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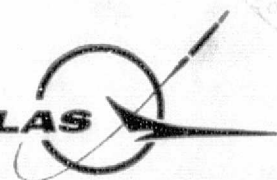
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SIMULATION PERFORMANCE VALIDATION TECHNIQUES DOCUMENT

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LIST OF PAGES

Title Page
ii to xvii
1-1 to 1-2
2-1
3-1 to 3-9
4-1
4.1-1 to 4.1-2
4.2-1 to 4.2-32
4.3-1 to 4.3-103
4.4-1 to 4.4-9
4.5-1 to 4.5-44
4.6-1 to 4.6-33
4.7-1 to 4.7-408
4.8-1 to 4.8-4
4.9-1 to 4.9-14
4.10-1 to 4.10-7
4.11-1 to 4.11-8
5-1
5.1-1 to 5.1-5
5.2-1 to 5.2-5
5.3-1 to 5.3-10
5.4-1 to 5.4-4
5.5-1 to 5.5-30
6-1 to 6-2
7-1 to 7-8

TABLE OF CONTENTS

	<u>PAGE</u>
LIST OF FIGURES	vi
• LIST OF TABLES	xii
LIST OF SYMBOLS	xv
SECTION 1 SUMMARY	1-1
SECTION 2 INTRODUCTION	2-1
SECTION 3 STUDY OBJECTIVES AND SCOPE	3-1
3.1 STUDY SUBTASK OBJECTIVES	3-1
3.2 SOFTWARE HIERARCHY & STUDY ORGANIZATION	3-4
SECTION 4 DEFINITION OF PERFORMANCE PARAMETER & STANDARDS OF PERFORMANCE	4-1
4.1 PERFORMANCE PARAMETER GUIDELINES	4.1-1
4.2 ALTERNATE DATA SOURCES	4.2-1
4.2.1 Sources of Directly-Usable Data	4.2-1
4.2.2 Sources of Base Information	4.2-23
4.3 ENVIRONMENT MODELS	4.3-1
4.3.1 Natural Environment	4.3-1
4.3.2 Artificial Environment	4.3-39
4.3.2.1 Ground Navigation/Communication	4.3-40
4.3.2.2 Payloads and Rendezvous Targets	4.3-81
4.3.2.3 Prelaunch/Launch Interface	4.3-95
4.4 CREW STATION MODULES	4.4-1
4.4.1 Visual Drives	4.4-1
4.4.2 Motion Drives	4.4-5
4.5 VEHICLE CONFIGURATION MODULES	4.5-1
4.5.1 Aerodynamics	4.5-2
4.5.2 Aerothermodynamics	4.5-19
4.5.3 Mass Properties	4.5-34
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 Jocking 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

	<u>PAGE</u>	
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
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
4.8	MODULE INTEGRATION	4.8-1
4.9	SPECIAL TEST REQUIREMENTS	4.9-1
4.9.1	Survey of Conventional Test Operations	4.9-1
4.9.2	Idealized Test Programs	4.9-12
4.9.3	Implementation of Test Enhancements	4.9-14
4.10	REFERENCE DATA FORMATS	4.10-1

	<u>PAGE</u>	
4.10.1	Reference Data Types	4.10-1
4.10.2	Reference Data Generation, Handling and Conversion	4.10-2
4.11	DATA BASE IMPACT	4.11-1
4.11.1	Data Base Organization and Structure	4.11-1
4.11.2	Data Base Management	4.11-4
SECTION 5	METHODS FOR VALIDATING PERFORMANCE	5-1
5.1	VALIDATION SOFTWARE STRUCTURE	5.1-1
5.1.1	Checkpoint Generation Routines	5.1-1
5.1.2	Simulation Software Module Drivers	5.1-4
5.1.3	External Data Files	5.1-4
5.2	MODULE INTEGRATION	5.2-1
5.2.1	Configuration Definitions	5.2-1
5.2.2	Pros & Cons of Defined Configurations	5.2-4
5.3	CHECK CASE FORMULATION	5.3-1
5.3.1	Check Case Design Principles	5.3-1
5.3.2	Check Cases for Initial Validation	5.3-5
5.3.3	Check Cases for Revalidation	5.3-8
5.4	REALTIME DATA ACQUISITION AND FORMATTING	5.4-1
5.4.1	Data Acquisition Requirements, Goals and Constraints	5.4-1
5.4.2	Data Acquisition Subsystem Design and Implementation	5.4-2
5.5	COMPARISON METHODS AND CRITERIA	5.5-1
5.5.1	Display Methods for Manual Comparison	5.5-1
5.5.2	Automated Comparison Techniques	5.5-9
5.5.3	Agreement Between Manual and Automated Comparisons	5.5-11
SECTION 6	CONCLUSIONS AND RECOMMENDATIONS	6-1
SECTION 7	REFERENCES	7-1

LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
3-1	Use of subtask outputs	3-3
4.2-1	Closed-form solution driver	4.2-4
4.2-2	Independent math model driver	4.2-8
4.2-3	SVDS input program structure	4.2-11
4.2-4	SVDS program functional flow	4.2-12
4.2-5	Reference trajectory tape format	4.2-13
4.2-6	SVDS plot tape format	4.2-14
4.2-7	SVDS program input	4.2-16
4.2-8	SVDS program output	4.2-17
4.2-9	Driver for existing program subroutines	4.2-18
4.2-10	Example test data	4.2-21
4.2-11	Functional flow for use of test data	4.2-22
4.2-12	PICRS information system relationships	4.2-29
4.2-13	Shuttle Information Service functions	4.2-31
4.3-1	Natural environment simulation module interfaces	4.3-2
4.3-2	Natural environment reference module	4.3-5
4.3-3	Orbital atmospheric density reference module	4.3-10
4.3-4	1962 Standard Atmosphere reference module	4.3-16
4.3-5	Atmospheric wind reference module	4.3-30
4.3-6	Gravity potential reference module	4.3-33
4.3-7	Sun/Moon ephemeris reference module	4.3-34
4.3-8	Math flow for natural environment checkpoint routine	4.3-38
4.3-9	Ground nav/comm simulation module interfaces	4.3-42
4.3-10	Artificial environment reference module	4.3-46
4.3-11	STDN/TDRS communication reference module	4.3-47
4.3-12	SGLS communication reference module	4.3-53
4.3-13	UHF communication reference module	4.3-55
4.3-14	Dual S-Band communication reference module	4.3-57
4.3-15	Ground nav/aids reference module	4.3-59
4.3-16	Ground nav/comm checkpoint generation routine	4.3-64
4.3-17	Dual S-Band checkpoint generation routine	4.3-68
4.3-18	UHF checkpoint generation routine	4.3-70
4.3-19	STDN/TDRS checkpoint generation routine	4.3-72
4.3-20	SGLS checkpoint generation routine	4.3-74

<u>FIGURE</u>		<u>DATE</u>
4.3-21	Ground nav/aids checkpoint generation routine	4.3-76
4.3-22	Ground nav/comm checkpoint completion module	4.3-78
4.3-23	Payload/target simulation module interfaces	4.3-85
4.3-24	Payload/target reference module	4.3-89
4.3-25	Prelaunch/launch-interface simulation module interfaces	4.3-98
4.3-26	Prelaunch/launch-interface reference module	4.3-102
4.4-1	Shuttle mission visual-scene content	4.4-2
4.4-2	Visual system interfaces	4.4-3
4.4-3	Payload-handling CGI display requirements	4.4-4
4.4-4	Synergistic motion-base configuration	4.4-7
4.4-5	Motion-base software interfaces	4.4-8
4.5-1	Shuttle vehicle body coordinate systems	4.5-4
4.5-2	Aerodynamics simulation module interfaces	4.5-5
4.5-3	Aerodynamics reference module	4.5-11
4.5-4	Reference data carpet plot	4.5-14
4.5-5	Orbiter lift/drag characteristics	4.5-16
4.5-6	Baseline entry trajectory event summary	4.5-17
4.5-7	Orbiter thermal protection subsystem	4.5-20
4.5-8	Bondline thermocouple locations	4.5-21
4.5-9	Typical thermocouple type locations	4.5-22
4.5-10	Aerothermodynamics simulation module interfaces	4.5-24
4.5-11	Aerothermodynamics reference module	4.5-26
4.5-12	Step input check case	4.5-33
4.5-13	Mass properties simulation module interfaces	4.5-36
4.5-14	Mass properties reference module	4.5-39
4.5-15	MASS 19 reference module	4.5-41
4.5-16	Payload/target mass properties reference module	4.5-43
4.6-1	Ground contact force and moment reactions	4.6-2
4.6-2	Steering and braking force and moment reactions	4.6-2
4.6-3	Docking-target precontact conditions	4.6-4
4.6-4	Payload deployment force and moment reactions	4.6-4
4.6-5	Vehicle dynamics simulation module interfaces	4.6-6
4.6-6	Bending & slosh dynamics reference module	4.6-15
4.6-7	Translational dynamics reference module	4.6-25
4.6-8	Rotational dynamics reference module	4.6-29

<u>FIGURE</u>		<u>PAGE</u>
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
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	PDR/i 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

<u>FIGURE</u>		<u>PAGE</u>
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
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
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

<u>FIGURE</u>		<u>PAGE</u>
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
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 checkpoint 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

<u>FIGURE</u>		<u>PAGE</u>
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 checkpoint 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
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
4.8-1	Probable integration sequence for spacecraft simulators	4.8-2
4.9-1	Coldplate heat transfer coefficients	4.9-4
4.9-2	Coolant pump flow rate characteristics	4.9-6
4.9-3	Integrated-system-test "script"	4.9-9
4.10-1	Universal format for validation data files	4.10-4
4.11-1	Validation data base scope and structure	4.11-2

<u>FIGURE</u>		<u>PAGE</u>
5.1-1	Basic performance-verification software flow	5.1-2
5.2-1	Example check cases for a module cluster	5.2-3
5.3-1	Two-dimensional illustrations of checkpoint generation methods	5.3-4
5.3-2	Confidence relationships for initial validation	5.3-7
5.3-3	Confidence relationships for revalidation	5.3-7
5.4-1	Realtime data acquisition subsystem interfaces	5.4-3
5.5-1	Example raw-data time-history plot	5.5-3
5.5-2	Example numerical-difference plot	5.5-5
5.5-3	Example simulation-error plot	5.5-6
5.5-4	Parameter-plane plotting formats	5.5-7
5.5-5	Contour plot of simulation error	5.5-8
5.5-6	Dynamical system used for experiment data	5.5-12
5.5-7	"Reference" time-history plot used in the experiment	5.5-13
5.5-8	Time-history plots used in the experiment	5.5-14
5.5-9	Instruction sheet for experimental subjects	5.5-24

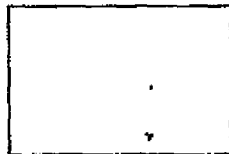
<u>TABLE</u>	LIST OF TABLES	<u>PAGE</u>
3-1	Simulation software structure overview	3-5
3-2	Complete simulation software hierarchy	3-7
4.2-1	Alternate data sources: pros & cons	4.2-2
4.2-2	Example shuttle fluid diagrams	4.2-25
4.2-3	Example system requirements documents	4.2-26
4.3-1	Natural environment simulation module parameters	4.3-3
4.3-2	Ground nav/comm simulation module parameters	4.3-43
4.3-3	Payload/target simulation module parameters	4.3-86
4.3-4	Prelaunch/launch-interface simulation module parameters	4.3-100
4.4-1	Visual drive module parameters	4.4-6
4.4-2	Motion-base drive module parameters	4.4-9
4.5-1	Aerodynamics simulation module parameters	4.5-6
4.5-2	Orbiter aerodynamic data tape information	4.5-7
4.5-3	Aerothermodynamics simulation module parameters	4.5-23
4.5-4	Mass properties simulation module parameters	4.5-37
4.6-1	Vehicle dynamics simulation module parameters	4.6-7
4.6-2	Mission-phase implementation of translational EOM simulation	4.6-10
4.6-3	Multiple-body EOM simulation modes	4.6-12
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	PDRS 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

<u>TABLE</u>		<u>PAGE</u>
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
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
4.9-1	Potentially useful test documentation	4.9-11
4.11-1	Basic CODASYL data base definitions	4.11-8
5.1-1	Generic validation software modules	5.1-3
5.2-1	Validation at various levels of integration	5.2-5
5.3-1	Mission/mission-phase check cases	5.3-10
5.5-1	Subjective ranking of experiment data	5.5-26
5.5-2	Subjective ranking for different experience groups	5.5-26
5.5-3	Objective ranking for simple criteria	5.5-27
5.5-4	Subjective vs. objective evaluation for simple criteria	5.5-29
5.5-5	Subjective vs. objective evaluation for feature extraction	5.5-29

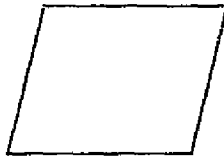
LIST OF SYMBOLS

1. FLOW CHART SYMBOLS

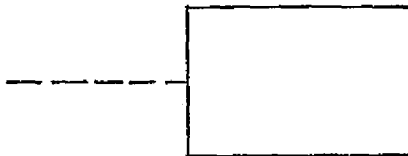
Flow charts shown in this report conform to American National Standard X3.5-1970, "Flow Chart Symbols and Their Usage in Information Processing". Symbols of interest are defined below.



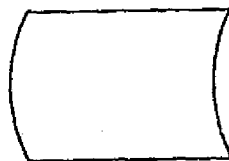
Process: Computation, storage move, etc.



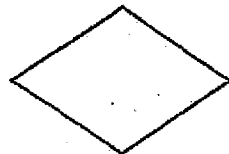
Input/Output



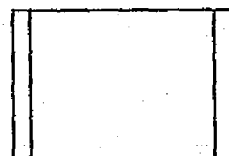
Comment, annotation



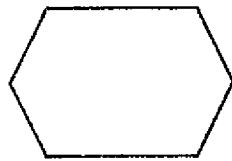
On-line storage (e.g., disk)



Decision



Predefined process, subroutine



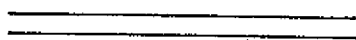
Preparation, initialization



Program terminus: begin, end, return, stop, etc.



Flowline connector



Parallel mode: multitasking, databus

2. ACRONYMS

The acronyms listed below are those of fairly general use within this report.

APU	Auxiliary Power Unit
ATCS	Active Thermal Control System
CGI	Computer-Generated Image
C & W	Caution & Warning
ECLS	Environmental Control/Life Support
EOM	Equations of Motion
EPG	Electrical Power Generation
EPS	Electrical Power Subsystem
ET	External Tank
GN&C	Guidance, Navigation & Control
IMU	Inertial Measurement Unit
MDM	Multiplexer/Demultiplexer
ME	Main Engine
MPS	Main Propulsion System
MSBLS	Microwave Scanning-Beam Landing System
OMS	Orbital Maneuvering System

PDR	Preliminary Design Review
PDRS	Payload Deployment & Retrieval System
PMS	Performance Monitoring System
PRSD	Power Reactants Supply & Distribution
P/T	Payload/Target
RCS	Reaction Control System
SGLS	Space/Ground Link System
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSFS	Space Shuttle Functional Simulation
STDN	Spaceflight Tracking & Data Network
SVDS	Space Vehicle Dynamic Simulation
TACAN	Tactical Air Navigation
TBS	To Be Supplied
TDRS	Tracking & Data Relay Satellite
UHF	Ultra-High Frequency

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 25 provided Figure 4.7-65, a schematic of the fuel cell interfaces with other systems. Figure 4.7-66 (also from Reference 25) 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

4.7-133

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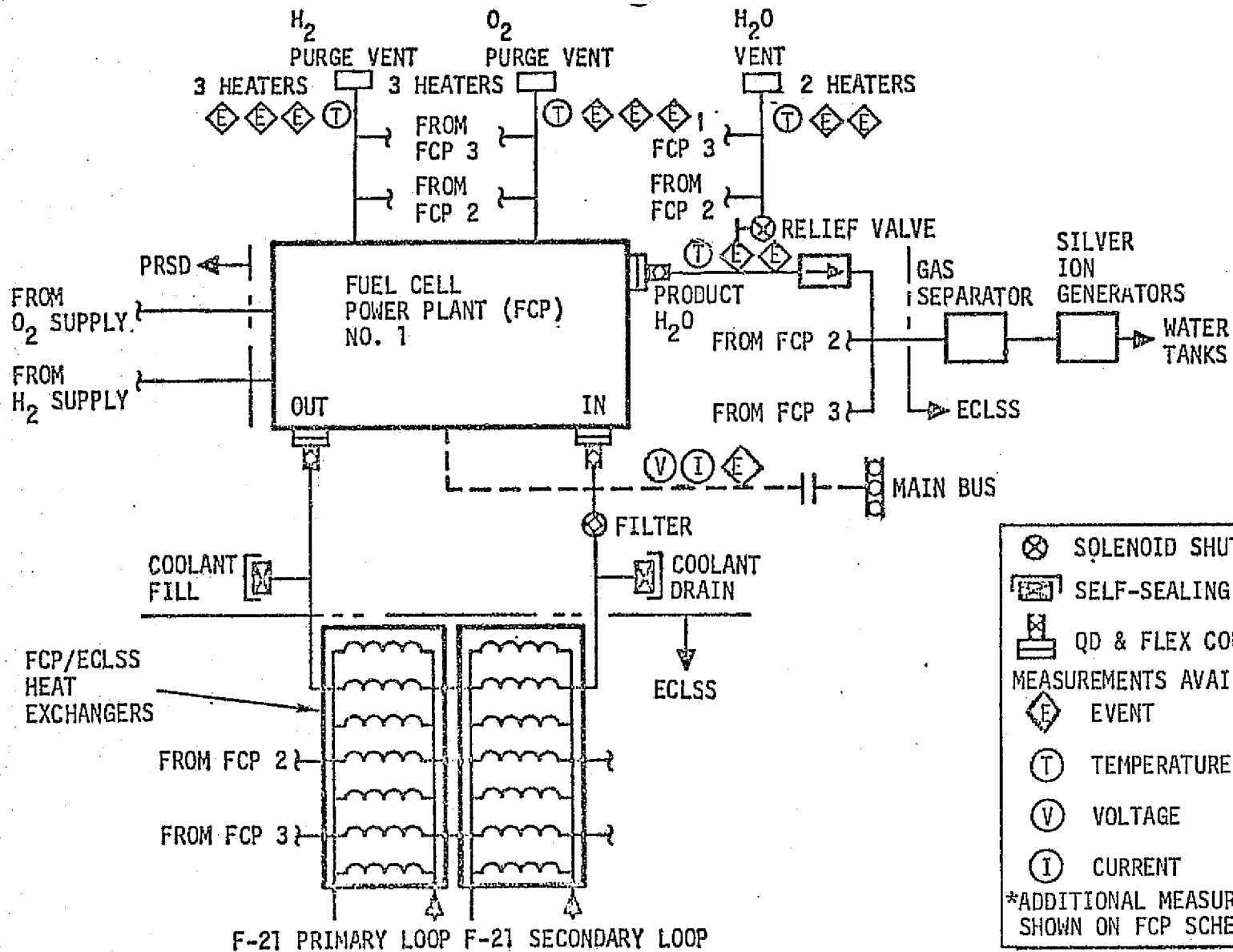


FIGURE 4.7-65 ELECTRICAL POWER GENERATION
(EPG) DESCRIPTION
FCP SUBSYSTEM SCHEMATIC

4.7-13A

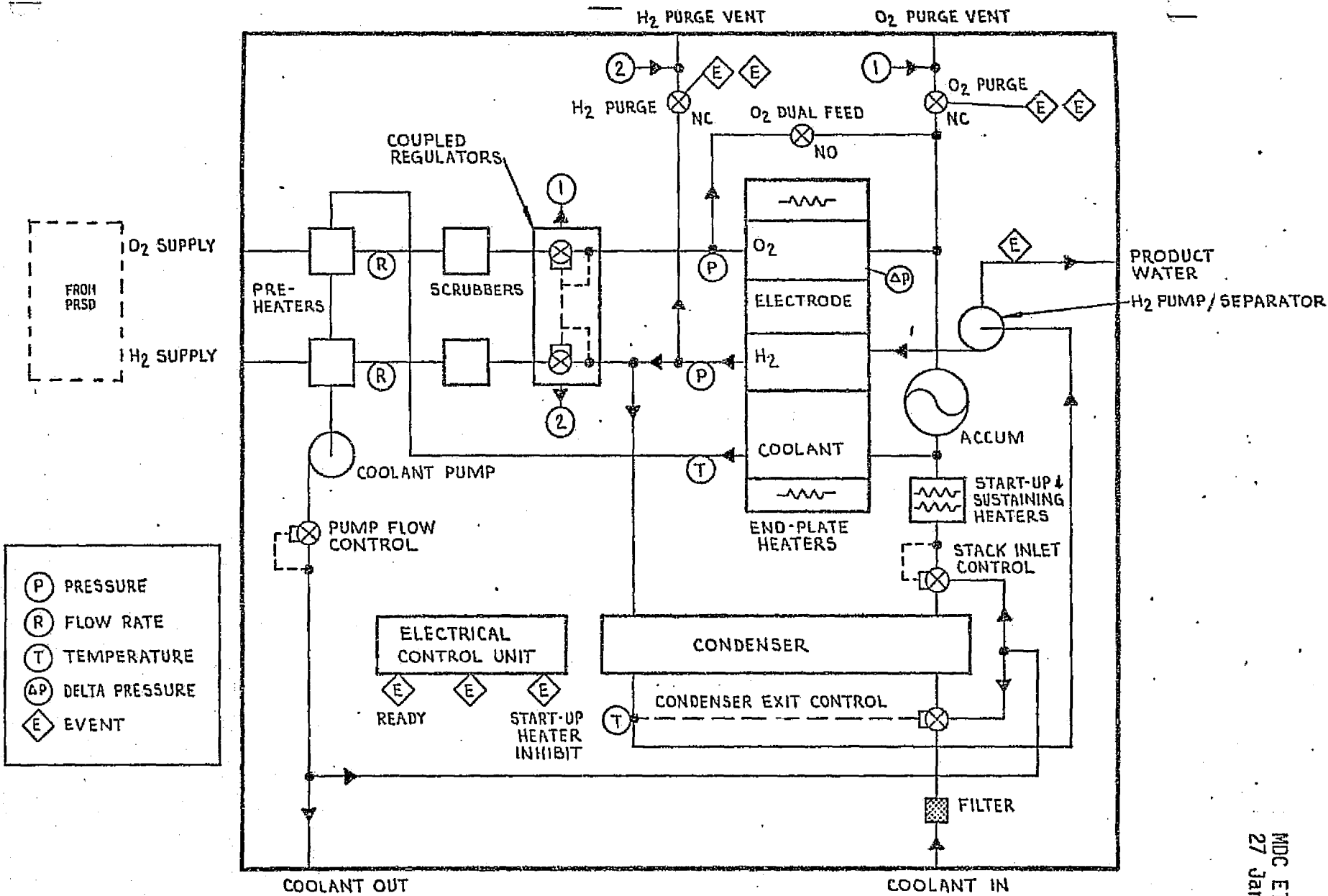


FIGURE 4.7-66, EPG DESCRIPTION, FUEL CELL POWER PLANT SCHEMATIC

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 25 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.

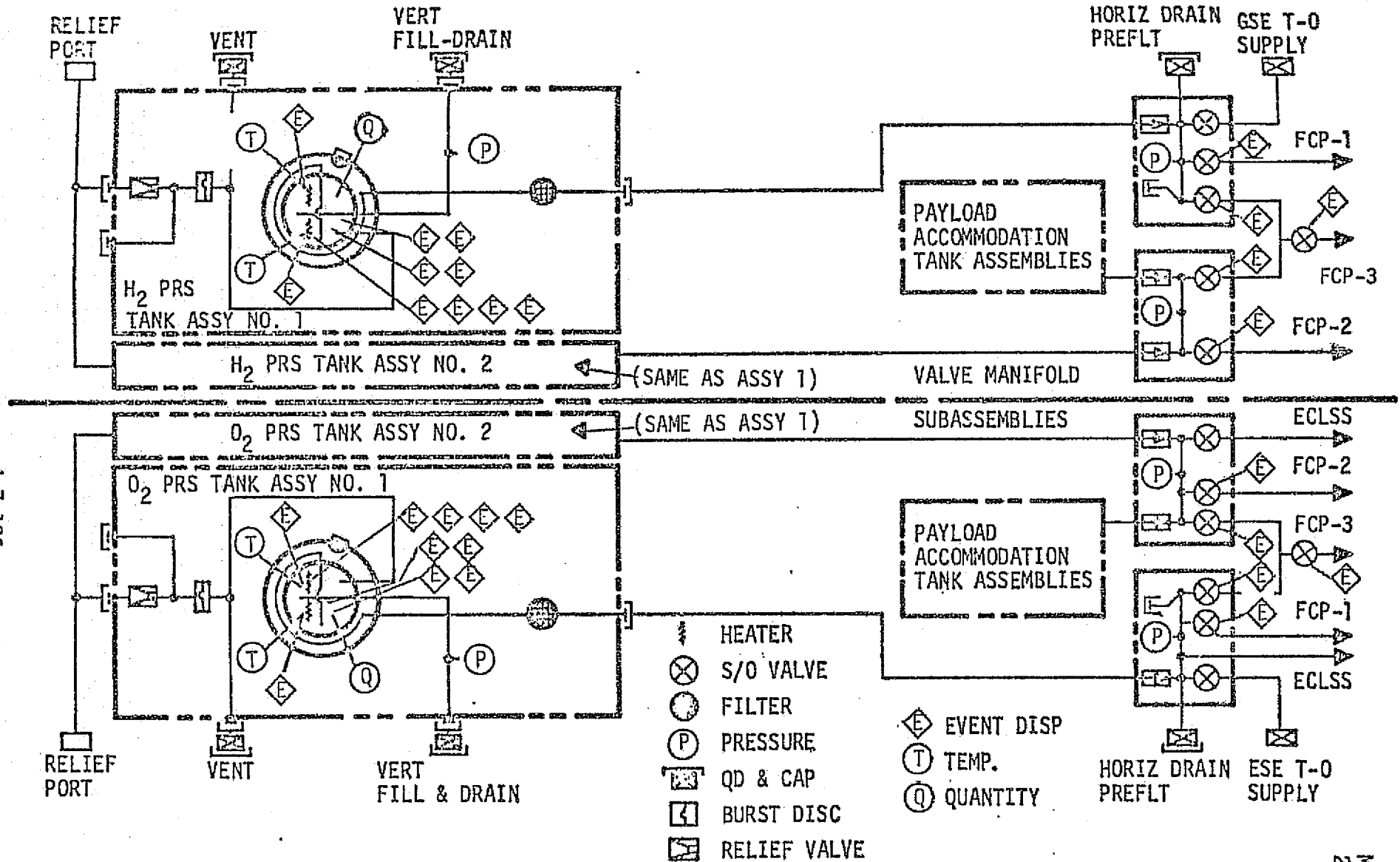


FIGURE 4.7-67 POWER REACTANT STORAGE AND DISTRIBUTION (PRSD) SUBSYSTEM SCHEMATIC

4.7-187

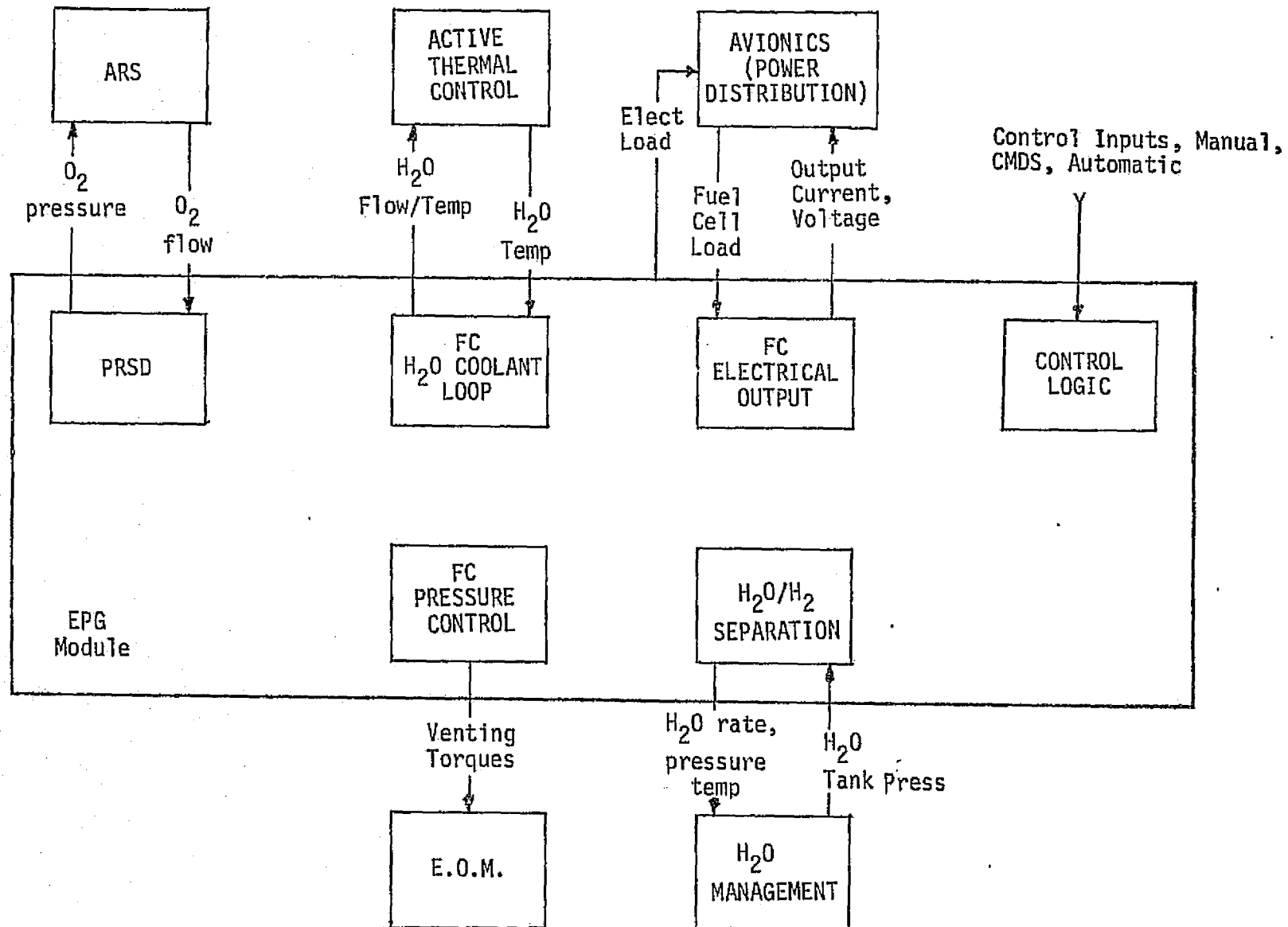


FIGURE 4.7-68. ELECTRICAL POWER GENERATION MODULE ELEMENTS AND INTERFACE WITH OTHER MODULES.

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 64. The requirements, analysis and predictions can be determined from Reference 22, design or analysis groups, and MPAD. Many of the test results can be acquired from individual acceptance tests and integrated-systems checkout. Reference 63 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 O₂ 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-H₂ parameters would be identical to the O₂ except for the fluid characteristics. Reference 65 can be used as a source of O₂ characteristics while Reference 66 provides the H₂ characteristics. Reference 22 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

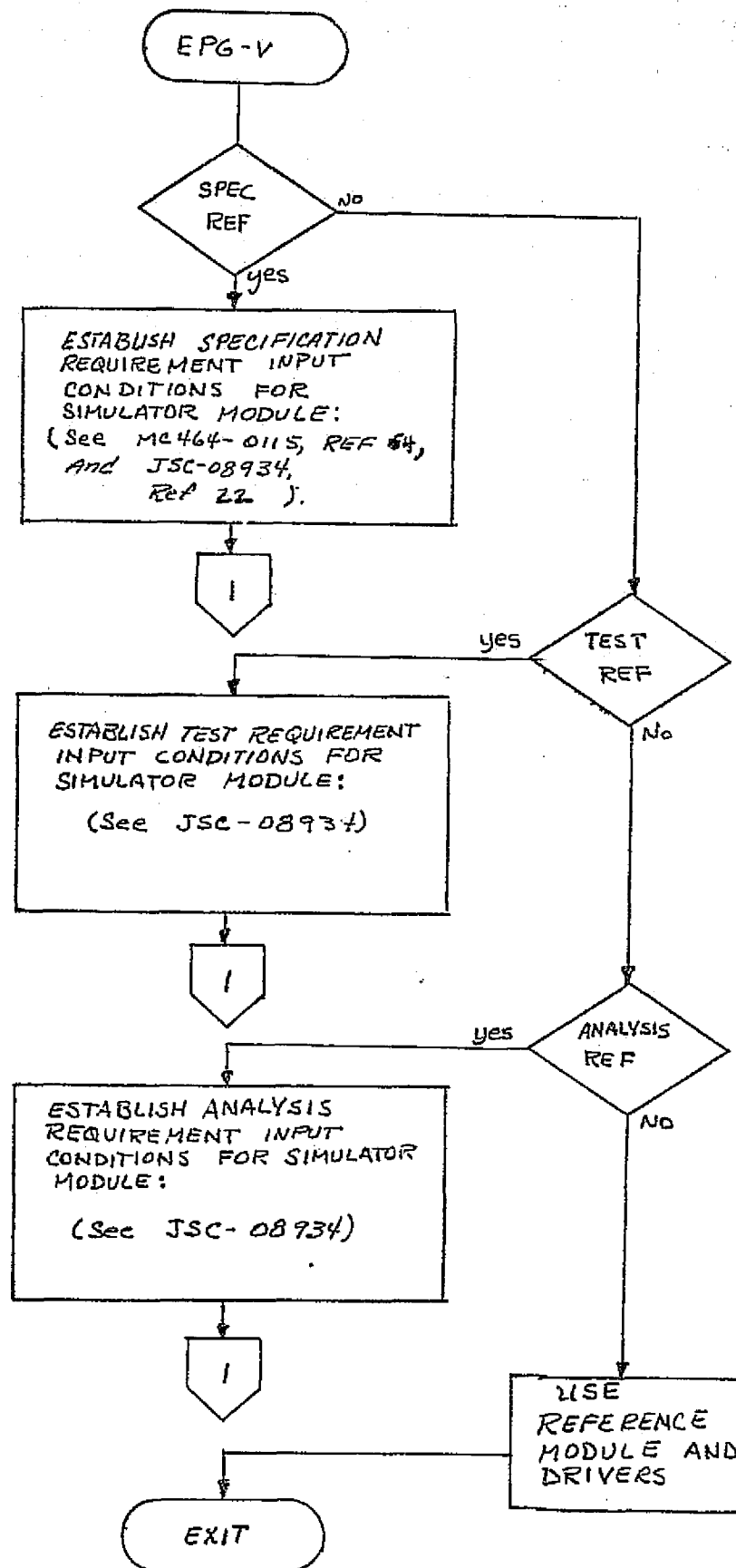


FIGURE 4.7-69. BASIC EPG VERIFICATION DATA SOURCE FLOW CHART

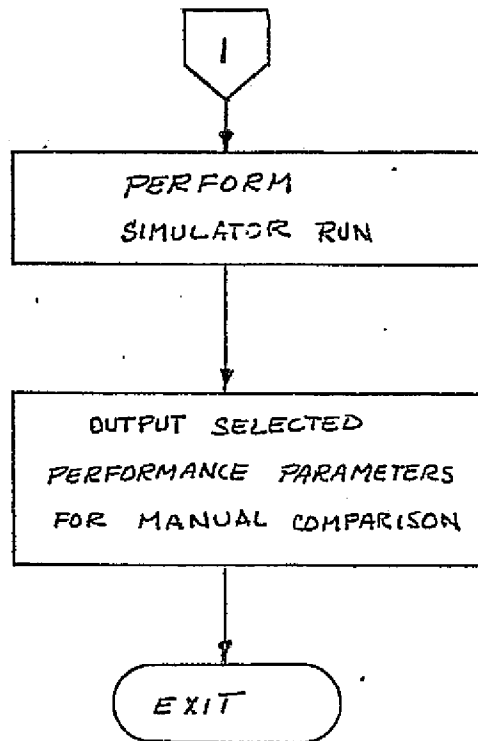


FIGURE 4.7-69. (CONTINUED)

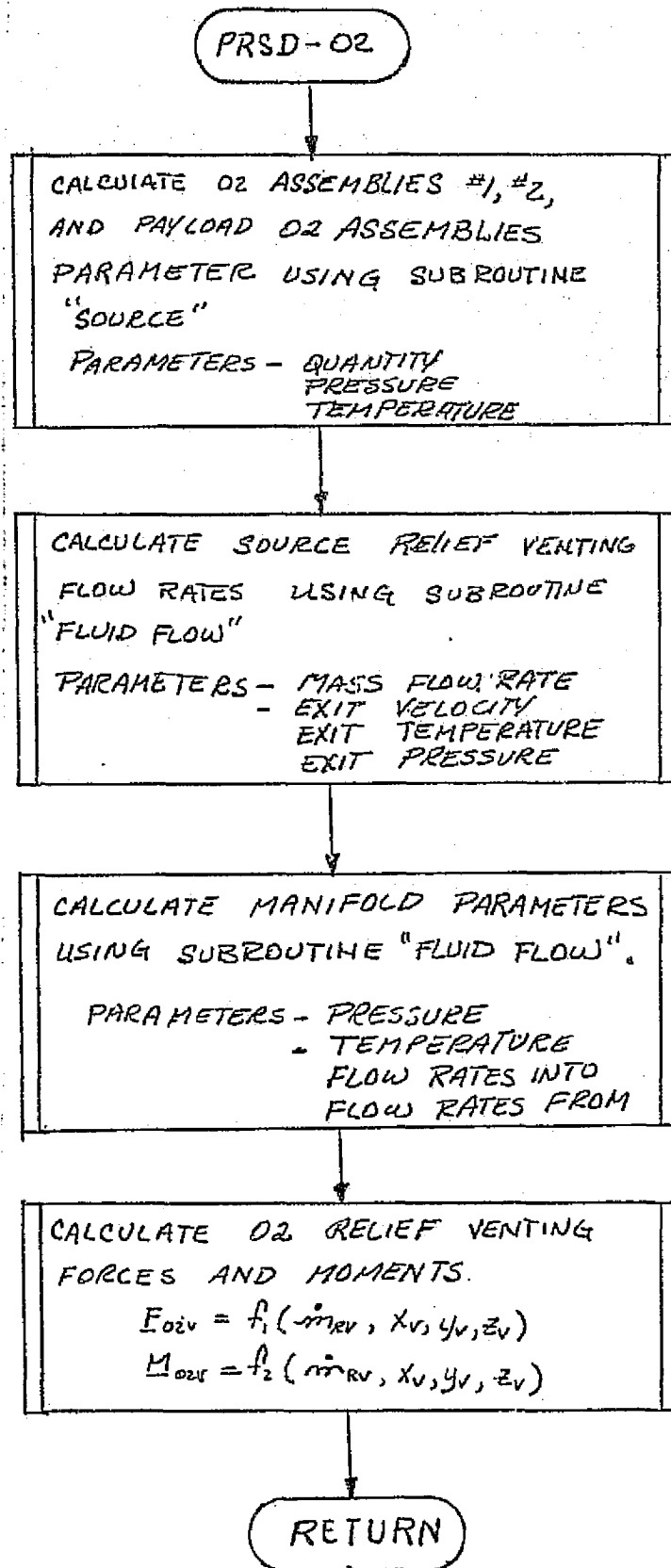
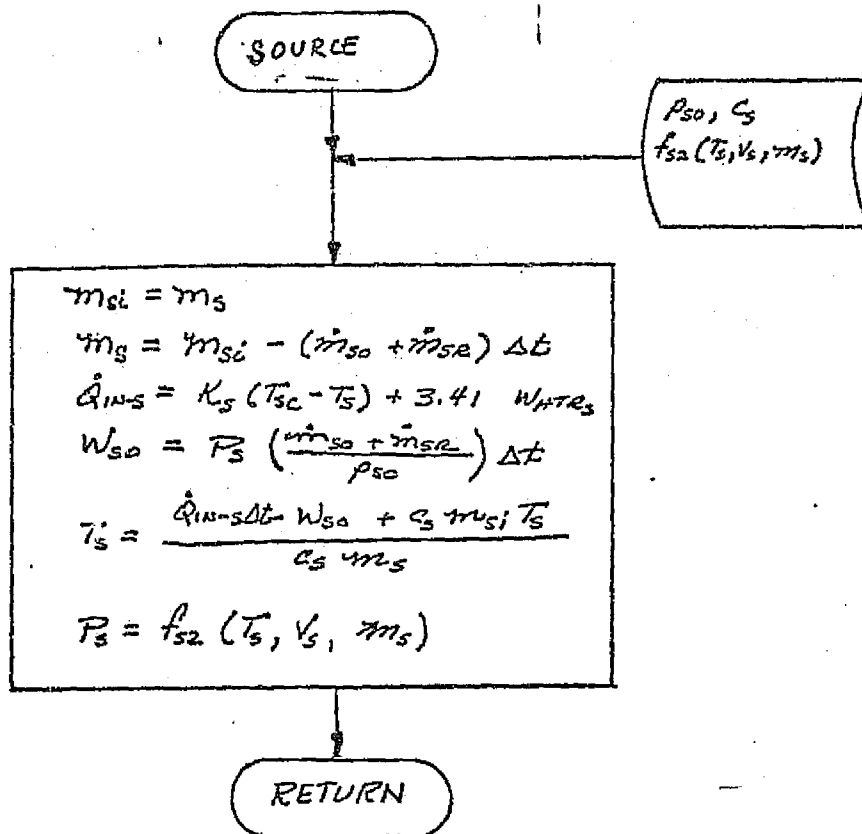


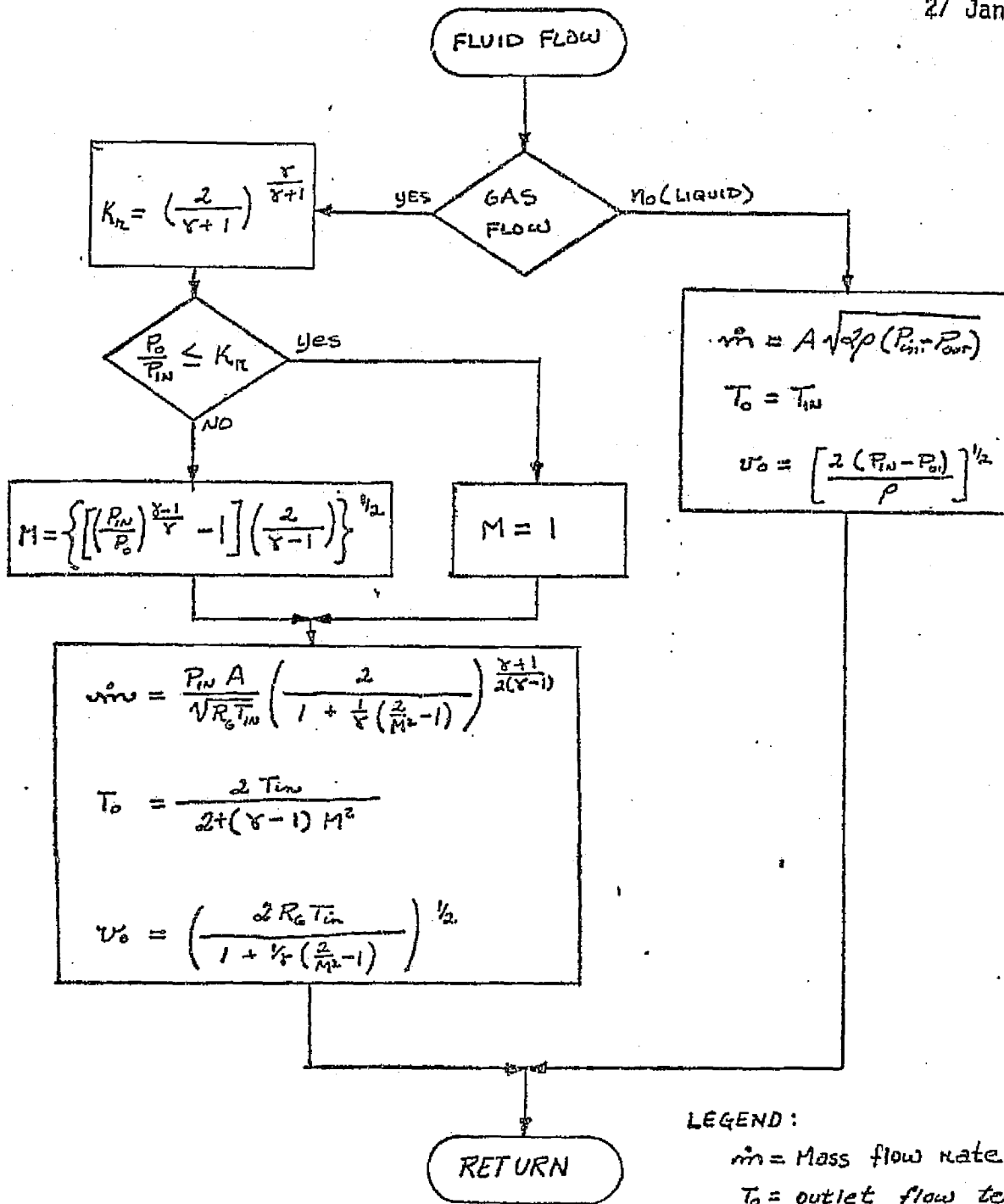
FIGURE 4.7-70. PRSD REFERENCE MODULE OVERALL MATH FLOW



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_s = FLUID DENSITY
- c_s = FLUID SPECIFIC HEAT
- T_{sc} = TANK COMPARTMENT TEMPERATURE
- W_{HTR_s} = 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_{cr} = critical Pressure Ratio
M = Mach number

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

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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 25) 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

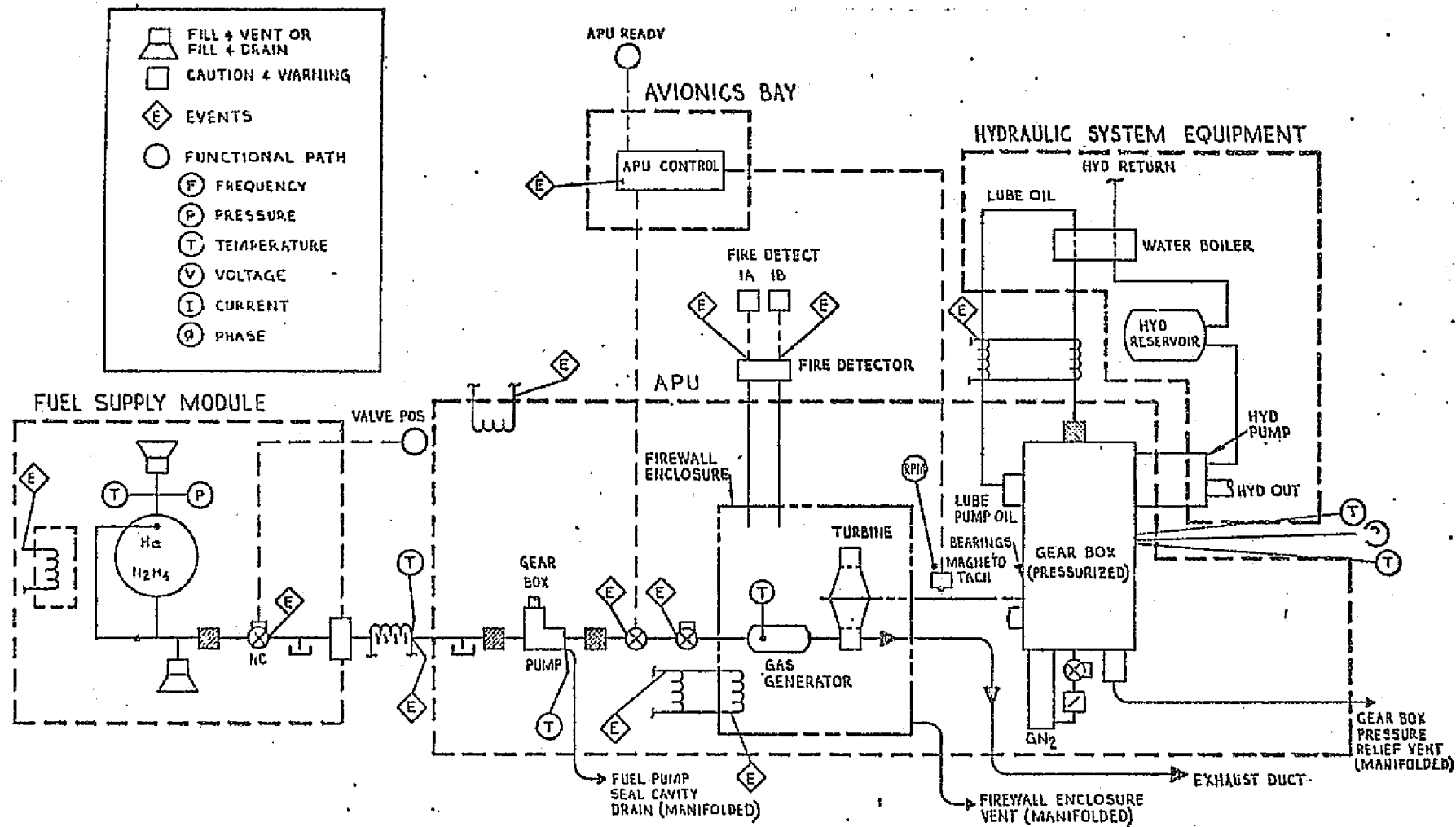


FIGURE 4.7-73 APU SUBSYSTEM OPERATIONAL MEASUREMENTS (TYP-4)

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

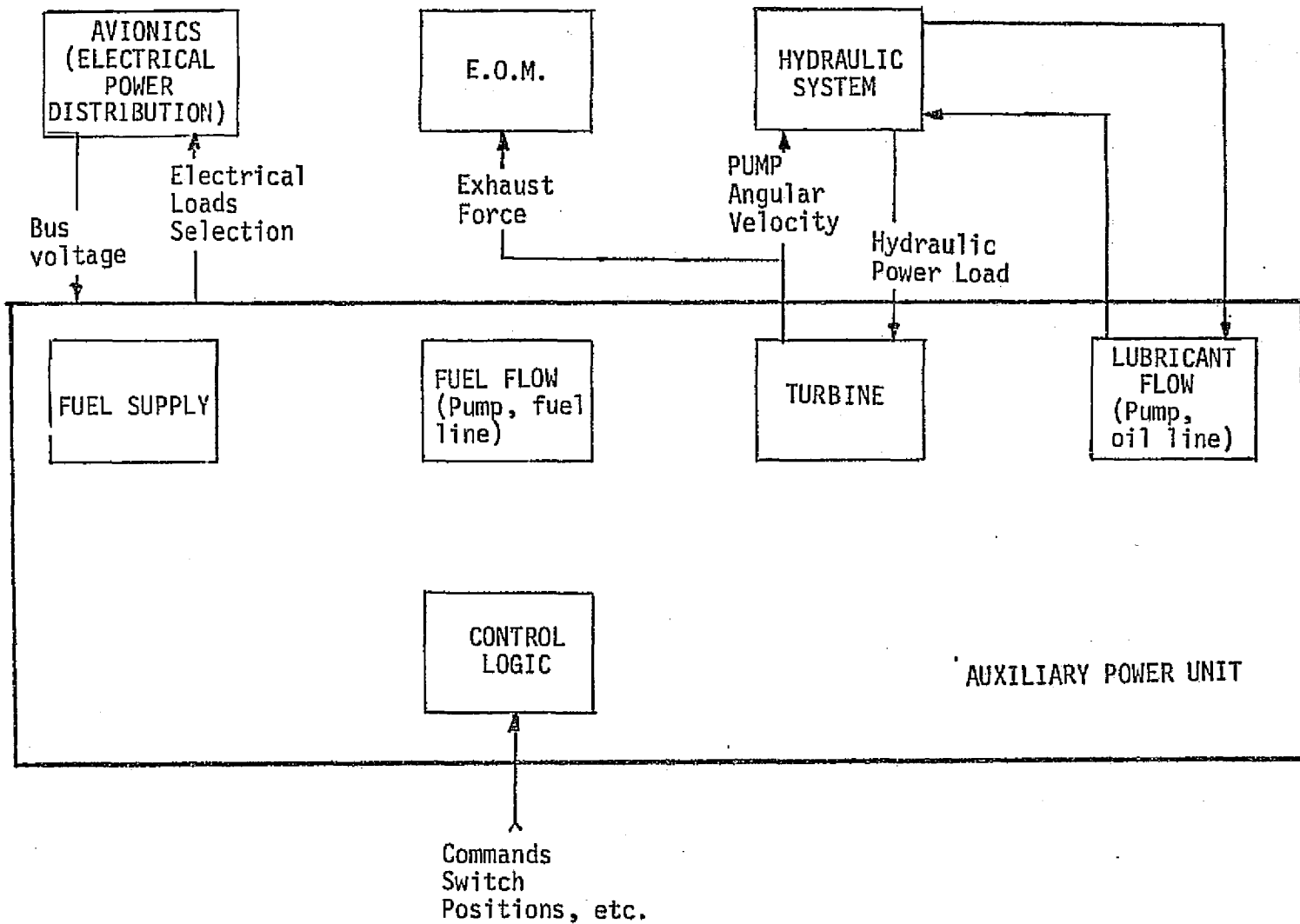


FIGURE 4.7-74. APU REFERENCE MODULE FUNCTIONAL ELEMENTS AND INTERFACES WITH OTHER MODULES.

TABLE 4.7-21 APU REFERENCE MODULE PARAMETER LIST (From Ref. 9)

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

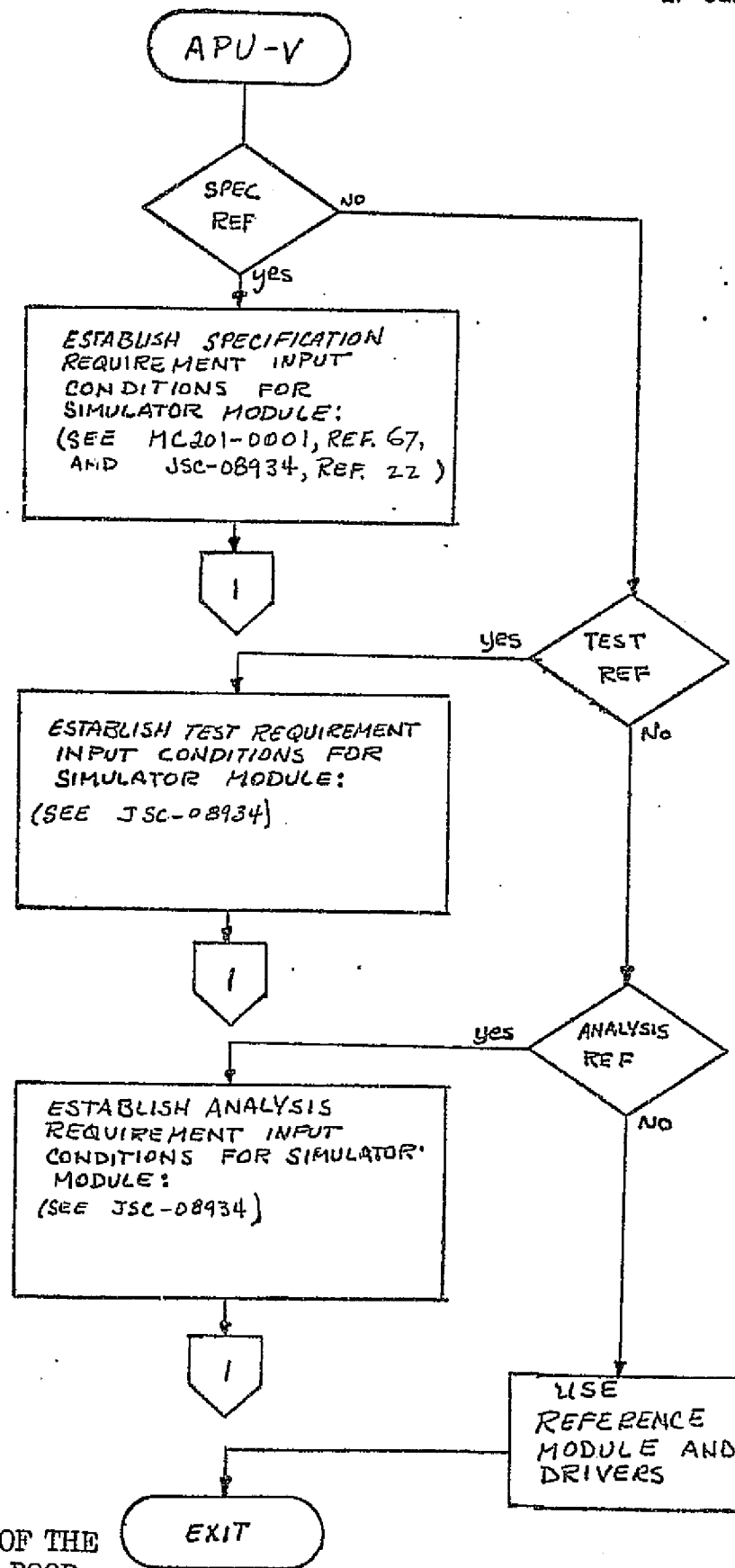
- Valve control(s) - function of input commands, turbine speed, temperatures.

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 67) - provides system and component design perfor-



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FIGURE 4.7-75. FLOW CHART FOR APU VERIFICATION
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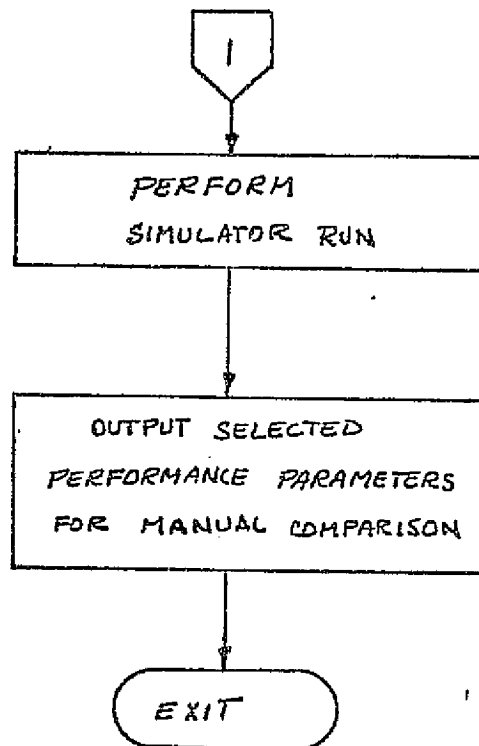


FIGURE 4.7-75. (CONTINUED)

mance requirements.

- JSC-08934, Vol. I (Reference 22) - provides a compilation of design requirements, analysis results, test results, and performance predictions for various Shuttle systems.
- SAPUCM (Reference 68) - 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:

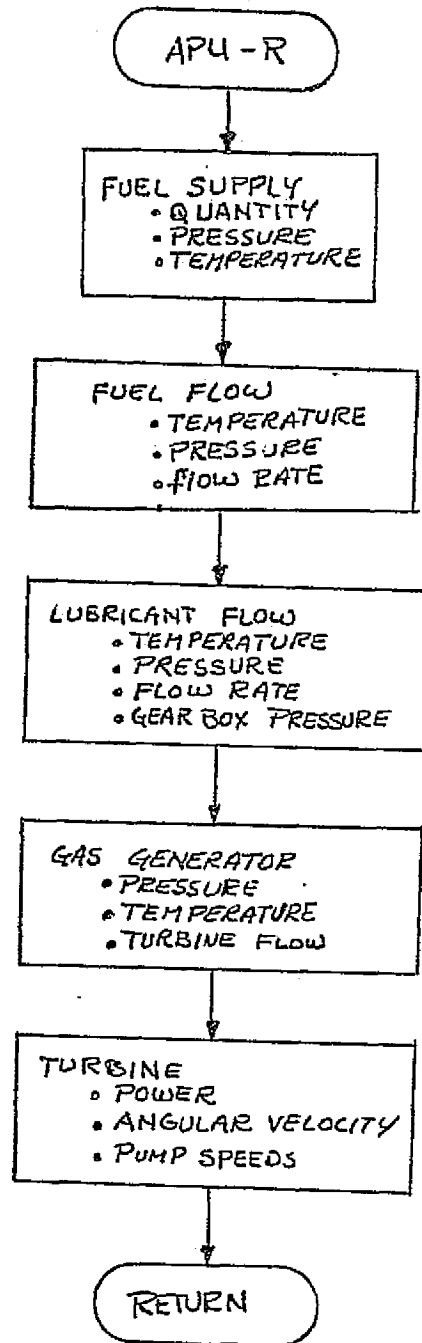
- Hydraulic power - system functions, power load, and lubricating oil (Gearbox) cooling
- Electrical power bus voltages
- Control logic inputs

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

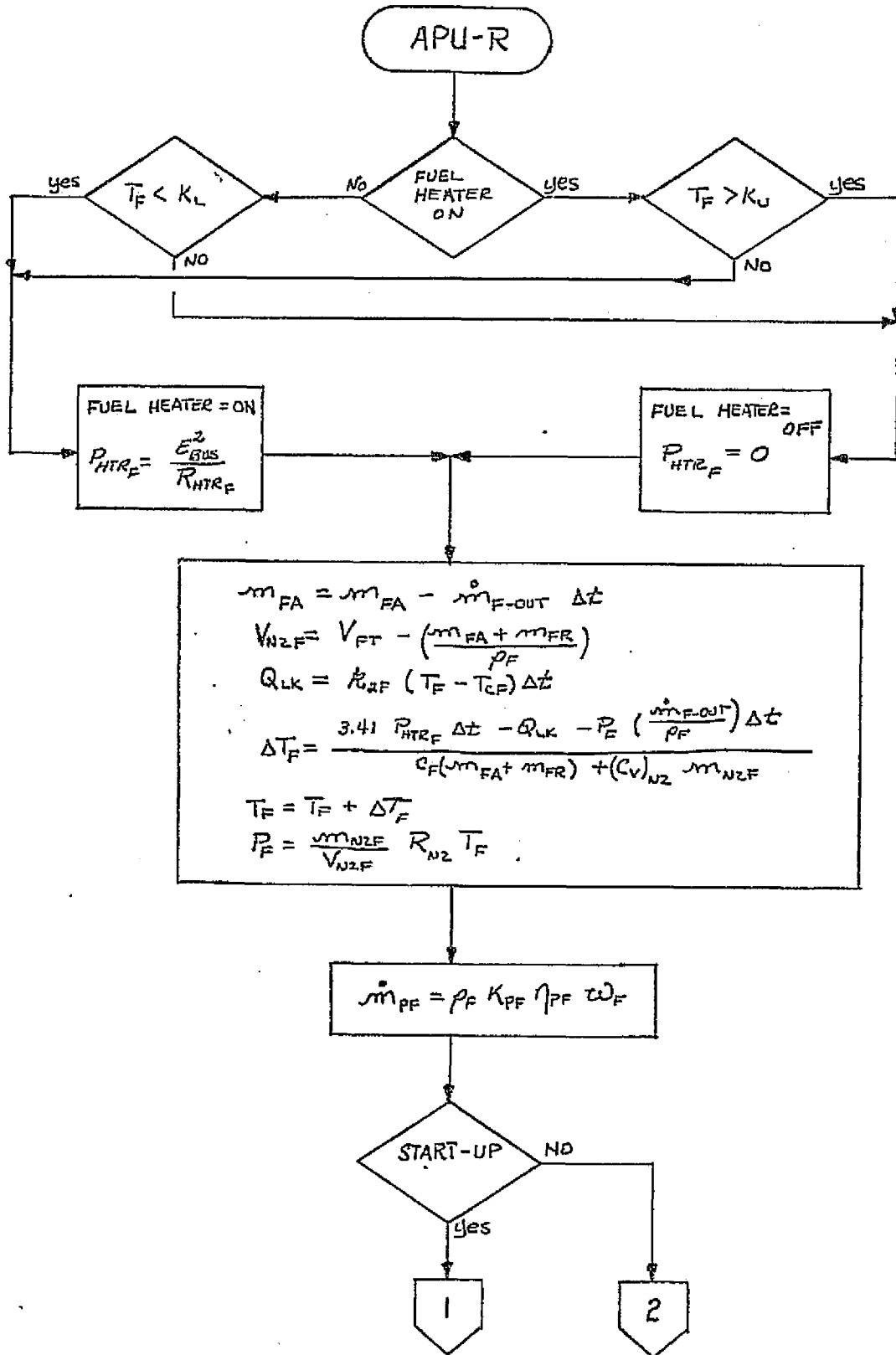
The impacts on the simulator data base are associated with the reference module, special drivers and check case data files. The selected APG reference module will have a large impact. The development of Figure 4.7-76 into a reference module (or the use of some detailed model) will be the bulk of the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

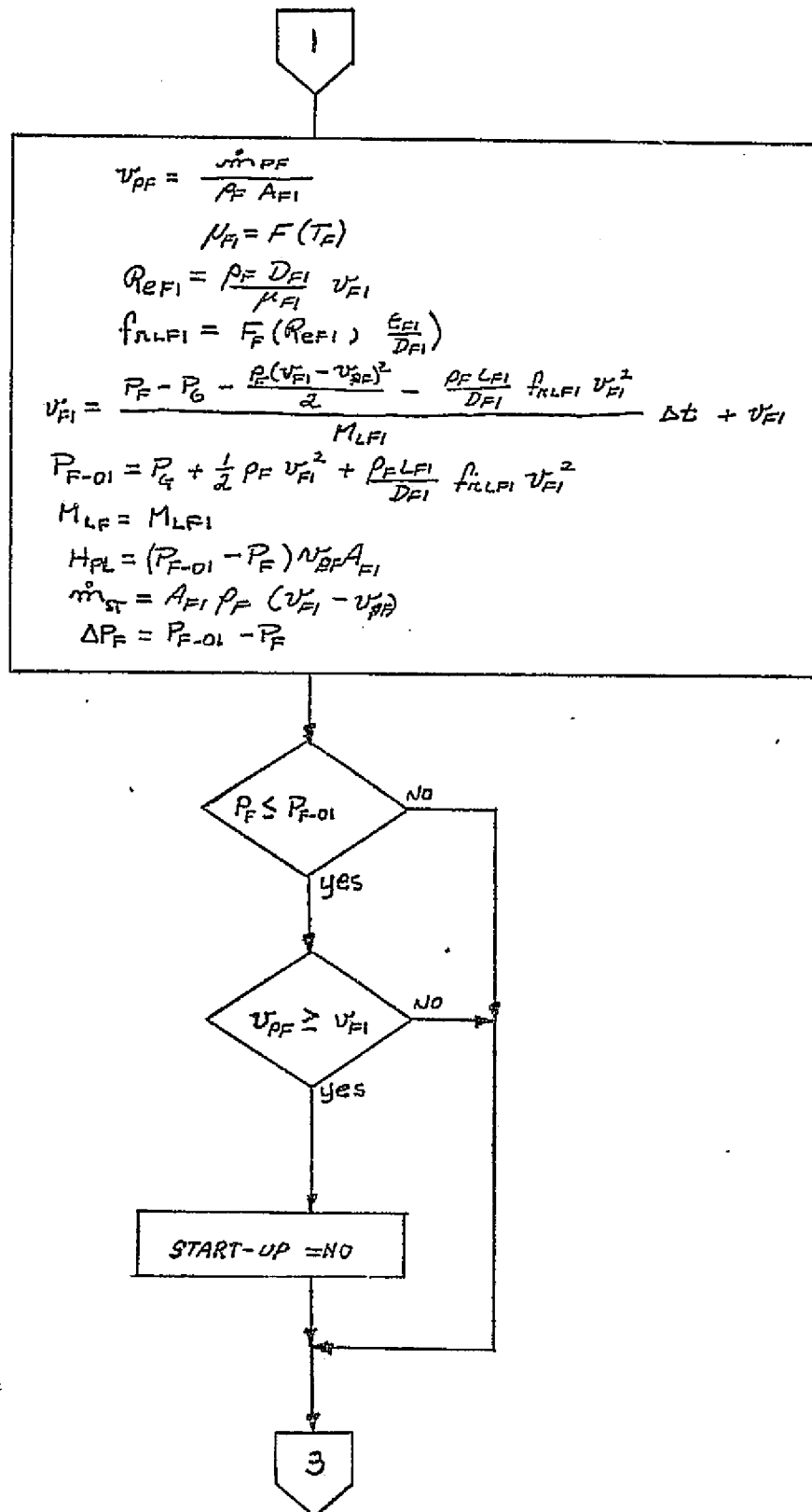


FIGURE 4.7-76. (CONTINUED)

4.7-210

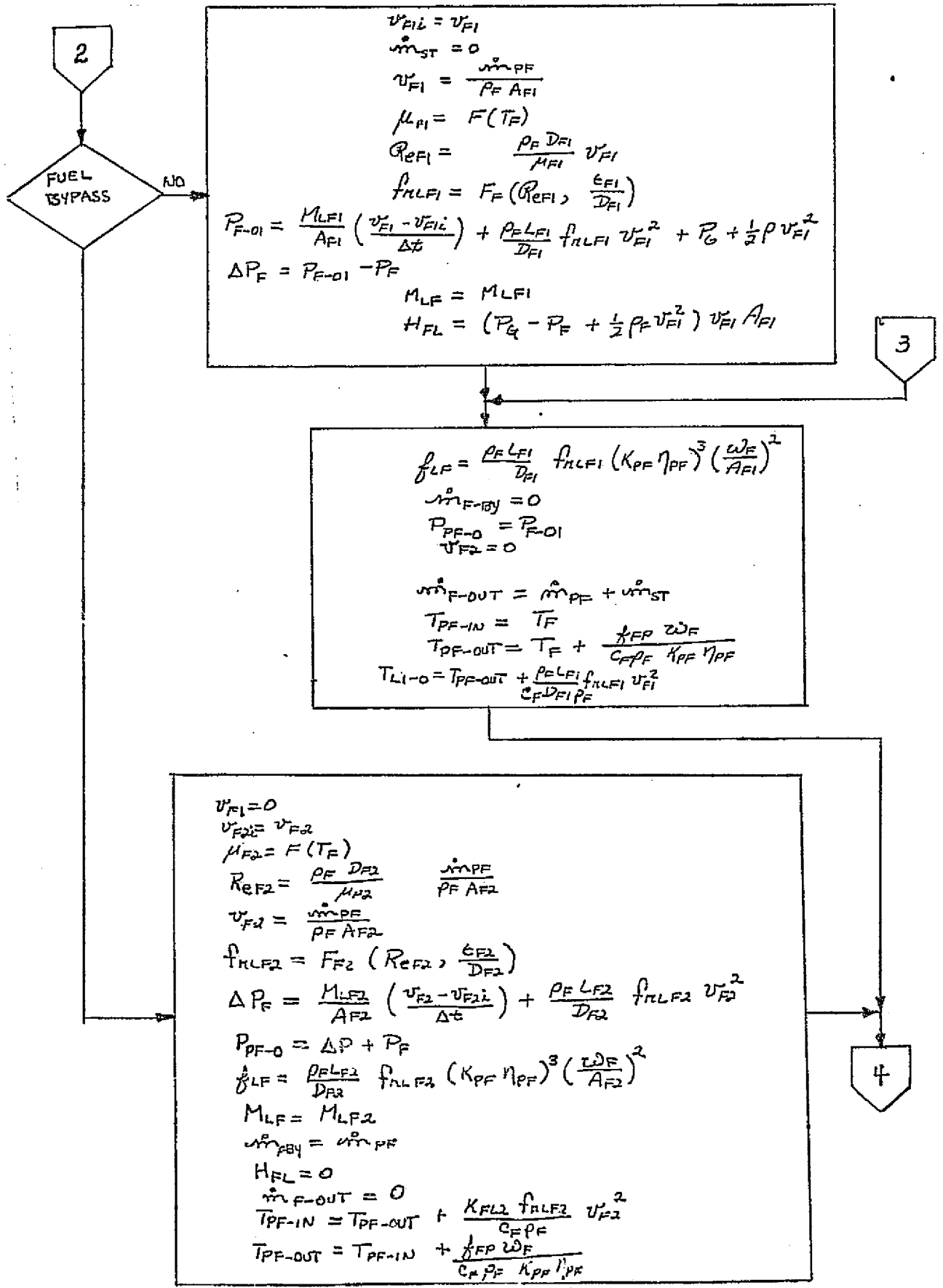


FIGURE 4.7-76. (CONTINUED)



