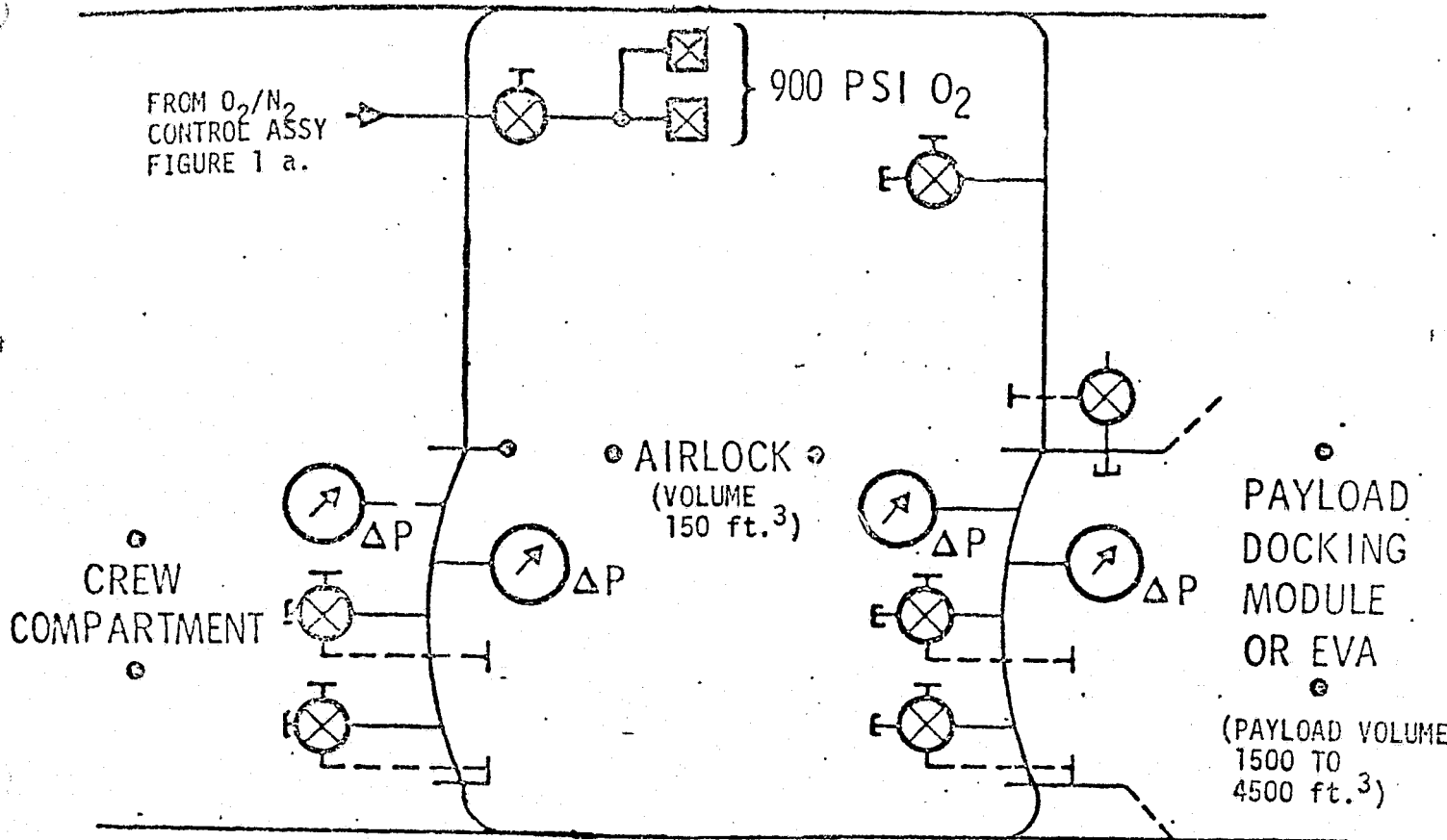


FIGURE 4.7-105. ATMOSPHERE PRESSURE CONTROL, AIRLOCK SUPPORT SUBSYSTEM SCHEMATIC

4.7-321

of the water tanks can be opened to the crew quarters atmosphere via a solenoid actuated valve. The potable water tanks pressure regulators also provide pressure relief for the water tanks. This relief is vented into the crew quarters and contributes to the total cabin pressure.

O₂ Supply and Distribution - The O₂ gas supply has three (3) sources. The primary and secondary supplies are from the Cryogenic O₂ Systems for the Power Reactants Storage and Distribution System (PRSD) which also provide O₂ to the fuel cells. The Cryogenic O₂ flows through restrictor/heat exchangers which provide flow control as well as increasing the gas temperature. Oxygen accumulators (surge tanks) act as pressure stabilizing and intermediate storage devices.

An auxiliary O₂ gas supply is also available. This is at an initial pressure of 3000 psi and must be regulated to approximately 450 psi to prevent over-pressurizing the O₂ distribution network. The 450 psi regulator also provides a distribution system over pressure relief at approximately 1100 psi. This O₂ relief is vented overboard and may generate vehicle attitude and rate disturbance torques.

The O₂ distribution networks are each made up of manual valves, solenoid valves and a pressure regulator. The 100 psi O₂ regulator provides the proper O₂ supply pressure to the O₂/N₂ cabin pressure controller. High pressure O₂ is provided to the four (4) emergency O₂ outlets in the crew compartment mid section, to the four (4) outlets for portable O₂ bottle filling, and to the two (2) airlock support outlets.

Mixture and Pressure Control - The cabin O₂/N₂ mixture control and cabin pressure control are provided by cabin pressure regulators, pressure relief valves, O₂ partial pressure controller, manual valves, and solenoid valves.

O₂ or N₂ is selected for cabin make-up gas by the O₂/N₂ mixture controller. The partial pressure of oxygen is sensed by the partial pressure controller and electronically opens (for O₂ partial pressure 3.45 psia) the N₂ supply solenoid

valve(s) which allows the 170 psi N_2 to flow to the cabin pressure regulator inlet. The N_2 pressure is greater than the 100 psi O_2 which feeds the regulator through a check valve. The higher pressure closes the check valve preventing O_2 from entering the regulator and N_2 only is supplied to the cabin. When the O_2 partial pressure is less than 2.95 psia, the N_2 solenoid valve is closed. This allows any cabin make-up gas flow to be O_2 . O_2 and N_2 flow sensors provide output to the caution and warning subsystem if flow is excessive. In addition, signals are provided to the caution and warning subsystem if the cabin O_2 partial pressure becomes too high or too low.

The cabin pressure control is provided by two (2) types of cabin pressure regulators, cabin relief pressure valves, and manual valves. The primary cabin pressure regulators maintain the cabin pressure at 14.7 psia under normal conditions. However, in the event of excess cabin leakage, additional cabin regulators operate to maintain the pressure at 8 psia.

Two cabin overpressure relief valves operate to limit the cabin high pressure at 15.5 to 16 psi above the vehicle external pressure. These relief valves can be electrically overridden if desired. Two reverse cabin pressure relief valves actuate to maintain a maximum 2 psid external pressure above the cabin pressure. These reverse pressure relief valves can be manually overridden when desired. The venting of these valves can cause body attitude and rate disturbance torques.

Manually actuated pressure equalization valves are used to pressurize and depressurize the airlock compartment. Each of the three (3) avionics bays is continually vented (at a low rate) to the spacecraft external ambient. This venting is required to prevent equipment outgassing products from entering the crew compartment. The inlet to each bay is open to the crew compartments via a relief valve. This valve maintains the bay pressure at 0 to 0.4 psi below the cabin pressure. In the event of a cabin rapid depressurization the same relief valve operates at 0.6 psi to prevent the bay over-pressurizing with respect to the crew compartment.

A cabin pressure decay rate detection provides signals to the caution and warning subsystem when the cabin pressure is decreasing at an excessive rate.

The continued venting of the three avionics bays, and pressurization/
depressurization of the airlock may cause vehicle attitude and rates disturbance
torques.

ARPCS Module Functions and Parameters

Figure 4.7-106 provides an overview of the ARPCS simulation module functional elements and interfaces with other modules. Basically there are four functions performed within the module. These functions are:

- Control logic
- O₂ and N₂ storage
- O₂ and N₂ pressure regulation and distribution
- Cabin pressure control

Table 4.7-30 provides a detailed listing of the parameters associated with the ARPCS module and designation of parameter type.

The following discussion identifies, in general, the functions performed in each element and the factors involved in the calculations.

Control Logic - The control logic functions are dependent on the position of manual valves, solenoid valves, switches, command inputs, bus voltages, etc. The logic outputs are used extensively in each of the other functional elements calculations. The valve logic can be determined from the plumbing schematic; however, the electrical logic is not presently known. The total logic will, of necessity, be highly dependent on the exact electrical design, and this study does not warrant accurate description of the logic. It is only necessary to recognize its existence, and the possibility of many combinations existing.

O₂ and N₂ Storage - The O₂ and N₂ storage functions are the calculation of remaining (or available) gas mass, source pressures, temperatures, inlet or outlet mass flow, etc. The parameters associated with these calculations are as follows:

- A. O₂ Accumulator Calculations
 1. O₂ quantity as a function of initial quantity, inlet flow, outlet flow, time, etc.
 2. Pressure as a function of quantity, temperature, tank volume.
 3. Temperature is a function of initial temperature, inlet O₂ temperature, heat leak, etc.
 4. Mass flow inlet as a function of cryogenic O₂ pressure, accumulator pressure, and restrictor flow/pressure characteristics.

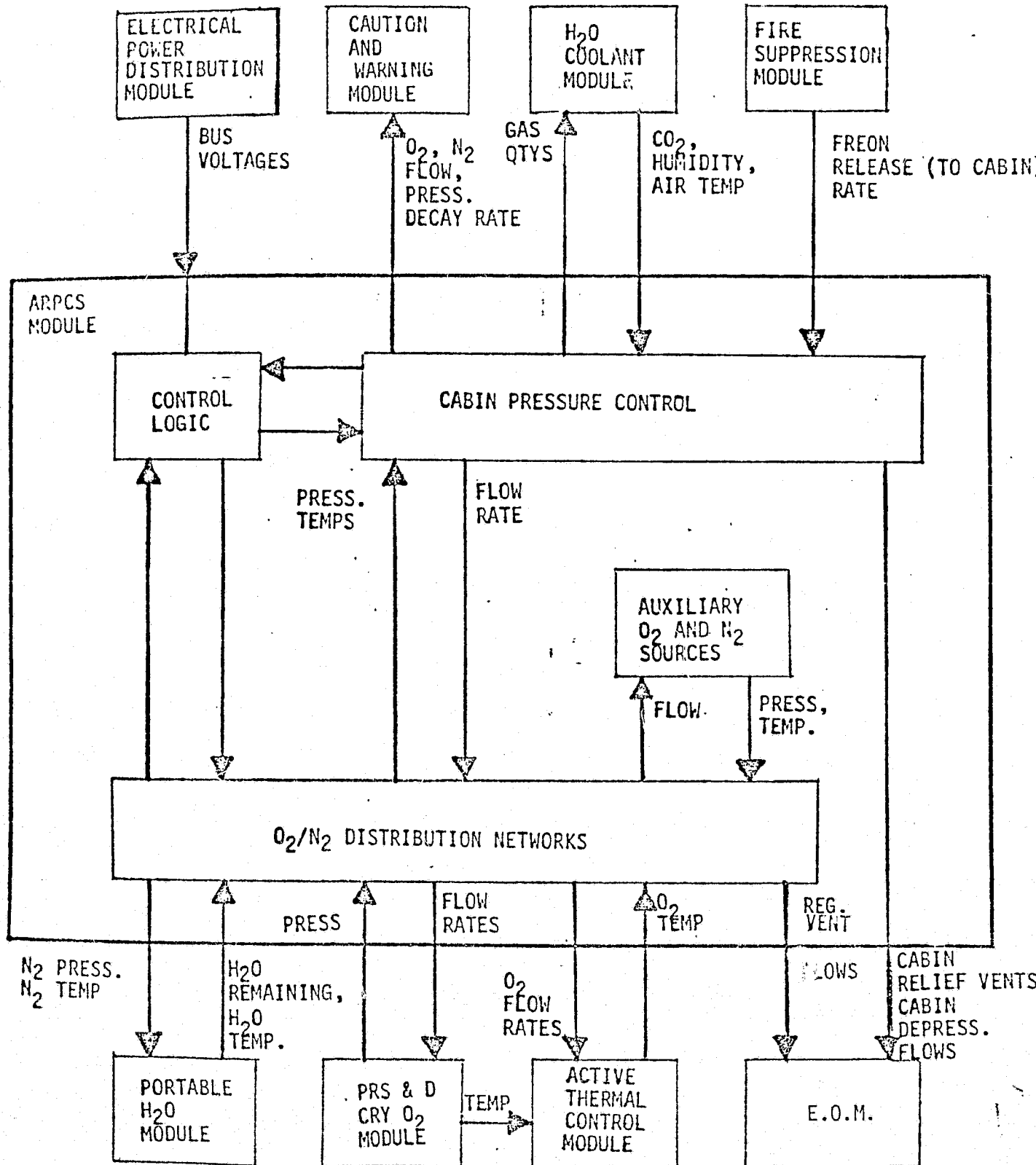


FIGURE 4.7-106 ARPCS MODULE FUNCTIONAL ELEMENTS AND MODULE INTERFACES

4.7-326

TABLE 4.7-30. ATMOSPHERE REVITALIZATION PRESSURE CONTROL SUBSYSTEM PARAMETERS

PARAMETER	TYPE ^a
Primary O ₂ Accumulator - inlet O ₂ temperature	I
Primary O ₂ Accumulator - cryo O ₂ pressure	I
Secondary O ₂ Accumulator - inlet O ₂ temperature	I
Secondary O ₂ Accumulator - cryo O ₂ pressure	I
Primary O ₂ Accumulator - O ₂ mass	CP
Secondary O ₂ Accumulator - O ₂ mass	CP
Primary O ₂ Accumulator - Pressure	P
Secondary O ₂ Accumulator - Pressure	P
Primary O ₂ Accumulator - Temperature	P
Secondary O ₂ Accumulator - Temperature	P
Primary O ₂ Accumulator - O ₂ inlet mass flow - cryo	I
Secondary O ₂ Accumulator - O ₂ inlet mass flow - cryo	I
PRIMARY O ₂ ACCUMULATOR - O ₂ mass outlet flow	P
SECONDARY O ₂ ACCUMULATOR - O ₂ mass outlet flow	P
AUXILIARY O ₂ TANK - O ₂ mass	CP
AUXILIARY O ₂ TANK - pressure	P
AUXILIARY O ₂ TANK - Temperature	P
AUXILIARY O ₂ TANK - O ₂ mass outlet flow	P
AIRLOCK SUPPORT - O ₂ pressure	P
AIRLOCK SUPPORT - O ₂ mass flow	P
N ₂ PRIMARY TANK - N ₂ Mass	CP
N ₂ AUXILIARY TANKS - N ₂ mass	CP
N ₂ PRIMARY TANK - pressure	P
N ₂ SECONDARY TANKS - pressure	P
N ₂ PRIMARY TANKS - temperature	P
N ₂ SECONDARY TANKS - temperature	P
N ₂ PRIMARY - N ₂ mass flow outlet	P
N ₂ SECONDARY - N ₂ mass flow outlet	P
Numerous Control Logic Outputs/Inputs	P
Electrical Power System - Bus Voltages	I
Aux O ₂ regulator - Output Pressure (include relief)	P
Aux O ₂ regulator - Input Pressure	P
Aux O ₂ regulator - Relief vent mass flow rate	P

TABLE 4.7-30. (CONTINUED)

PARAMETER	TYPE ^a
MID SECTION EMERG O ₂ flow 1 - mass flow	P
MID SECTION EMERG O ₂ flow 2 - mass flow	P
MID SECTION EMERG O ₂ flow 3 - mass flow	P
MID SECTION EMERG O ₂ flow 4 - mass flow	P
PORTABLE O ₂ bottle fill - 1 bottle pressure	P
PORTABLE O ₂ bottle fill - 2 bottle pressure	P
PORTABLE O ₂ bottle fill - 3 bottle pressure	P
PORTABLE O ₂ bottle fill - 4 bottle pressure	P
PORTABLE O ₂ bottle fill 1 - mass flow	P
PORTABLE O ₂ bottle fill 2 - mass flow	P
PORTABLE O ₂ bottle fill 3 - mass flow	P
PORTABLE O ₂ bottle fill 4 - mass flow	P
PRIMARY O ₂ - 100 PSI reg - inlet pressure	P
PRIMARY O ₂ - 100 PSI reg - outlet pressure	P
PRIMARY O ₂ - 100 PSI reg - mass flow	P
PRIMARY O ₂ - 100 PSI reg - relief vent mass flow	P
SECONDARY O ₂ - 100 PSI reg - inlet pressure	P
SECONDARY O ₂ - 100 PSI reg - outlet pressure	P
SECONDARY O ₂ - 100 PSI reg - mass flow	P
SECONDARY O ₂ - 100 PSI reg - relief vent mass flow	P
PAYLOAD N ₂ tanks - mass	CP
PAYLOAD N ₂ tanks - pressure	P
PAYLOAD N ₂ tanks - temperature	P
PAYLOAD N ₂ tanks - mass flow out	P
PRIMARY N ₂ 175 PSI reg - inlet pressure	P
PRIMARY N ₂ 175 PSI reg - outlet pressure	P
PRIMARY N ₂ 175 PSI reg - mass flow	P
PRIMARY N ₂ 175 PSI reg - relief vent flow	P

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FIG 4.7-30. (CONTINUED).

PARAMETER	TYPE ^a
SECONDARY N ₂ 175 PSI reg - inlet pressure	P
SECONDARY N ₂ 175 PSI reg - outlet pressure	P
SECONDARY N ₂ 175 PSI reg - mass flow	
SECONDARY N ₂ 175 PSI reg - relief vent mass flow	P
PRIMARY N ₂ Check valve - outlet pressure	P
SECONDARY N ₂ Check valve - outlet pressure	P
PRIMARY POTABLE H ₂ O Bottle Regulator - inlet pressure	P
Primary POTABLE H ₂ O Bottle Regulator - relief vent flow to cabin	P
PRIMARY POTABLE H ₂ O Bottle Regulator - flow rate	P
SECONDARY POTABLE H ₂ O Bottle Regulator - inlet pressure	P
SECONDARY POTABLE H ₂ O Bottle Regulator - relief vent flow to cabin	P
SECONDARY POTABLE H ₂ O Bottle Regulator - flow rate	P
POTABLE H ₂ O tank 3 - N ₂ (gas) quantity	CP
POTABLE H ₂ O tank 3 - Gas Pressure	P
POTABLE H ₂ O tank 3 - temperature	P
POTABLE H ₂ O tank 3 - Gas flow/bottles 1 & 2	P
POTABLE H ₂ O tank 3 - Gas volume	P
POTABLE H ₂ O tank 3 - H ₂ O mass remaining	I
POTABLE H ₂ O tanks 1 and 2 - N ₂ (Gas) mass	P
POTABLE H ₂ O tanks 1 and 2 - Gas pressure	P
POTABLE H ₂ O tanks 1 and 2 - temperature	P
POTABLE H ₂ O tanks 1 and 2 - Gas flow to cabin	P
POTABLE H ₂ O tanks 1 and 2 - Gas volume	P
POTABLE H ₂ O tanks 1 and 2 - H ₂ O mass remaining 1	I
POTABLE H ₂ O tanks 1 and 2 - H ₂ O mass remaining 2	I
Crew Compartment CO ₂ Partial Pressure	P
Pri N ₂ to Cabin Pressure Controller - Pressure	P
Sec N ₂ to Cabin Pressure Controller - Pressure	P

TABLE 4.7-30. (CONTINUED)

PARAMETER	TYPE ^a
Pri O ₂ to Cabin Pressure Controller - Pressure	P
Sec O ₂ to Cabin Pressure Controller - Pressure	P
Pri Cabin Pressure Regulator - inlet pressure	P
Sec Cabin Pressure Regulator - inlet pressure	P
Pri O ₂ mass flow to cabin	CP
Sec O ₂ mass flow to cabin	CP
Pri N ₂ mass flow to cabin	CP
Sec N ₂ mass flow to cabin	CP
Pressurized Volume	P
Crew Compartment Pressure - total	P
Crew Compartment Pressure - O ₂ Partial Pressure	CP
Crew Compartment Pressure - Decay rate	CP
Crew Compartment - O ₂ mass	P
Crew Compartment - N ₂ mass	P
Crew Compartment - temperature (gas)	I
Crew Compartment - O ₂ leakage, loss	P
Crew Compartment - N ₂ leakage, loss	P
Airlock Compartment - O ₂ mass	P
Airlock Compartment - N ₂ mass	P
Airlock Compartment - Pressure	P
Airlock Compartment - O ₂ mass loss /gain	P
Airlock Compartment - N ₂ mass loss/gain	P
Payload Compartment - O ₂ mass	P
Payload Compartment - N ₂ mass	P
Payload Compartment - Pressure	P
Payload Compartment - O ₂ mass loss/gain	P
Payload Compartment - N ₂ mass loss/gain	P
Avionics Bay 1 - O ₂ mass	P
Avionics Bay 1 - N ₂ mass	P
Avionics Bay 1 - Pressure	P

TABLE 4.7-3). (COMPLETE)

PARAMETER	TYPE ^a
Avionics Bay 1 - O ₂ mass loss/gain	P
Avionics Bay 1 - N ₂ mass loss/gain	P
Avionics Bay 1 - Gas temperature	I
Avionics Bay 2 - O ₂ mass	P
Avionics Bay 2 - N ₂ mass	P
Avionics Bay 2 - pressure	P
Avionics Bay 2 - O ₂ mass loss/gain	P
Avionics Bay 2 - N ₂ mass loss/gain	P
Avionics Bay 2 - Gas temperature	I
Avionics Bay 3 - O ₂ mass	P
Avionics Bay 3 - N ₂ mass	P
Avionics Bay 3 - Pressure	P
Avionics Bay 3 - O ₂ mass loss/gain	P
Avionics Bay 3 - N ₂ mass loss/gain	P
Avionics Bay 3 - Gas temperature	I

- ^a
- P = Performance Parameter
 - CP = Critical Performance Parameter
 - I = Input parameter (from another module)

B. Auxiliary O₂ Calculations

1. O₂ quantity remained as a function of time, initial quantity, flow, etc.
2. O₂ source pressure as a function of quantity, temperature, tank volume.
3. Temperature as a function of initial temperature, heat leak, etc.

C. N₂ Source Calculations

1. Primary, auxiliary, and payload N₂ quantities as a function of initial quantities, outlet flow, etc.
2. Primary, auxiliary and payload temperature as a function of initial temperatures, heat leaks, etc.
3. Primary, auxiliary and payload source pressures as a function of temperature, tank volumes, quantity, etc.

D. Components characteristics needed to perform these calculations are:

1. Cryogenic O₂ restrictor/heat exchanger O₂ flow versus differential pressure characteristic.
2. O₂ accumulator volumes
3. O₂ and N₂ tank volumes

Pressure Regulation and Distribution - The O₂ and N₂ pressure regulation and distribution functions are the calculation of the pressures, temperatures, flow rates, etc. throughout the distribution networks. The parameters associated with the calculations are as follows:

A. O₂ Distribution Network Calculations

1. Gas temperatures as a function of source temperature and heat leaks.
2. Pressures as a function of regulator characteristics, inlet pressures, relief characteristics, line volumes, flow rates, etc.
3. Total system flow rate as a function of demand, leakage, etc.
4. O₂ delivery flow rates to the four Emergency O₂ outlets as a function of inlet/outlet pressures, valve/line flow characteristics.
5. O₂ delivery flow rates to the four portable O₂ fill outlets as a function of inlet/outlet pressures, fill tank volume, valve/line flow characteristics, etc.

B. N₂ Distribution Network Calculations

1. Temperatures as a function of source temperatures and heat leaks.
2. Pressures as a function of regulator characteristics, inlet pressures/relief characteristics, line volumes, flow rates, etc.
3. Total system flow rate as a function of demand, leakage, etc.
4. N₂ gas flow rate and quantity delivered to the potable water tanks as functions of regulator characteristics, H₂O tank N₂ volume, remaining H₂O quantity, etc.
5. N₂ gas flow to cabin via the valve opening the H₂O tanks N₂ side to cabin.

C. The component characteristics needed to perform these calculations are:

1. Pressure regulators flow characteristics, relief pressure points, and regulation pressure points.
2. Line/equipment volumes.

Cabin Pressure Control - The cabin pressure control functions are the calculation of various compartment pressures, O₂ and N₂ gas quantities, gas flow rates into and out of the cabins, and pressure decay rates. The parameters associated with these calculations are as follows:

A. Flow Rates

1. O₂ flow rate to cabin as function of pressures, partial pressure controller characteristics, cabin pressure regulator characteristics, etc.
2. N₂ flow rate to cabin as function of pressures partial pressure controller characteristics, cabin pressure regulator characteristics.
3. O₂ and N₂ flow from cabin, as function of pressures, cabin leak rates, relief valves, depressurization valves, etc.

B. Gas Quantities

1. O₂ and N₂ quantities in cabin as a function of initial quantities, flow rates into and out of cabin, etc.

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C. Cabin Pressure

1. Caution and warning signals as functions of pressures.
2. Cabin pressures as a function of various gas partial pressures.
3. O_2 partial pressure as a function of O_2 quantity, cabin temperature, cabin volumes.
4. N_2 partial pressure as a function of N_2 quantities, cabin temperature, cabin volumes.

D. Component characteristics required to perform these calculations are:

1. Cabin pressure regulators flow/pressure characteristics, regulation points, etc.
2. Cabin pressure relief valves flow/pressure characteristics, open and close points for solenoid valves.
3. O_2 partial pressure controller operating voltage levels, open and close points for solenoid valves.
4. Avionics bays vent orifice flow/pressure characteristics (effective flow area), etc.
5. Airlock vent and equalization valve flow/pressure characteristics.
6. Cabin or compartment gas volumes, leakage, etc.

ARPCS Reference Data Sources and Formats

Reference modules for ARPCS module validation can be developed from routines described in Reference 69 and 70. The G189A (see Ref. 69) program was developed for JSC and provides a versatile analytical tool for support of environmental systems work. Reference 70 describes environmental analysis subroutine used for mission analysis and consumables studies.

Figure 4.7-107 is a flow chart for calculation of gas flow into or from a manifold or compartment from various source, as well as calculating the resulting pressure, temperature, etc. This routine is used in providing a reference module for cabin pressure control. (see Figure 4.7-108) and N₂ distribution/source (Figure 4.7-109). The O₂ distribution network module can be developed in a similar way. It should be noted that the proper system control logic must be integrated into these modules.

The system and component design performance requirements, analysis, performance predictions, and test results provide data for direct comparison with the Shuttle simulation results. Reference 31 will provide these types of data as they become available. The design requirements can be determined from Reference 71.