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

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

$$\dot{m}_{F1} = v_{F1} \rho_F A_{F1}$$

$$\dot{m}_{P0} = \rho_0 K_{P0} \eta_{P0} W_0$$

$$T_{P0-0} = T_{GB} + \frac{f_{OP} W_0}{C_0 \rho_0 K_{P0} \eta_{P0}}$$

$$v_{0i} = v_0$$

$$K_{OL} = \frac{\rho_0 L_0}{D_0}$$

$$\mu_0 = F(T_{GB})$$

$$v_0 = \frac{\dot{m}_{P0}}{\rho_0 A_{OL}}$$

$$Re_0 = \frac{\rho_0 D_0}{\mu_0} v_0$$

$$f_{NLO} = F(Re_0, \frac{L_0}{D_0})$$

$$\Delta P_0 = \frac{M_{LO}}{A_{OL}} \left(\frac{v_0 - v_{0i}}{\Delta t} \right) - \frac{\rho_0 L_0}{D_0} f_{NLO} v_0^2 - \frac{1}{2} \rho_0 v_0^2$$

$$P_{OP-OUT} = P_{GB} + \Delta P_0$$

$$f_0 = f_{OP} + K_{OL} f_{NLO} (K_{P0} \eta_{P0})^3 \left(\frac{W_0}{A_{OL}} \right)^2$$

$$J_0 = J_{OP} + (\eta_{P0} K_{P0})^2 M_{LO}$$

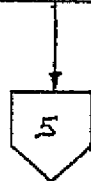
$$T_{OL-OUT} = T_{GB0} + \frac{K_{OL} f_{NLO} v_0^2}{C_0 \rho_0}$$

$$H_{OL} = \frac{1}{2} \rho_0 v_0^3 A_0$$

$$\dot{Q}_{GB-IN} = \frac{f_{GS} W_T^2}{2} + \frac{1}{2} \dot{m}_{P0} v_0^2$$

$$\dot{Q}_{GB-OUT} = C_0 \dot{m}_{P0} (T_{GB} - T_{OL-OUT}) - C_{VNZ} \dot{m}_{DNZ} (T_{GB} - T_{SNZ})$$

$$T_{GB} = \Delta t \left(\frac{\dot{Q}_{GB-IN} - \dot{Q}_{GB-OUT}}{C_0 m_{OR} + C_{VNZ} m_{DNZ} + C_{GB} m_{GB}} \right) + T_{GB}$$



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FIGURE 4.7-76. (CONTINUED)

4.7-212

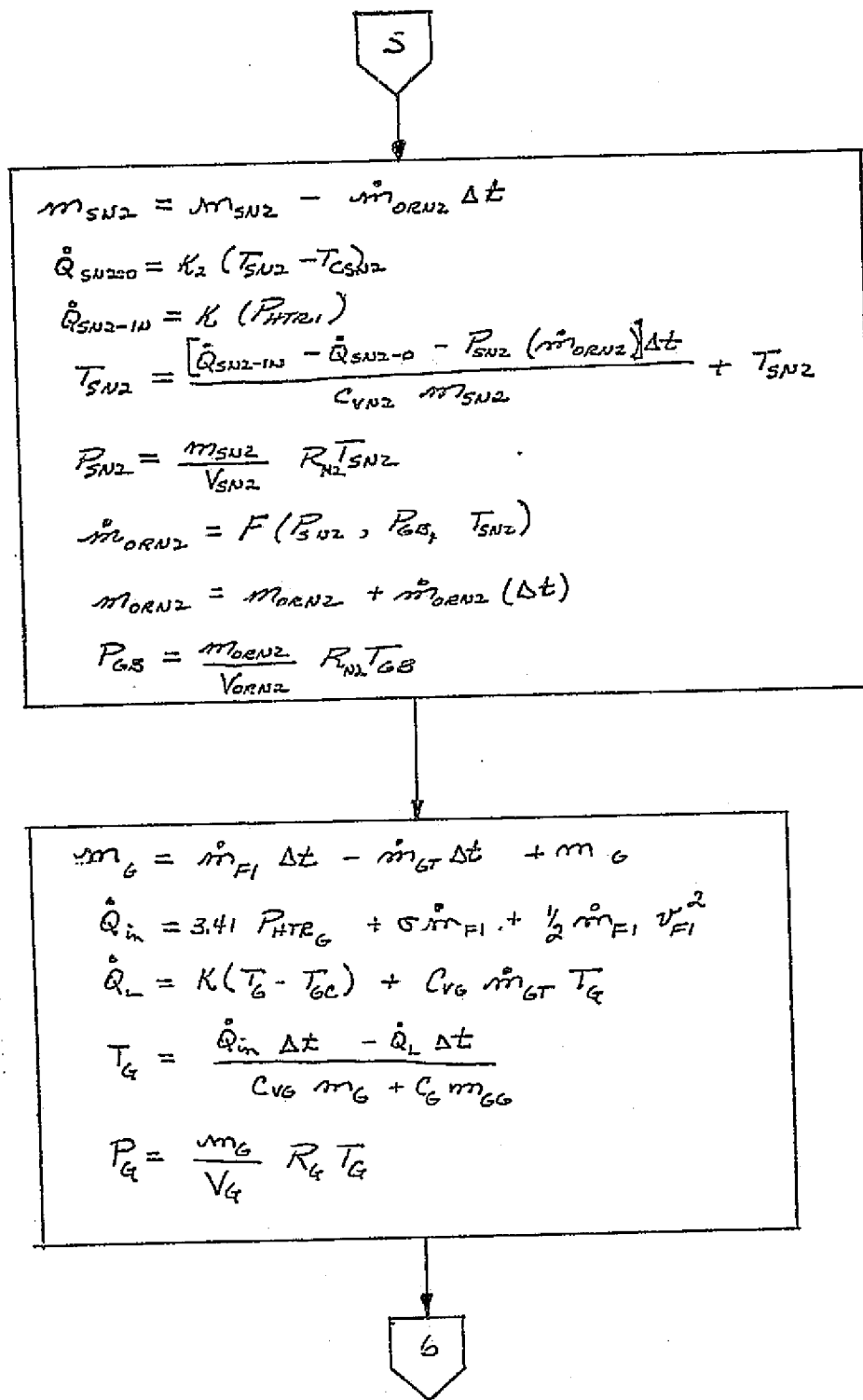


FIGURE 4.7-76. (CONTINUED)

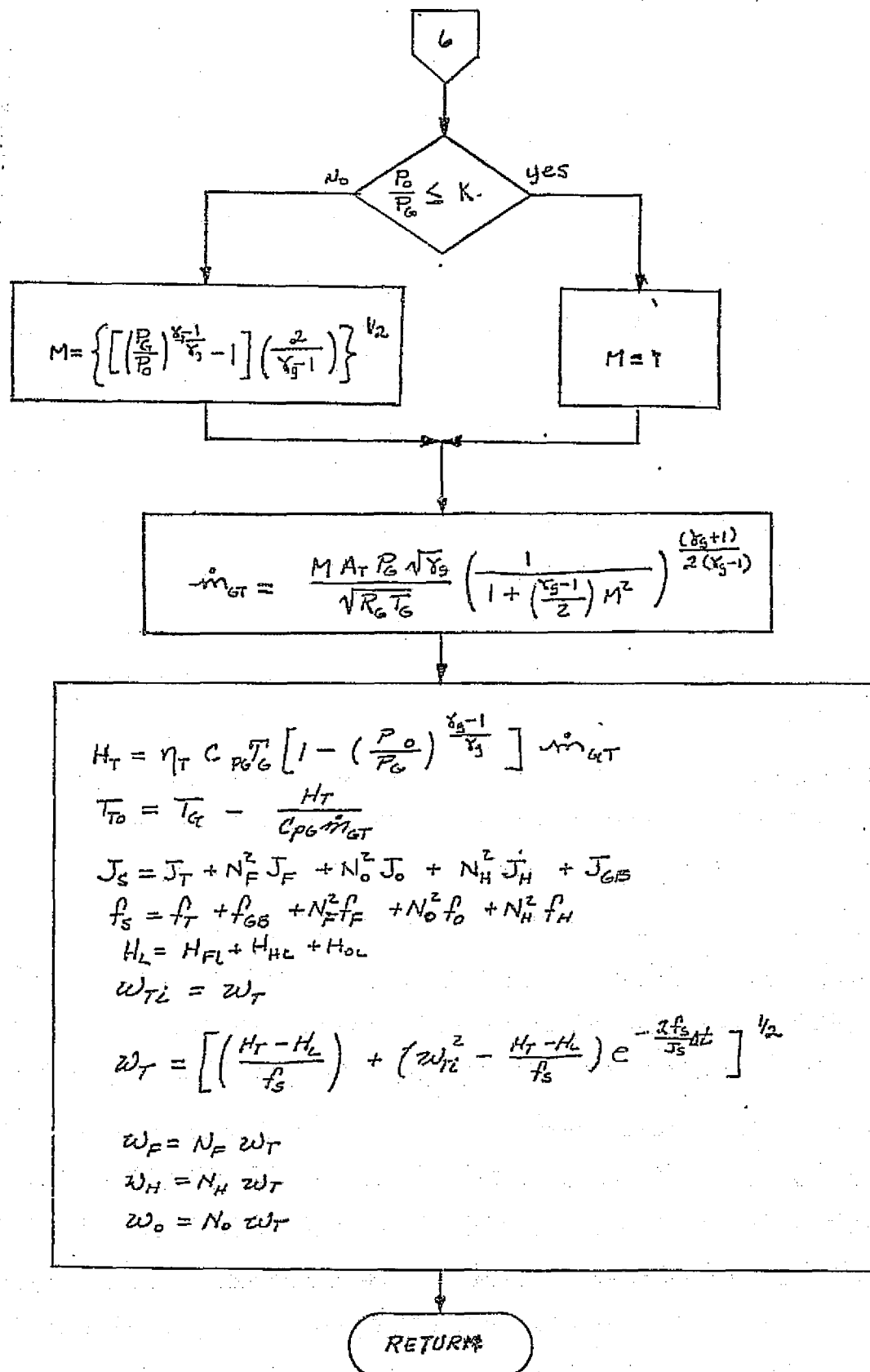


FIGURE 4.7-76. (CONTINUED)

- LEGEND:
- m_{GS} - 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_{N_2U} - 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_{OL-OUT} - Gear Box lubricant return temperature
 - T_{OBS} - 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

 - δ - Fuel heat of formation

FIGURE 4.7-76. (CONTINUED)

4.7-215

- \dot{m}_{FOUT} - Mass flow rate of fuel from fuel tank
 \dot{m}_{PF} - Fuel pump mass flow rate
 \dot{m}_{SLT} - 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}_{ORNZ} - 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

- P_F - Fuel tank pressure
 P_G - Gas generator pressure
 P_{FP-O} - Fuel pump outlet pressure
 ΔP_F - Fuel pump pressure rise
 P_{LP-OUT} - Lubricant pump outlet pressure
 ΔP_L - Lubricant pump pressure rise
 P_{GB} - Gear Box lubricant pressure
 P_{N_2} - Gear Box N_2 source tank pressure
 P_T - Turbine outlet pressure
- ~~P_{HTF} - Fuel heater electrical power
 P_{HTG} - Gas Generator heater electrical power~~
- A_{F1} - Fuel delivery line flow area
 A_{F2} - Fuel bypass line flow area
 A_{OL} - Lubricant line flow area
 A_T - Turbine flow area
- v_{FP} - Fuel pump fuel velocity
 v_{F1} - Fuel delivery line velocity
 v_{F2} - Fuel bypass line velocity
 v_o - Lubricant line velocity
- R_{EF1} - Reynold's number for fuel delivery line
 R_{EF2} - Reynold's number for fuel bypass line
 R_{EO} - Reynold's number for oil line
 D_{F1} - Diameter of fuel delivery line
 D_{F2} - Diameter of fuel bypass line
 D_o - Diameter of oil line
 ϵ_{F1} - Roughness factor of fuel delivery line
 ϵ_{F2} - Roughness factor of fuel bypass line
 L_{F1} - Length of fuel delivery line
 L_{F2} - Length of fuel bypass line
 L_o - Length of oil line

FIGURE A.7-76. (CONTINUED)

- f_s - System friction at turbine
- f_{ILO} - Oil line friction factor
- f_{FLFI} - Fuel delivery line friction factor
- f_{FLFZ} - 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_P - 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)

MDC E1136
27 January 1975

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:

- o three-gimbal platform - as used in the Apollo Command Module.
- o four-gimbal platform - as used in the Gemini spacecraft and currently baselined for Shuttle (see Refs. 25, 69).
- o 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.

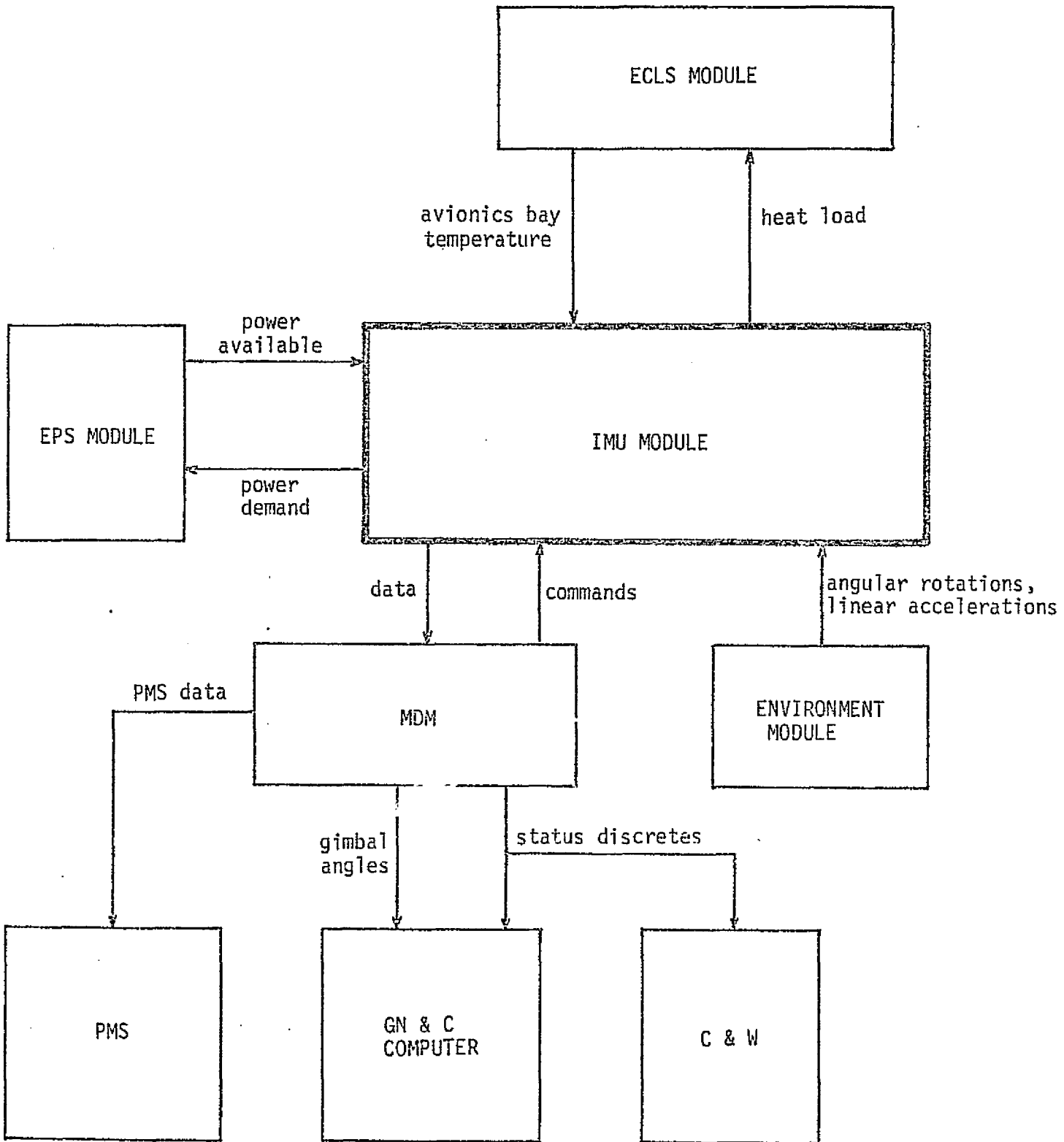


FIGURE 4.7-77 . IMU MODULE INTERFACES

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

Outputs of the IMU fall into four categories:

- o Status discrettes which are used by the flight software and the Caution and Warning (C & W) system.
- o PMS (Performance Monitor System) Data, which are used by the flight software performance monitor system for its redundancy management function.
- o 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.
- o 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. 25 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 32), 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
\mathcal{E}	"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
φ, θ, ψ	Gimbal angles (roll, pitch, yaw)	CP
V_x, V_y, V_z	ΔV accumulator outputs	P
\underline{a}_{imu}	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 discretets 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:

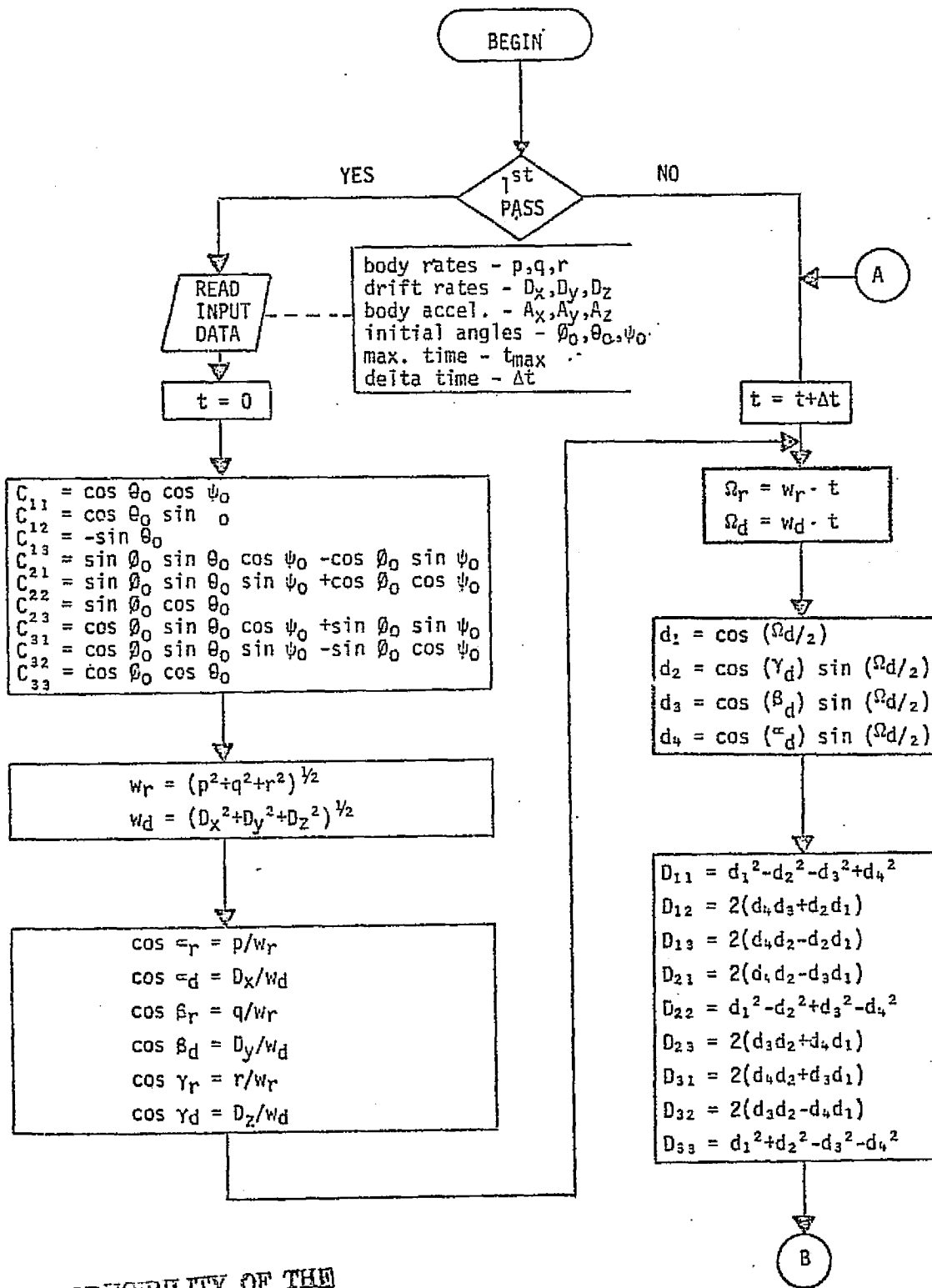
- body rates (p, q, r) - three components of angular velocity about the body axes.
- drift rates (D_x, D_y, D_z) - three components of angular velocity about the stable member reference axes. (These rates can also be interpreted as gyro torquing commands from the flight software.)

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.



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FIGURE 4.7-78 CONSTANT RATE INPUT METHOD

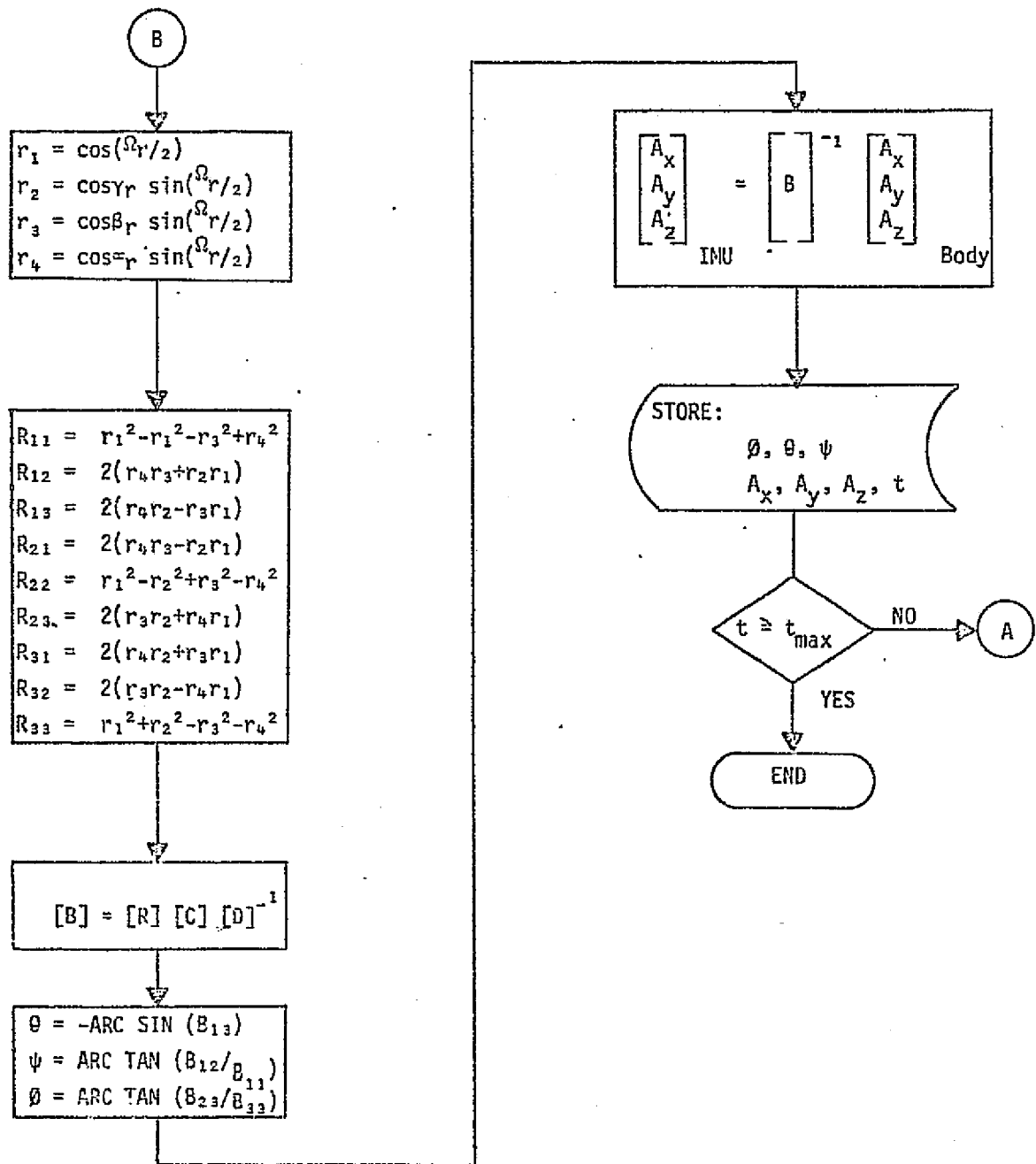


FIGURE 4.7-78 (CONTINUED)

- 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:

$$\begin{aligned} \phi &= A \sin w_1 t \quad \rightarrow \quad \dot{\phi} = A w_1 \cos w_1 t \\ \theta &= \frac{B}{C} \tan^{-1} \left(\frac{t-D}{C} \right) \quad \rightarrow \quad \dot{\theta} = \frac{B}{C^2 + (t^2 - D^2)} \end{aligned}$$

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

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

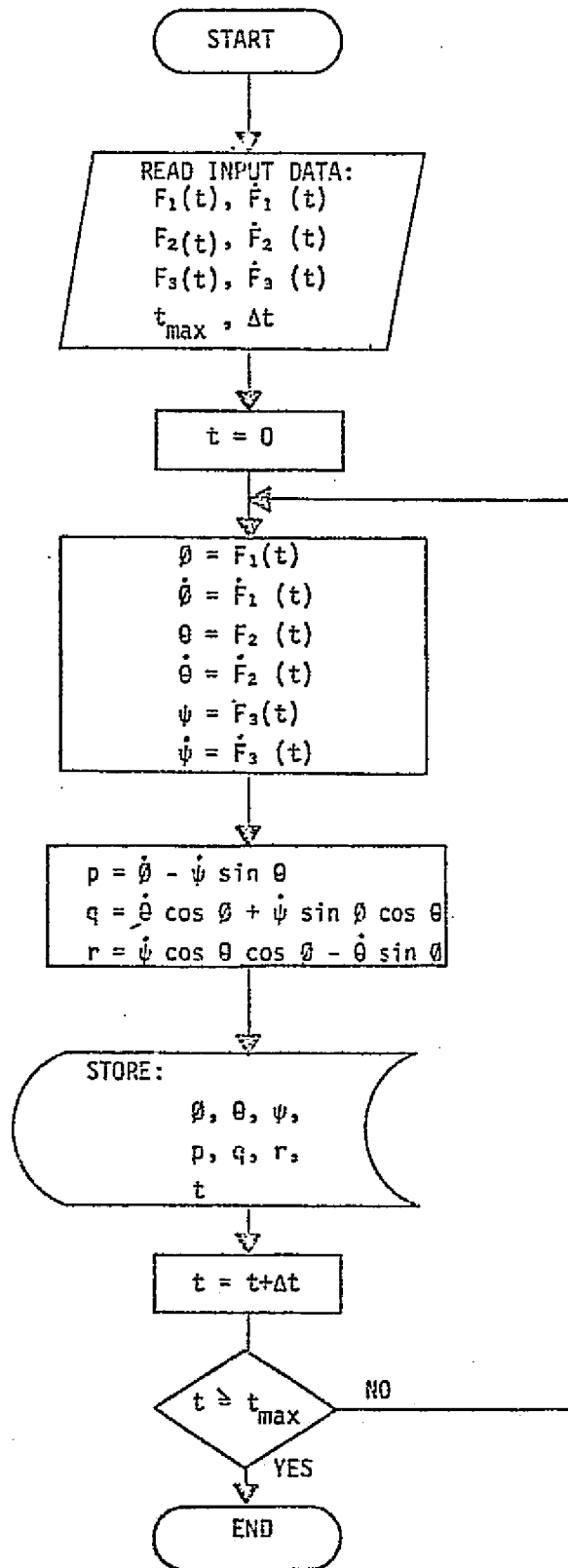


FIGURE 4.7-79 CLOSED FORM GIMBAL ANGLE METHOD

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.

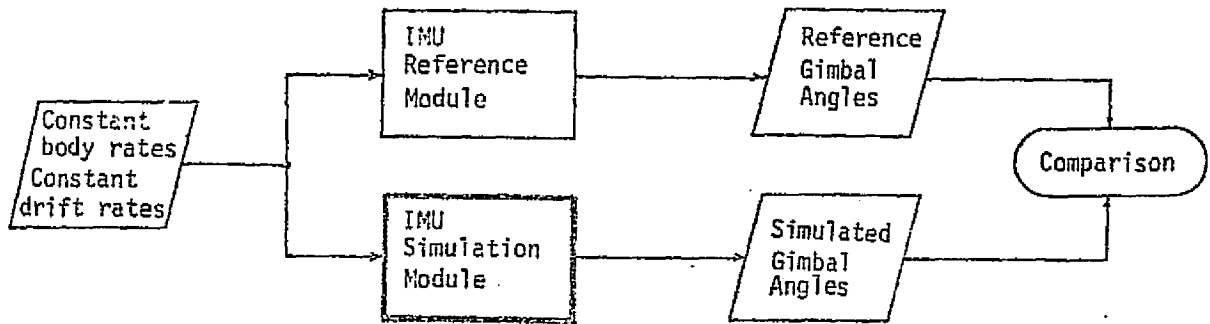
IMU Validation Methods and Check Cases

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

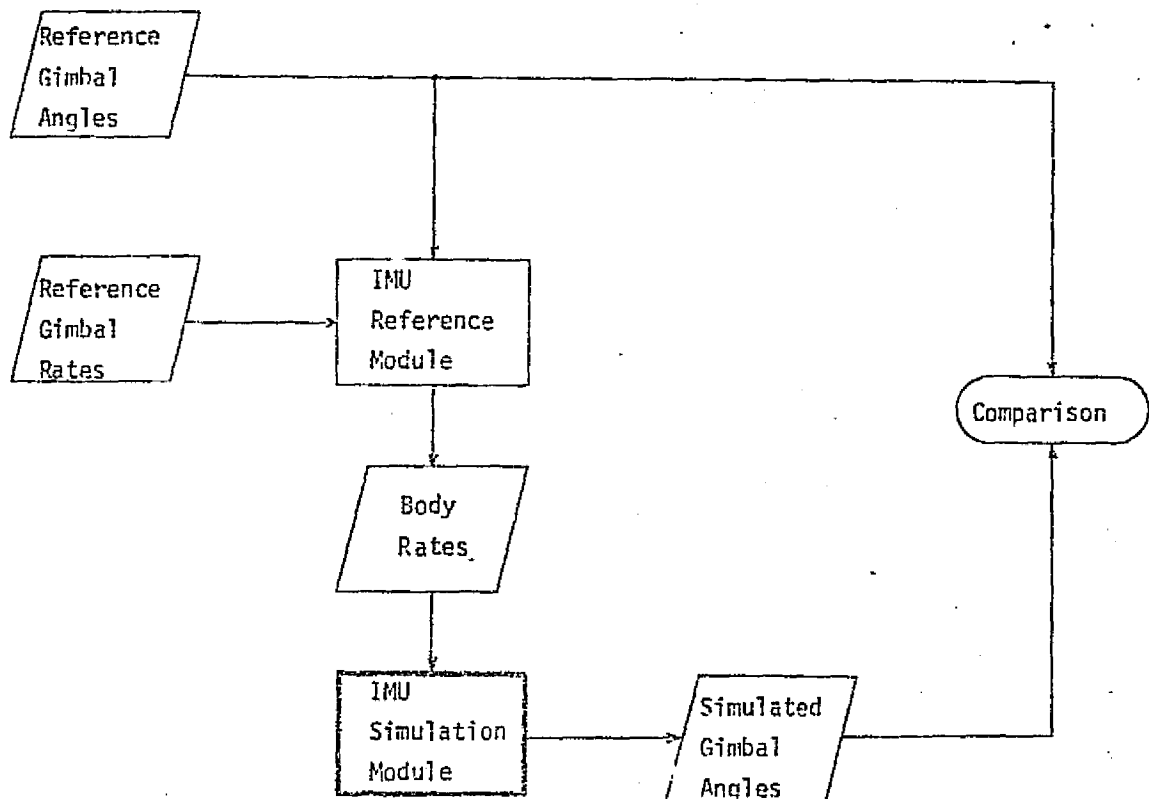
To use the constant rate input method, Figure 4.7-80 (a), input constant body rates and/or drift rates to the IMU reference module and the IMU simulation module, thus obtaining comparable gimbal-angle time histories.

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. 25, 71, 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 discretas. 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

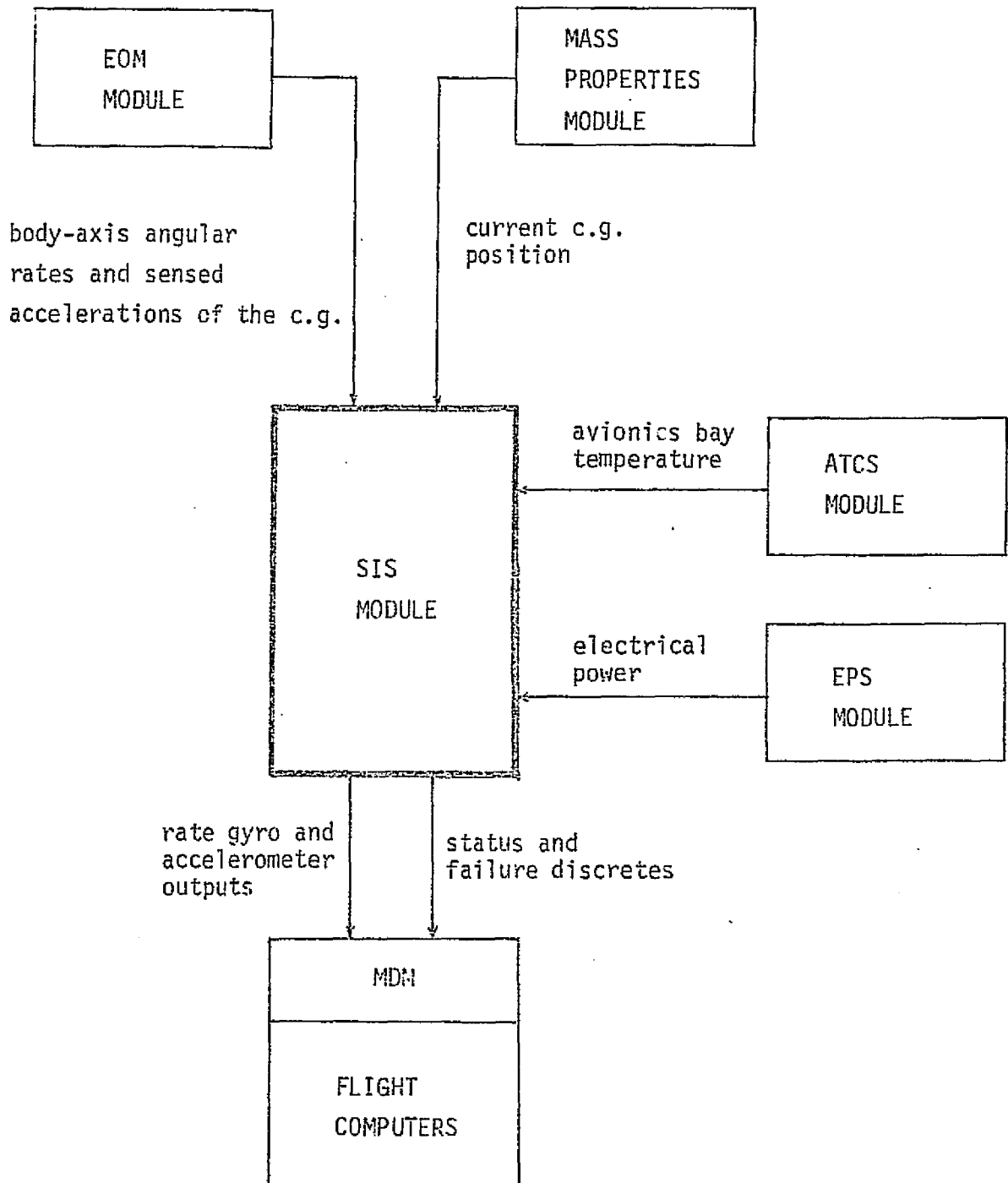


FIGURE 4.7-81. STRAPDOWN INERTIAL SENSOR MODULE INTERFACES.

TABLE 4.7-23. STRAPDOWN INERTIAL SENSOR MODULE PARAMETERS

SYMBOL	DEFINITION	TYPE ^a
$\bar{x}, \bar{y}, \bar{z}$	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

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

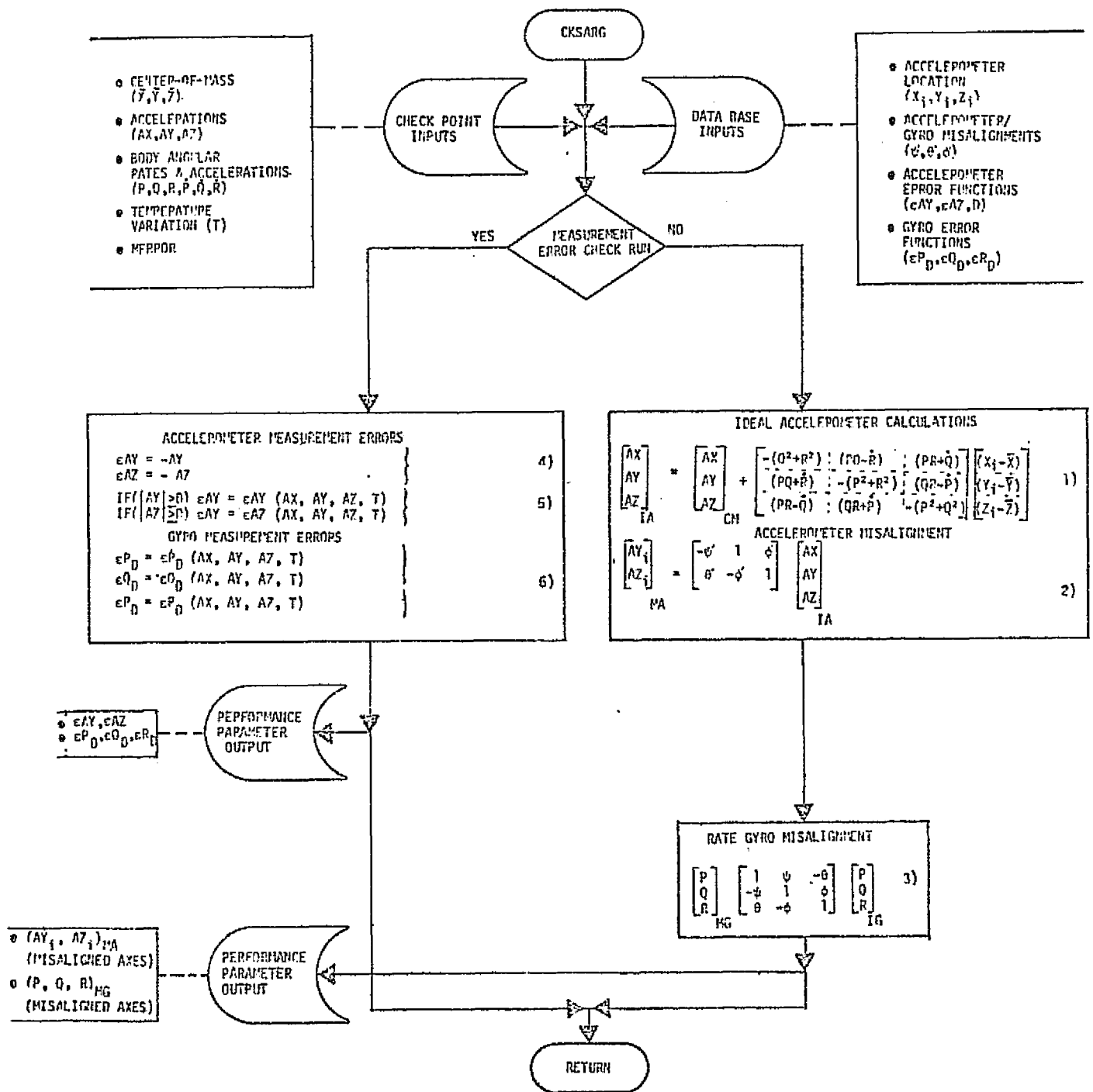


FIGURE 4.7-82. STRAPDOWN INERTIAL SENSOR REFERENCE MODULE MATH FLOW.

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:

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

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. 70. 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

same 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. 62, the MEC software by Ref 72. The EIU is described by Ref. 73. Specifications for the other PSIU's have apparently not been issued yet.

The MEC and EIU together perform the following functions:

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

Figure 4.7-83 (after Ref. 62) 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

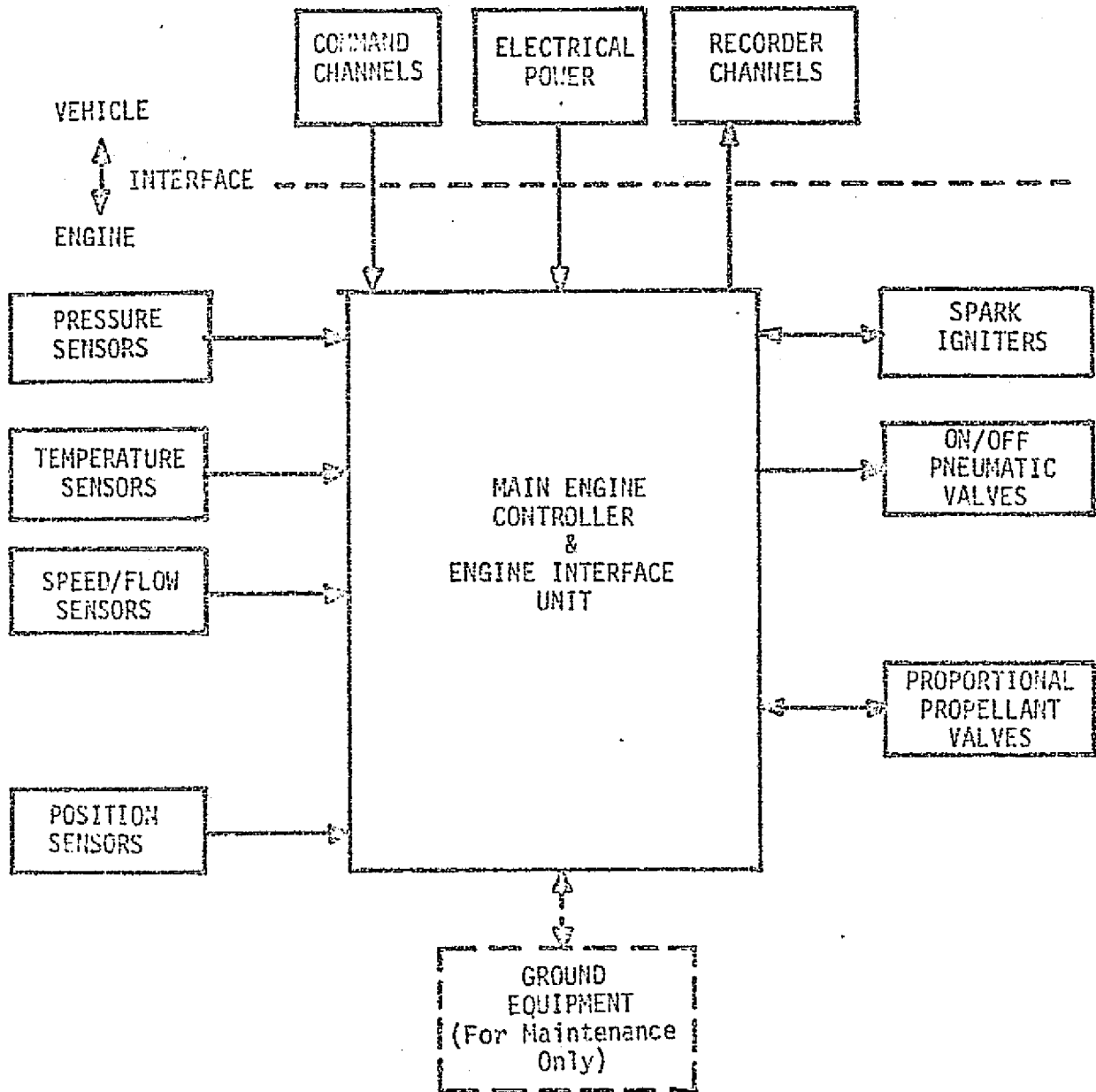


FIGURE 4.7-83 . MEC/EIU HARDWARE INTERFACES

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. 74 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. 75); additional detail may be found in Ref. 76. 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:

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

4.7-246

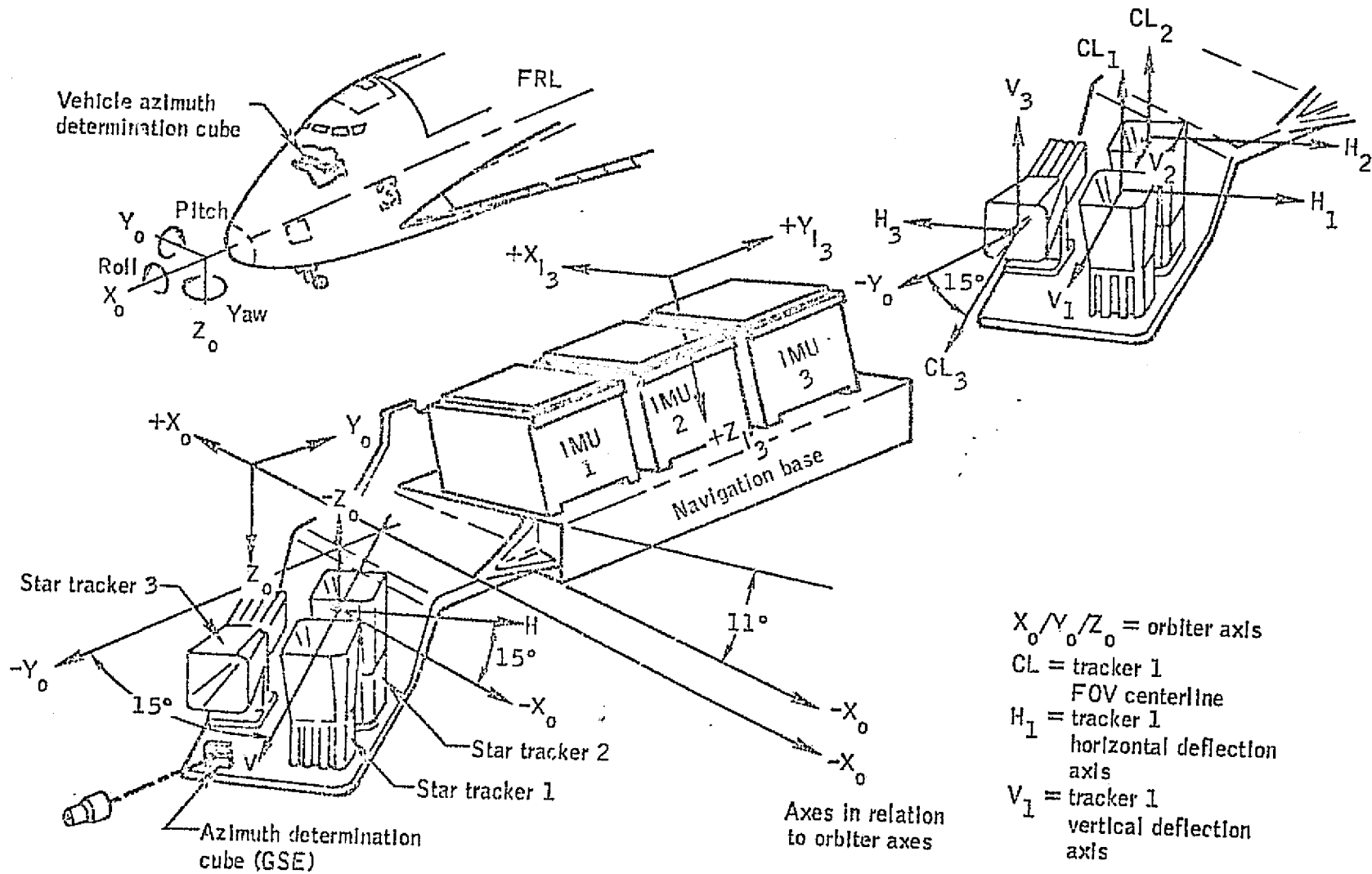


FIGURE 4.7-84. STAR TRACKER PHYSICAL ARRANGEMENT

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4.7-2A7

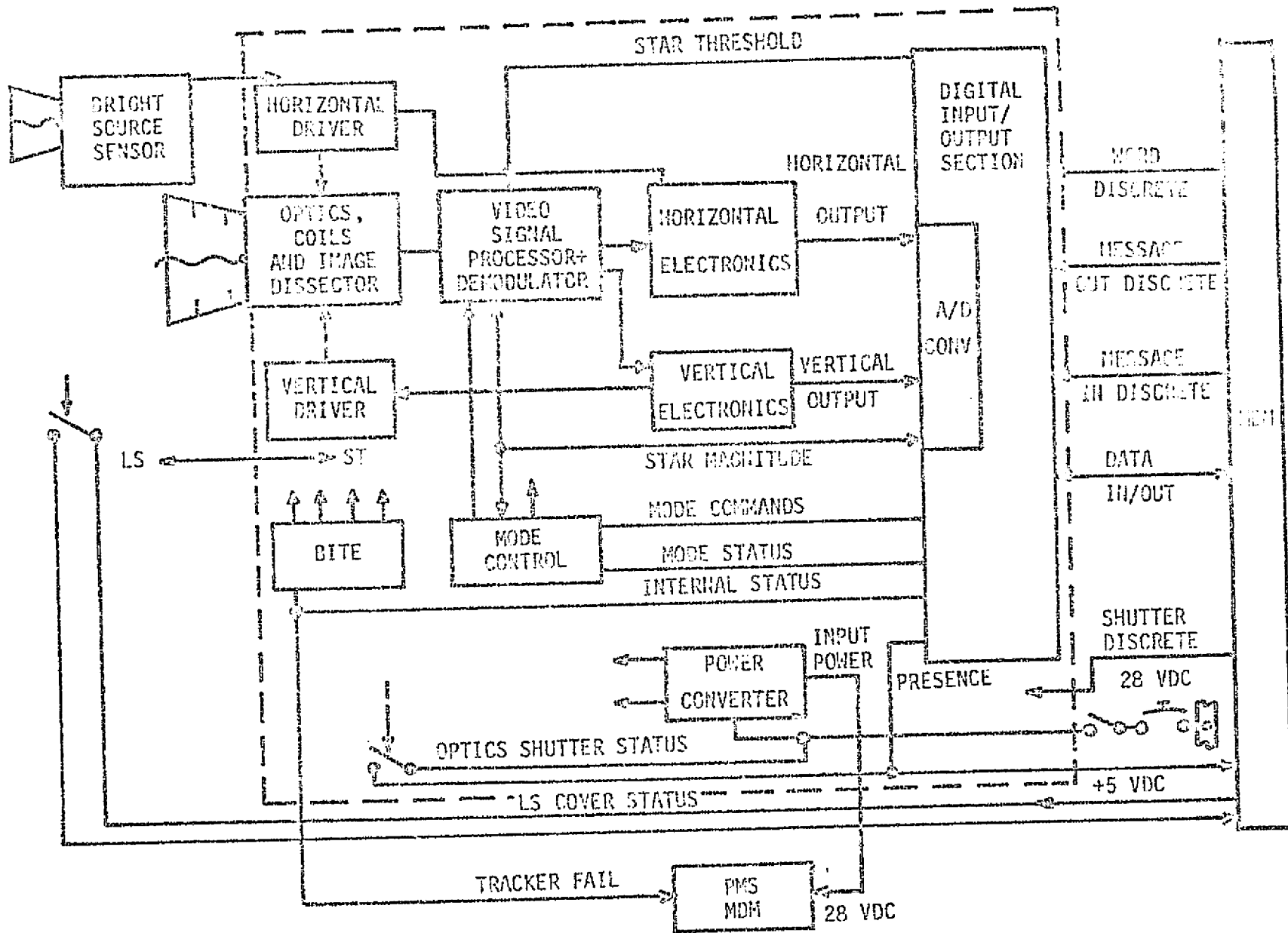


FIGURE 4.7-B5. STAR TRACKER FUNCTIONAL BLOCK DIAGRAM (REFERENCE)

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. 75 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. 77) 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.

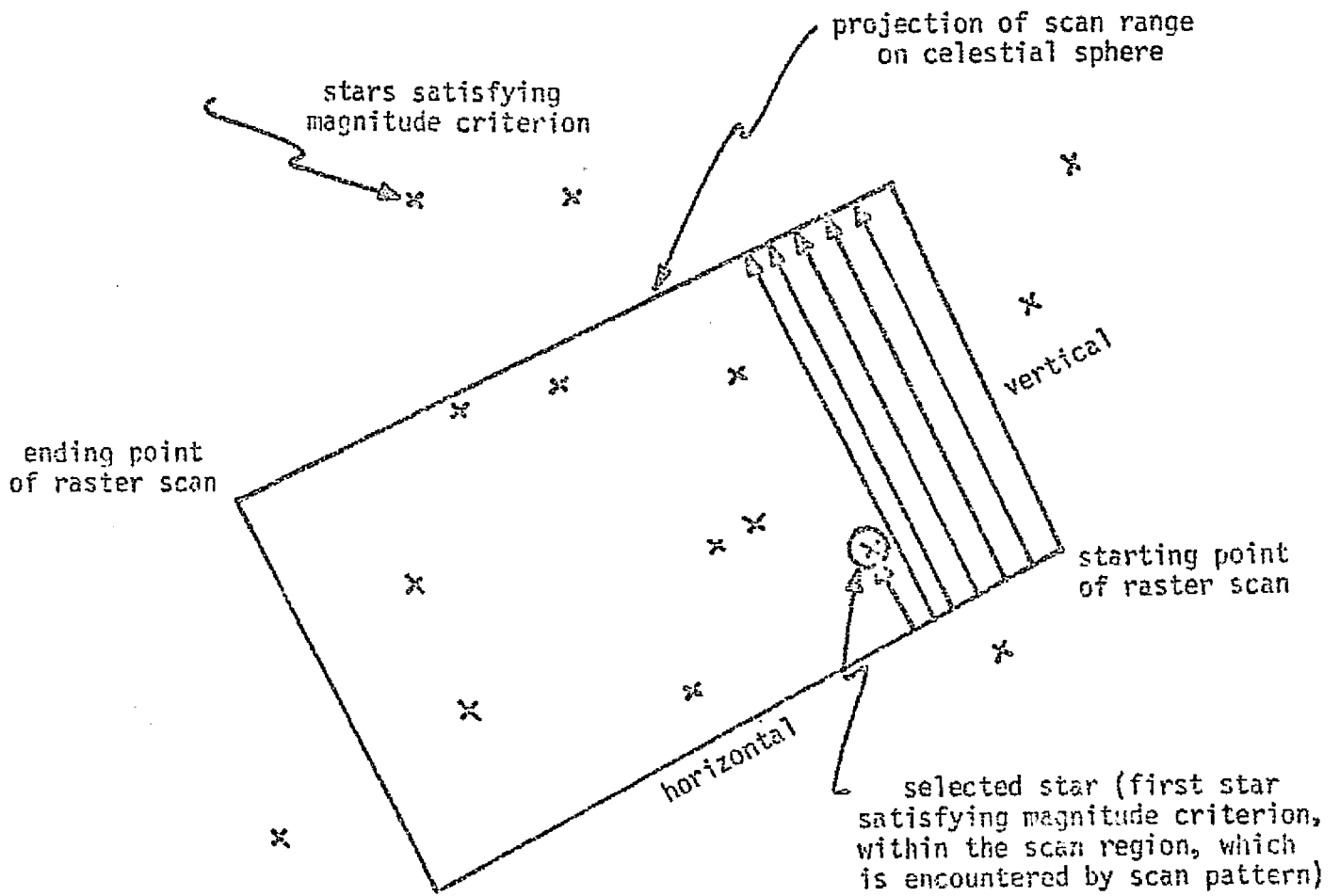


FIGURE 4.7-86. TYPICAL SCAN-PATTERN RELATIONSHIPS

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. 78. However, we recommend the module now being developed and checked out for inclusion in SVDS, the math flow of which (Ref. 79) 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. 75 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

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

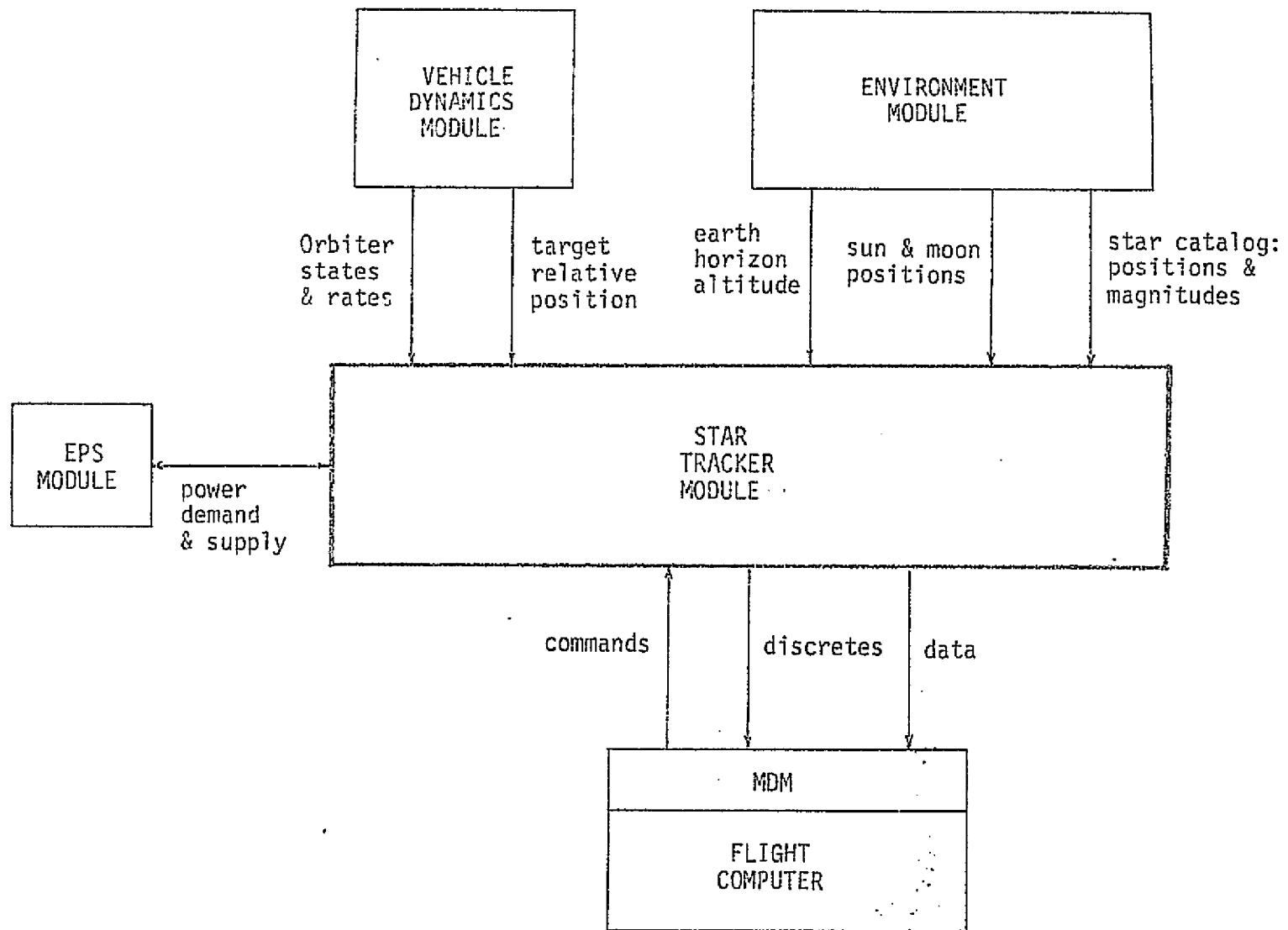


FIGURE 4.7-37. STAR TRACKER SIMULATION MODULE INTERFACES

Program STTRK

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

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

XATH angular factor for the earth's atmosphere

RE effective radius of the earth for sun occultation

RRZY rendez-vous 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

ITX(3) star tracker activation flags

HAUTO(3) auto-optics flags

MBCON(3) beacon tracking flags

PSICOM(2,3) auto-optics angular commands

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

IANERR
INDISE
IMISAL
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

PSID(2,3)

simulated star tracker angles

FIGURE 4.7-88. STAR TRACKER REFERENCE MODULE MATH FLOW

4.7-254

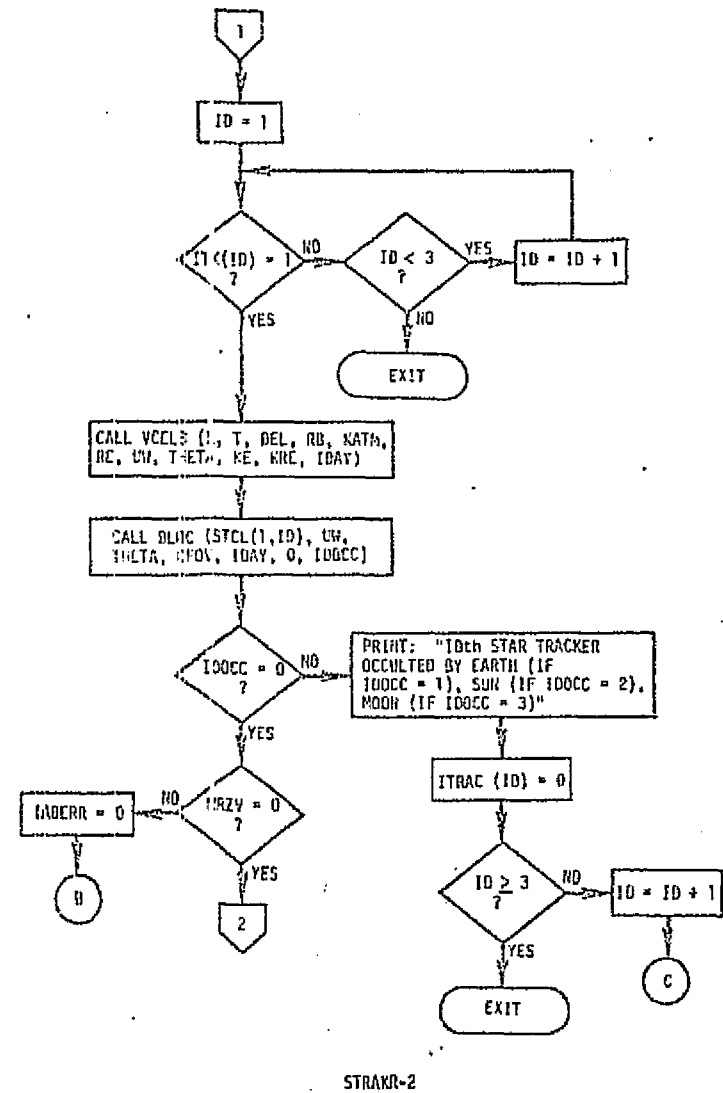
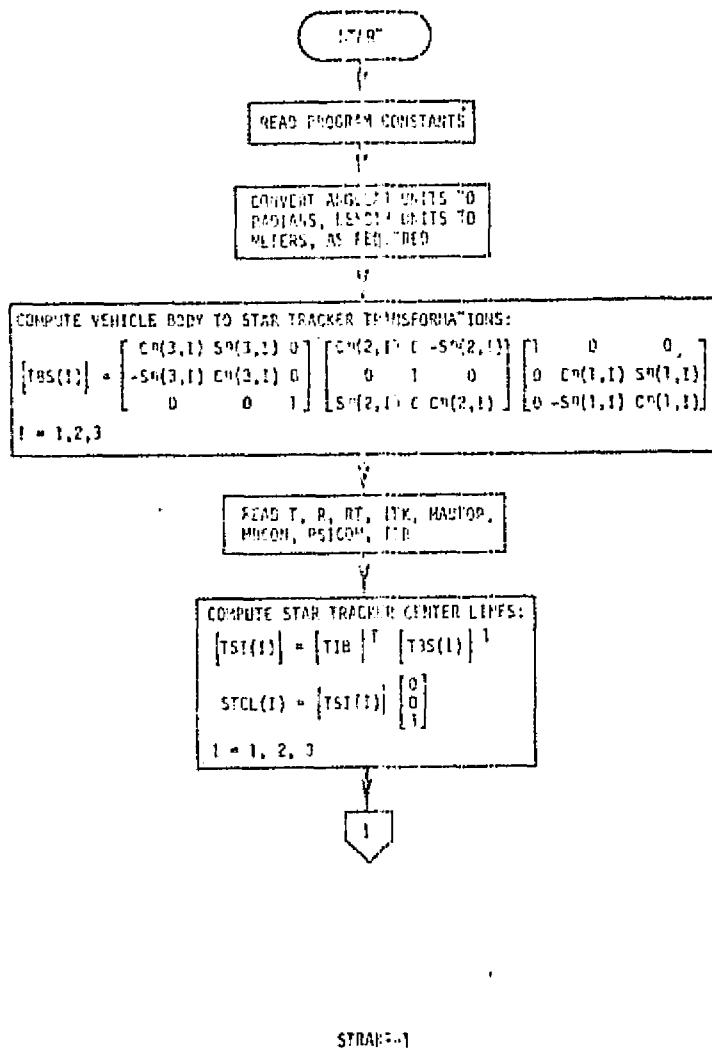
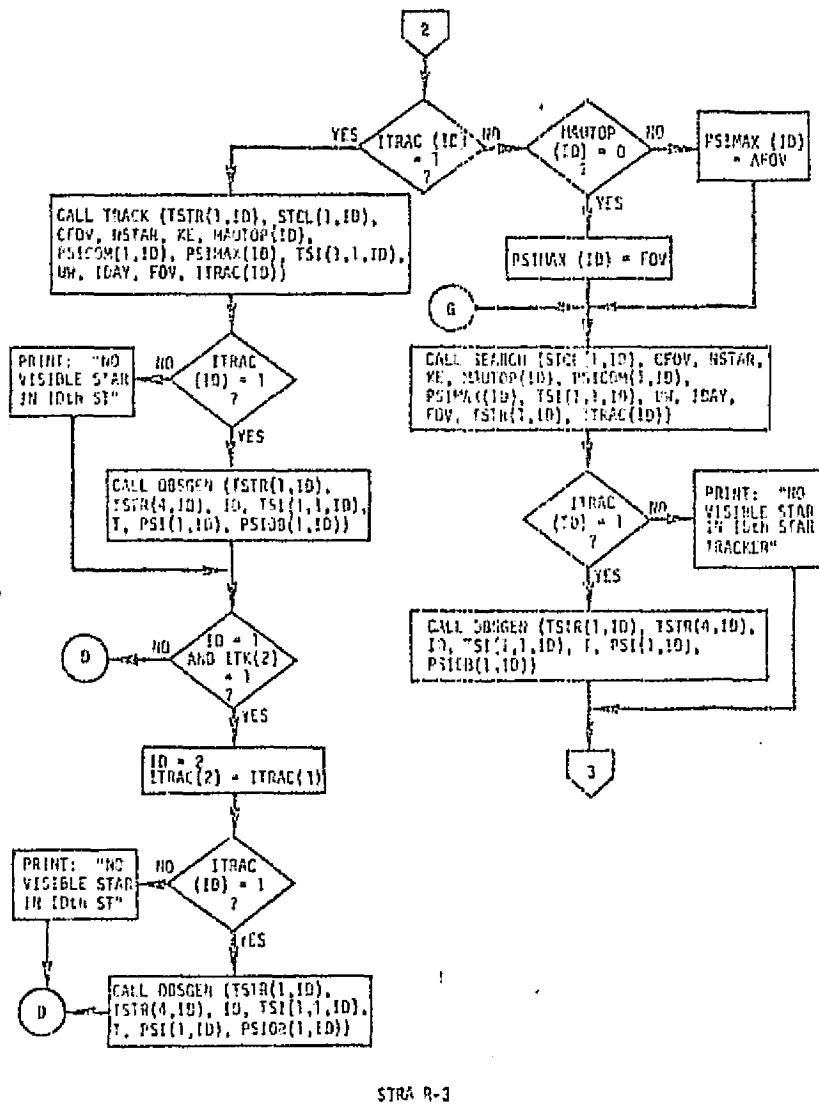
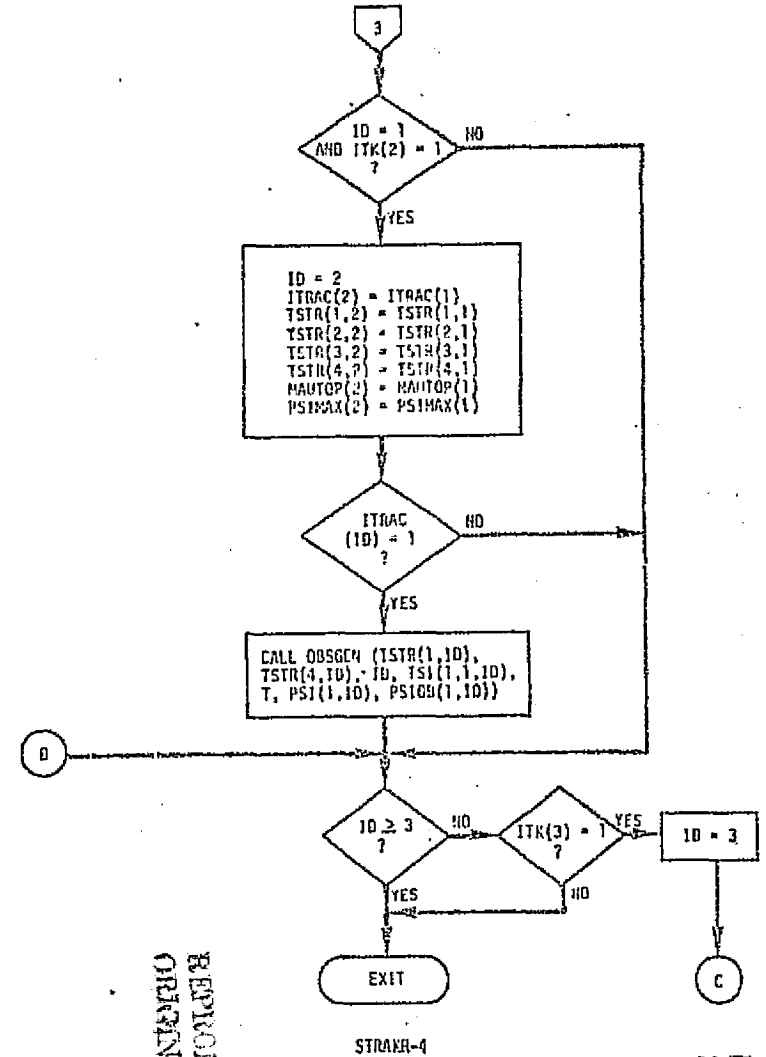


FIGURE 4.7-88. (CONTINUED)

4.7-255



STRA R-1



STRAKR-4

FIGURE 4.7-88. (CONTINUED)

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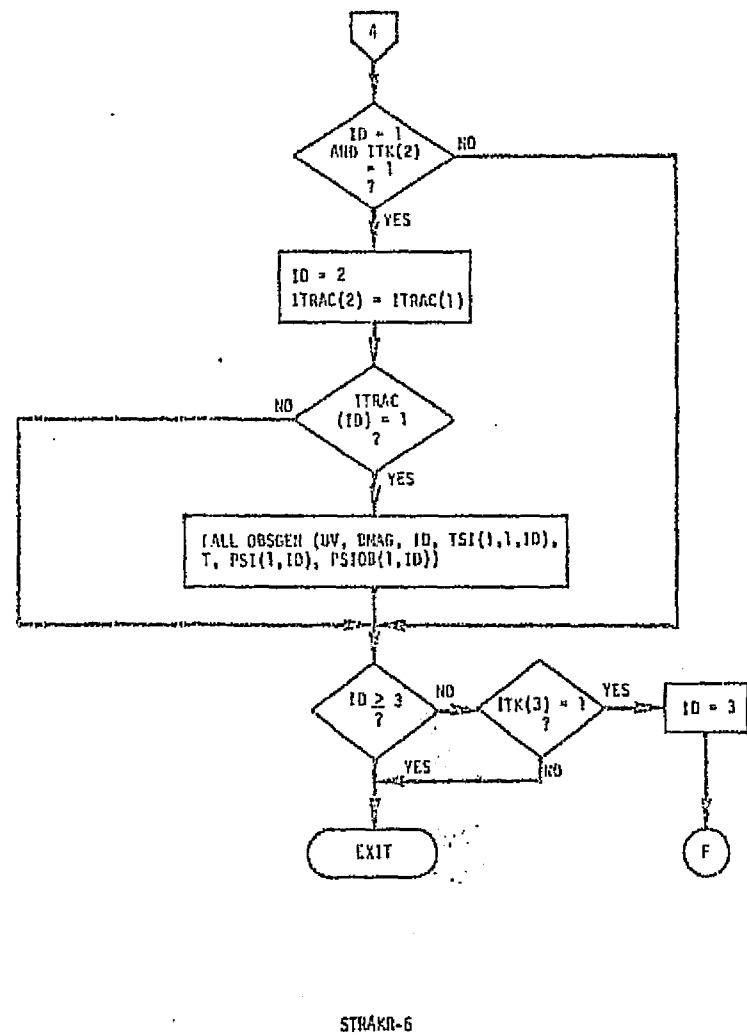
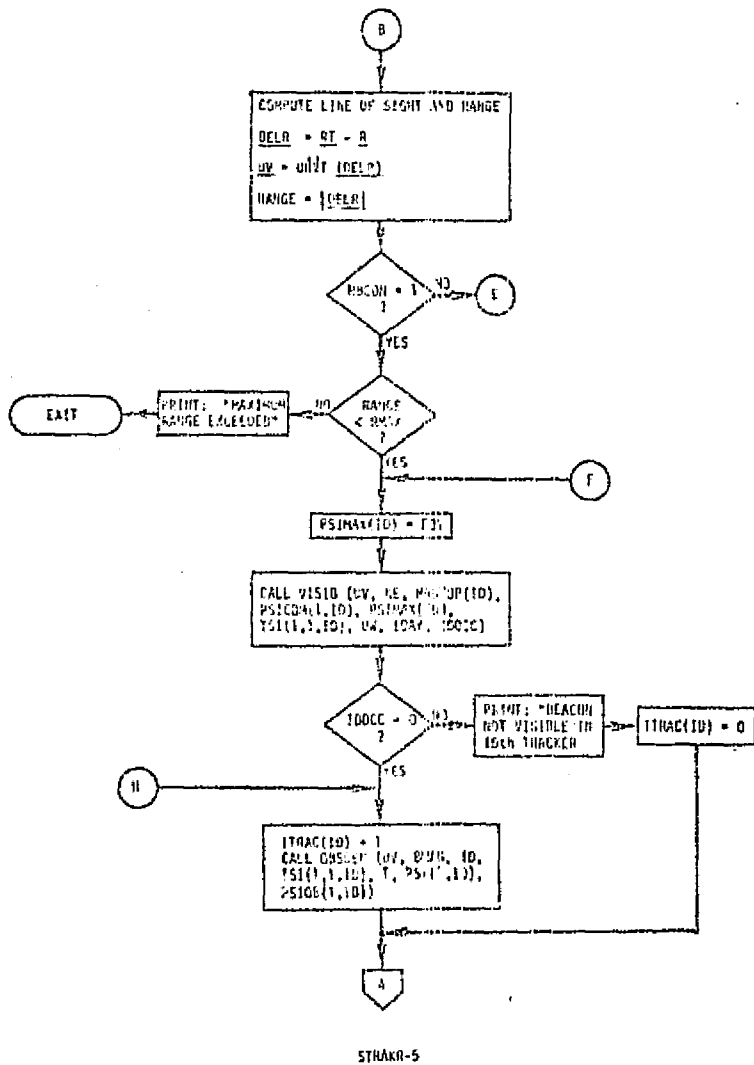
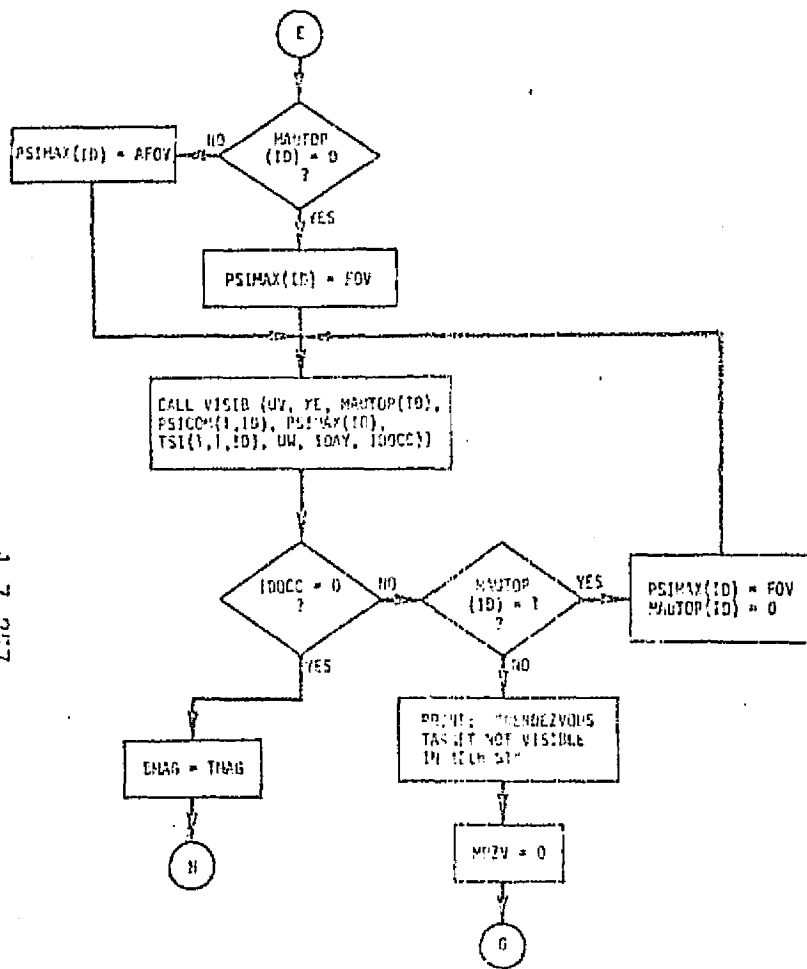


FIGURE 4.7-88. (CONTINUED)

4.7-257



STAR-7

Subroutine ABERR (T, 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:

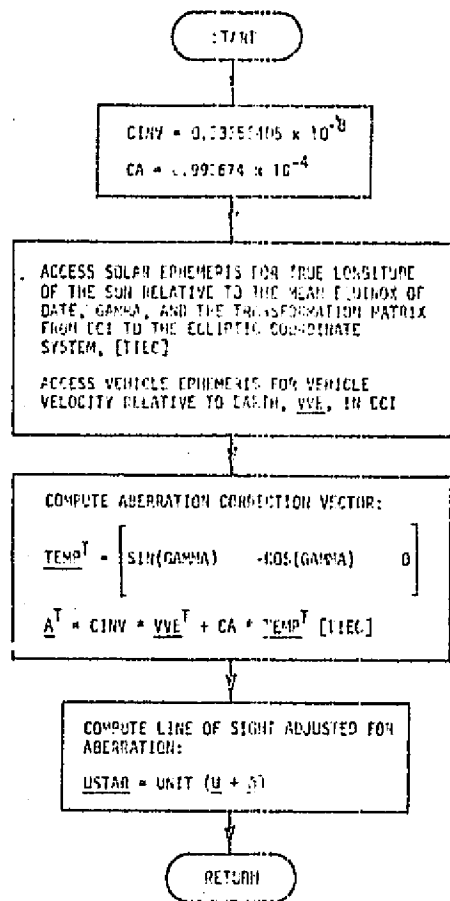
T elapsed time from the clock epoch
U(3) geometrical line of sight to star

Output:

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

FIGURE 4.7-33. (CONTINUED)

4.7-250



ABERR-1

Subroutine: ELOC (V, UH, THETA, CFOV, IDAY, IEARTH, IDOCC)

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

Inputs:

V(3)	target line of sight or ST centerline
UH(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
IDAY	orbital phase (day/night) flag
IEARTH	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

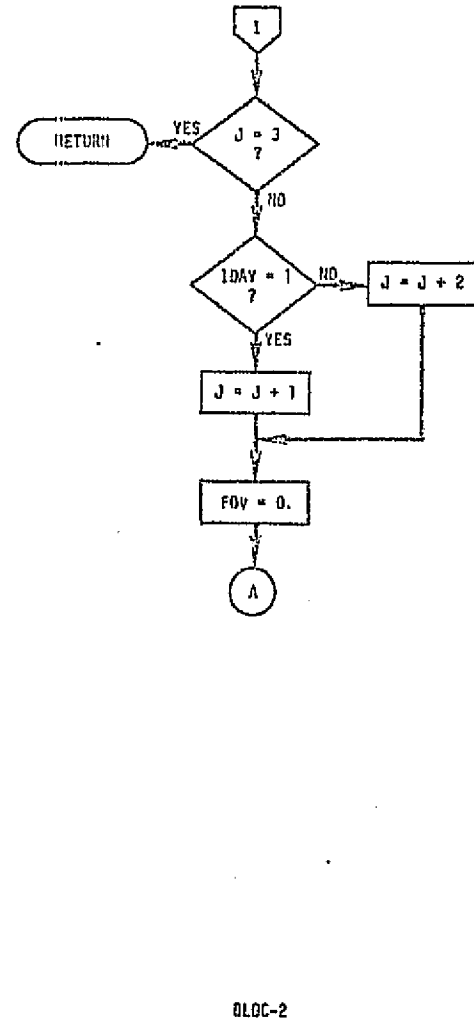
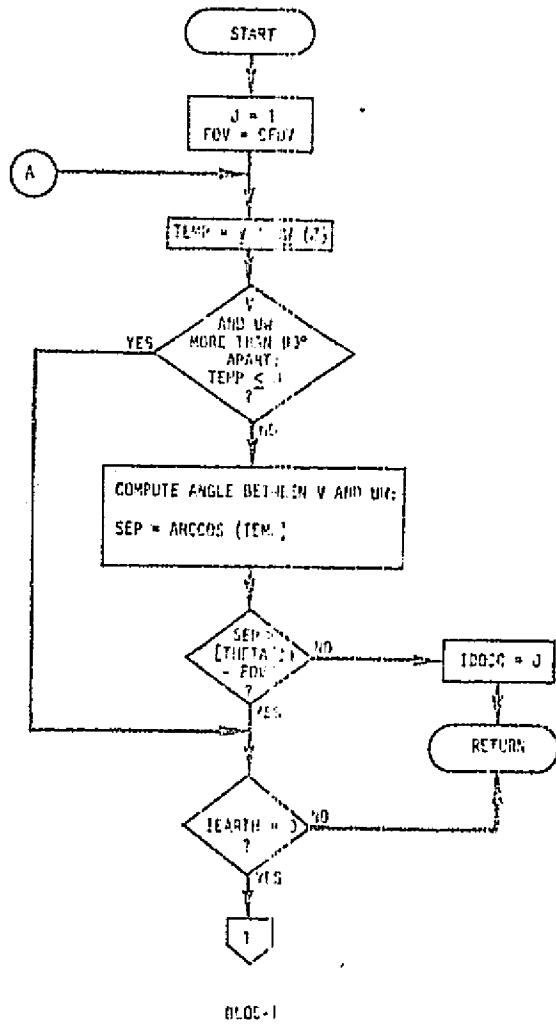


FIGURE 4.7-88. (CONTINUED)

4.7-207

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

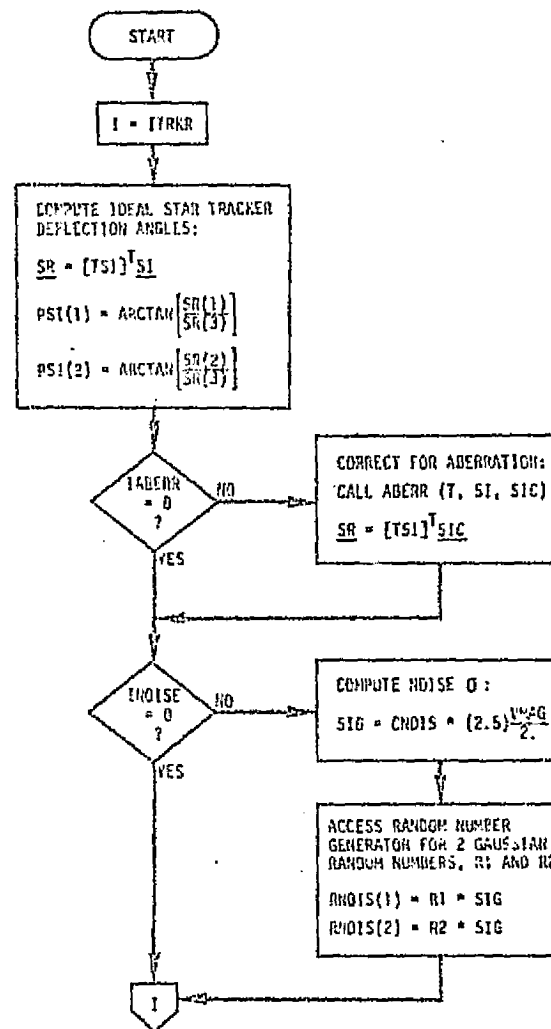
Purpose: To compute simulated star tracker deflection angles

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-SI transformation matrix
- T elapsed time since the clock epoch
- ABERR }
 NOISE }
 ABERR } error option flag:
 NOISE } (input via COMMON)
- COMMON 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)

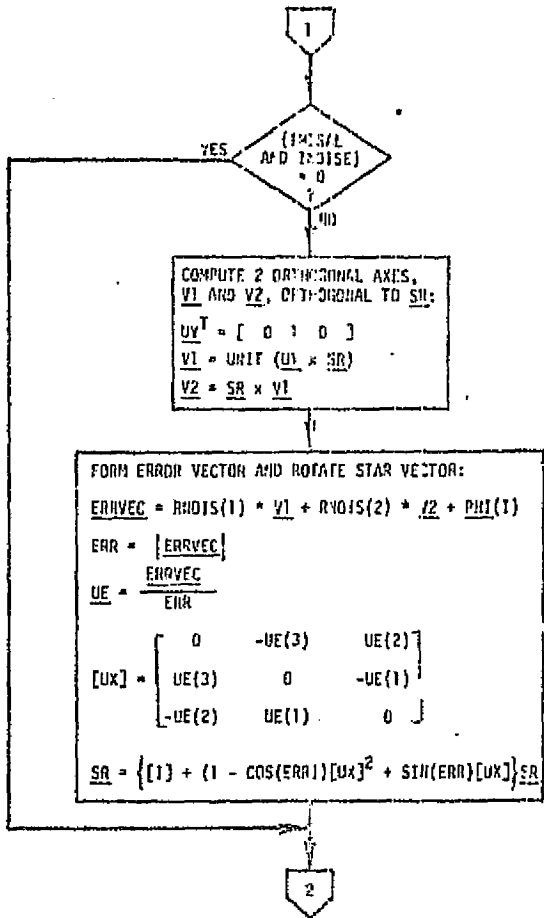
Outputs:

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

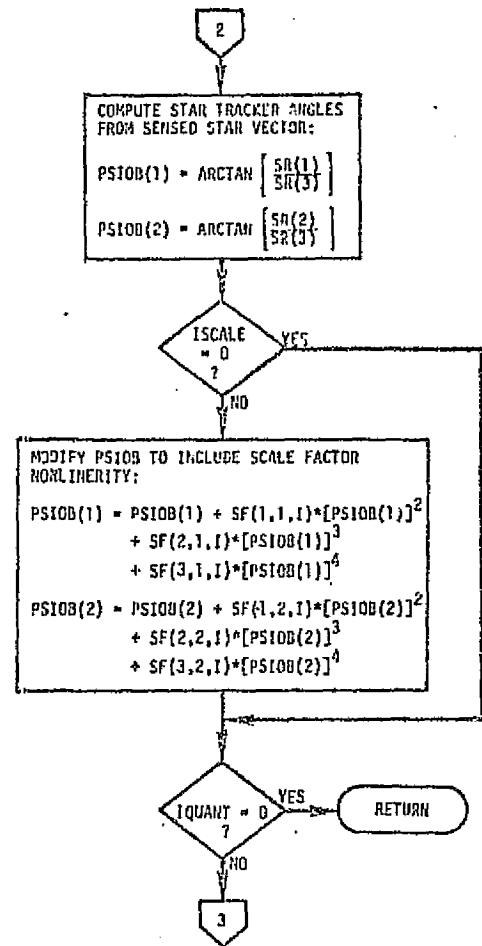


ODSGEN-1

FIGURE 4.7-88. (CONTINUED)



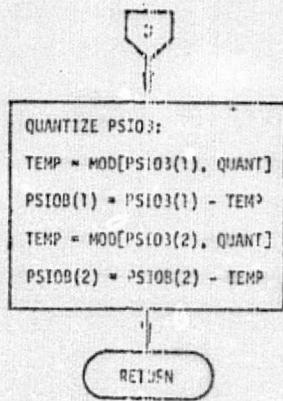
OBSGEN-2



OBSGEN-3

FIGURE 4.7-88. (CONTINUED)

4.7-262



015:EN-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:

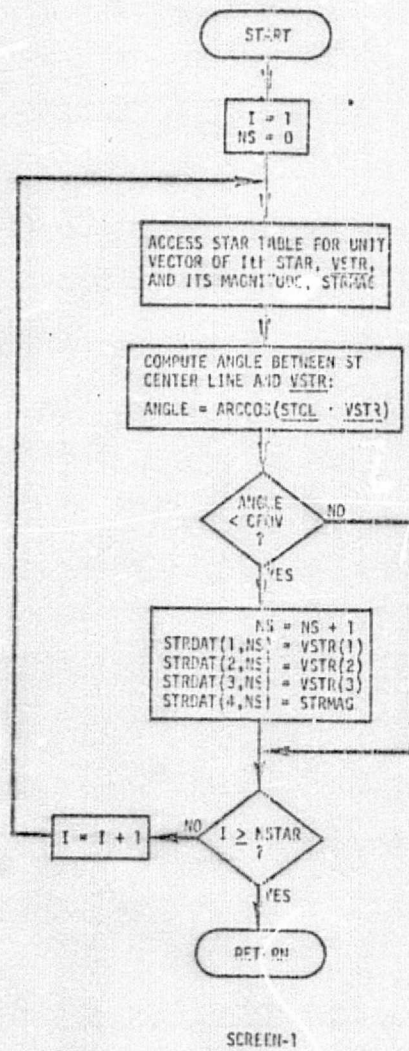
STCL(3) ST centerline in ECI coordinates
 CFOV half-angle of the circular field of view encompassing the ST search raster pattern
 NSTAR number of stars in the star table

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



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

Purpose: To detect a target star for tracking

Inputs:

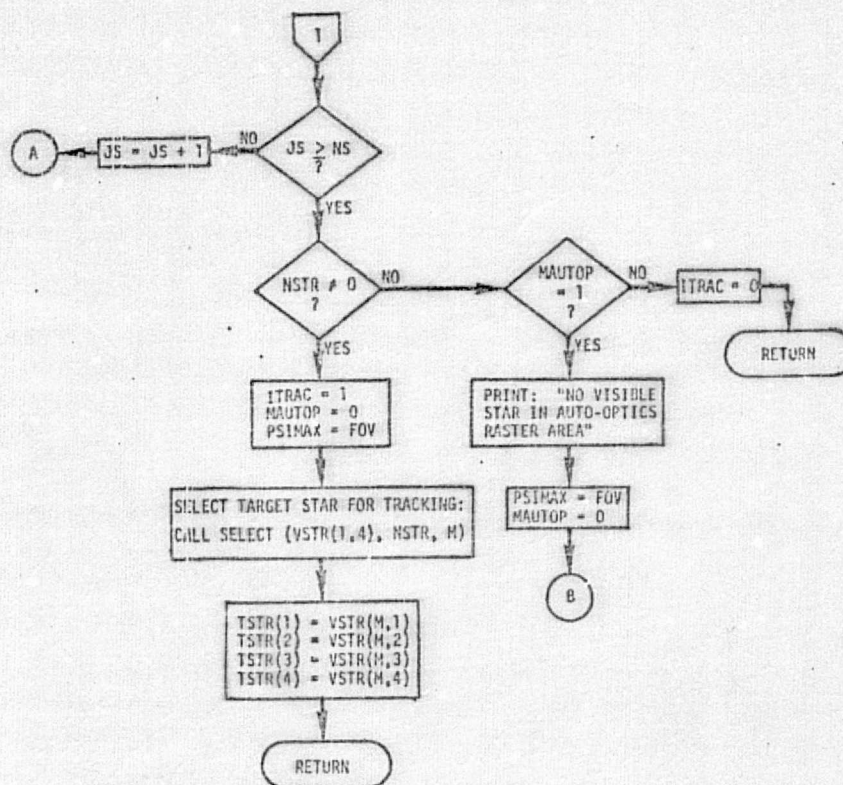
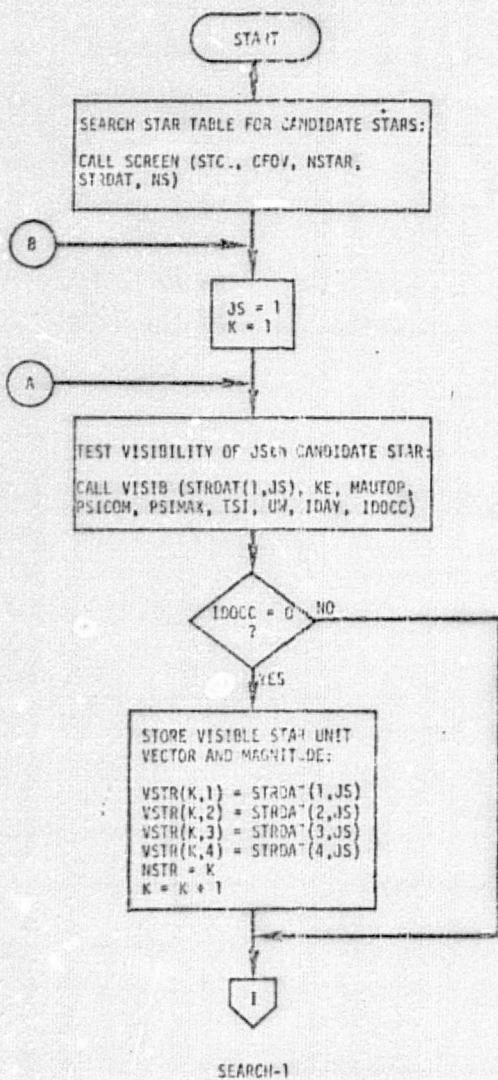
STCL(3)	star tracker centerline
CFOV	half-angle of circular field of view enclosing the tracker search raster pattern
NSTAR	number of stars in the star table
KE	effective half-angle of the earth
MAUTCP	auto-optics mode flag
PSICM(2)	auto-optics deflection commands
PSIMAX	raster limit
TSI(3,3)	ST-to-ECI 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

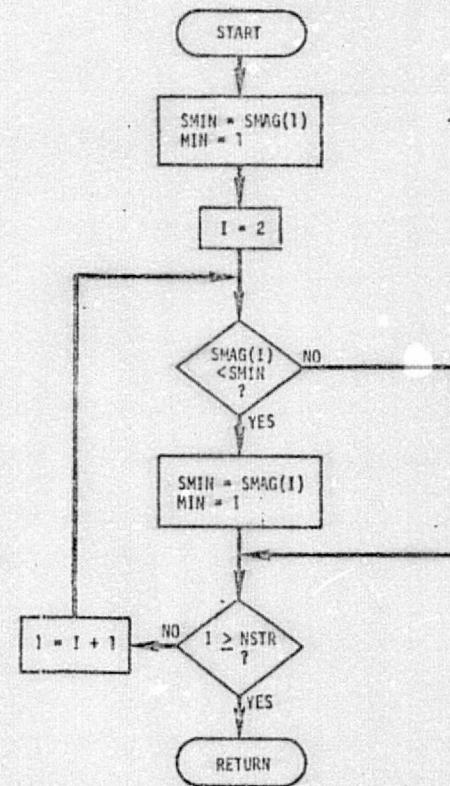
Inputs:

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)

4.7-266

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

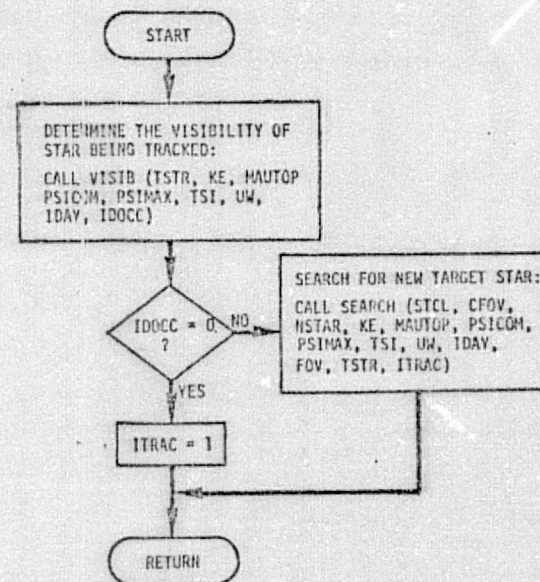
Purpose: To test the visibility of the star being tracked and to search for a new target star if the visibility test is failed.

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

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A.7-267

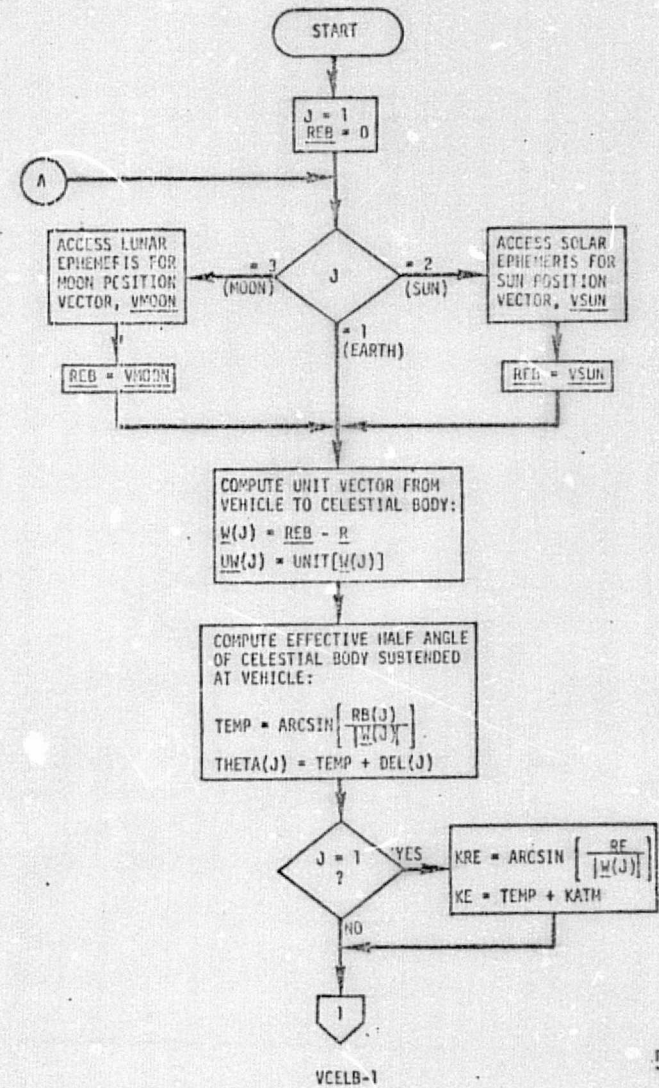
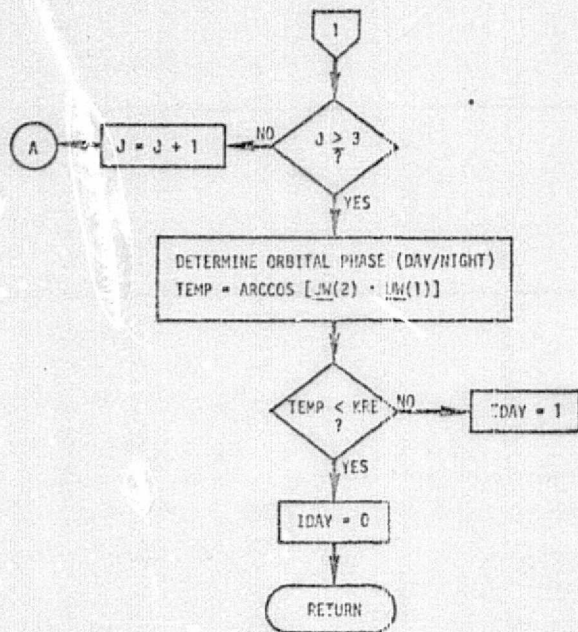


FIGURE 4.7-88. (CONTINUED)

4.7-268



VCELB-2

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

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

Inputs:

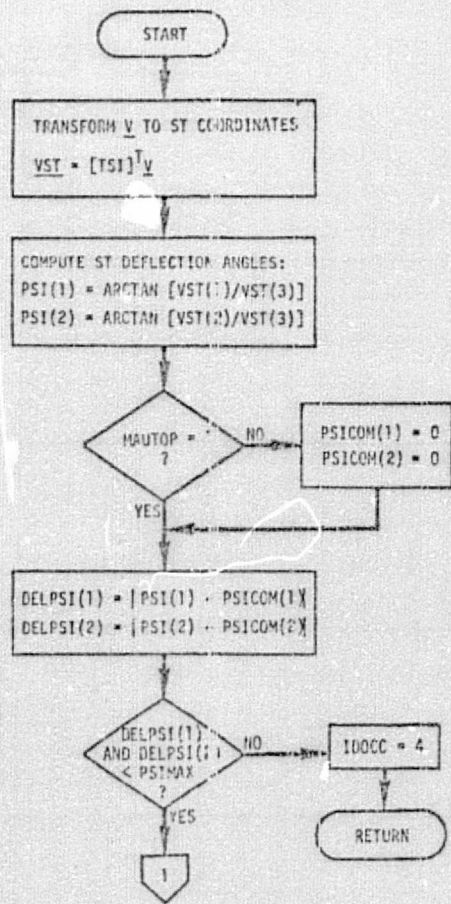
V(3)	target line of sight in ECI
KE	effective half-angle of the earth subtended at the vehicle
MAUTOP	auto-optics mode flag
PSICOM(2)	auto-optics angular commands
PSIMAX	raster limit
TSI(3,3)	SI-to-ECI transformation matrix
UM(3,3)	unit vectors from vehicle to the earth, sun, and moon
IDAY	orbital phase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

Outputs:

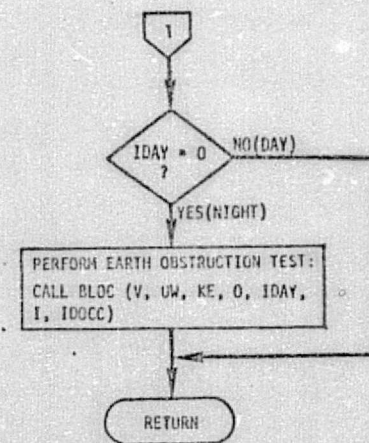
ISOCC	visibility flag
	ISOCC = 0: target visible
	= 1: earth occultation
	= 4: target outside specified raster area

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. 80 . 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. 25 , 82 .)

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.

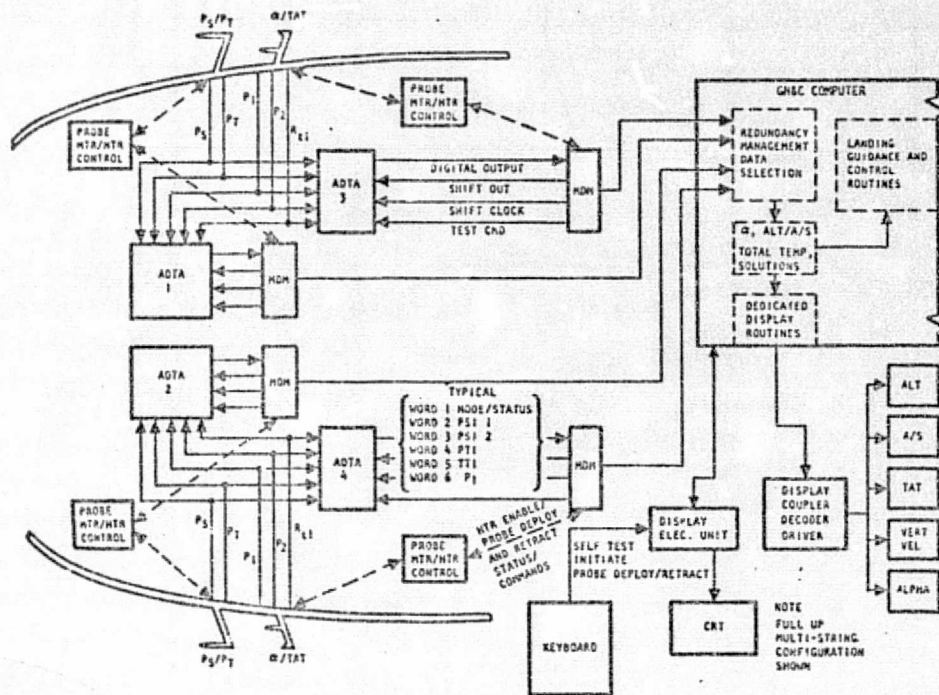


FIGURE 4.7-89 AIR DATA SYSTEM FUNCTIONAL CONFIGURATION (ORBITER 103)

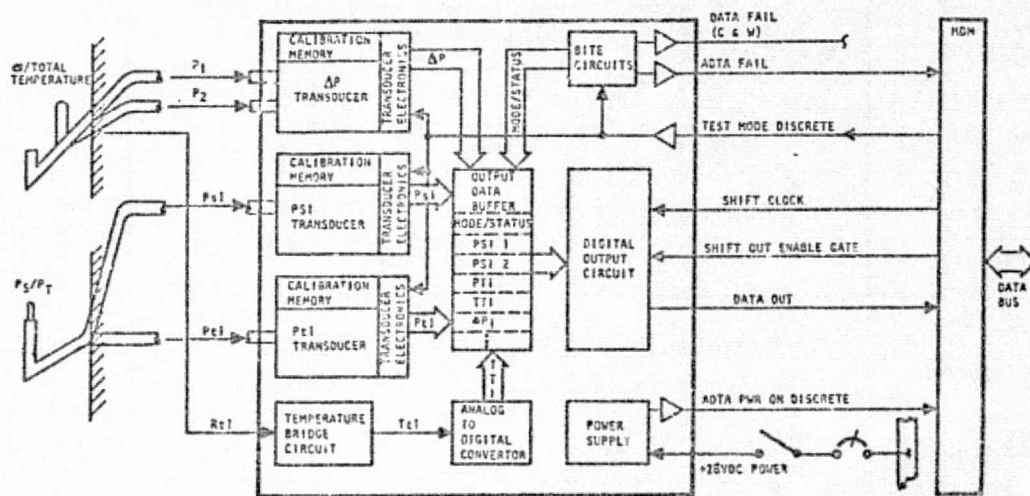


FIGURE 4.7-90 INTERNAL ADTA FUNCTIONAL CONFIGURATION

4.7-274

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

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

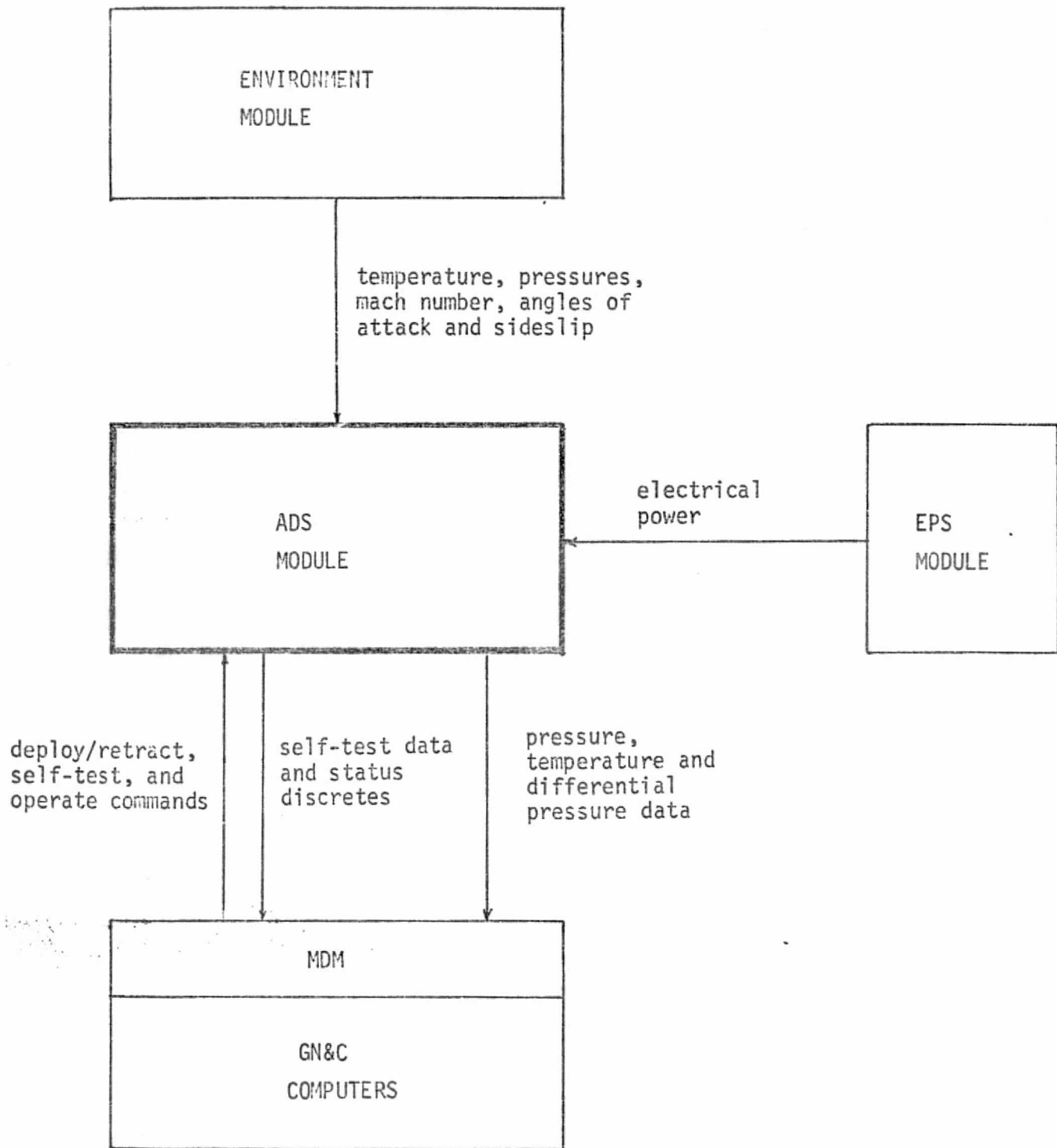


FIGURE 4.7-91. ADS MODULE INTERFACES

Modelling 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 81.

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

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

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

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

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

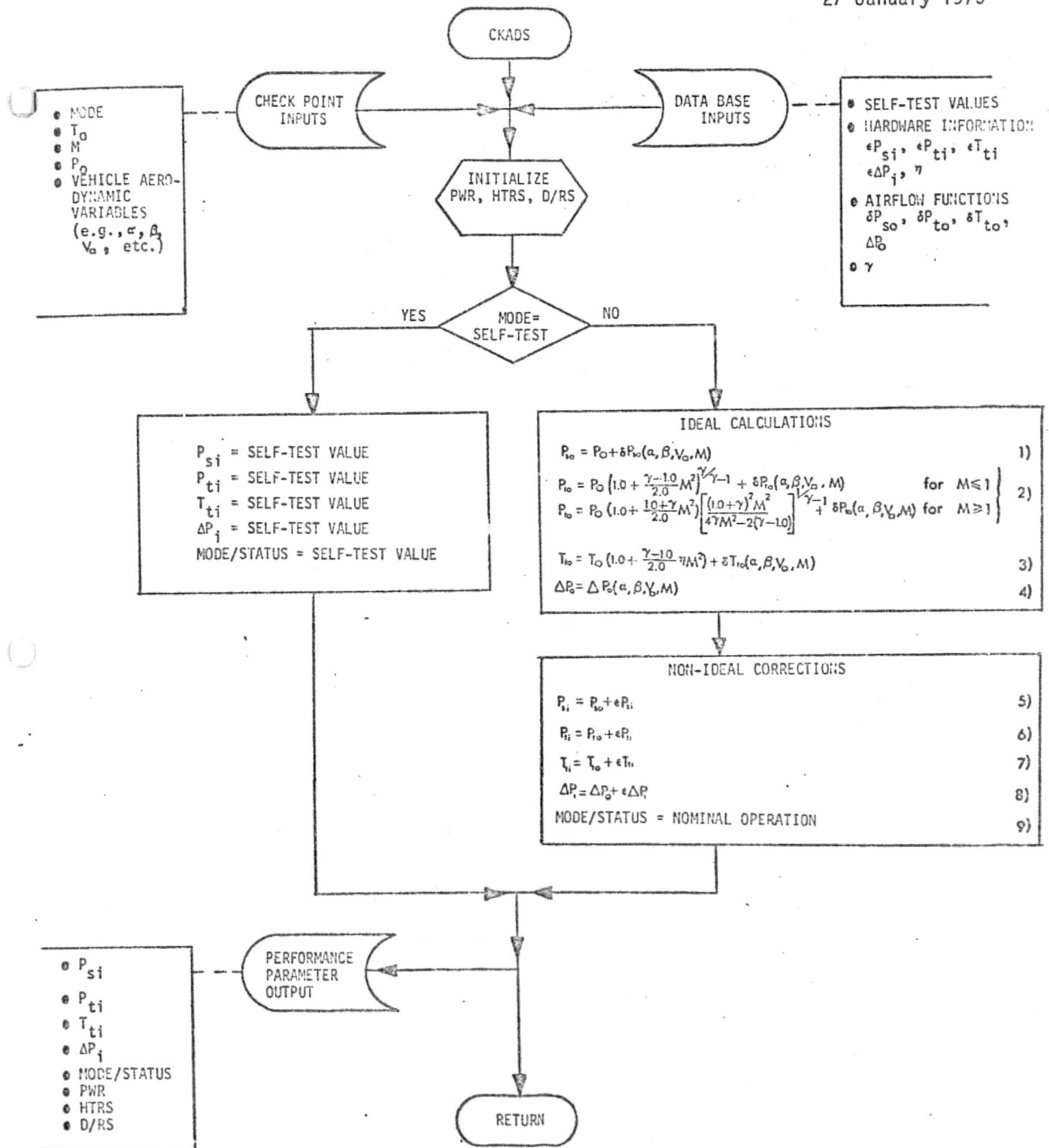


FIGURE 4.7-92 AIR DATA SYSTEM REFERENCE DATA MODULE

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)
η	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. 70) 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. 83 through 92) 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

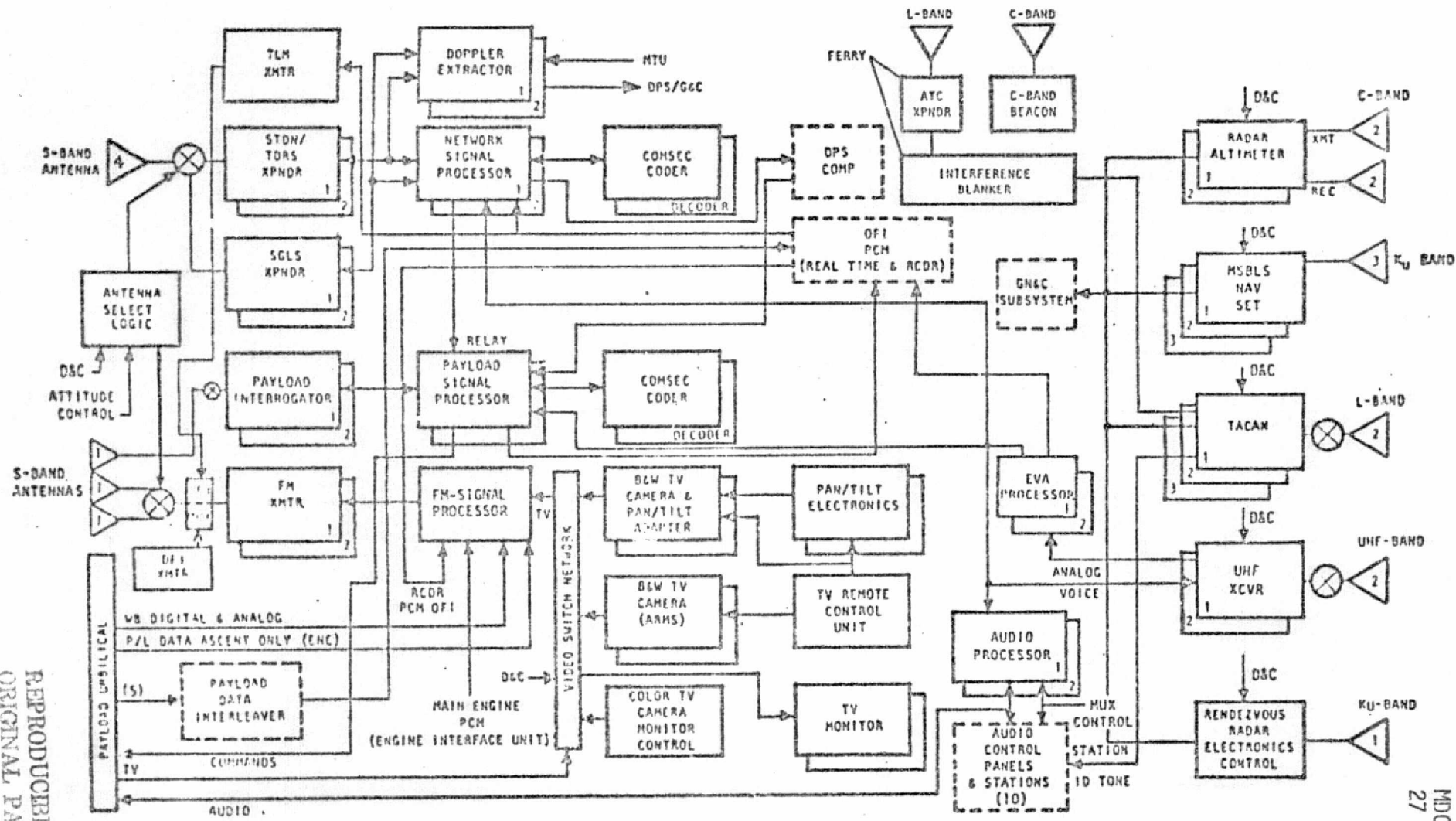


FIGURE 4.7-93 COMMUNICATIONS AND TRACKING SUBSYSTEM BLOCK DIAGRAM

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
$\hat{\phi}_T, \hat{\psi}_T$	Measured target angle and angular rate	CP

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

4.7-285

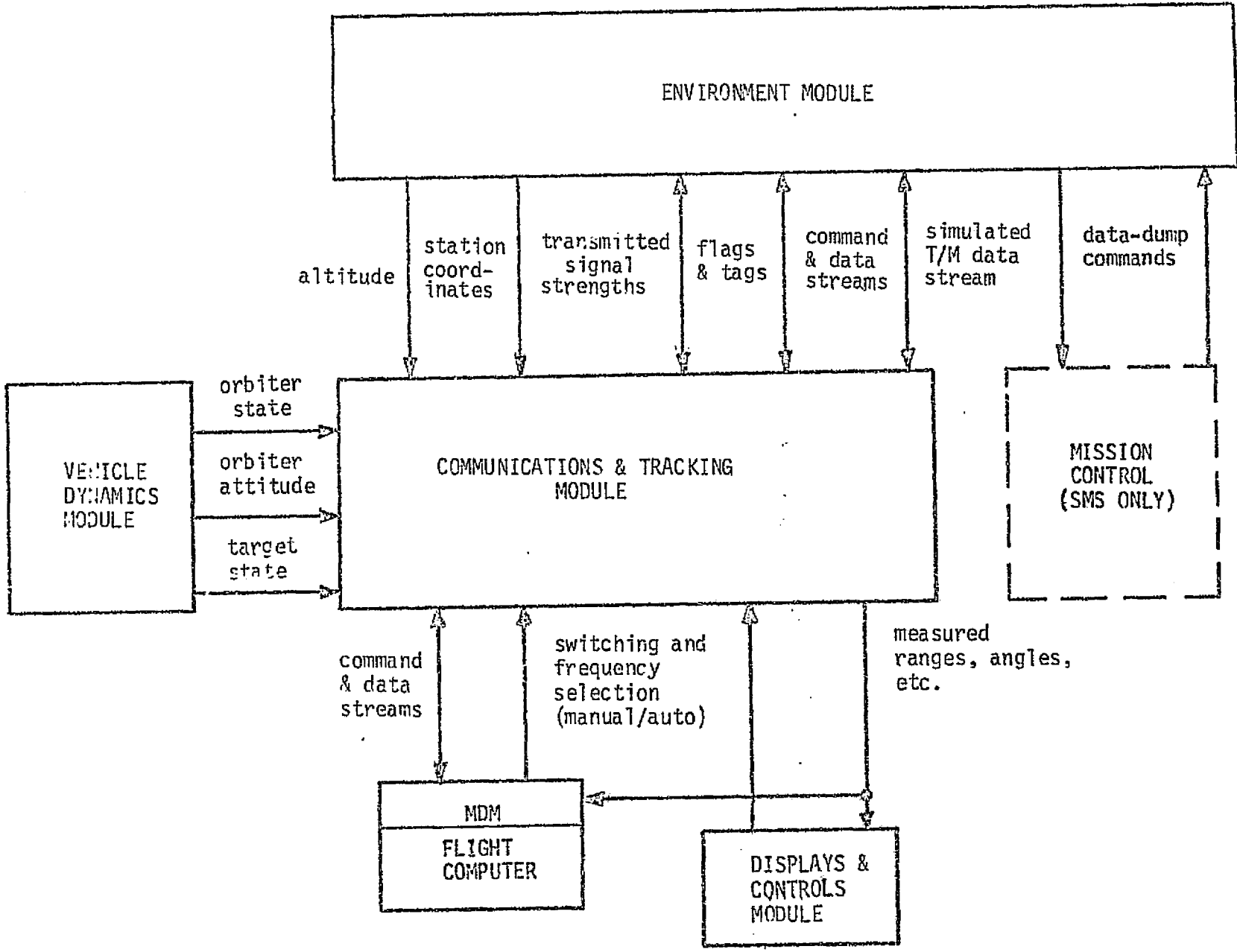


FIGURE 4.7-94. COMMUNICATIONS & TRACKING MODULE INTERFACES

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. 93. 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. 47). 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

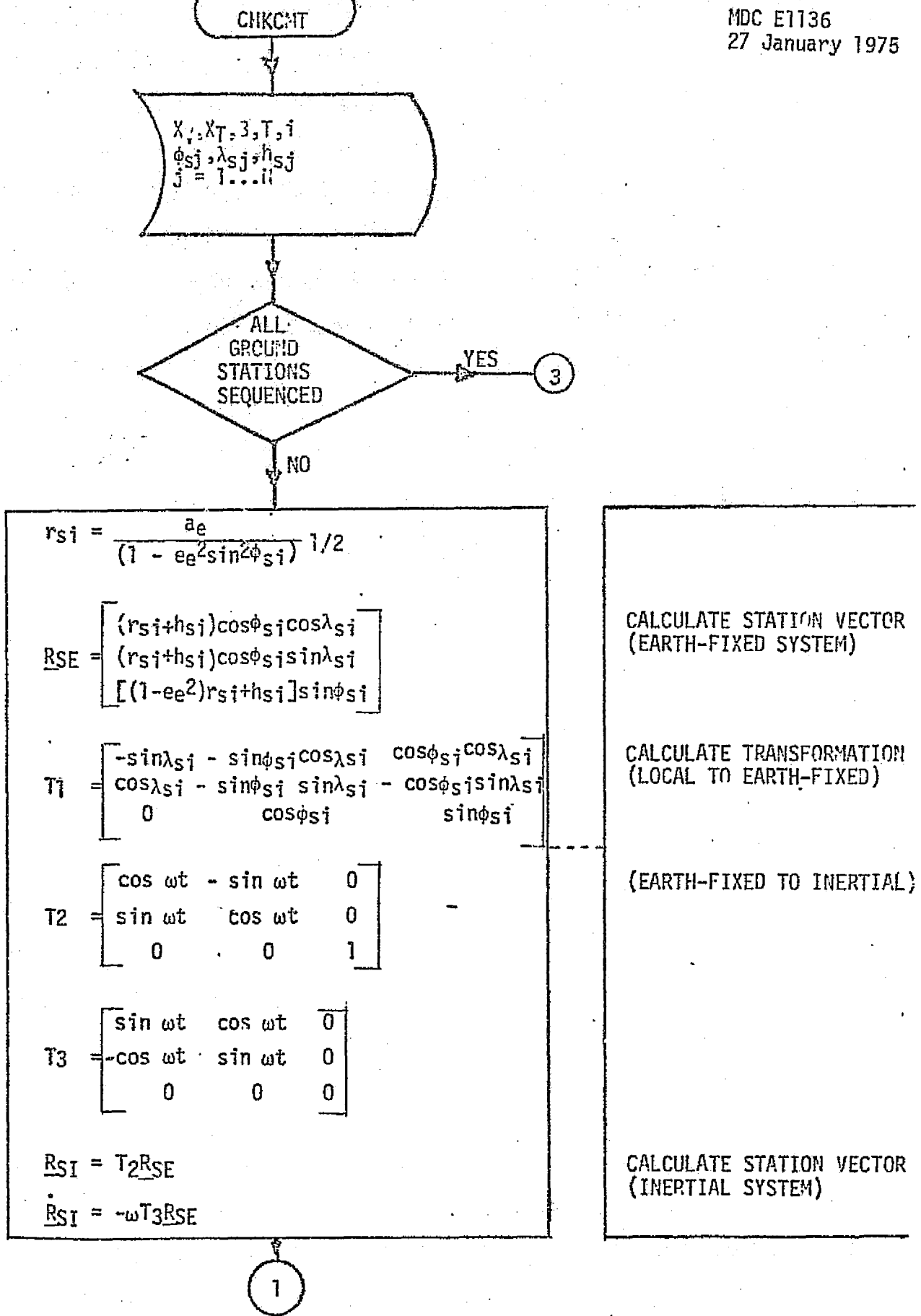


FIGURE 4.7-95 COMMUNICATIONS AND TRACKING REFERENCE MODULE MATH FLOW.

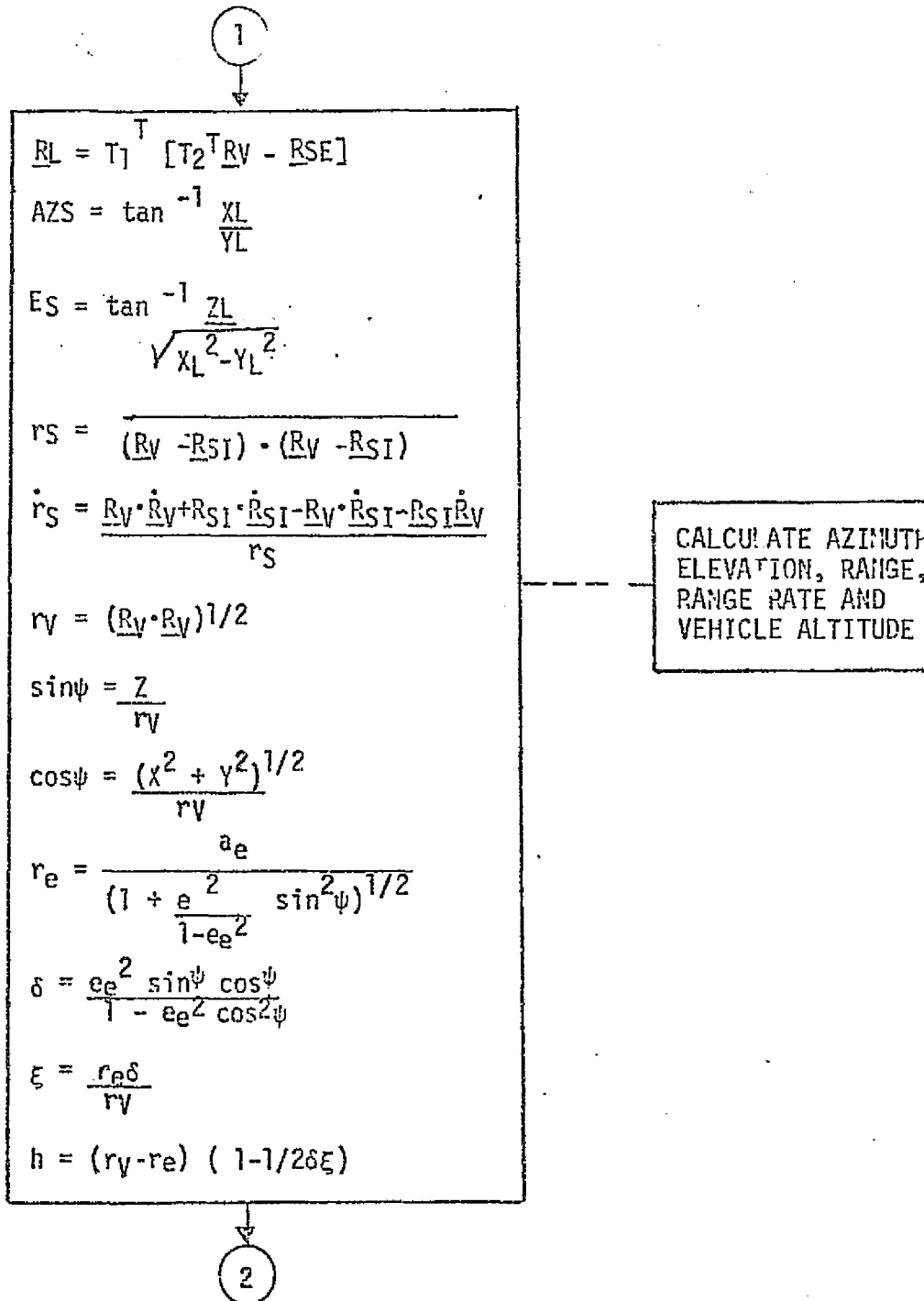


FIGURE 4.7-95 (CONTINUED)

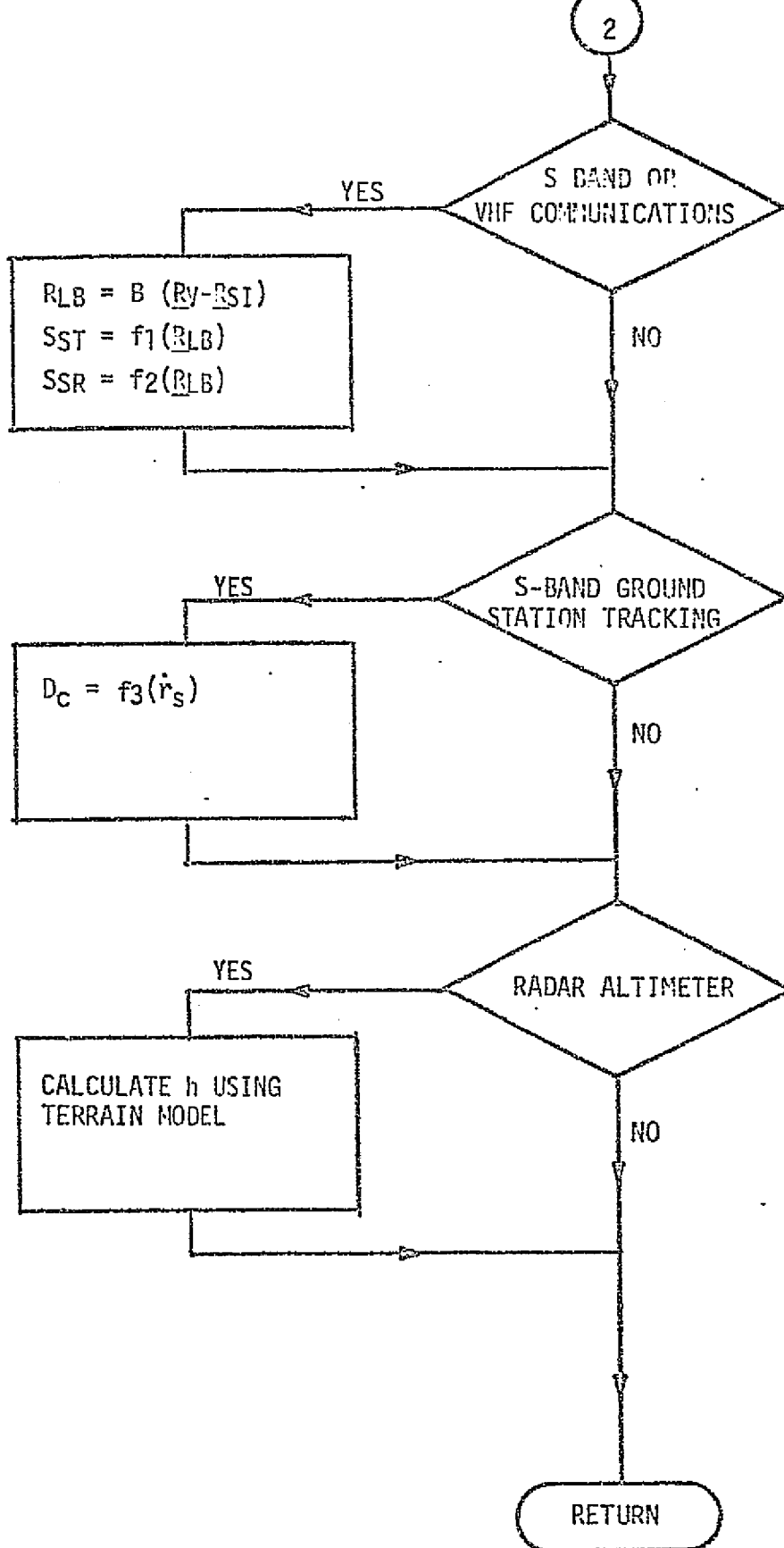


FIGURE 4.7-95 (CONTINUED)

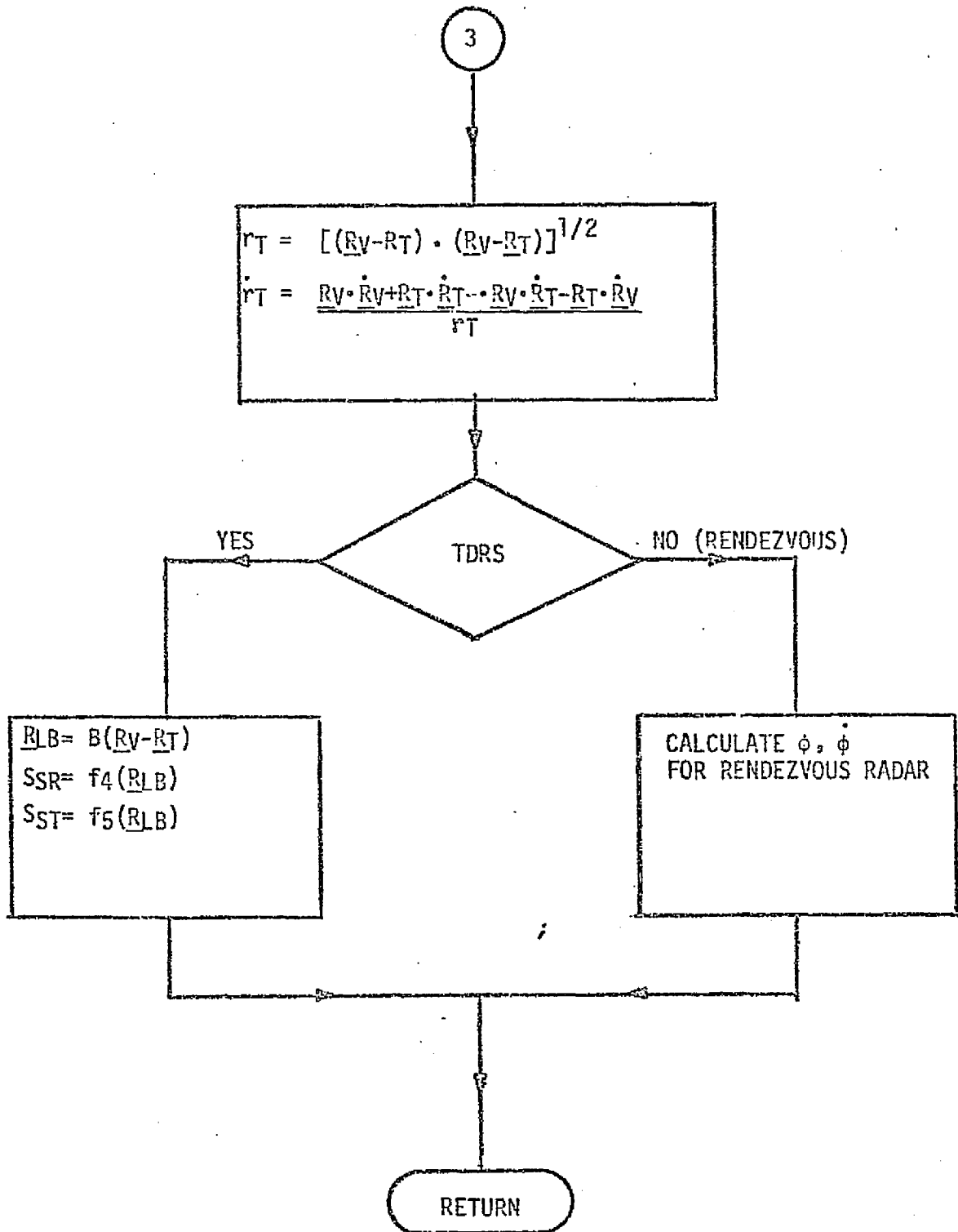


FIGURE 4.7-95 (CONTINUED)

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
ae	Earth semimajor axis
ee	Earth eccentricity
ωt	Angle between vernal equinox and Greenwich Meridian (Note t depends on time of reference frame initialization)
ω	Earth rotation rate
f1	Function relating Doppler counts to range rate (Ground Transmission)
f2	Function relating antenna transmitted signal strength to line of sight (vehicle to ground station)
f3	Function relating antenna received signal strength to line of sight (ground station to vehicle)
f4	Function relating antenna transmitted signal strength to line of sight (vehicle to TDRS)
f5	Function relating antenna received signal strength to line of sight (TDRS to vehicle)

FIGURE 4.7-05 (CONCLUDED).

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

$B = 3 \times 3$ coordinate transformation matrix

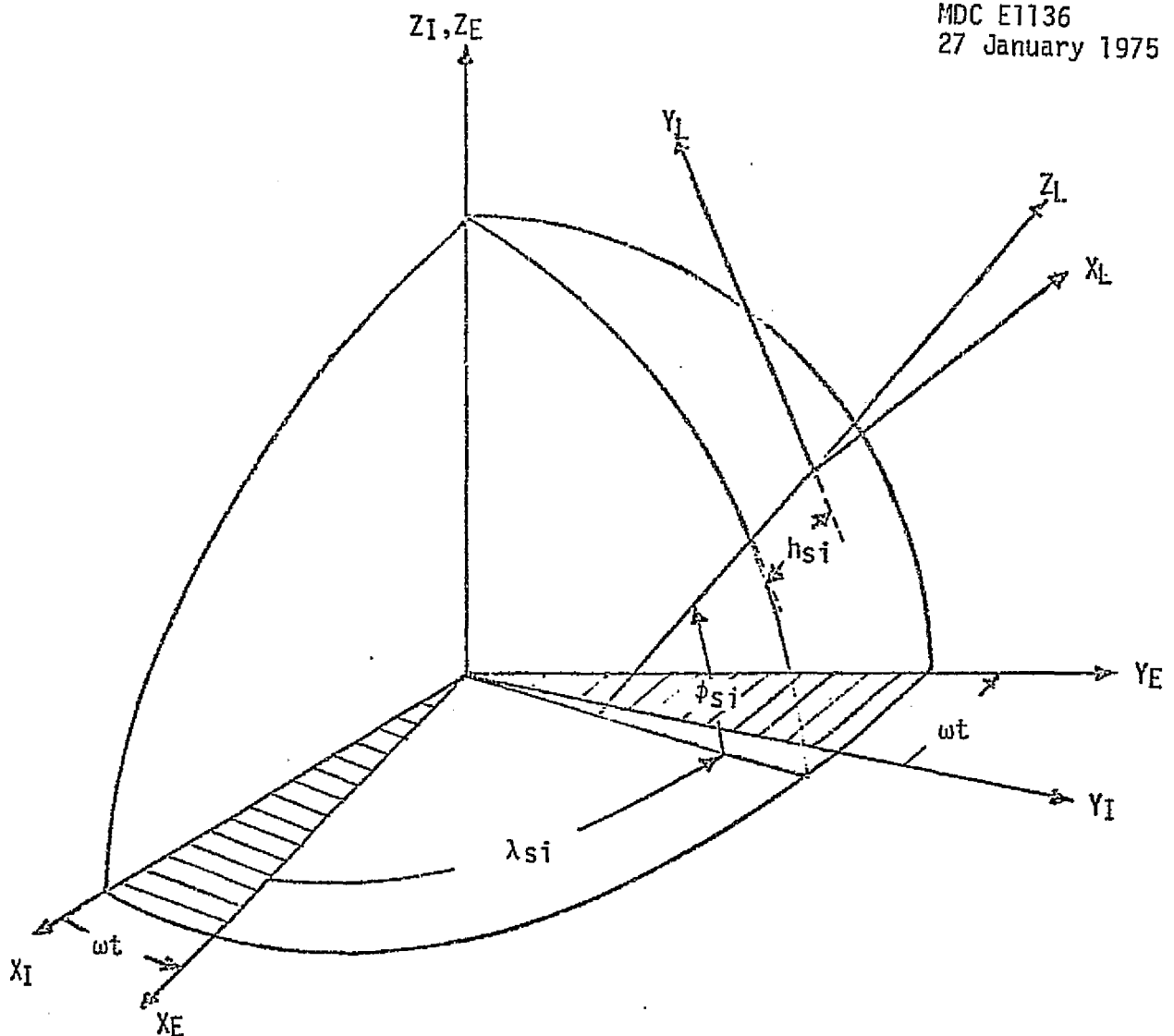
$T =$ universal time

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_I - 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.