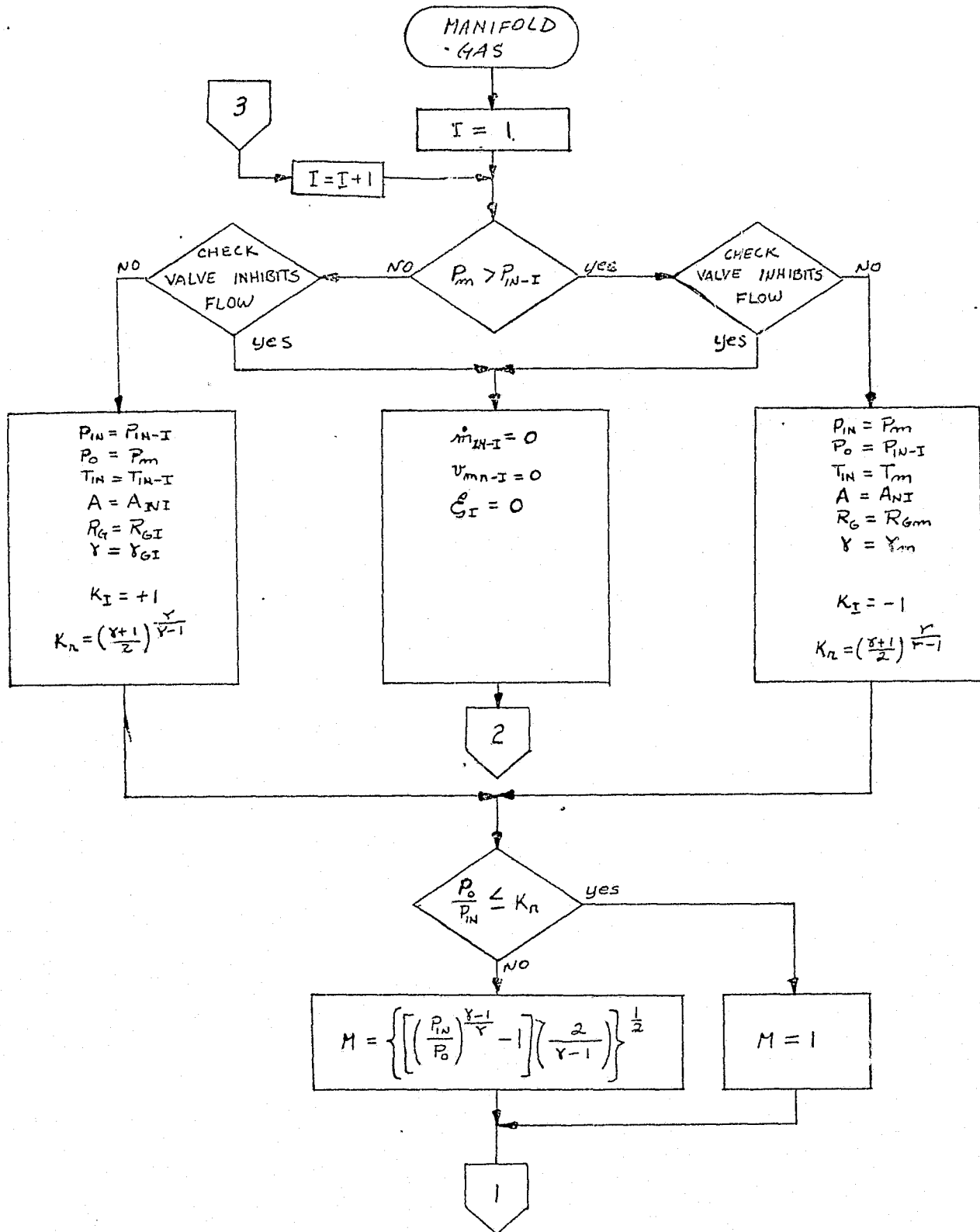


FIGURE 4.7-107, MANIFOLD GAS REFERENCE MODULE MATH FLOW

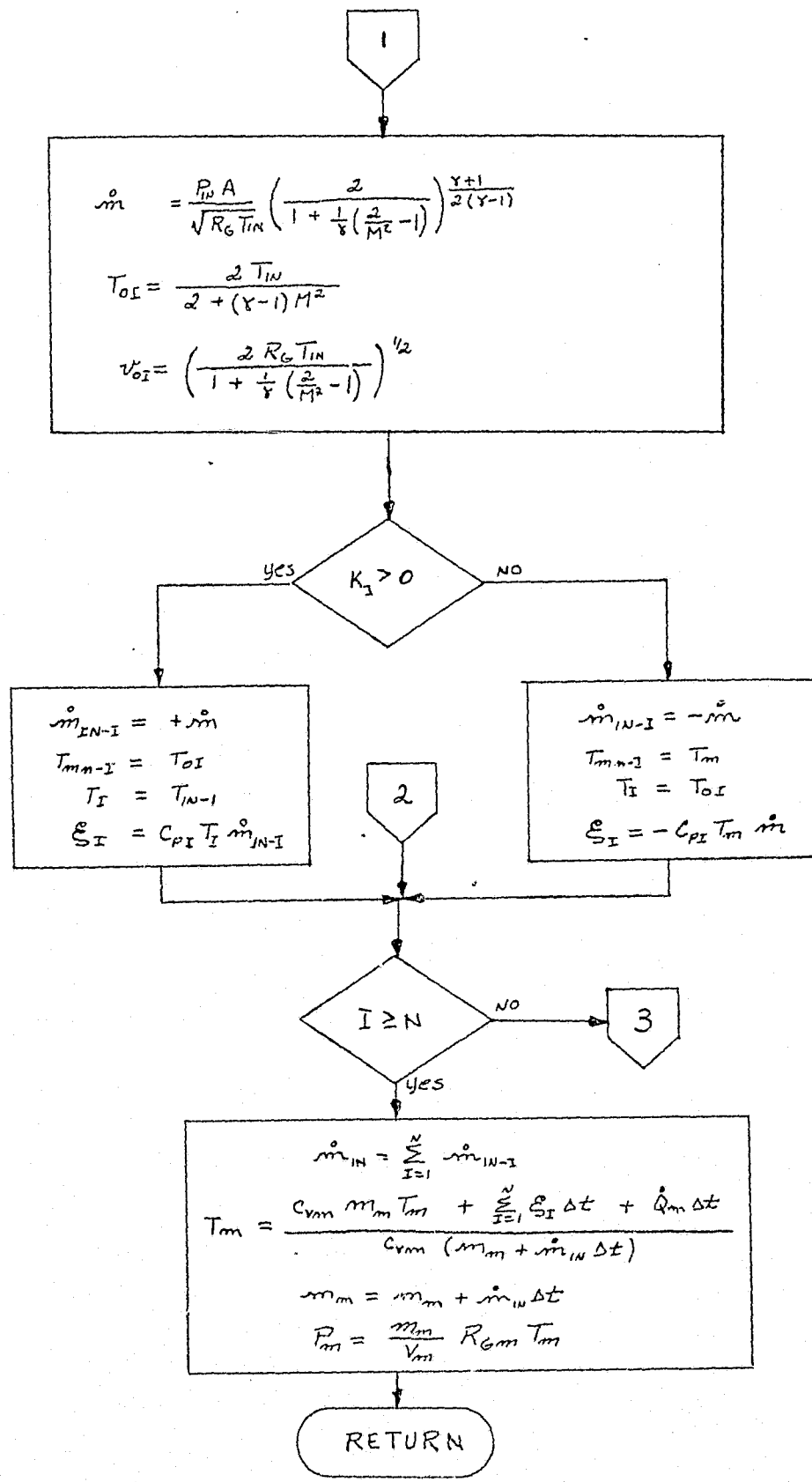


FIGURE 4.7-107. (CONTINUED)

LEGEND:

- P_m - Manifold pressure
 P_{IN-I} - Pressure of I^{th} load/source
 T_{IN-I} - Temperature of I^{th} load/source
 \dot{m}_{MN-I} - Flow rate from I^{th} load/source into manifold
 T_{MN-I} - Temperature into manifold from I^{th} tank
 T_I - Temperature delivered to I^{th} load/source
 v_{OI} - Fluid velocity from I^{th} tank into manifold
 T_m - Fluid temperature in manifold
 ρ_c - Fluid density
 m_m - Fluid mass in manifold
 c - Fluid specific heat
 Δt - Time increment
 A_{IN-I} - Flow area from I^{th} load/source into manifold
 K_c - Critical pressure ratio

FIGURE 4.7-107. (CONTINUED)

4.7-338

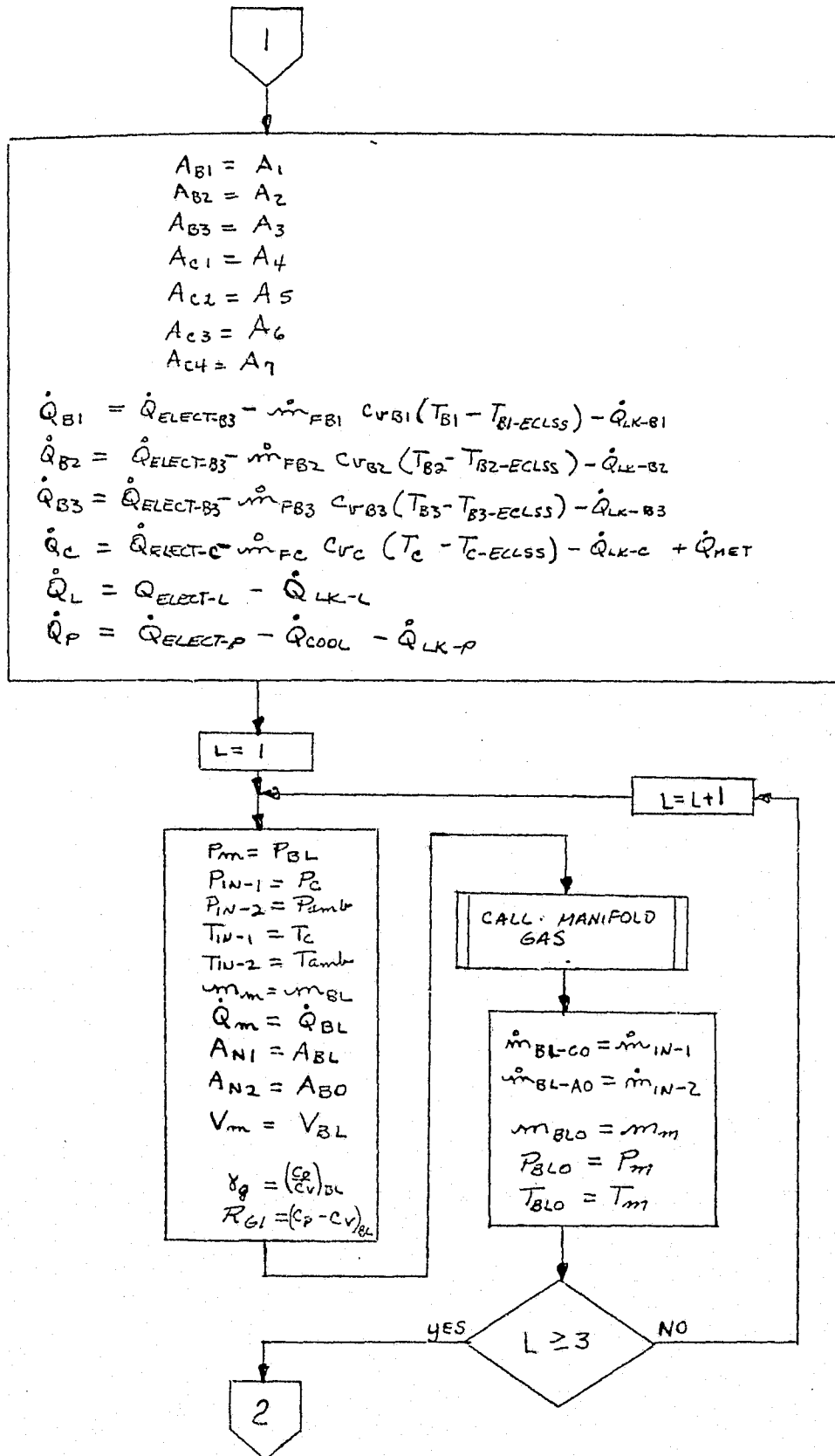


FIGURE 4.7-108. (CONTINUED).

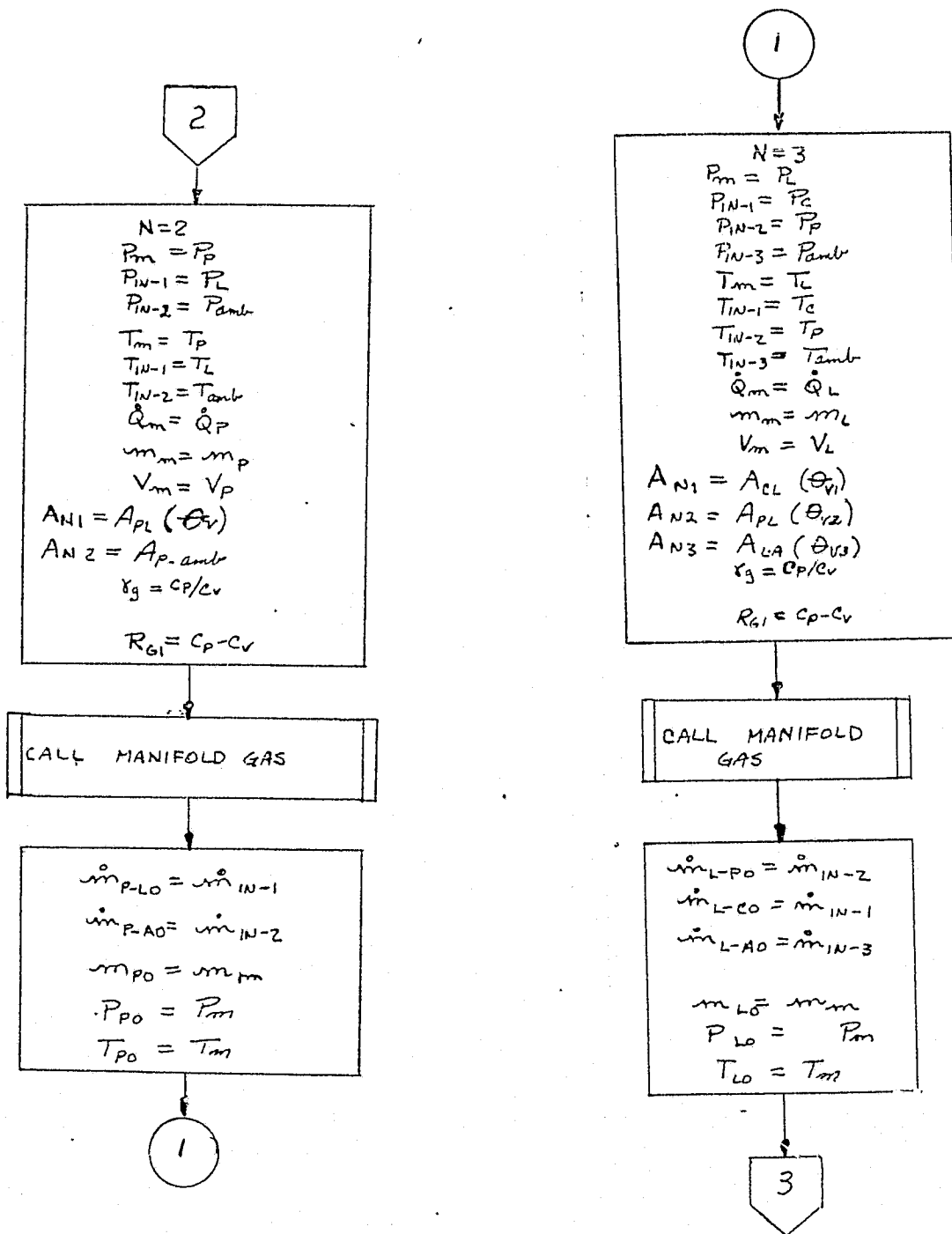
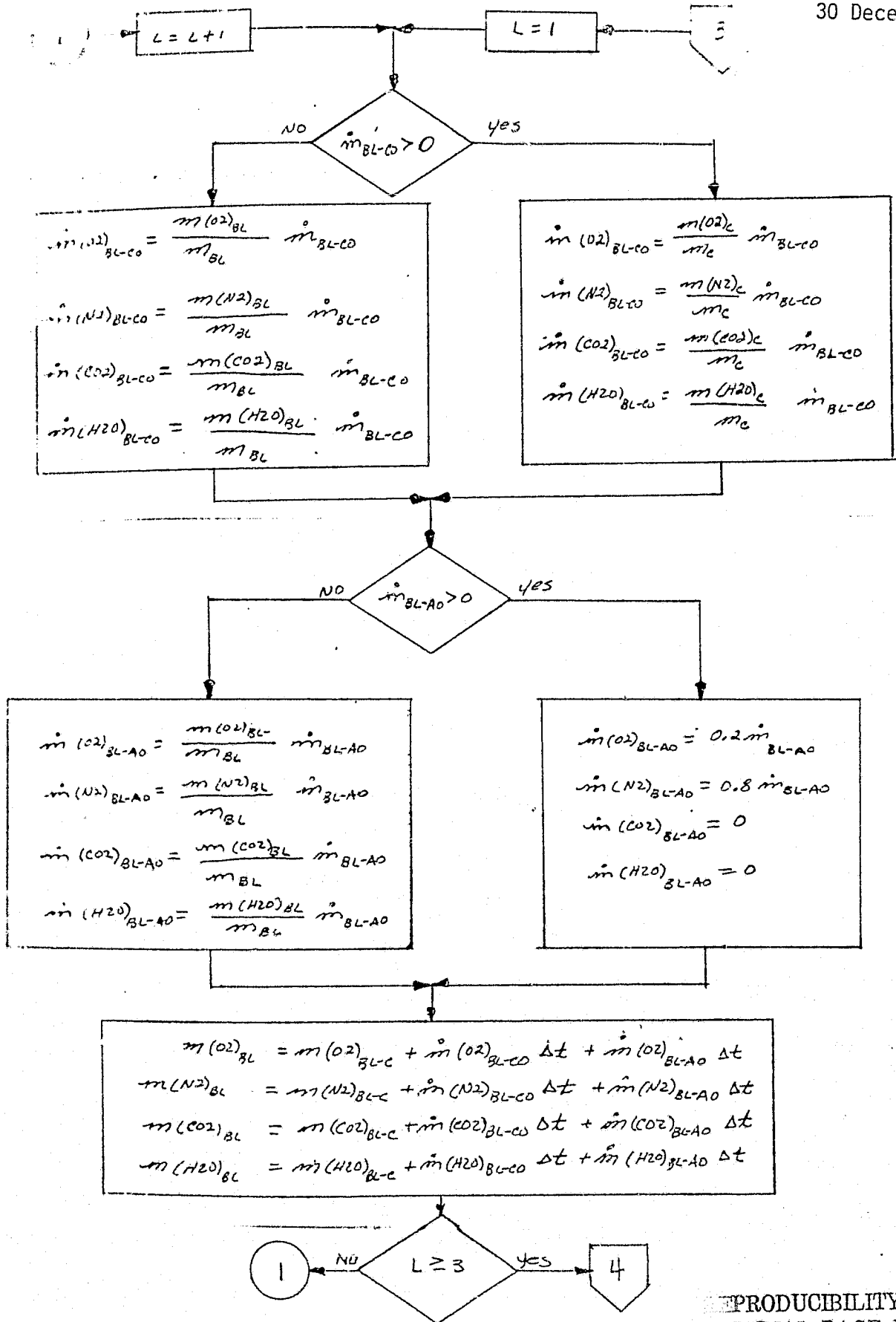


FIGURE 4.7-108. (CONTINUED)



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FIGURE 4.7-108. (CONTINUED)

4.7-342

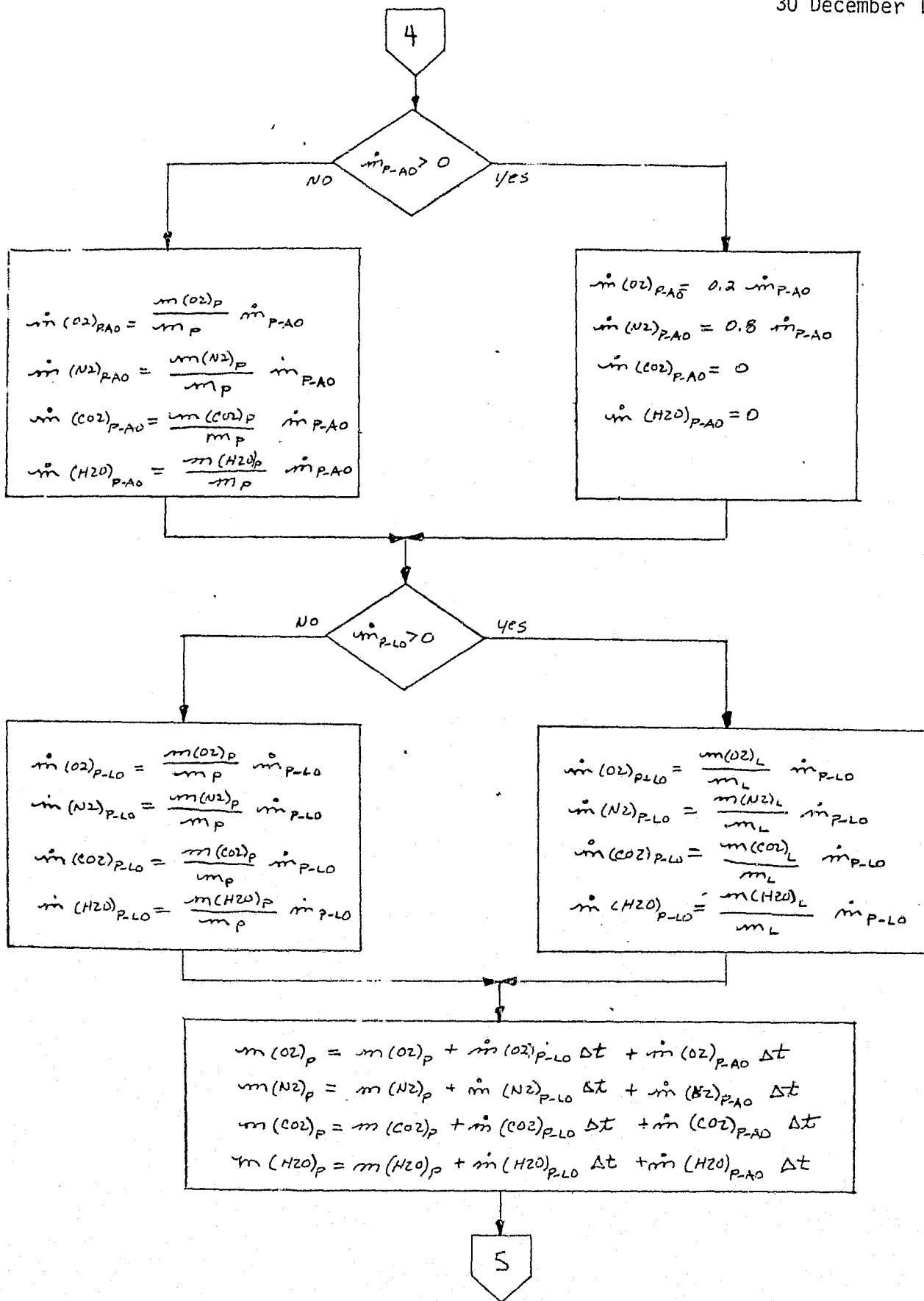


FIGURE 4.7-108. (CONTINUED)

4.7-343

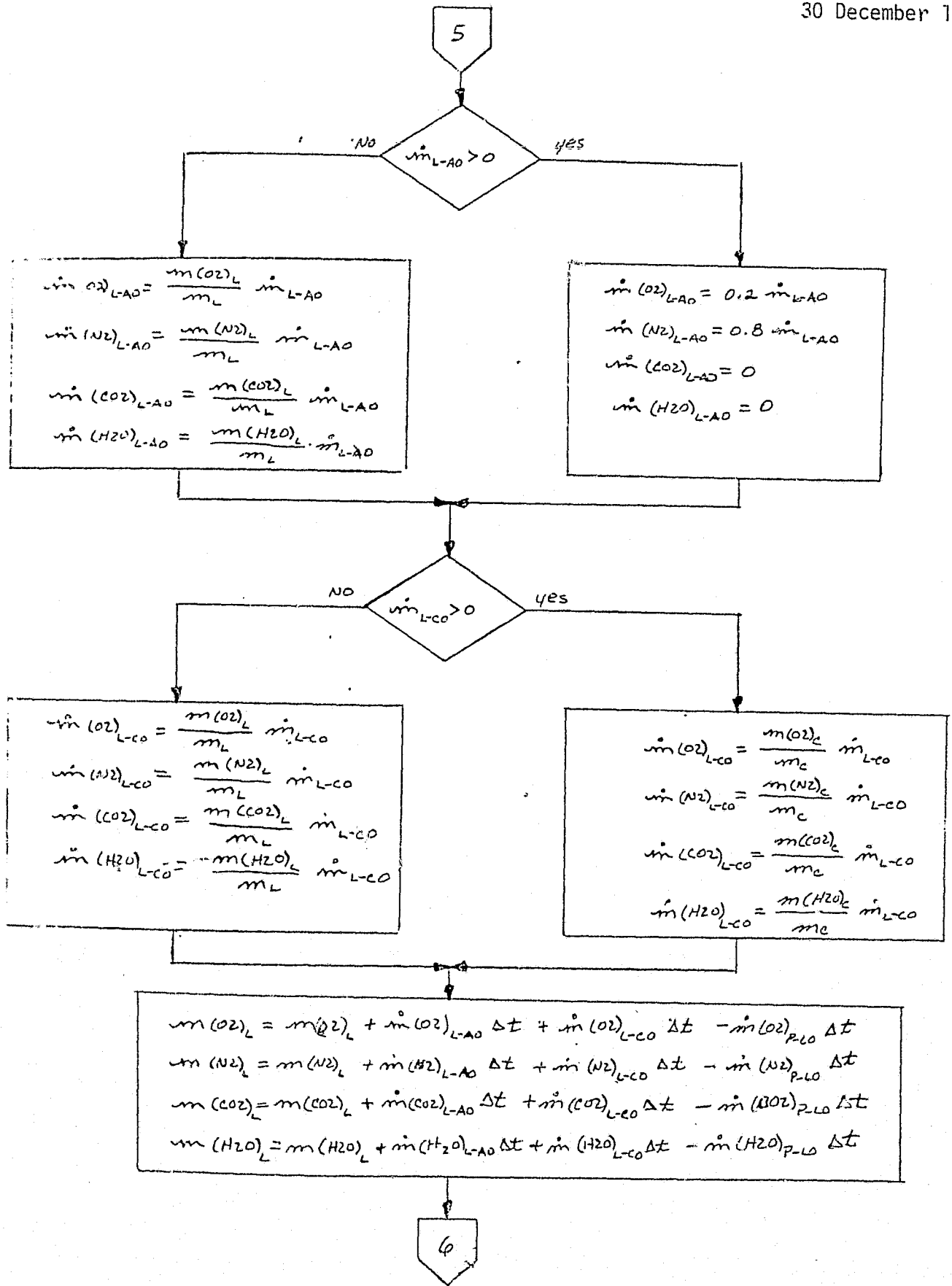


FIGURE 4.7-108. (CONTINUED)

4.7-344

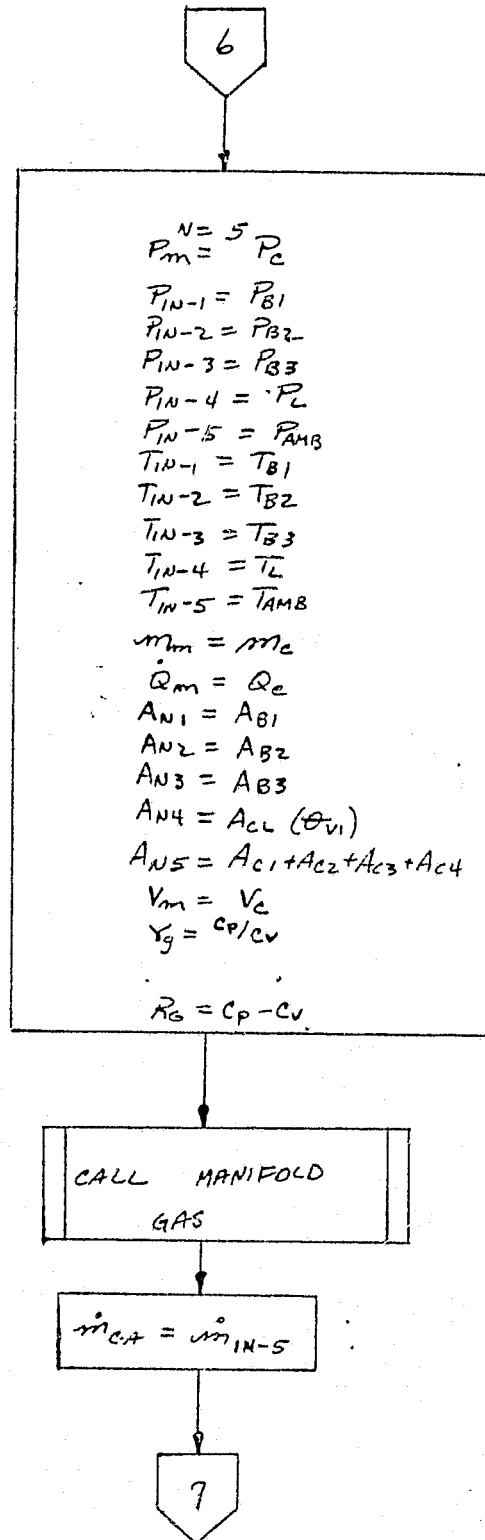


FIGURE 4.7-108. (CONTINUED)

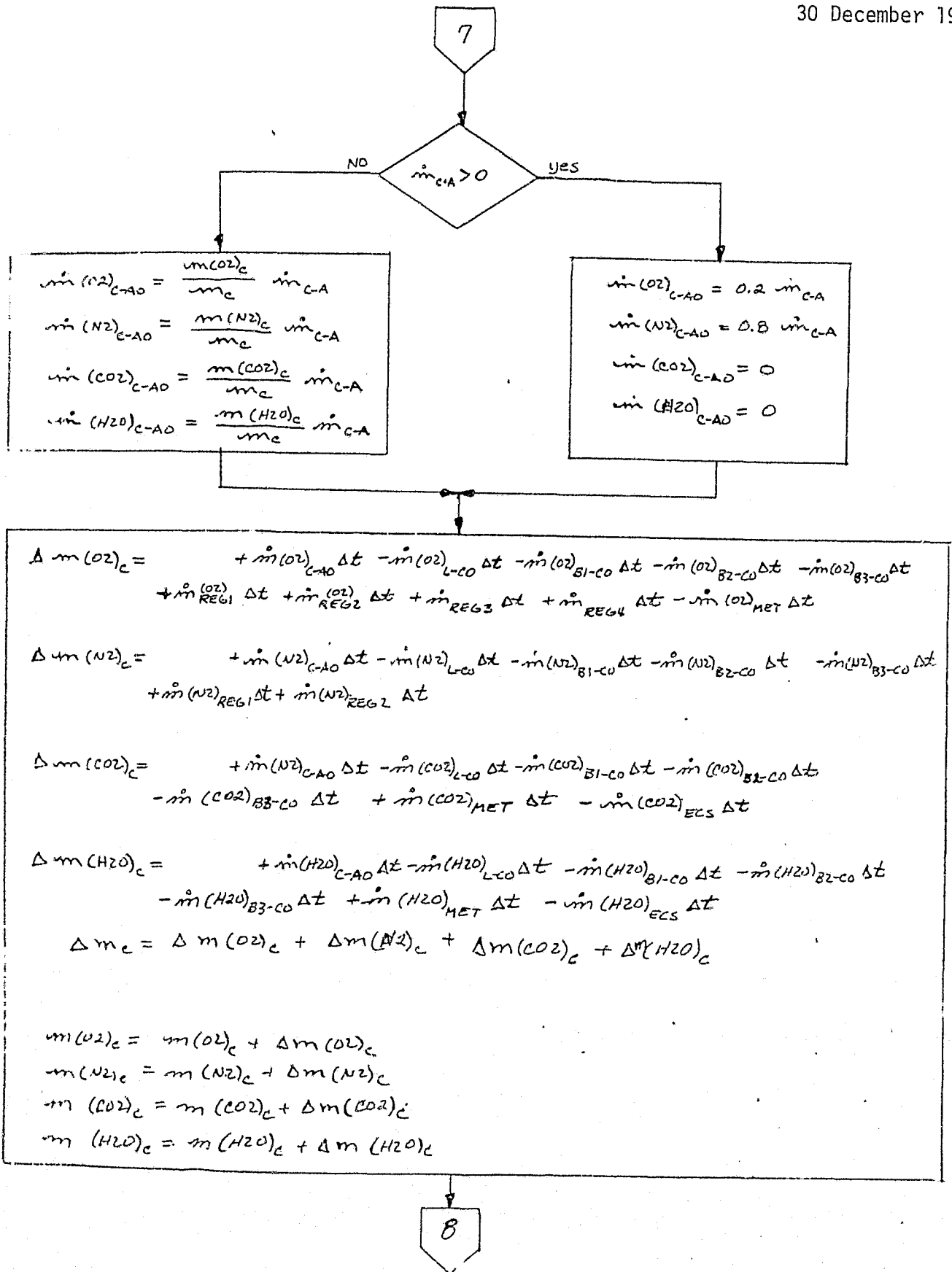


FIGURE 4.7-108. (CONTINUED)

4.7-346



$$\begin{aligned} & \left[\dot{m}_{CO_2} T_m + C_{P(CO_2)} \Delta T \left[\dot{m}_{REG1}^{(CO_2)} T_{REG1} + \dot{m}_{REG2}^{(CO_2)} T_{REG2} + \dot{m}_{REG3}^{(CO_2)} T_{REG3} + \dot{m}_{REG4}^{(CO_2)} T_{REG4} \right] \right. \\ & + C_{P(N_2)} \Delta T \left[\dot{m}_{REG1}^{(N_2)} T_{REG1} + \dot{m}_{REG2}^{(N_2)} T_{REG2} \right] + C_{V(CO_2)} \Delta T \dot{m}_{MET}^{(CO_2)} T_c \\ & \left. + C_{V(CO_2)} \Delta T \left[\dot{m}_{MET}^{(CO_2)} T_{MET} - \dot{m}_{ECS}^{(CO_2)} T_c \right] + C_{V(H_2O)} \Delta T \left[\dot{m}_{MET}^{(H_2O)} T_{MET} - \dot{m}_{ECS}^{(H_2O)} T_c \right] \right] \end{aligned}$$

$$(C_v)_c = \frac{m_{CO_2}_c C_{V(CO_2)} + m_{N_2}_c C_{V(N_2)} + m_{CO_2}_c C_{V(CO_2)} + m_{H_2O}_c C_{V(H_2O)}}{m_c + \Delta m_c}$$

$$(C_p)_c = \frac{m_{CO_2}_c C_{P(CO_2)} + m_{N_2}_c C_{P(N_2)} + m_{CO_2}_c C_{P(CO_2)} + m_{H_2O}_c C_{P(H_2O)}}{m_c + \Delta m_c}$$

$$R_c = (C_p)_c - (C_v)_c$$

$$T_c = \frac{\sigma}{(C_v)_c (m_c + \Delta m_c)}$$

$$m_c = m_c + \Delta m_c$$

$$P_c = \frac{m_c}{V_c} R_c T_c$$

$$m_{B1} = m_{B10}$$

$$m_{B2} = m_{B20}$$

$$m_{B3} = m_{B30}$$

$$m_L = m_{L0}$$

$$m_P = m_{P0}$$

$$T_{B1} = T_{B10}$$

$$T_{B2} = T_{B20}$$

$$T_{B3} = T_{B30}$$

$$T_L = T_{L0}$$

$$T_P = T_{P0}$$

$$P_{B1} = P_{B10}$$

$$P_{B2} = P_{B20}$$

$$P_{B3} = P_{B30}$$

$$P_L = P_{L0}$$

$$P_P = P_{P0}$$

RETURN

FIGURE 4.7-108. (CONTINUED)

5
C-5

LEGEND:

- P_C - Crew Compartment Pressure
- P_L - Lock Compartment Pressure
- P_P - Payload Compartment Pressure
- P_{B1} - Avionics Bay 1 Pressure
- P_{B2} - Avionics Bay 2 Pressure
- P_{B3} - Avionics Bay 3 Pressure
- P_{amb} - Ambient Pressure
- T_{amb} - Ambient Temperature
- $T_{(L)-ECLSS}$ - Compartment heat exchanger outlet temperature
- T_C - Crew Compartment Temperature
- T_L - Lock Compartment Temperature
- T_P - Payload Compartment Temperature
- T_{B1} - Avionics Bay 1 Temperature
- T_{B2} - Avionics Bay 2 Temperature
- T_{B3} - Avionics Bay 3 Temperature
- A_j - Effective flow area of relief valves, lines, etc., between compartments
- \dot{Q}_C - Heat gain rate of crew compartment
- \dot{Q}_L - Heat gain rate of lock compartment
- \dot{Q}_P - Heat gain rate of Payload compartment
- \dot{Q}_{B1} - Heat gain rate of Bay 1 compartment
- \dot{Q}_{B2} - Heat gain rate of Bay 2 compartment
- \dot{Q}_{B3} - Heat gain rate of Bay 3 compartment
- $\dot{Q}_{ELECT-(L)}$ - Electrical heat rate for compartment
- $\dot{Q}_{LK-(L)}$ - Heat leakage rate from compartment
- \dot{Q}_{MET} - Metabolic heat rate
- $V_{(L)}$ - Compartment volume
- C_P - Constant pressure specific heat of gas
- C_V - Constant volume specific heat of gas
- R_g - Gas Constant
- γ - Specific heat ratio of gas
- $\dot{m}_{(x)-y}$ - Gas flow rate into compartment (x) from compartment y
- $\dot{m}_{(O_2)_{x-y}}$ - O_2 gas flow rate into compartment x from compartment y.
- $\dot{m}_{(N_2)_{x-y}}$ - N_2 gas flow rate into compartment x from compartment y.
- $\dot{m}_{(CO_2)_{x-y}}$ - CO_2 gas flow rate into compartment x from compartment y.
- $\dot{m}_{(H_2O)_{x-y}}$ - H_2O gas flow rate into compartment x from compartment y.

FIGURE 4.7-108. (CONTINUED)

4.7-34B

$m(O_2)_x$ - X compartment O_2 gas quantity
 $m(N_2)_x$ - X compartment N_2 gas quantity
 $m(CO_2)_x$ - X compartment CO_2 gas quantity
 $m(H_2O)_x$ - X compartment H_2O gas quantity

FIGURE 4.7-108 (CONTINUED)

4.7-349

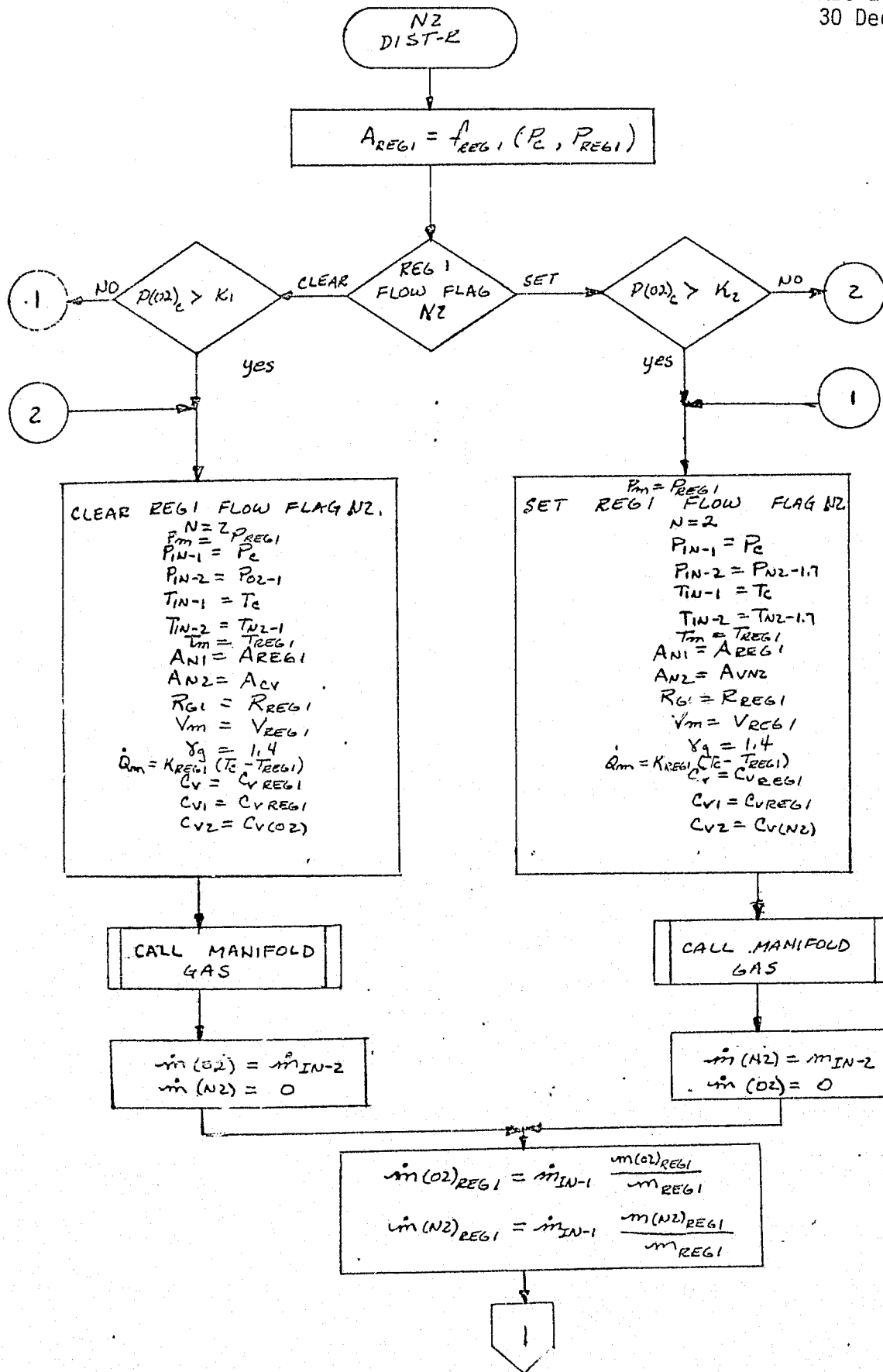


FIGURE 4.7-109. N₂ SOURCE/DISTRIBUTION NETWORK REFERENCE MODULE MATH FLOW

4.7-350

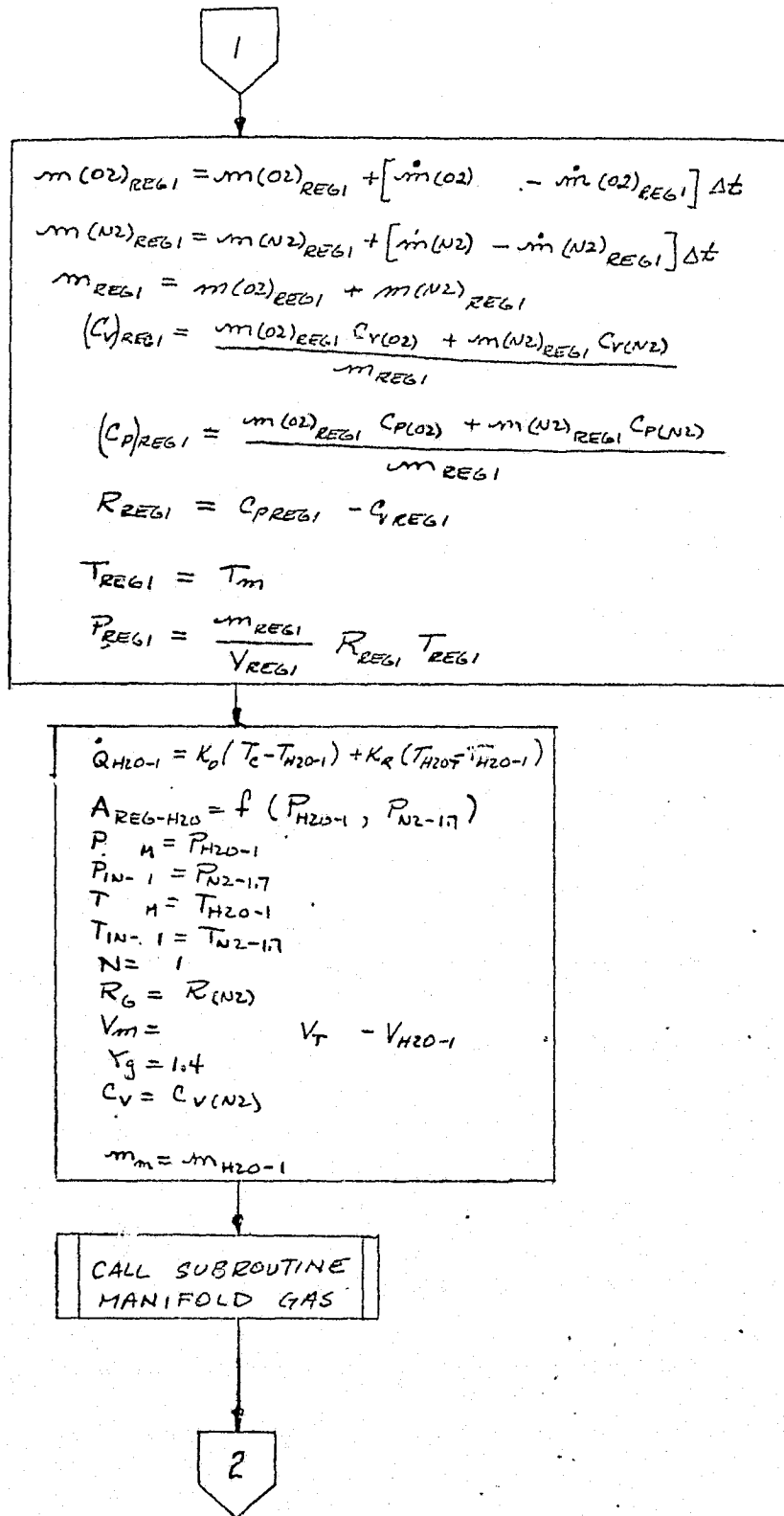


FIGURE 4.7-109. (CONTINUED)

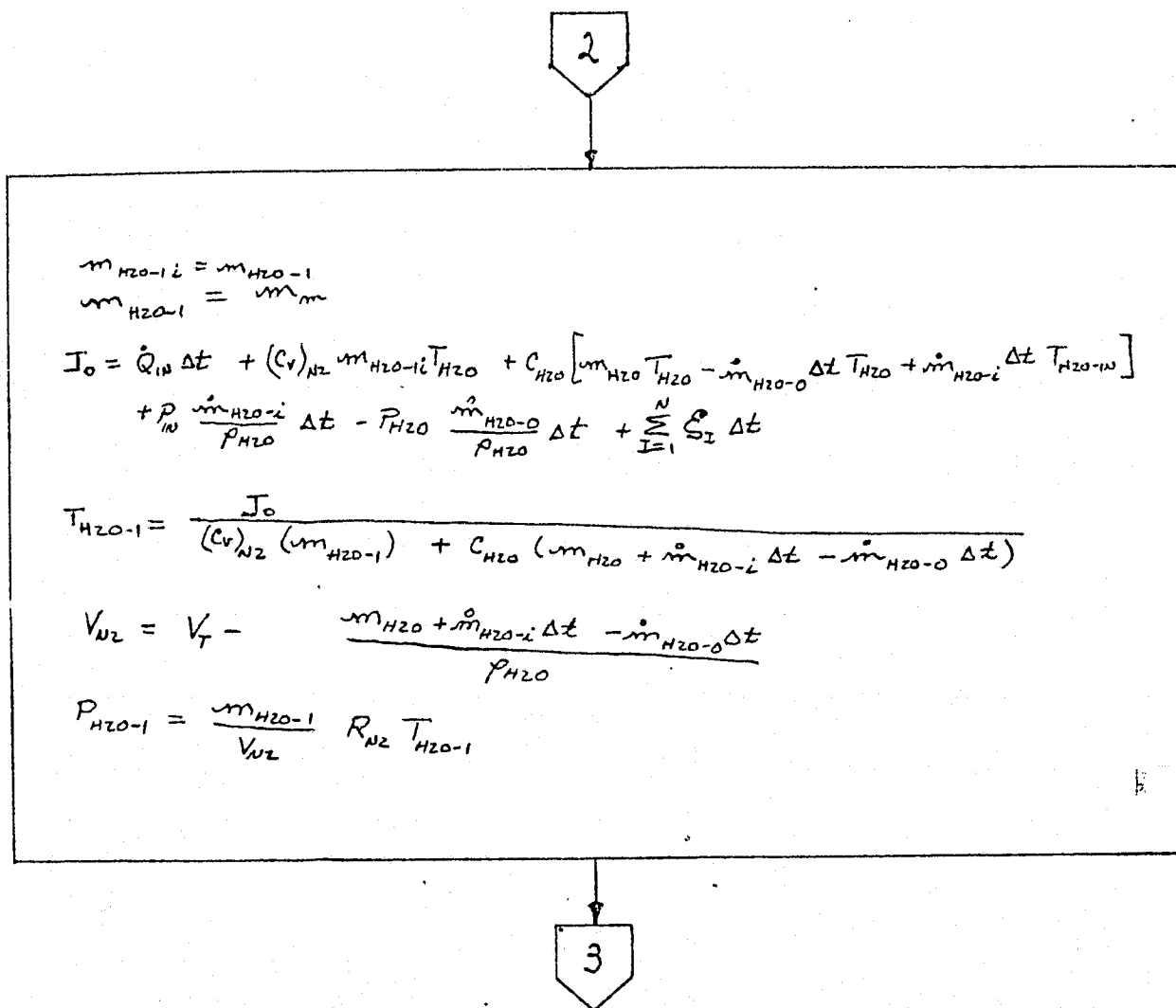
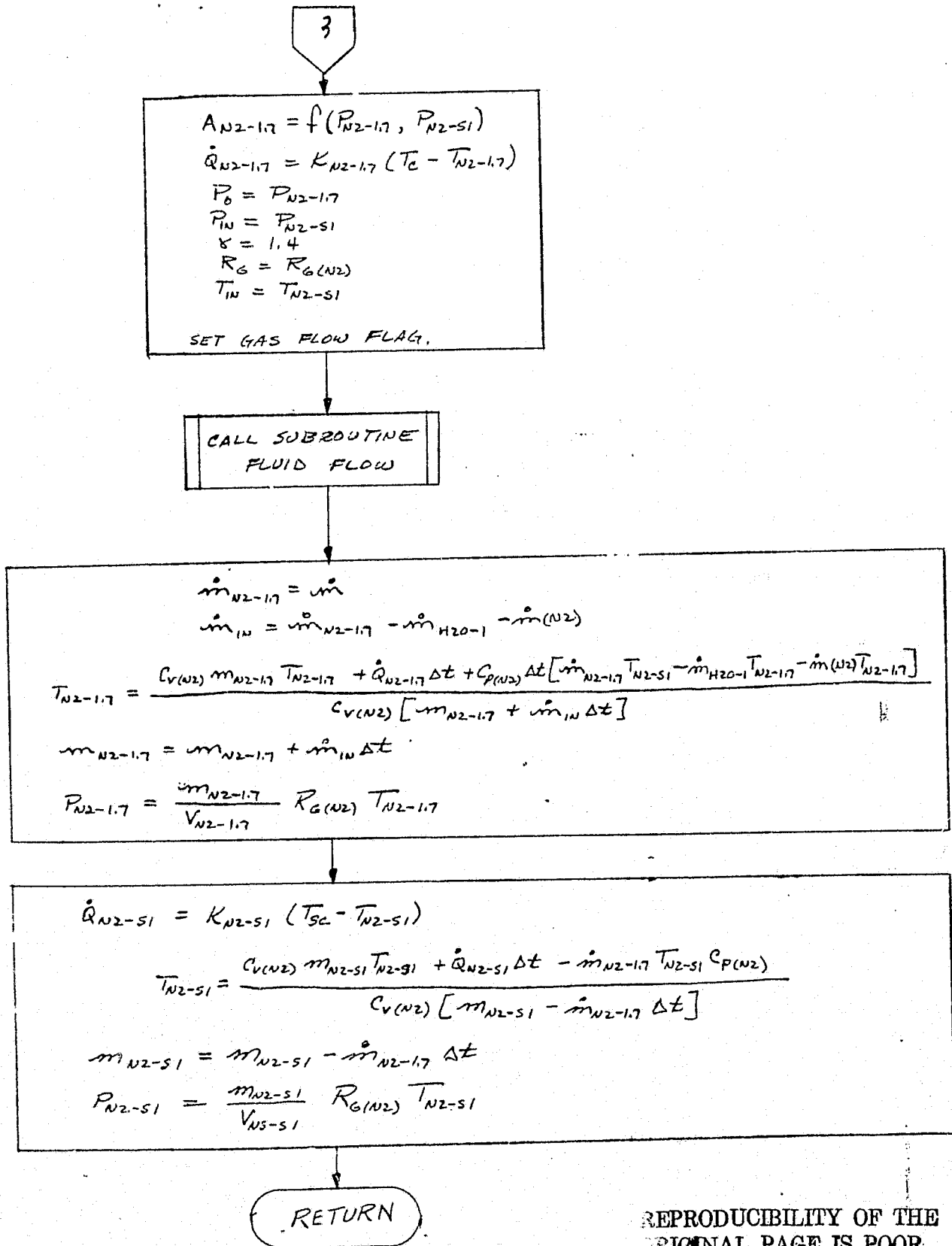


FIGURE 4.7-109. (CONTINUED)



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FIGURE 4.7-109 (CONTINUED)

4.7-353

LEGEND:

- P_{REG1} - Cabin Pressure Regulator inlet pressure
 P_c - Cabin Pressure (Crew Compartment)
 P_{O_2-1} - O_2 Regulator (100 psi) outlet pressure
 $P_{N_2-1.7}$ - N_2 170 psi Regulator outlet pressure
 P_{H_2O-1} - H_2O tank regulated pressure
 P_{N_2-51} - N_2 170 psi Regulator inlet pressure

 T_c - Cabin temperature
 T_{REG1} - Cabin pressure regulator inlet temperature
 $T_{N_2-1.7}$ - N_2 170 psi pressure regulator inlet temperature
 T_{H_2O-1} - H_2O tank gas temperature
 T_{N_2-51} - N_2 170 psi regulator inlet temperature
 V_{REG-1} - Cabin pressure regulator inlet manifold volume
 V_{H_2O-1} - Volume of H_2O in H_2O tank
 V_T - Volume of H_2O tank
 V_{N_2-51} - Volume of manifold inlet to N_2 pressure regulator
 $V_{N_2-1.7}$ - N_2 170 psi regulator outlet volume
 A_{REG1} - Effective flow area of cabin pressure regulator
 A_{REG-H_2O} - Effective flow area of H_2O tank pressure regulator
 C_p - Specific heat at constant pressure
 C_v - Specific heat at constant volume
 C_{H_2O} - Specific heat of liquid water

 $\dot{m}(O_2)$ - O_2 flow rate into cabin
 $\dot{m}(N_2)$ - N_2 flow rate into cabin
 $\dot{m}_{N_2-1.7}$ - Flow rate of N_2 170 psi regulator
 \dot{m}_{H_2O-i} - H_2O flow rate into H_2O tank
 \dot{m}_{H_2O-o} - H_2O flow rate out of H_2O tank
 N_2 quantity in H_2O tank

 $m(O_2)_{REG1}$ - Cabin pressure regulator inlet line O_2 mass quantity
 $m(N_2)_{REG1}$ - Cabin pressure regulator inlet line N_2 mass quantity
 m_{H_2O-1} - H_2O tank gas quantity
 m_{N_2-51} - N_2 170 psi regulator inlet quantity

FIGURE 4.7-109 (CONTINUED)