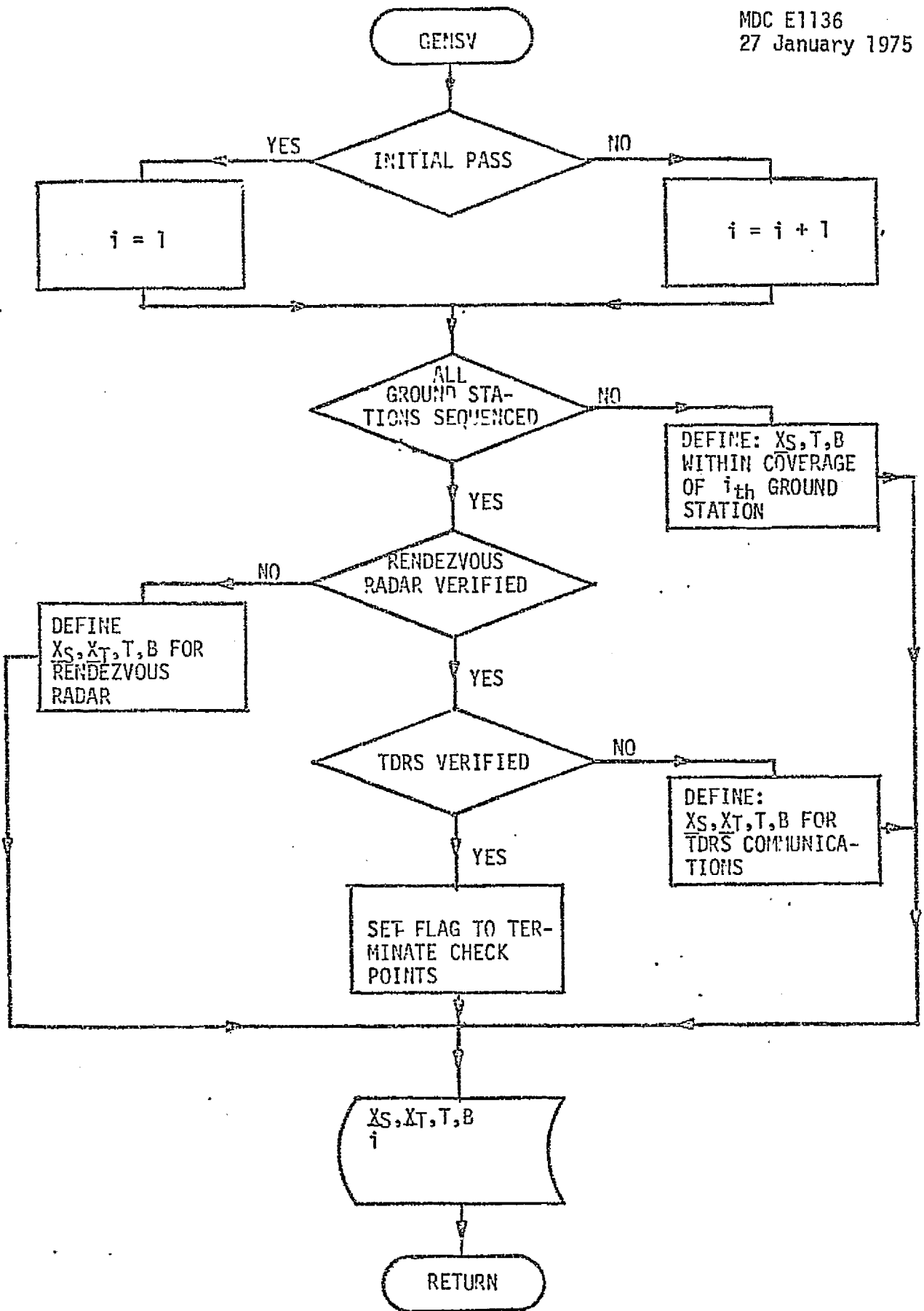


FIGURE 4.7-97 COMMUNICATIONS AND TRACKING CHECKPOINT-GENERATION MATH FLOW.

4.7-294

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. 94), 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. 95) 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. 96) recognizes two types of discrete commands output by the flight computer: critical and non-critical. Critical command words must be

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.

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4.7-209

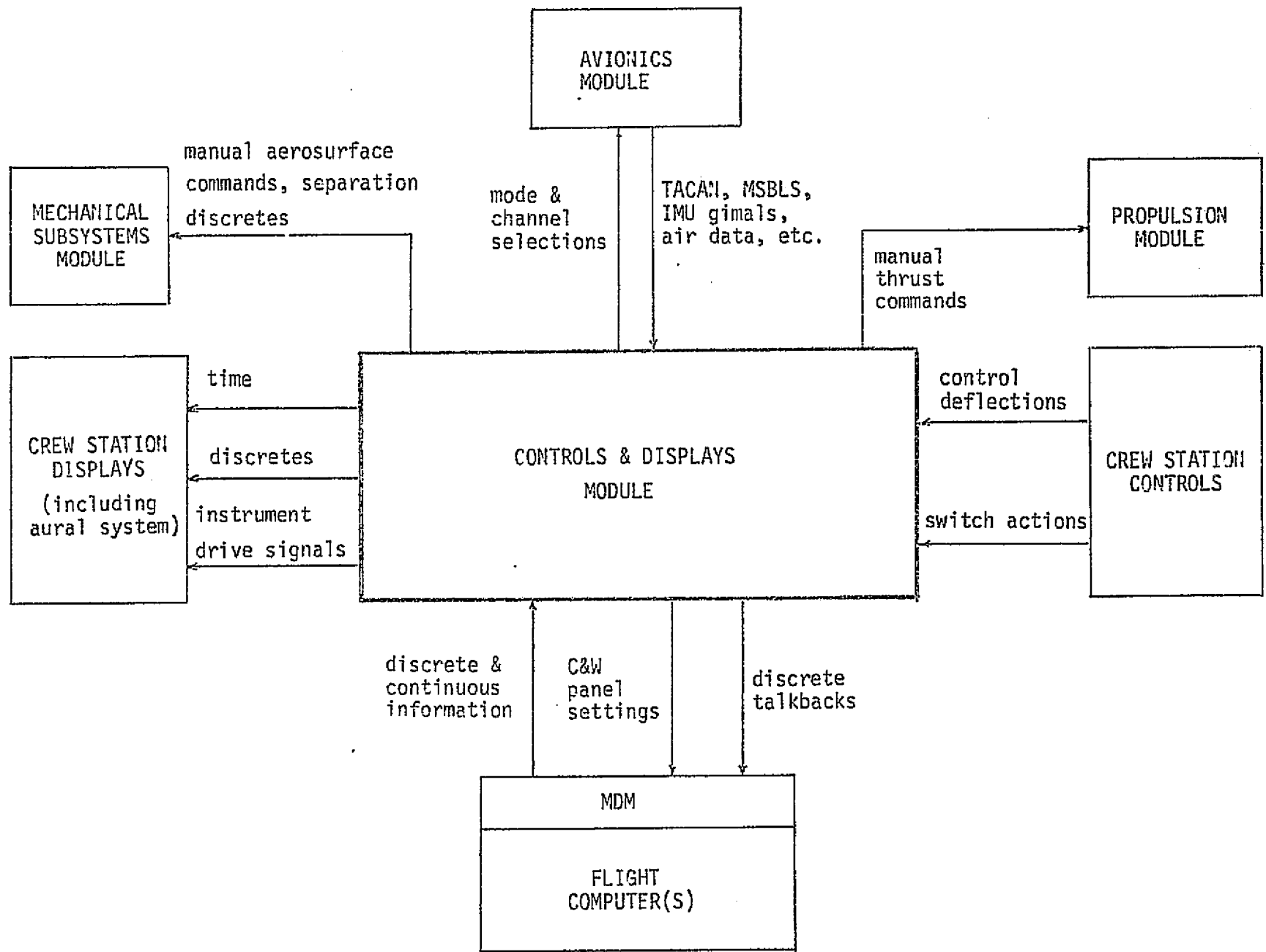


FIGURE 4.7-93. CONTROLS AND DISPLAYS MODULE INTERFACES

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

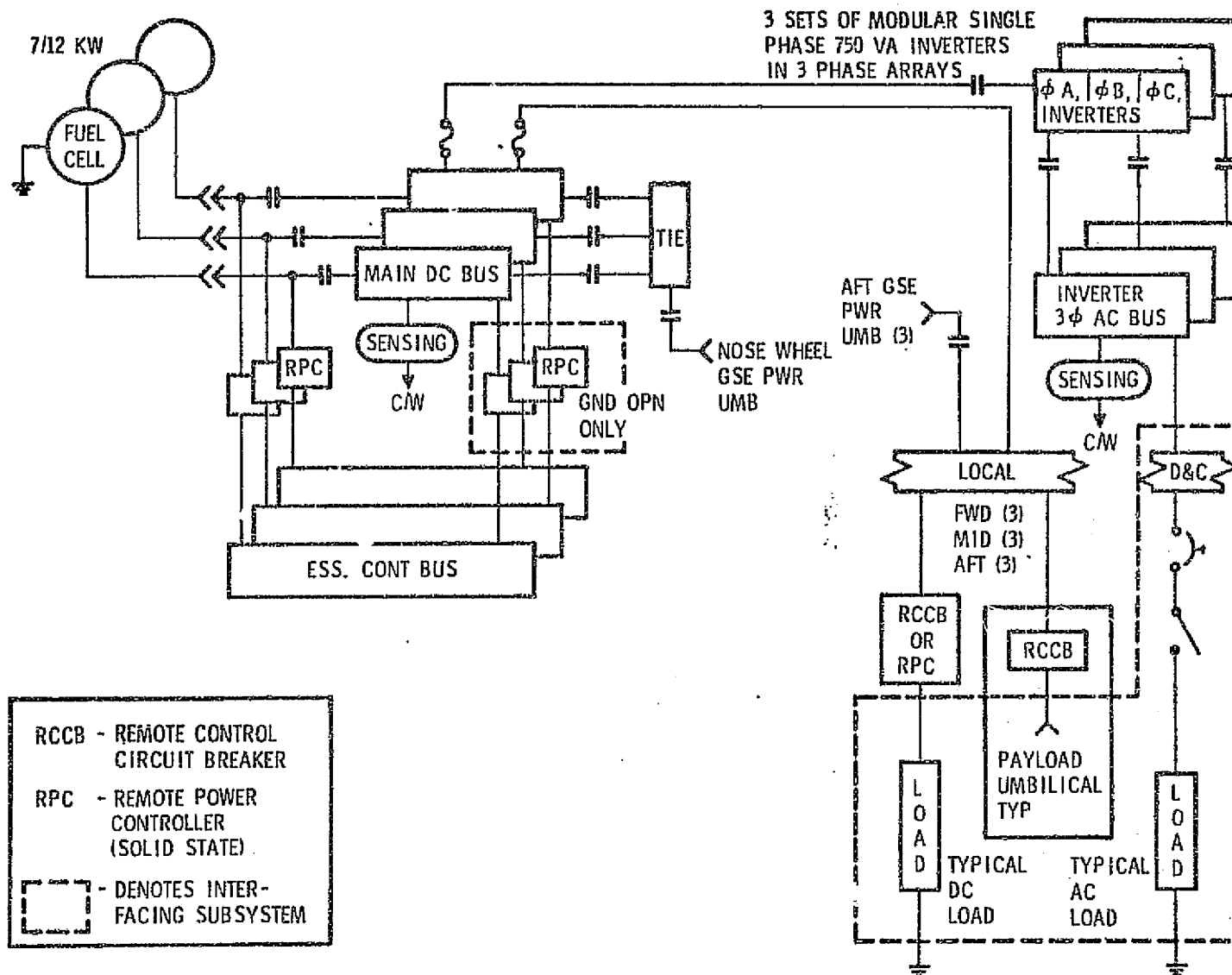


FIGURE 4.7-99. ELECTRICAL POWER DISTRIBUTION AND CONTROL-SUBSYSTEM SCHEMATIC

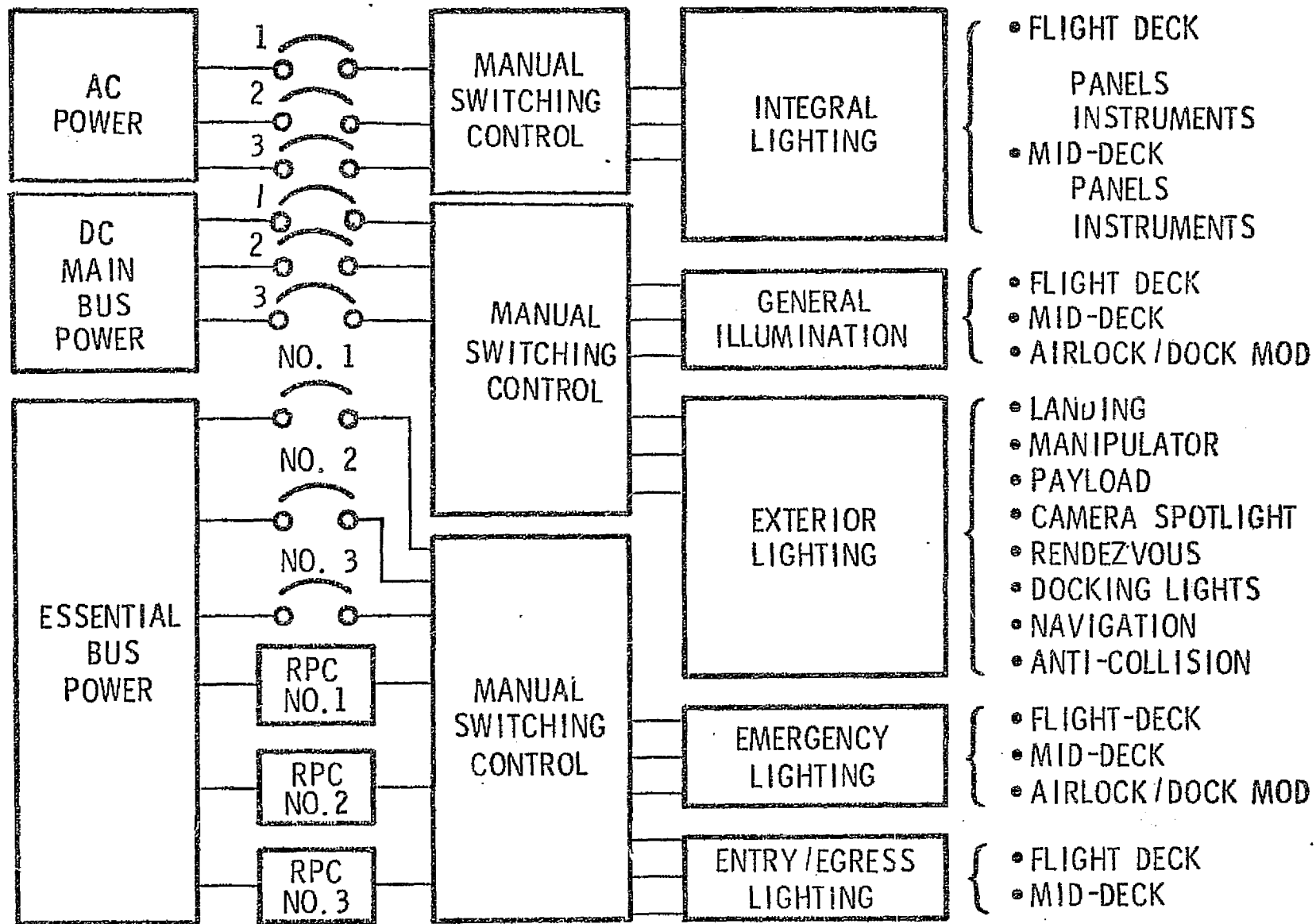


FIGURE 4.7-100. ILLUMINATION SUBSYSTEM SCHEMATIC

4.7-306

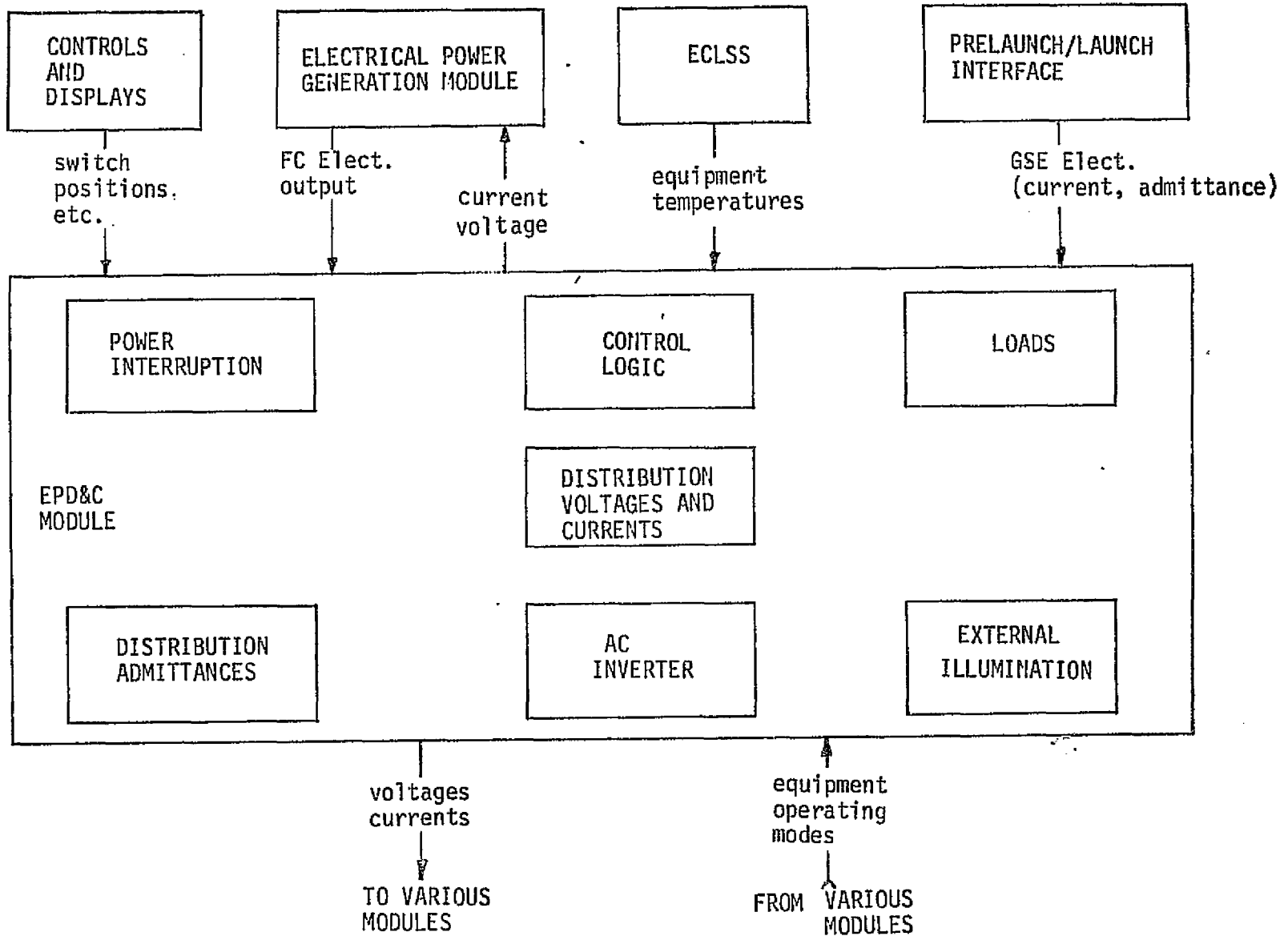


FIGURE 4.7-101. ELECTRICAL POWER DISTRIBUTION AND CONTROL MODULE ELEMENTS AND INTERFACES.

TABLE 4.7-29. EPD&C PERFORMANCE PARAMETERS

PARAMETER	TYPE ^a
Switch position, selections, etc.	I
Equipment operating modes, on/off	I
FC electrical outputs - (Norton's equivalent current, admittance)	I
GSE electrical outputs - (Norton's equivalent current, admittance)	I
Equipment temperatures	I
Bus voltages	CP
Load voltages	P
Bus currents	CP
Load currents	P
Bus distribution admittances	P
Load admittances	P
External illumination light operating modes	P
Power interruption devices - total current	P
- overload trip time	CP
- device open	P

^aTYPE:

CP = critical parameter

P = performance parameter

I = input

- 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 22 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. 100). 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:

$$E_x = \frac{\Delta_x}{\Delta_0}$$

E_x = x-node voltage

Δ_0 = 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.

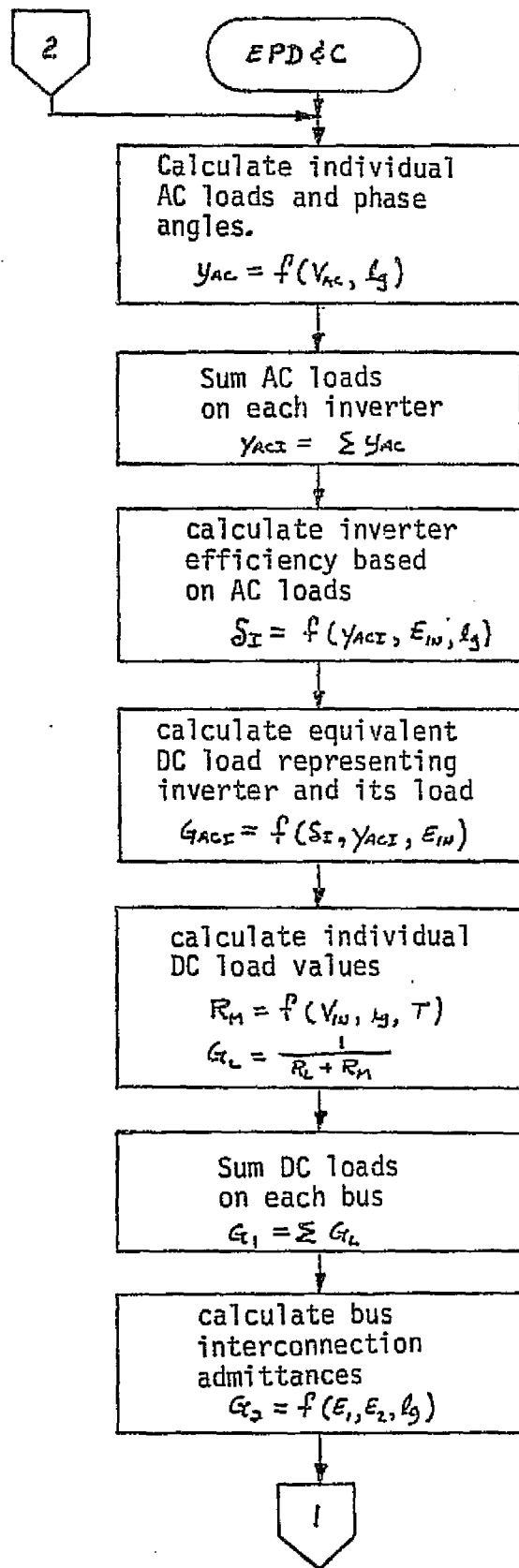


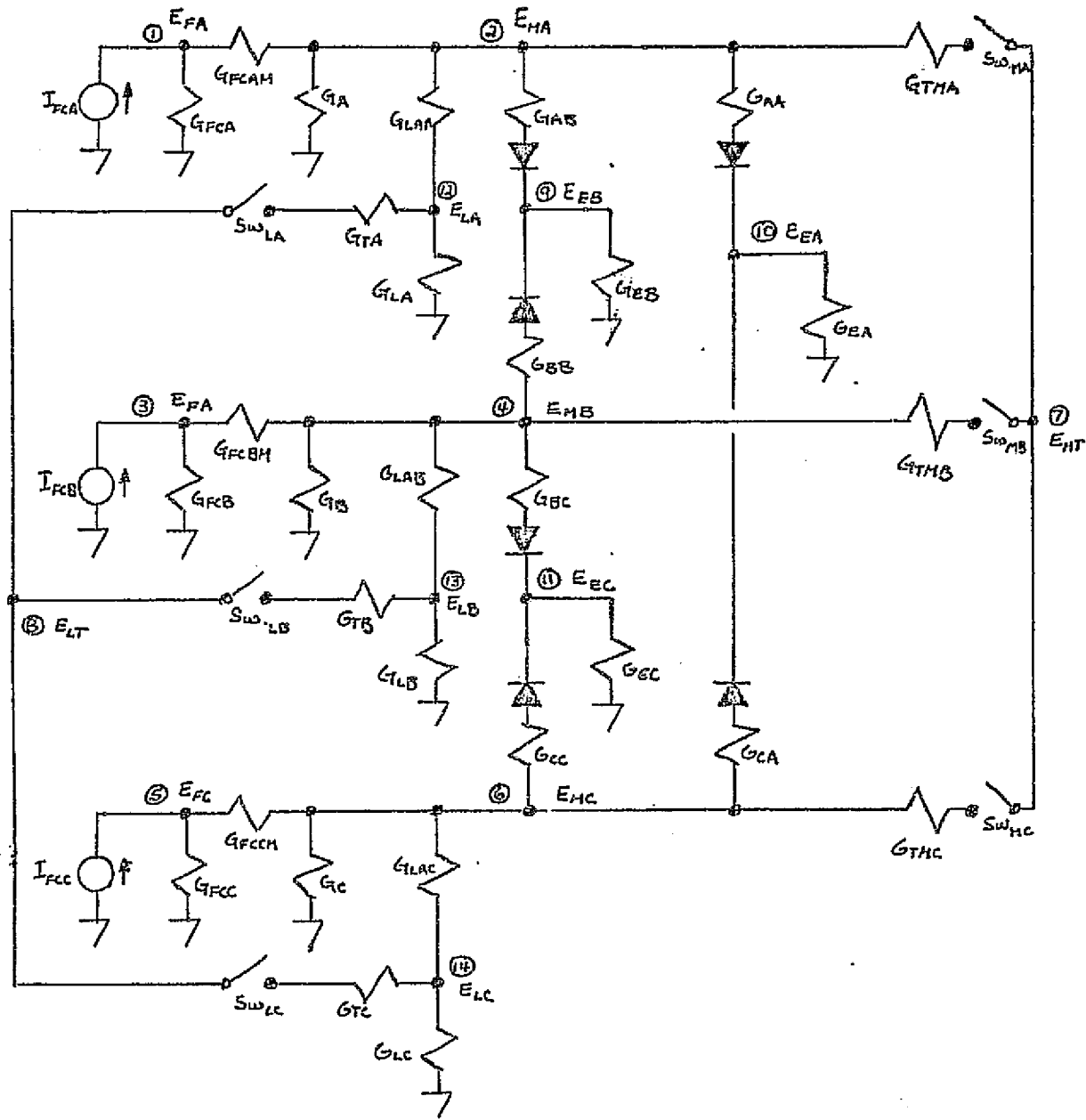
FIGURE 4.7-102 ELECTRIC POWER DISTRIBUTION AND CONTROL SUBSYSTEM REFERENCE MODULE MATH FLOW.

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_{Lr}	= 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)

4.7-313



$$[I] = [G][E]$$

$$[I] \equiv \begin{bmatrix} I_{FCA} \\ 0 \\ I_{FCB} \\ 0 \\ I_{FCC} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$[E] \equiv \begin{bmatrix} E_{FA} \\ E_{HA} \\ E_{FB} \\ E_{MB} \\ E_{FC} \\ E_{HC} \\ E_{HT} \\ E_{LT} \\ E_{EB} \\ E_{EA} \\ E_{EC} \\ E_{LA} \\ E_{LB} \\ E_{LC} \end{bmatrix}$$

FIGURE 4.7-103. ELECTRICAL POWER DISTRIBUTION AND CONTROL EQUIVALENT CIRCUIT AND MATRIX DEFINITIONS

4.7-314

G

III

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	$-G_{THA}$	0	$-G_{AB}$	$-G_{AA}$	0	$-G_{LAA}$	0	0	0
0	0	G_{33}	$-G_{FCBH}$	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	$-G_{LAC}$
0	0	0	0	0	$-G_{FCCM}$	G_{66}	$-G_{TMC}$	0	0	$-G_{CA}$	$-G_{CC}$	0	0	0
0	$-G_{THA}$	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	0	$-G_{TA}$	$-G_{TB}$	$-G_{TC}$
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	$-G_{TA}$	0	0	0	$G_{12 12}$	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.

$$G_{11} = G_{FCA} + G_{FCAM}$$

$$G_{22} = G_{FCM} + G_A + G_{LAA} + G_{AB} + G_{AA} + G_{THA}$$

$$G_{33} = G_{FCB} + G_{FCBM}$$

$$G_{44} = G_{FCBM} + G_B + G_{LAB} + G_{BB} + G_{BC} + G_{TMB}$$

$$G_{55} = G_{FCC} + G_{FCCM}$$

$$G_{66} = G_{FCBM} + G_C + G_{LAC} + G_{CC} + G_{CA} + G_{TMC}$$

$$G_{77} = G_{THA} + G_{TMB} + G_{TMC}$$

$$G_{88} = G_{TA} + G_{TB} + G_{TC}$$

$$G_{99} = G_{AB} + G_{BB} + G_{BB}$$

$$G_{10 10} = G_{CA} + G_{EA} + G_{AA}$$

$$G_{11 11} = G_{BC} + G_{EC} + G_{CC}$$

$$G_{12 12} = G_{LAA} + G_{TA} + G_{LA}$$

$$G_{13 13} = G_{LAB} + G_{TB} + G_{LB}$$

$$G_{14 14} = G_{LAC} + G_{TC} + G_{LC}$$

FIGURE 4.7-103. (CONTINUED)

LEGEND:

- | | | |
|-------------|---|---|
| I_{FCA} | } | = Norton's equivalent current sources representing the fuel cell A, B, C outputs. |
| I_{FLB} | | |
| I_{FLC} | | |
| G_{FCA} | } | = Norton's equivalent admittance for the fuel cells A, B, C. |
| G_{FCB} | | |
| G_{FCC} | | |
| $G_{FC()}M$ | | = Admittances connecting fuel cell output to main buses. |
| G_A | } | = Equivalent loads on main buses A, B, C including forward local/middle local/AC bus loads and wiring losses. |
| G_B | | |
| G_C | | |
| G_{LAA} | } | = Admittance between main buses and AFT local buses A, B, C. |
| G_{LAB} | | |
| G_{LAC} | | |
| G_{LA} | } | = Admittance loads on AFT local buses A, B, C. |
| G_{LB} | | |
| G_{LC} | | |
| G_{TA} | } | = Admittance between AFT local buses A, B, C and AFT Bus Tie. |
| G_{TB} | | |
| G_{TC} | | |
| G_{TMA} | } | = Admittances between main buses A, B, C and main Bus Tie. |
| G_{TMB} | | |
| G_{TMC} | | |
| G_{AA} | } | = Admittance between main buses A, C and essential bus A. |
| G_{CA} | | |

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 111), specification MC250-0002 (Reference 103), 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

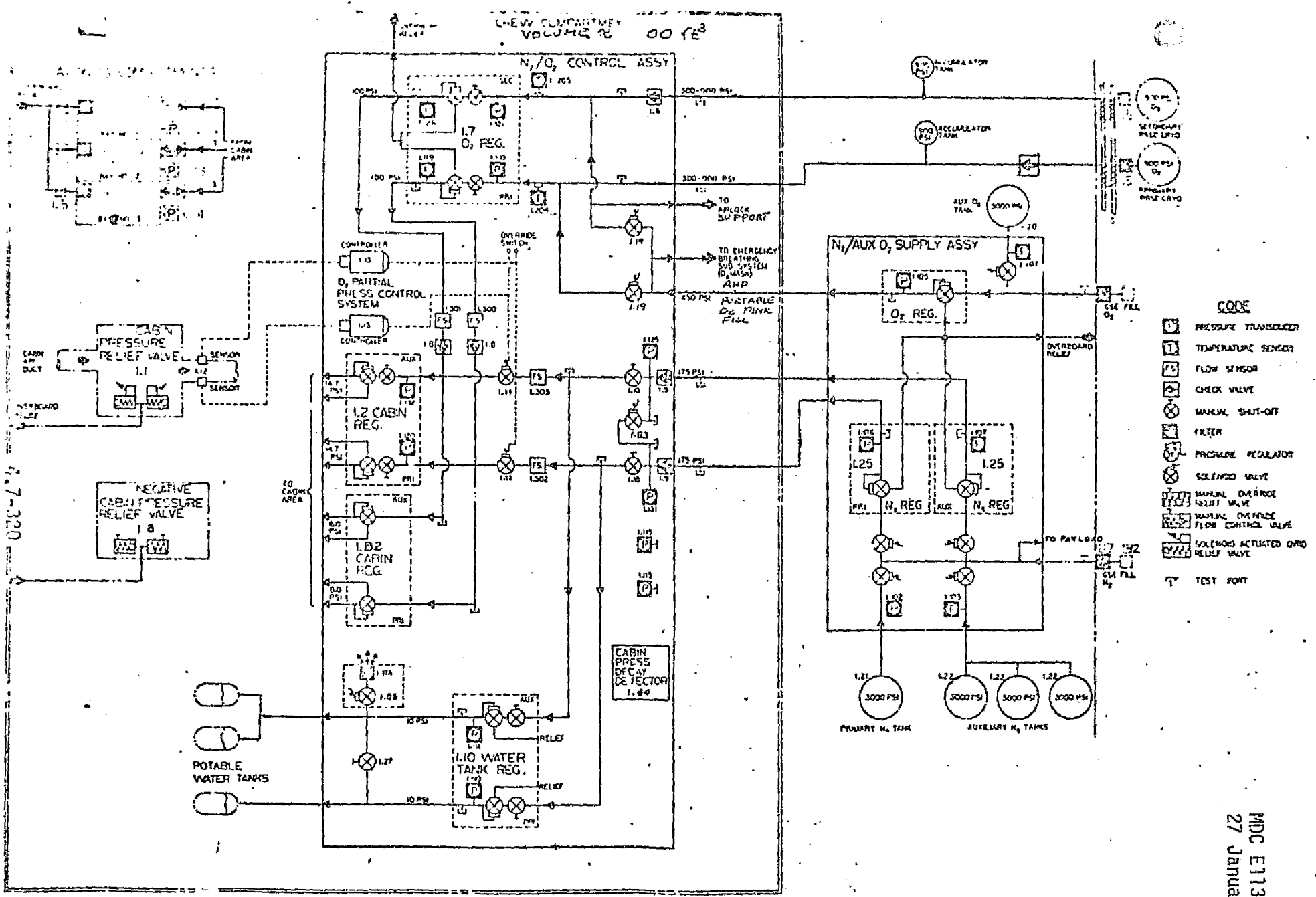


FIGURE 4.7-104. ATMOSPHERE REVITALIZATION PRESSURE CONTROL SUBSYSTEM SCHEMATIC

MDC E1136
 27 January 1975

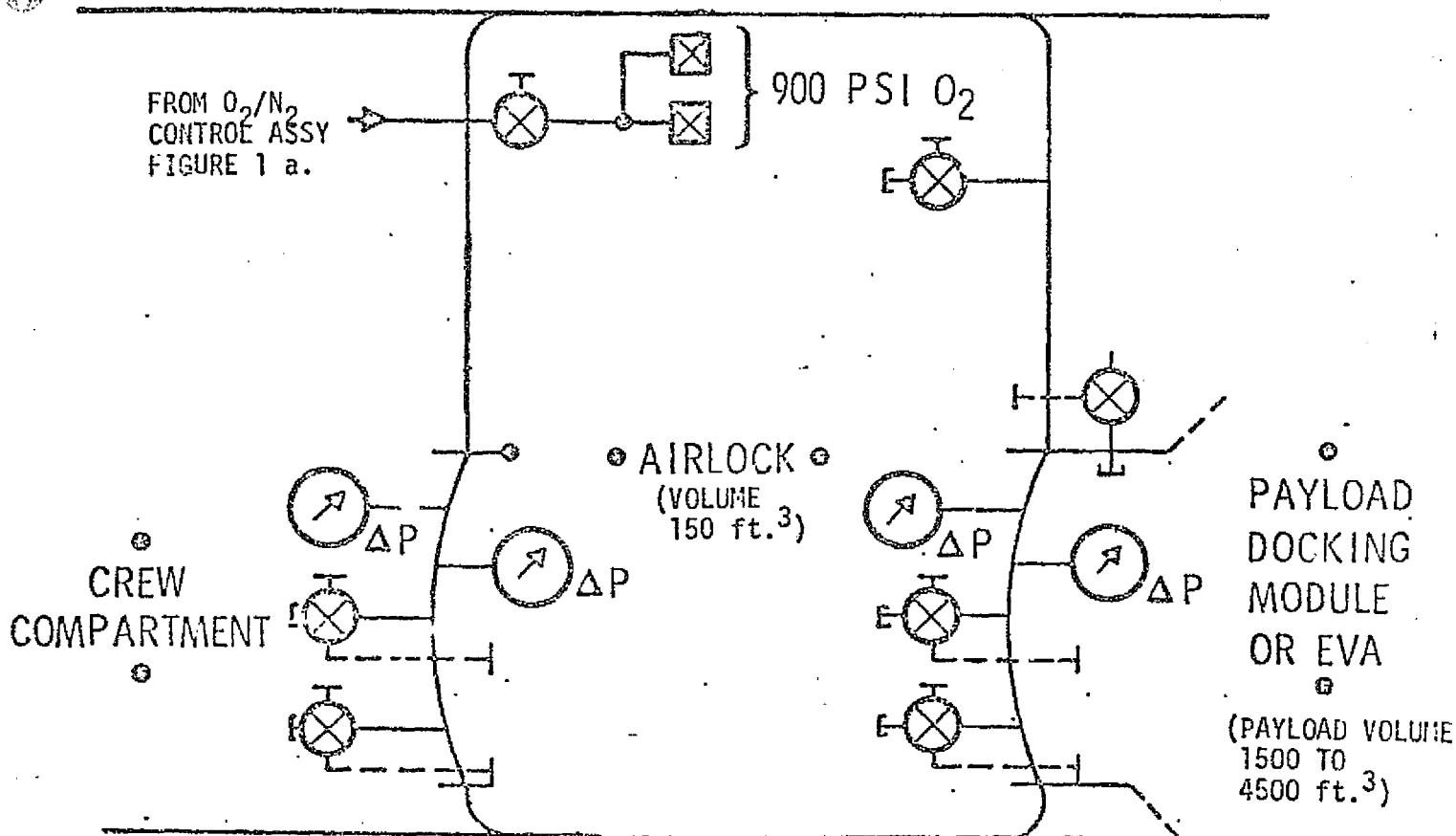


FIGURE 4.7-105. ATMOSPHERE PRESSURE CONTROL, AIRLOCK SUPPORT SUBSYSTEM SCHEMATIC

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 N₂ to flow to the cabin pressure regulator inlet. The N₂ pressure is greater than the 100 psi O₂ which feeds the regulator through a check valve. The higher pressure closes the check valve preventing O₂ from entering the regulator and N₂ only is supplied to the cabin. When the O₂ partial pressure is less than 2.95 psia, the N₂ solenoid valve is closed. This allows any cabin make-up gas flow to be O₂. O₂ and N₂ 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 O₂ 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.

① 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.

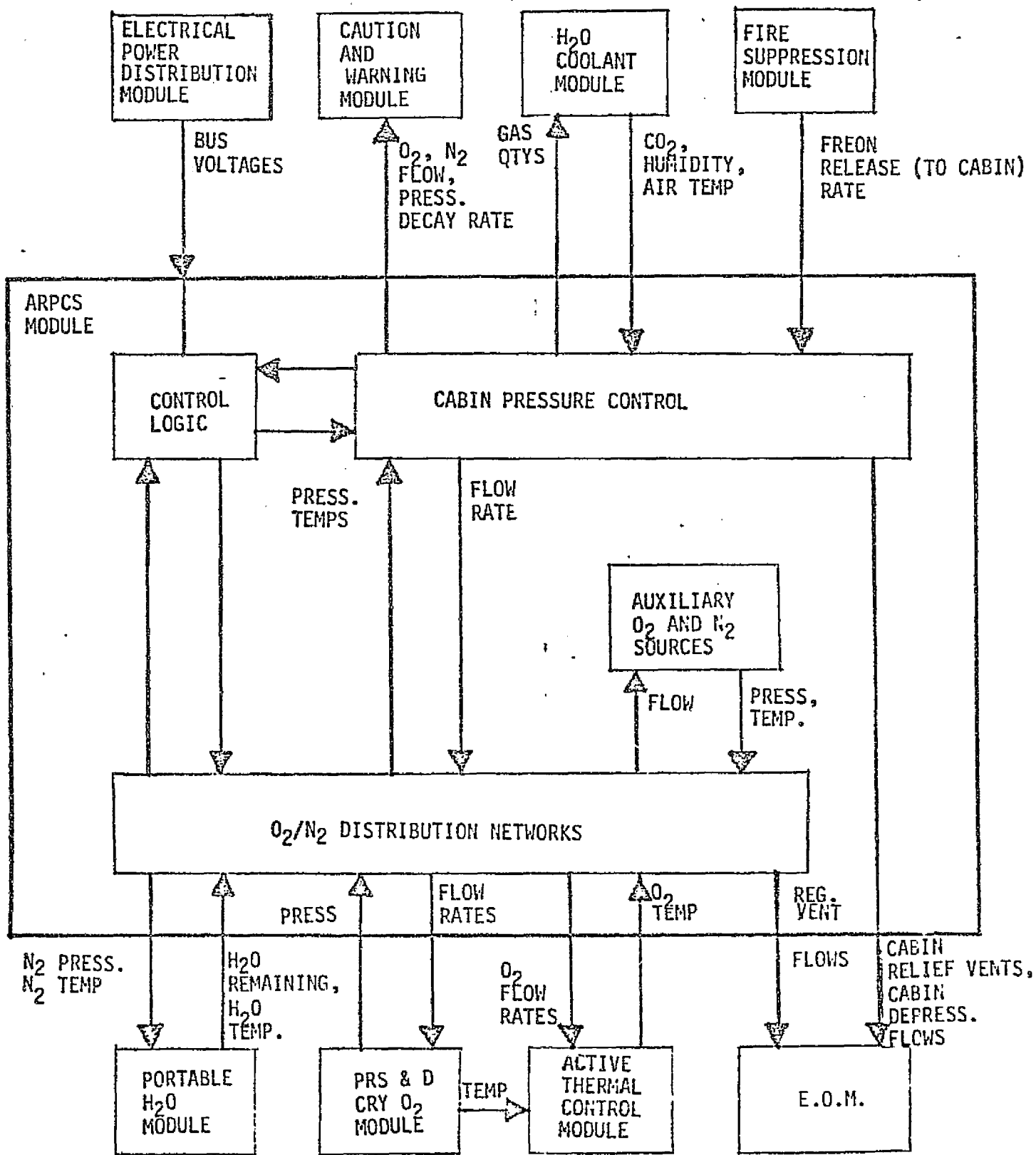


FIGURE 4.7-106 ARPCS MODULE FUNCTIONAL ELEMENTS AND MODULE INTERFACES

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

TABLE 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 4.7-31. (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, g 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.

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 101 and 102. The G189A (see Ref. 12) program was developed for JSC and provides a versatile analytical tool for support of environmental systems work. Reference 102 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 sources, 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 22 will provide these types of data as they become available. The design requirements can be determined from Reference 103.

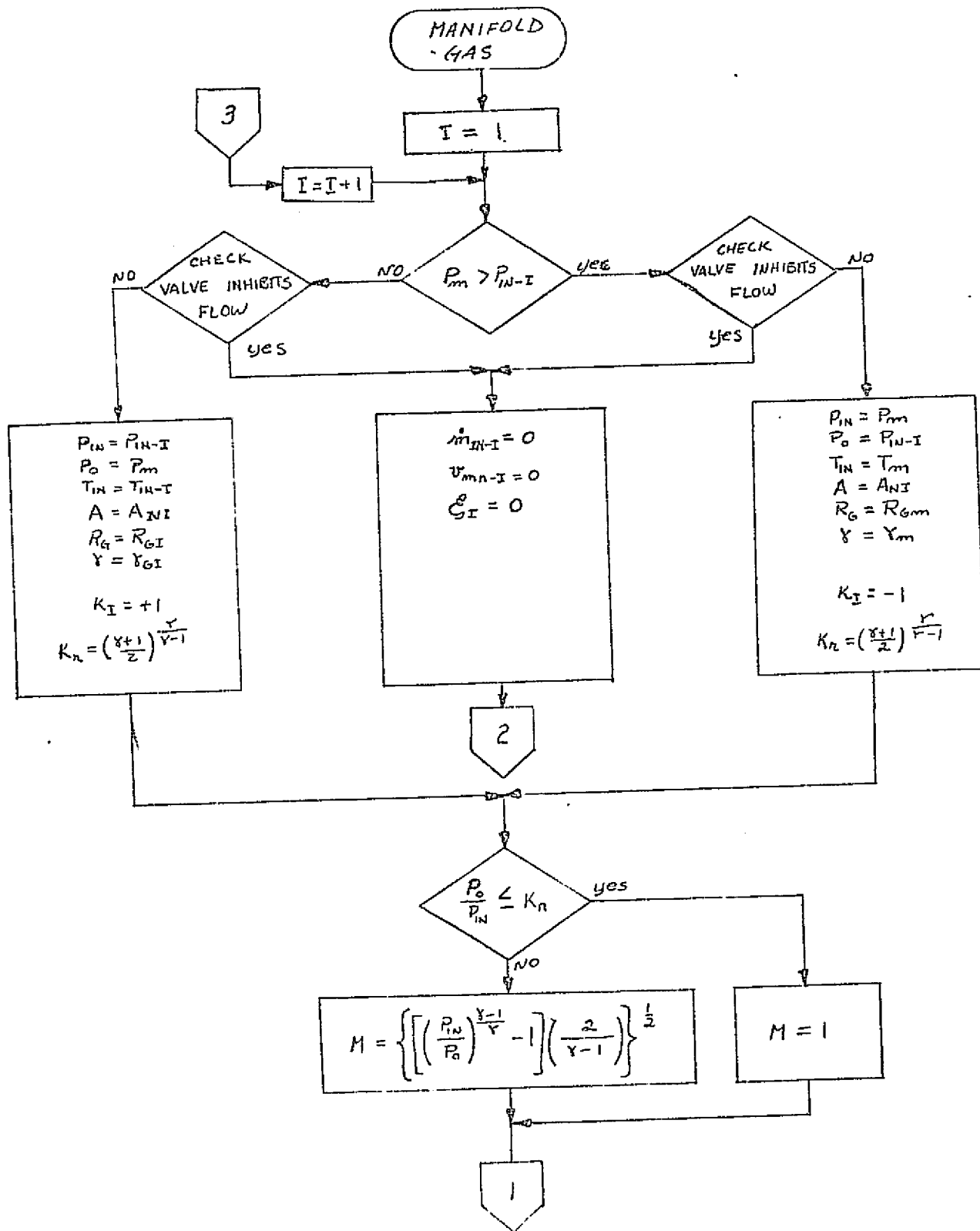


FIGURE 4.7-107. MANIFOLD GAS REFERENCE MODULE MATH FLOW

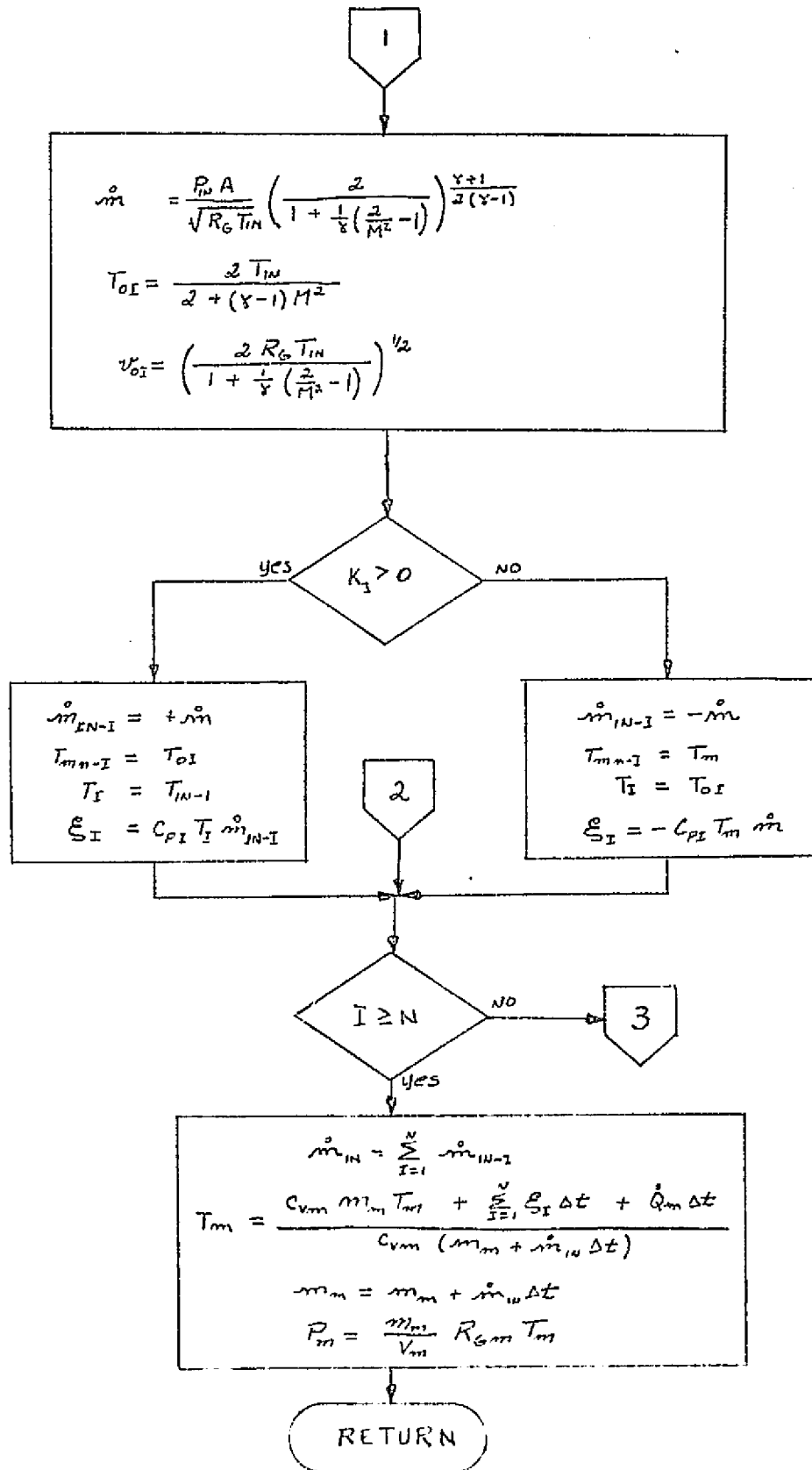


FIGURE 4.7-107. (CONTINUED)

4.7-337

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}_{IN-I} - Flow rate from I^{th} load/source into manifold
- T_{IN-I} - Temperature into manifold ; 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 - 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)

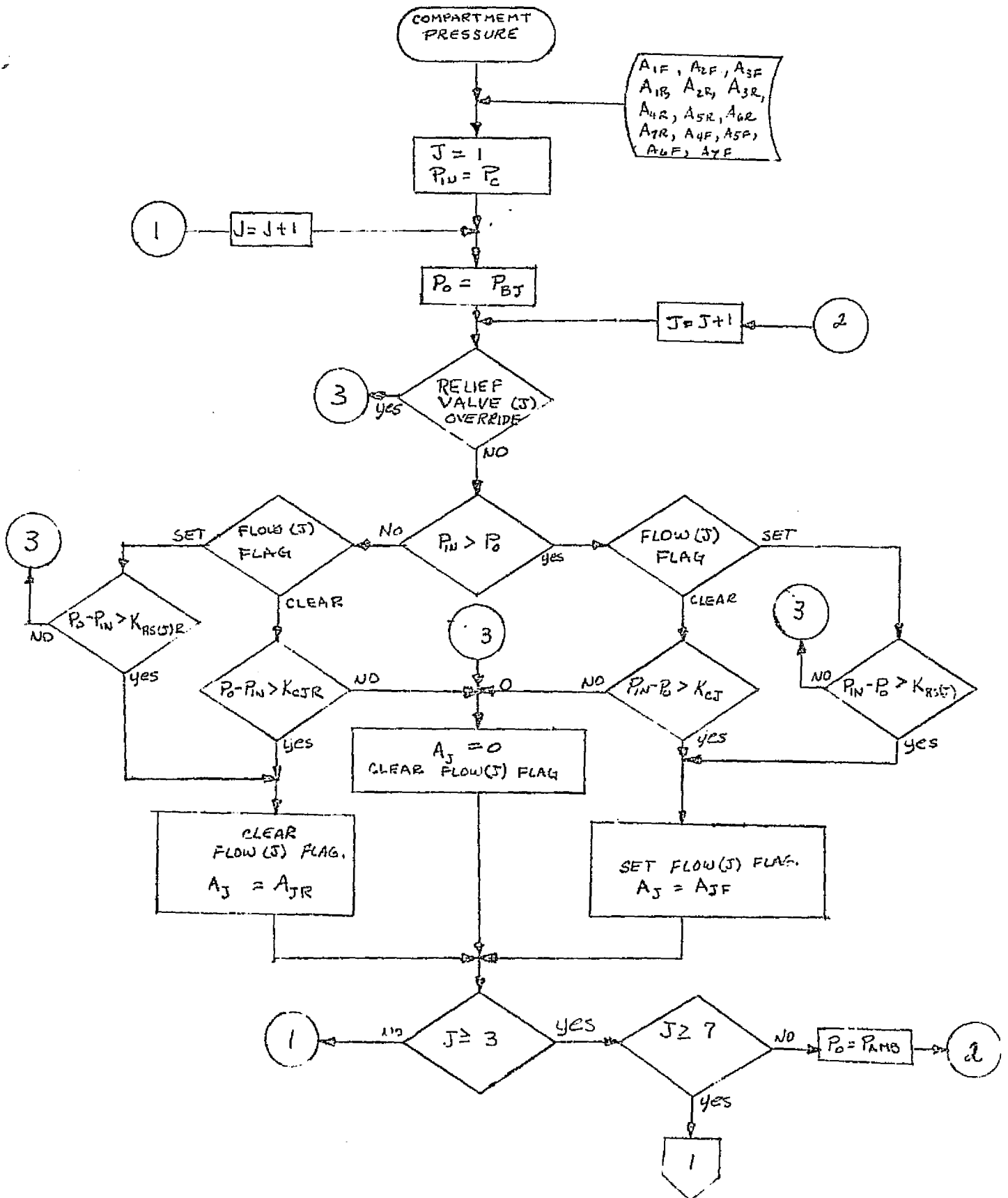


FIGURE 4.7-108. CABIN PRESSURE CONTROL REFERENCE MODULE MATH FLOW
4.7-339

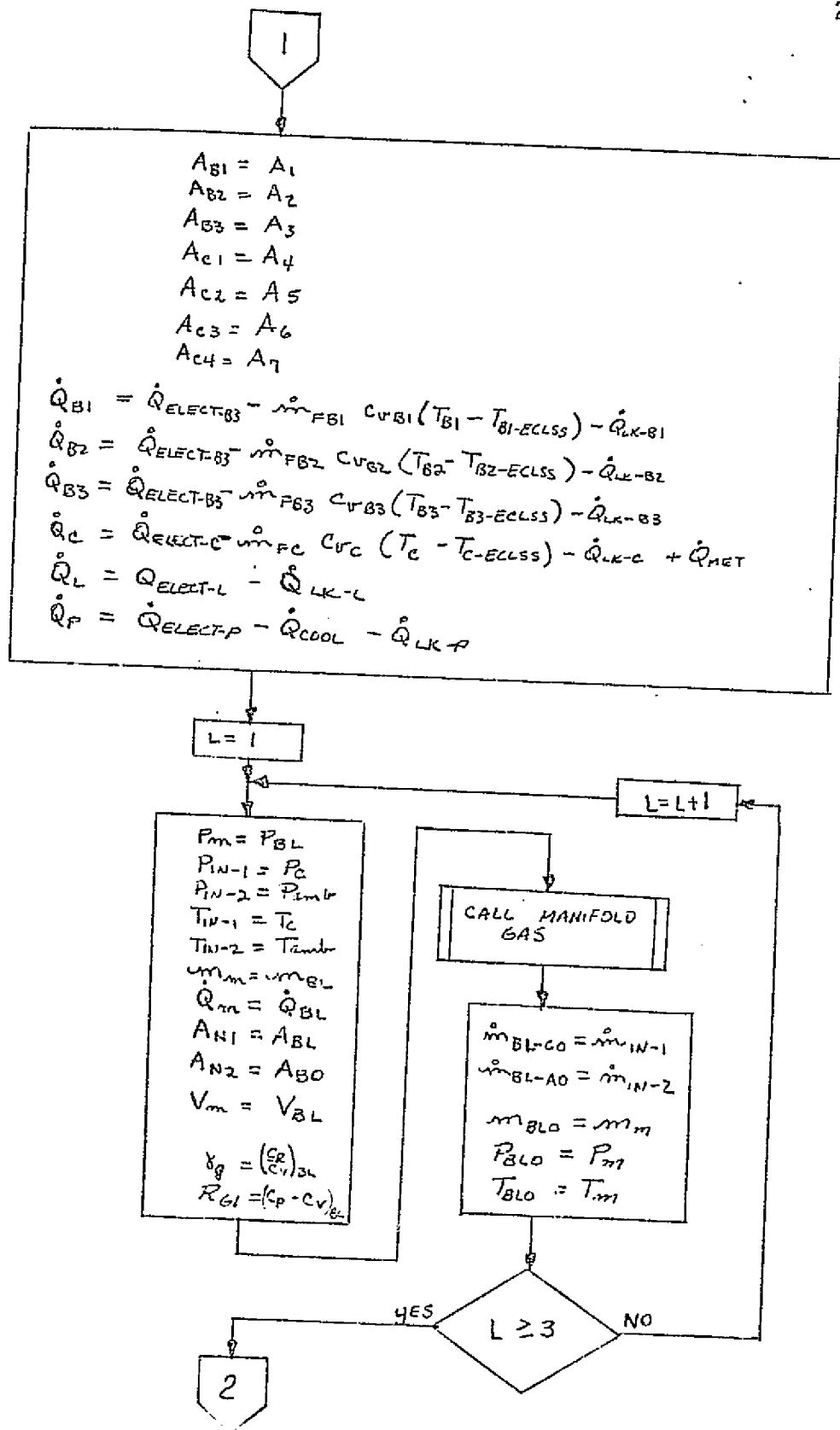


FIGURE 4.7-100. (CONTINUED)

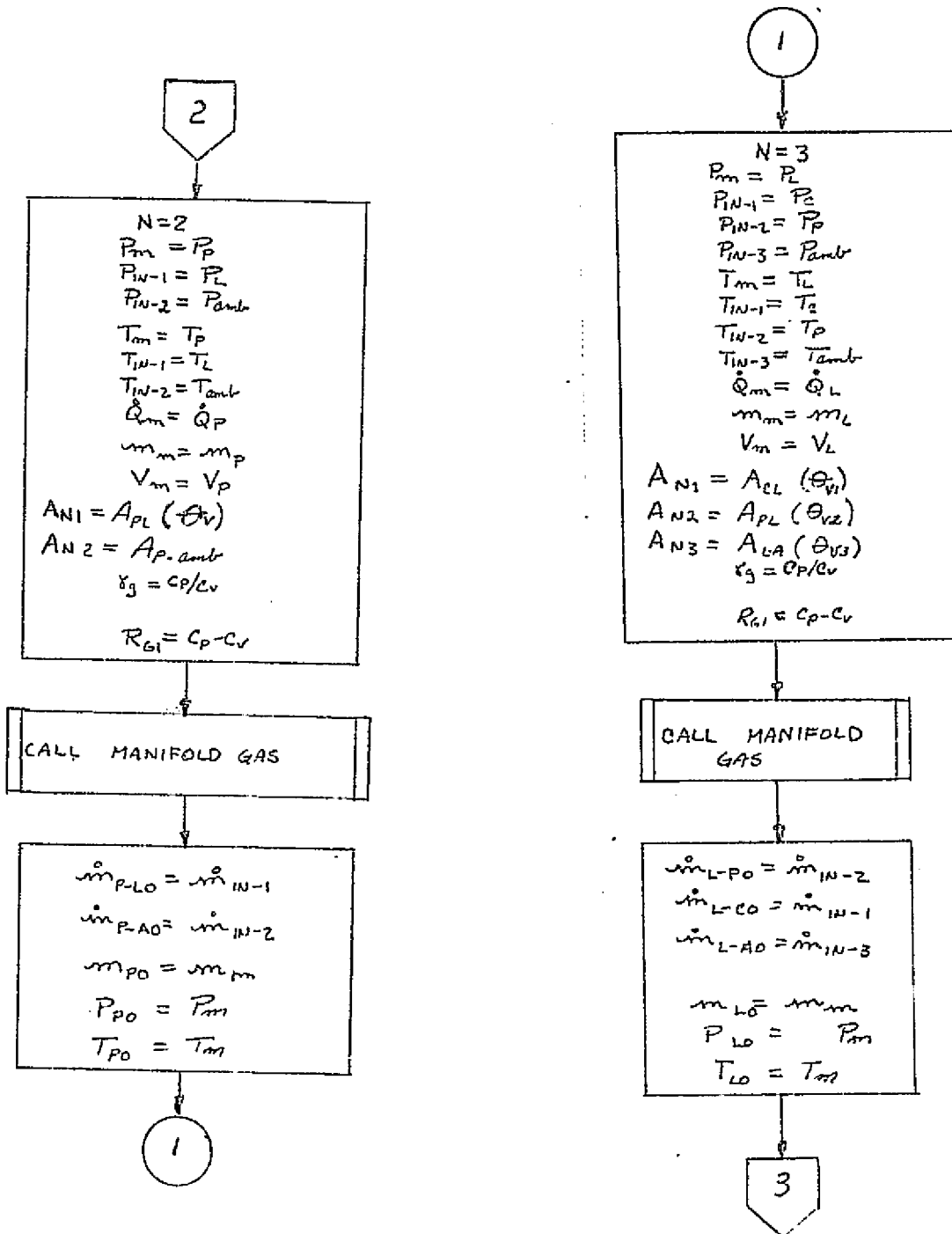


FIGURE 4.7-103. (CONTINUED)

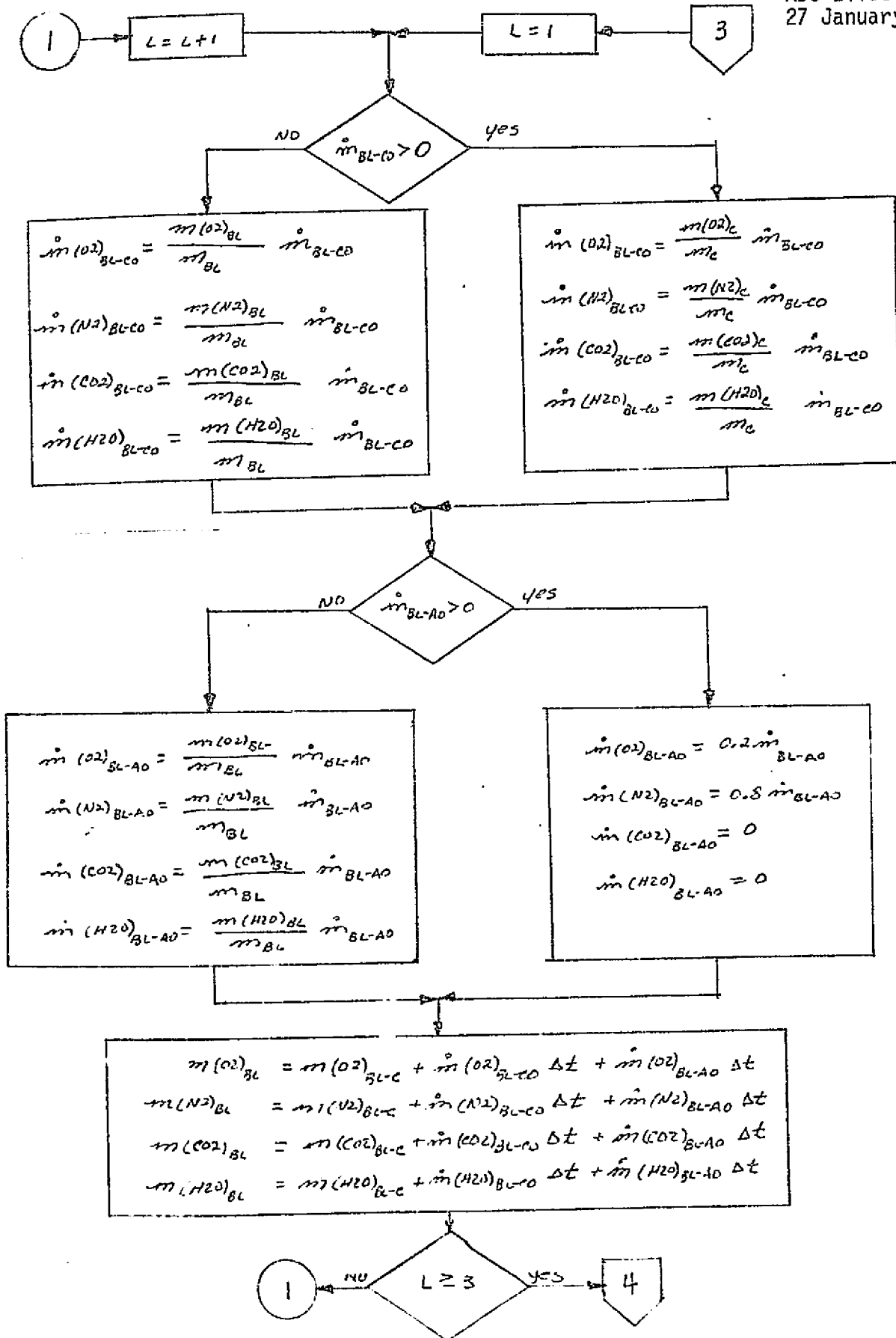


FIGURE 4.7-103. (CONTINUED)

4.7-312

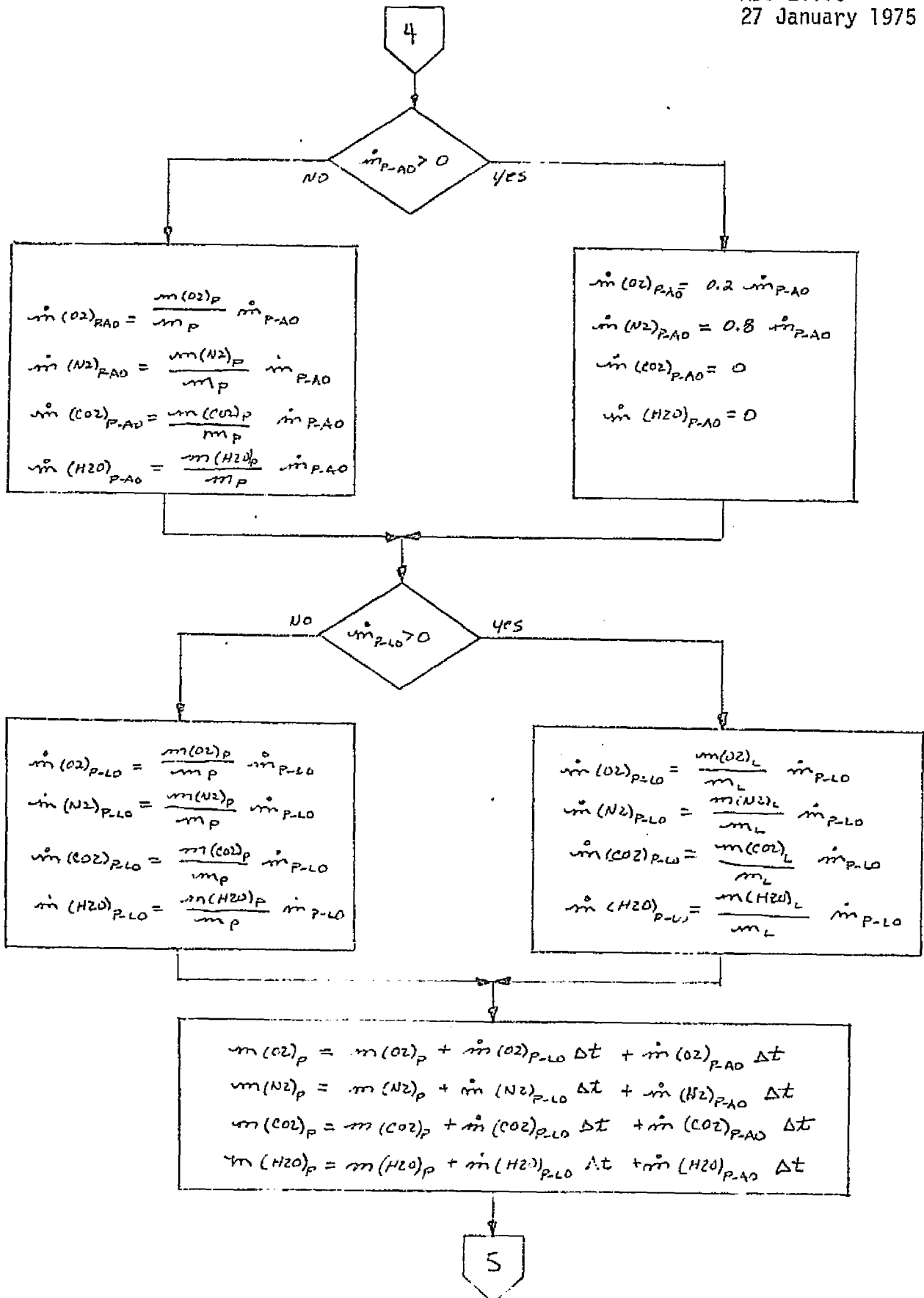


FIGURE 4.7-100. (CONTINUED)

4.7-343

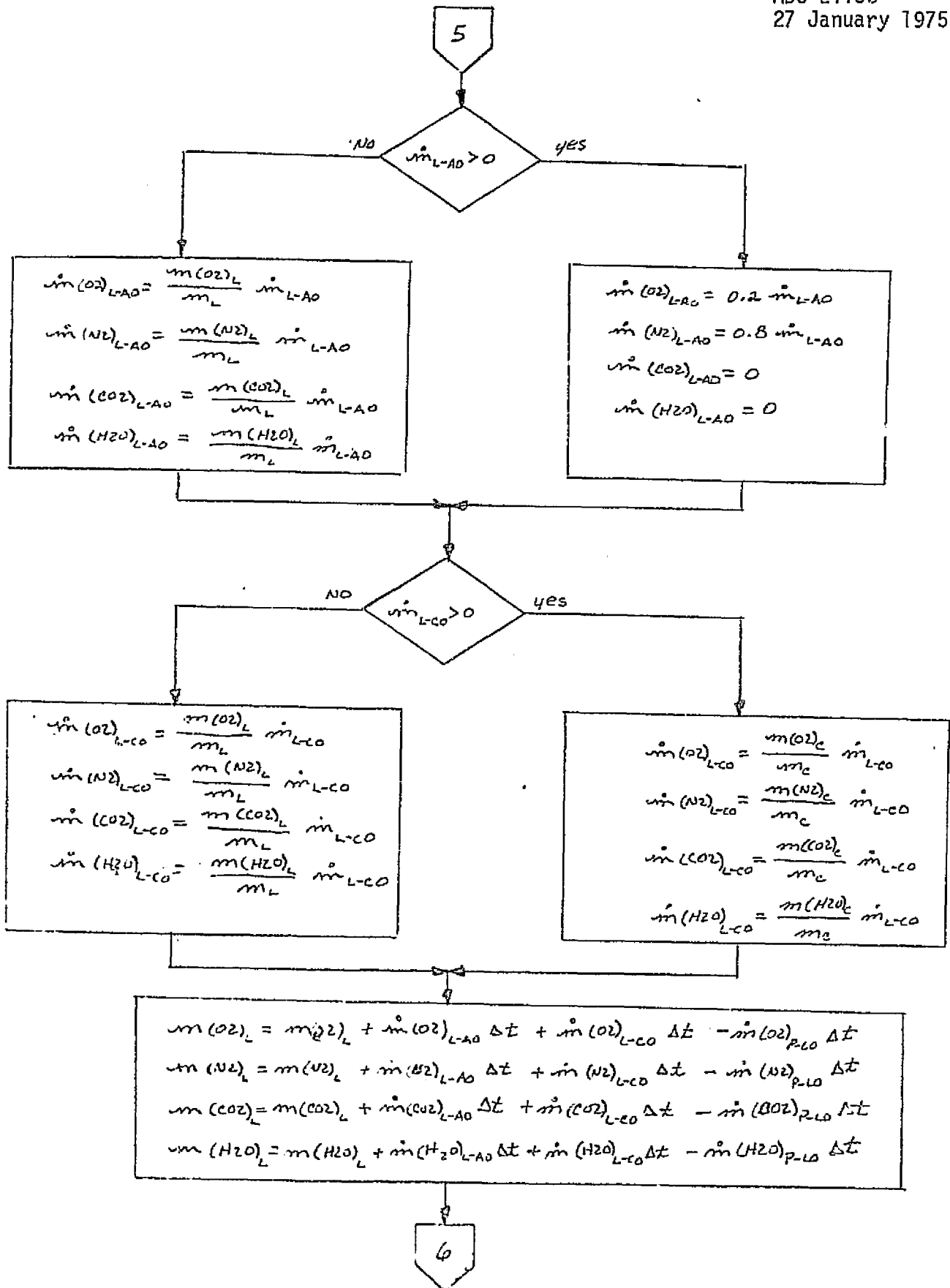


FIGURE 4.7-103. (CONTINUED)