4.7-354

γ -Specific heat ratio (CP/CV)
 R_g - Gas constant

FIGURE 4.7-109 (CONTINUED)

4.7-355

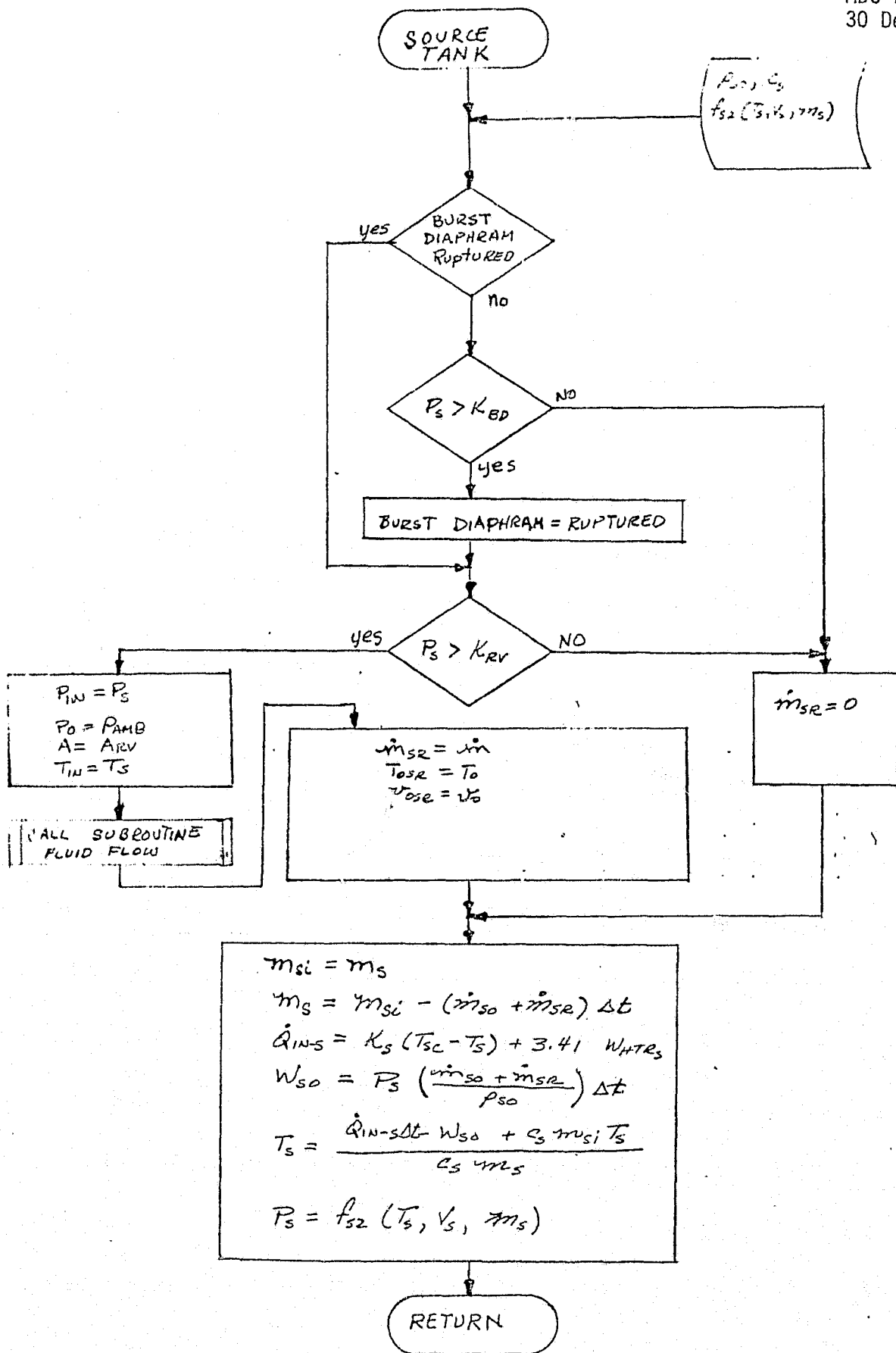


FIGURE 4.7-110 N₂ SOURCE FLOW CHART

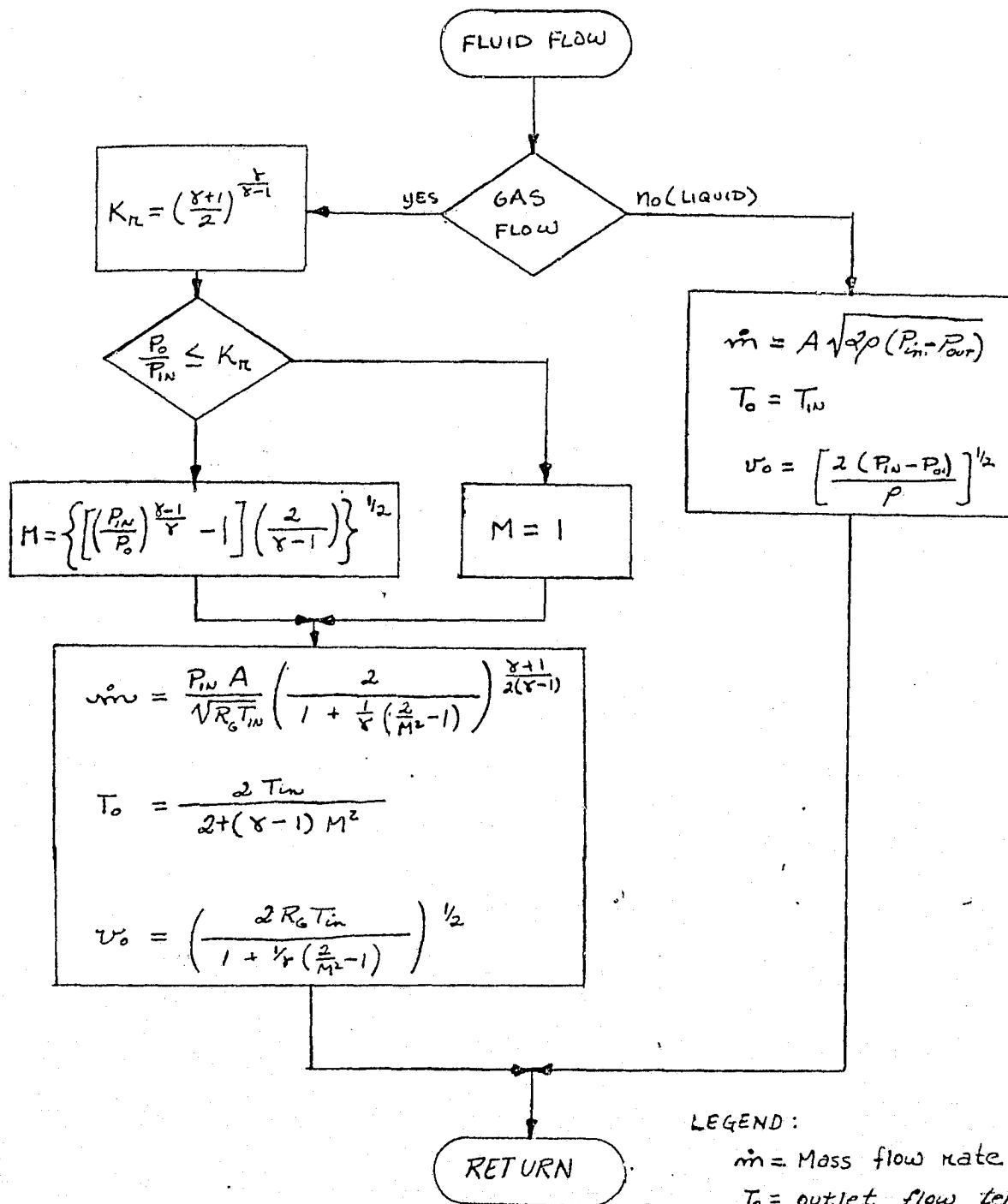
4.7-356

LEGEND:

- P_S - Tank pressure
- P_{amb} - Ambient pressure
- A_{rel} - Effective flow area of relief line/valve
- T_S - Temperature of tank
- T_{sc} - Tank compartment temperature
- \dot{m}_{SR} - Flow rate through relief line
- \dot{m}_{SD} - Flow rate to distribution system
- m_S - Quantity of gas in source tank
- ρ_{SO} - Gas density in tank
- W_{HTS} - Tank electrical heater power
- \dot{Q}_{IN-S} - Heat leak into tank
- C_S - Gas specific heat
- V_S - Tank volume

FIGURE 4.7-110. (CONTINUED)

4.7-357



LEGEND:

- \dot{m} = Mass flow rate.
- T_0 = outlet flow temperature
- P_0 = outlet Pressure
- T_{IN} = inlet Temperature
- P_{IN} = inlet Pressure
- R_G = Gas constant
- γ = Specific heat ratio
- A = effective flow Area.
- ρ = density

K_{cr} = critical Pressure Ratio
 M = Mach number

FIGURE 4.7-111. FLUID FLOW SUBROUTINE FLOW CHART

4.7.1.5 Validation Methods and Check Cases

The verification approach for the ARPCS simulation module utilizes and expands upon the technique presented in Section 5.1. The use of this flow chart allows the comparison of the simulation module with various types of checkcases (test, analysis, software model, etc.). Figure 4.7-112 presents the flowchart for checkpoint generation subroutine in Figure 5.1-1. Figure 4.7-113 is the sub-subroutine shown in Figure 4.7-112 as "COMBCHK" and generates the "all checkpoints sequenced flag".

Some liberty was taken in the notation for variables in these flow charts. With the exceptions of time (t), initialization time (t₀), computation time (Δt), and COMBCHK variables, the variables used represent a group or "set" of parameters rather than a single variable. Each parameter set is associated with a particular driver, function or logic. For example, the variable PAOS (JAOS) represents a set of parameters including pressure, O₂ quantity, etc. associated with the auxiliary O₂ supply. The identification of the actual parameters is dependent on exact system design and simulation fidelity desired.

This verification technique provides the following capabilities:

- Initialization of parameters
- Interfacing module drivers
- ARPCS functional element drivers
- Time-dependent evaluations
- Multiple evaluations in a single run.

Initialization - At the start of each checkcase the ARPCS module and driver parameters, logic, and conditions are set to pre-determined values. The values may change as the checkcase is allowed to continue.

External Module Drivers - The parameters normally provided by interfacing modules are provided by module drivers. These drivers supply parameter values which can be held constant or allowed to vary according to calculations performed within the driver. The following module drivers were identified:

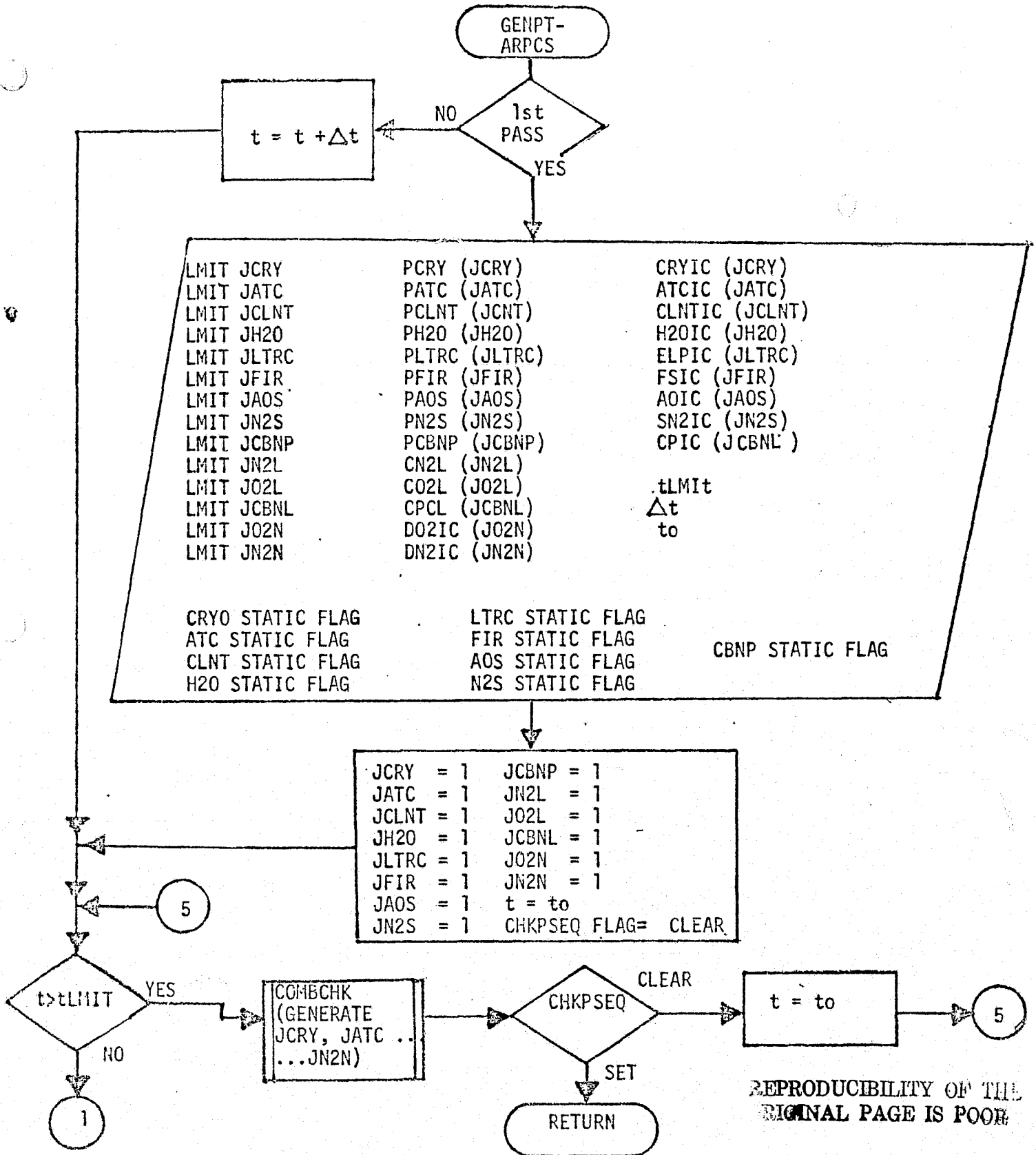


FIGURE 4.7-112. CHECK POINT DRIVER, ATMOSPHERE REVITALIZATION PRESSURE CONTROL SUBSYSTEM (ARPCS) FLOWCHART

4.7-360

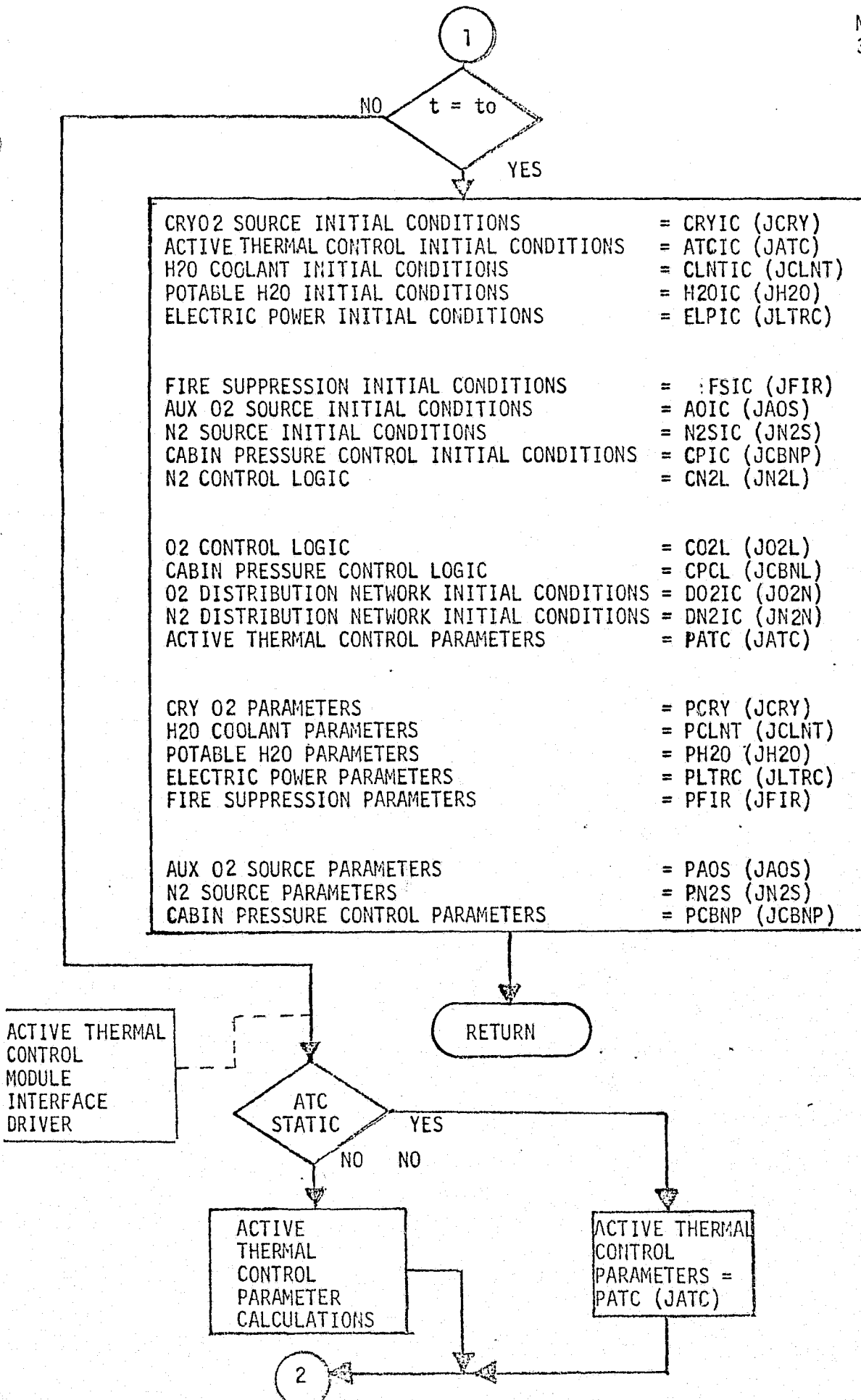


FIGURE 4.7-112(CONTINUED)

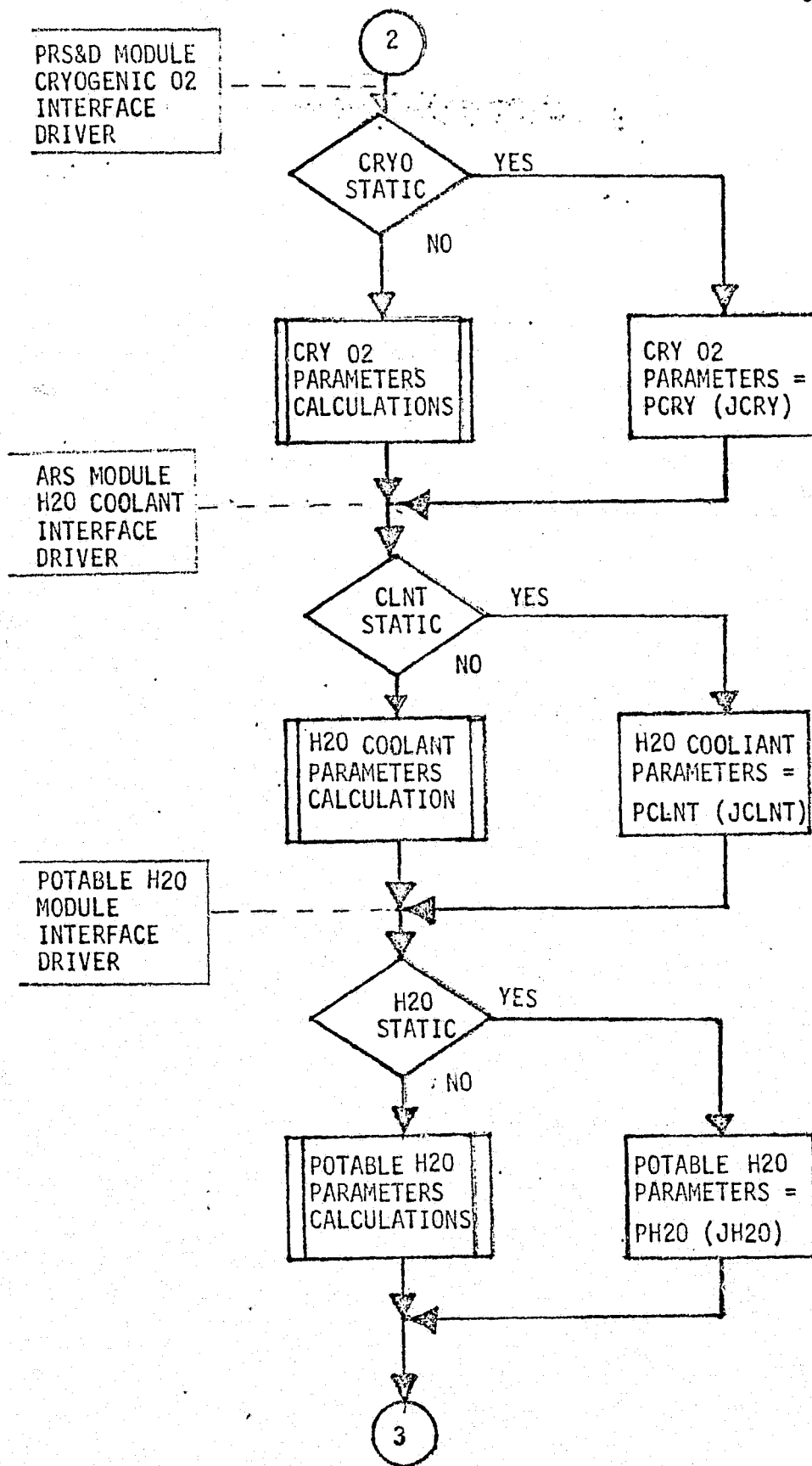


FIGURE 4.7-112 (continued)

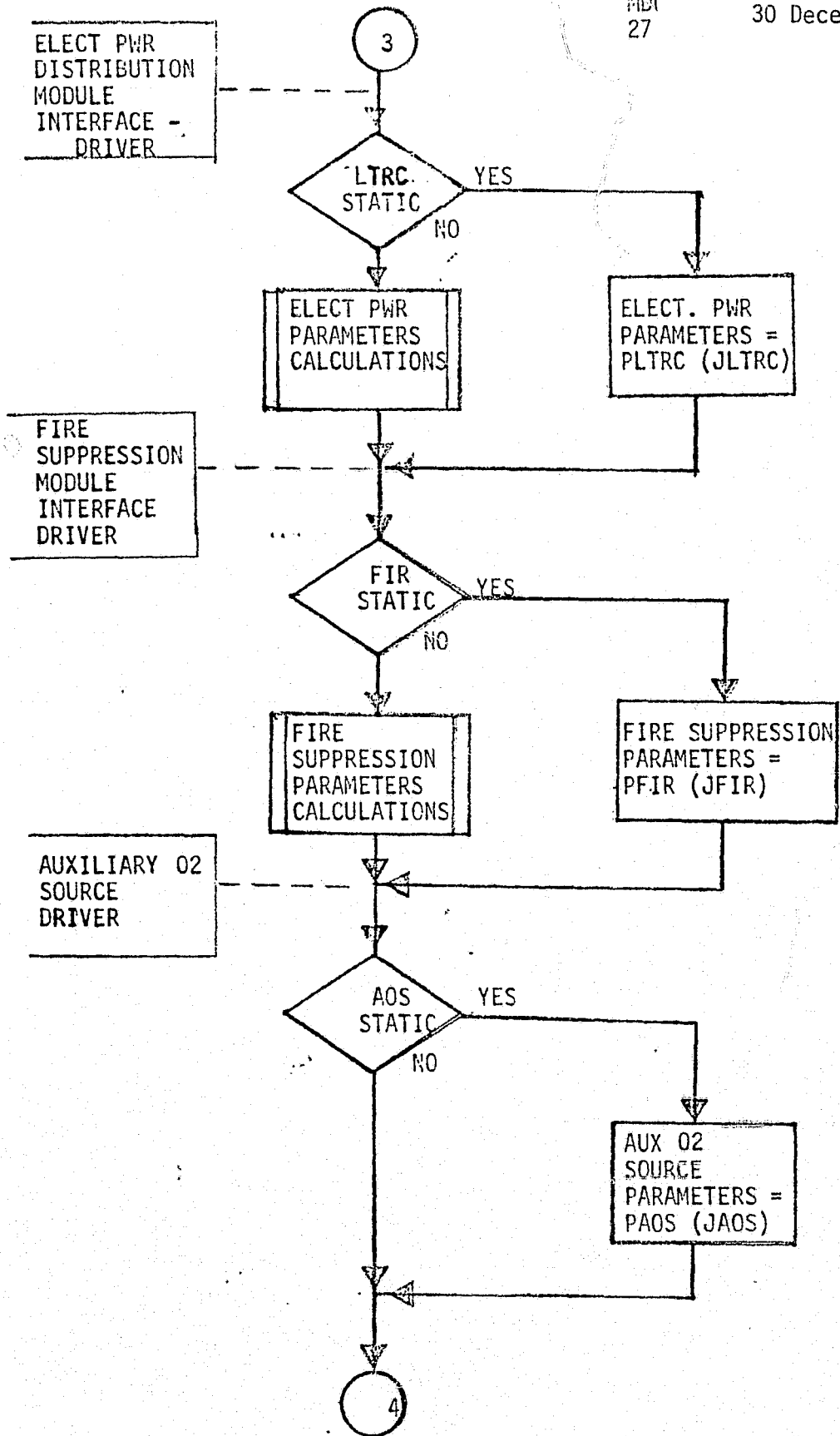


FIGURE 4.7-112 (CONTINUED)

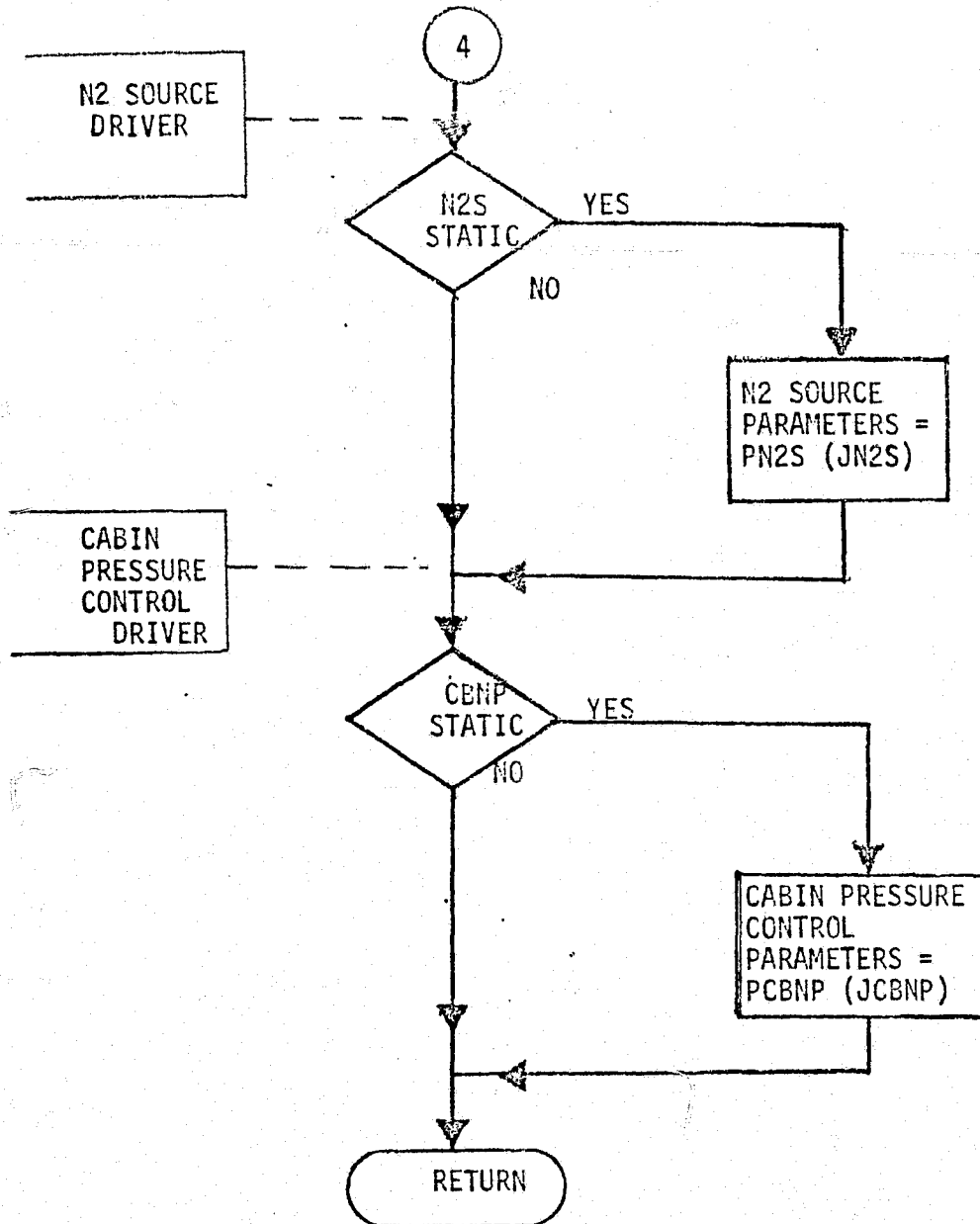


FIGURE 4.7-112 (CONTINUED)

LEGEND:

t_0	=	Universal time at initialization
Δt	=	Computation time
tCMIT	=	Limit on time
CMIT	=	Limit
CRY	=	Cryogenic element
ATC	=	Active Thermal Control Element
CLNT	=	Coolant element
H ₂ O	=	H ₂ O element
LTRC	=	Electric element
FIR	=	Fire Suppression element
AOS	=	Auxilliary O ₂ element
N ₂ S	=	N ₂ source element
CBNP	=	Cabin Pressure element
N ₂ L	=	N ₂ logic element
O ₂ L	=	O ₂ logic element
CBNL	=	Cabin Logic element
O ₂ N	=	O ₂ network element
N ₂ N	=	N ₂ network element
J ___	=	Indexing variable for indicated parameters
___IC	=	Indicated parameter initial conditions
P ___	=	Parameters for indicated element

FIGURE 4.7-112 (COMPLETE)

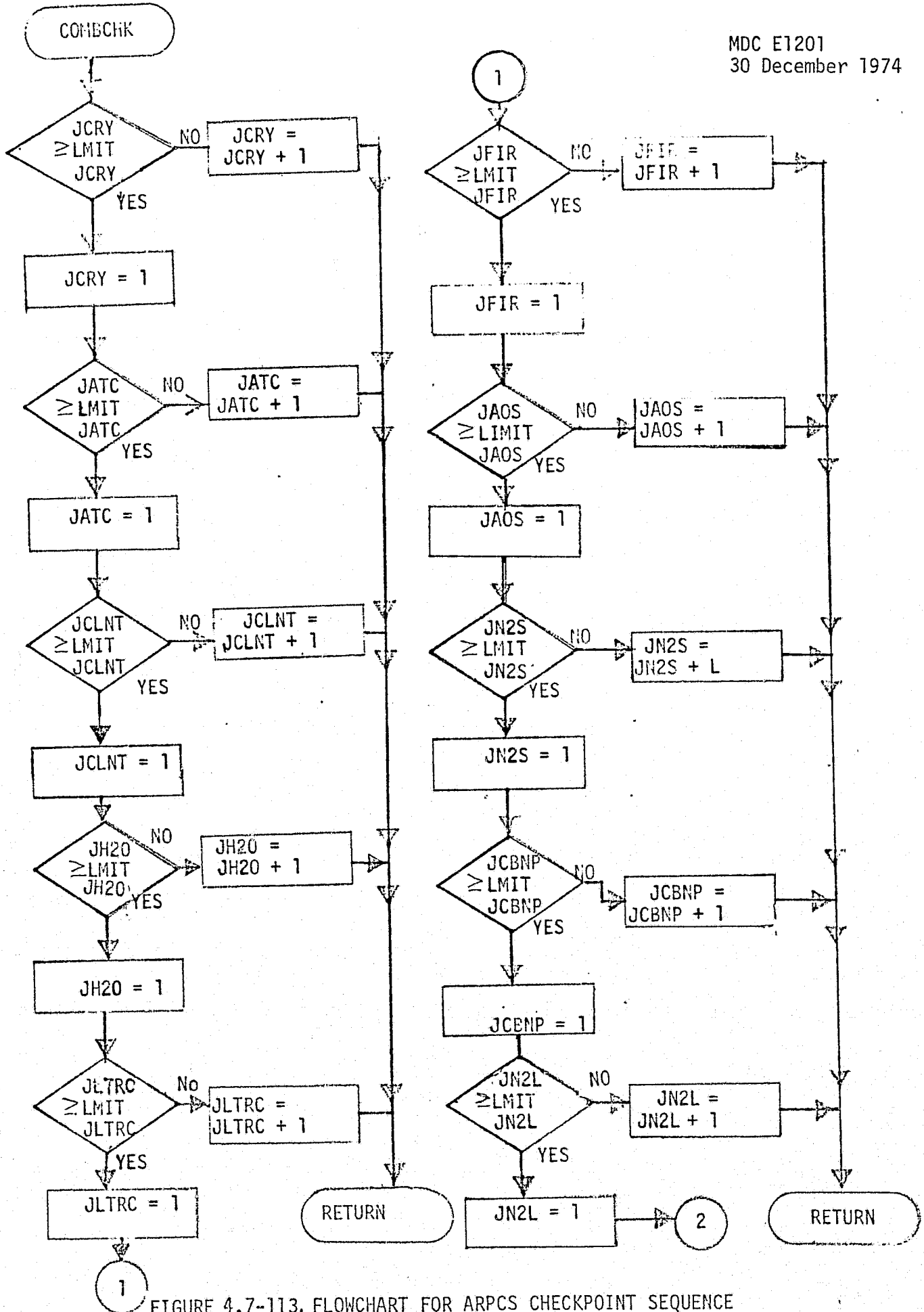
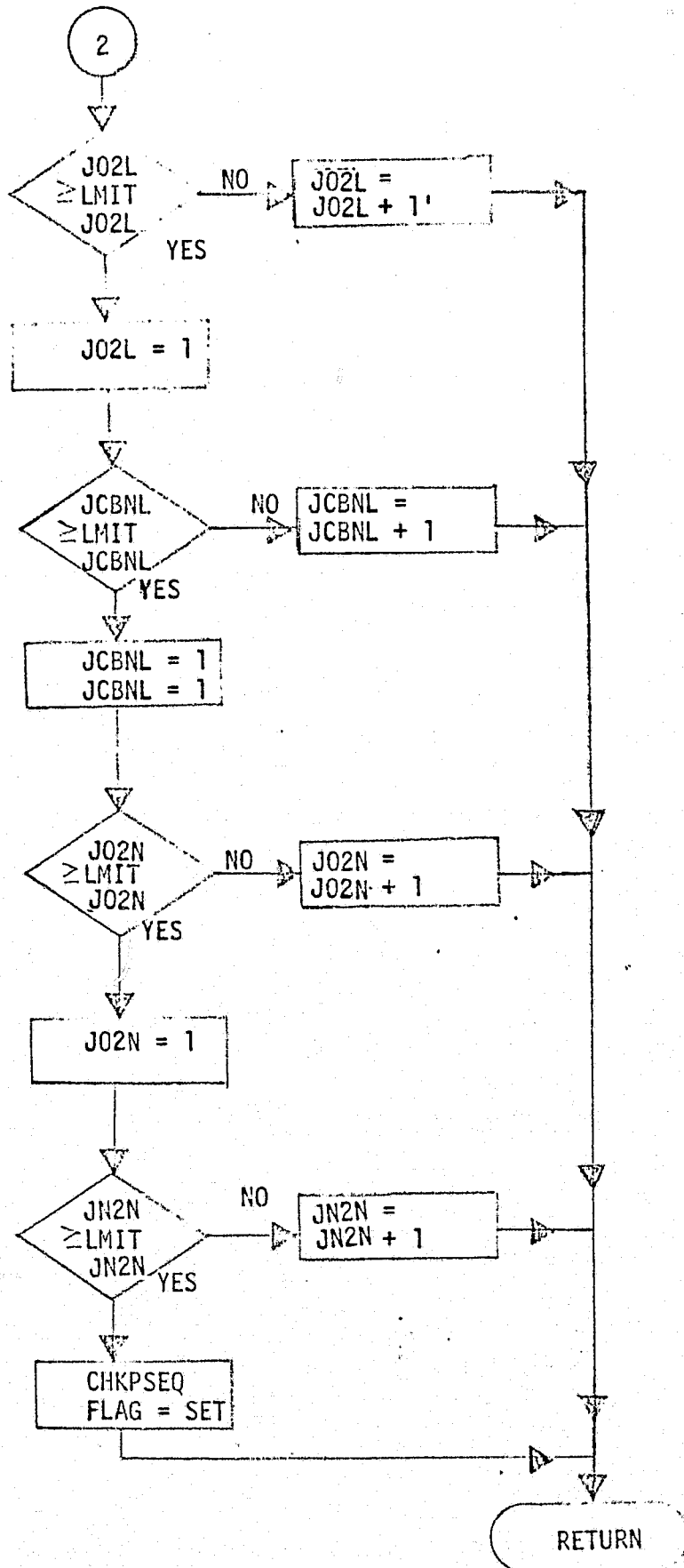


FIGURE 4.7-113. FLOWCHART FOR ARPCS CHECKPOINT SEQUENCE



LEGEND:
(See Figure 4.7-112.)

FIGURE 4.7-113 (CONTINUED)

- PRSD Cryogenic O₂ supply - provides O₂ supply pressure temperature, quantity, etc.
- Active Thermal Control - provided cryogenic O₂ feed temperature, etc.
- ARS-H₂O Coolant - provides cabin temperature, CO₂ quantity, humidity, etc.
- Potable H₂O Management - provides quantity H₂O remaining (each tank), temperature, etc. for N₂ pressure quantity, etc. calculations.
- Electrical Power Distribution - provides bus voltages for logic, etc.
- Fire Suppression - provides freon quantity release rate into cabin for cabin pressure calculations, etc.

Functional Element Drivers - Certain intramodule parameters provide logic changes, etc. which require thorough verification. Drivers are included to provide ease in this verification. Those drivers identified were:

- Auxiliary O₂ source - parameters include tank pressure, quantity, etc.
- N₂ source - parameters include tank pressures, quantities, etc.
- Cabin pressure control - parameters include cabin total pressure, pressure decay rate, O₂ partial pressure, etc.

Multiple Evaluations - The sub-subroutine "COMBCHK" (Figure 4.7-113) generates the values of indexing variables controlling the checkcase conditions and determines when all check points have been sequenced (CHKPSEQ). Since the number of checkcases performed during a single run is the product of the number of parameter sets (LMIT JCRY, etc.), care must be taken to prevent a large number of unnecessary checkcases being performed. Effort must be made to complete the module verification with a minimum number of checkcases. This may be best accomplished by restricting certain parameter sets to nominal values, while cycling through the more significant parameter sets. The run could then be repeated for different parameter sets.

ARPCS Data Base Impact

The major impact to the ARPCS data base is the impact of the reference module (Figures 4.7-107, 4.7-108, and 4.7-109) and the functional element/module drivers of Figure 4.7-112. Most processing subroutines (data input/output routines) would be common to all modules being validated. Data files are required for storage of the output data tables. The use of analysis/test/design requirements as reference data requires the use of special drivers. These drivers establish and maintain the conditions within and interfacing with the module which correspond to the analysis/test/design conditions. The plotting or formatting of the simulation results would require a few utility subroutines of small data base impact.

4.7.6.1.2 ARS-CACS Subsystem Description

The ARS Cabin Atmosphere Control Subsystem provides the circulation of the atmosphere, temperature and humidity control, and CO₂ and odor control. Figure 4.7-114 provides a simple schematic of the interfaces with other ECLSS modules.

Atmosphere Circulation - This subsystem provides atmosphere circulation for the crew quarters, and avionics bays. A simple schematic of the crew quarters circulation is shown in Figure 4.7-115 and the avionics bay schematic is shown in Figure 4.7-116.

Temperature Control - This element provides cooling and heating of the cabin atmosphere. Thermal transport is accomplished by means of two water loops, as shown in Figure 4.7-116. The primary and secondary loops are identical, except that the secondary loop has one water pump vice two as in the primary loop.

Heat rejection from the water loops to the ATCS is accomplished at the cabin interchanger through which both water loops and both ATCS freon loops flow. Two water sublimators receiving water from the potable water system provide an active heat sink during launch and orbital periods when the payload bay doors, housing the space radiator system on the underside, are closed. The sublimators are active during entry to an altitude of 100K feet. Between 100K feet and 20K feet there is no active heat rejection from the Orbiter, and temperatures are governed by the bulk thermal capacitance of the vehicle. Below 20K feet through landing, ammonia evaporators in the ATCS are activated for heat rejection.

Figure 4.7-115 from Reference 12 shows the Orbiter cabin atmosphere thermal and purification system. Three fans circulate cabin air through an aerosol filter, through lithium hydroxide canisters for CO₂ removal, then on through a condensing (cooling) heat exchanger for temperature and humidity control. Condensate is removed to the waste management system. The condensing heat exchanger is part of the water coolant loop system shown as the "cabin HX" in Figure 4.7-114. The cabin temperature is maintained by controlling the airflow through the cabin heat exchanger by means of a controller regulating bypass flow around the heat exchanger. The controller is regulated by a temperature selector. If cabin heat input is required the controller activates electric heaters in the bypass loop.

4.7-371

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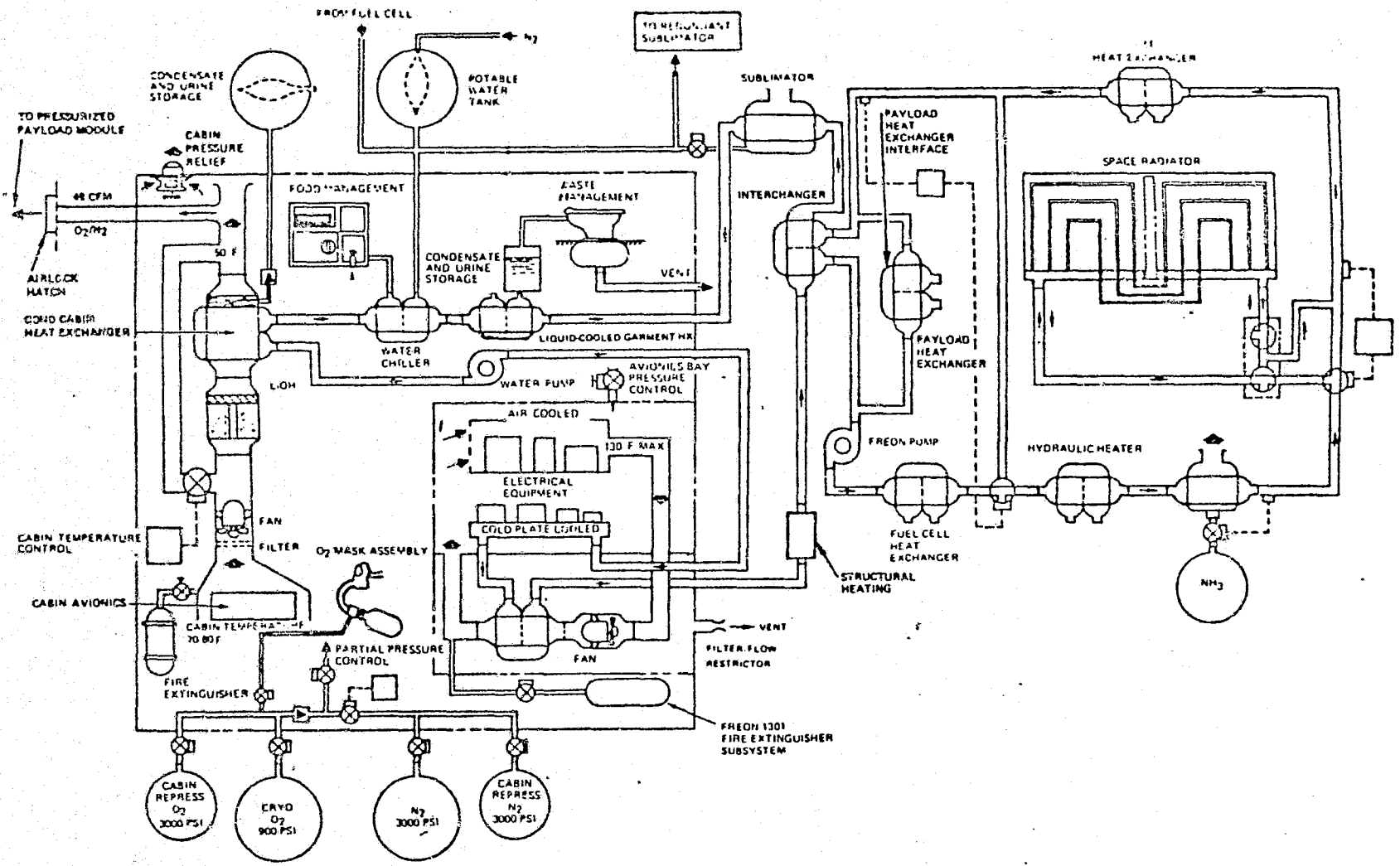


FIGURE 4.7-114 ENVIRONMENT CONTROL AND LIFE SUPPORT SUBSYSTEM (ECLSS) SCHEMATIC

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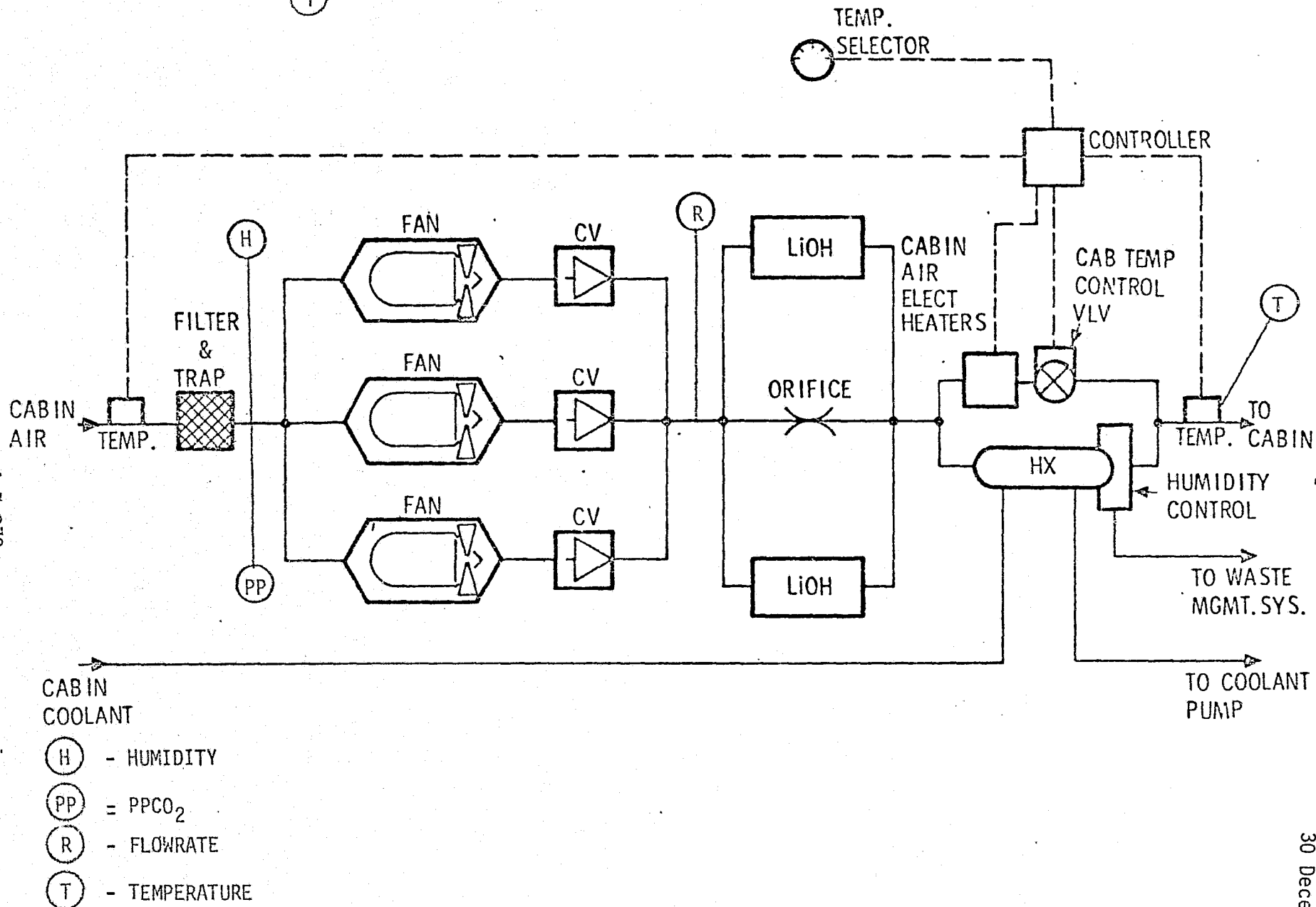


FIGURE 4.7-115 ECLSS CABIN TEMPERATURE, HUMIDITY AND CO₂ CONTROL SCHEMATIC

4.7-373

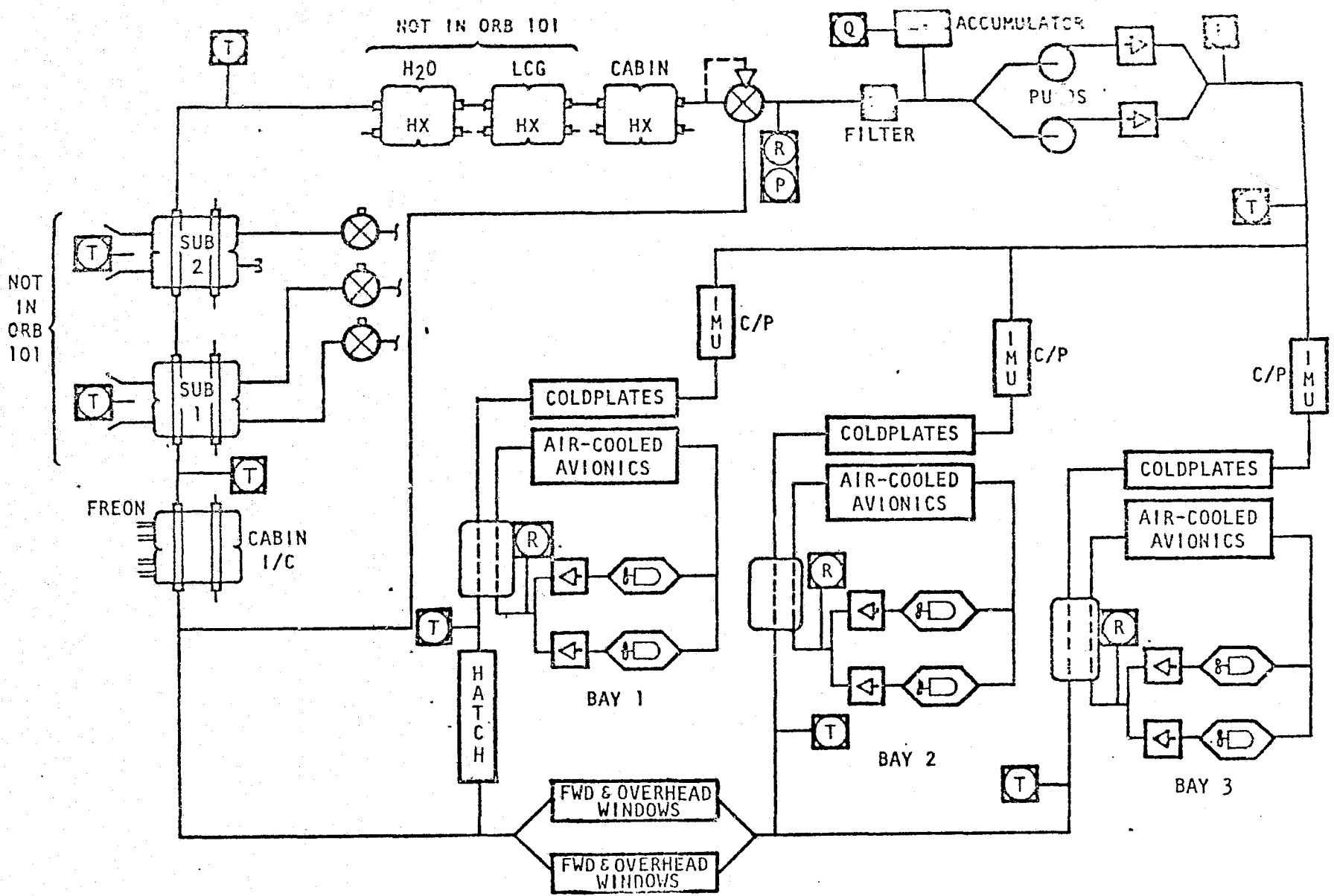


FIGURE 4.7-116. PRIMARY WATER COOLANT LOOP SCHEMATIC

ARS-CACS Module Functions and Parameters

Figure 4.7-117 provides an overview of the ARS-CACS simulation module functional elements and interfaces with other modules. There are five basic functions performed within the module: air circulation, $\text{CO}_2/\text{H}_2\text{O}$ control, H_2O coolant flow, thermal control, and control logic. Tables 4.7-31, 4.7-32, and 4.7-33 provide a listing of the atmosphere control module parameters. The following discussion is related to the calculations performed within each of the module elements.

Air Circulation - Air circulation calculations are provided for each of the three avionics bays and the crew quarters.

- Fan/Duct flow rates - These are functions of input voltages, air density, duct pressure drop and fan efficiency.
- Duct pressure drop - a function of air velocity, density, and duct configuration or branches.
- Condensate line inlet pressure - a function of pump outlet pressure and duct pressure drop.
- Duct air temperature - functions of cabin temperature, duct velocity, fan power, heat exchanger outlet temperature, air cooled equipment electrical power, and electrical heaters electrical power.

CO_2 Control - This control is provided for the crew quarters.

- CO_2 removal rate - a function of cabin CO_2 pressure, air flow rate through LiOH canisters, and air temperature.

H_2O Coolant Loop Flow - Calculates H_2O coolant loop flow rates and pressures.

- Pump flow rate - a function of input voltage, pump pressure rise, and inlet pressure.
- Loop pressure drop - a function of H_2O pump flow rate, H_2O temperature, and branch flow rates.
- Branch flow rates - functions of pump flow rates and cabin heat exchanger outlet H_2O temperature.
- Accumulator H_2O Quantity - a function of H_2O temperature.
- Accumulator Pressure - a function of H_2O quantity and temperature.