4.7-344

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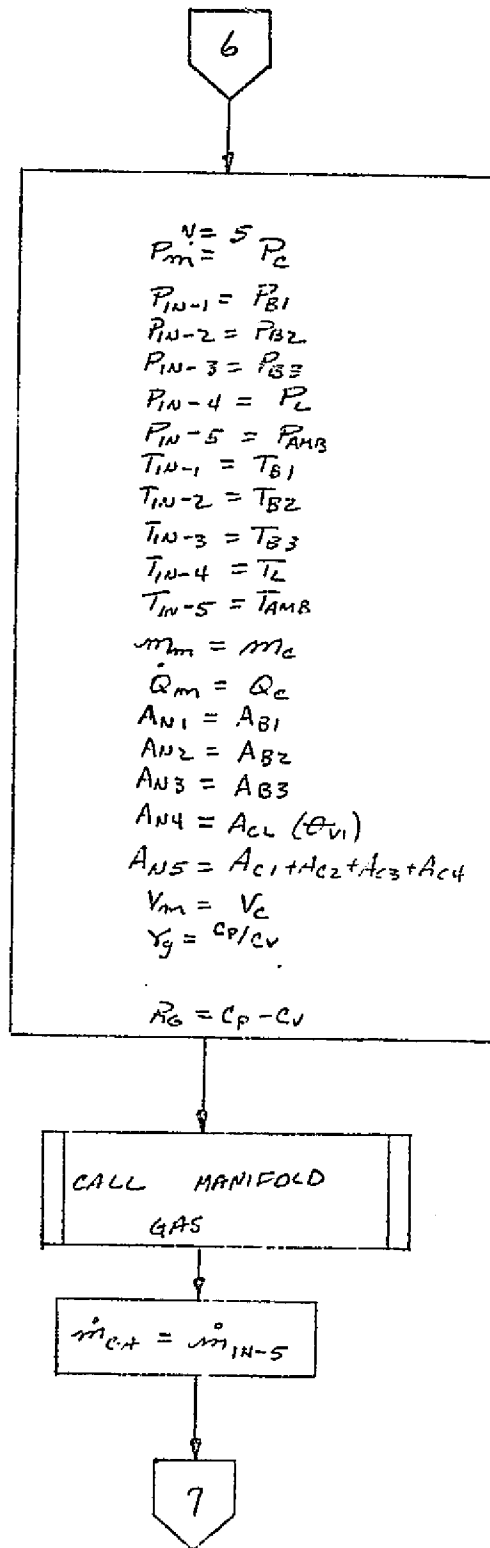


FIGURE 4.7-103. (CONTINUED)

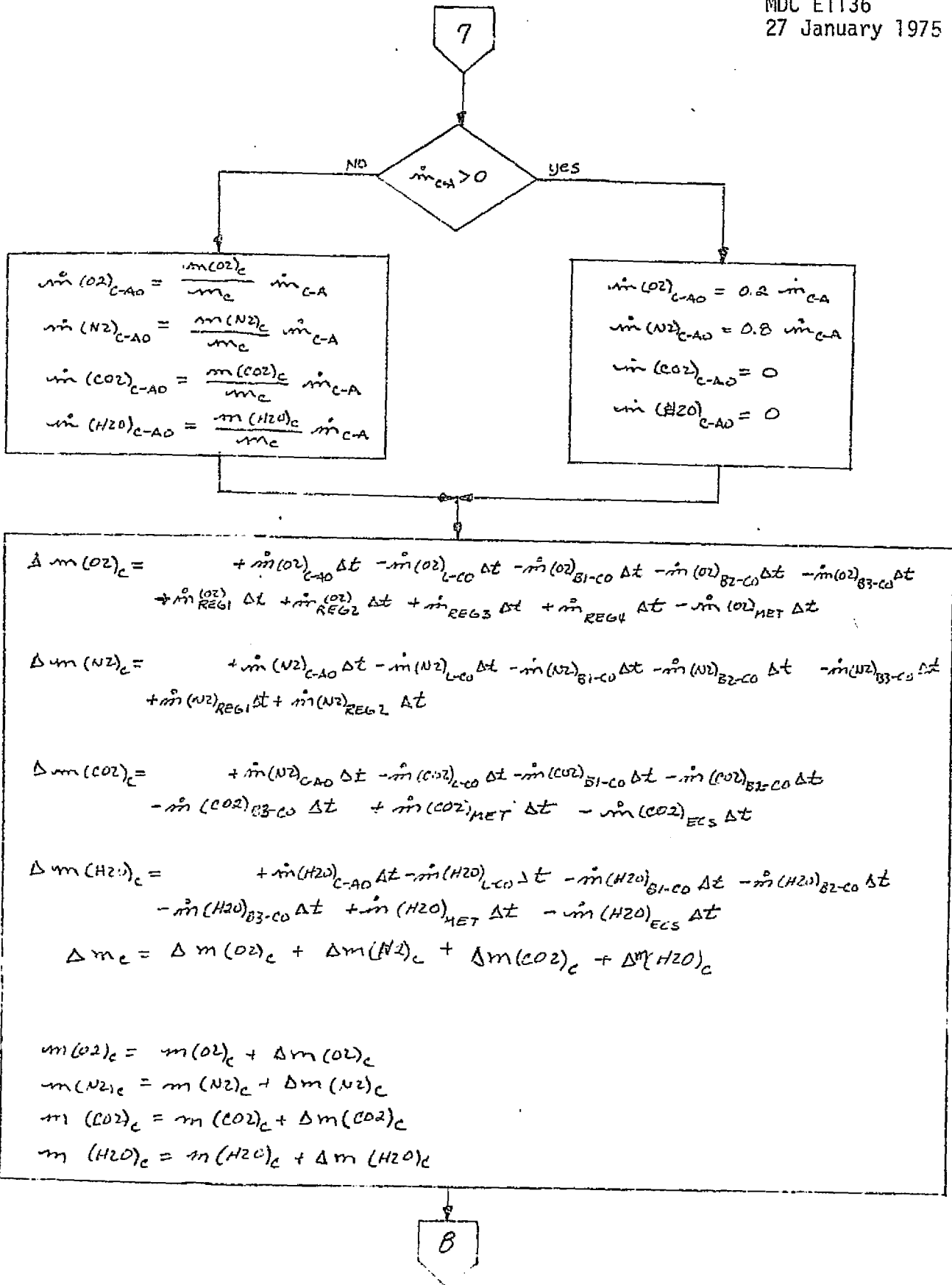


FIGURE 4.7-100. (CONTINUED)

4.7-346

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$$\begin{aligned} \dot{Q} = & (C_v) m_m \dot{T}_m + C_{p(O_2)} \Delta t \left[\dot{m}_{(O_2)_{REG1}} T_{REG1} + \dot{m}_{(O_2)_{REG2}} T_{REG2} + \dot{m}_{REG3} T_{REG3} + \dot{m}_{REG4} T_{REG4} \right] \\ & + C_{p(N_2)} \Delta t \left[\dot{m}_{(N_2)_{REG1}} T_{REG1} + \dot{m}_{(N_2)_{REG2}} T_{REG2} \right] + C_{v(O_2)} \Delta t \dot{m}_{(O_2)_{MET}} T_c \\ & + C_{v(CO_2)} \Delta t \left[\dot{m}_{(CO_2)_{MET}} T_{MET} - \dot{m}_{(CO_2)_{ECS}} T_c \right] + C_{v(H_2O)} \Delta t \left[\dot{m}_{(H_2O)_{MET}} T_{MET} - \dot{m}_{(H_2O)_{ECS}} T_c \right] \end{aligned}$$

$$(C_v)_c = \frac{m_{(O_2)_c} C_{v(O_2)} + m_{(N_2)_c} C_{v(N_2)} + m_{(CO_2)_c} C_{v(CO_2)} + m_{(H_2O)_c} C_{v(H_2O)}}{m_c + \Delta m_c}$$

$$(C_p)_c = \frac{m_{(O_2)_c} C_{p(O_2)} + m_{(N_2)_c} C_{p(N_2)} + m_{(CO_2)_c} C_{p(CO_2)} + m_{(H_2O)_c} C_{p(H_2O)}}{m_c + \Delta m_c}$$

$$R_c = (C_p)_c - (C_v)_c$$

$$T_c = \frac{\dot{Q}}{(C_v)_c (m_c + \Delta m_c)}$$

$$m_c = m_c + \Delta m_c$$

$$P_c = \frac{m_c}{V_c} R_c T_c$$

$$m_{B1} = m_{B10}$$

$$m_{B2} = m_{B20}$$

$$m_{B3} = m_{B30}$$

$$m_L = m_{L0}$$

$$m_P = m_{P0}$$

$$T_{B1} = T_{B10}$$

$$T_{B2} = T_{B20}$$

$$T_{B3} = T_{B30}$$

$$T_L = T_{L0}$$

$$T_P = T_{P0}$$

$$P_{B1} = P_{B10}$$

$$P_{B2} = P_{B20}$$

$$P_{B3} = P_{B30}$$

$$P_L = P_{L0}$$

$$P_P = P_{P0}$$

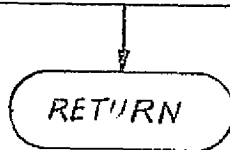


FIGURE 4.7-100. (CONTINUED)

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_T - 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 4.7-100. (CONTINUED)

4.7-303

$m(O_2)_X$ - 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 4.7-138 (CONTINUED)

4.7-349

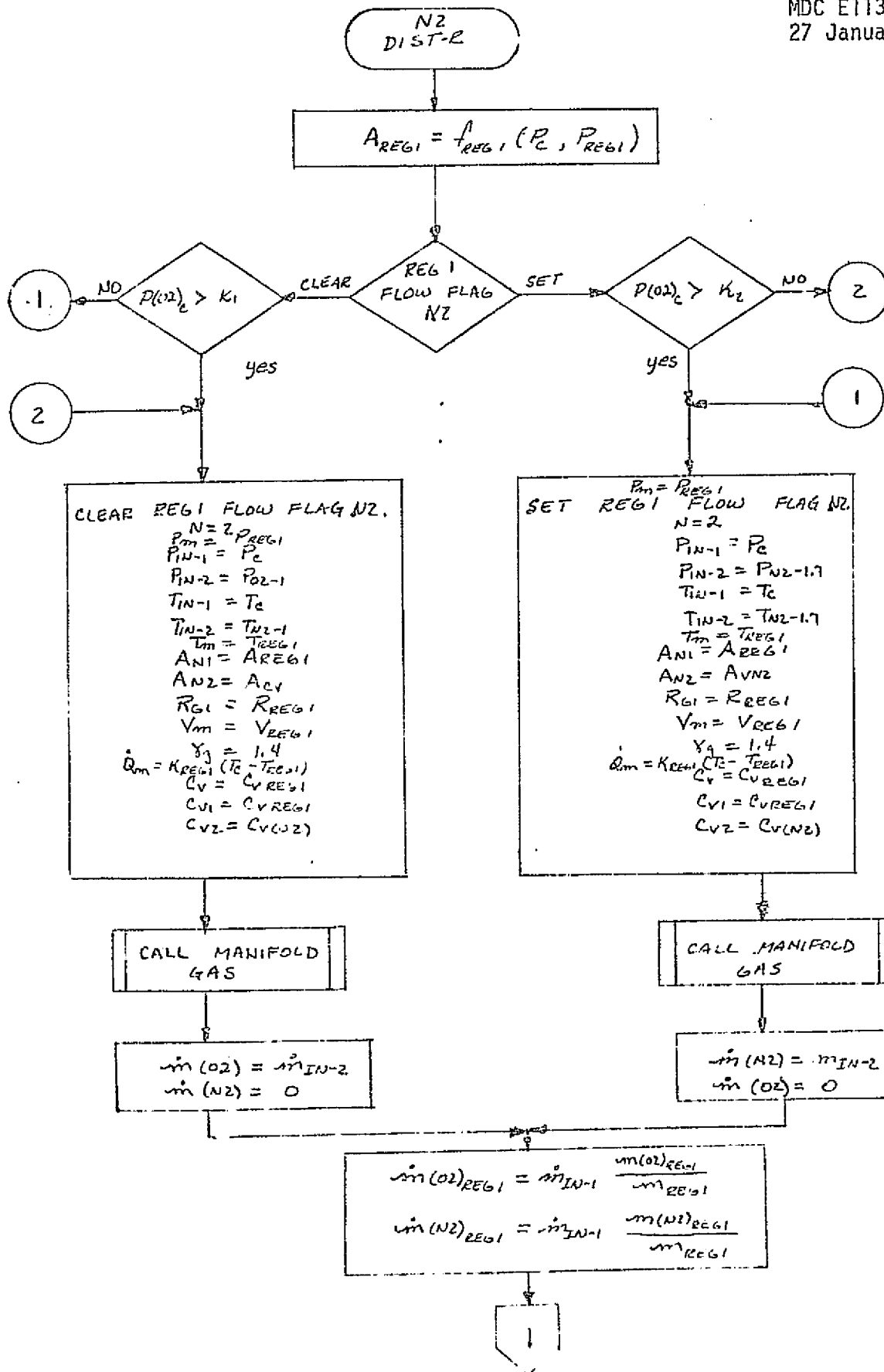


FIGURE A.7-10), N₂ SOURCE/DISTRIBUTION NETWORK REFERENCE MODULE MATH FLOW

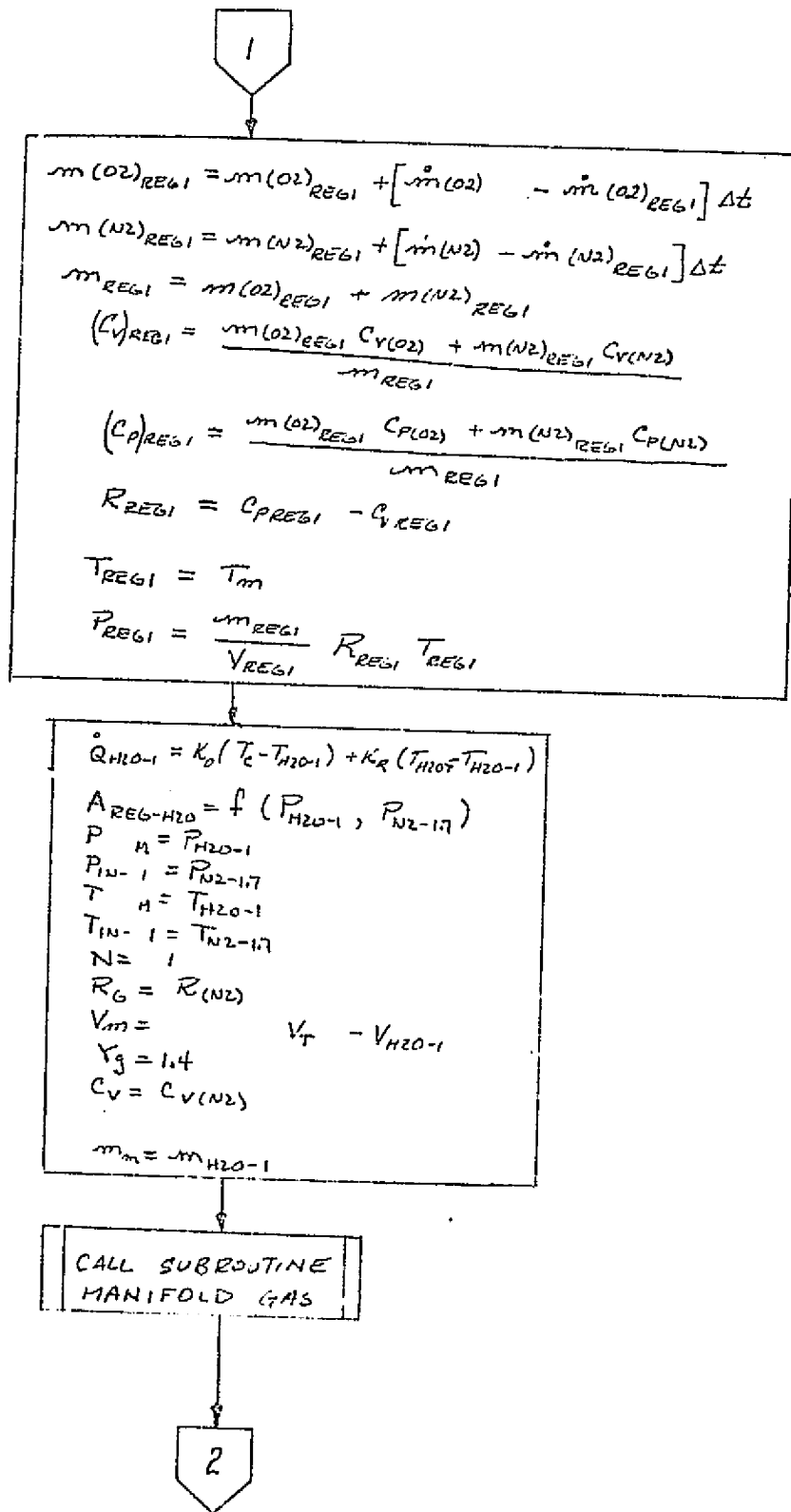


FIGURE 4.7-109. (CONTINUED)

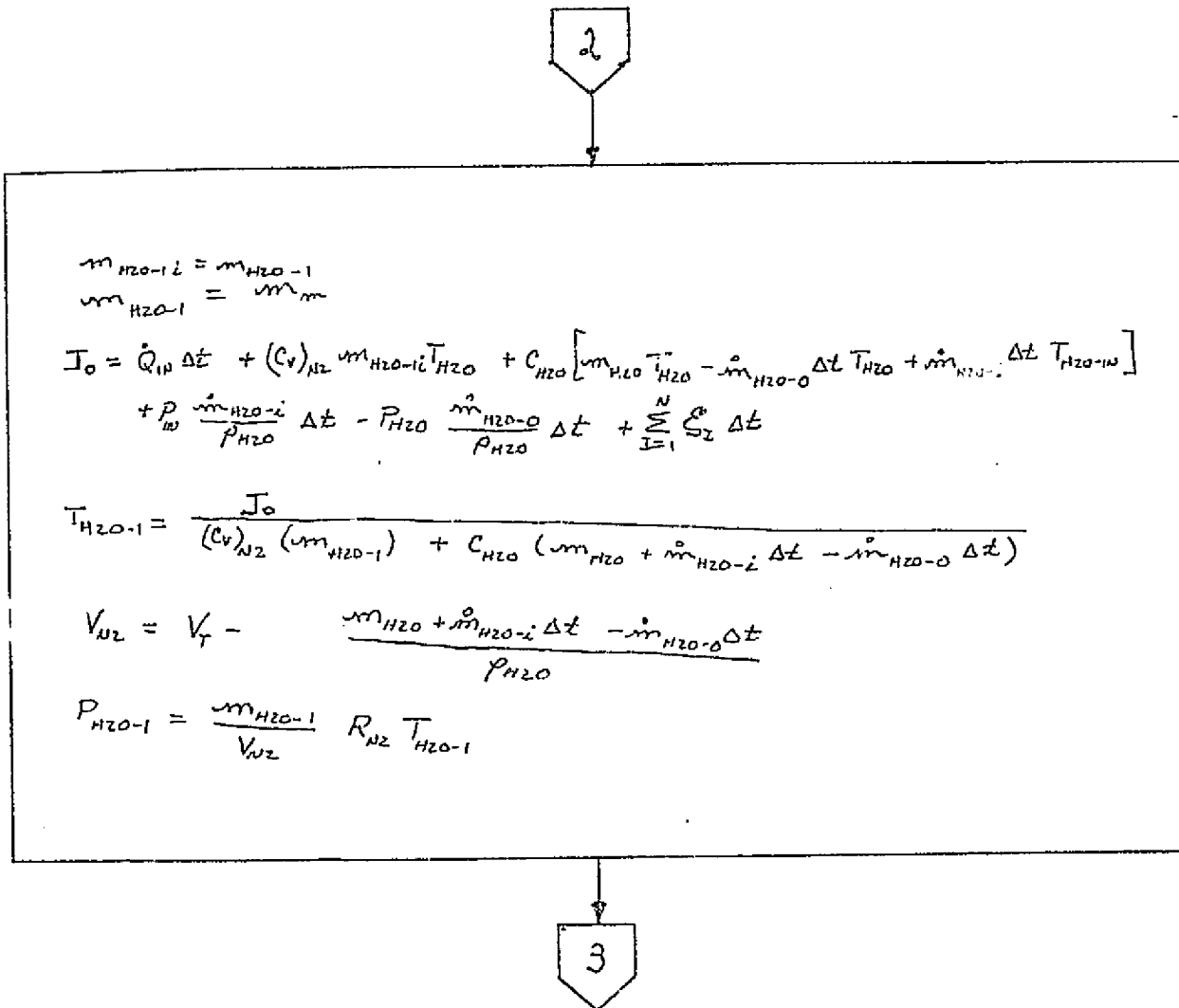


FIGURE 4.7-109. (CONTINUED)

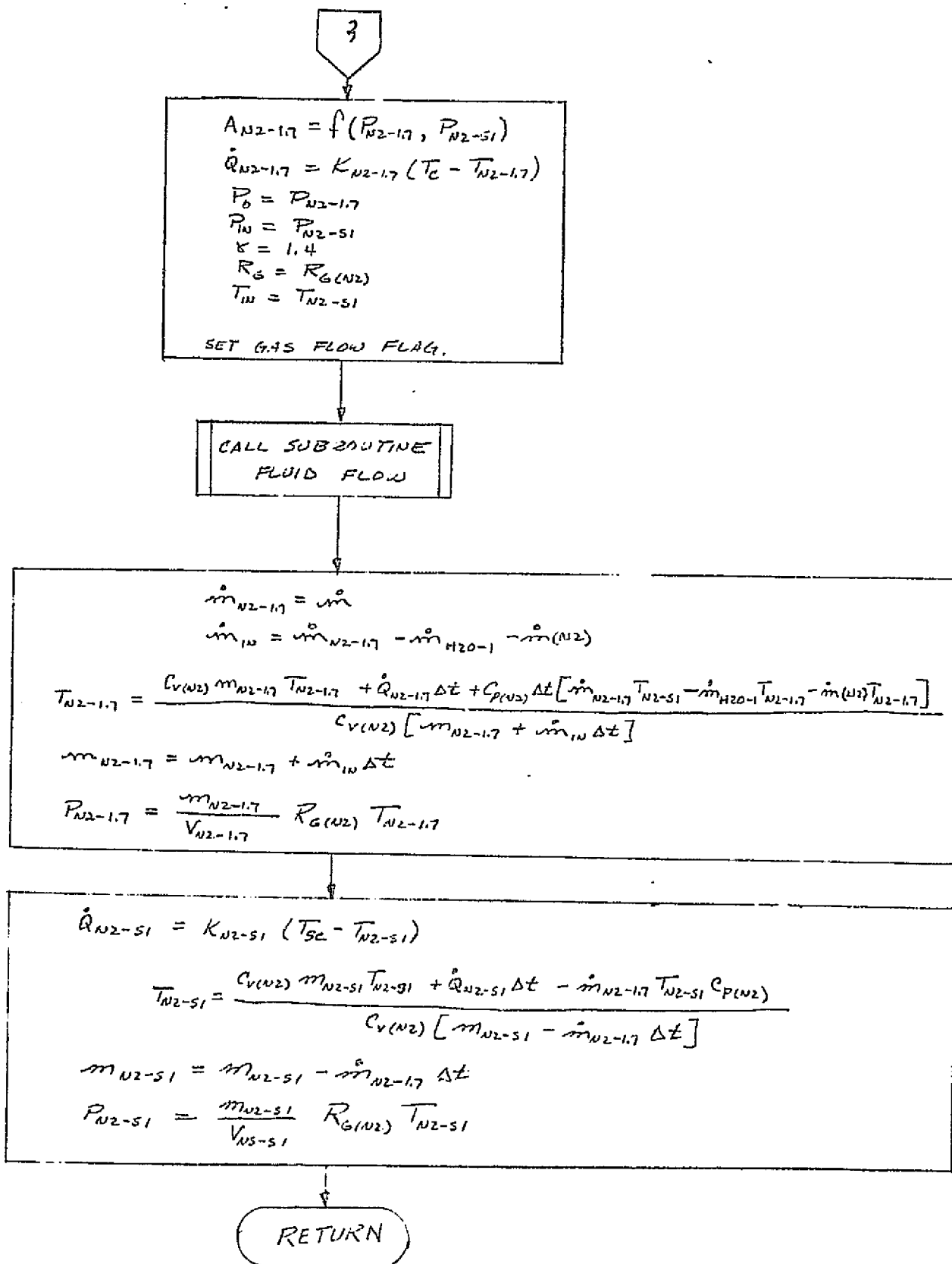


FIGURE 4.7-10.0 (CONTINUED)

4.7-353

LEGEND:

- P_{REG-1} - 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_{REG-1} - 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_{REG-1} - 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
 m_{H_2O} - H_2O quantity in H_2O tank

 $m(O_2)_{REG-1}$ - Cabin pressure regulator inlet line O_2 mass quantity
 $m(N_2)_{REG-1}$ - 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 4.7-100 (CONTINUED)

4.7-254

γ - Specific heat ratio (CP/CV)
 R_g - Gas constant

FIGURE 4.7-109 (CONTINUED)

4.7-355

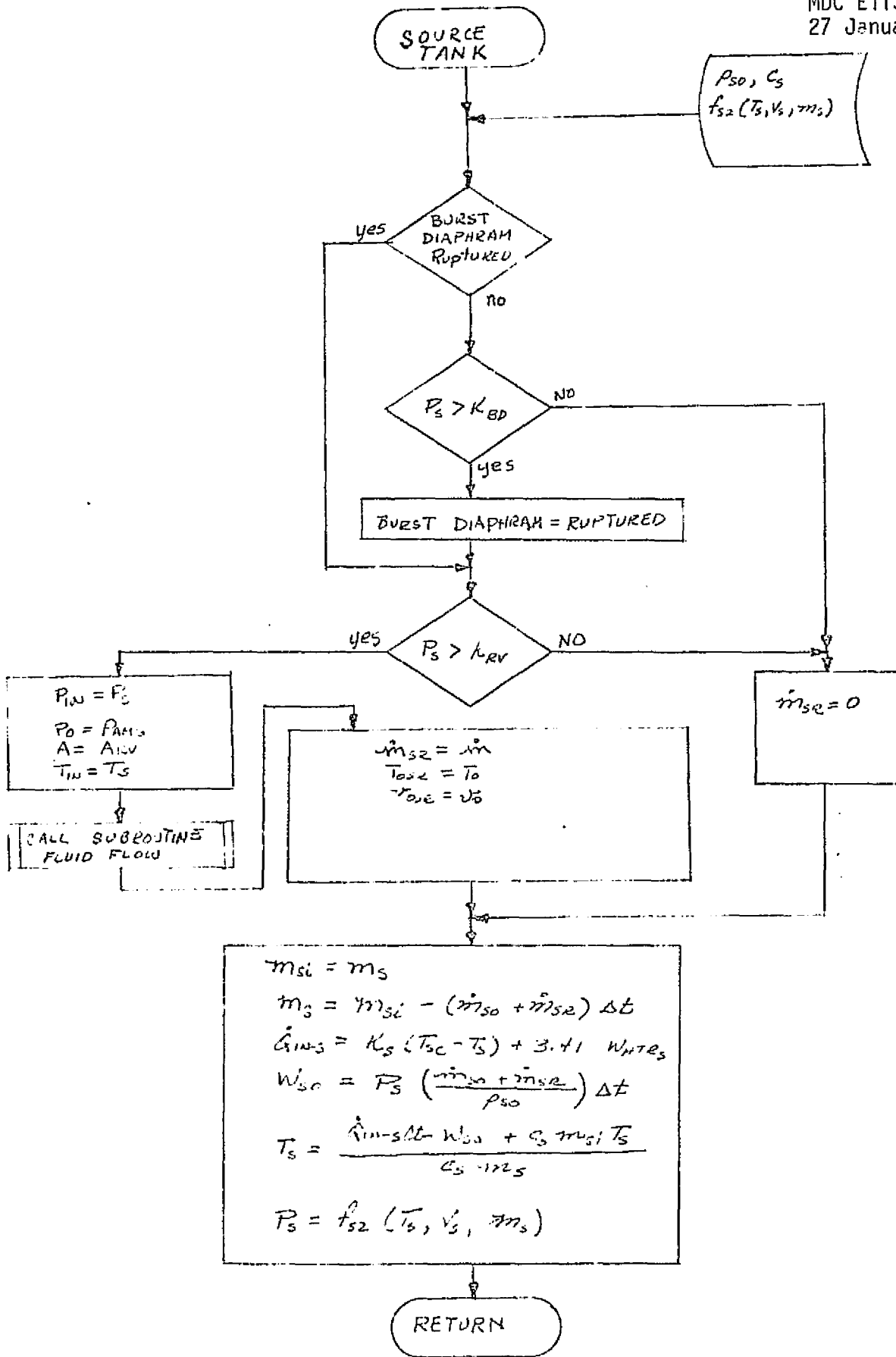


FIGURE A.7-110 N₂ SOURCE FLOW CHART

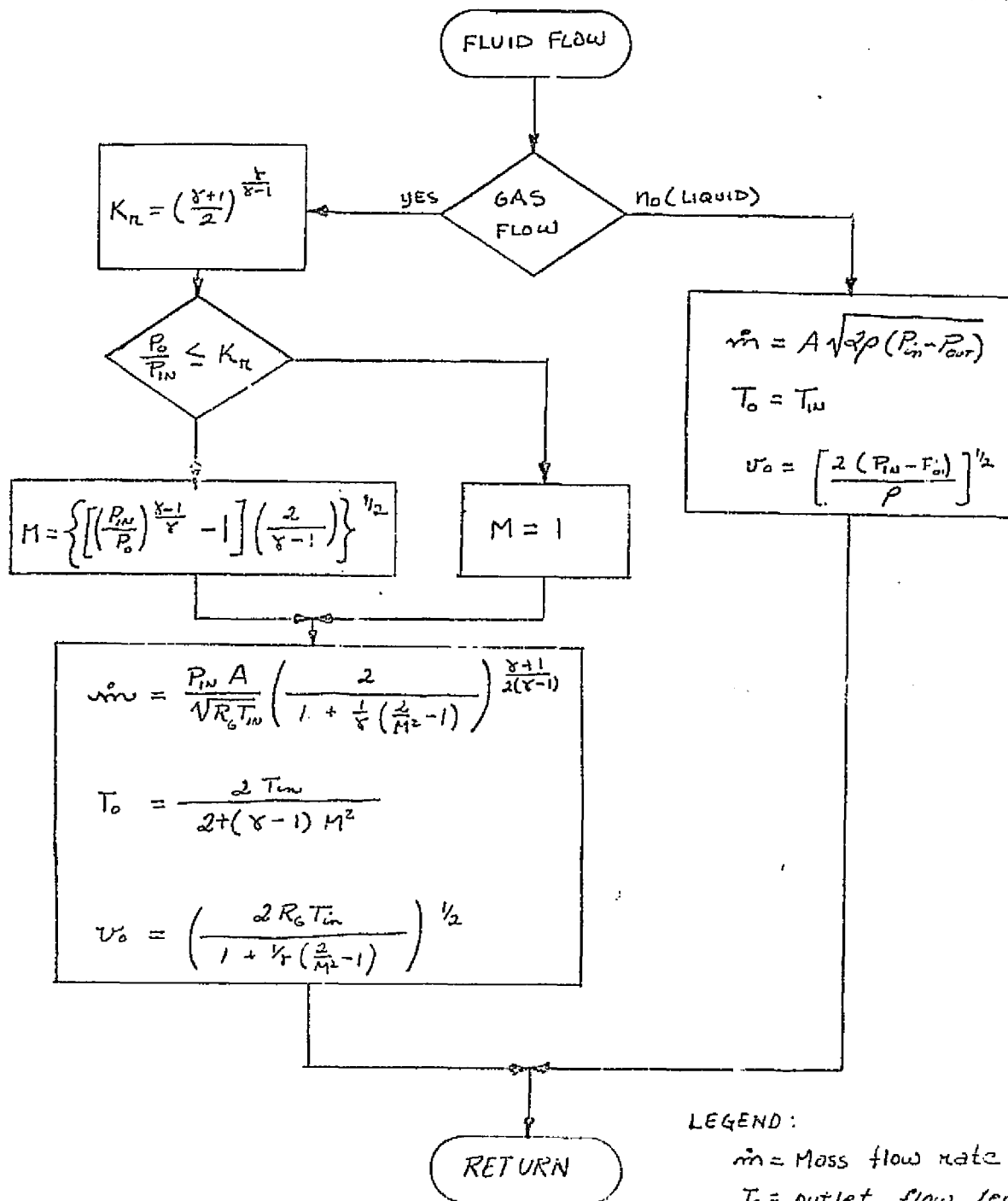
A.7-35C

LEGEND:

P_S - Tank pressure
 P_{amb} - Ambient pressure
 A_{EV} - 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}_{SO} - Flow rate to distribution system
 m_S - Quantity of gas in source tank
 ρ_{SO} - Gas density in tank
 W_{HTR_S} - 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



K_n = 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 4.7-111. FLUID FLOW SUBROUTINE FLOW CHART

ARPCS 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 (t_0), 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, O_2 quantity, etc. associated with the auxiliary O_2 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:

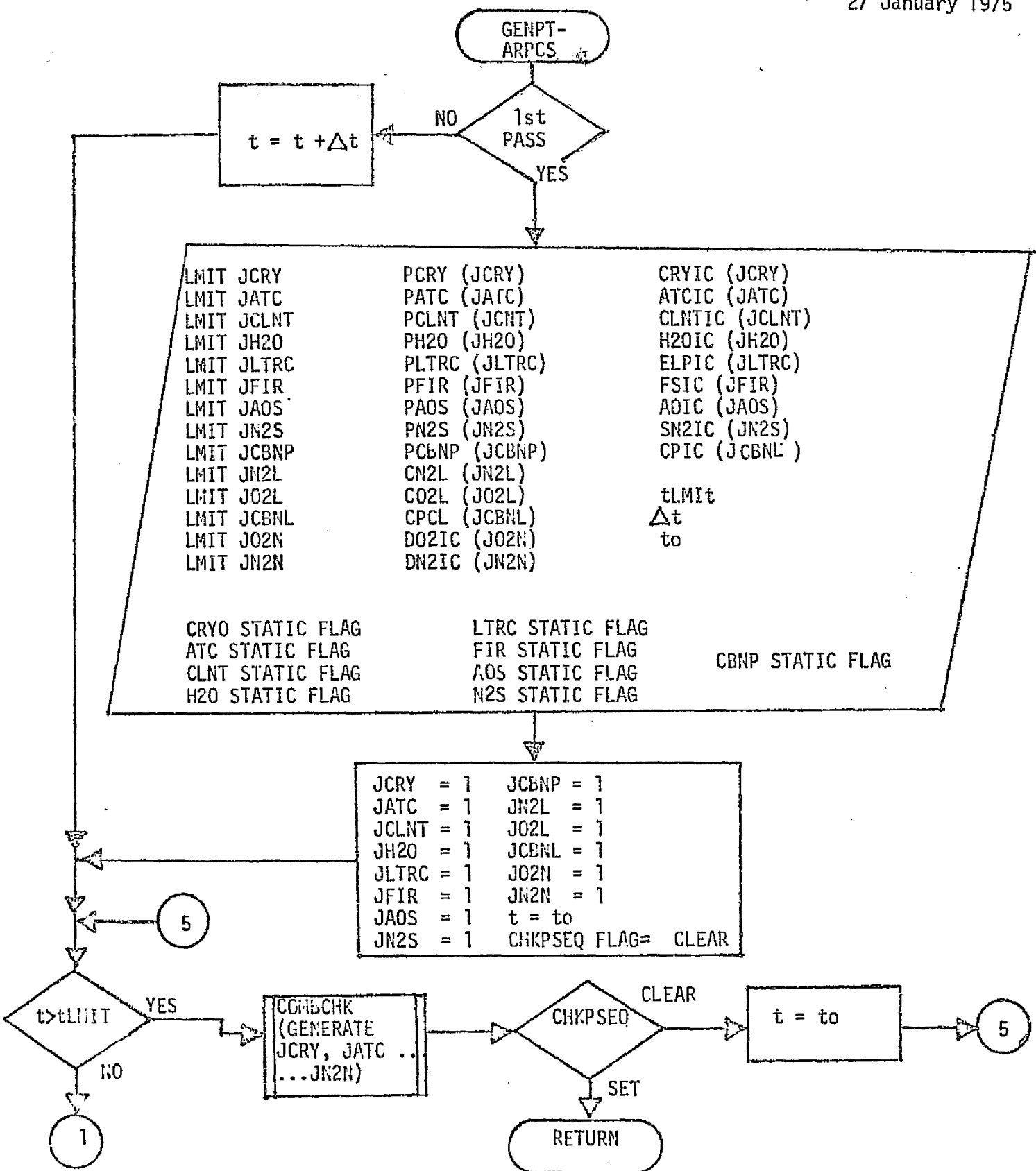


FIGURE 4.7-112. CHECK POINT DRIVER, ATMOSPHERE REVITALIZATION PRESSURE CONTROL SUBSYSTEM (ARPCS) FLOWCHART

4.7-300

3
2

1

NO

$t = t_0$

YES

CRYO2 SOURCE INITIAL CONDITIONS	=	CRYIC (JCRY)
ACTIVE THERMAL CONTROL INITIAL CONDITIONS	=	ATCIC (JATC)
H2O COOLANT INITIAL CONDITIONS	=	CLNTIC (JCLNT)
POTABLE H2O INITIAL CONDITIONS	=	H2OIC (JH2O)
ELECTRIC POWER INITIAL CONDITIONS	=	ELPIC (JLTRC)
FIRE SUPPRESSION INITIAL CONDITIONS	=	FSIC (JFIR)
AUX O2 SOURCE INITIAL CONDITIONS	=	AOIC (JAOS)
N2 SOURCE INITIAL CONDITIONS	=	N2SIC (JN2S)
CABIN PRESSURE CONTROL INITIAL CONDITIONS	=	CPIC (JCBNP)
N2 CONTROL LOGIC	=	CN2L (JN2L)
O2 CONTROL LOGIC	=	CO2L (JO2L)
CABIN PRESSURE CONTROL LOGIC	=	CPCL (JCBNL)
O2 DISTRIBUTION NETWORK INITIAL CONDITIONS	=	DO2IC (JO2N)
N2 DISTRIBUTION NETWORK INITIAL CONDITIONS	=	DN2IC (JN2N)
ACTIVE THERMAL CONTROL PARAMETERS	=	PATC (JATC)
CRY O2 PARAMETERS	=	PCRY (JCRY)
H2O COOLANT PARAMETERS	=	PCLNT (JCLNT)
POTABLE H2O PARAMETERS	=	PH2O (JH2O)
ELECTRIC POWER PARAMETERS	=	PLTRC (JLTRC)
FIRE SUPPRESSION PARAMETERS	=	PFIR (JFIR)
AUX O2 SOURCE PARAMETERS	=	PAOS (JAOS)
N2 SOURCE PARAMETERS	=	PN2S (JN2S)
CABIN PRESSURE CONTROL PARAMETERS	=	PCBNP (JCBNP)

RETURN

ACTIVE THERMAL CONTROL MODULE INTERFACE DRIVER

ATC STATIC

YES

NO

NO

ACTIVE THERMAL CONTROL PARAMETER CALCULATIONS

ACTIVE THERMAL CONTROL PARAMETERS = PATC (JATC)

2

FIGURE 4.7-112 (CONTINUED)

4.7-201

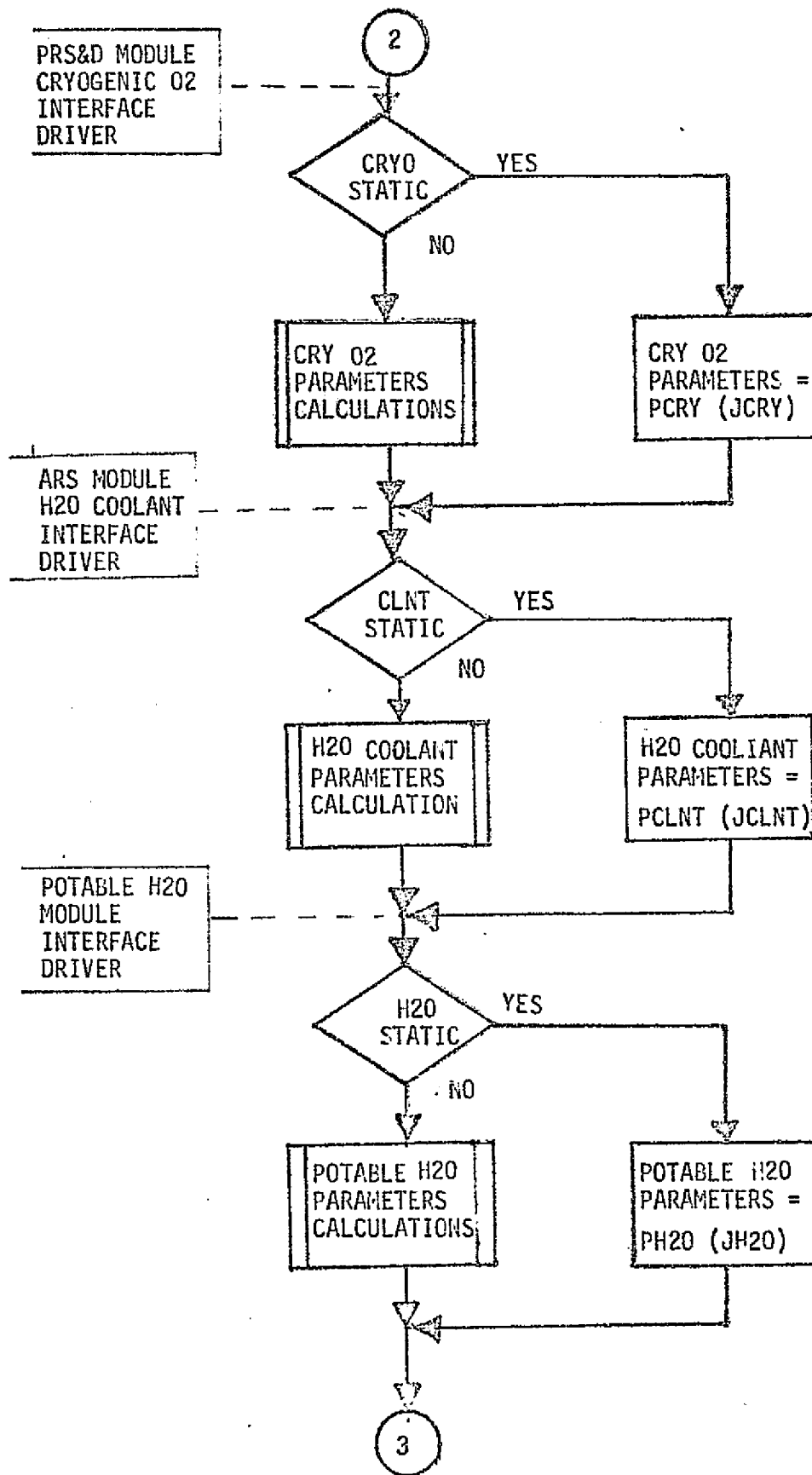


FIGURE 4.7-112 (continued)

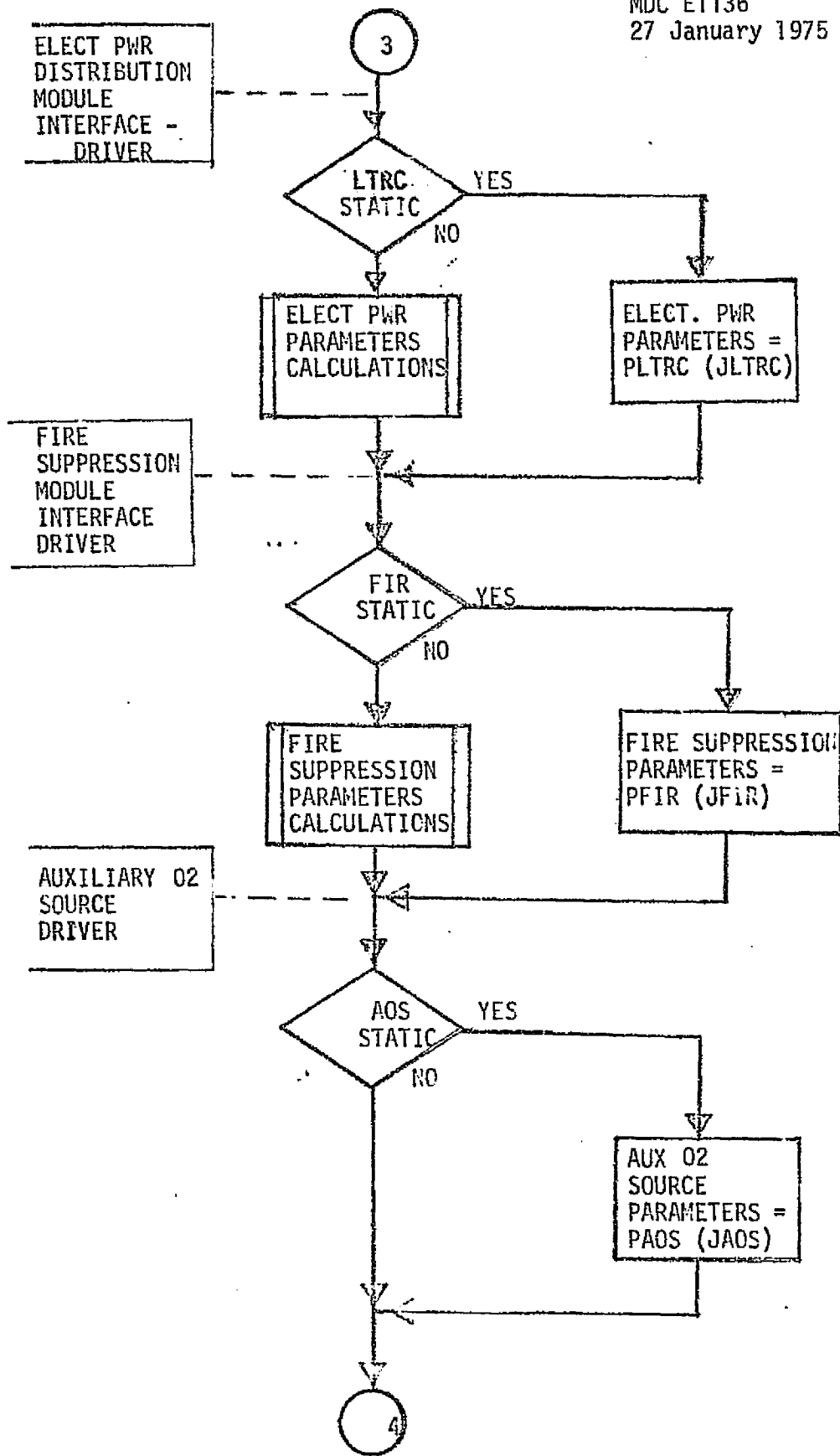


FIGURE 4.7-112 (CONTINUED)

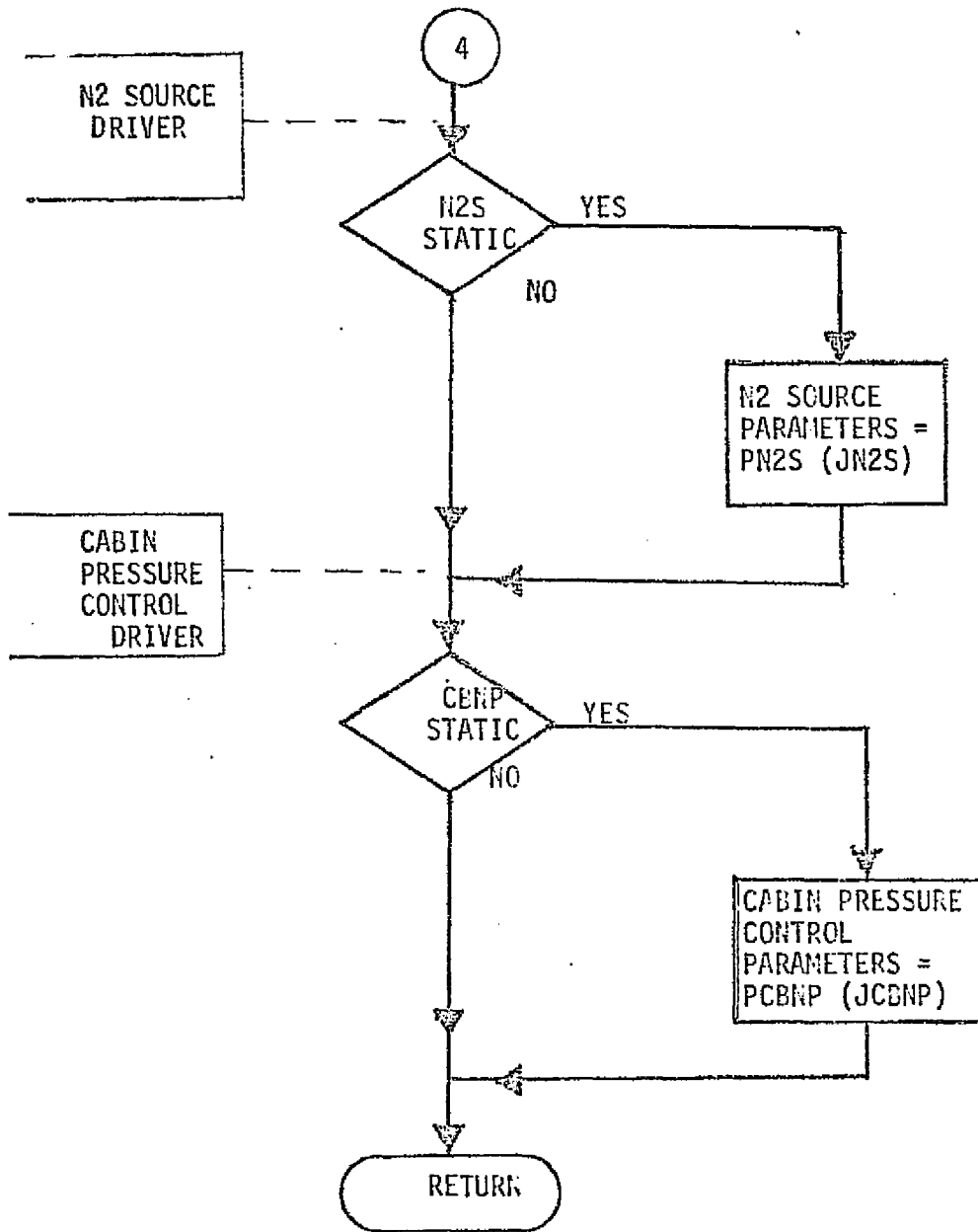


FIGURE 4.7-112 (CONTINUED)

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
H2O	=	H ₂ O element
LTRC	=	Electric element
FIR	=	Fire Suppression element
AOS	=	Auxilliary O ₂ element
N2S	=	N ₂ source element
CBNP	=	Cabin Pressure element
N2L	=	N ₂ logic element
O2L	=	O ₂ logic element
CBNL	=	Cabin Logic element
O2N	=	O ₂ network element
N2N	=	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)

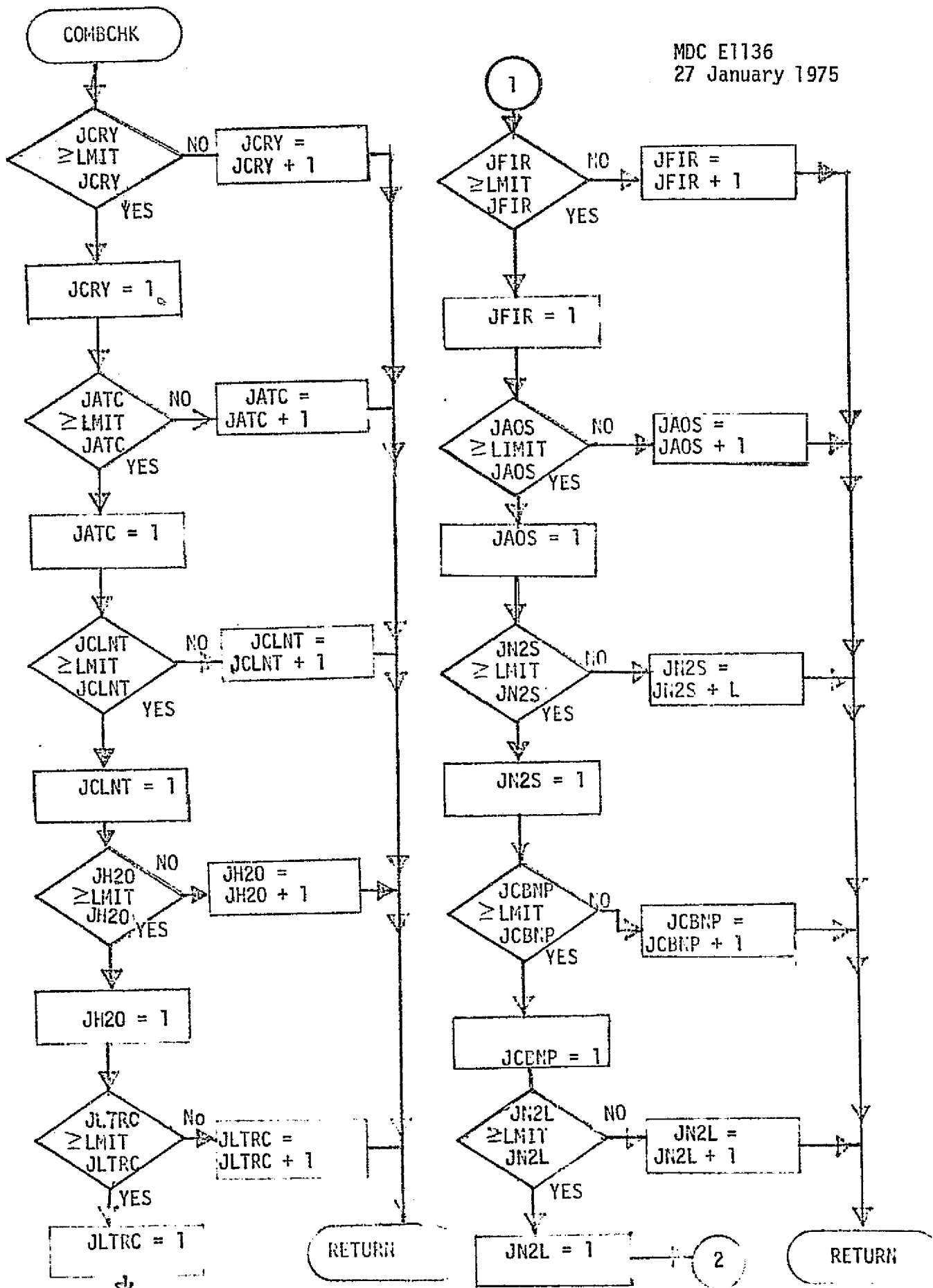
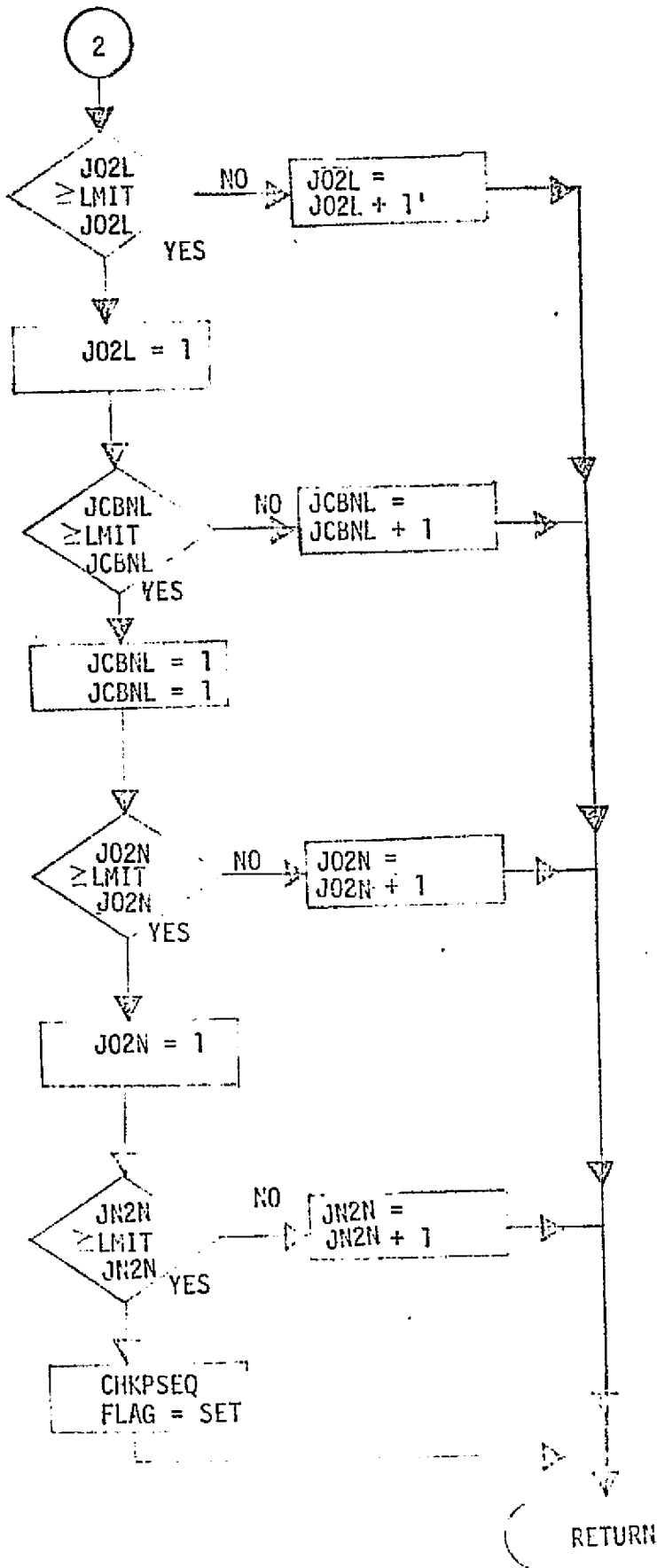


FIGURE 4.7-113. FLOWCHART FOR ARPCS CHECKPOINT SEQUENCE

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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 23 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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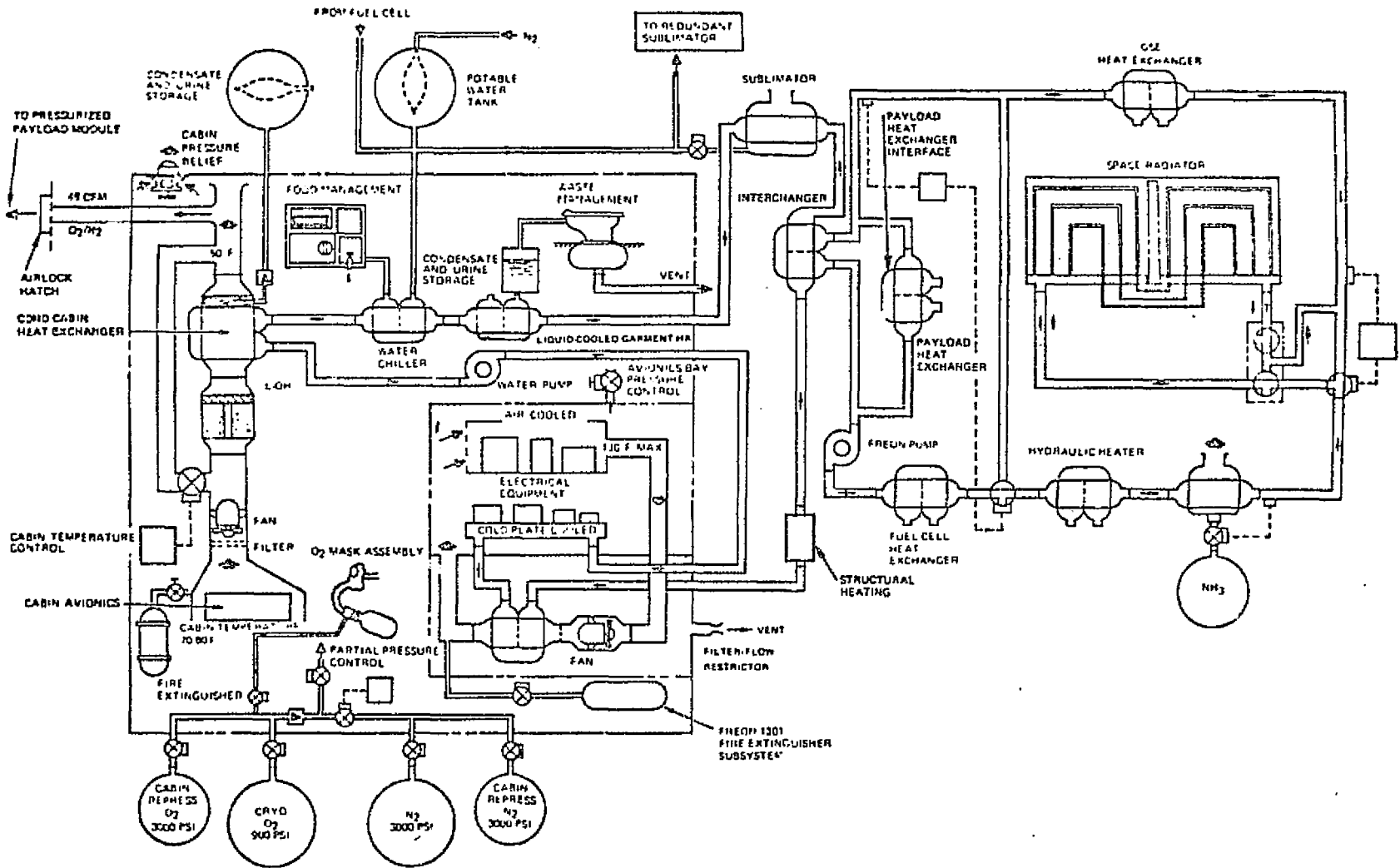


FIGURE 4.7-114 ENVIRONMENT CONTROL AND LIFE SUPPORT SUBSYSTEM (ECLSS) SCHEMATIC

4.7-372

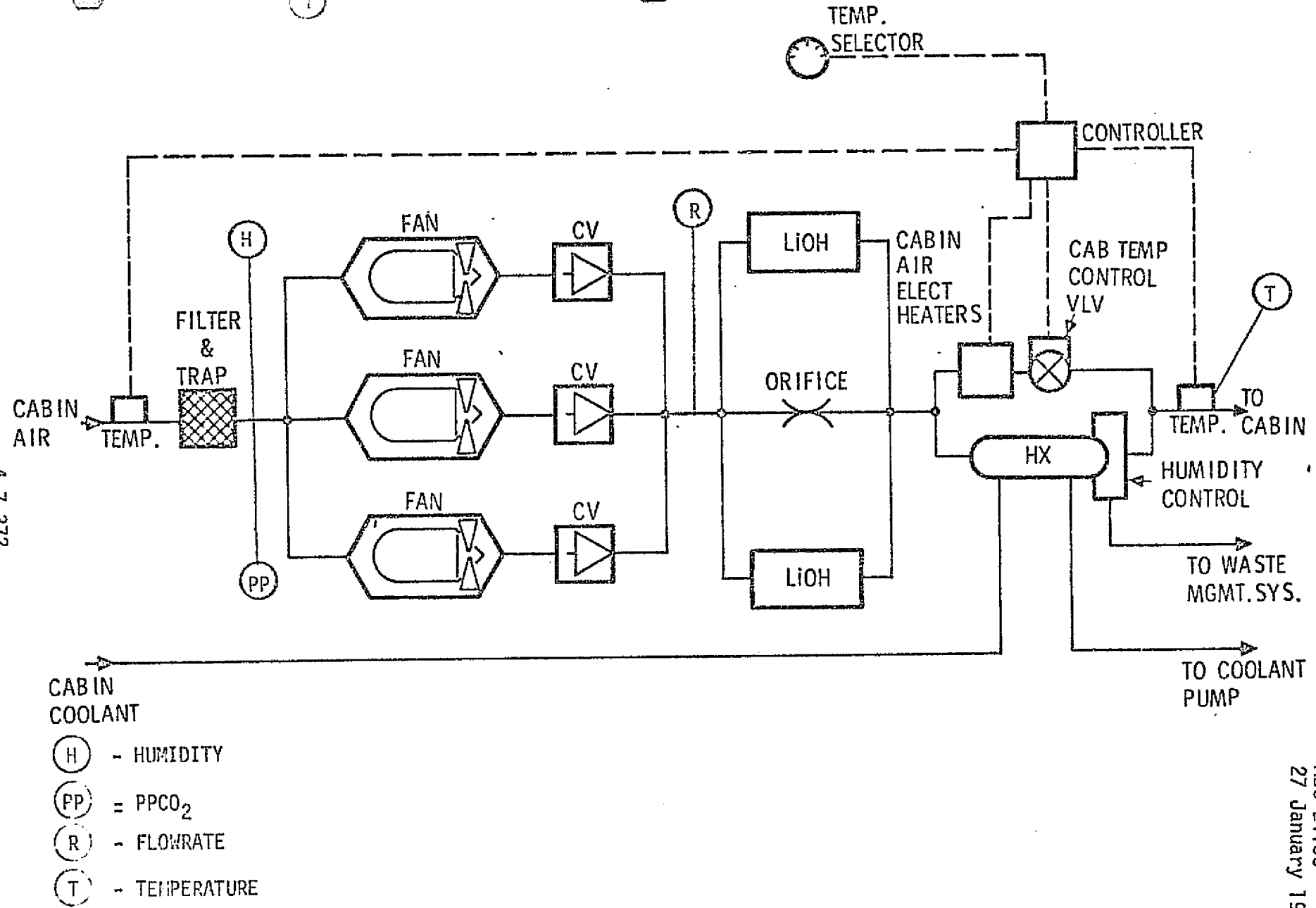


FIGURE 4.7-115 ECLSS CABIN TEMPERATURE, HUMIDITY AND CO₂ CONTROL SCHEMATIC

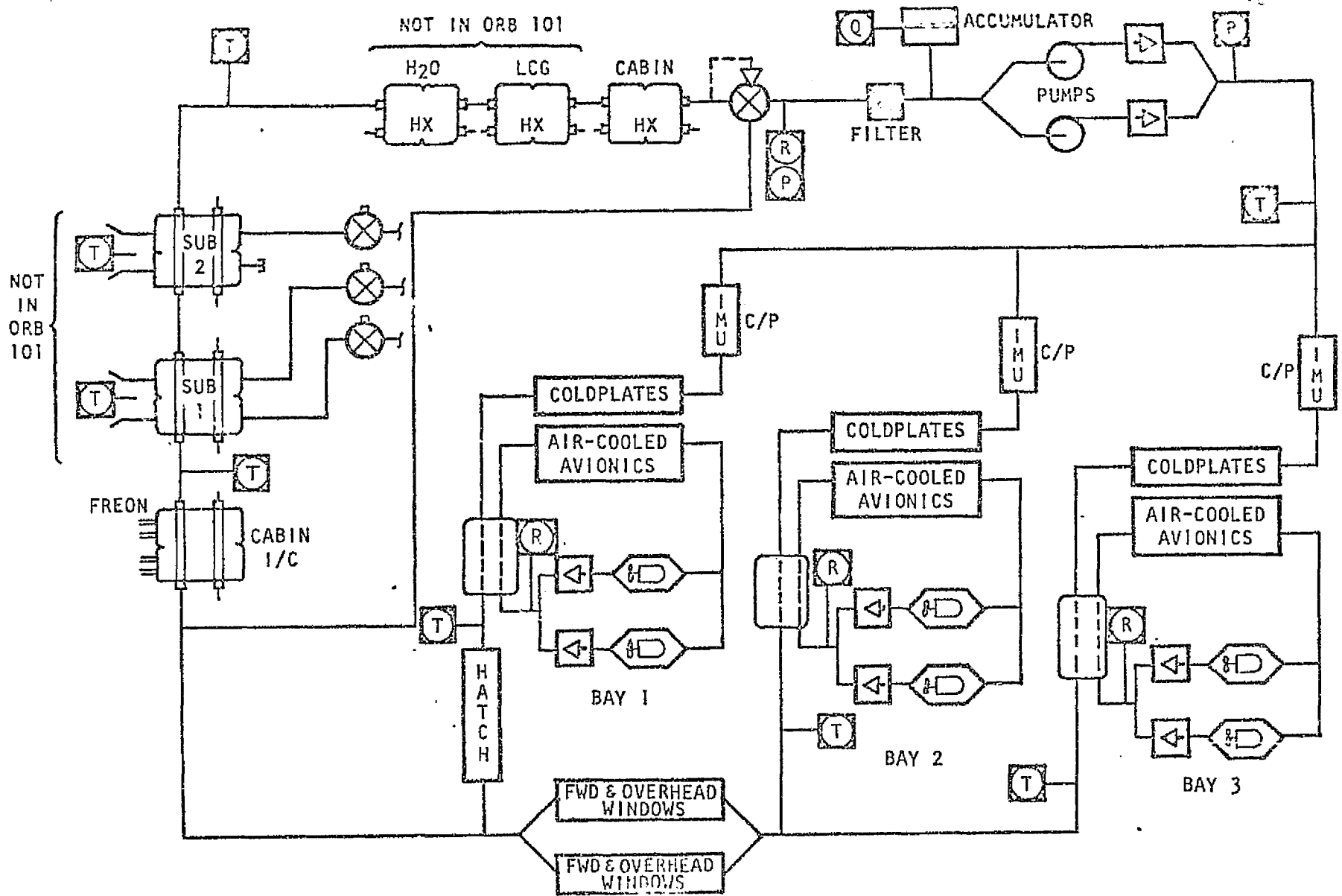


FIGURE 4.7-116. PRIMARY WATER COOLANT LOOP SCHEMATIC

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, CO₂/H₂O control, H₂O 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.

CO₂ Control - This control is provided for the crew quarters.

- CO₂ removal rate - a function of cabin CO₂ pressure, air flow rate through LiOH canisters, and air temperature.

H₂O Coolant Loop Flow - Calculates H₂O 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 H₂O pump flow rate, H₂O temperature, and branch flow rates.
- Branch flow rates - functions of pump flow rates and cabin heat exchanger outlet H₂O temperature.
- Accumulator H₂O Quantity - a function of H₂O temperature.
- Accumulator Pressure - a function of H₂O quantity and temperature.