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4.7-375

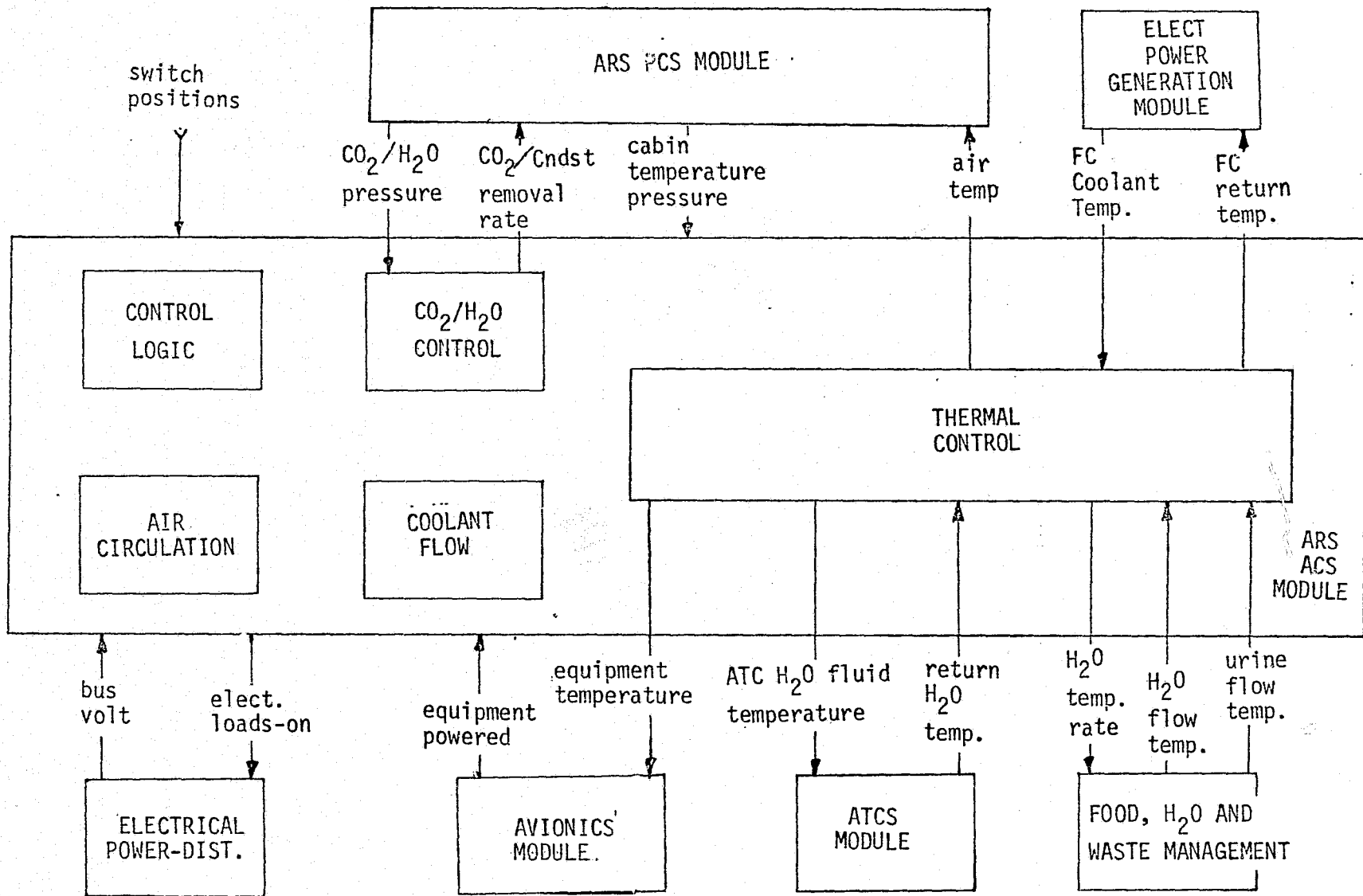


FIGURE 4.7-117 ATMOSPHERE REVITALIZATION SYSTEM, CABIN ATMOSPHERE CONTROL SUBSYSTEM, MODULE FUNCTIONAL ELEMENTS AND INTERFACES

TABLE 4.7-31 WATER COOLANT LOOP MODEL INPUT DATA

PARAMETER	TYPE ^a
SPECIFIC HEATS	DB
HEAT TRANSFER COEFFICIENTS	DB
SOURCE HEAT CAPACITIES	DB
SOURCE TEMPERATURES	DB
LOOP TEMPERATURES	DB
INTERNAL HEAT LOADS	DB
TRAJECTORY AND ATTITUDE HEAT LOAD TABLES	DB
TRAJECTORY AND ATTITUDE	I
MISSION PHASE FLAGS	I
WATER PUMP/LOOP FLOW CHARACTERISTICS	DB
INTERFACING MODULE PARAMETERS	I
WATER PUMP POWER	DB
AVIONICS EQUIPMENT POWER ^c	DB
AVIONICS BAY FAN/AIR FLOWRATE CHARACTERISTICS	DB
AVIONICS BAY FAN POWER	DB
WATER PUMP AND AVIONICS BAY FAN ON-OFF DISCRETES	I
AVIONICS EQUIPMENT ON-OFF DISCRETES ^c	I
POTABLE WATER USAGE	I
SUBLIMATOR OPERATING CHARACTERISTICS	DB
LIQUID COOLED GARMENT HEAT LOADS	DB

a DB - from Data Base

I - Input

TABLE 4.7-32 WATER COOLANT LOOP MODEL OUTPUT DATA

PARAMETER	TYPE ^a
H ₂ O ACCUMULATOR QUANTITY - PCL & SCL	P
AVIONICS BAY 1 AIR FLOW	P
AVIONICS BAY 2 AIR FLOW	P
AVIONICS BAY 3 AIR FLOW	P
SUBLIMATOR OUTLET TEMP - PCL & SCL	CP
H ₂ O COOLANT FLOW RATE - PCL & SCL	P
SUBLIMATOR 1 VAPOR VENT TEMP	P
SUBLIMATOR 2 VAPOR VENT TEMP	P
H ₂ O PUMP OUTLET PRESSURE - PCL & SCL	P
AVIONICS BAY 1 OUTLET TEMP - PCL & SCL	CP
AVIONICS BAY 2 OUTLET TEMP - PCL & SCL	CP
AVIONICS BAY 3 OUTLET TEMP - PCL & SCL	CP
CABIN INTERCHANGER OUTLET TEMP - PCL & SCL	CP
SOURCE TEMPERATURES (ALL CAPACITIVE LOADS)	P
LOOP TEMPERATURES (NON-TELEMETERED) - PCL & SCL	P
FLOW RATES (NON-TELEMETERED) - PCL & SCL	P
HEAT TRANSFER RATES (NON-TELEMETERED) - PCL & SCL	P
H ₂ O PUMP OUTLET TEMP - PCL & SCL	CP

- a P - Performance Parameter
CP - Critical Performance Parameter

TABLE 4.7-33, CABIN ATMOSPHERE PERFORMANCE PARAMETERS

PARAMETER	TYPE ^a
METABOLIC HEAT, CO ₂ AND WATER PRODUCTION	DB
CABIN EQUIPMENT HEATING RATES	I
TRAJECTORY/ATTITUDE CABIN HEATING RATES	I
CABIN FAN PERFORMANCE DATA	DB
CABIN FAN ON-OFF DISCRETES	P
LiOH CANISTER ON-LINE TIME	P
LiOH CANISTER PERFORMANCE CHARACTERISTICS	DB
TEMPERATURE SELECTOR SETTING	P
BULK CABIN THERMAL CAPACITANCE	DB
CONDENSING HEAT EXCHANGER CHARACTERISTICS	DB
CONTROLLER/BYPASS THROTTLE CHARACTERISTICS	DB
CABIN TEMPERATURE	CP
CABIN HUMIDITY	CP
CABIN CO ₂ PARTIAL PRESSURE	CP
CABIN AIR FLOW RATE	CP
OUTLET HUMIDITY	P
OUTLET CO ₂ PARTIAL PRESSURE	P
OUTLET TEMPERATURE	CP
CONDENSING Hx AIR FLOW RATE	P
CONDENSING Hx OUTLET AIR TEMPERATURE	P

- a P - Performance Parameter
 CP - Critical Performance Parameter
 I - Input

Thermal Control - Temperature calculations are provided for the H₂O coolant loops and interfacing module.

- Pump outlet temperature - a function of H₂O flow, pump inlet temperature, pump pressure rise, and pump input electrical power.
- Coldplate equipment temperature - functions of electrical power, inlet H₂O temperature, equipment temperature, and H₂O flow rate.
- Heat exchanger outlet H₂O temperatures - functions of inlet H₂O temperature, H₂O flow rate, interchange fluid inlet temperatures, and interchange fluid flow rate.
- Heat exchanger outlet interchange fluid temperatures - functions of interchange fluid inlet temperature and flow rate and the H₂O inlet temperature and flow rate.
- Accumulator H₂O inlet temperature - a function of cabin heat exchanger outlet H₂O temperature/flow rate, bypass temperature and flow rate.
- Pump inlet temperature - a function of the accumulator inlet temperature, accumulator temperature and H₂O flow rate.

ARS-CACS Reference Data Sources and Data Format

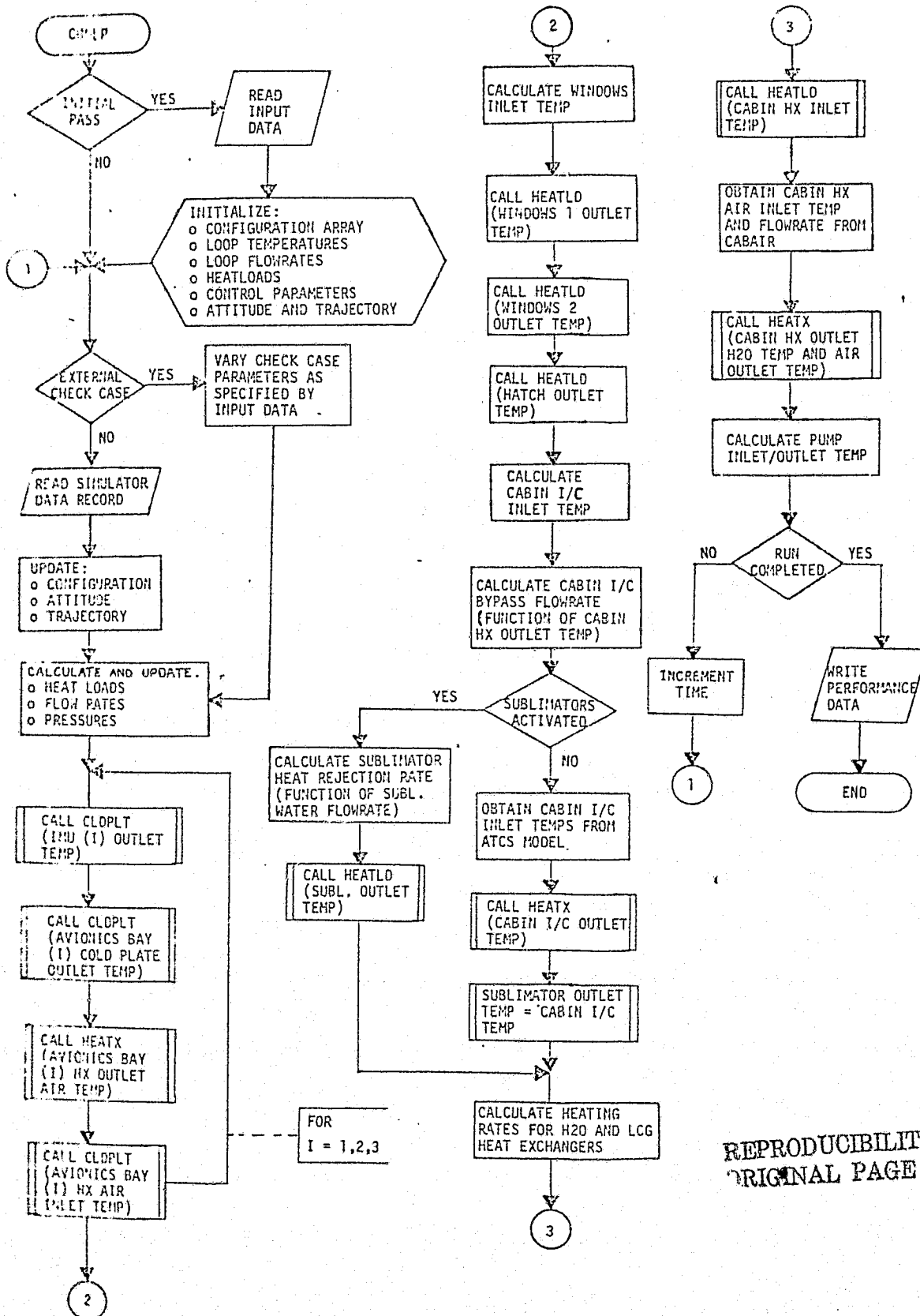
Various reference data sources exist for the ARS-CACS. Data concerning component and system performance requirements, predictions, and tests are available from References 31 and 72. In addition, several computer programs are available for development into a reference model or performing analyses. References 69 and 70 described component subroutines which can be combined to provide a system simulation reference module. Reference 73 is an ARS/ATCS performance routine designed for use with the Wang 700-series programmable calculator system. The use of this type of equipment allows an average runs time of five minutes per case, as opposed to hours or days turnaround with a regular computer facility. References 74 and 75 provide data for Orbiter heat exchanger calculations. The following discussion pertains to the development of a independent reference module.

Final performance evaluation of the simulator subsystems modules is best accomplished by evaluating the dynamic response of all crew station displayed and telemetered parameters pertaining to that subsystem, in a full-up simulation (all interfaces operating) of a mission phase or a transition from one mission phase to another. Certain parametric data, other than displayed data, is required to verify proper interfacing and coupling with other subsystem modules, e.g., the heat load from the H₂O coolant loops transferred to the ATCS.

Static check cases can be run with simpler verification models, however, the validation of simulator response to combinations of off-nominal operating conditions, insertion of malfunctions, etc., is not readily performed using simple check case models. The subject thermal and atmospheric control models are presented as examples of what a verification model involves in terms of input data and interface requirements. Maximum use should be made of existing hardware sizing and subsystem analysis programs with their data packages in developing an integrated verification module, e.g., Reference 69.

Primary and Secondary H₂O Coolant Loop Model - The math flow for the H₂O coolant loops model (COOLP) is shown in Figure 4.7-118. This model is applicable for generating static or programmed parametric variation check case data from a given set of input data, as well as generating performance data from a dynamic simulation run (whereby the simulator supplies the systems configuration and trajectory data). Basically COOLP calculates the outlet temperature of each heat transfer device in the order of the device position in the loop. Appropriate mixing calculations are performed at device output convergence points. Reference is made to three subroutines for calculating outlet temperatures for three types of heat transfer devices: a) coldplate, b) heat exchanger, and c) a direct heat load such as structural cooling, windows, etc.

COOLP uses an incremental time base for the computations. Typically the time increment would correspond to the computation cycle of the simulator module being checked. The device inlet temperature is related to the preceding device outlet temperature and assumed constant during the integration time period.



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FIGURE 4.7-118. REFERENCE MODULE, WATER COOLANT LOOP (COOLP) FLOWCHART

The PRI and SEC H₂O loops are identical except for flow rate, i.e., all heat transfer devices are serviced by both loops. The model combines the flow in both loops, and the calculated loop temperatures are applicable for both loops. Parameters for a non-operating loop could be set to some predetermined value based on the temperatures maintained by the operating loop.

The comp cycle begins at the outlet of the H₂O pumps and proceeds around the loop as shown in Figure 4.7-118 using internally calculated flow rates and heat loads as applicable. Not all the coolant loop flow paths are represented for the sake of simplicity, e.g., the avionics bay cold plates really consist of a series/parallel arrangement of cold plates for each piece of equipment. Some unidentified functions are those of the cabin interchanger bypass flow which is controlled by the cabin HX outlet temperature, and the sublimator operation.

Table 4.7-31 is a representative set of input data required to operate COOLP. A complete set of starting conditions is required including load source and loop temperatures. Data pertaining to vehicle and subsystem configuration is contained in a configuration array of discrettes which is continuously updated during the course of a run. These data are used to internally compute flow rates and heat loads from tabular type input data. A number of scripted malfunctions can be handled by inputs to the configuration array.

Operational data such as heat capacities, heat transfer coefficients, etc., will probably not be available until late in the subsystem design/test stage; however, high fidelity data of this type is not required for accurate equilibrium solutions. Starting conditions (namely initial loop temperatures, bypass flow rates, etc.) can be determined and trimmed by running the model until it reaches equilibrium for given static heat loads and vehicle configuration.

The output parameters for directly evaluating the performance of the H₂O coolant loop module are listed in Table 4.7-32. All the telemetered parameters are available for display on any of four crew station CRT's via keyboard callup. Other parameters (such as avionics equipment case temperatures) can be checked

using this model; however, they are not identified here. The output from COOLP can be used to provide checks on such things as equipment overtemp condition sensing and proper alarm response. Parameters such as accumulator quantities are scripted unless a malfunction such as a leak is input, whereby internal computations would be made prior to outputting the data.

Cabin Atmosphere Control - The math flow for the cabin atmosphere control model (CABAIR) is shown in Figure 4.7-119. As with COOLP this model is capable of running prescribed check cases or evaluating a simulator run. The output from this model consists primarily of cabin temperatures, humidity, and CO₂ partial pressure profiles for given starting conditions and dynamic load conditions. The air flow into the system is based on the running status and performance characteristics of the three cabin fans. Flow rates through each of the LIOH canisters and the cabin HX are determined in order to calculate the CO₂ and water removal rates and heat transfer to the H₂O coolant loops or heat input to the cabin as required.

CO₂ Level

CO₂ is removed by passing cabin air over LIOH beds contained in a canister. The reaction ($2 \text{ LIOH} + \text{CO}_2 \rightarrow \text{Li}_2 \text{CO}_3 + \text{H}_2\text{O}$) results in heat production as well as water which is removed by the subsystem. The efficiency of the LIOH canisters in removing CO₂ is a function of bed geometry and on-line time. The cabin CO₂ level is determined by the time integral of the net of the removal and metabolic production rates.

Cabin Temperature

Cabin air temperature is determined by calculating the net cabin heat production (or loss) and using appropriate starting conditions and thermal capacitance. Heat production sources include metabolic, cabin equipment, LIOH canister operation, and wall heating. The heat removal is governed by the cabin temp selector which controls the air flow through the cabin heat exchanger. The cabin heat exchanger heat removal rate in turn is a function of the running condition of the H₂O coolant loops and the ATCS.

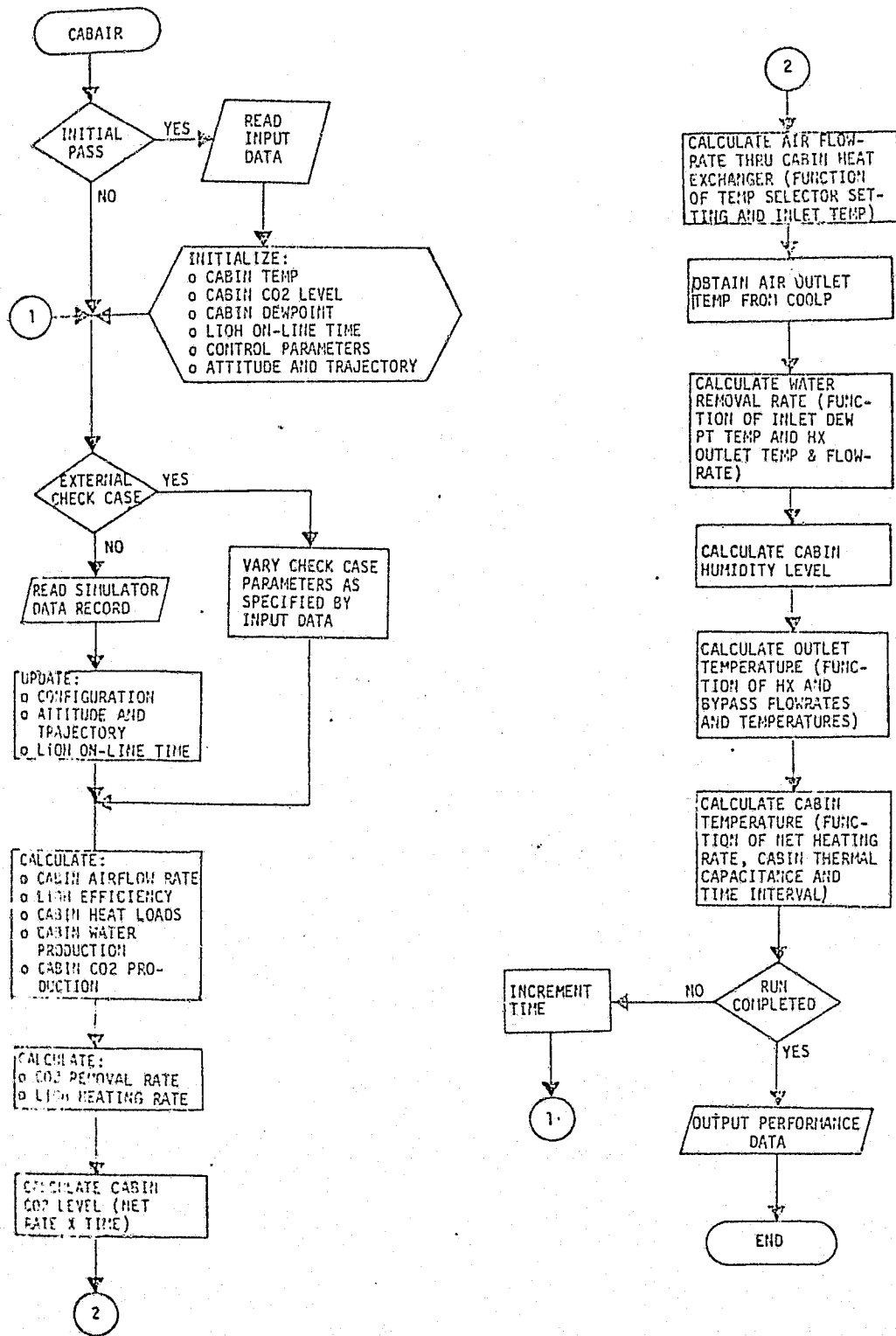


FIGURE 4.7-119 REFERENCE MODULE, ARS CABIN ATMOSPHERE FLOWCHART

Cabin Humidity

The cabin humidity is determined by calculating the net cabin water production. Water sources include metabolic, food and waste management, LiOH canister operation, etc. The removal is a function of the cabin heat exchanger air flow rate, air inlet dew point and outlet air temperature. The calculated water removal rate is required by the condensate and urine storage model.

ARS-ACS Validation Methods and Check Cases

The methods of Sections 5.1 and 4.2 can be used to verify the ARS-ACS simulation module. These methods require the use of interface drivers (to provide interfacing module functions) and the module functional element drivers to establish and maintain desired conditions for each check case. Drivers are required for the following:

- o ARS-ARPCS module
- o Electrical Power Generation
- o Electrical Power Distribution
- o Active Thermal Control module
- o Food, Water and Waste Management module

These drivers should provide capabilities for parameter initialization, transient response, steady state response, static inputs, and multiple check case execution during a single simulation run.

The check cases implemented should include step inputs with a comparison of the transient and steady-state responses. Initial check cases should also provide a thorough exercise of the module internal responses, as outlined in the design requirements documents. Latter check cases should implement refinements due to actual component and system design/tests. Actual systems/component test conditions can be input as a check case with simulation results compared directly to the test results. Other check cases should include the maximum, minimum, and nominal load conditions for each subsystem.

ARS-ACS Data Base Impact

The ARS-ACS reference module and the module drivers previously discussed represent a large impact to the simulation data base. Most of the processing subroutines (data input/output; data comparison) would be common to all modules being validated. Data files are required for input and output data tables.

4.7.6.2 Active Thermal Control System

The Active Thermal Control System (ATCS) provides the positive means of preventing orbiter equipment and fluids from exceeding permissible temperature extremes. This section describes the current system design, the expected simulation module's functions, identifies parameters associated with the module, and discusses techniques of verification of the module performance.

ATCS Description

The ATCS transfers heat from "heat sources" to "heat sinks" via a circulating fluid and interconnecting valves and tubing. The heat sources include coldplate mounted equipment, warmer fluids flowing through heat exchangers, and pumps. The heat sinks include fluid evaporators, colder fluids in heat exchangers, and the radiator. The heat sources and sinks are connected by controlling valves, tubing and fluid accumulators. The Orbiter uses two coolant loops which are identical, except that the primary loop has two pumps and accumulators, while the secondary loop has only one pump and accumulator. Figure 4.7-120 (see Refs. 75 and 78) is a schematic of the ATCS. A brief description of the major components and their pertinent performance characteristics follows.

Fluid - The circulating cooling liquid used in the Orbiter ATCS is Freon 21. The primary characteristics of interest are the density and specific heat, both of which vary with the fluid temperature. The consideration of these temperature variations in the simulation is dependent on the required fidelity.

Pump(s) - The role of the fluid pump is to provide the energy (pressure rise) necessary for circulation of the fluid through the loop components. The pump flow rate produced will vary with its input voltage and the system's resistance to fluid flow (pressure drop). Voltage regulation can be used to reduce the effects of the voltage variations. The system resistance (pressure drop) will vary with the selection of flow paths.

Fluid Accumulators - The purpose of the accumulator is to provide adequate system fluid volume for thermal expansion, slow leakage, and to provide adequate fluid pressure ranges throughout the expected temperature range. The major performance characteristics are the fluid volume and the pressure exerted on the fluid. The pressure is maintained by a sealed bellows.

4.7-387

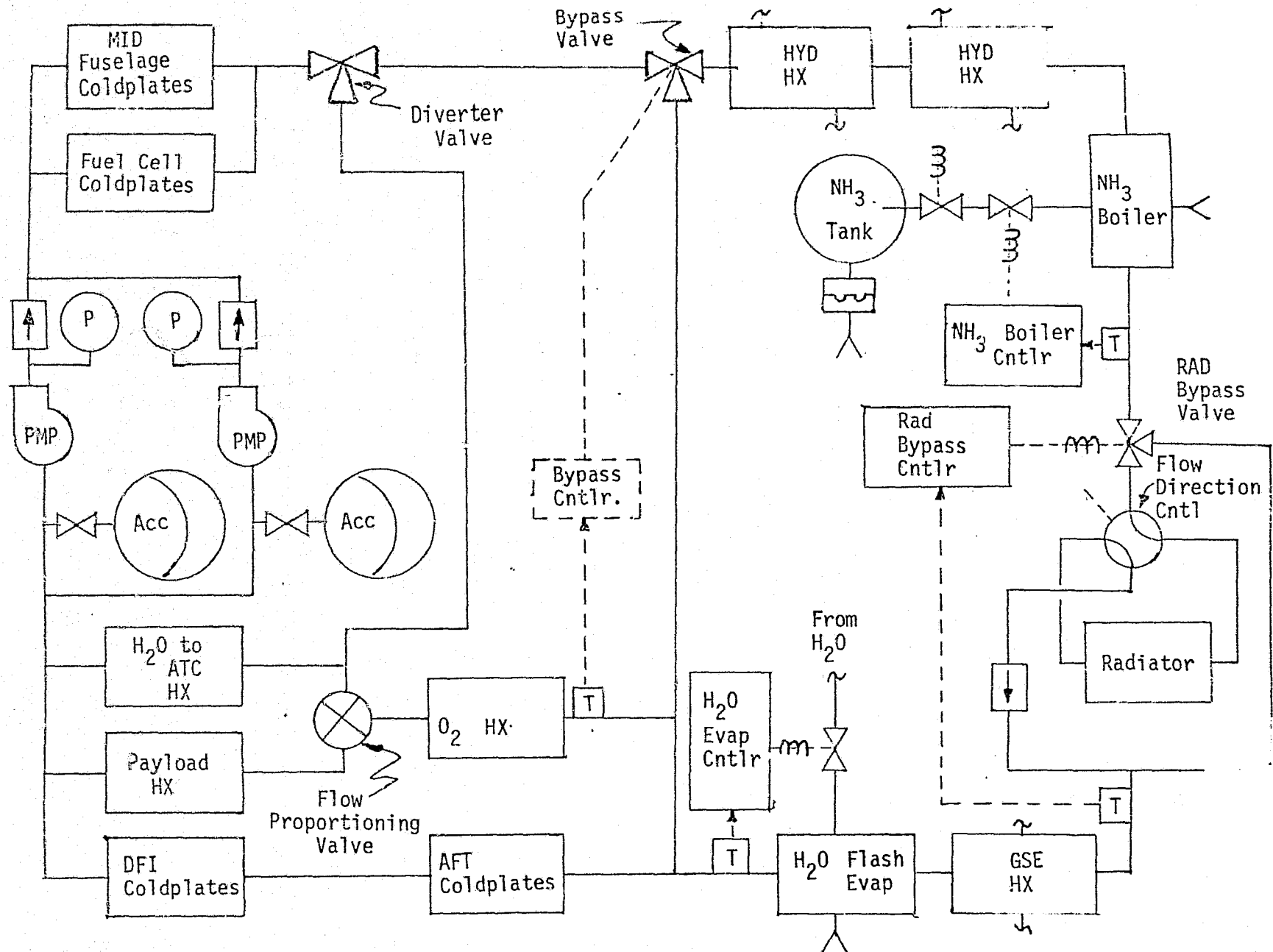


FIGURE 4.7-120 ACTIVE THERMAL CONTROL SYSTEM (ATCS) SCHEMATIC

Heat Exchangers - Heat exchangers provide the means of transfer of heat from one fluid to another flowing fluid. The major performance characteristic of interest is the "overall heat transfer coefficient ($U_o A$)," which varies with the flow rates and inlet temperatures of the fluids. A second characteristic is the fluid's pressure drop as functions of the fluid flow rates. These pressure drop characteristics are used in determining the total system pressure drop and corresponding loop fluid flow rates.

Evaporators - The H_2O evaporator and NH_3 Boiler are essentially heat exchangers with one of the flowing fluids being allowed to vaporize within the exchanger. The energy required for the fluid's vaporization is absorbed from the fluid being cooled. This vaporizing fluid is operated "open-cycle" being vented overboard. The amount of cooling is dependent on the flow rate and the specific heat of vaporization of the fluid being evaporated. The effective heat transfer is therefore dependent on the cooled fluid inlet temperature and flow rate and the quantity rate of fluid evaporated.

The H_2O evaporator uses water from the H_2O management subsystem as the evaporating fluid. The NH_3 Boiler uses ammonia from three storage tanks for the evaporating fluid. The H_2O evaporator is used on-orbit when the payload bay door is closed. The NH_3 Boiler is used after entry, below 100K feet.

Coldplates - The coldplates provide heat transfer from the mounted equipment to the cooling fluid circulating through the coldplates. The primary performance characteristic is the effective thermal conductance. This characteristic varies according to the cooling fluid inlet temperature, flow rate and the mounted equipment temperature.

Radiator - The radiator cools the Freon 21 by radiating the heat into space. The heat rejection is dependent on the fluid inlet temperature, fluid flow rate, surface emissivity, surface absorptivity, and the surface area exposed to sunlight, earth, and space.

Control Logic - The exact switching logic is not currently known. The logic, however, represents the control inputs for pump operation, valve positioning, loop selection, etc. These inputs can be manual controls, radio frequency commands, or automatic equipment commands. The functions of the logic are normally dependent on the voltage level, pressure level, temperatures, etc.

ATCS Module Functions and Parameters

The functions provided by the ATCS module include calculations and performance determination pertaining to control logic, coldplates, heat exchangers, evaporators, radiator, and pumps. Figure 4.7-121 is a block diagram which illustrates the module functional elements and interfaces with other modules. Table 4.7-34 provides a listing of the parameters associated with the ATCS module. The following paragraphs describe the functions performed by each element.

Control Logic - This element provides logic determination of loop selection, pump enabling, valve positioning, etc., allowing control of the freon fluid flow rates, interfaces, temperatures, etc. Inputs would include manual switch and valve positions, radio frequency command, automatic commands, and computer commands. Most of these controls are dependent on electrical bus voltage levels to actuate relays, valves, or other circuits. The logic would also include the following:

- Bypass Valve Position controller: a function of the bus voltage(s) and H₂O evaporator outlet freon temperature, etc.
- Radiator Bypass Valve Position Control: a function of the bus voltage(s) and the radiator outlet freon temperature, etc.
- Radiator Flow Direction Valve Position: a function of the payload door position, etc.

Coldplates - This element provides the calculations of the thermal conditions of the coldplate mounted equipment and the effect on the coolant fluids. The coldplates cooled are the mid-fuselage, aft-fuselage, and DFI coldplates. The following calculations should be provided for each coldplate or group of coldplates:

- Equipment temperatures: functions of equipment mass, equipment specific heat, previous temperature, heat dissipation, coldplate freon inlet temperature, freon flow rate, freon specific heat, heat transfer of the coldplates, heat conduction to walls, etc.

4.7-300

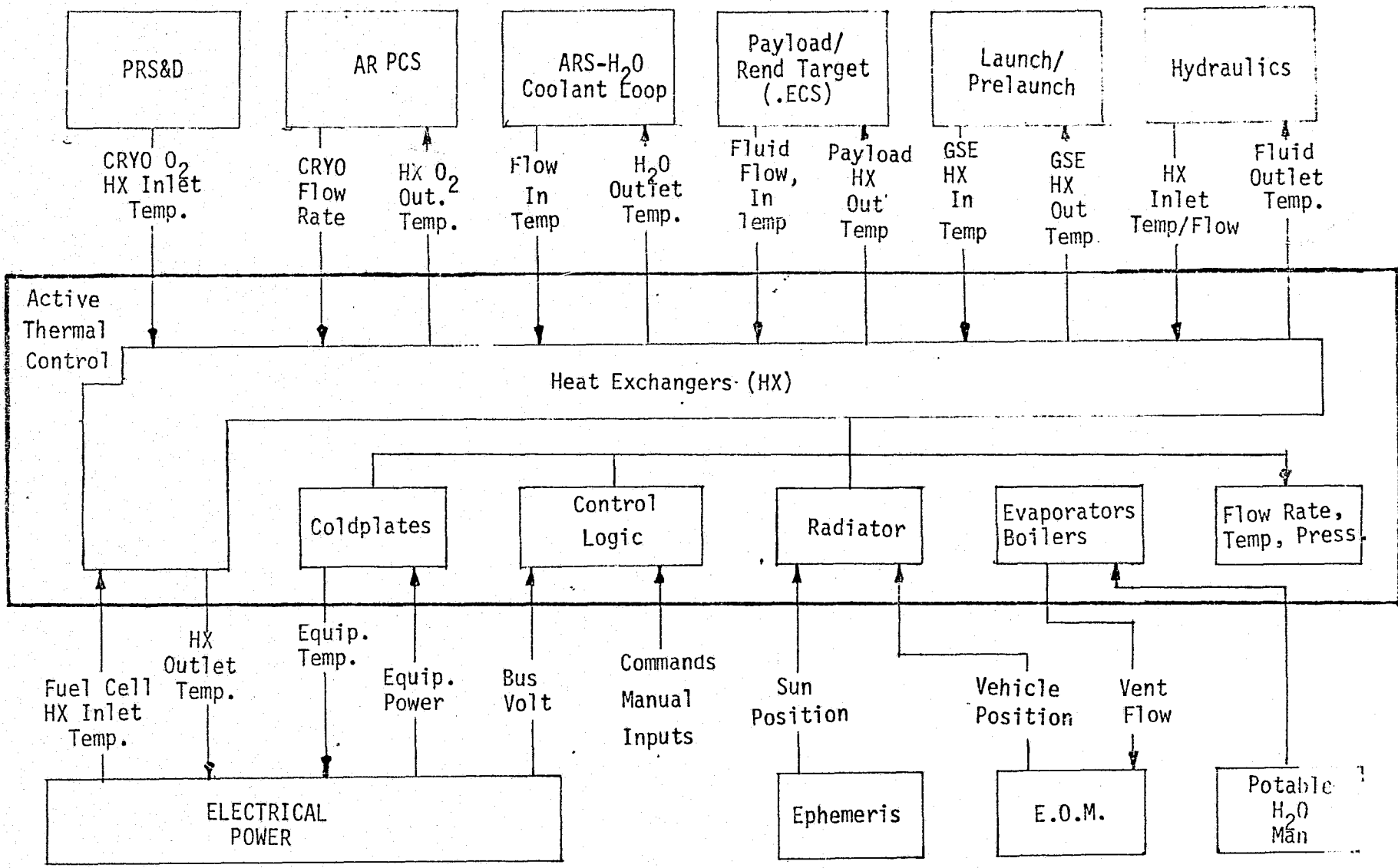


FIGURE 4.7-121 ACTIVE THERMAL CONTROL MODULE FUNCTIONAL ELEMENTS AND INTERFACES

TABLE 4.7-34. ACTIVE THERMAL CONTROL PARAMETERS

Parameter	Type ^a
Electrical power bus voltages	I
Switches/control selections	I
Coldplate equipment heat loads or power (DFI, AFT fuselage, MID fuselage)	I
Heat exchangers (H ₂ O payload, Cryo O ₂ , fuel cell, hydraulics 1/2, fluid inlet temps./specific heats/flow rates)	I
Heat exchanger U ₀ A (overall heat transfer conductance)	I
Sun angle	I
Shuttle attitude	I
GSE heat exchanger freon outlet temp.	I
H ₂ O evaporator, H ₂ O inlet temp./pressure/flow rate	I
Freon pumps on - (primary: 1, 2; secondary)	P
Freon system, branch flow rates	P
Freon pump outlet pressure, pressure rise	CP
Freon accumulator position (quantity)	P
Freon temperature (into and out of coldplates, heat exchangers, radiator, evaporators)	CP
Coldplate equipment temperatures (DFI, AFT & MID fuselage)	CP
Heat exchangers - 2nd fluid outlet temperature (H ₂ O, payload, Cryo O ₂ , fuel cell, hydraulics 1/2)	CP
Evaporators - evaporation fluid outlet temperature/vapor pressure (NH ₃ , H ₂ O)	CP
Specific heats (freon, fluids, equipment)	P
Controlled valve positions (Diverter, flow proportioning, bypass, radiator bypass, radiator flow direction, NH ₃ evaporator valves, H ₂ O evaporator valves, accumulator control valves)	P
NH ₃ flow rate/quantity remaining/pressure	CP
Radiator temperatures	P

a

CP = Critical Performance Parameter

P = Performance Parameter

I = Input

- Freon outlet temperature: function of equipment temperature, heat transfer, inlet freon temperature, inlet freon flow rate, specific heat of freon, etc.

Heat Exchangers - This element provides the interface relationships and functions defining the thermal interchange with other modules. This interchange includes PRSD. Cryogenic O₂ heating for the ARPCS, fuel cell heat dissipation from the power generation circulation system, H₂O coolant loop heat transfer for the ARS, hydraulic fluid warming for the hydraulics systems, heat transfer from payload coolant loops and heat dissipation to the ground cooling loop of the prelaunch/launch module. The calculation of the fluid outlet temperatures are provided for each interface.

- Outlet temperatures: functions of inlet fluid temperatures, fluid flow rates, heat conductance of the heat exchanger, and fluid specific heats.

Evaporators - This element provides the calculations associated with the NH₃ boiler subsystem and control of the H₂O evaporator as follows:

A. NH₃ Boiler

1. Quantity NH₃ remaining: function of flow rate, flow time, leakage, vent rate, starting quantity for each of three tanks.
2. Tank pressure: function of NH₃ quantity remaining, temperature, for each of three tanks.
3. Tank vent flow: function of tank pressure, density.
4. Evaporator NH₃ valve position: function of electrical bus voltage, evaporator outlet freon temperature.
5. NH₃ evaporator flow rates: function of NH₃ tank pressure, valve position, and density.
6. Freon outlet temperature: function of the inlet freon temperature, freon flow rate, specific heat, NH₃ flow rate, NH₃ inlet temperature, NH₃ specific heat, NH₃ heat of vaporization.

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27 January 1975

B. H₂O Evaporator

1. H₂O flow control valve position: function of bus voltage level, outlet freon temperature.
2. Outlet freon temperature: a function of H₂O flow rate, inlet freon temperature, freon flow rate, inlet H₂O temperature, specific heat of fluids, water heat of vaporization.

Radiator - This element determines thermal results and conditions for heat rejection.

- Radiator temperatures: function of the inlet freon temperature, freon flow rate, heat rejection, mass, specific heat, freon flow direction (payload door position).
- Radiator heat rejection: a function of the radiator temperature, vehicle attitude, vehicle state vector, beta angle, payload door position, freon flow direction.
- Radiator outlet freon temperature: a function of freon flow rate, inlet freon temperature, heat rejection, freon flow direction, radiator bypass valve position, specific heat, etc.

Freon Flow/Pressure/Temperatures - This element determines the freon system/branch flow rates, pressures, and integrated temperatures.

- System/Branch flow rates: functions of the system configuration, pump selection/enabling, freon temperatures, pump and equipment flow/pressure characteristics, bus voltage level.
- System pressures: functions of the flow rates, temperatures, accumulator quantities, flow/pressure characteristics, system configuration, bus voltage level.
- Integrated freon temperatures: function of mixing freon flow rates/temperatures, system configuration.
- Accumulator freon quantity: function of the freon leakage, flow rate, temperature.

ATCS Reference Data Sources and Formats

ATCS System and component design performance requirements, analysis, predictions, and tests provide data for direct comparison with the Shuttle simulation results. Figure 4.7-122 is an overview flow chart of a method of reference source selection and comparison. Reference 31 (updated at intervals) is a source of component and systems performance data regarding design requirements analysis, tests, and actual flight. Design requirements are available from Reference 76. The analysis and test results should be available from Shuttle design and evaluation groups.

In addition, several computer programs are available which can be used to develop suitable reference modules or to use in performing analysis of the system. References 69 and 70 provide descriptions of system component subroutines which can be combined to provide a reference module for the ATCS. The G189A program of Reference 69 was developed for JSC and is a versatile analytical tool for support of environmental systems work. Reference 73 describes an ARS/ATCS performance subroutine designed for use with the Wang 700 series programmable calculator. This subroutine allows an average run time of five minutes per case as opposed to hours or days turnaround when using the regular computer facilities. Figure 4.7-123 provides a overview flow chart of an ATCS reference module.

ATCS Validation Methods and Check Cases

The ATCS module can be verified by the techniques described in Sections 4.2 and 5.1. During the verification the following drivers are required to provide the necessary range of inputs and conditions for establishing each checkpoint.

- Electrical Power Generation
- PRS and D
- ARPCS
- ARS
- Payload thermal control loop
- Prelaunch/launch GSE cooling
- Hydraulic subsystem heating
- Food, H₂O, waste management
- Equations of motion
- Intra module functional elements

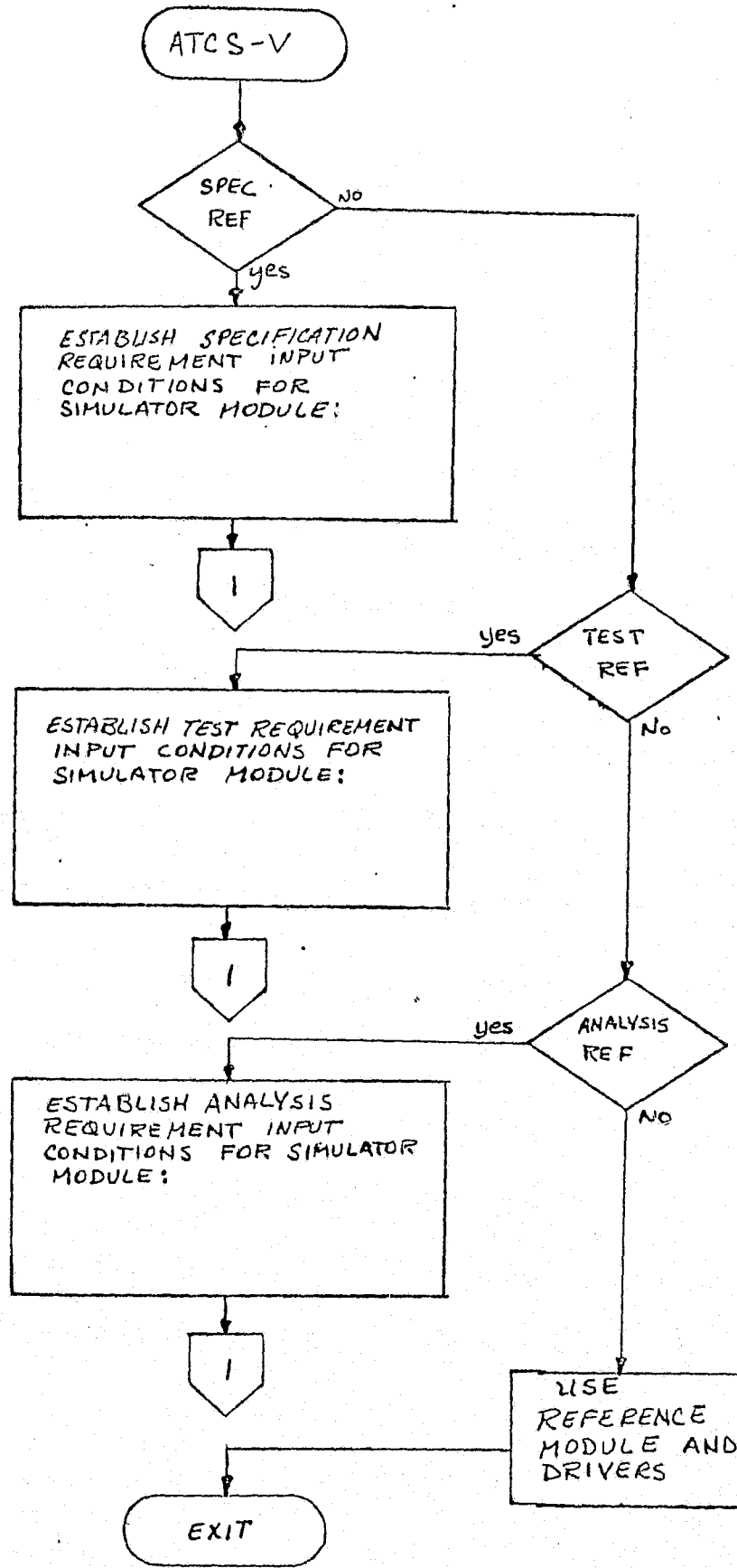


FIGURE 4.7-122 ACTIVE THERMAL CONTROL SYSTEM VERIFICATION OVERVIEW

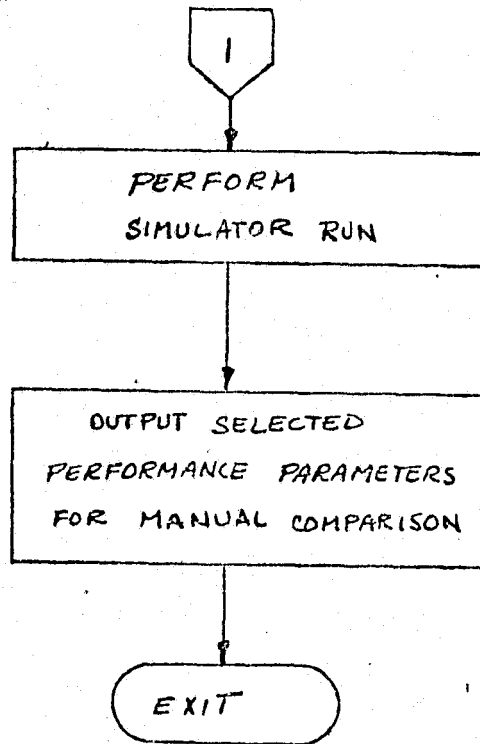


FIGURE 4.7-122 (CONTINUED)

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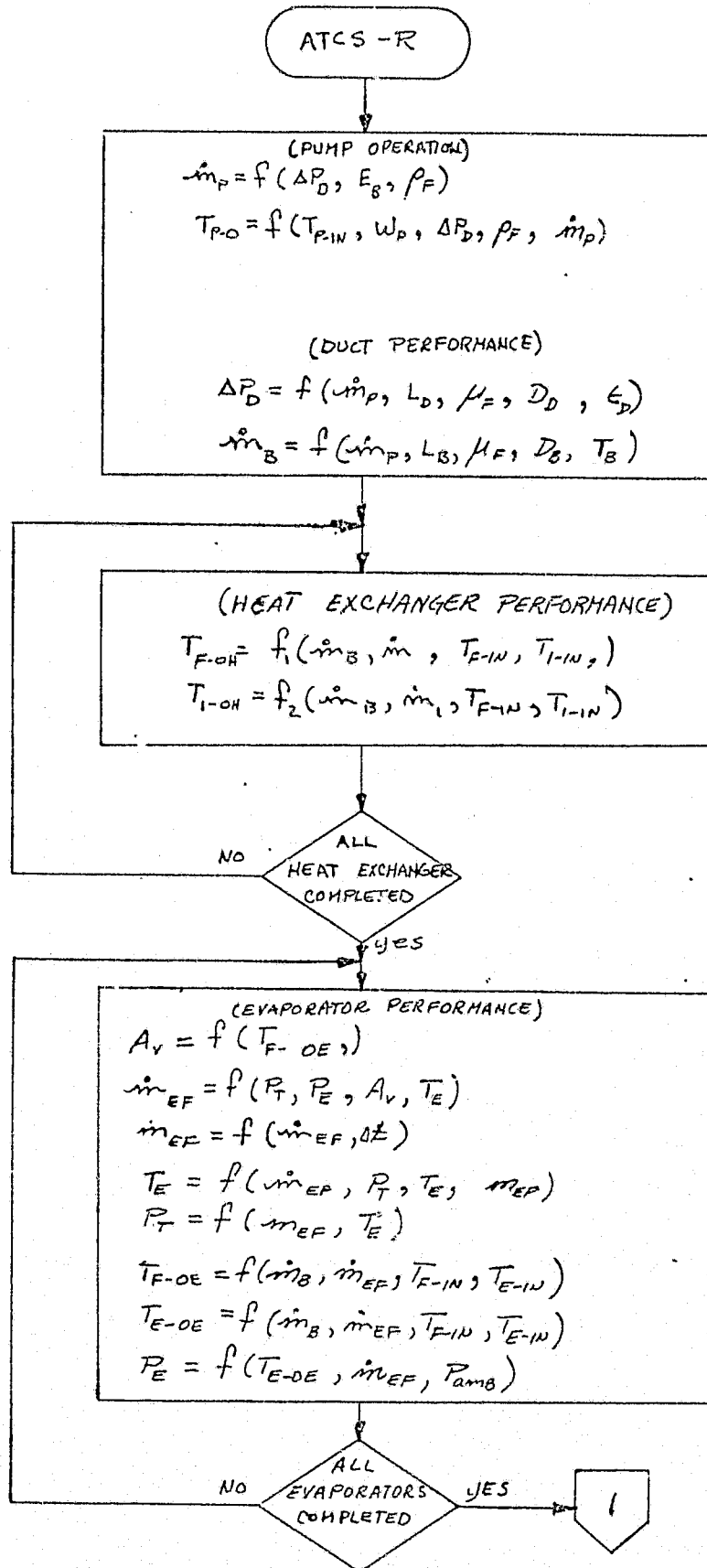


FIGURE 4.7-123 ATCS REFERENCE MODULE OVERVIEW MATH FLOW

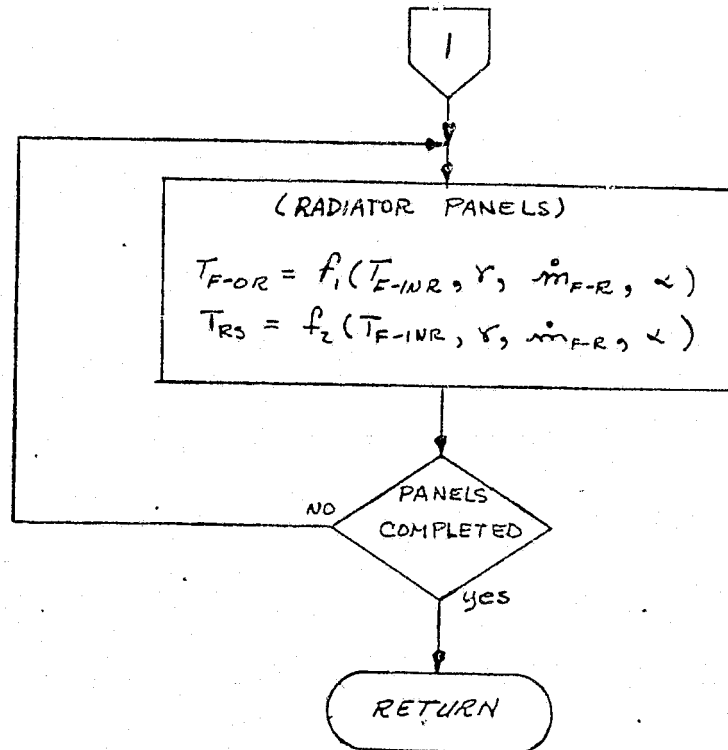


FIGURE 4.7-123 (CONTINUED)

LEGEND:

- A_v - Effective flow area of control valves
 \dot{m}_{EF} - Evaporator fluid quantity
 \dot{m}_p - Pump freon flow rate
 \dot{m}_B - Freon loop branch flow rate
 \dot{m}_I - Heat exchanger Interfaces circuit flow rate
 \dot{m}_{EF} - Evaporator fluid flow rate
 \dot{m}_{FR} - Freon flow rate through radiator
 γ - Sun rays incidence angle with radiator panel
 α - Earth view angle with radiator panels
- T_F - Freon average temperature
 T_B - Branch freon temperature
 T_{F-OH} - Heat exchanger freon outlet temperature
 T_{I-OH} - Heat exchanger interface circuit outlet temperature
 T_{F-IN} - Heat exchanger freon inlet temperature
 T_{I-IN} - Heat exchanger Interface circuit inlet temperature
 T_{F-OE} - Evaporator outlet freon temperature
 T_E - Evaporator fluid tank temperature
 T_{E-OE} - Evaporator outlet evaporation fluid temperature
 T_{F-INE} - Evaporator freon inlet temperature
 T_{E-IN} - Evaporator inlet evaporation fluid temperature
 T_{F-INR} - Radiator inlet freon temperature
 T_{F-OR} - Radiator outlet freon temperature
 T_{RS} - Temperature of radiator surface
- ΔP_D - Freon loop pressure drop
 L_D - Freon loop effective length
 L_B - Effective branch length
 D_D - Freon loop flow diameter
 D_B - Branch flow diameter
 μ_F - Freon viscosity
 ϵ_D - Freon loop effective roughness
- P_T - Evaporator storage tank pressure
 P_E - Evaporator pressure on evaporation fluid circuit
 P_{amb} - Ambient pressure

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FIGURE 4.7-123 (CONTINUED)

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The system design requirements (see Ref. 76) provide component and system maximum/minimum acceptable performance levels. These requirements should provide the initial check case conditions. The results of various contractor- and NASA-performed analysis, studies, and evaluations can provide higher fidelity verification check cases. Later, data from actual systems and component tests as well as actual flight performance can be used to establish the more severe verification check cases for both the module and the individual functional elements.

The check cases should include the exercise of each individual functional element and of the module functioning as a unit. The approach for individual functional element verification is to nullify or isolate all interaction with other elements and allow the calculation of selected outputs for controlled input parameters.

ATCS Data Base Impact

The ATCS reference module and the ATCS module drivers as previously discussed will have a large impact on the simulator data base. The processing subroutines (such as data input/output and data comparison) are of small impact, and most of them will be common to all the modules being validated.

4.7.6.3 Food, Water and Waste Management (FWWM)

This system provides control, storage and utilization of food, water and waste. The simplified schematic of the water subsystem (from Ref. 78) is shown in Figure 4.7-124. Figure 4.7-125 is a schematic of the waste management subsystem (also from Ref. 78).