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4.7-375

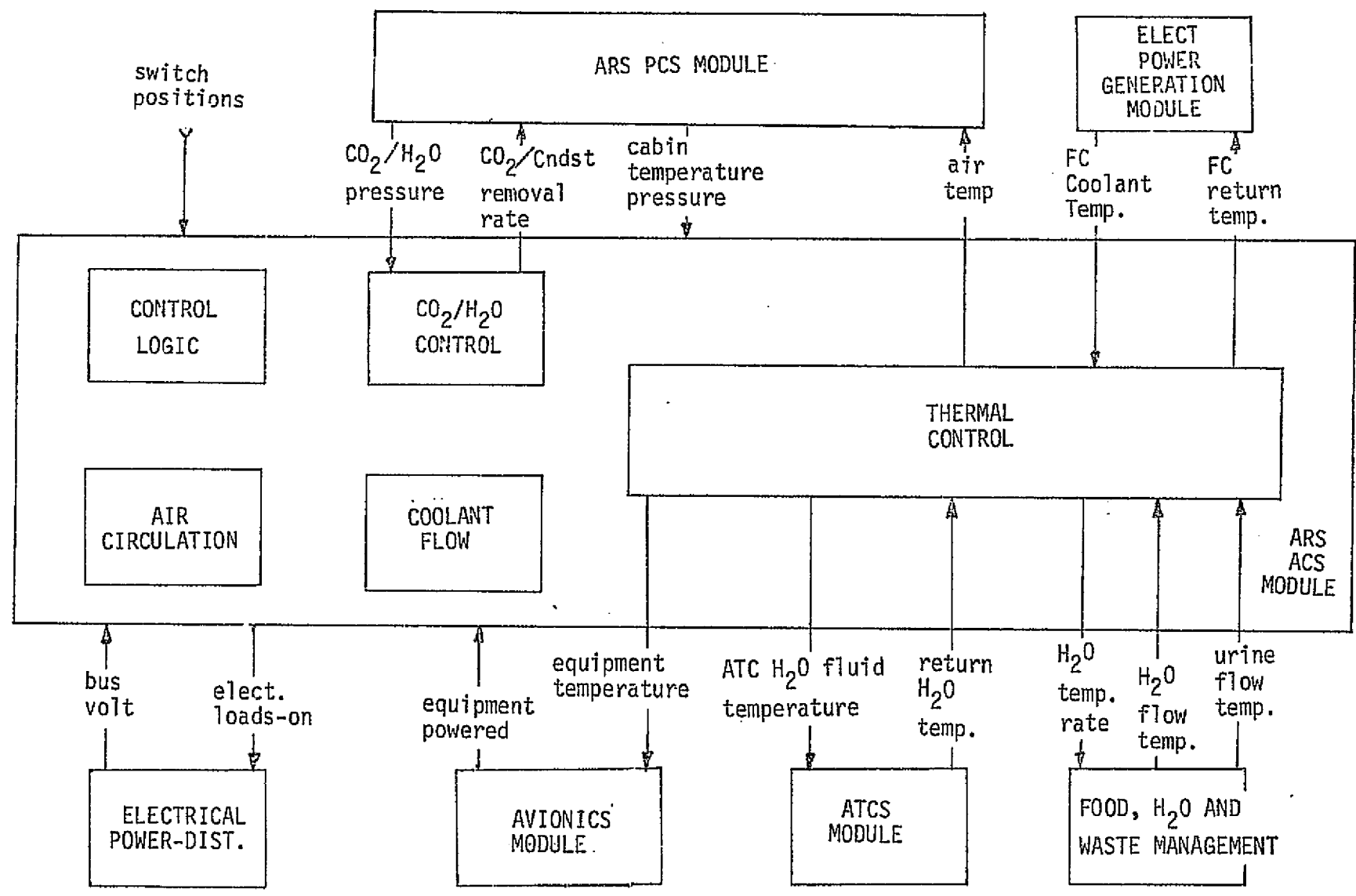


FIGURE 4.7-117 ATMOSPHERE REVITALIZATION SYSTEM, CABIN ATMOSPHERE CONTROL SUBSYSTEM, MODULE FUNCTIONAL ELEMENTS AND INTERFACES

MDC E1136
27 January 1975

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 PPESSURE - 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.

- o Pump outlet temperature - a function of H₂O flow, pump inlet temperature, pump pressure rise, and pump input electrical power.
- o Coldplate equipment temperature - functions of electrical power, inlet H₂O temperature, equipment temperature, and H₂O flow rate.
- o Heat exchanger outlet H₂O temperatures - functions of inlet H₂O temperature, H₂O flow rate, interchange fluid inlet temperatures, and interchange fluid flow rate.
- o Heat exchanger outlet interchange fluid temperatures - functions of interchange fluid inlet temperature and flow rate and the H₂O inlet temperature and flow rate.
- o Accumulator H₂O inlet temperature - a function of cabin heat exchanger outlet H₂O temperature/flow rate, bypass temperature and flow rate.
- o Pump inlet temperature - a function of the accumulator inlet temperature, accumulator temperature and H₂O flow rate.

ARS-CACS Reference Data Sources and Data Format

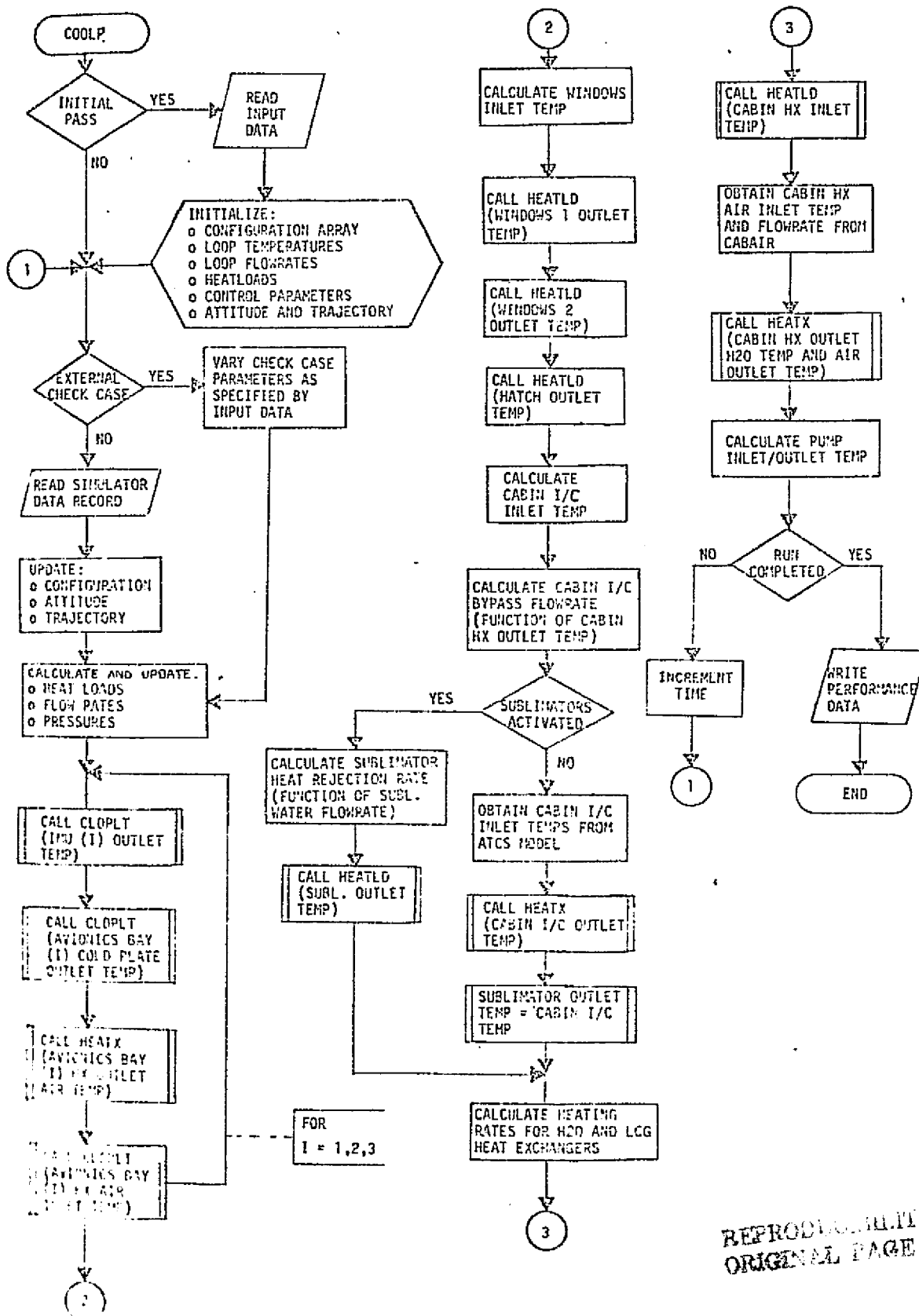
Various reference data sources exist for the ARS-CACS. Data concerning component and system performance requirements, predictions, and tests are available from References 22 and 104. In addition, several computer programs are available for development into a reference model or performing analyses. References 12 and 102 described component subroutines which can be combined to provide a system simulation reference module. Reference 105 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 106 and 107 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 12.

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 temperature 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 4.7-11B 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.

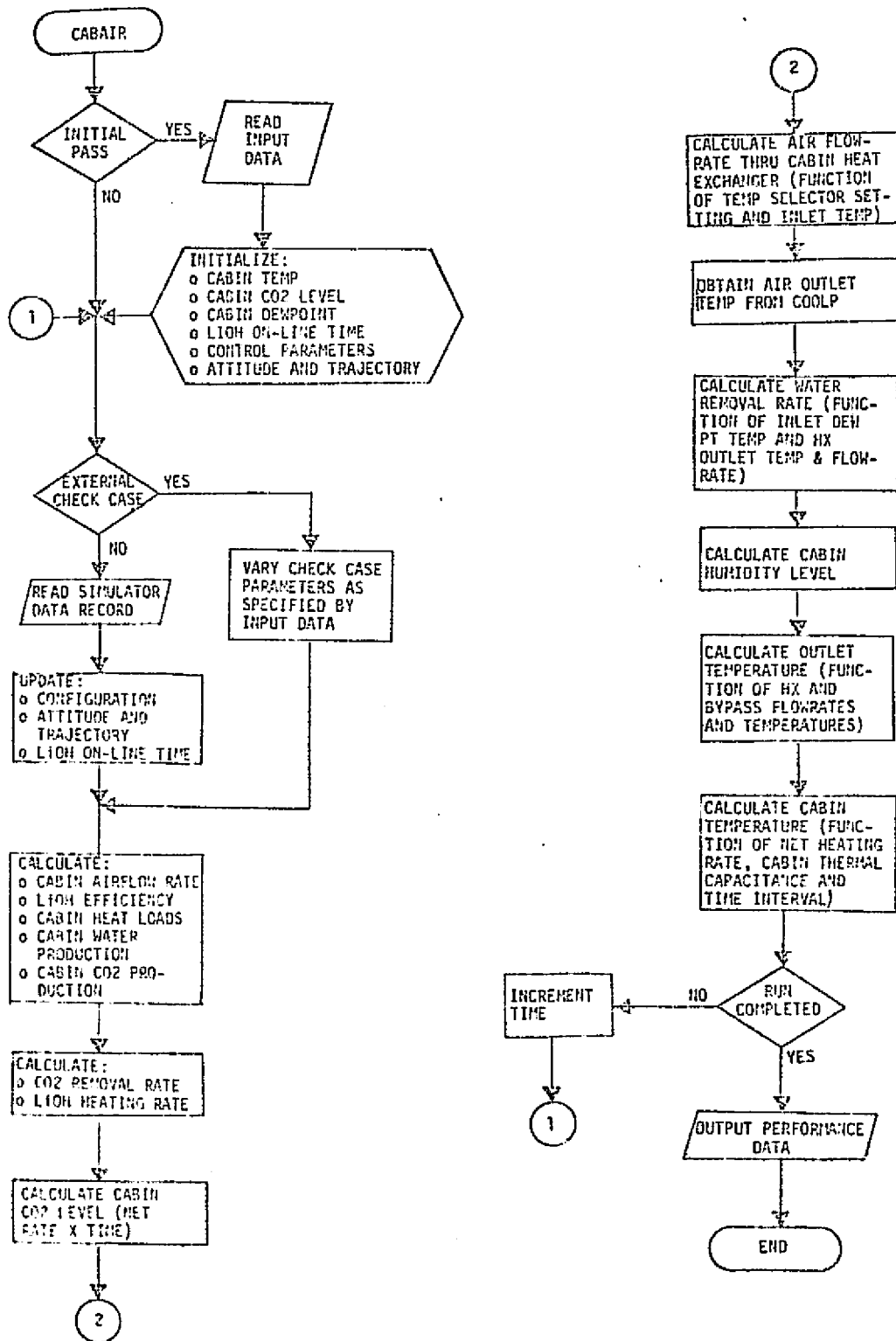


FIGURE 2.7-11: REFERENCE MODULE, ARS CABIN ATMOSPHERE FLOWCHART

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.

27 January 1975

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. 107 and 110) 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.

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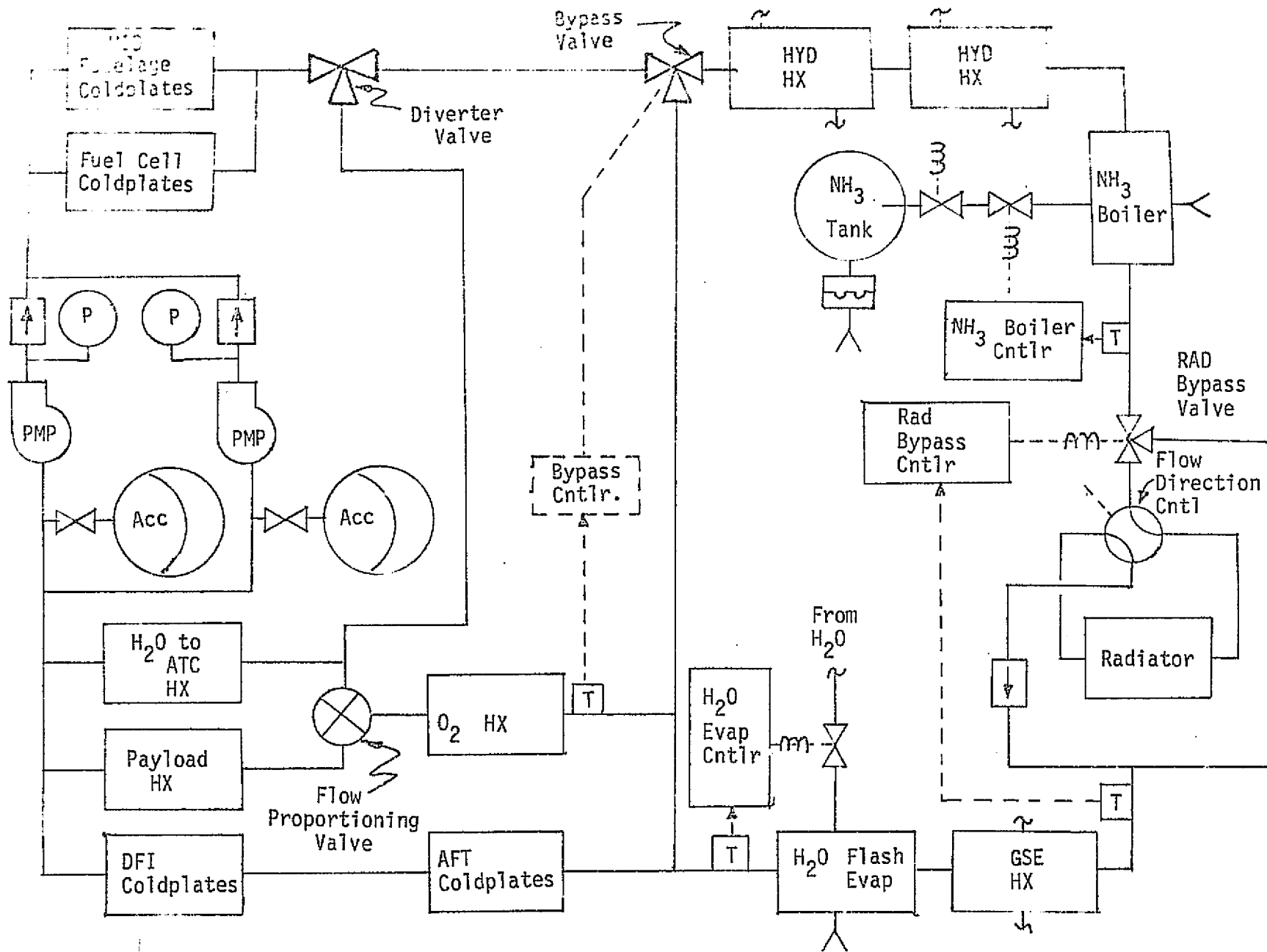


FIGURE 4.7-120 ACTIVE THERMAL CONTROL SYSTEM (ATCS) SCHEMATIC

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.

4.7-310

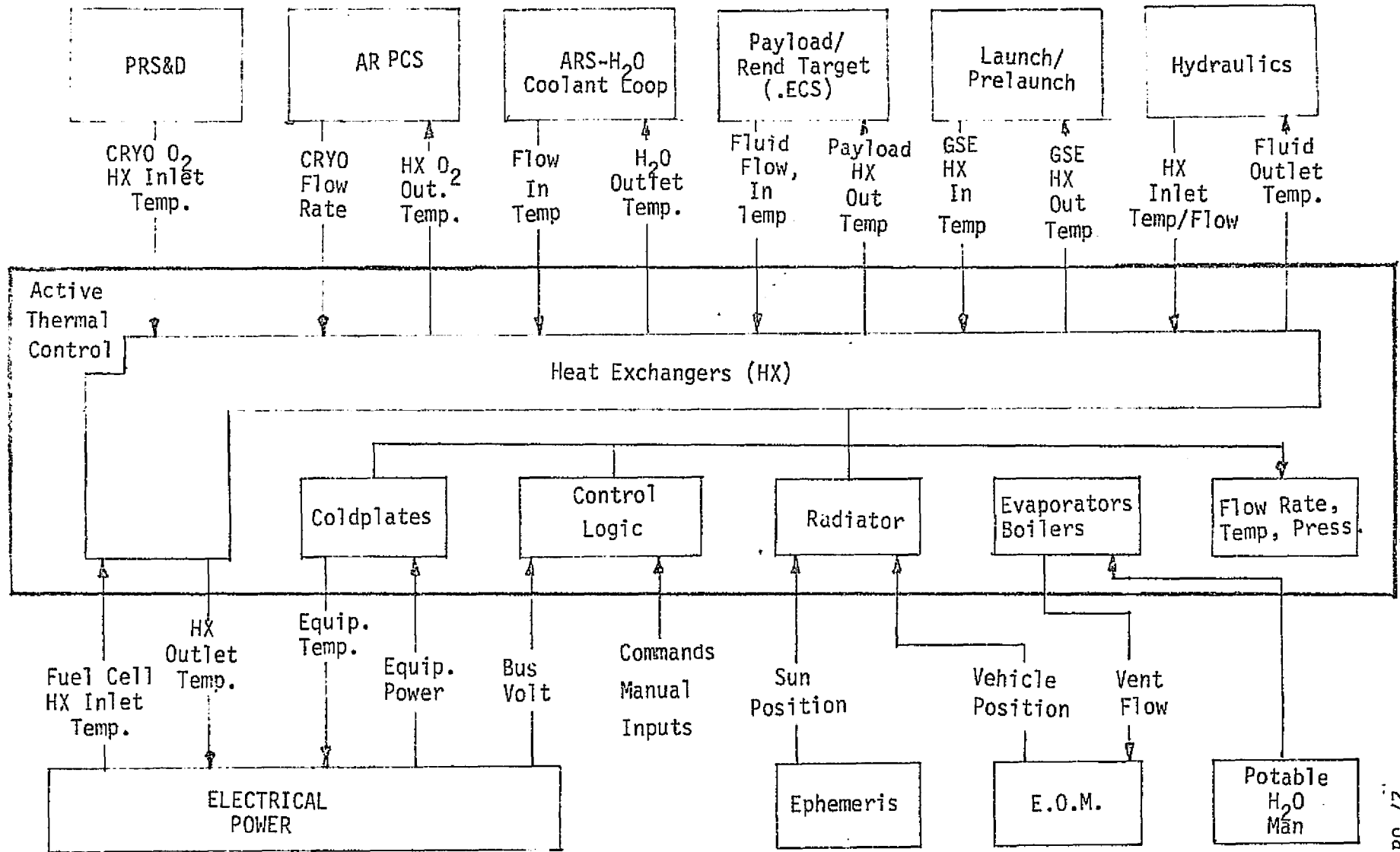


FIGURE 4.7-121 ACTIVE THERMAL CONTROL MODULE FUNCTIONAL ELEMENTS AND INTERFACES

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

4.7-301

- 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 O_2 heating for the ARPCS, fuel cell heat dissipation from the power generation circulation system, H_2O 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 NH_3 boiler subsystem and control of the H_2O evaporator as follows:

A. NH_3 Boiler

1. Quantity NH_3 remaining: function of flow rate, flow time, leakage, vent rate, starting quantity for each of three tanks.
2. Tank pressure: function of NH_3 quantity remaining, temperature, for each of three tanks.
3. Tank vent flow: function of tank pressure, density.
4. Evaporator NH_3 valve position: function of electrical bus voltage, evaporator outlet freon temperature.
5. NH_3 evaporator flow rates: function of NH_3 tank pressure, valve position, and density.
6. Freon outlet temperature: function of the inlet freon temperature, freon flow rate, specific heat, NH_3 flow rate, NH_3 inlet temperature, NH_3 specific heat, NH_3 heat of vaporization.

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

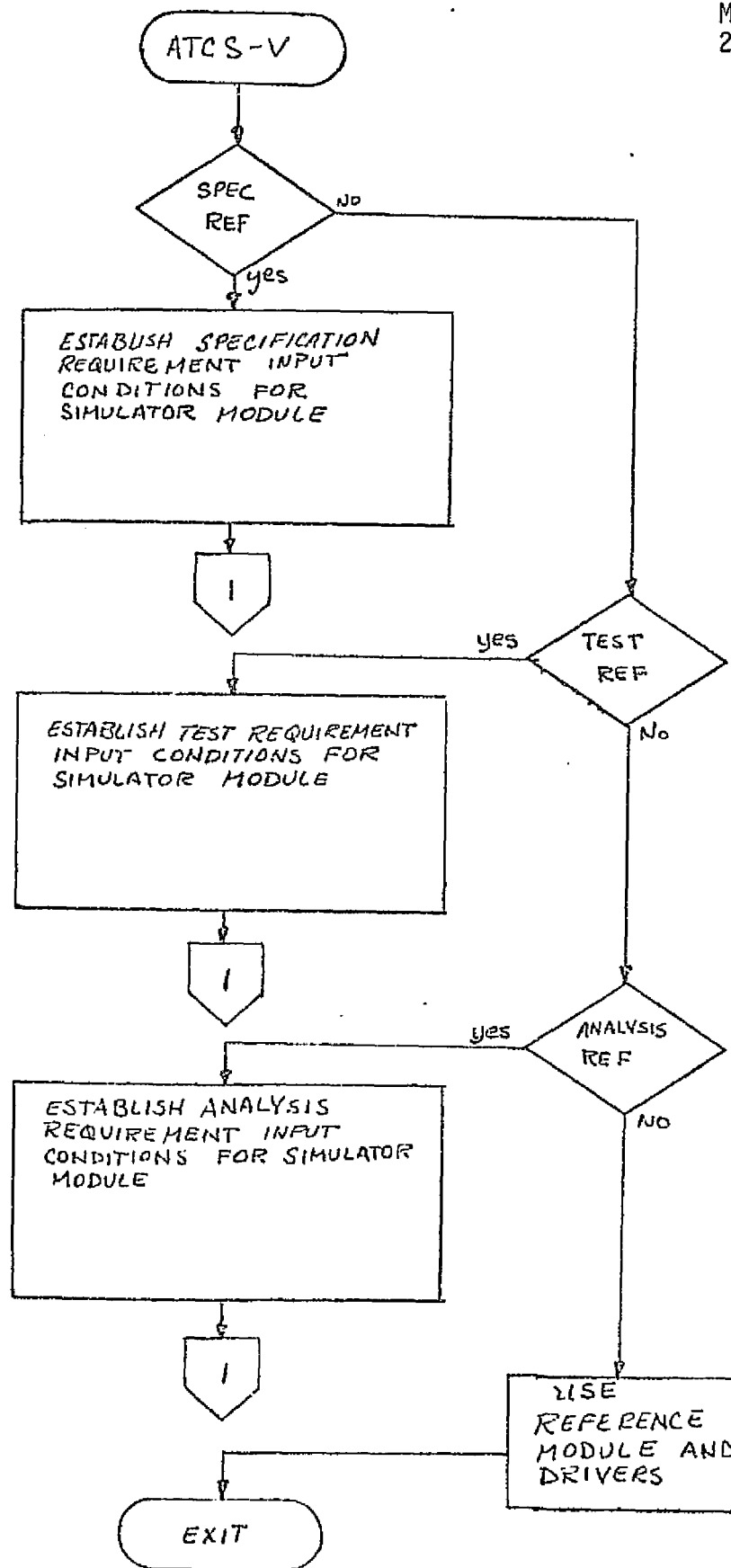
ATCS System and component design performance requirements, analysis, predictions, and tests provide data for direct comparison with the Shuttle simulation results. Figure 4.7-122 is an overview flow chart of a method of reference source selection and comparison. Reference 22 (updated at intervals) is a source of component and systems performance data regarding design requirements analysis, tests, and actual flight. Design requirements are available from Reference 108. 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 12 and 102 provide descriptions of system component subroutines which can be combined to provide a reference module for the ATCS. The G189A program of Reference 12 was developed for JSC and is a versatile analytical tool for support of environmental systems work. Reference 105 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

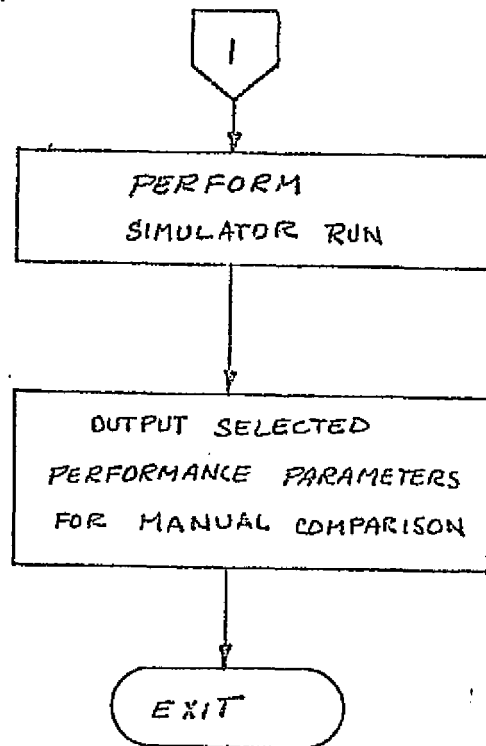
The ATCS module can be verified by the techniques described in Sections 4.2 and 5.1. During the verification the following drivers are required to provide the necessary range of inputs and conditions for establishing each checkpoint.

- o Electrical Power Generation
- o PRS and D
- o ARPCS
- o ARS
- o Payload thermal control loop
- o Prelaunch/launch GSE cooling
- o Hydraulic subsystem heating
- o Food, H₂O, waste management
- o Equations of motion
- o Intra module functional elements



ACTIVE THERMAL CONTROL SYSTEM VERIFICATION OVERVIEW

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FIGURE 4.7-122 (CONTINUED)
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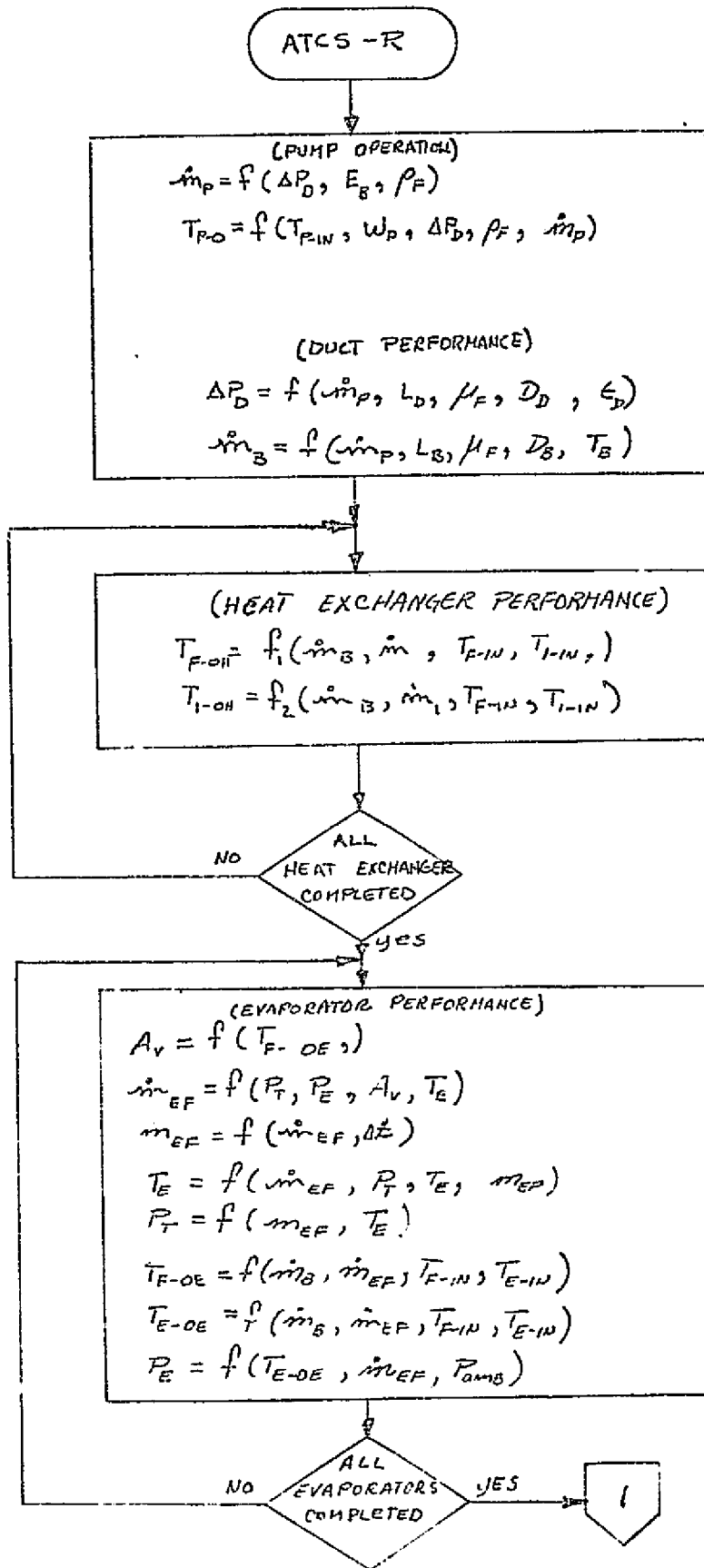


FIGURE 4.7-123 ATCS REFERENCE MODULE OVERVIEW MATH FLOW

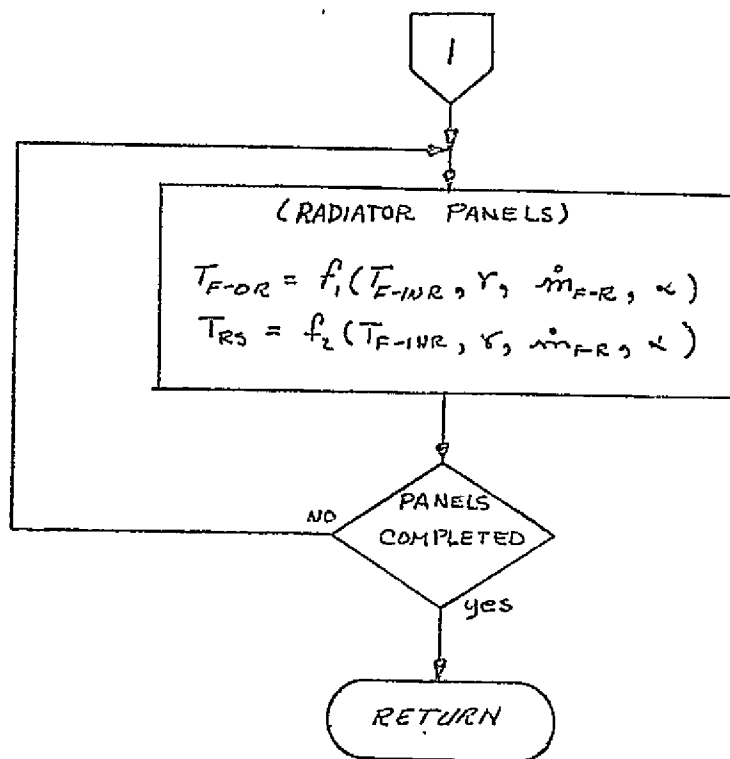


FIGURE 4.7-123 (CONTINUED)

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}_{IT} - 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
- $T_{F-IN E}$ - Evaporator freon inlet temperature
- T_{E-IN} - Evaporator inlet evaporation fluid temperature
- $T_{F-IN R}$ - 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

FIGURE 4.7-123 (CONTINUED)

The system design requirements (see Ref. 108) 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. 110) is shown in Figure 4.7-124. Figure 4.7-125 is a schematic of the waste management subsystem (also from Ref. 110).

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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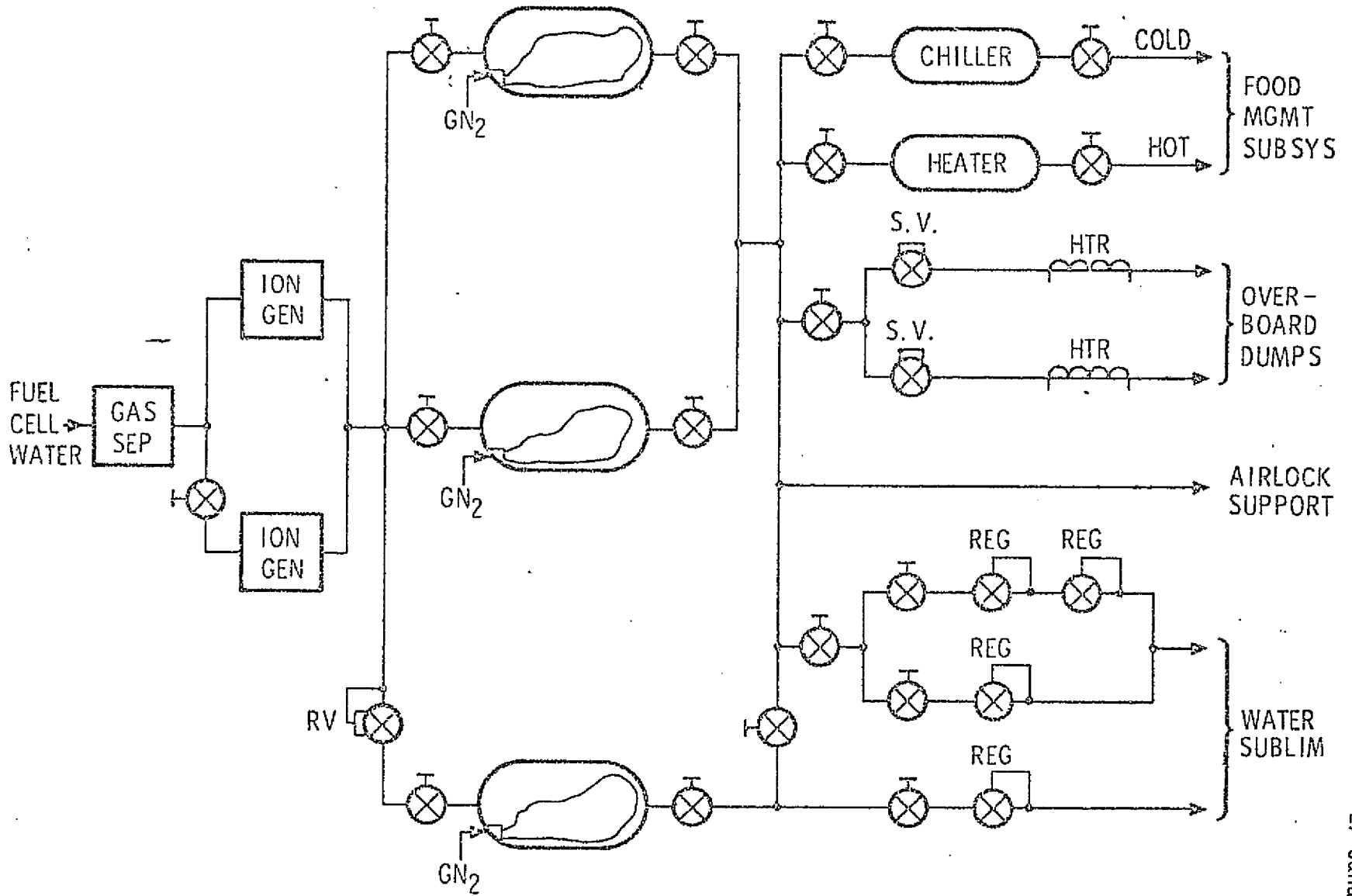


FIGURE 4.7-124 ECLSS WATER MANAGEMENT SUBSYSTEM

4.7-102

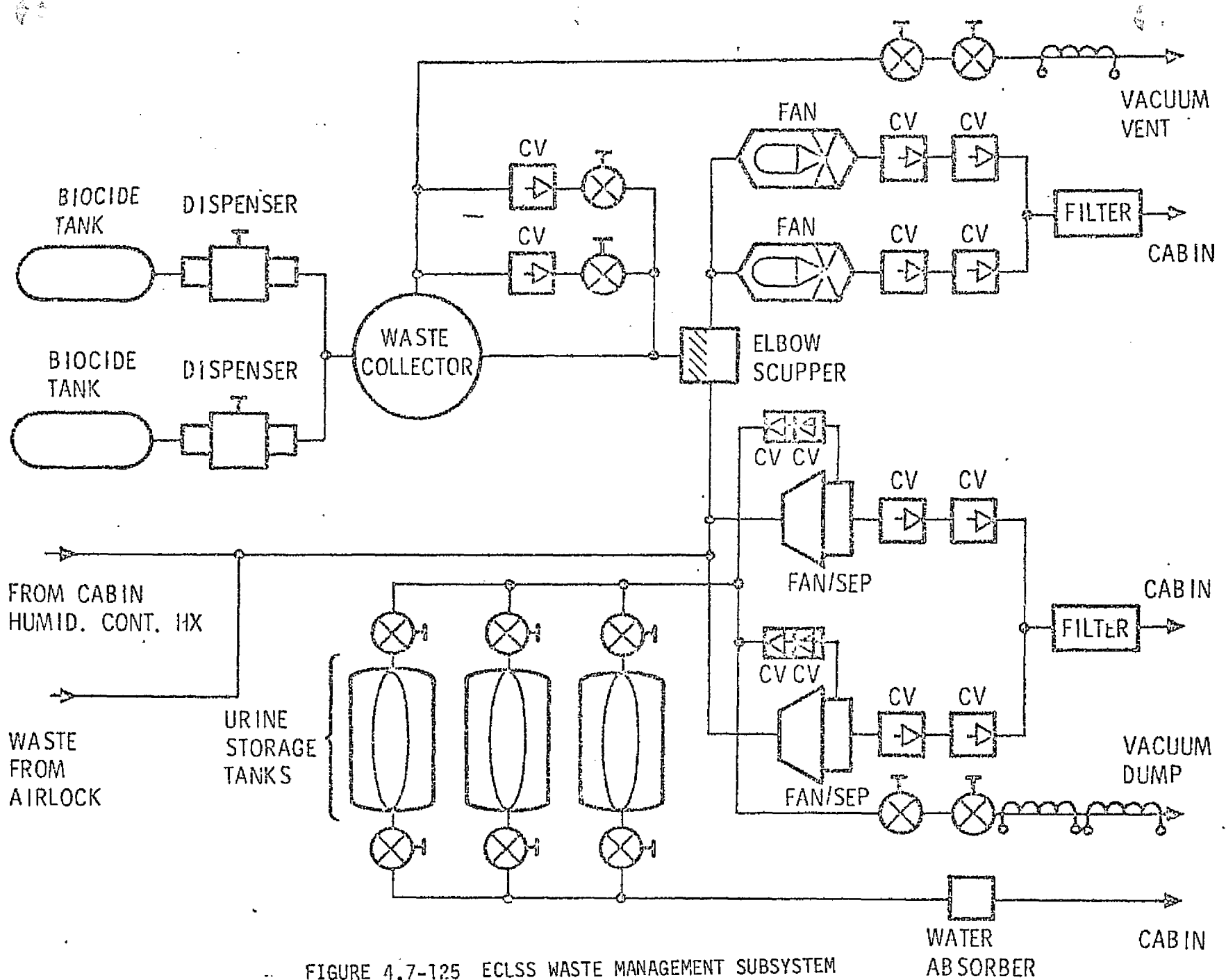


FIGURE 4.7-125 ECLSS WASTE MANAGEMENT SUBSYSTEM

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 22, 109, and 23 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

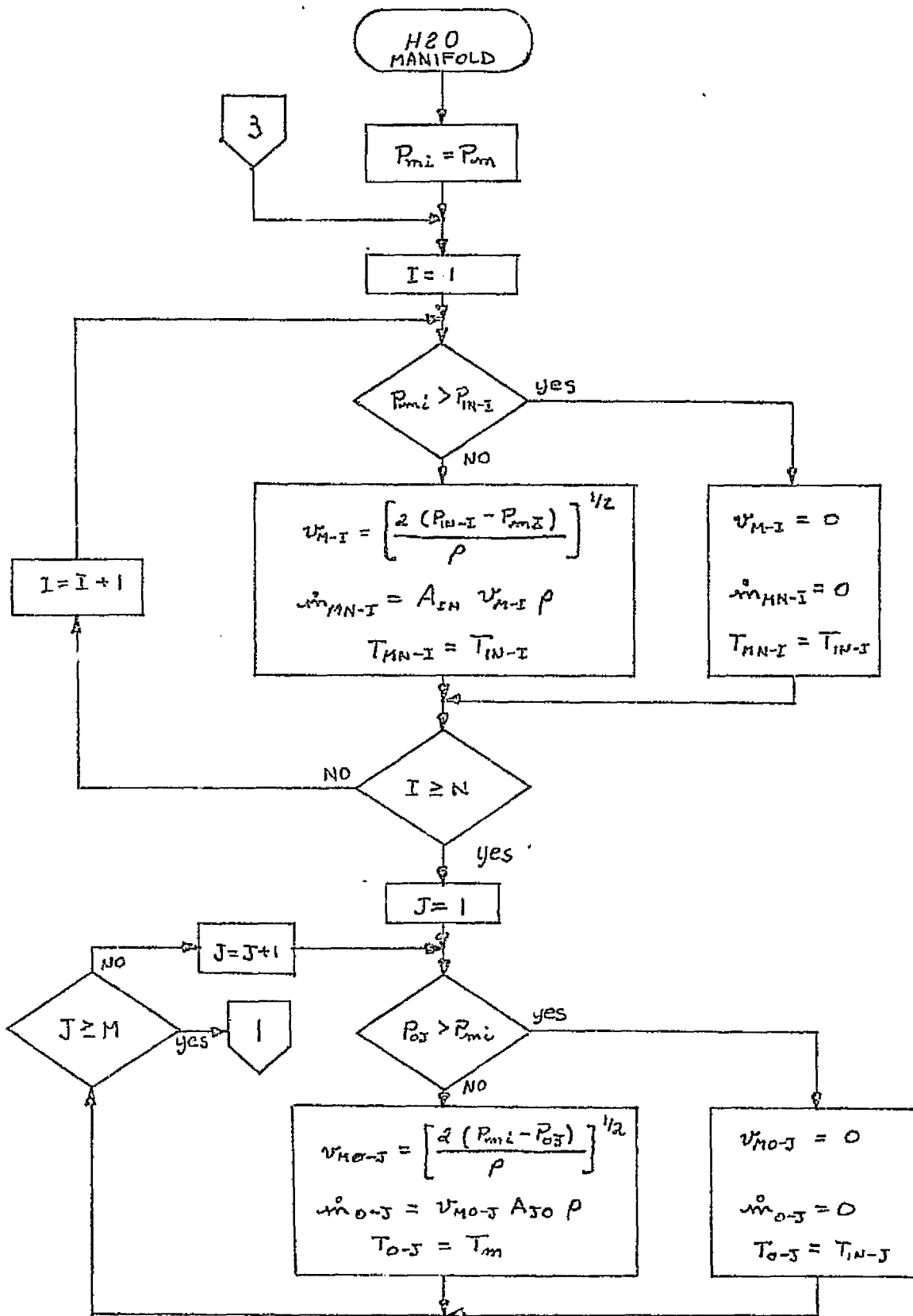


FIGURE 4.7-1:26 POTABLE WATER MANAGEMENT FLOW CHART

4.7-4.15

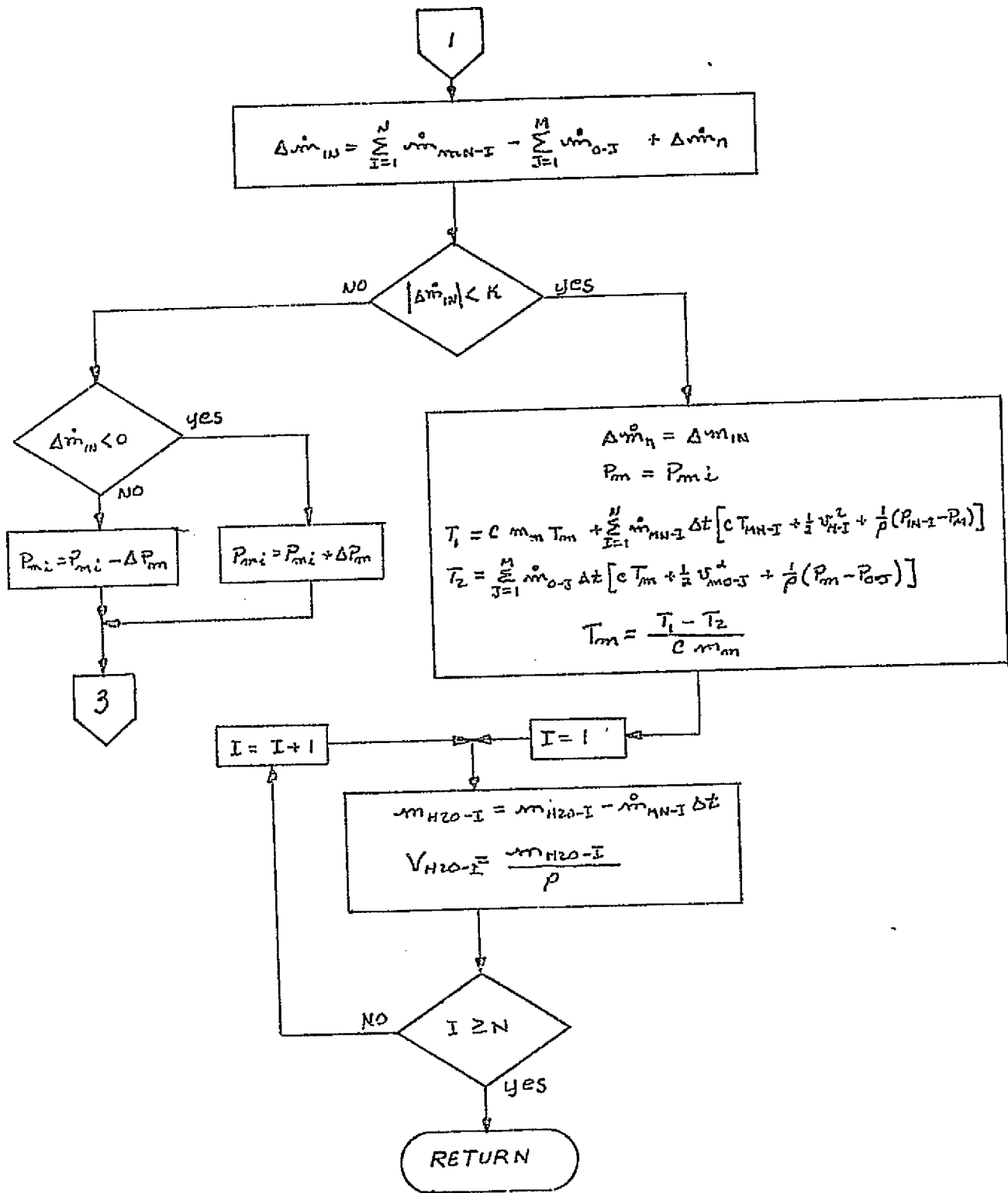


FIGURE 4.7-126 (CONTINUED)

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}_{IN-I} - Liquid flow rate from I^{th} tank into manifold
 \dot{m}_{0-J} - Liquid flow rate from manifold to J^{th} load
 T_{IN-I} - Liquid temperature into manifold from I^{th} tank
 T_{0-J} - Fluid temperature delivered to J^{th} load
 v_{H-I} - Fluid velocity from I^{th} tank into manifold
 v_{H0-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_{H2O-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_{H2O-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.

4.8 MODULE INTEGRATION

The size and complexity of the simulators we are concerned with in this study militates against the use of either a pure "top-down" or "bottom-up" integration sequence. We anticipate that simulation integration will proceed, instead, by a process of "agglomeration." That is, validated modules which have a high degree of interaction will be integrated into distinct "clusters." When these individual clusters have been validated, they will be integrated with each other, again on the basis of their degree of interaction, until the complete simulation has been integrated.

Validation aspects of the clustering process are discussed in Section 5.2. This section is concerned only with the definition of a probable integration sequence for a large spacecraft simulator. The basic information used to develop this sequence is taken from our module interface diagrams: Figures 4.3-2, 4, 6, 7; 4.4-2, 3; 4.5-2, 4, 5; 4.6-1; and 4.7-11, 28, 42, 67, 70, 84, 94, 116, 135, 162, 174, 187, 202, 222, 234, 242, 252, 276, 285, 299, 306, 326, 375, and 390.

Figure 4.8-1 depicts an integration sequence developed on the basis of this information. No "drivers" are shown explicitly on this figure, the assumption being that whatever drivers are necessary for the modules in question will be provided. Wherever possible, the actual simulation executive should be used as the basic driver, with additional drivers or "stub" subroutines used to substitute for modules not yet integrated.

Major stages in the integration process are separately identified as named clusters in the line of integration flow. In several cases, a "replica" of a module or cluster (e.g., the ECLS and the Trajectory Cluster) is shown in use on more than one line of flow. When these distinct lines are merged, excess replicas will of course be removed. In open-loop applications, previously-written tapes may be used in place of an on-line replica of the required module/cluster.

In addition to the natural sequence of integration derived on the basis of hardware/software interactions, the timing of the process will be constrained by the availability of modules; this is particularly true of hardware. The flight computer/flight hardware interface device (FC/FHID), for example, may

4.8-2

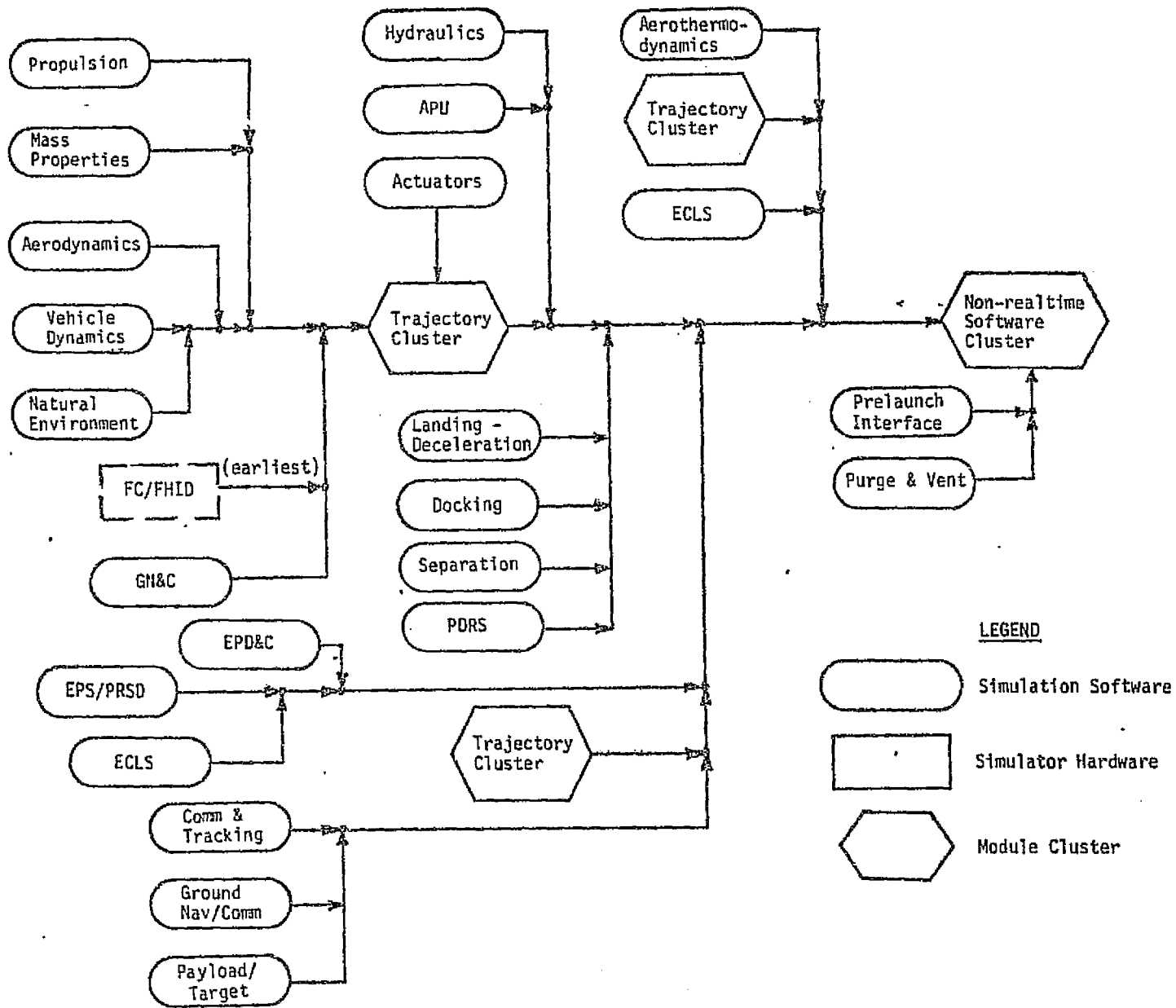


FIGURE 4.8-1 . A PROBABLE INTEGRATION SEQUENCE FOR SPACECRAFT SIMULATIONS

4.8-3

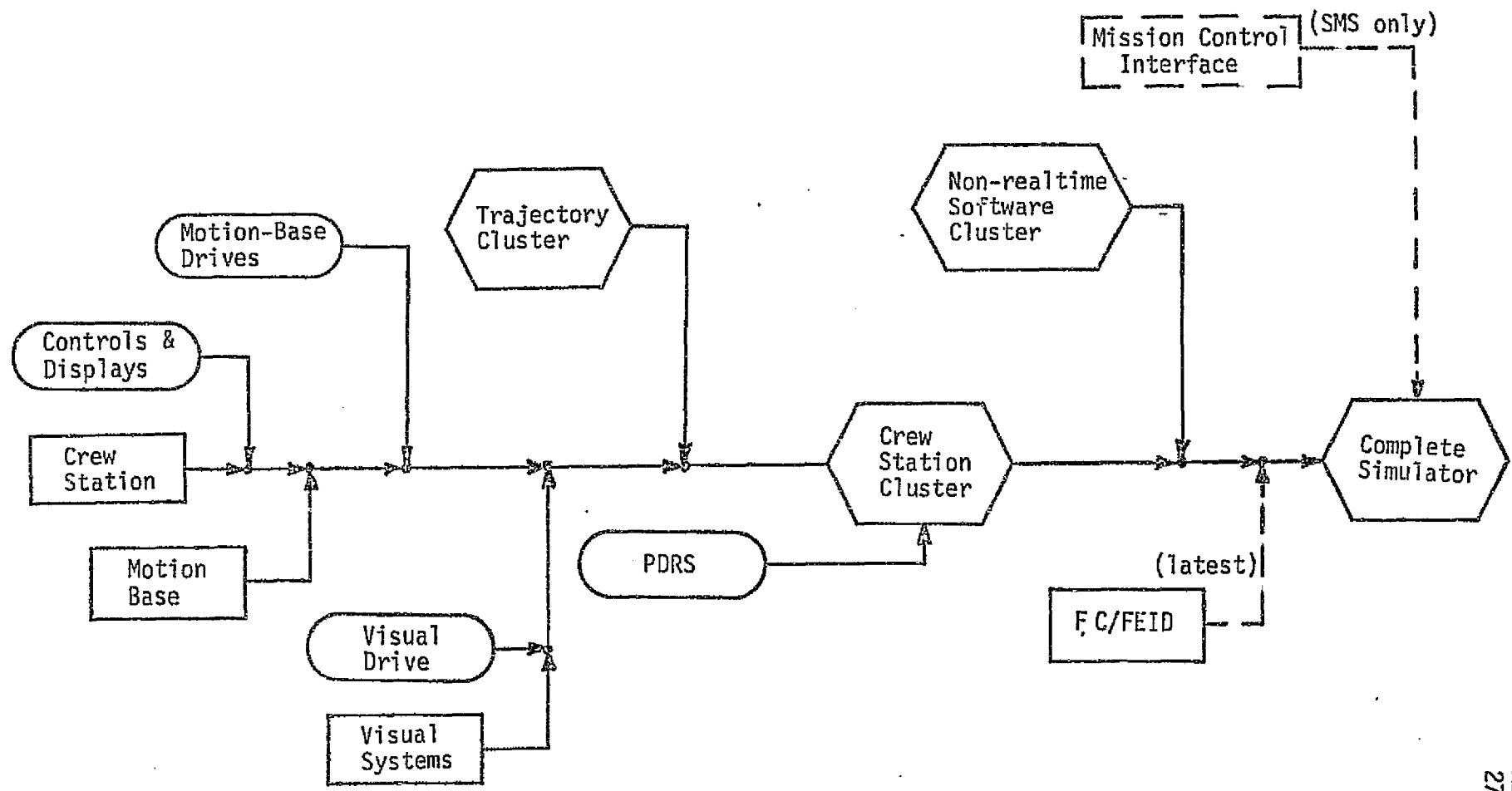


FIGURE 4.8-1 . (CONTINUED)

profitably be integrated anywhere between the "earliest" and "latest" positions shown on the figure. If the FC/FEID is unavailable when desired, its functions must also be provided by a driver of some sort (a functional simulation or emulation). Of course, the most efficient overall development will result if hardware and software development is scheduled to provide modules in a sequence which is compatible with the natural integration sequence.

4.9 SPECIAL TEST REQUIREMENTS

Spacecraft hardware tests are conducted for both static and dynamic test conditions, at the component level, integrated subsystem/system level, and the total vehicle level. In these respects, the hardware test sequence seems to resemble the simulation validation sequence as we know it. This would lead us to expect test data to be an important category of reference data for simulation validation.

However, it is important to remember that the goal of hardware testing is to prove out the hardware, not to support simulation programs. Thus, certain characteristics of test programs and normally-available test data tend to reduce their utility for simulation validation. This section first discusses the general characteristics of various test programs and of the resulting data, based upon experience from past space programs. It then suggests potential changes in test operations, data-gathering and data-handling which would enhance the usefulness of test data for simulation validation. Finally, some consideration is given to the question of how simulation project personnel might interface with test groups to affect implementation of the desired changes. (This topic, however, is not strictly within the scope of this study.)

Suggestions for the use of test data to validate individual simulation modules will be found in various module-oriented sections (e.g., 4.5.2, 4.7.1.4).

4.9.1 Survey of Conventional Test Operations

There are three basic classes of testing performed during the development of a space vehicle: component tests, system tests, and vehicle tests. In this section, we discuss various characteristics of these tests -- purpose, time frame, types of data taken, documentation, and potential problems in using the test data for simulation validation. Example data are shown.

4.9.1.1 Component-Level Tests

We expect component-level tests to be the most fruitful in terms of providing directly-usable reference data. Component tests will fit the simulator development cycle best, and provide data which is more performance-oriented than the other classes of test.

Development and Bench Tests

These tests are intended to verify hardware design concepts, establish design parameters, predict flight hardware performance, and identify the potential influence of such environmental factors as temperature, voltage level, acceleration, etc.

Test Characteristics -- These tests, conducted with early prototype hardware, occur rather early in the hardware design phase. For many onboard systems, this time period will coincide with the simulation software development phase. Tests are often quite rigorous with regard to the range of environmental conditions and input forcing functions. Extensive engineering analysis is often performed upon the resulting data, including updating of the contractor's local analysis/simulation programs to reflect the performance parameters as estimated from test data.

Typical Documentation -- Both informal and formal test documentation may be generated. The informal documentation (recorded during the actual conduct of the test) may consist solely of hand-entered parameter and environmental values, with various annotations. In modern test laboratories, however, it is becoming common to record test data automatically, using on-line minicomputers. The data format, however, will be highly customized, and probably rather abbreviated, whether in hard copy, punched tape, or magnetic tape.

The formal documentation will be free-form test reports, reproducing the more significant portions of the test data (raw and/or reduced), and providing some engineering analysis of the significance of the results in terms of the performance of the component.

Potential Problems -- The formal test documentation is not often widely distributed; simulation personnel must often make personal contact with cognizant engineers to even become aware of the existence of such documentation. The informal documentation, obscurely formatted, often cannot be used without the aid of the people who were actually involved in the generation and/or reduction of the data. Even the formal documentation will often require further analysis to be put into a form useful for module validation. Finally, the performance data may be obsolete, due to design changes based upon the test results; indeed, this is the basic reason for conducting such tests.

Example -- Figure 4.9-1 resulted from the evaluation of development test data for certain Skylab I electrical-equipment coldplate heat transfer coefficients; see Ref. 14 .

Qualification Tests

"Qual tests" are performed to verify that components operate within specification limits, during and/or following exposure to specified environmental extremes, such as shock, vibration, temperature, and overvoltage. Life tests also fall in this category.

Test Characteristics -- These tests are started early in the component's production history, and are continued through the component production phase, often on a 100% testing basis. Very little parametric data is collected from qualification tests, which are intended only to provide go/no-go information at specification limits.

Typical Documentation -- Qualification test results, considered highly significant to the success of the hardware program, are quite formally and thoroughly documented. The reports are widely distributed and widely evaluated.

Potential Problems -- The test data is not parametric in nature, and is almost always at extremes of environmental conditions, providing little or no information about performance under nominal conditions.

Acceptance Tests

Acceptance tests are conducted on individual production units, prior to installation in the flight vehicle, to verify that each unit has been properly assembled, and performs within specification over a reasonable range of operating parameters.

Test Characteristics -- These tests are conducted with production hardware slated for installation in actual flight vehicles. Accurate, parametric performance data reflecting normal operational conditions is recorded for each individual unit, and tagged with the serial number for the production unit. Since data is available for multiple units, it becomes possible to determine the inherent scatter in the performance-parameter data, which helps to establish fidelity criteria for simulation validation.

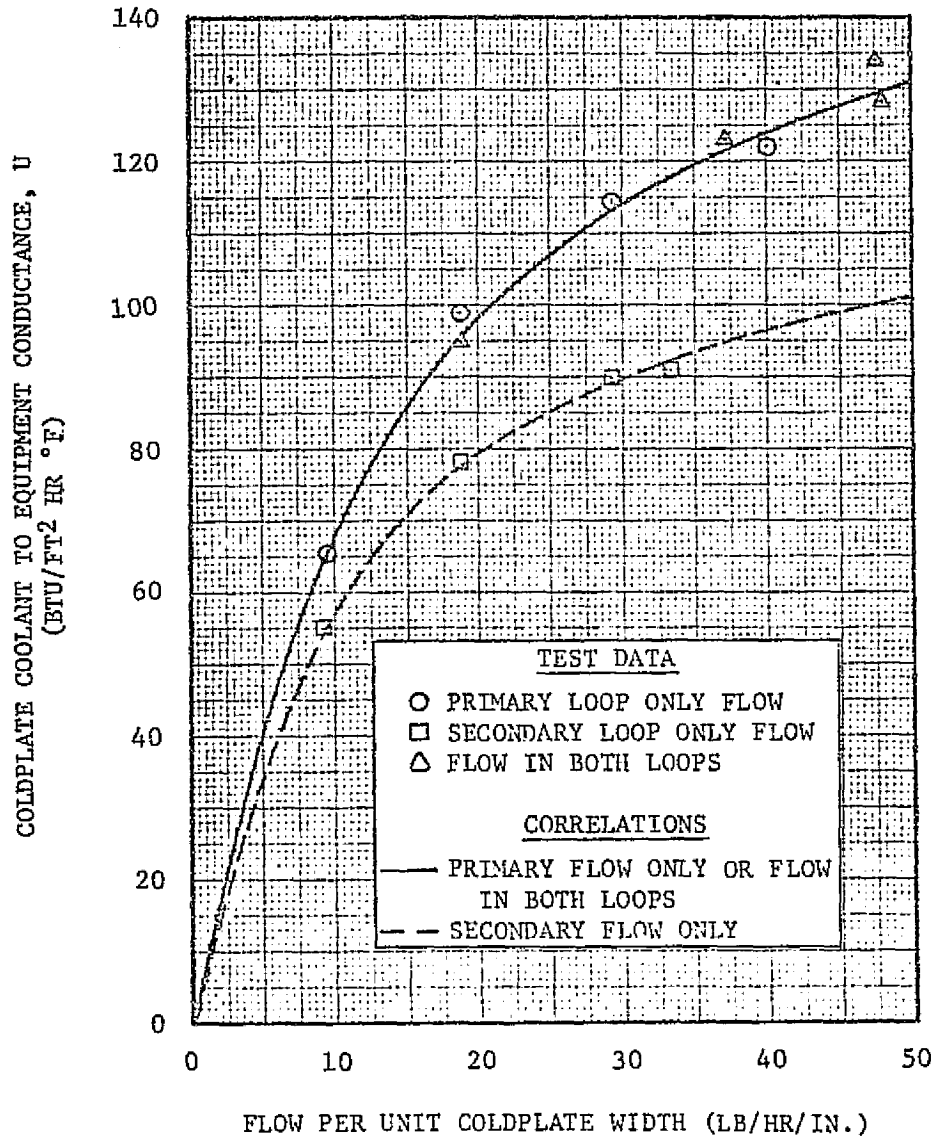


FIGURE 4.9-1. COLDPLATE HEAT TRANSFER CHARACTERISTICS

Typical Documentation -- Rather thorough, formal documentation is prepared for each serial-numbered component. The tests results, however, normally remain with the unit until installation, and do not receive wide distribution.

Potential Problems -- Acceptance-test data does not become available in time for initial simulation validation, although it can serve as a good reference for simulation updating. The data must generally be "filtered" and reformatted to be directly useful for validation. Test documentation normally remains with the tested unit, and is not widely distributed, posing something of a retrieval problem.

Examples -- Figure 4.9-2, from Ref. 14, shows typical acceptance-test data from an individual component (a pump for a Skylab coolant loop). Also see Figure 4.2-10 of Section 4.2.1.4, which shows operational envelope data, compiled from a number of individual acceptance-test results on individual pumps, which were retrieved via considerable "legwork."

4.9.1.2 Systems-Level Tests

Systems-level tests are conducted after components have been integrated into subsystems and systems and, in some cases, installed on the space vehicle. They normally require rather complex setup and operational procedures, which must be faithfully duplicated for the results to be meaningful.

Systems Development Tests

These tests verify system conceptual designs, and lend confidence to the results of prior analyses and simulations.

Test Characteristics -- The tests are performed late in the design phase. Complete or partially integrated subsystems are operated with simulated external inputs, loads, etc. Data may be taken at isolated performance points, or may be parametric over an operational range of interest. The type and amount of data taken will depend upon the (formal or informal) test plan, the degree of prior confidence held by the investigators, and upon whether initial results turn out as expected. Unexpected results will usually induce the investigators to take more data, and to exercise the system over a wider range, in the interest of later analysis.

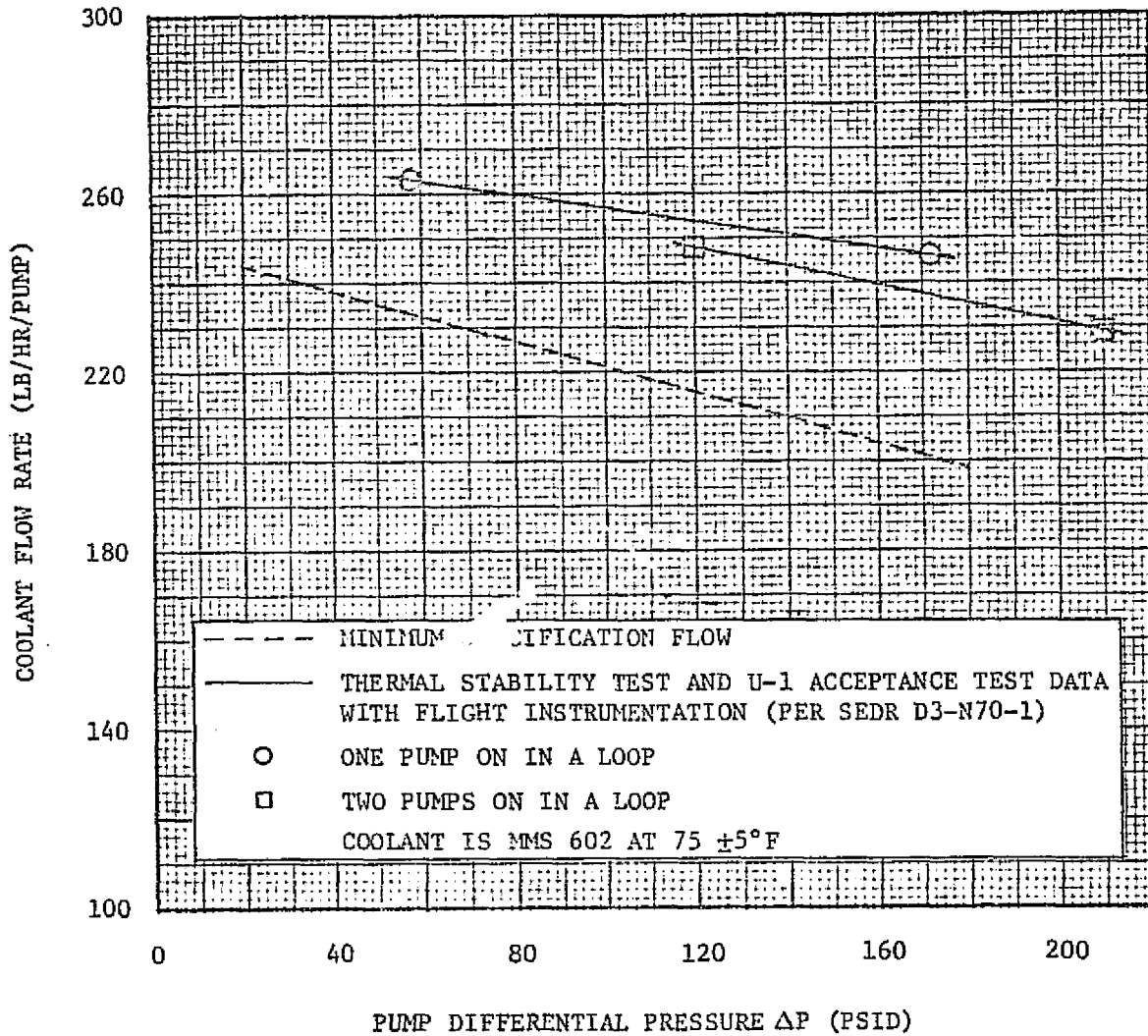


FIGURE 4.9-2. COOLANT PUMP FLOW RATE CHARACTERISTICS

Typical Documentation -- Semi-formal documentation is normally prepared, consisting of a brief cover report of problems, conclusions, etc., followed by a description of the test procedure and reproduction of the test data sheets as recorded during the test. Generally, the only information which becomes widely known is the problems encountered.

Potential Problems -- Data becomes available rather late for simulation use. The systems as tested may lack certain components, and test conditions may be unrealistic and/or hard to duplicate in a simulation. The data may be incomplete and in an inconvenient format.

Example -- APU spin-up tests (rotation vs. time); APU fuel consumption under various hydraulic loads.

Integrated Systems Test

This is a go/no-go test series for the integrated vehicle, to verify that the performance of the various interacting systems is correct (within the acceptable range of values).

Test Characteristics -- With multiple systems installed in the vehicle, energized and operated according to a rather precise and complex procedure, isolated performance data points are taken over a range of conditions. Since the test is of a go/no-go nature, the actual parameter values are often not recorded if they fall within the expected range.

Typical Documentation -- The test report will include a description of the test procedure or "script," and indicate whether the data taken fell within the expected range; few actual performance parameter values are provided.

Potential Problems -- Integrated systems tests occur during the vehicle integration phase, late relative to simulator requirements. Little useful data is provided in the test results, and what useful data is available is difficult and time-consuming to extract. The test setup is difficult to duplicate on the simulator, even if the published script is followed exactly.

Example -- Figure 4.9-3 was excerpted from a ten-page test procedure published in Ref. 113.

Vehicle Prelaunch Checkout

These tests are conducted to verify operability of each vehicle prior to launch.

Test Characteristics -- These tests require highly complex procedures, which are often fully or partially automated using a variety of computer systems. Isolated performance data points are taken, and tested against acceptable ranges; actual parameter values are often not recorded.