FWWM System Description

Food Management - This subsystem provides for the storage and preparation of crew meals.

Water Management - The water management subsystem provides for the collection of fuel cell product water, storage in the three potable water bottles, and subsequent delivery to water sublimators, overboard dumps, airlock, and food management subsystem.

Waste Management - This subsystem provides for the collection, storage, and disposal of condensate (from the ARS subsystem) and human waste.

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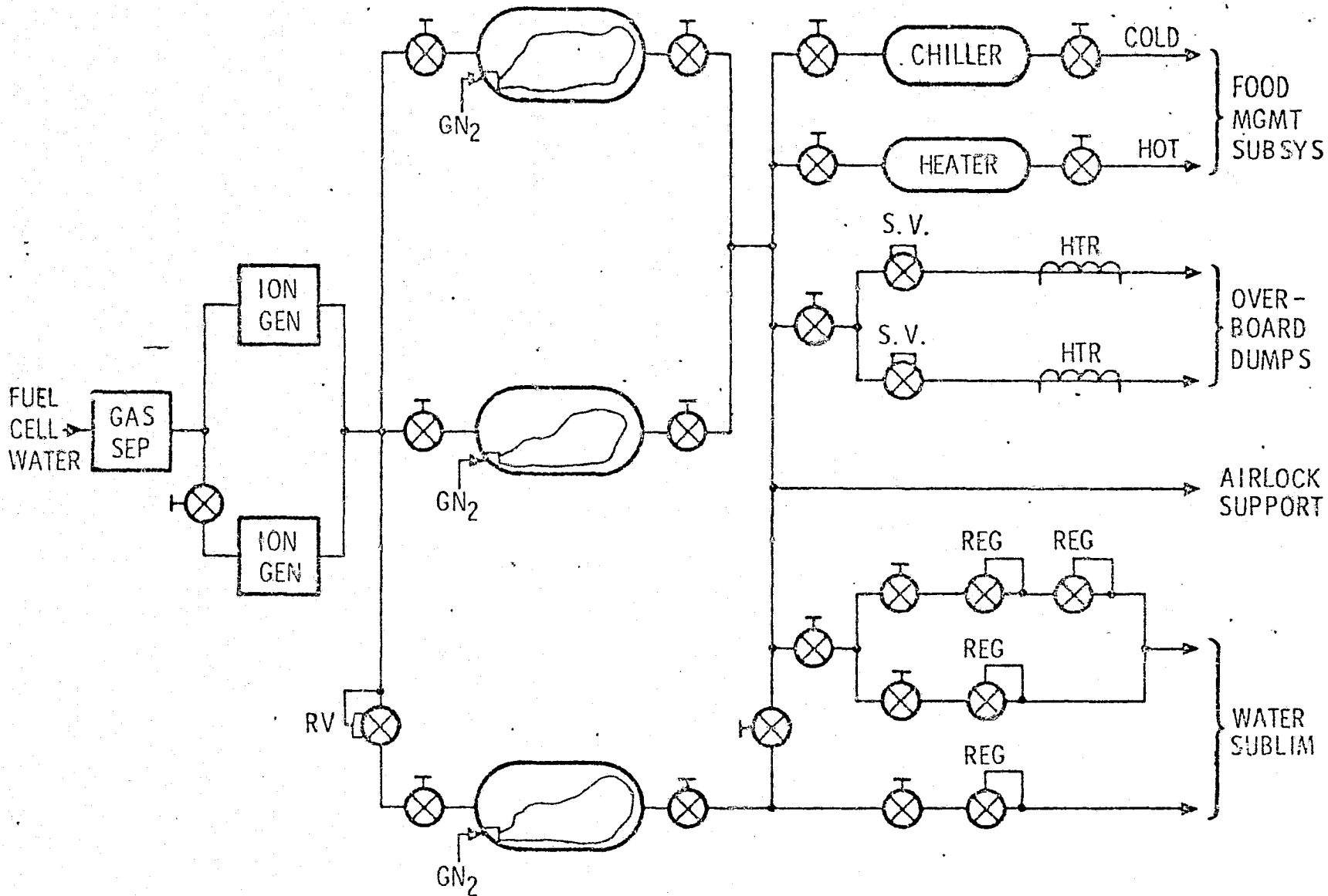


FIGURE 4.7-124 ECLSS WATER MANAGEMENT SUBSYSTEM

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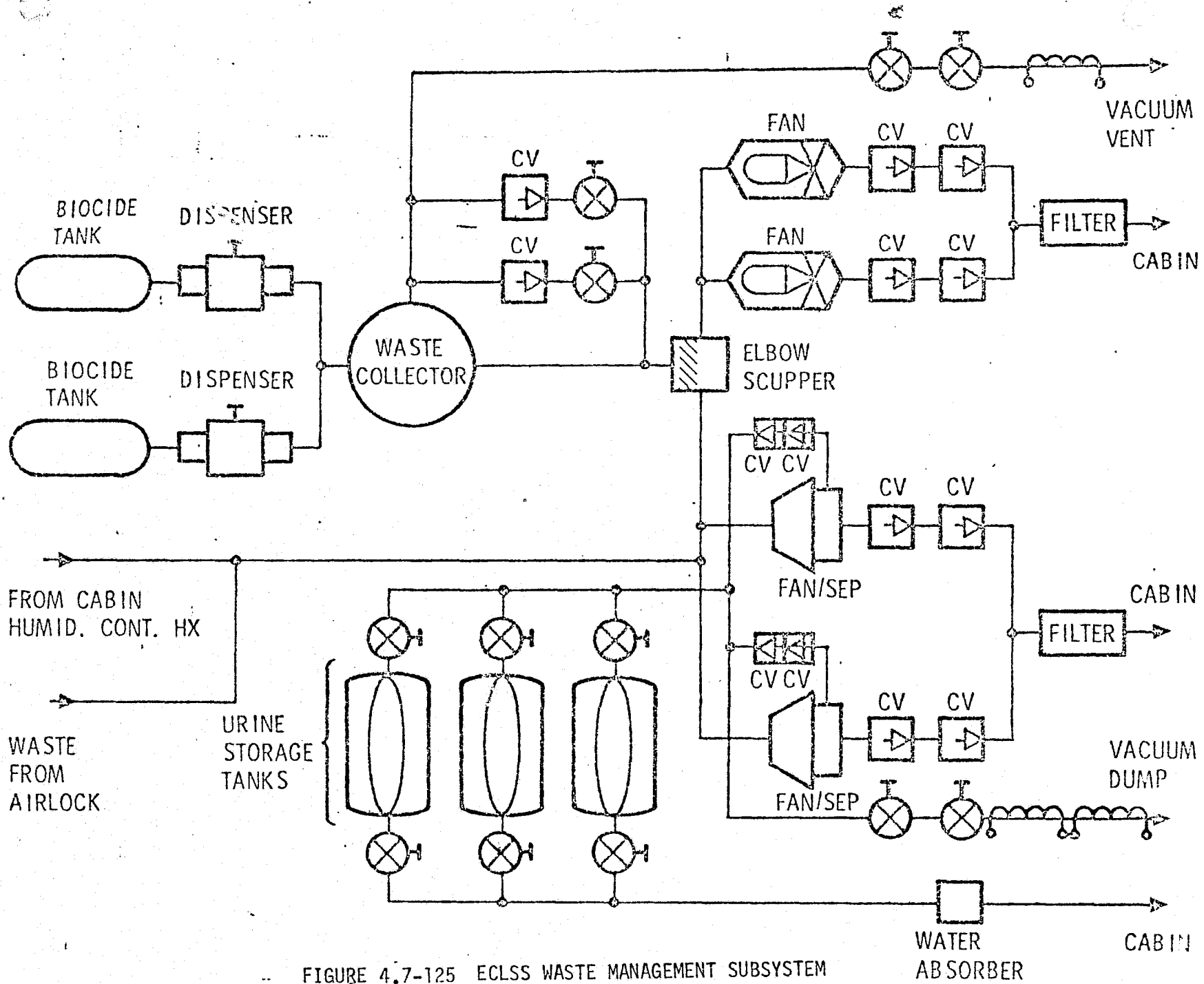


FIGURE 4.7-125 ECLSS WASTE MANAGEMENT SUBSYSTEM

FWM Module Functions and Parameters

The food management system is a lower-deck function, and thus will not be dynamically simulated. The waste management system only requires the condensate collection (flow rate) to be dynamically simulated. The water management subsystem, however, interfaces dynamically with the fuel cell and ARS-water coolant loop (water sublimators). The module performance parameters are identified in Table 4.7-35.

Water Management - This functional element provides the following calculations.

- Water flow rates to using outlets - functions of the tank pressures, outlet pressures, and effective flow areas.
- Tank H₂O quantities - functions of initial quantity, flow rates, and time.

Waste Management - This functional element provides the calculation of the condensate flow rate from the condensing heat exchanger to the urine storage tank or vacuum dump. The flow rate is a function of the heat exchangers inlet pressure, condensate quantity and tank pressure.

FWM Reference Data Sources and Formats

FWM subsystem design requirements, analysis, and test results can be used for module verification. In addition, certain math models described in previous portions of Section 4.7.6 can be utilized for this module. Figure 4.7-126 to calculate the liquid flow rates, can be developed into a suitable reference module. Those portions that are not dynamically simulated can be functionally provided by a performance profile (i.e., a tabular function of time). Reference 31, 77, and 12 are sources of component and subsystem performance requirements and data.

FWM Validation Methods and Check Cases

This module can be verified by the techniques described in Section 4.2 and 5.1. Module drivers are required to provide the fuel cell inlet water flow rates, water sublimator pressure, water tank pressure/temperature, and condensing heat exchanger inlet pressure. Check cases can be developed utilizing component and systems maximum and minimum performance design requirements, analysis, and system evaluations.

TABLE 4.7-35 FOOD, WATER AND WASTE MANAGEMENT PARAMETERS

PARAMETER	TYPE ^a
Condensate heat exchanger H ₂ O quantity/pressure	I
Ambient pressure	I
Fuel cell water flow rates/temperatures	I
Water chiller and heater flow rates	I
Water sublimator pressure	I
Water container pressure/temperature	I
Water sublimator pressure regulator flow areas	P
Water container water quantities	CP
Fan/Separator flow rates	P
Urine tank quantities/pressures	P

^ap = Performance Parameter

CP = Critical Performance Parameter

i = Input Parameter

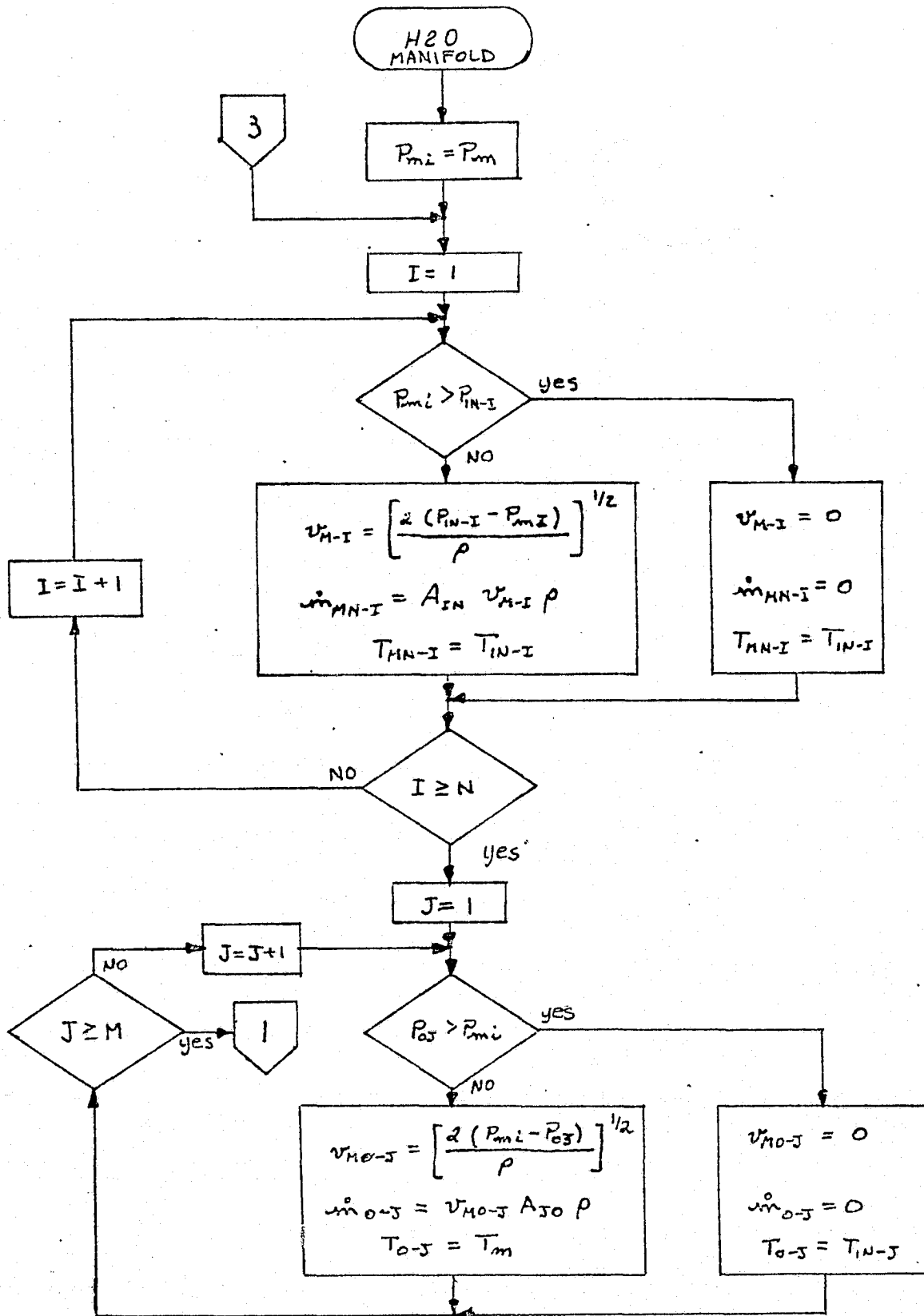


FIGURE 4.7-126 POTABLE WATER MANAGEMENT FLOW CHART

4.7-405

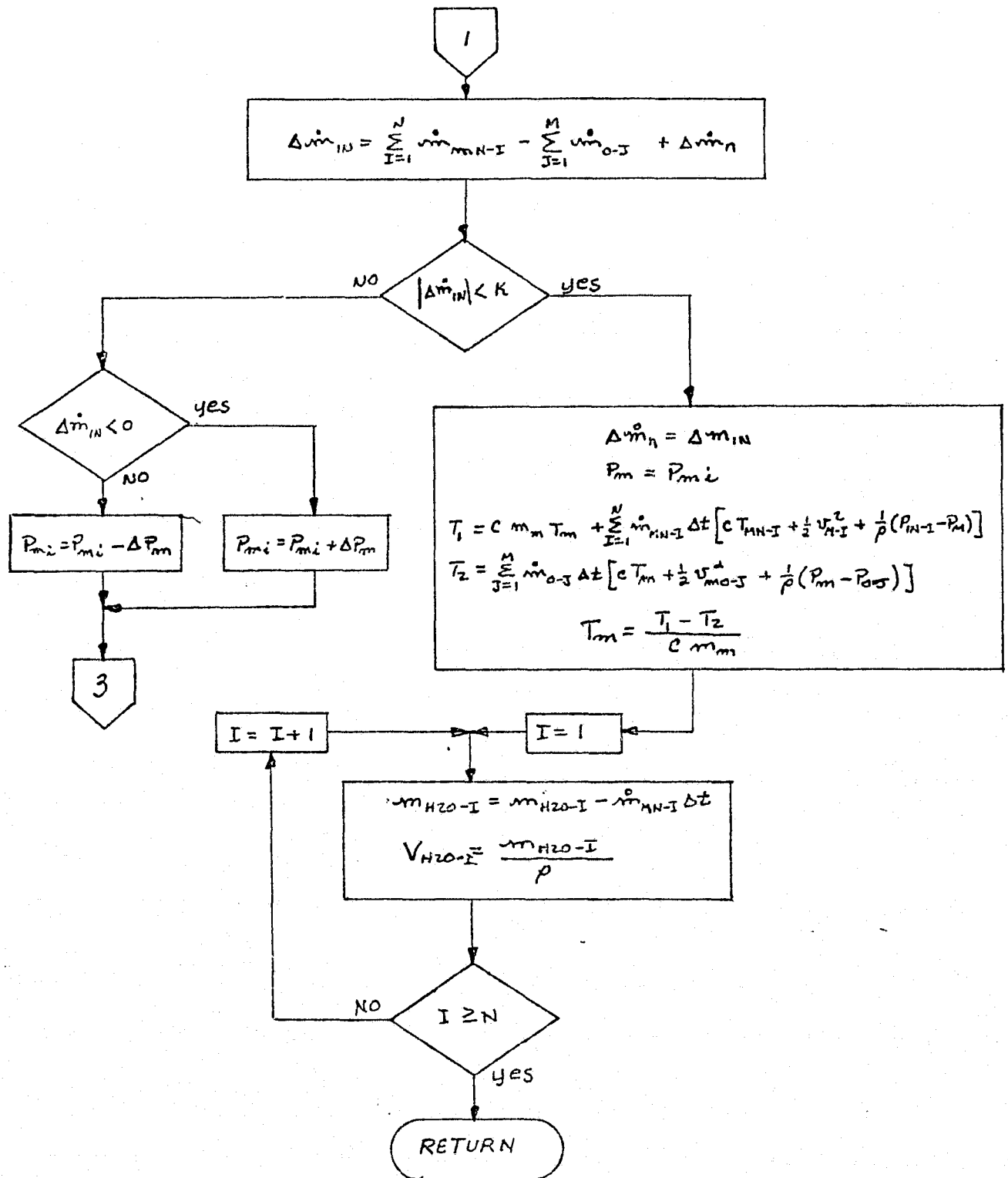


FIGURE 4.7-126 (CONTINUED)

4.7-406

LEGEND:

- P_{0J} - Pressure of J^{th} load
- P_M - Manifold pressure
- P_{IN-I} - Source pressure of I^{th} tank
- T_{IN-I} - Source temperature of I^{th} tank fluid
- \dot{m}_{M-I} - Liquid flow rate from I^{th} tank into manifold
- \dot{m}_{O-J} - Liquid flow rate from manifold to J^{th} load
- T_{M-I} - Liquid temperature into manifold from I^{th} tank
- T_{O-J} - Fluid temperature delivered to J^{th} load
- v_{M-I} - Fluid velocity from I^{th} tank into manifold
- v_{M-O-J} - Fluid velocity from manifold to J^{th} load
- T_M - Fluid temperature in manifold
- ρ_c - Fluid density
- m_m - Fluid mass in manifold
- m_{H_2O-I} - I^{th} tank fluid quantity
- c - Fluid specific heat
- Δt - Time increment
- A_{IN} - Flow area from I^{th} tank into manifold
- A_{JO} - Flow area from manifold to J^{th} load
- V_{H_2O-I} - Volume of fluid in I^{th} tank

FIGURE 4.7-126 (CONTINUED)

FWM Data Base Impact

Impact to the simulation data base is small. The reference module should be relatively simple. Few drivers are required, and the comparison/processing subroutines would be common to other simulation modules.

SECTION 5

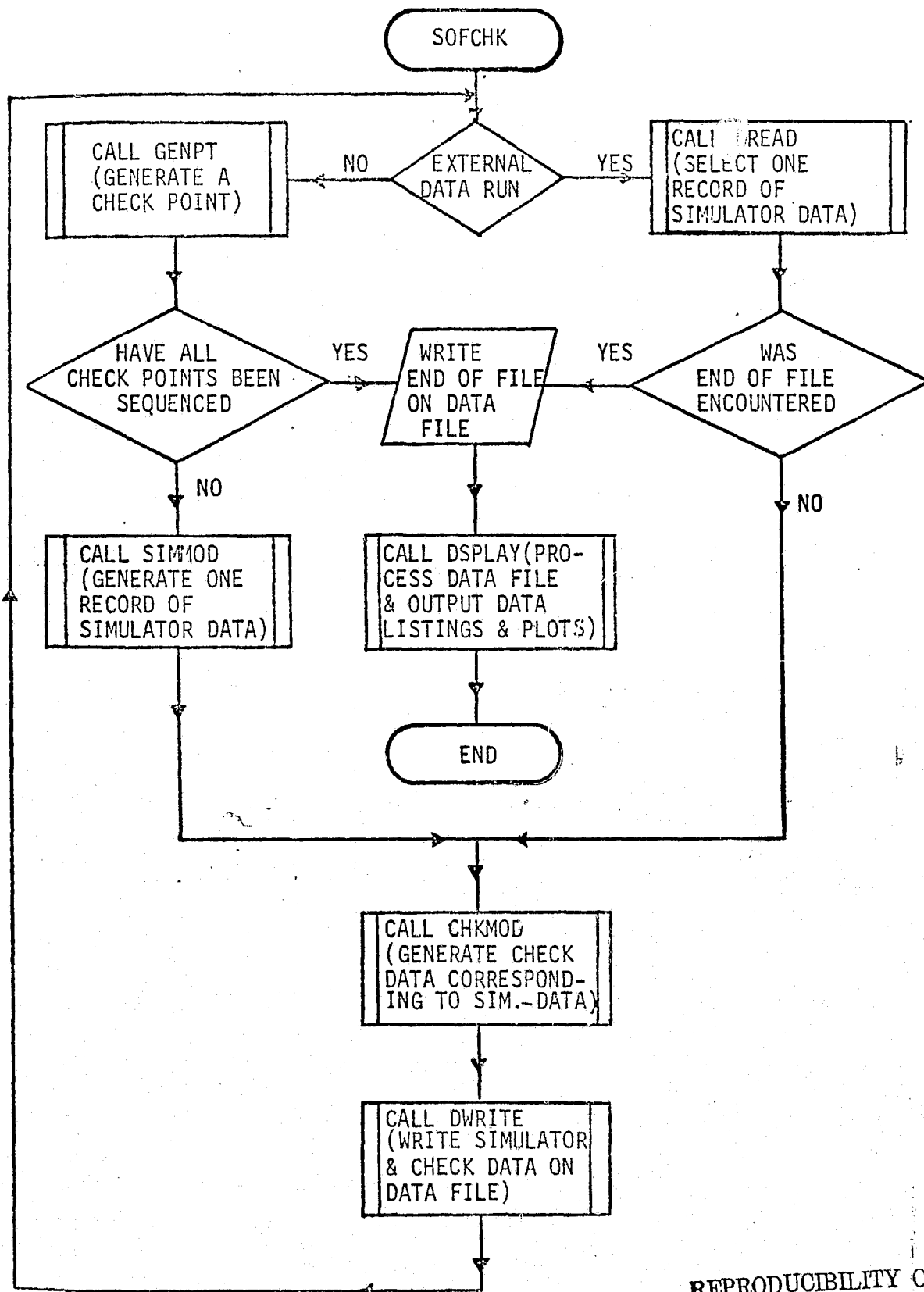
METHODS FOR VALIDATING PERFORMANCE

The process of simulation validation consists of exercising a simulation with properly-chosen inputs, gathering the output performance parameter data which it generates in response to these inputs, and comparing these data to reference data representing the real world which the simulation is intended to represent. Support software required to efficiently perform these operations is briefly discussed below. Additional detail will be provided in a later report.

5.1 VALIDATION SOFTWARE STRUCTURE

Figure 5-1 depicts a support-software organization suitable for the generation, handling, comparison and display of simulation and reference data required to perform simulation software validation. A complete validation software system will consist of a basic "driver" or executive (denoted SOFCHK in the figure) and a set of service routines, briefly identified in Table 5-1.

These routines will, of course, vary in degree of generality. Routines GENPT, SIMMOD, and CHKMOD must be completely "customized" for each simulator module being validated. Routine DREAD will be a data-driven input routine, designed to be compatible with the basic data-output structure of the simulator being validated. Finally, routines DWRITE and DSPLAY should be highly independent of the characteristics of the module being validated. The greater the degree of generality designed into the support software, of course, the less specialized coding and setup required to validate each individual module.



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FIGURE 5-1. VALIDATION SOFTWARE OVERALL FLOW

TABLE 5-1. VALIDATION SUBROUTINES^a

SUBROUTINE	PURPOSE
DREAD	Reads records from a data tape or disc file generated during a simulator performance run; selects data for the appropriate module and places it into a data array.
GENPT	Generates a checkpoint which includes all data required for input into the module to be verified.
SIMMOD	Interfaces with the simulation software module and places the input and output data into a data array.
CHKMOD	Interfaces the "reference" software module and places the input and output data into a data array compatible with the simulation software data array.
DWRITE	Writes the data from the simulator software module and the reference module onto a data file to be used for comparison processing.
DSPLAY	Processes the data file written by DWRITE. Performs automated comparisons of simulation and reference data, and/or generates listings and plots for manual comparison of data. Incorporates a variety of differencing techniques and comparison criteria.

^aMath flows and comprehensive discussions of these routines will be provided in a later report.

5.2 DATA ACQUISITION AND FORMATTING

For efficient manual or automatic comparison of the reference and simulation performance-parameter data, it is necessary that these data be put into compatible formats.

The means for manual comparison will almost always be a time-history plot of the system module's response to its inputs. If both the reference and simulation data are in machine-readable form, service routines may be used to overplot them on the same set of axes, in any convenient scale. In many cases, however, the reference data will be in the form of external hard-copy, previously plotted. It is then necessary that the service routines used for plotting the simulation performance-parameter data allow full control of scaling, to force the simulation data plot to be exactly comparable to the reference data plot. Then manual comparison can be accomplished by simply overlaying the two plots.

For automatic comparison, the reference and simulation data will have to be put out on temporary files, which are compatible with respect to units, axes, machine code (BCD/EBCDIC, 7-track/9-track, etc.), and time spacing. Generally, the process of ensuring compatibility will be undertaken by the module drivers. In some cases, however, it will be necessary to reprocess an existing data-file; e. g., machine-code conversion, time interpolation.

5.3 COMPARISON METHODS AND CRITERIA

As previously mentioned, manual comparison will normally be performed by overplotting data available to the machine, or by overlaying a newly-generated data plot on an existing plot. The comparison criteria in manual

comparison will generally be more or less subjective, based upon the validator's experience with similar simulation programs, knowledge of the overall fidelity standard of the particular simulator, known inaccuracies in the basic data (e. g., aerodynamic coefficients), and the importance of the particular performance parameter to the validity of training or procedures development to be done on that simulator.

To accomplish automatic validation, it is necessary that such subjective criteria be translated into objective terms, and then into some machine algorithm (maximum error, average percent error, integral of squared error, etc.) which assigns a numerical value to the degree of mismatch between the reference and simulation data time-histories. Finally, this mismatch value must be compared to a numerical acceptance value, beyond which the fidelity is considered unacceptable. The choice of mismatch algorithms and acceptance values will require considerable judgement and experience. In practice, the validator will often use these computed mismatch values as a guide in perturbing the values of simulation parameters (gains, time constants, etc.), attempting to secure the best possible match.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

1. Attention should be concentrated upon the "critical" performance parameters of each simulation module in performing simulation validation.
2. There are four general classes of reference data sources for simulation validation: closed-form solutions, independent math models, existing analysis/simulation programs, and test data. Each has particular advantages and disadvantages.
3. The SVDS and SSFS subroutine libraries offer many potential reference modules for simulation validation. However, modifications will be necessary in many cases.
4. Driver routines will be needed for module validation exercises -- both to provide the inputs representing interfacing modules, and to ensure format compatibility between the reference and simulation modules.
5. Service routines will be required for printout, plotting, data comparison, and data base management.
6. Most simulation modules will require both static and dynamic check cases for thorough validation.
7. Modules must be validated in isolation, as well as at various stages of simulation integration.

SECTION 7

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