Typical Documentation -- Much of the data remains within the checkout complex in volatile form, and is never published. Summary reports usually only cover anomalies observed, and are not widely distributed.

Potential Problems -- Very little useful data can be expected from prelaunch checkout. Tests occur very late for simulation purposes.

4.9.1.3 Vehicle Flight Tests

Flight tests are conducted to verify the operational readiness of the complete vehicle and its onboard systems in its actual environment. Successful flight tests develop confidence in in-space capabilities, procedures, etc.

Test Characteristics -- Flight tests provide data which reflect the actual operational environment of the vehicle. Great quantities of data are recorded -- both external (ground tracking) and onboard-system performance parameters (telemetry stream and onboard recording). The data stream includes both discretetes, such as switch settings and event markers, and continuous parameters, such as accelerations, temperatures, voltages, etc. Rather complex commutation and framing schemes are necessary to record such a quantity of data. For example, the onboard data acquisition system used during DC-10 flight tests is described by Ref. 112 as follows:

"Most data recorded in the airborne system are digital, although it also has a secondary FM-FM recording capability. The 400 telemetry channels are divided into 90 recording at prime

SEQUENCE	SYSTEM AREA	DESCRIPTION	REMARKS
02-031	EMC	PHOTOGRAPH VOLTAGE SPECTRUM (FREQUENCY DOMAIN, 1 KHZ TO 110 MHZ) OF EXTERNAL POWER (POSITIVE LEAD ON PIN G, NEGATIVE LEAD ON PIN U). CAUTION ALWAYS USE X10 ATTENUATOR PROBE WHEN USING FET PROBE TO AVOID TEST EQUIPMENT DAMAGE.	
02-032	EMC	OPEN SWITCH S1 ON BREAKOUT BOX (EXT PWR IN). PHOTOGRAPH CURRENT SPECTRUM (FREQUENCY DOMAIN, 1 KHZ TO 110 MHZ). CLOSE SWITCH.	
02-033	EMC	OPEN SWITCH S12 ON BREAKOUT BOX (EXT PWR RET). PHOTOGRAPH CURRENT SPECTRUM (FREQUENCY DOMAIN, 1 KHZ TO 110 MHZ). CLOSE SWITCH.	
02-034	EMC	RECORD MEMORY VOLTMETER READINGS AND RESET THE METERS NORM _____ VOLTS 10 S _____ VOLTS	
02-035	LCP	MOVE AUXILIARY FIRING SWITCH S9 TO STANDBY AND HOLD AGAINST DETENT SPRING.	
02-036	HARCO	PLACE OPERATION POWER SWITCH TO NORMAL.	
02-037	LCP	VERIFY LCCP STANDBY WINDOW AND READY TO FIRE WINDOW ILLUMINATED. STANDBY _____ CHECK READY TO FIRE _____ CHECK	
02-038	HARCO	VERIFY: IGNITER EXTENDED-OFF _____ CHECK OPERATION POWER-ILLUMINATED _____ CHECK	
02-039	EMC	RECORD MEMORY VOLTMETER READINGS AND RESET THE METERS NORM _____ VOLTS 10 S _____ VOLTS	

FIGURE 4.9-3. EXCERPT FROM AN INTEGRATED-SYSTEM TEST "SCRIPT."

sampling rates, 290 recording at a 10:1 subcommutation rate, and 20 recording at a 20:1 subcommutation rate. The prime channel sampling rate can be changed in flight from 400 to 10 samples per second in six stages.

"The up-to-2400 parameters on one aircraft are transmitted over the 400 channels by onboard multiplexing of some data. Data from 64 temperature sensors on an engine may be multiplexed on board into one channel, for example."

Typical Documentation -- Qualitative and semiquantitative data is provided by crew debriefing reports, flight control reports, and final summary reports. The informal reports become available soon after the flight, while the formal summary reports may not be published until months later.

The bulk of the quantitative data remains available on magnetic tapes. Depending upon the software, hardware and retrieval aids provided, it may be a fairly simple matter to obtain tabulations and plots of any desired parameter time-histories from a particular flight -- or it may be extremely difficult. Where the inputs and outputs for an onboard system can both be obtained as functions of time, the validator will have a directly-usable, highly realistic check case for simulation validation.

Potential Problems -- Flight test data becomes available too late for initial simulation development and validation, but should be useful for subsequent updating. The available check cases are constrained by the actual mission timeline, and may require complex setup to duplicate the operational conditions on the simulator. It may be difficult to obtain sufficient data to accurately define the environmental conditions in which the vehicle was operating. Potential availability of the data is sharply dependent upon the power of the retrieval and data-reduction aids provided by the spacecraft project.

4.9.1.4 Shuttle-Related Test Documents

Table 4.9-1 provides a list of currently-published documents relating to planned tests for the Shuttle program.

TABLE 4.9-1 . POTENTIALLY USEFUL TEST DOCUMENTATION

MJ072-0004-3	Shuttle Master Verification Plan, Volume 3: Orbiter Verification Plan
ML0101-0001	Test Requirements: In-Process and Acceptance-Orbiter
SD72-SH-0009	Orbiter Quality Assurance Plan
SD72-SH-0112-6-II	RDD-Major Ground Test-Thermal Vacuum Test Program: CMS-RCS POD
SD72-SH-0112-12	RDD-Subsystem Ground Test-Docking Mechanism Dynamic Simulation
SD-72-SH-0112-13	RDD-Ground Subsystem Test-Orbiter/External Tank Separation Subsystem Test
SD72-SH-0112-18	RDD-Subsystem Ground Test-APU Integration Test
SD72-SH-0112-19	RDD-Subsystem Ground Test-ECLSS Test Article
SD72-SH-0112-21	RDD-Subsystem Ground Test-Escape System Test Article
SD73-SH-0062	Checkout Plan: Orbiter and Combined Elements Ground Operations
SD73-SH-0094	Manual, Technical and Non-Destructive Testing, Space Shuttle Specification for Preparation of
SD73-SH-0298	Avionics Development Laboratory General Test Plan
SD74-SH-0011 through SD74-SH-0049	Subsystem Certification Plans

4.9.2 Idealized Test Programs

Based upon an understanding of historical norms in test operations, we are now in a position to consider what changes would be desirable to make test data a more valuable source of reference data for simulation validation. Efforts should be concentrated upon component-level tests, for at least two reasons:

- (a) Component-level tests appear to be an inherently more valuable source of reference data.
- (b) System-level and vehicle-level tests are already so complex and expensive that resistance will likely be encountered to any changes which would make them still more complex and expensive. We recommend a three-step approach to maximizing test-data utility: (1) identify required data, (2) develop an idealized test plan, and (3) define the data recording and documentation desired.

4.9.2.1 Identify Required Data

In the analysis of spacecraft subsystems and associated simulation modules provided in Section 4.7, we have identified inputs, performance parameters and critical performance parameters for each module. Obviously, the data most desired from a test are the values of the component inputs and the critical performance parameters. Fortunately, these will in most cases also be the data most desired from the test by the hardware designers. For high-fidelity simulation, non-critical performance parameters will also be desired, but at lower priority, thus giving the test designers a "shopping list" against which they can evaluate potential time and cost impacts of setting up increased test instrumentation and recording capability.

The workload of establishing data requirements for each onboard component will be minimized by unifying the analysis of similar components, regardless of their end use. The guiding philosophy would be that, for example, "a pump is a pump is a pump," whether it is a fuel pump in the main propulsion system, a coolant pump in the ECLS, or a lubricant pump for the APU. The parameters of interest - RPM, differential pressure, flow rate, etc. -- would then be the same for all pumps on the vehicle.

4.9.2.2 Develop an Idealized Test Plan

The ideal test for a component is one which would translate directly into a check case for validation of the associated simulation module. The analysis steps necessary to define such a test are as follows:

- (a) From preliminary analysis or simulation results, determine the expected range of the component inputs and performance parameters.
- (b) From similar performance predictions, define the expected shape of the performance curve between its upper and lower limits.
- (c) Determine the minimum number of input values necessary to define this performance curve, and the best choice of values based upon the curve shape. This will commonly lead to non-uniform spacing of checkpoint values -- widely spaced in regions of expected uniform slope, closely spaced in regions of expected high curvature.

Similar considerations will apply for defining the time-spacing of data-points for dynamic response of a component, based upon the estimated transfer function of the component and the expected bandwidth of input forcing functions. Standard test descriptions would be prepared for basically-similar components, such as pumps, as discussed above. Performance curves for all such similar components would be expected to be similar in shape.

4.9.2.3 Define Desired Data Recording and Documentation

During the conduct of the actual test, the data to be recorded will consist of environmental conditions, input stimuli, and output responses of the component/system. These should, of course, be actual values, rather than go/no-go assessments. Accuracy, time spacing, and other data attributes will generally be selected by the test personnel on the basis of available instrumentation and the requirements and goals of the test. Accuracy estimates will be helpful in making proper use of the test data.

The normal recording format and medium will be hard-copy tabulations, either handwritten or minicomputer printout. Where available, graphical data will be very desirable. Magnetic tape records will probably not be available, and are likely to be incompatible in format with the simulation computer in any event.

Test documentation should include units, scale factors, known biases, and any other adjustments necessary to use the data as a simulation check case.

4.9.3 Implementation of Test Enhancements

Although simulation personnel should make every reasonable effort to communicate their requirements to test personnel, it must be assumed that the goals and economic constraints of the hardware programs will take precedence. Thus, the simulation/validation test-interface group should become familiar enough with test operations, requirements and instrumentation to assess the potential impact of whatever enhancements they plan to request.

This will require the early establishment and continuing maintenance of effective liaison with design and testing groups, to accomplish the following:

- Communicate their needs for performance-oriented data from component/system testing.
- Make test personnel aware of the data formats and documentation which would make test data most useful for simulation validation.
- Ensure that they will receive available test data in a timely manner.
- Evaluate the probable impact of unexpected test results upon hardware designs, operational procedures, etc.

In some large test organizations (e.g., the DC-10 flight test organization), a formal structure for integration of various user's requirements into test design will already be in existence; the simulation personnel will need only to make use of the existing interfaces. (It is to be expected that PICRS will provide assistance in this area.) Where formal lines of communication do not yet exist, the simulation program will need to make efforts to establish new working interfaces, to make their requirements known. Ideally, the personnel assigned to this liaison function would have extensive experience both in simulation development and hardware design and testing. Where such personnel are initially unavailable, some cross-training will be required.

4.10 REFERENCE DATA FORMATS

This section discusses methods for formatting of reference and simulation data, to obtain the following benefits:

- o Maintain compatibility between reference module and simulation module inputs and outputs.
- o Optimize verification data-handling, comparison and evaluation processes-- manual and automatic.
- o Minimize simulator verification data base impact.

4.10.1 Reference Data Types

Reference data to be used as standards of performance for simulation validation may be available in either machine-readable or non-machine-readable form.

4.10.1.1 Non-Machine-Readable Reference Data

Non-machine-readable reference data -- numerical tabulations and plots -- will become available to the validation staff from several sources:

- o System and subsystem data books, which compile data derived from performance predictions, analysis/simulation programs, and component/system tests.
- o Component, subsystem and system tests, providing raw data taken during test execution, and/or reduced data published in test reports (see Sect. 4.9).
- o Printout and/or plots from existing analysis/simulation programs not under the control of the validation staff.

4.10.1.2 Machine-Readable Reference Data

Machine-readable reference data may be provided by any of the following means:

- o Standard plot tapes generated by multi-user analysis/simulation programs, such as SYDS (see Sect. 4.2.1.3).

- o Output data files (tape or disk) generated by either an existing analysis/simulation program operated under control of the validation staff, or a new reference module developed specifically for validation purposes. (This includes highly-detailed reference trajectory tapes.)
- o Basic data tapes provided by an outside contractor or agency (e. g., planetary ephemeris tapes, vehicle aerodynamic data tapes).

4.10.2 Reference Data Generation, Handling and Conversion

Clearly, radically different methods are required for the handling of machine-readable and non-machine-readable data. For non-machine-readable data, we have the options of either performing the comparison/evaluation in a purely manual mode, or hand-entering the data into the computer for automated comparison/evaluation. For machine-readable data, we may either put the data out for manual comparison/evaluation, or perform automated comparison/evaluation within the computer (see also Sect. 5.5).

4.10.2.1 Handling of Non-Machine-Readable Data

We recommend that when the reference data is in non-machine-readable form, the comparison and evaluation required for simulation validation be performed in a purely manual mode. To simplify the manual operations, reduce workload and fatigue, and eliminate all possible sources of error or misjudgement, it is essential that the simulation data be mapped into a format which is as nearly identical as possible with the pre-existing format of the reference data.

Formatting factors involved in tabular data include headers, physical arrangement of data on the page, spacing of independent-variable values, and units, axes, and numerical format of individual numerical entries.

Graphical output from simulation module drivers should be designed to enable the simulation-data plot to be exactly overlaid on the reference-data plot, for convenient "eyeball" evaluation of fidelity. The factors which must be controlled to enable such overlaying include axis conventions and units of the basic data, as well as axis lengths, origins and scale factors of the plot itself. Since plots found in data books and other sources may not be reproduced in their original full size, highly flexible formatting and scaling capabilities will be

required for the simulation data-handling support software.

Since great flexibility is desired for the required data-handling support software, consideration should be given to "human engineering" factors in the design of this software -- i.e., command vocabulary and formats, control of options, free-form input, etc. The goals of the support-software design should be to provide all required formatting capability, achieve a practical minimum of workload in obtaining the required hard-copy, and minimize the potential for errors induced by the support software itself.

Hand-entry conversion of non-machine-readable data into machine-readable form is definitely not recommended. The labor and error potential of the required manual operations, in our view, more than offset the potential gains of automating the comparison and evaluation.

4.10.2.2. Handling of Machine-Readable Data

When both the reference and simulation data are in machine-readable form, the basic processing for comparison and evaluation is rather simple (see Sect. 5.5). The bulk of the programming effort and computer time is likely to be expended in pure data-handling: file searching and retrieval, record searching and retrieval, data formatting and adjustment, etc. For that reason, we believe that substantial benefits can be realized from the early establishment, continuing maintenance, and broadest possible application of a universal data format.

Formats for New Validation Software

This universal format would encompass axis conventions and units, decimal formatting of discretely, fixed-point and floating-point data, data sampling rates and the mapping of software input and output data streams into time-tagged "pages" or "frames" of data. The basic properties of such a universal data format are illustrated in Fig. 4.10-1. (Also see Sect. 4.9.1.3 for a brief description of the framing scheme used for onboard recording and telemetry of DC-10 flight test data.) The formatting and framing information necessary to utilize the data would automatically be recorded on a "header" preceding each data file.

With the amount of study and development which has already gone into the next generation of training and procedures-development simulators for NASA-JSC, it

<u>ITEM #</u>	<u>DESCRIPTION</u>
1	Data file identification (fixed-length alphanumeric title)
2	Date file was generated
3	Type of data: reference, simulation, both
4-5	Identification of reference and simulation modules used to generate data
5	Data word length
6	K=Number of words per data frame
7	Nominal frame rate (frames per second)
8	M=Total number of frames (if known)
9	N=Total number of parameters in this file
10	Identification name or code for first parameter
11	Location of parameter #1 in each frame in which it appears
12	Word length for parameter #1 (several short parameters may be "packed" into a single word)
13	Frame frequency for parameter #1
14	(Same information for parameters 2 through N)
:	
.	
4N + 9	

(a) Header Block

FIGURE 4.10-1. SCHEMATIC OF A UNIVERSAL FORMAT FOR VALIDATION DATA FILES

<u>FRAME #</u>	<u>WORD #</u>	<u>DESCRIPTION</u>
1	1	$t_1 =$ Frame Time
	2-K	Parameter values at time t_1
2	1	t_2
	2-K	Parameter values at time t_2
.		
.		
.		
M	1	t_m
	2-K	Parameter values at time t_m
M+1		End of file mark

(b) Data Frames

FIGURE 4.10-1 (continued)

should be possible to define the universal format with high confidence, rather early in the simulation design phase. A growth margin can be allowed by leaving some spare capacity in each data frame. In this way, drastic redesign of the format, and resulting obsolescence of existing programs and data files, should be avoidable for the life of the program. The frame size would, of course, have to be consistent with the block-length constraints of the host-computer operating system and I/O peripherals.

In application, the universal format would be built into all new support software developed for simulation validation. This would include:

- o New reference-data generation programs (See Sects. 4.2.1.1, 4.2.1.2).

- o "Driver" routines for simulation software modules and clusters of modules (see Sects. 5.1, 5.2).

- o Routines for realtime data acquisition during operation of the all-up simulator (see Sect. 5.4).

- o Service routines for reference/simulation display, comparison and evaluation (see Sects. 5.1, 5.5).

Since a truly universal format will have to be designed to accommodate high-volume data generation processes (up to and including an all-up high-fidelity simulation), there will be some sacrifice in "micro-efficiency" when it is used for the low-volume applications, such as individual modules, small clusters, and low-fidelity simulations. However, this sacrifice will be counterbalanced by the increase in "macro-efficiency" over the entire program, resulting from the ability to standardize the input and output routines of all validation support software. An intermediate approach between a single universal format and a plethora of custom formats would be the definition of a small number of "semi-universal" subset formats: one for vehicle dynamics and environment parameters, one for onboard-system parameters, another for simulator hardware parameters, etc.

Software-development effort and data-base impact will be minimized by the absence of custom data read/write routines for individual modules and module clusters. Finally, data-handling errors will be minimized, both by the standardized arrangement of data on all validation data-files, and by the use of the header record on each data-file.

This universal format concept has been applied with considerable success in the data-reduction programs for the Skylab Earth Resources Experiments Package (EREP) and the Earth Observation Aircraft Program (EOAP). In these programs, users at scattered geographic locations, with widely varying needs for data, benefited greatly from the standardized input/output interface provided by this approach.

Reformatting Data from Existing Software

Even if the universal data format approach is adopted for all new validation software, pre-existing software will have a variety of individual formats. Two approaches are available for integrating these programs into the overall validation system, and making effective use of their reference-data capabilities: build format conversion into the software, or reformat its data-files with a post-processor.

If a copy of the program is under the control of the validation staff, it may be feasible (depending upon the complexity of the program and the completeness of its documentation) to build-in compatible I/O routines. From that point onward, all data generated by the program will be in the universal format.

For programs which are not under the control of the validation staff, or are too difficult to modify, it will be necessary to use a custom-built post-processor to reformat the output from the existing program. Such post-processors will also be required for reference data which already exists in the form of a card, tape or disk file.

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4.11 DATA BASE IMPACT

A large and complex data base will be built up during the simulation development and verification phases. This section discusses the overall organization and structure of this data base, as well as the software, procedures and personnel required for data base management.

4.11.1 Data Base Organization and Structure

Figure 4.11-1 shows in tree form the overall scope and structure of the validation data base. We define the data base to include information in both machine-readable and hard copy form.

4.11.1.1 Machine-Readable Information

Machine-readable information may be in the form of disk or drum storage, magnetic tape, or punched cards. Due to the great differences in costs of the various media, it will be desirable to distinguish between active and inactive data base materials, and keep only the most active in rapid-access storage.

Active Materials

Frequently-used materials which will need to be maintained in on-line storage or convenient-access tape files will include:

- A. Simulation module checkpoint data, for modules currently being validated
(See Sect. 5.1.1.)
- B. Active reference and simulation data:
 - 1. Module level
 - 2. Module "cluster" level
 - 3. All-up simulator
 - 4. Reference trajectories
- C. Active Reference modules
- D. Validation Service routines:
 - 1. Tabulation software
 - 2. Plot software
 - 3. Real-time data acquisition software (see Sect. 5.4)
 - 4. Module and cluster drivers
 - 5. Driver-interface data-location routine (COIGEN or equivalent; see Sect. 5.1.2)
 - 6. Reference-data conversion routines (See Sect. 4.10.2.2)
 - 7. Comparison and evaluation routines (see Sect. 5.5)
- E. Data base management software 4.11-1

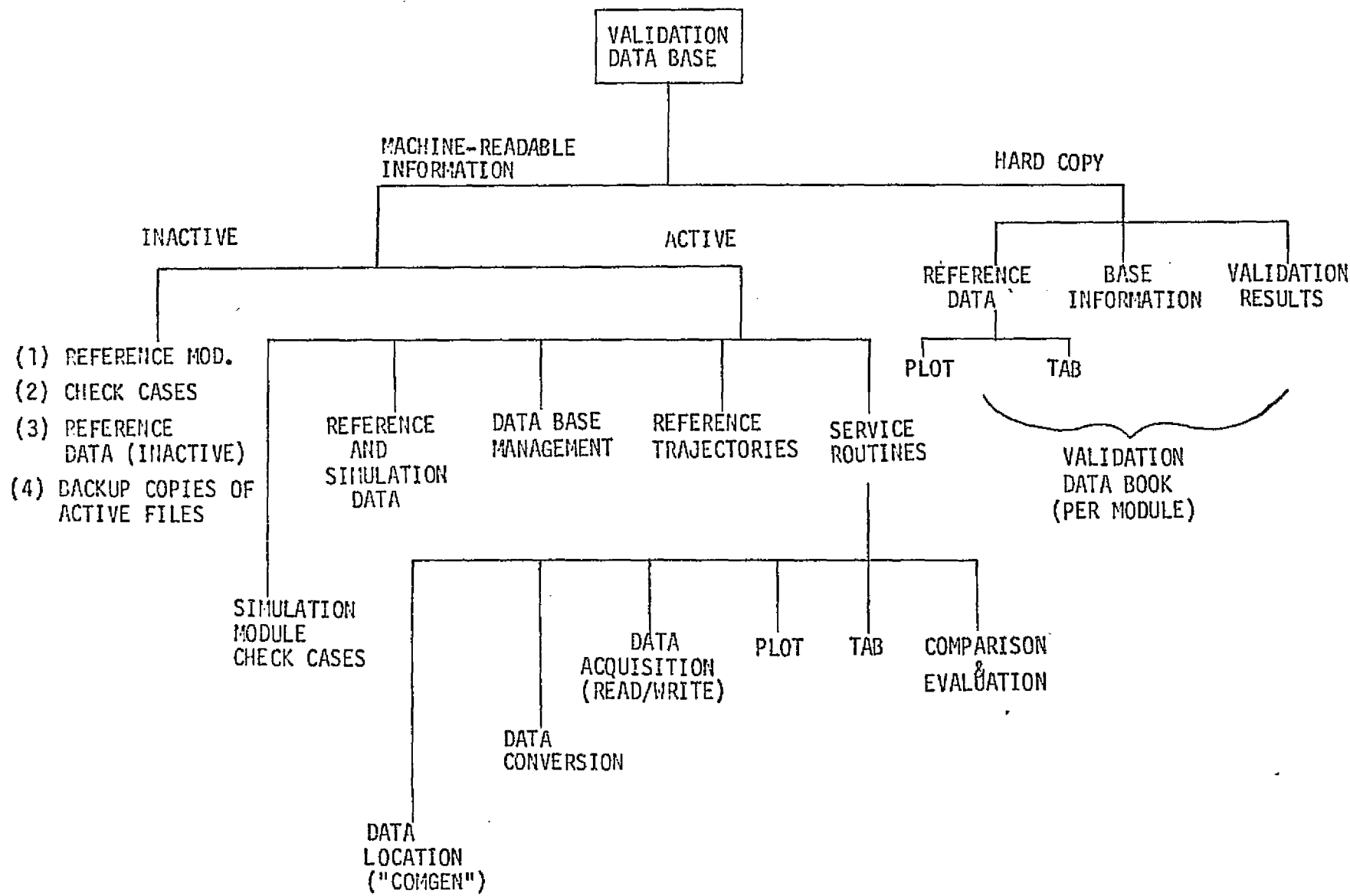


FIGURE 4.11-1. VALIDATION DATA BASE SCOPE AND STRUCTURE

Inactive Materials

Lower-activity materials which can be kept on magnetic tape (or, for low-volume data, on punched cards) include backup copies of currently-active files (for recovery from possible catastrophic failures of the system hardware or software), plus check-case data and reference modules for portions of the simulation which have passed their initial validation. These materials would be retained for potential use in revalidation efforts following later modifications. However, in some cases the modifications will invalidate the existing check-case data and/or dictate modifications to the reference module.

4.11.1.2 Hard Copy

The hard-copy portion of the data base will, like the machine-readable portion, include both active and inactive elements, with similar requirements for access, updating and purging. The hard-copy files will encompass three general categories of information: base information, reference data, and validation results. The most significant information from all three categories would be compiled into a module-organized "validation data book". This data book would serve as a reference for the ongoing staff, for training of new members of the validation staff, and for coordination with other project personnel.

Base information (see Sect. 4.2.2) is information which is not directly usable as validation check cases, but supports the development of check cases and/or software to generate check cases. This includes system descriptions, specifications, operational data books, performance parameter definitions, etc. Sections 4.2 - 4.7 of this report are base information for simulation validation.

Reference data hard copy will include data which is not available in machine-readable form, as well as printouts and plots of machine-readable data made for engineering analysis. This will include all four categories of reference data identified in Sect. 4.2.1 -- closed-form solutions, independent math models, existing analysis/simulation programs, and test data. Recent versions of software listings will also be retained in hard-copy form.

Validation results will be retained in raw form, in informal summary reports covering the validation of individual modules, and in formal validation reports issued at major milestones of the validation process.

4.11.2 Data Base Management

The total Data Base Management System (DBMS) includes the hardware (host computer and peripherals), support software, procedures, personnel, and documentation. Some of the factors to be considered in assessing the magnitude of the data base management problem, and thereby defining the requirements, design, and implementation plans for the DBMS, are as follows:

- o The total amount of data to be handled
- o The complexity of the data structure (i.e., the number of "dimensions" of identification by which a particular data item might be sought by an eventual user)
- o Desired efficiency, in terms of utilization of physical facilities and computer resources
- o Desired efficiency in terms of use of support-personnel resources and user interface
- o Duration of the program over which the data base will have to be maintained (ten years or more)
- o Modularity and extensibility of the DBMS as requirements change
- o Reliability requirements, in terms of probabilities of incorrect filing, retrieving, updating or purging of data
- o Stability of the system -- i.e., freedom from "crashes" and catastrophic loss of data or access capability
- o Data security

A few of these factors are briefly discussed below.

4.11.2.1 DBMS Requirements and Design

Data Dictionary

The design of any DBMS begins with the development of a "data dictionary". Whether the system is manual or automated, dealing with hard-copy or machine-readable data or both, it cannot function effectively without a comprehensive data dictionary. The data dictionary simply defines the standards for identification of data items as they are brought into the system, which in turn tells each user how to identify an item which he is trying to get out of the system.

Dimensions of the identification for an item sought may include: the subsystem of interest, the name of the simulation module for that subsystem, the date or version of the module, the source of the reference data, the name and version of the reference module, identification of the check case(s), identification of a reference mission or mission phase, and the time period of interest during the mission. Standardization of names and formats for these identifiers will be required to formulate data requests in an unambiguous and reliable manner, and allow efficient access to the desired data.

The data dictionary will require frequent updating, especially in the early stages of buildup of the data base. However, the initial definition of the system's data structures and the data dictionary should be made general enough that it will not be necessary to go back later and modify the identifiers for data which has already been filed.

Data Directory

A companion to the data dictionary is the "data directory", which is simply a list of all files and documents existing in the system as of a particular time. The data directory will also require frequent updating, and may eventually become so large as to be difficult to maintain in hard-copy form.

Query and Report Language

The query and report language is the means of interface between the data base and its users and support personnel. A "query" will consist of commands, data identifiers, and data destinations. A "report" may consist of actual hard-copy produced on a line printer or plotter, a display of tabular or graphical data on an on-line terminal, or simply making desired software or data accessible to an application program. Whether formulated in English-like statements or abbreviated numerical codes, whether in batch or on-line mode, user queries will be of forms such as:

"Copy program xxx onto file yyy"

"Copy xxx data-file onto unit yyy"

"Printout xxx data-file in format yyy"

"Get mission xxx; plot parameter yyy against parameter zzz from time t_1 to time t_2 with scale factors s_1 and s_2 "

Data base support personnel will also need to make commands of the forms such as:

"Add program xxx to the system"

"Copy the data on file xxx into the system, with identifiers I_1, I_2, \dots, I_n "

"Delete file xxx"

"Replace file xxx with file yyy"

Data Base Reliability and Stability

The reliability (freedom from error) and stability (freedom from crashes) of the DBMS can obviously be no better than those of the hardware and operating system of the computer in which it resides (along with applications software, simulation software, compilers, etc.). Unless properly designed and implemented, moreover, they are apt to be a good deal worse! It should be clear that the DBMS must be as modular and as well validated as the software it serves, if it is to make a contribution to the solution of the validation problem, rather than be an additional source of problems. Finally, as added insurance from crashes, backup tapes of the data base should be made at intervals.

Data base stability also encompasses the idea of freedom from major redesigns during the lifetime of the program. This is ensured by:

- A. Building sufficient scope and flexibility into the data structure and data dictionary
- B. Modular organization of the data base and the DBMS, and
- C. A phased implementation of the DBMS, enabling detection and correction of potential inadequacies before too great an investment is tied up in the data base.

Data Security

Data security, in the sense of prevention of uncontrolled access to data, may or may not be required in this application, depending upon whether JSC simulators are used to support classified (DoD) missions. Another aspect of data security is the prevention of inadvertant modification or destruction of programs and data by machine error, entry of incorrect codes, etc. CODASYL data base standards (see below) include provisions for both kinds of data security.

The probability of inadvertant destruction of data can be sharply reduced simply by limiting the number of people who are able to enter data-modification commands. That is, data-modification commands should be intercepted by the DBMS unless enabled by appropriate "passwords". These passwords would be known to data base support personnel, but not communicated to any other users of the system.

4.11.2.2 DBMS Implementation

It should be clear from the foregoing discussion that the development of a DBMS to support the development and validation of a large-scale simulator is not only a large task in itself, but is a task quite unlike the development of the simulation software. It requires different personnel capabilities, different computer capabilities, different language properties, and an entirely different conceptual base. For these reasons, we recommend that a thorough and serious "make or buy" analysis be conducted before jumping into the DBMS development.

A wide variety of DBMS software (much of it catalogued in Ref. 114) is available on the open market -- from simple file-management systems costing \$5000 or less to full-scale DBMS/report generators costing upwards of \$200,000. Some of these packages have been proved in years of operating experience at dozens of installations, and are supported by their vendors with on-site installation and training, extensive documentation, periodic updates, and performance guarantees.

If the decision is made to proceed with in-house DBMS development, we recommend that most of the lead personnel assigned to the program have extensive prior experience in data base design and implementation. The remainder of the personnel requirements can be filled by cross-training of simulation types. Any in-house development should also be consistent with CODASYL (Committee on Data System Languages) standards. This will enable the DBMS development to profit from the years of study expended by the CODASYL Data Base Task Group, and provide easier access to the most-current DBMS technology. Table 4.11-1, from Ref. 115, provides a few of the most important definitions of data base concepts, as formulated and standardized by CODASYL.

TABLE 4.11-1. BASIC CODASYL DATA BASE DEFINITIONS

Data Item	The smallest data base unit referenced by an assigned name.
Record	A collection of one or more data items; contains a named description of data items and attributes.
Set	Establishes a named logical relationship between two or more record types; the basic data base building block which allows the data base designer to establish complex data structures.
Area	A named subdivision of logical address space in a data base; each record must reside in an area which contains one or more records.
Schema	A complete description of all data items, record types, set types, and areas which exist in a data base; the foundation of a data base dictionary system.
Subschema	A logical subset of the schema which names only those record types, set types, and areas that are accessed by one or more specific applications programs.
CALC	Refers to one common method of record placement and retrieval within a data base; provides an access point via a "hashing" algorithm.

SECTION 5

METHODS FOR VALIDATING PERFORMANCE

The total process of simulation validation consists of:

1. Exercising a simulation with properly-chosen inputs,
2. Gathering the output performance parameter data which it generates in response to these inputs, and
3. Evaluating the simulation fidelity by comparing these data to reference data representing the real world which the simulation is intended to represent.

Techniques and support software for the efficient performance of these operations are discussed in this section. The discussion includes overall validation software structure, the performance of validation at various levels of simulation integration, guidelines for check case formulation, methods for realtime acquisition and formatting of data from an all-up operational simulator, and methods and criteria for comparison and evaluation of simulation data.

5.1 VALIDATION SOFTWARE STRUCTURE

Figure 5.1-1 depicts a support-software flow for the overall generation, handling, comparison and display of simulation and reference data as used in performance verification. The complete support-software system will consist of the validation executive shown in this figure, modelling routines as discussed in Section 4, and a set of service routines. Table 5.1-1 briefly discusses the role of each part of the overall software system.

To reduce the amount of specialized coding and setup required to perform each individual validation exercise, it is desirable to build as much generality as possible into the service routines. Characteristics of the major routines are briefly discussed in the following subsections.

5.1.1 Checkpoint Generation Routines

Checkpoint generation routines provide a series of check case input values for static and/or dynamic exercise of the reference and simulation modules. The checkpoint generation routines will provide the user with the capability to set up a complete set of check cases in a convenient manner (rather than manually defining and entering the checkpoint data for each individual check case). It will incorporate logic to generate various combinations of discrete parameters, thus exercising various operational modes and logic paths of the software, as well as to vary continuous parameters over various ranges of values, thus verifying the operational envelope of the simulation. The checkpoints may be generated individually on-line, under control of the validation executive, or may be generated all at once and placed on a data file (see Sect. 4.10) for later input.

As discussed in Sect. 5.3, it is generally impractical to exercise a module over all combinations of a set of input values. For example, if a module has eight on/off discrettes used for mode control, 256 check cases will be required to test all possible combinations of these discrettes; if it has six continuous input parameters, 729 check cases would be required to test all combinations of high, nominal and low values of these parameters; and $256 \times 729 = 186,624!$ The checkpoint generation routines must then provide flexible logic to generate only required and meaningful combinations of inputs. Both systematic and random variation of parameters will prove useful in module validation. Examples of checkpoint

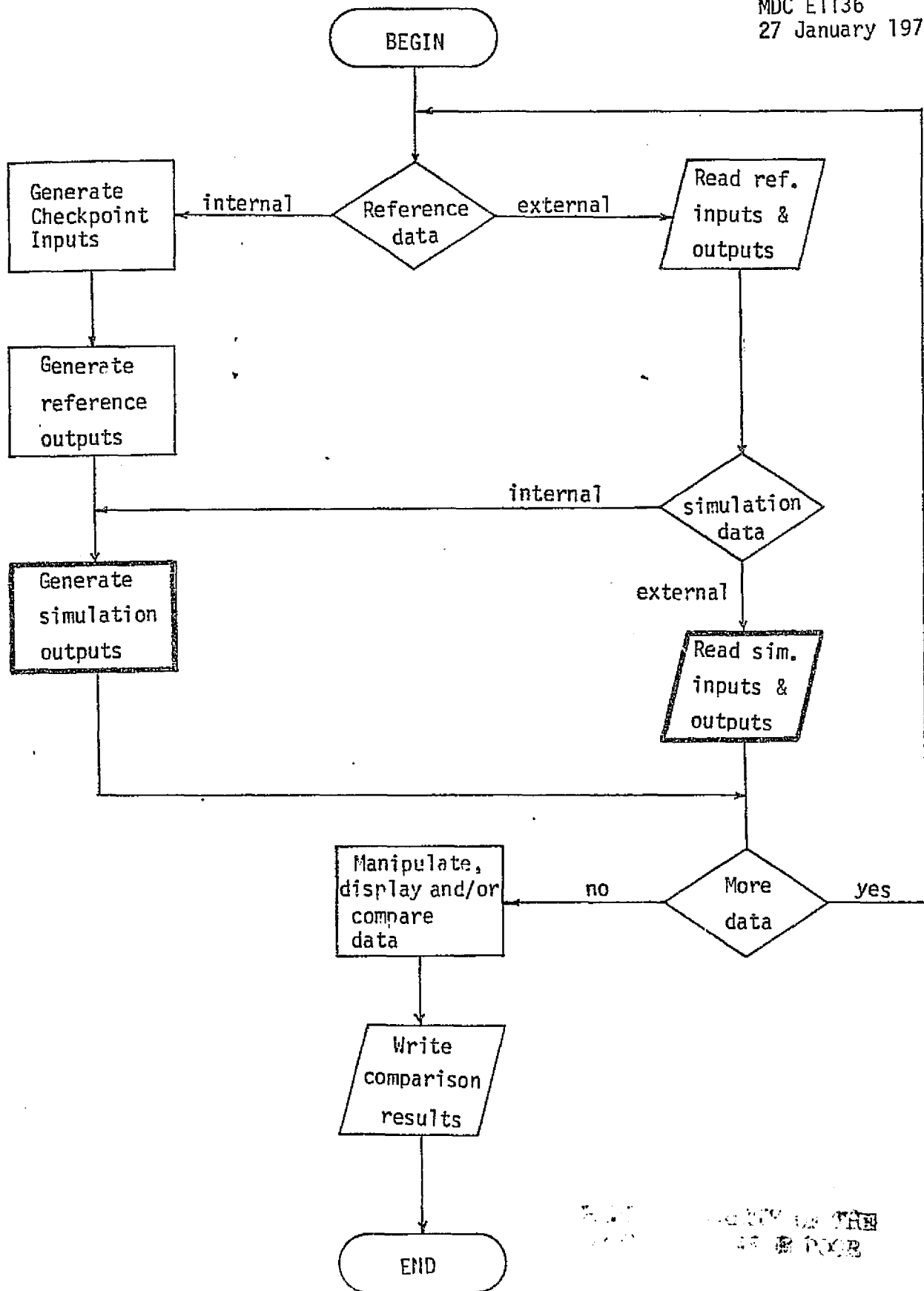


FIGURE 5.1 - 1. BASIC PERFORMANCE-VERIFICATION EXECUTIVE SOFTWARE FLOW

TABLE 5.1-1. VALIDATION SOFTWARE MODULES (GENERIC)

ROUTINE	FUNCTIONS
Executive	Overall sequencing, interfacing and control.
Data read routine	Reads records from a data file generated by a prior simulator performance run, and/or a reference data generation program, strips data for the appropriate module and places it into a data array.
Checkpoint generation routine	Generates checkpoints including all data required for input into the module to be verified.
Simulation module interface routine (driver)	Interfaces with the simulation software module, placing input and output data into a data array.
Reference Module	Generates reference performance parameter data, placing the input and output data into an array compatible with the simulation software data array.
Data write routine	Writes the data from the simulator software module and the reference module onto a temporary file, to be read back in for comparison processing.
Data comparison routine	Processes the data file previously written. Incorporates a variety of differencing techniques and comparison criteria. Performs automated comparisons of simulation and reference data.
Data display routine	Generates listings and plots of raw or processed data for manual interpretation.

generation routines are shown in Figs. 4.3-16 through 4.3-22, 4.7-112 and 4.7-113.

5.1.2 Simulation Software Module Drivers

Driver routines perform an interfacing function (analogous to the "patchboard" in a piece of test hardware). The driver obtains checkpoint inputs from an internal array or an external data file, passes these inputs to the simulation software in the proper order, format, and common locations, accepts outputs generated by the simulation software from their appropriate common locations, and places these values into an output data file for later comparison, evaluation and display.

The normal interfacing method for simulation modules in their eventual operating environment will, in most cases, be by means of a large total-simulation "common" package. Due to the size and complexity of the total simulation, it seems very likely that some type of support software -- COMGEN (Ref. 116) or equivalent -- will be used for development, analysis and maintenance of the simulation common package. Therefore, the same interfacing mode and support software should be used for interfacing of simulation modules with their drivers and other validation service routines. Likewise, the same relative common structure and support software should be used for reference module development, thus providing an additional area of standardization and removing another potential source of error.

5.1.3 External Data Files

In many cases, either the reference or simulation data (rarely, both the reference and simulation data) will be handled as an external data file, rather than being generated on-line during the validation exercise. The validation exercise, in turn, will typically generate a new external data file, consisting of interleaved reference and simulation data vs. time, for post-processing by comparison, evaluation and display routines. Some of these data files will be "volatile" (i. e., discarded soon after processing is complete), while others will be retained in the data base for varying periods of time.

Section 4.10 discusses the generation and formatting of reference data files, either by newly-developed reference modules or by use of existing analysis/simulation programs adapted for validation purposes. Section 5.4 discusses the generation and formatting of simulation data files by realtime acquisition of data from an operational all-up simulator. In both applications, it seems clear that the magnitude of the analysis, development and maintenance efforts will be minimized, and the occurrence of errors in data-handling sharply reduced, by the use of standard or "universal" formats for all data files in the system.

5.2 MODULE INTEGRATION

Simulator validation is performed at various stages of integration during the course of simulator development. This is true whether integration and validation are conducted in "top-down" or "bottom-up" fashion. This section defines four configurations of simulation software linked with validation support software which can be used for the exercises required for performance verification, and discusses the utility of each of these configurations in accomplishing total simulation validation.

5.2.1 Configuration Definitions

Isolated Module

For the present purpose, a "module" is defined as a "set of software elements which is invoked as a unit and performs a defined function." Any single module of simulation software can be verified in isolation by use of a properly-designed "driver" (interface routine) with appropriate static and/or dynamic check cases. To do this, the driver must substitute for all other modules which, in the eventual integrated simulation, will interface with the module under test. That is, the driver must provide all continuous and discrete inputs needed to initialize the module and control its execution, as well as exercise it for performance verification. These inputs must be properly scaled, formatted and routed (by use of argument lists and/or common-storage locations). Similarly, module outputs must be scaled, formatted and routed for storage, manipulation, comparison and/or display.

Integrated "Cluster" of Modules

Two or more naturally interacting modules can be operated together by a single driver, thus providing for each other some of the data, control, and I/O functions which would otherwise have to be provided by the driver. Section 4.8 provides examples of natural clusters of modules. The limiting case of cluster testing is off-line (non-realtime) operation of the total software system without its simulator hardware interfaces.

The exercise of an integrated cluster could conceivably be the initial validation for all of the modules in the cluster; more commonly, however, some or all of the modules will have previously been individually validated more or less

thoroughly, either in isolation or as part of a different cluster.

Figure 5.2-1 provides examples of dynamical check cases (step-input responses) which could be run on a cluster consisting of aerodynamics, vehicle dynamics and environment, together with an appropriate driver.

Modified All-Up Simulator

During initial integration of the simulator software and hardware into an operable all-up simulation, temporary modifications can be made for verification purposes. Two types of modifications are considered:

- Emplacement of "probes" or "test points" for insertion of stimuli and/or tapping of responses at points which would not normally be accessible via standard output.
- Interruption of normal signal flow within the simulation system, to artificially decouple various interacting functions (e.g., the aerodynamics from the equations of motion) and thus simplify signal/error propagation characteristics.

The first approach is used, for example, at NASA-LRC; control commands from a "canned man" (a data tape) are inserted downstream of the manual controls. This ensures check case repeatability and objective evaluation of simulation performance. Both approaches are to be used in the acceptance testing of the USAF F-15 simulator now being developed under the aegis of McDonnell Aircraft Company.

Interrupted signal flows must of course be reconnected to return the simulator to normal operation. Certain of the test points, however, might profitably be left in place permanently, for convenience in reverification efforts following later modifications.

Normal All-Up Simulator

The complete man-in-loop simulator, in its normal operating configuration, can be exercised by check cases of two different kinds:

- Specially-constructed test cases (not necessarily representing any anticipated real-world mission or mission phase), providing rigorous exercise of the simulation, high repeatability, and easy interpretability of results.

MACH = XXX
WEIGHT = XXX
CG = XXX
 δ_e = XXX

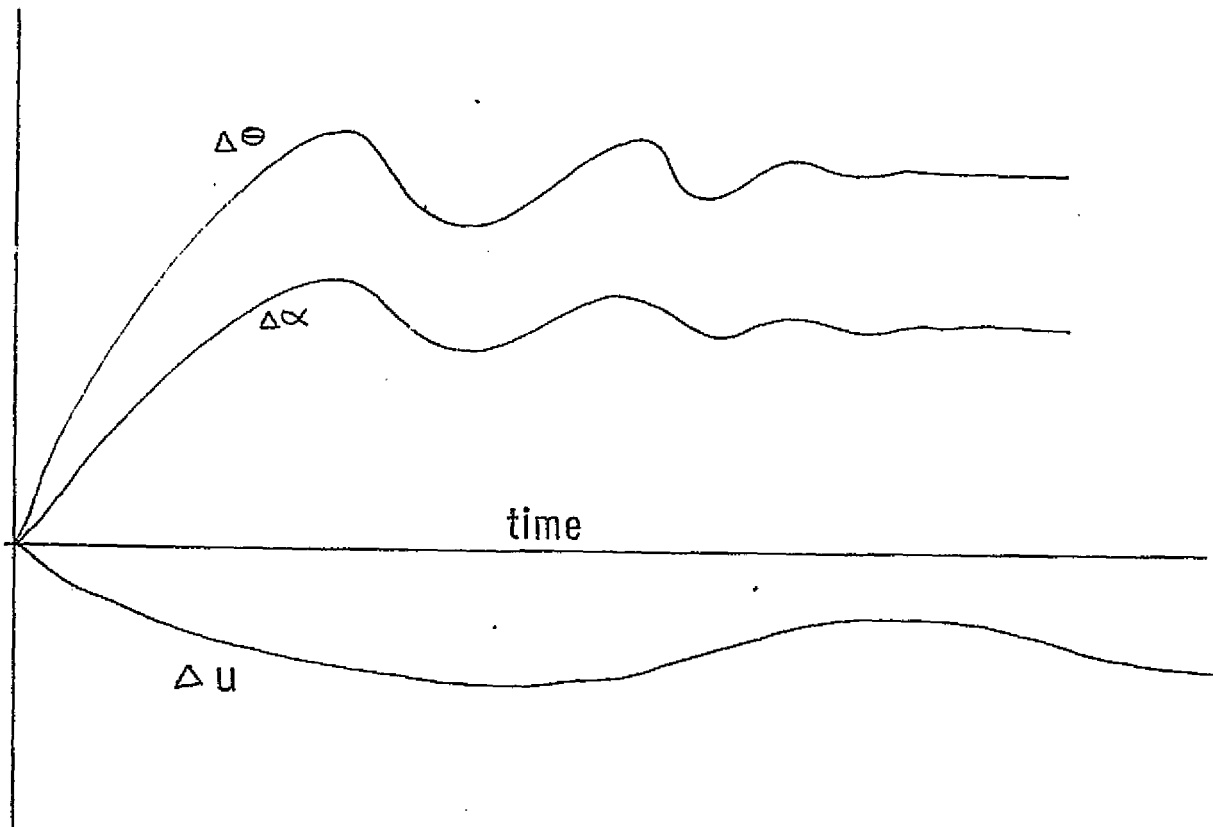


FIGURE 5.2-1. EXAMPLE CHECK CASES FOR A SMALL CLUSTER OF MODULES.

- Realistic mission/mission phase check cases; e.g., a reference mission, an anticipated future mission, or a re-enactment of a previous mission.

5.2.2 Pros and Cons of Defined Configurations

The four test configurations just described are often considered as the normal evolutionary stages in validation of simulators; every module would be expected to pass through all four states in turn. It is also often assumed that a "complete" verification of all possible functions is performed at each stage, before proceeding to the next. Thus, isolated-module configurations would be used to verify all functions of individual modules, so that when they were integrated into clusters, all that would remain to be verified would be their relative interfaces and interactions. This is the traditional "bottom-up" integration/validation methodology.

Recent advances in software-development methodology, particularly an increasing emphasis upon "top-down" testing, make it appropriate to question these conventional assumptions, and to consider whether, for some modules, it may be reasonable to de-emphasize isolated-module validation in favor of validation at a higher level of integration. Table 5.2-1 provides an objective look at the capabilities and limitations of validation exercises performed at each of the above-defined levels of integration. These considerations are essential to any effort to allocate overall simulation validation effort.

TABLE 5.2-1. CONSIDERATIONS RELEVANT TO PERFORMING VALIDATION AT VARIOUS LEVELS OF INTEGRATION

VALIDATION CONFIGURATION	PRIMARY OBJECTIVE	ADVANTAGES	DISADVANTAGES
Isolated Module (software only)	To Validate Detailed Simulation Capabilities of each Module	Easiest to devise check cases for which correct answers are known exactly. Easiest to fault-isolate following check-case failure ^a . Easiest to ensure thorough exercise of module. Can be executed offline (batch runs).	Generation of each driver represents extra coding and debugging effort. (Development of "general-purpose" drivers will reduce the cumulative effort, but some tailoring of the driver to each module under test will still be necessary.) For "trivially" simple modules, the validation benefits may not be commensurate with the effort of building the driver and setting up and executing the check cases. Does not explicitly verify module-to-module interfaces.
Integrated Cluster of Modules (software only)	To Validate Interfaces Among Highly-Interactive Modules	Driver can be simplified, because some required data is supplied by modules in the cluster. Less cumulative coding and debugging effort devoted to generation of drivers; a single driver serves validation of multiple modules. All exercises are "non-trivial". Verifies some module-to-module linkage. Can be executed offline (batch runs).	May be difficult to thoroughly exercise and validate all modules in the cluster. May sometimes be difficult to devise test cases for which correct answers are known exactly. May sometimes be difficult to fault-isolate following check-case failure ^a .
Modified all-up Simulator (hardware and software)	To Simplify Signal Error Propagation for System-Level Validation	No coding and debugging of drivers. Allows extensive verification of module-to-module linkage.	May be a complex, laborious process to modify and restore simulation, and to set up for check-case execution. Potential for later difficulties if all modifications are not restored to normal configuration. Requires realtime operation of dedicated system. Difficult to know correct answers for all variables which will be exercised by each check case. Difficult to fault-isolate following check-case failure ^a . Few individual simulation modules will be thoroughly exercised. Difficult to obtain repeatable results from man-in-loop operation.
Normal all-up simulator (hardware and software)	To Validate Dynamic Adequacy of Total Simulator System	No coding and debugging of drivers. Allows complete verification of hardware and software interfaces. Successful operation builds confidence in complete simulator system. Contributes to simulator acceptance ^a .	May be a complex, laborious process to set up simulator for check-case execution. Requires realtime operation of dedicated system. Difficult to know correct answers for all variables exercised by each check case. Very difficult to fault-isolate following check-case failure ^a . Few individual simulation modules will be thoroughly exercised. Difficult to obtain repeatable results from man-in-loop operation.

^aNot explicitly in the scope of this study.

5.3 CHECK CASE FORMULATION

This section deals with the problem of providing a thorough validation exercise of a simulation in an efficient manner. Thoroughness is essential to provide high confidence that the simulation will function properly over its entire range of operation, and for long periods of time. Efficiency is essential because the simulation is large and complex, and validation will require large expenditures of computer and personnel resources.

The topics covered in this section are check case design principles, application of these principles to initial validation of modules and integrated simulations, and application to revalidation of modules and integrated simulations. Interestingly enough, the same principles lead to diametrically opposite approaches for initial validation vs. revalidation.

5.3.1 Check Case Design Principles

Criteria for selection/construction of a set of check cases include thoroughness, efficiency, and order of execution; implementation methods include manual selection, complete and incomplete factorial designs, orthogonal designs, and random (Monte Carlo) variation of parameters.

5.3.1.1 Thoroughness

It is convenient to visualize the operational range of a particular simulation as a "parameter space" -- the range of values which its input parameters (including time) are allowed to assume. The process of validation exercise then consists of supplying check case inputs which "sweep out" the parameter space over a broad enough range and at a close enough spacing that we become confident that the simulation will perform properly when given any input lying in that space. Discrete and continuous regions of the parameter space must be considered separately.

Discrete regions of parameter space arise when a simulation has internal logical breaks which result in different modes of operation for different values of its input parameters. These internal logical breaks may be activated either by input of discrete variables (failure flags, switch settings, etc.), or by input of continuous variables whose values cross over certain breakpoints in the logic (e. g., altitude ranges in an atmosphere routine, mach-number ranges in aerodynamic tables).

The range of variation of continuous input parameters should reflect the spectrum of missions for which the simulator will be used, including nominal, off-nominal, failure and abort cases. Within the simulation module, variation of the values of its continuous input parameters may result in variations in amplitude, frequency, linearity, or other attributes of its response in a smoothly-varying manner, rather than by discrete switching between modes of response.

5.3.1.2 Efficiency

Efficiency in this context refers to minimizing to the expenditure of computer and personnel resources needed to attain a certain level of confidence in the fidelity of the simulation over its entire operational range. Efficiency can be gained in two ways:

- o By minimizing the total number of check cases needed to attain a given level of confidence, and
- o By minimizing the resources needed to generate, execute, and interpret each individual check case.

The second approach is discussed in other sections of this report.

A useful viewpoint for attacking the minimization of the number of check cases is the economic concept of "marginal utility". The marginal utility of a check case is the increase in confidence derived if it executes successfully, or the diagnostic information derived if it fails. To maximize the marginal utility of each check case, it is necessary to minimize inter-case redundancy. That is, each additional check case must be made sufficiently different (in a meaningful way) from previously-executed check cases that it provides new information about the module performance, rather than just reconfirming what has already been demonstrated.

Although in practical cases it is difficult to quantify the marginal utility of a check case (or even to quantify the current level of confidence in the simulation), even an intuitive understanding of the concept will help to prevent over-validation in some regimes of operation at the expense of under-validation in other regimes of equal importance. In conducting parametric studies resulting in performance curves, for example (see Sect. 4.9.2.2), the

input points should be spaced just closely enough to define the shape of the curve, as predicted from preliminary analysis or test data -- not necessarily closely enough to draw a smooth curve starting from scratch.

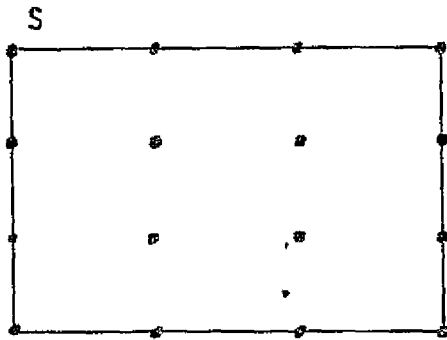
5.3.1.3 Order of Execution

Obviously, the marginal value of a particular check case depends not only upon the properties of that check case itself, but also upon the check cases which have previously been executed. To define an "optimum" ordering of check cases, it is helpful to consider what will be known, and what decision will result, if each check case passes, or if it fails. The cost of that decision or state of knowledge is then the cumulative cost of all check cases which have been executed up to that point. This viewpoint has different implications for initial validation and revalidation.

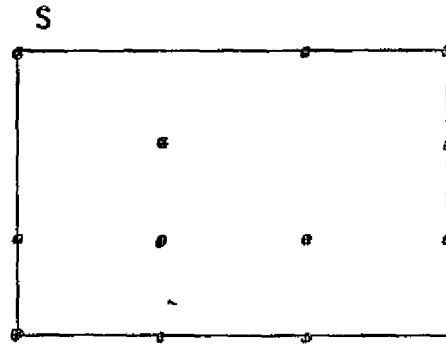
5.3.1.4 Basic Check Case Selection/Construction Methods

Four basic methods of constructing sampling points in a parameter space are the complete factorial, incomplete factorial, orthogonal, and random methods. These four methods are shown for two-dimensional space in Fig. 5.3-1; however, it is important to realize that the parameter spaces in simulation validation will be many-dimensional.

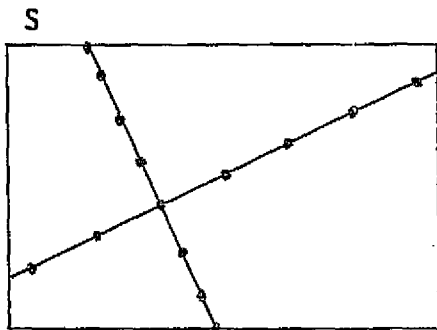
In a complete-factorial parameter-variation scheme, every possible combination of parameter values (for a fixed spacing in each dimension) occurs exactly once. Thus, the checkpoints define a more or less closely-spaced grid spanning the parameter space. As the number of dimensions increases, the number of checkpoints increases explosively. For example (see Sect. 5.1.1), running all combinations of low, nominal and high values for six continuous parameters, and all combinations of on/off values for eight discrettes will require 186,624 checkpoints. In an incomplete-factorial scheme, the checkpoints still lie on a grid, but some of the grid points are void. Although every individual parameter takes on every possible value (for the given grid spacing) at least once, many possible combinations of values do not occur.



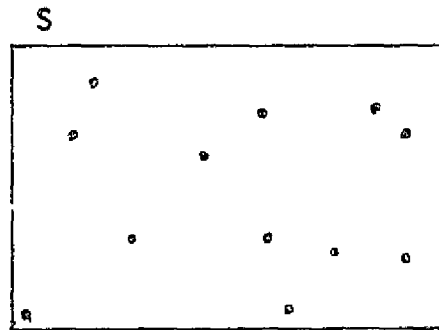
(a) Complete Factorial



(b) Incomplete factorial



(c) Orthogonal lines



(d) Random

FIGURE 5.3-1 TWO-DIMENSIONAL ILLUSTRATIONS OF FOUR METHODS OF CHECKPOINT GENERATION

(RECTANGLE REPRESENTS PARAMETER SPACE, S.)

The orthogonal-line method is a further extension of the incomplete factorial concept. Here all checkpoints lie on perpendicular lines, extending out to the boundaries of the parameter space. The orthogonality of the lines tends to achieve the goal of maximizing the difference between checkpoints, and the limitation to these lines sharply reduces the total number of check cases, as compared to factorial schemes. If the lines are skewed relative to the coordinate axes of the parameter space, the basic benefit of the factorial schemes -- the use of combinations of parameter variations -- is retained.

Random or Monte Carlo variation of input parameters is inefficient for parameter spaces of few dimensions, but research in optimization methods has shown that the relative efficiency of Monte Carlo methods improves as the dimensionality of the problem increases (Ref. 117). Historically, Monte Carlo methods have been of greatest value in attacking complex problems which proved impractical to solve by more systematic methods (Ref. 118). The checkpoints may be generated by a uniform distribution (i. e., with equal probability of falling anywhere in the parameter space), or may be distributed more densely either in the nominal operating regime or near the extremes, whichever is desired.

All of the above-described methods are suitable for implementation in automatic checkpoint-generation routines. Check cases may also be generated manually, either using one of these basic methods, or based upon the analyst's intuitive understanding of the system and its simulation requirements, and a "feel" for what choices of input parameter values will provide the most information about the simulation fidelity.

5.3.2 Check Cases for Initial Validation

Check case ordering is an important aspect of initial-validation strategy, both for modules and integrated simulations. The ordering of check cases for initial validation should result in a more-or-less gradual process of expanding the envelope (by analogy to hardware testing and vehicle flight testing). This is based upon a pessimistic initial assumption (since nothing has yet been proven about the module's capability) that, for some or all of its required operational range, the simulation will fail to perform satisfactorily. When it does fail, it must be fixed, and some or all of the previously-executed check cases repeated. Therefore, we would like to minimize the resources expended up to the point of

failure. Figure 5.3-2 depicts, in general terms, the relationship between objective confidence level and the number of check cases executed, for initial simulation validation.

5.3.2.1 Initial Validation of Individual Modules

The first check case(s) presented to an individual module should verify some minimal operational capability -- the simplest logical flow, most linear regime, etc. (Again by analogy to hardware testing, this is sometimes called a "smoke test" (Ref. 119); "plug it in and see if it smokes.") Successive cases become increasingly more rigorous, until the complete envelope has been attained.

The output data density also varies during the course of module validation. Most or all of the performance parameters would be output in the early stages, gradually scaling down to just the critical performance parameters as validation progresses successfully. Failed check cases would probably be rerun with more complete output for diagnostic purposes.

5.3.2.2 Initial Validation of Integrated Simulations

At all stages of simulation integration (see Sects. 4.8, 5.2), the operational modes of the individual modules, as well as the types and values of inputs they receive, are determined basically by the overall mission phase and vehicle operational mode. Therefore, integrated-simulation check cases should be mission-oriented sequences.

The process of envelope expansion in this context will consist of execution of longer, more complete, and more rigorous mission segments. Starting with a "mini-phase" or mission-phase segment, well within the nominal operational regime, the duration would be extended out to include a complete mission phase, at the same time that the forcing parameters -- trajectory parameters, failures, etc. -- are made more extreme. When operational capability has been verified for mission phases individually, the capability to progress from one phase to another, and from nominal operation to abort modes, should then be verified.

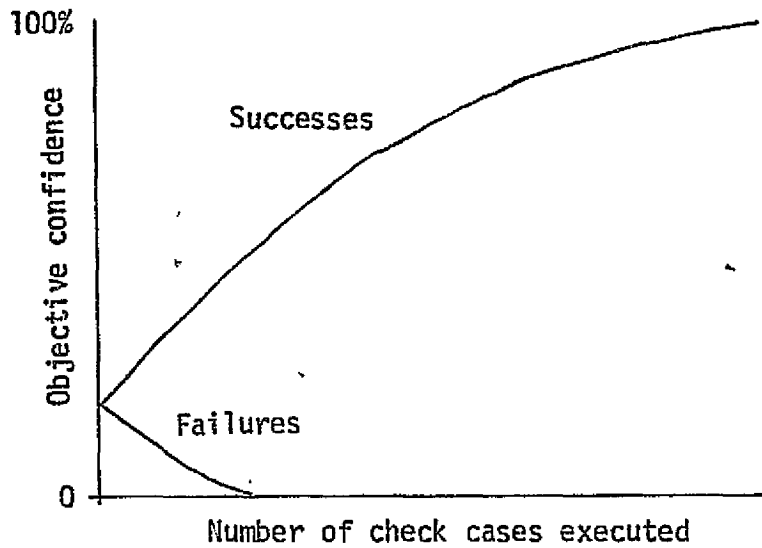


FIGURE 5.3-2. CONFIDENCE RELATIONSHIPS FOR INITIAL VALIDATION

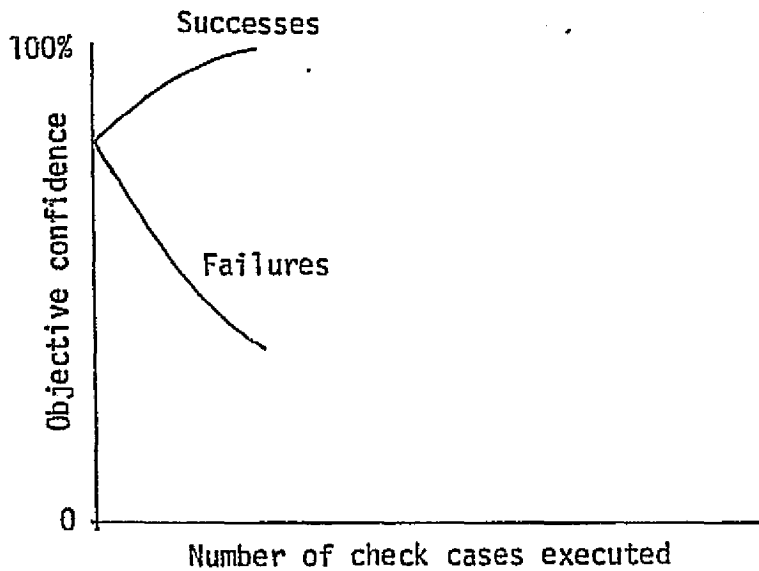


FIGURE 5.3-3. CONFIDENCE RELATIONSHIPS FOR REVALIDATION

Most integrated-simulation validation will be based upon output of critical parameters only. For diagnostic purposes in the event of check-case failure, complete performance parameter output from suspect areas may be obtained. However, complete output of all performance parameters of the simulation may not be possible within realtime constraints (see Sect. 5.4). In any event, a powerful data-handling system will be required to make effective use of so much data.

5.3.3 Check Cases for Revalidation

By contrast to the initial validation problem, revalidation strategy should be based upon the optimistic assumption (due to prior successful experience with the simulation before it was modified) that it will perform satisfactorily over its required operational range. Therefore, revalidation is treated as a process of envelope contraction. The process is started by executing a small set of check cases (ideally, a single check case) which, if successful, will verify both the nominal and extreme operational capability.

If the initial test results in one or more failures, progressively less rigorous exercises are performed, until the root of the failure is uncovered. Figure 5.3-3 depicts the relationship between objective confidence level and the number of check cases executed, for simulation revalidation.

The data density is low for the initial test (critical performance parameters only), and increased only for diagnostic purposes in the event of failure. Check case "failure," of course, may be due to improper implementation of the simulation modification, or may simply mean that the old check case (retained in the data base) has been invalidated by the modification.

5.3.3.1 Module Revalidation Check Cases

The initial check case for revalidation of a simulation module should be a fairly long time-sequence of discrete and continuous inputs which forces the module to select all of its operational modes, perform in its nominal operational regime, and operate out to its specification limits.

5.3.3.2 Integrated Simulation Revalidation Check Cases

Depending upon the magnitude and type of modification made, revalidation check cases for the integrated simulation may be either complete mission phases or a short but complete end-to-end mission (either a once-around mission or a return-to-launch-site abort). Table 5.3-1 suggests the scope of potential mission/mission phase check cases for revalidation.

Each such check case should provide a rigorous exercise of the all-up system, in terms of trajectory parameters, maneuvers, visual and motion-base exercise and synchronization, etc. Manual inputs, such as stick motions and switch settings, should be provided by a "canned man" (a pre-recorded data file) for check case repeatability. For rapid and accurate evaluation, the maneuver sequences should result in easily-recognizable decision points -- out-the-window views, insertion, touchdown, stopping point on runway, etc.

As with all integrated-simulation operations, validation outputs should be limited to the critical performance parameters.

TABLE 5.3-1. SUMMARY OF MISSION/MISSION PHASE CHECK CASES.

MISSION/MISSION PHASE	DESCRIPTION	TYPICAL PERFORMANCE PARAMETERS
• LAUNCH TO TOUCHDOWN	• TOTAL SPACE MISSION WHICH INCLUDES ASCENT, ONE ORBIT REVOLUTION, ENTRY, TAEM AND AUTOLAND	• ATTITUDES AND RATES, ALTITUDE, MACH NO., RANGE, RANGE RATE, ANGLE-OF-ATTACK.
• ASCENT	• FLIGHT IN THE ATMOSPHERE POWERED BY BOOSTER SOLID ROCKET MOTORS AND ORBITER MAIN PROPULSION TO ORBIT INSERTION.	• ATTITUDES AND RATES; ALTITUDE AND ALTITUDE RATE, DOWNRANGE, SLANT RANGE, VEHICLE VELOCITY.
• ON-ORBIT	• CIRCULAR OR ELLIPTICAL EARTH ORBIT WHICH CAN INCLUDE ANY ONE, ALL OR NONE OF THE ON-ORBIT MANEUVERS	• ATTITUDES AND RATES; ORBITAL VELOCITY & ALTITUDE, PROPELLANT USAGE
- RENDEZVOUS	- PHASE WHICH BEGINS WITH FIRST CATCH-UP MANEUVER AFTER INSERTION AND CONTINUES THROUGH BRAKING AND DOCKING	• TARGET EPHEMERIS, RENDEZVOUS TIME, RANGE, RANGE RATE AND ELEVATION ANGLE
- STATIONKEEPING	- INSPECTION OR WAIT PERIOD IN THE VICINITY OF THE TARGET VEHICLE	• RANGE, RANGE RATE, LINE-OF-SIGHT RATES
- PAYLOAD HANDLING	- DEPLOYMENT AND RETRIEVAL PROCEDURES FOR ON-ORBIT PAYLOADS	• PAYLOAD ATTITUDE, RANGE, RANGE RATE, PAYLOAD SUBSYSTEM PARAMETERS
• ENTRY	• PORTION OF THE ORBITER FLIGHT WHICH INCLUDES THE DEORBIT MANEUVER THROUGH THE START OF THE SUBSONIC FLIGHT REGION.	• ANGLE-OF-ATTACK, RANGE, RANGE RATE, MACH NO., ALTITUDE DYNAMIC, PRESSURE, AERODYNAMIC HEATING RATES.
• TAEM	• THAT PHASE OF THE ORBITER'S REENTRY TRAJECTORY WHICH STARTS WITH THE SUBSONIC FLIGHT REGION AND CONTINUES TO FINAL APPROACH.	• ANGLE-OF-ATTACK, BANK ANGLE, SPEED BRAKE POSITION, MACH NO., ALTITUDE, HEADING, RANGE.
• AUTOLAND	• MISSION PHASE BEGINNING WITH THE FINAL APPROACH AND CONTINUING THROUGH LANDING, ROLLOUT AND BRAKING.	• ALTITUDE, SINK RATE, GLIDE SLOPE ERROR, LOCALIZER ERROR, PITCH, ROLL, YAW AND CORRESPONDING RATES.
• FERRY	• TOTAL AEROFLIGHT MISSION WHICH INCLUDES TAKEOFF, CRUISE, APPROACH, MANUAL LANDING, ROLLOUT AND BRAKING.	• ANGLE-OF-ATTACK, ALTITUDE, MACH NO., PITCH, ROLL, YAW & CORRESPONDING RATES, FLIGHT PATH ANGLE.

5.3-10

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27 January 1975

5.4 REALTIME DATA ACQUISITION AND FORMATTING

This section discusses requirements and techniques for realtime acquisition of performance parameter data from an operational all-up spacecraft simulator. Although such data may be used for on-line manual monitoring or "quick look" assessment of simulation performance, the basic purpose of the data is for validation post-processing.

Reference 120 describes a similar application of realtime data acquisition on the Shuttle Procedures Simulator, undertaken in support of the Crew Procedures Development Techniques Study performed at NASA-JSC.

5.4.1 Data Acquisition Requirements, Goals and Constraints

The basic purpose of the realtime data acquisition subsystem is to build a properly-formatted data file of time-tagged data -- flight crew inputs and simulation performance parameters -- for later processing by validation service routines. As a secondary function, it may be desirable to provide summary instructor/operator station CRT displays for on-line monitoring of the most critical aspects of simulation performance, or for "quick look" assessment of simulation performance immediately after a simulator run.

Since the data may be intended for use in initial validation, revalidation, or problem diagnosis, the data acquisition subsystem must provide capabilities for convenient variation of data density, both in terms of the number of parameters recorded and the sampling frequency; see Sect. 5.3. The data file must be formatted in a manner consistent with other validation data files (see Sect. 4.10); that is, in time-tagged "pages" or "frames" of data of standardized arrangement and format, preceded by a header frame of standardized type, and ending with a standard end-of-file flag.

The data acquisition subsystem must be properly synchronized with the realtime simulation executive, such that all data recorded in a particular frame is actually updated as of the time shown in that frame. It must have access to all simulation data common-storage areas, and appropriate data buffers and I/O channels. Most importantly, the data acquisition system must not interfere with realtime simulator operation, either by pre-empting required main storage or by preventing the simulation from keeping up with real time.

5.4.2 Data Acquisition Subsystem Design and Implementation

Overall control, storage, and input/output relationships for the realtime data acquisition subsystem are sketched in Fig. 5.4.-1.

5.4.2.1 Data Acquisition Control Module

The control module performs interfacing and synchronization with the simulation, and controls buffering, manipulation and transfer of data to the output file. Prior to the start of the simulation run, the control module performs the following initialization functions:

- (a) Accepts inputs defining the desired data density (number of output parameters and sampling frequency), and instructions for formatting the individual parameter values and mapping them onto the output data frames. This information is then written onto the data-file header block (see Sect. 4.10).
- (b) Establishes linkages to the simulation common-storage blocks. This would probably be achieved by use of the same basic common package support software used for the simulation (COMGEN or equivalent; see Sect. 5.1.2).
- (c) Establishes linkages to the buffer areas and input/output channels provided. This would normally be controlled by the host computer operating system.

5.4.2.2 Operational Interface with Realtime Simulation

Upon receipt of each "transfer enable" discrete from the simulation executive, the data acquisition control module accesses the desired parameter values from common storage, and loads them into the buffer area. It may also be necessary to pick up certain hardware-related variables (e. g., switch settings, visual and motion-system parameters) from simulator I/O channels. Depending upon the update cycle of the simulation software, multiple transfers may be necessary to acquire all of the data required for a particular frame.

To prevent data acquisition from interfering with simulator realtime operation, it may be necessary to restrict the size of the data acquisition software and its associated buffers to conserve main storage, and/or to restrict the data-density to conserve execution time. During execution, the priority of the data acquisition function must be set low enough that data-acquisition operations can be deferred or interrupted in the event that the simulation threatens to lose synchronization with real time. This would lead to "dropouts" on the data file, and some compromise of its usefulness for validation. Such occurrences should be flagged by the control module.

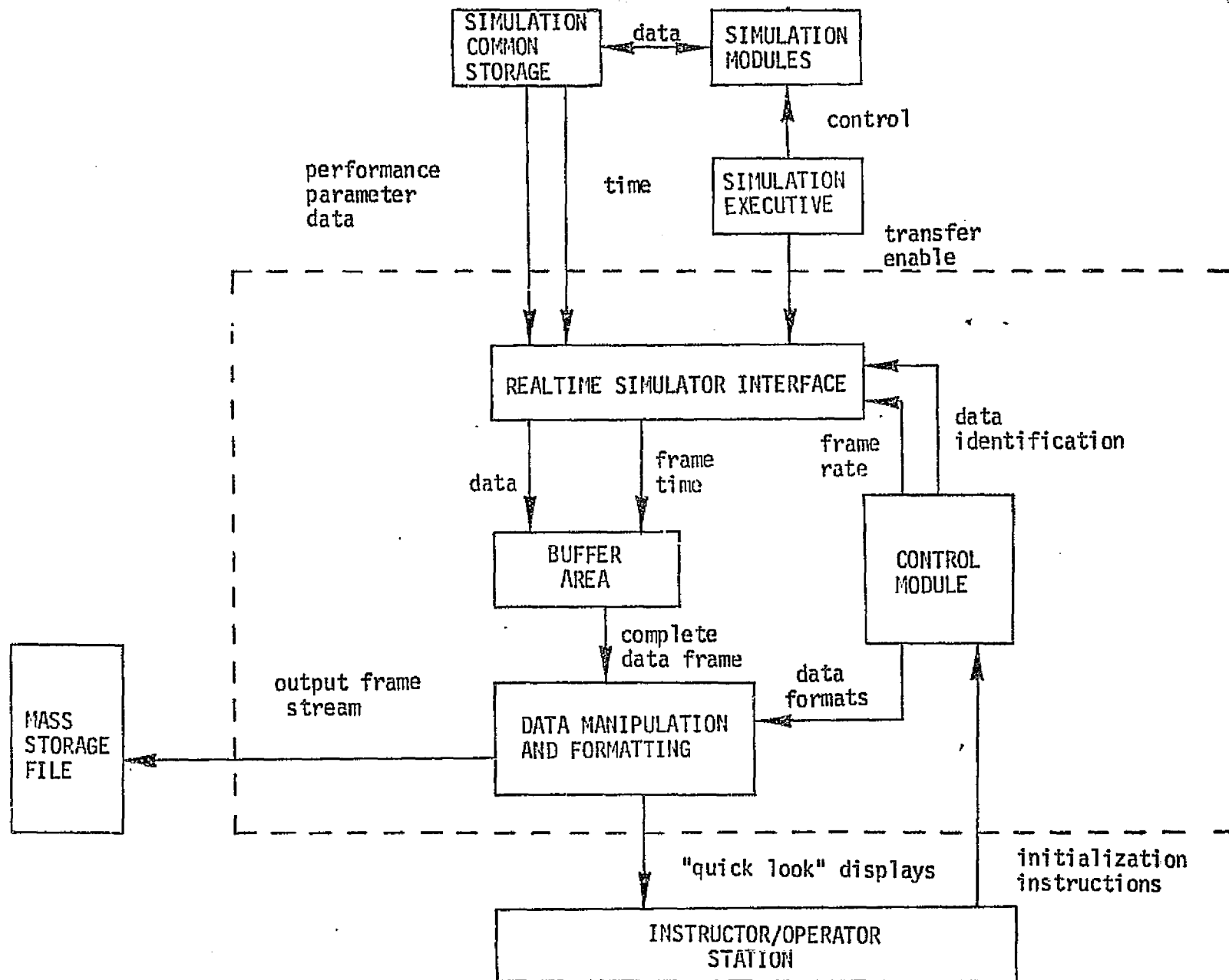


FIGURE 5.4-1 REALTIME DATA ACQUISITION SUBSYSTEM FUNCTIONAL ELEMENTS AND INTERFACES

5.4.2.3 Data Buffering

A buffer area in main storage must be provided to hold newly-acquired data while it is manipulated for formatting and output. This buffer area must be large enough to hold a complete frame at one time, since output will be in terms of complete frames.

5.4.2.4 Data Manipulation

Using the instructions loaded at initialization time, the data acquisition software will take data from the buffer area, format it for output or display, and transfer it out on the appropriate output channel. In its primary operational mode, generation of a data file for validation post-processing, the formatting operations will consist of:

- o formatting of individual data items (scaling, fixed-point and floating-point formatting, packing, etc.), and
- o frame generation (ordering outputs for the current frame, multiplexing, etc.)

If secondary capabilities for realtime display are implemented, the selected parameters from the buffer area will also be put out onto tabular CRT displays at selected update rates (consistent with human reading-speed limitations). Display updates could be performed at fixed intervals, on the basis of the amount of change in the parameters of interest, or upon the occurrence of certain discrete events. Realtime graphical displays may also be provided, if sufficient computational time is available. Quick-look graphical displays could easily be generated when the simulator is in "hold" mode.

5.5 COMPARISON METHODS AND CRITERIA

When the reference data and simulation data for a particular check case or set of check cases are both available in machine-readable, compatible form, the comparison and evaluation may be implemented in either of two ways:

- (a) Use the validation support software to display the reference and simulation data in a form designed to enhance the ease and reliability of manual comparison and evaluation.
- (b) Perform automatic comparison and evaluation within the validation support software.

Automated comparison/evaluation is desirable on grounds of accuracy, internal consistency, speed, and of course, cost. To be useful, however, it is essential that automated comparison/evaluation methods give results which are consistent with the subjective judgement of experienced simulation engineers.

Whether the comparison is performed manually or automatically, the level of fidelity which is considered acceptable will vary for different modules, and for different operational ranges and modes of a single module. For all modules, the criteria for acceptability will become more demanding as a function of time, as the vehicle, subsystems and environment become better defined, and higher-confidence reference data becomes available.

Whenever the fidelity of a particular module is judged to be unacceptable, the normal response of the simulation staff would be to attempt to obtain acceptable fidelity by tinkering with the "characteristic parameters" (gains, time constants, and other coefficients) of the simulation module, before attempting a basic redesign of the module. Although such techniques are not strictly within the scope of this study, they are briefly discussed both for manual and automated comparison methods.

5.5.1 Display Methods for Manual Comparison

The validation support software must provide a variety of tabulation, plotting and processing capabilities to present the reference and simulation data in formats enabling efficient manual comparison and evaluation.

5.5.1.1 Tabular Displays

Tabular displays, although ineffective for time-history data, are useful for highly accurate single-point comparisons of reference and simulation data; for example:

- The times at which certain discrete events occurred.
- Vehicle state variables at the end of a particular mission phase or maneuver sequence -- ascent, rendezvous, etc.
- Summary or end-point variables, such as consumables.
- Fixed-time comparison of matching variables from replicated modules, such as IMU gimbal angles or bus voltages.

5.5.1.2 Raw-Data Plots

The most useful presentation for manual comparison/evaluation will be time-history over plots of reference and simulation data on the same axes, as shown in Figure 5.5-1. This plot is scaled to give maximum resolution for the available picture area, which results in uneven scale parameters. If ease of interpolation or intercomparison of various plots in a set of data were desired, it would be necessary to use preassigned scale factors. The support software must therefore offer a variety of formatting and scaling capabilities, including logarithmic scaling for parameters of broad dynamic range (e.g., atmospheric density).

Interpretation of time-history plots to modify module parameters for a better match will require consideration of individual attributes of the response, such as initial mismatch, oscillation frequency, damping, phase error, and steady-state error. The subjective "weighting" assigned to the various attributes of the simulation response will depend upon the context. For example, if the parameter is to be integrated, steady-state error might be most important; but in a motion-base or visual system, the initial response would be most important as a source of cues to the pilot.

Depending upon the familiarity and complexity of the system, it may be fairly obvious which parameters should be changed to improve each attribute of the response, or considerable experimentation may be required. This type of experimentation is best done on via on-line graphic-display terminals (which were used with considerable success in the DC-10 performance monitor development program).

5.5-3

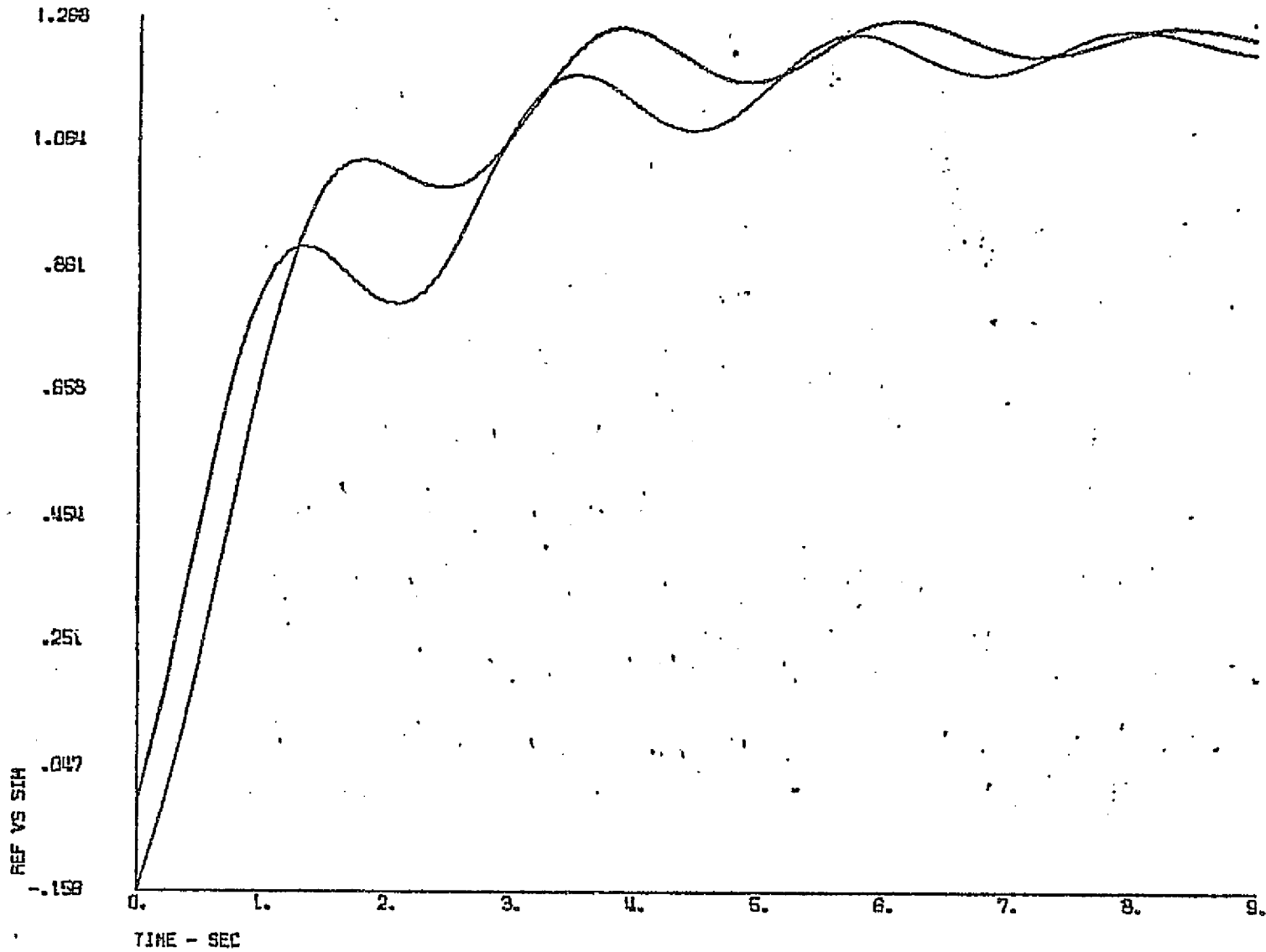


FIGURE 5.5-1. EXAMPLE RAW-DATA TIME-HISTORY PLOT.

Therefore, the validation support system should include this software and hardware capability.

5.5.1.3 Difference and Error Plots

Numerical differencing (differentiation) can be used as a check on smoothness of a module's input/output response, in those cases where a module has discrete switching between modes of operation, or uses a piecewise fit to cover its overall dynamic range (e.g., atmosphere and aerodynamic routines). Figure 5.5-2 shows the appearance of irregularities at boundaries of the piecewise fit used in an atmosphere routine, as amplified by the use of numerical differencing.

It is also sometimes convenient to generate a plot of the error between the simulated and reference data, appropriately rescaled. Fixed or percentage tolerance bands can be simultaneously plotted on the same axes to aid evaluation. Figure 5.5-3 shows an example error plot for an atmosphere routine.

As with the raw-data plots, linear, logarithmic and other forms of scaling may be used, as appropriate to the range and type of parameter variation.

5.5.1.4 Parameter-Plane Plots

The "parameter plane" or "calibration curve" format may be used to advantage for certain static check cases resulting from a parametric study. In this format, illustrated in Figure 5.5-4, the reference value and simulation value for each checkpoint are used as the plotting coordinates. Thus, a perfect match between reference and simulation data, over the range of interest, will put all plotted points on a diagonal line of unit slope (shown dashed in the figure). Bias, scale factor, and other forms of error will result in departures from this ideal line. Fixed or percentage tolerance bands can also be placed on the parameter-plane plot, as shown.

A special form of parameter-plane plot, which is useful for summarizing large quantities of essentially static data, is the contour plot, in which contours of simulation error value (or percentage) are plotted against two of the input parameters of interest, over a range of variation. Use of the contour plot, where appropriate, can focus attention upon the regions of greatest inaccuracy of a simulation module. A hypothetical example is shown in Figure 5.5-5.

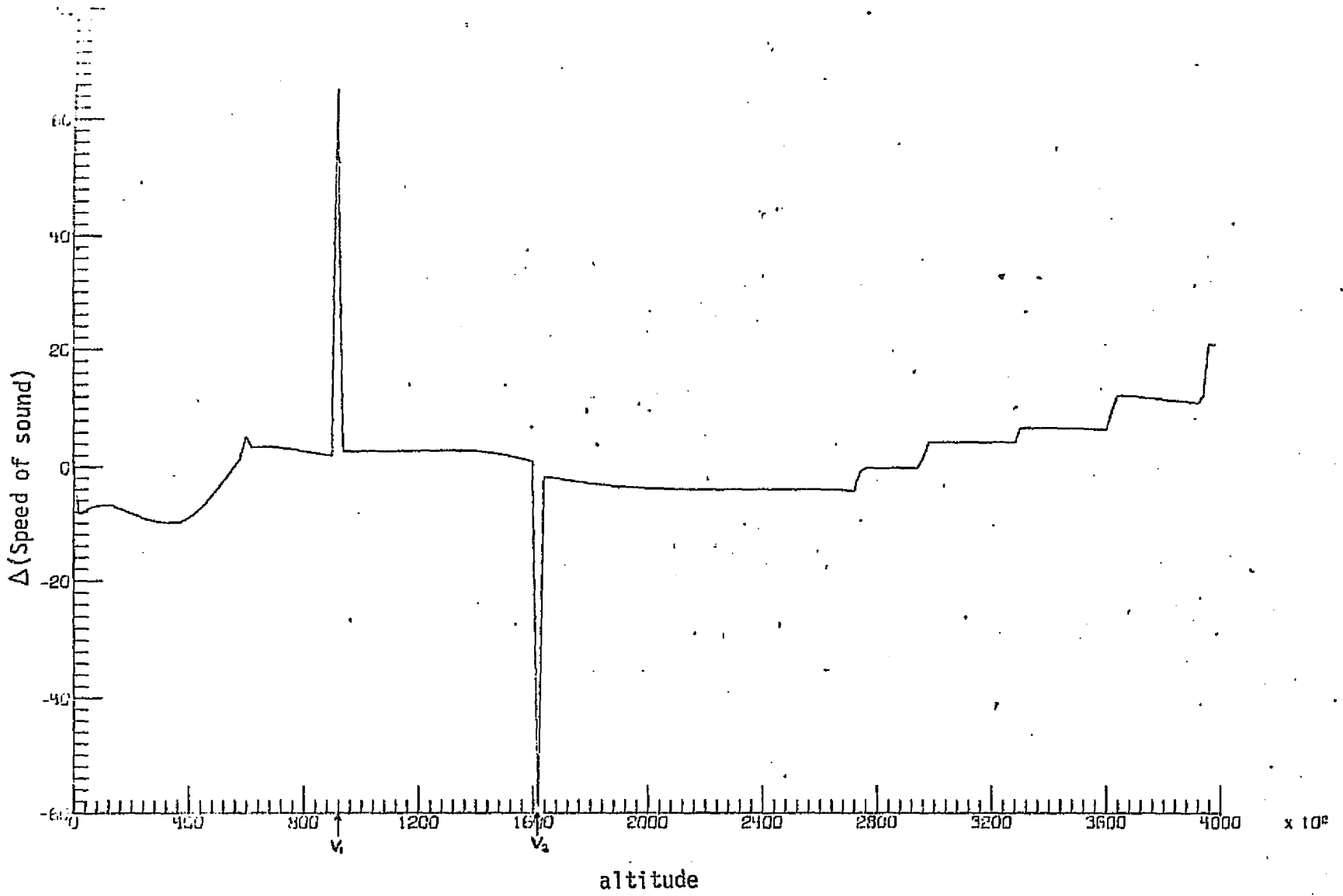


FIGURE 5.5-2: EXAMPLE NUMERICAL-DIFFERENCE PLOT (ATMOSPHERE ROUTINE).

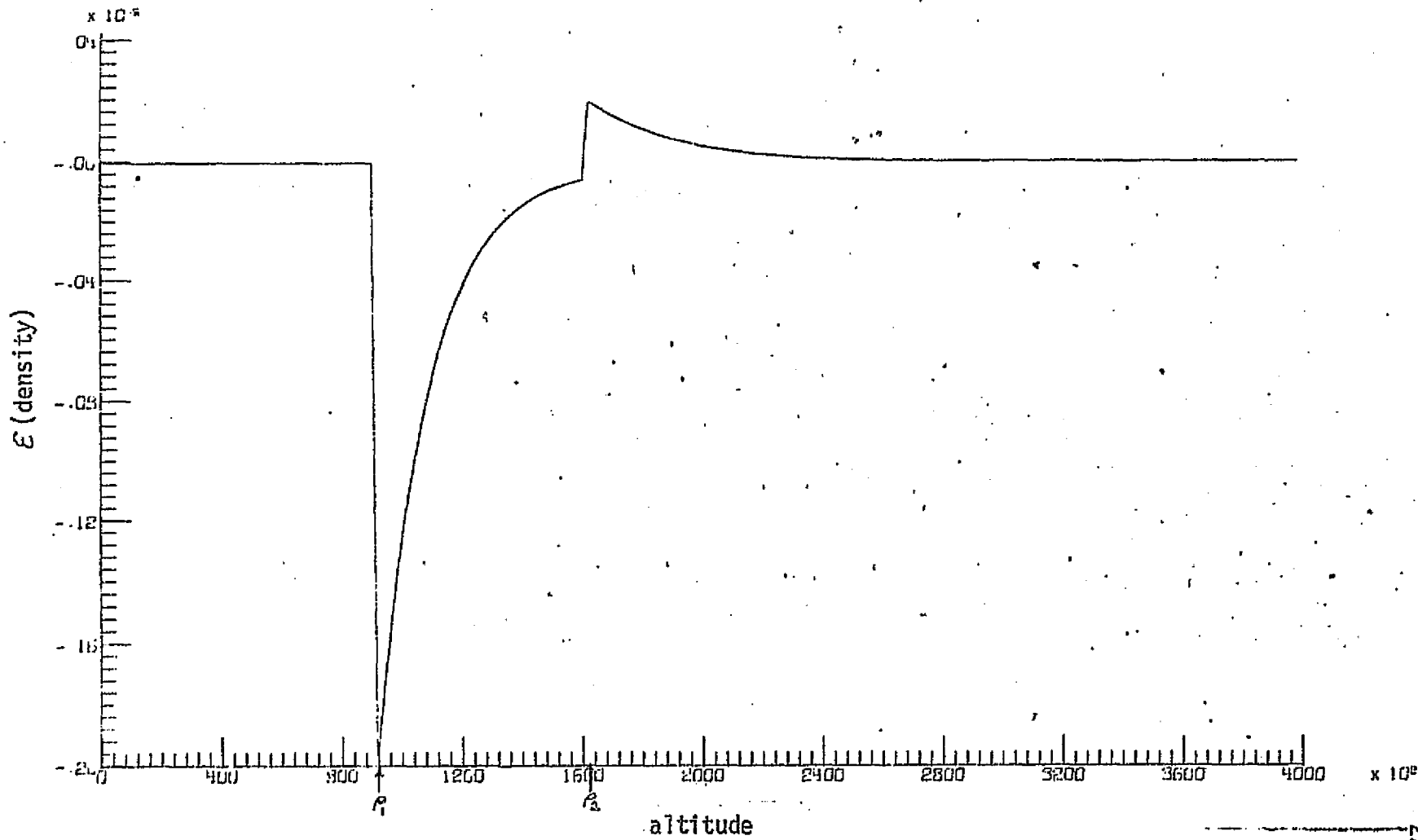
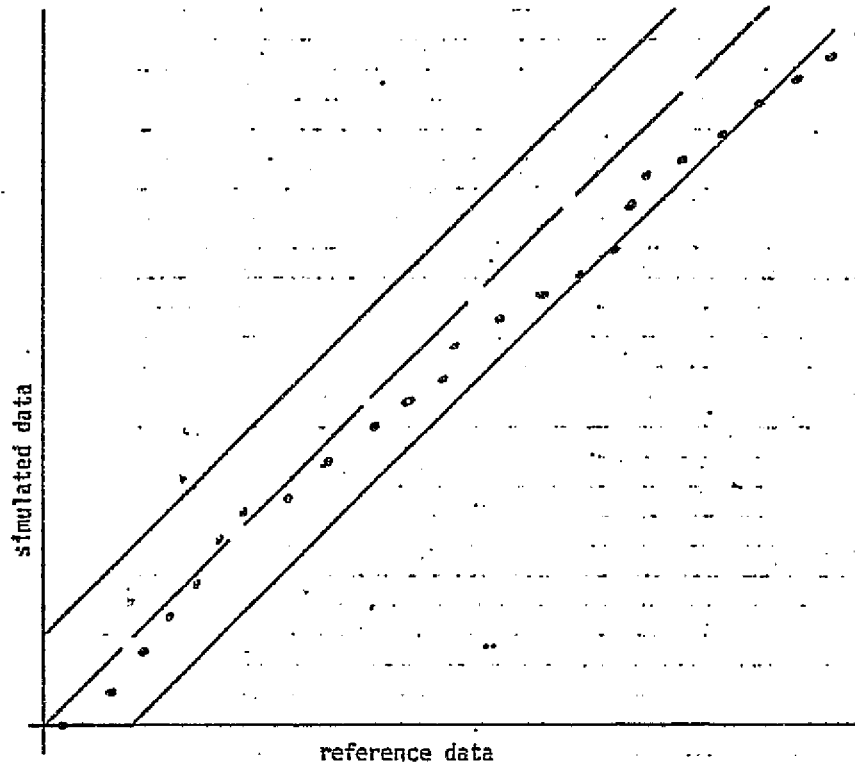
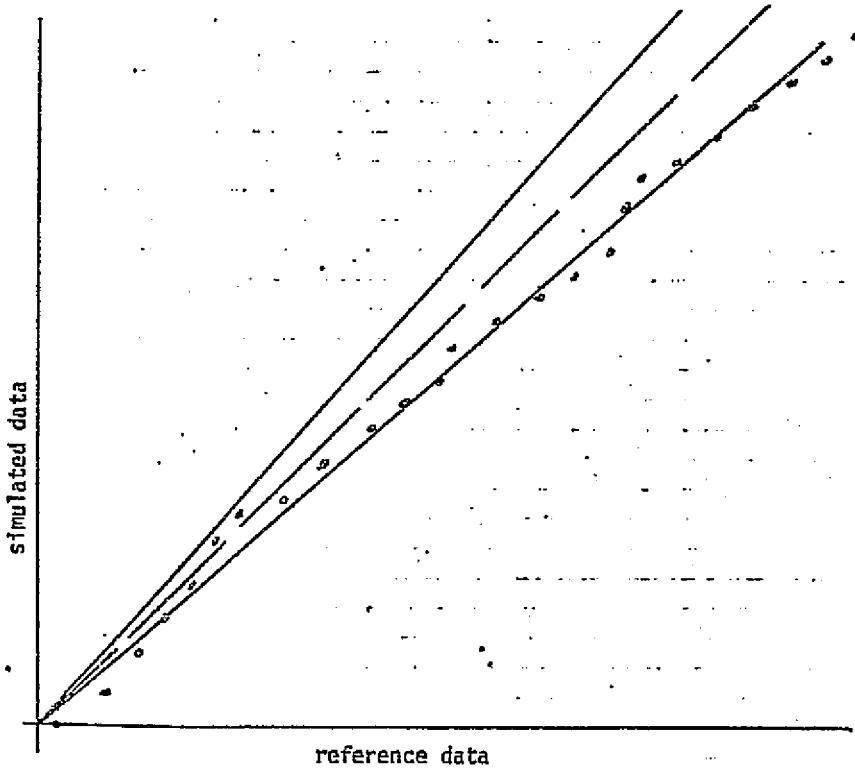


FIGURE 5.5-3. EXAMPLE SIMULATION ERROR PLOT (ATMOSPHERE ROUTINE).



(a) Fixed Tolerance Band.



(b) Percentage Tolerance Band.

FIGURE 5.5-4 . PARAMETER-PLANE PLOTTING FORMAT

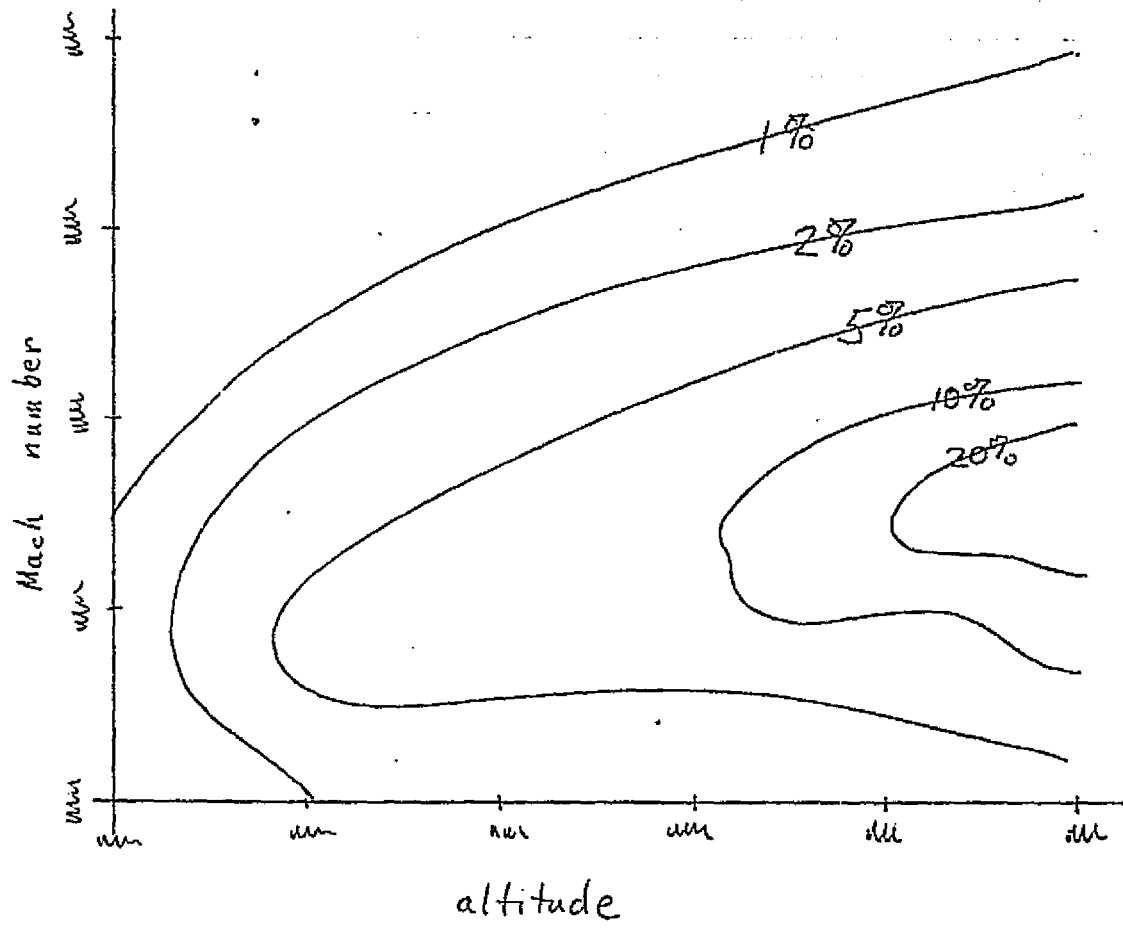


FIGURE 5.5-5 . HYPOTHETICAL CONTOUR PLOT OF SIMULATION ERROR.

5.5.2 Automated Comparison Techniques

Computers are, of course, incapable of making subjective judgements about the "goodness" of the match between reference and simulation data. An automated comparison/evaluation program will perform some processing (which may range from elementary to quite complex) of the reference and simulation data, resulting in one or more numbers which quantify the degree of mismatch. The mismatch value(s) are then compared against criterion values provided by the validator, and the simulation is thus classified as acceptable or unacceptable.

The experience and judgement of the validator are, of course, embodied in the selection of the criterion values used to separate acceptable from unacceptable performance. As stated above, the acceptance criteria will vary for different modules, for different operational modes and regimes, and as a function of time.

Variation of simulation module characteristic parameters to improve the match can easily be automated, since all quantities involved in the process are available to the computer in numerical form. The match between simulation and reference data can be "optimized" (relative to the comparison technique in use) either by systematic or random perturbation of the module characteristic parameters. Descriptions of optimization algorithms (stepwise variation, gradient search, Monte Carlo, etc.) are widely available in the literature.

5.5.2.1 Tolerance Bands

A very simple routine can be used to find the maximum error between the reference and simulation data,

$$E_{\max} = \max \{ |r(t) - s(t)| : 0 \leq t \leq T \}$$

and compare this to a preassigned tolerance. In some cases -- where the data covers a wide dynamic range, but does not pass through zero -- it will be appropriate to use the maximum percentage error, rather than the maximum absolute error.

Where smoothness at certain representational boundaries is an important criterion of simulation quality, tolerances may be applied to the first and/or second differences (derivatives) of the simulation data.

5.5.2.2 Integral Criteria

A variety of simple integral transformations may be used to convert the mismatch between reference and simulation time-history data into a single number for evaluation purposes. Several of these transformations are listed below:

Integral of error:

$$IE = \int_0^T [r(t) - s(t)] dt$$

Integral of absolute error:

$$IAE = \int_0^T |r(t) - s(t)| dt$$

Time-weighted integral of absolute error:

$$IAET = \int_0^T |r(t) - s(t)| t dt$$

Integral of squared error:

$$ISE = \int_0^T [r(t) - s(t)]^2 dt$$

Time-weighted integral of squared error:

$$ISET = \int_0^T [r(t) - s(t)]^2 t dt$$

The IE criterion appears at the outset to be too simple to be workable, since errors of opposite sign will cancel, giving an unrealistically small mismatch value. The squared-error criteria, ISE and ISET, as compared to IAE and IAET, assign increasingly higher weight to large deviations, which seems a reasonable thing to do. Even higher powers can be used, such as I4E, I6E. The time-weighted criteria, IAET and ISET, give higher weight to persistent errors than transient errors, and higher weight to bias errors than to oscillating errors. Further properties of various integral criteria are discussed in Ref. 121.

5.5.2.3 Feature Extraction

A potential problem in the use of the simple criteria described above is that the individual attributes of the response -- frequency, damping, phase, etc. -- cannot be individually identified in the result. It then appears desirable to devise algorithms for processing time-history data to extract these individual attributes of the response. If desired, a single numerical criterion could then be devised by forming a weighted sum of the errors in the individual attributes; the weighting could be varied with the simulation context, as previously indicated.

Limited experience to date indicates that feature extraction is likely to be difficult for complex systems. Further work in this area should be undertaken.

5.5.3 Agreement Between Manual and Automated Comparisons

A simple experiment was conducted to shed some light on how well the results of automated comparison might be expected to agree with subjective judgements of simulation fidelity.

5.5.3.1 Experiment Description

The simple linear system shown in Figure 5.5-6 was forced with a unit step input. With a selected set of parameters and zero initial conditions, the "reference" time-history shown in Figure 5.5-7 was obtained. "Simulation" time-history data was generated by using the same linear system, with random errors in parameters and/or initial conditions. Ten simulation cases were generated in this manner. For each case, a time-history plot was generated for subjective evaluation, while the fidelity was also evaluated by a number of objective criteria. The resulting plots are shown in Figure 5.5-8.

Copies of the ten time-history plots were made with uniform scaling, and distributed to ten experimental subjects. All subjects were engineers at our Houston Operations facility. The subjects were classified by their experience in simulation: those in the "high" experience group had from one to fourteen years' experience (mean of 6.0 years); those in the "low" experience group had from zero to one year experience (mean of 0.4 years).

Each subject was instructed to rank the ten cases as to how well the simulation data matched the reference data; the actual instruction sheet is reproduced in Figure 5.5-9. The subjects were not told what criteria to use in this evaluation, nor informed as to the context of the simulation from which the data were taken. Conversations with subjects following the experiment indicated that the weight given to various response attributes -- initial response, final error, oscillation amplitude and damping, etc. -- varied widely among subjects; however, several subjects in the high experience group indicated that they gave highest weighting to initial response characteristics, perhaps due to familiarity with the role of visual/motion cues in simulators.

5.5-12

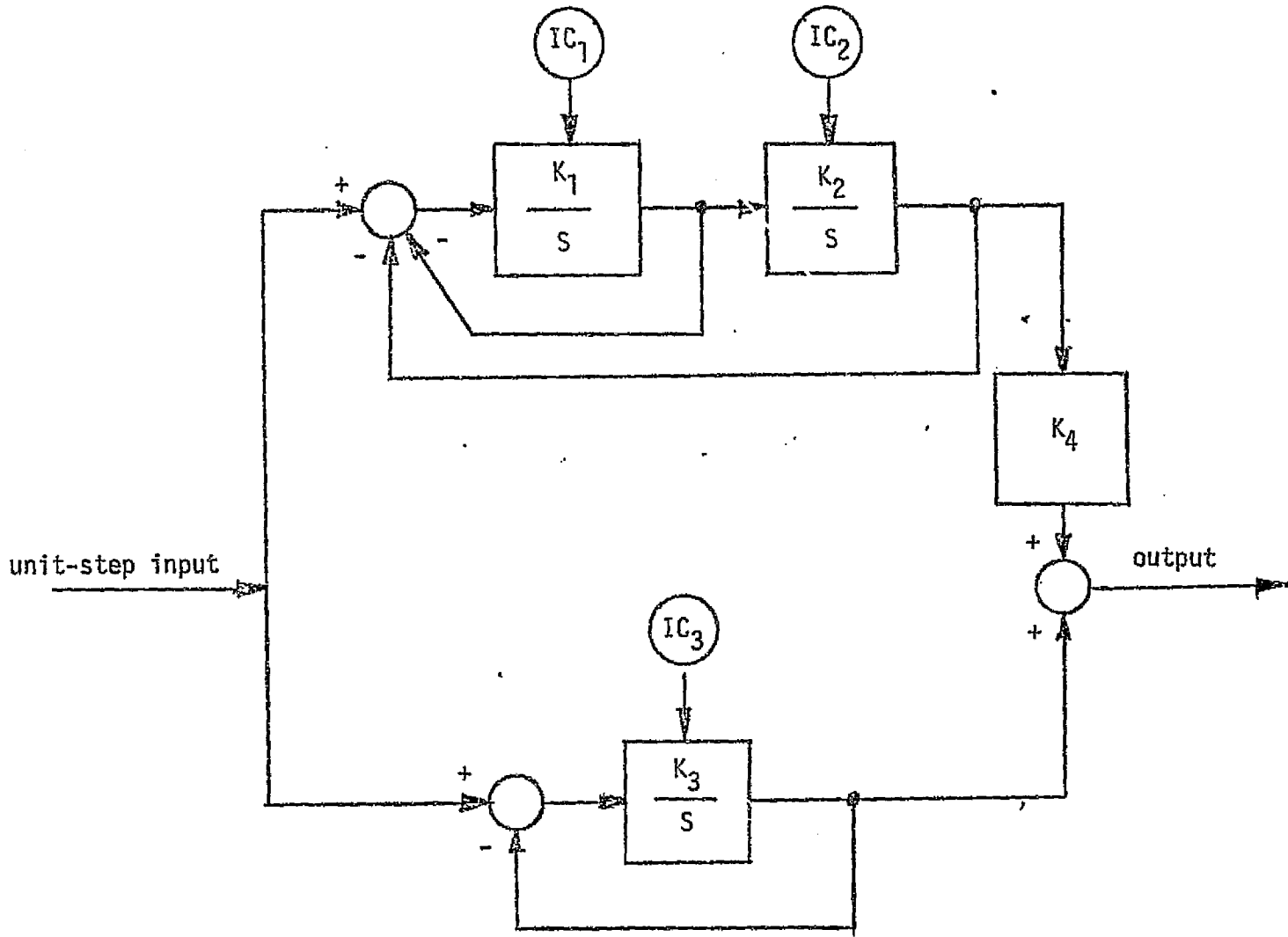


FIGURE 5.5-6 . DYNAMICAL SYSTEM USED FOR EXPERIMENT DATA.

5.5-13

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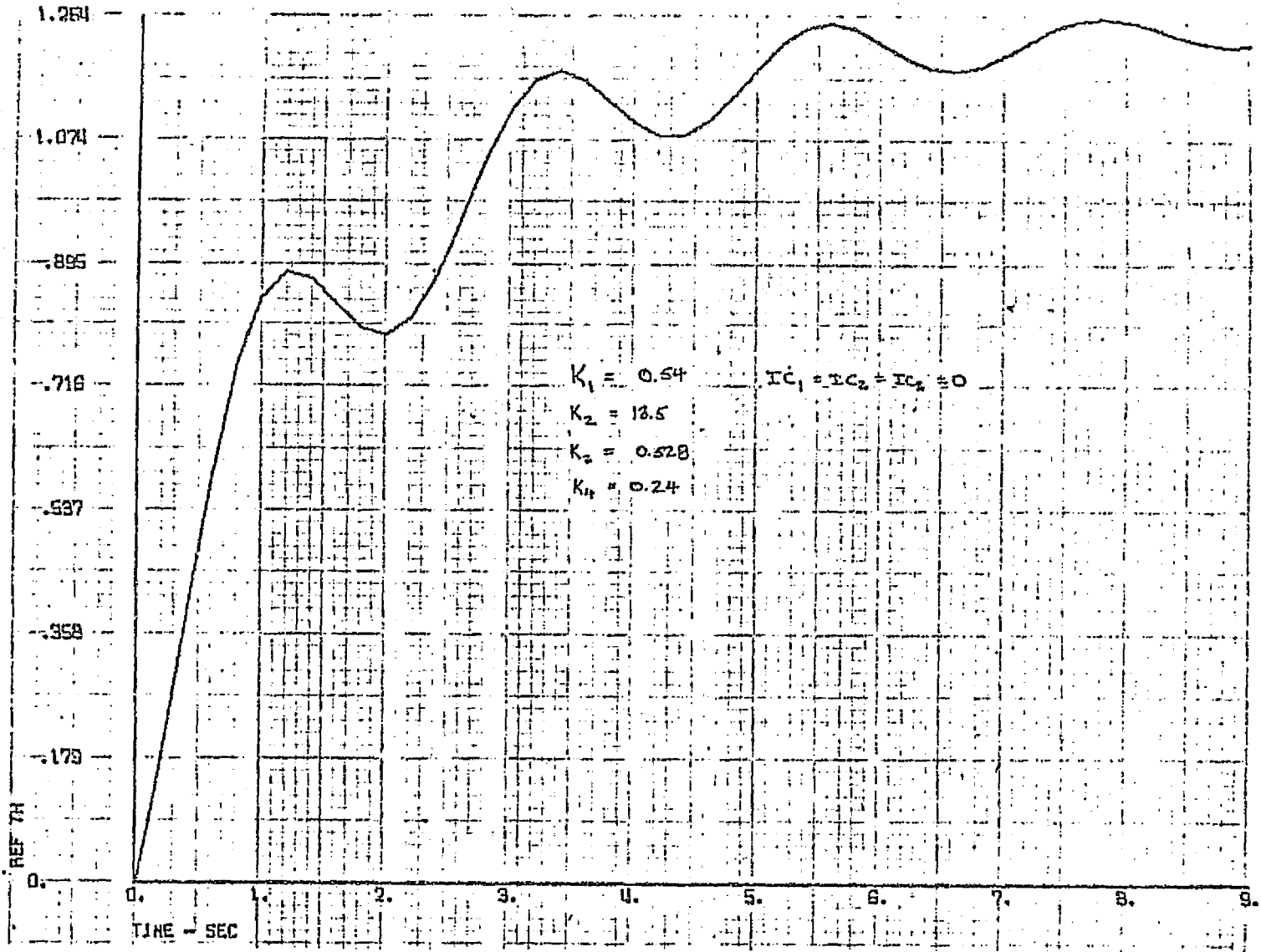


FIGURE 5.5-7 . "REFERENCE" TIME-HISTORY FOR EXPERIMENT

5,5-14

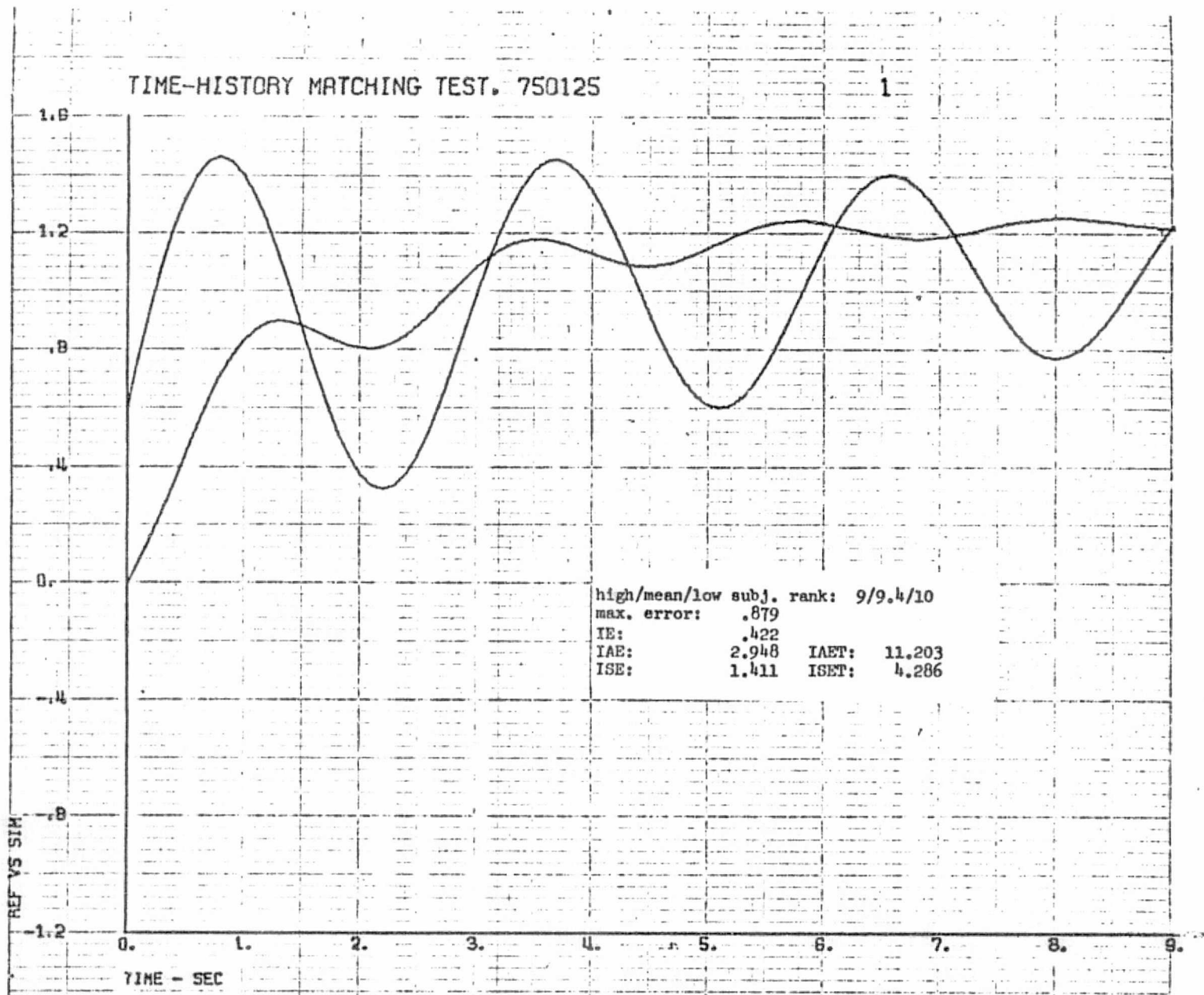


FIGURE 5.5-8 . TIME-HISTORY PLOTS OF "REFERENCE" AND "SIMULATION" DATA USED IN THE EXPERIMENT.

5.5-15

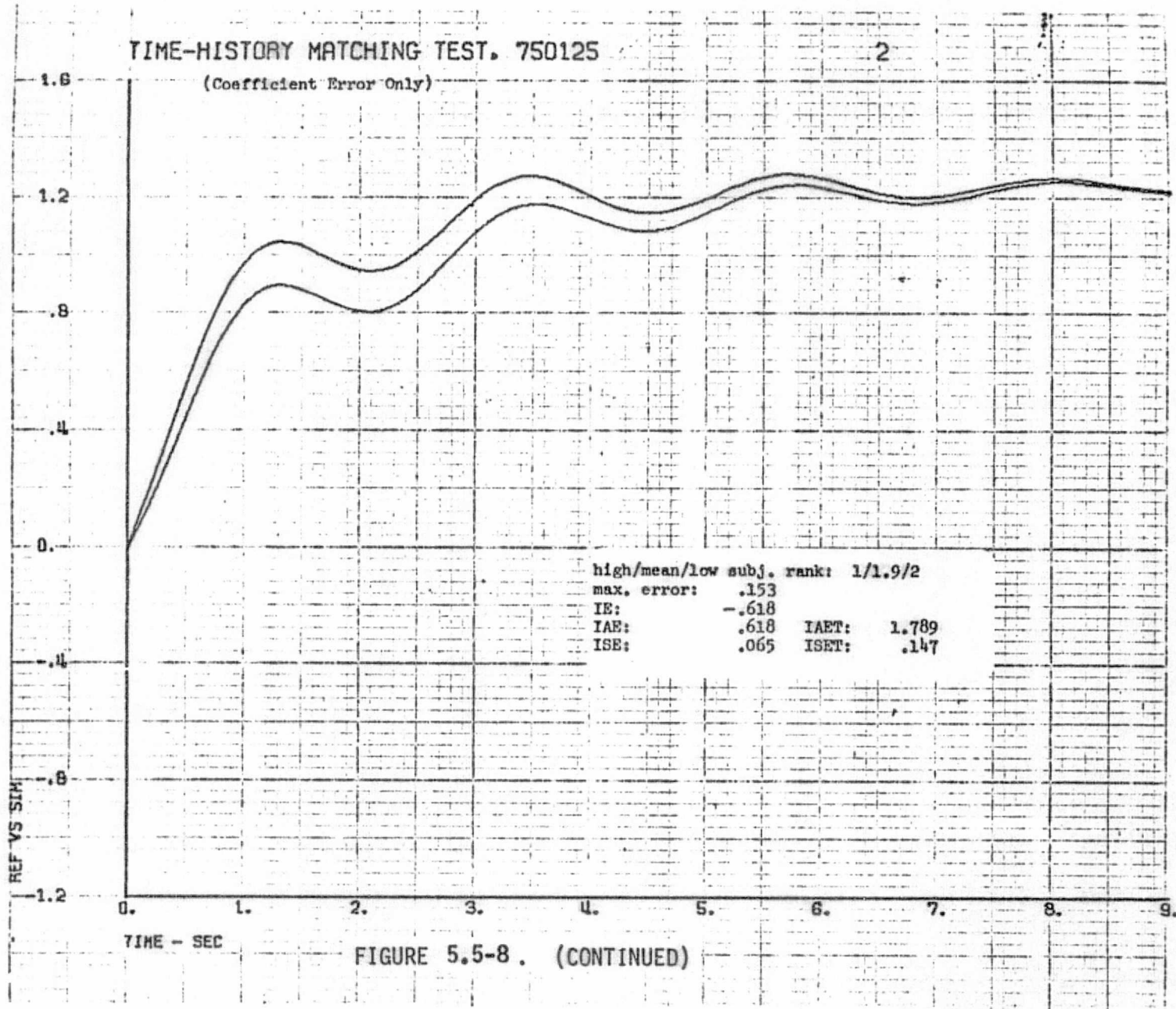


FIGURE 5.5-8. (CONTINUED)

5.5-16

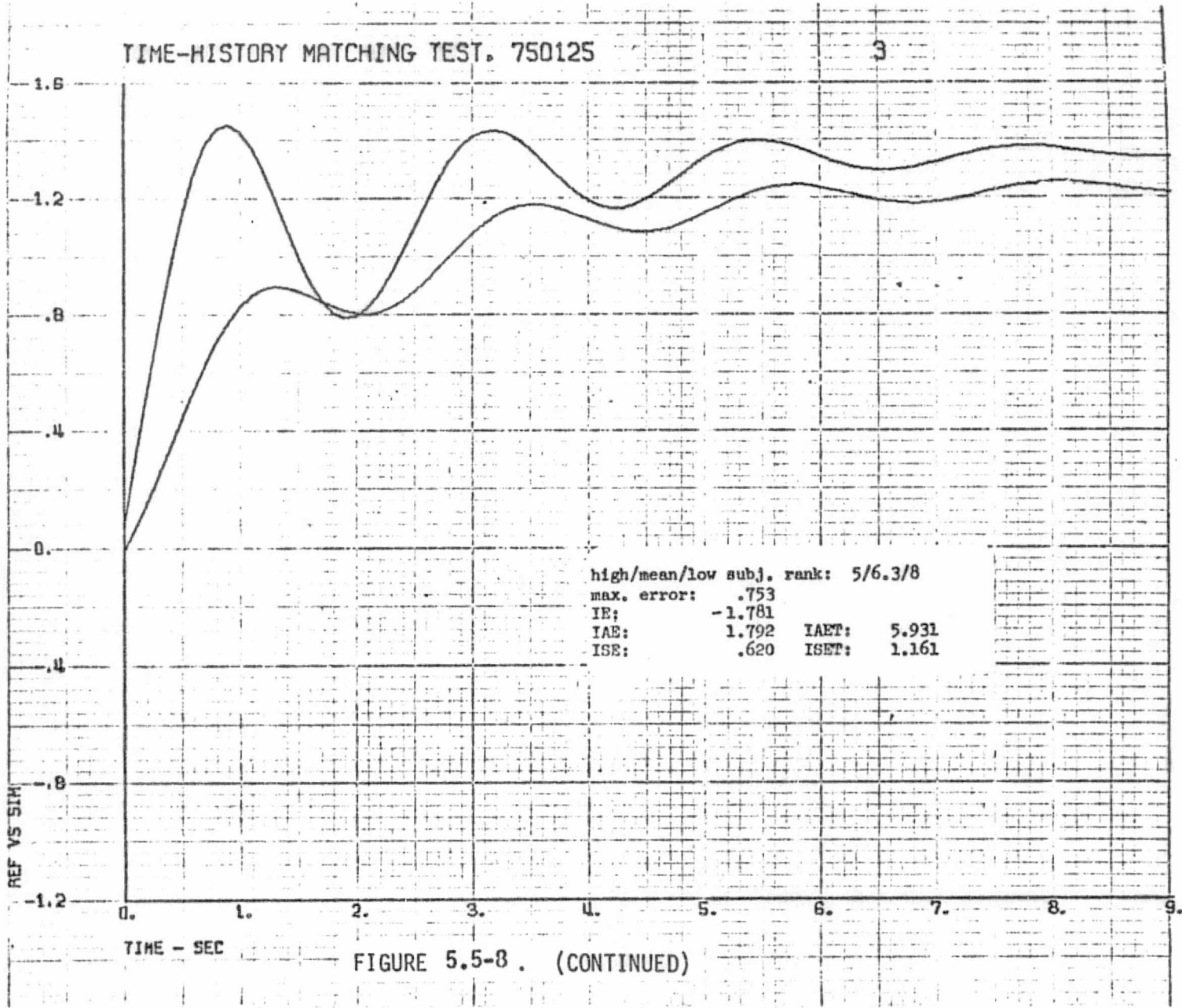


FIGURE 5.5-8. (CONTINUED)

5.5-17

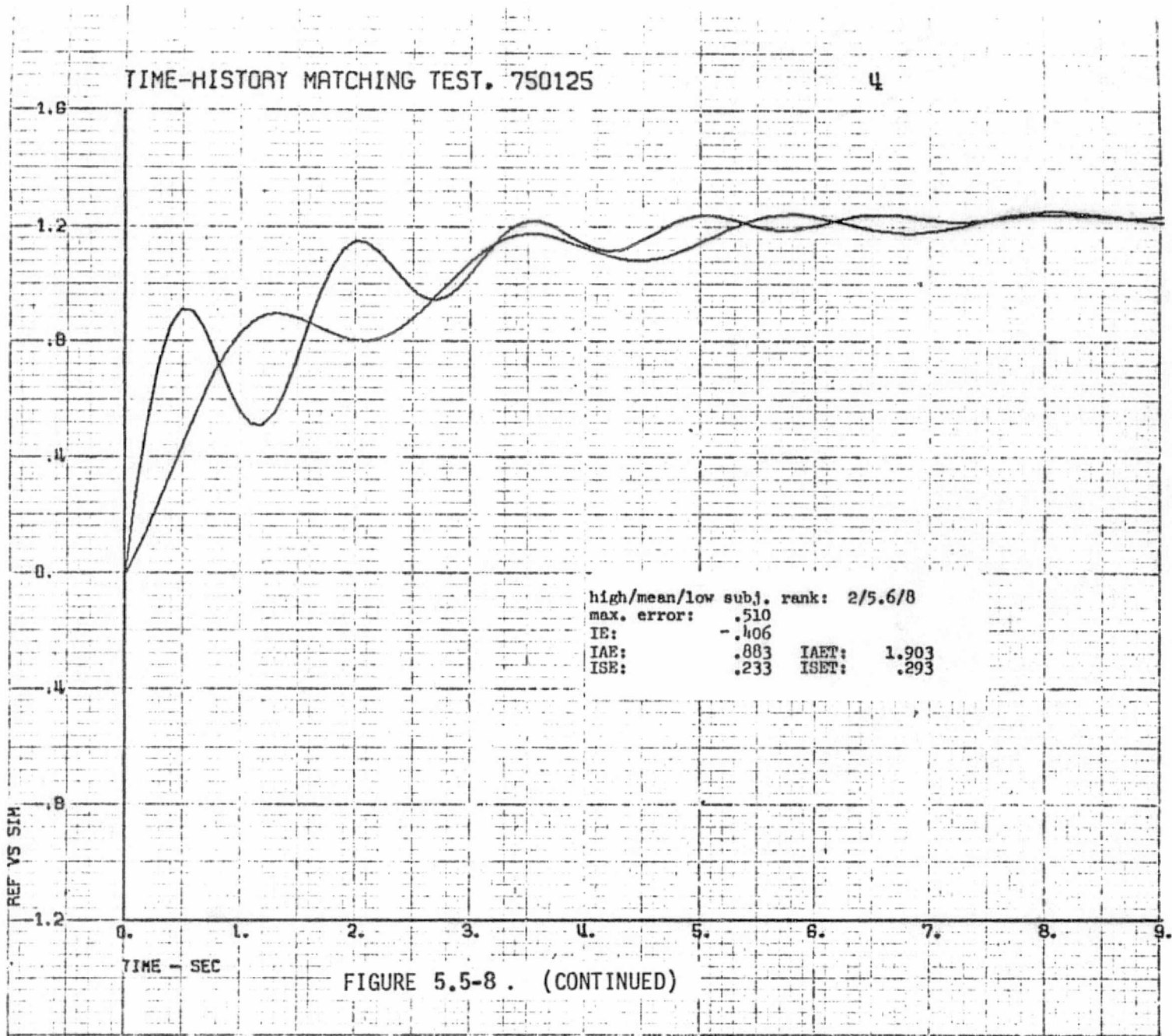
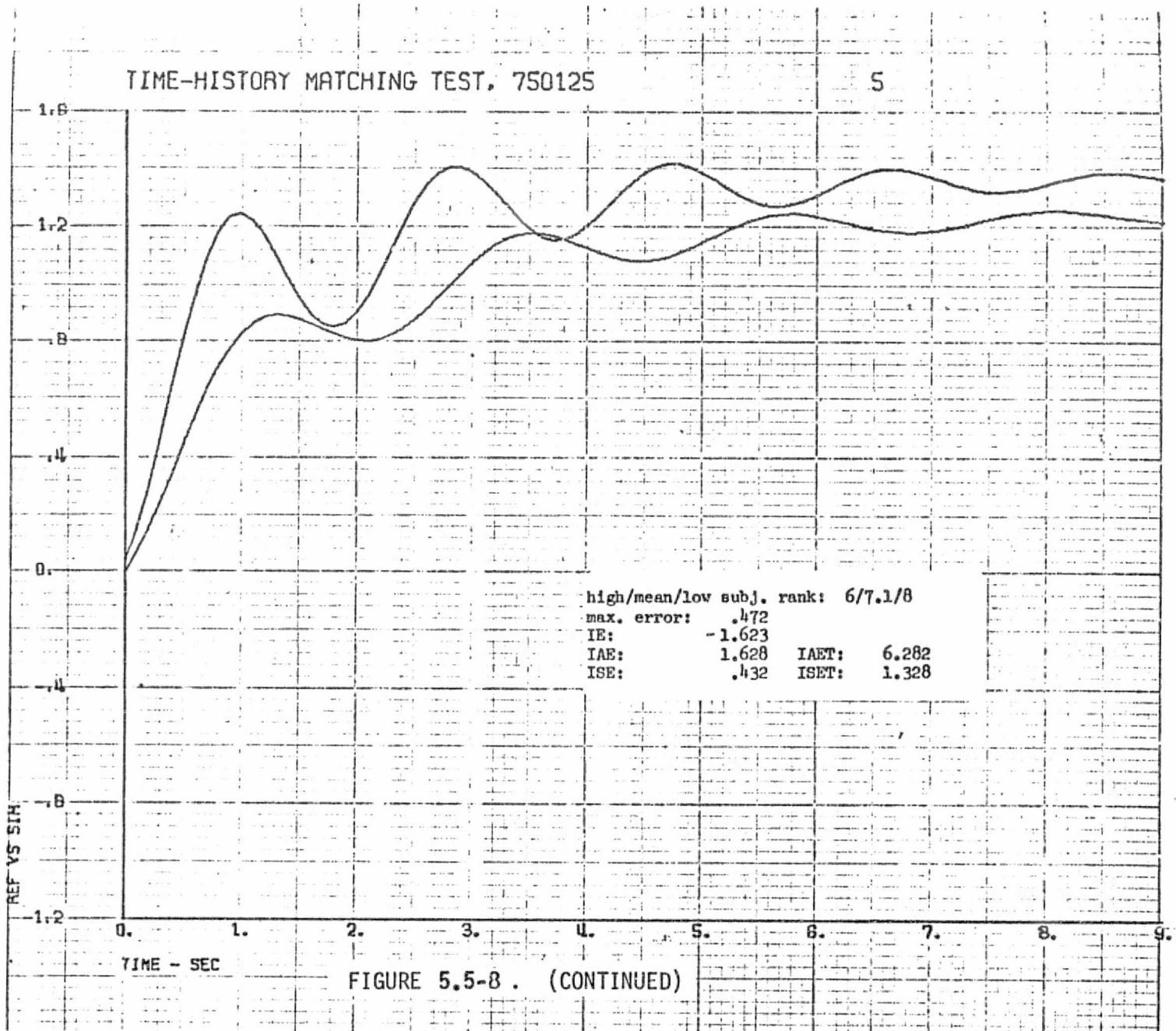


FIGURE 5.5-8. (CONTINUED)

5.5-18

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5.5-19

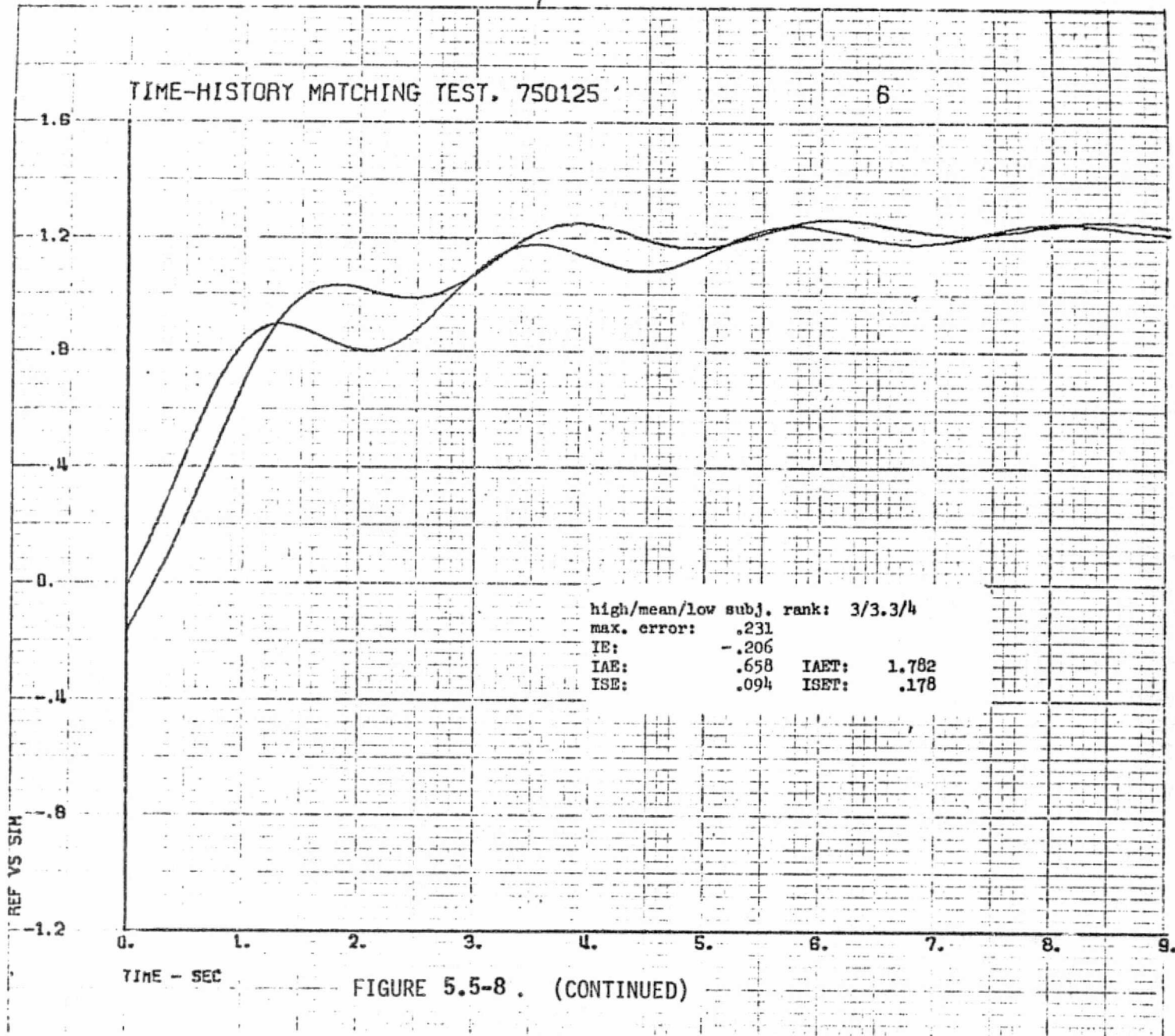


FIGURE 5.5-8 . (CONTINUED)

5.5-20

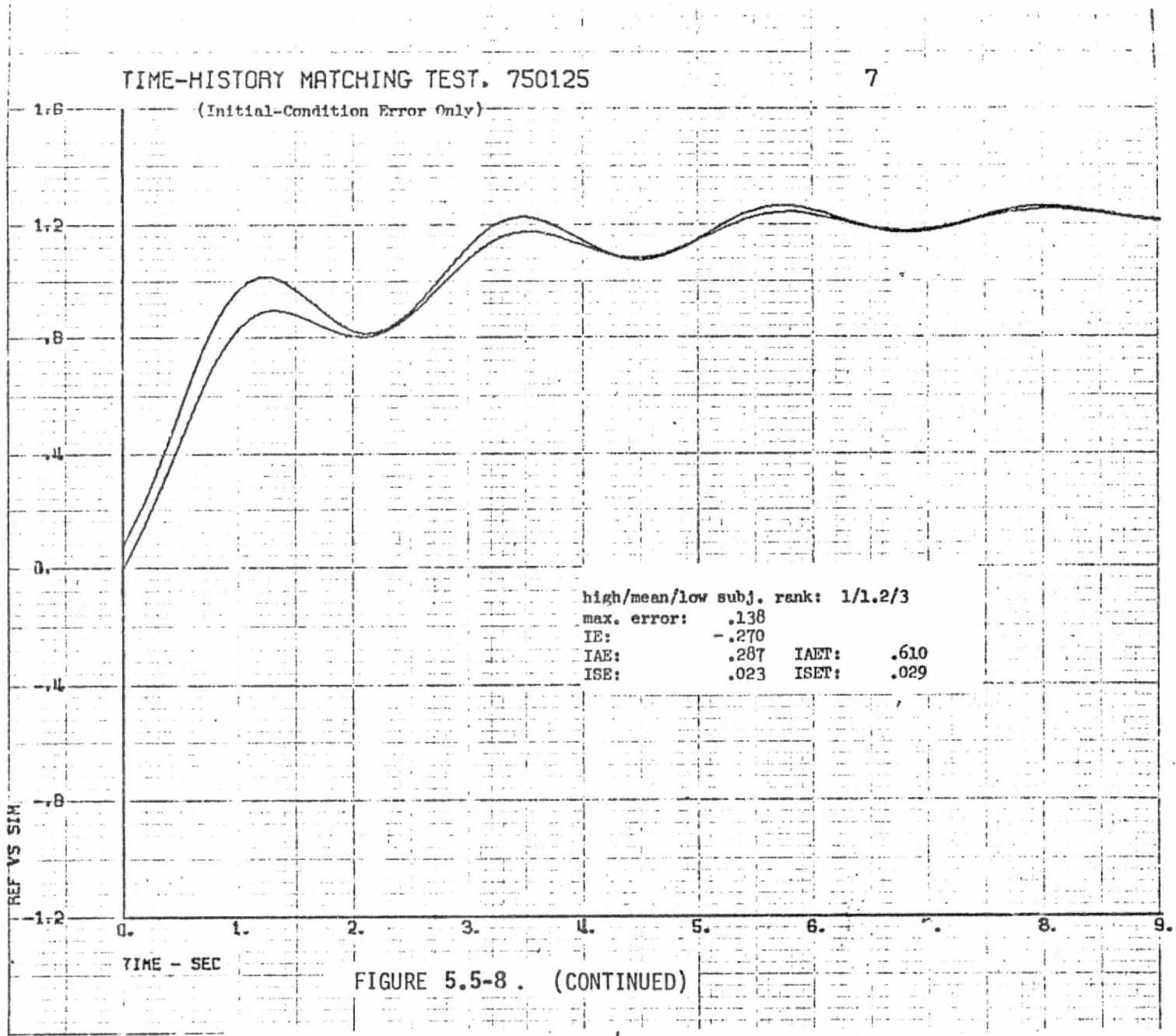


FIGURE 5.5-8. (CONTINUED)

5.5-21

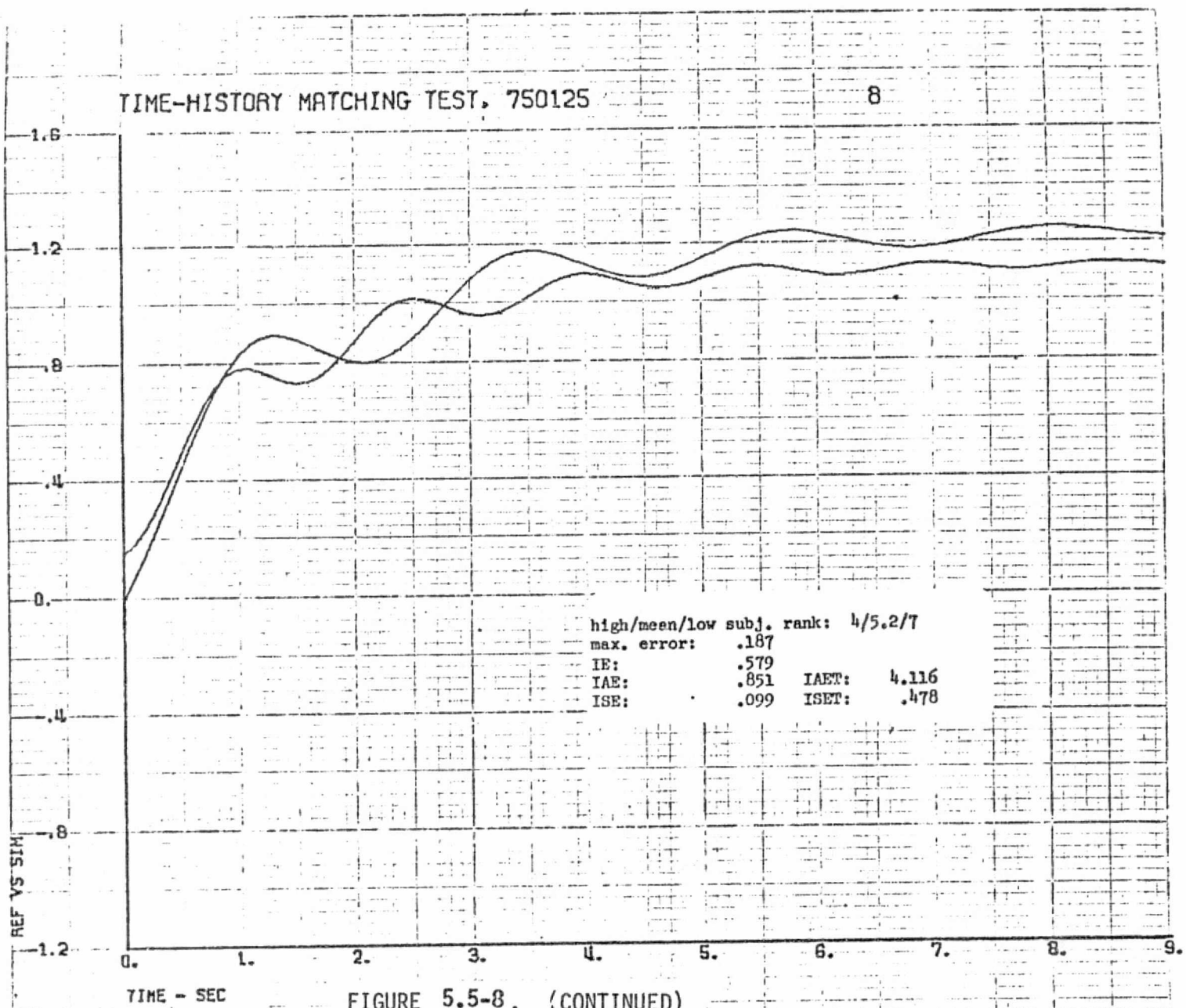
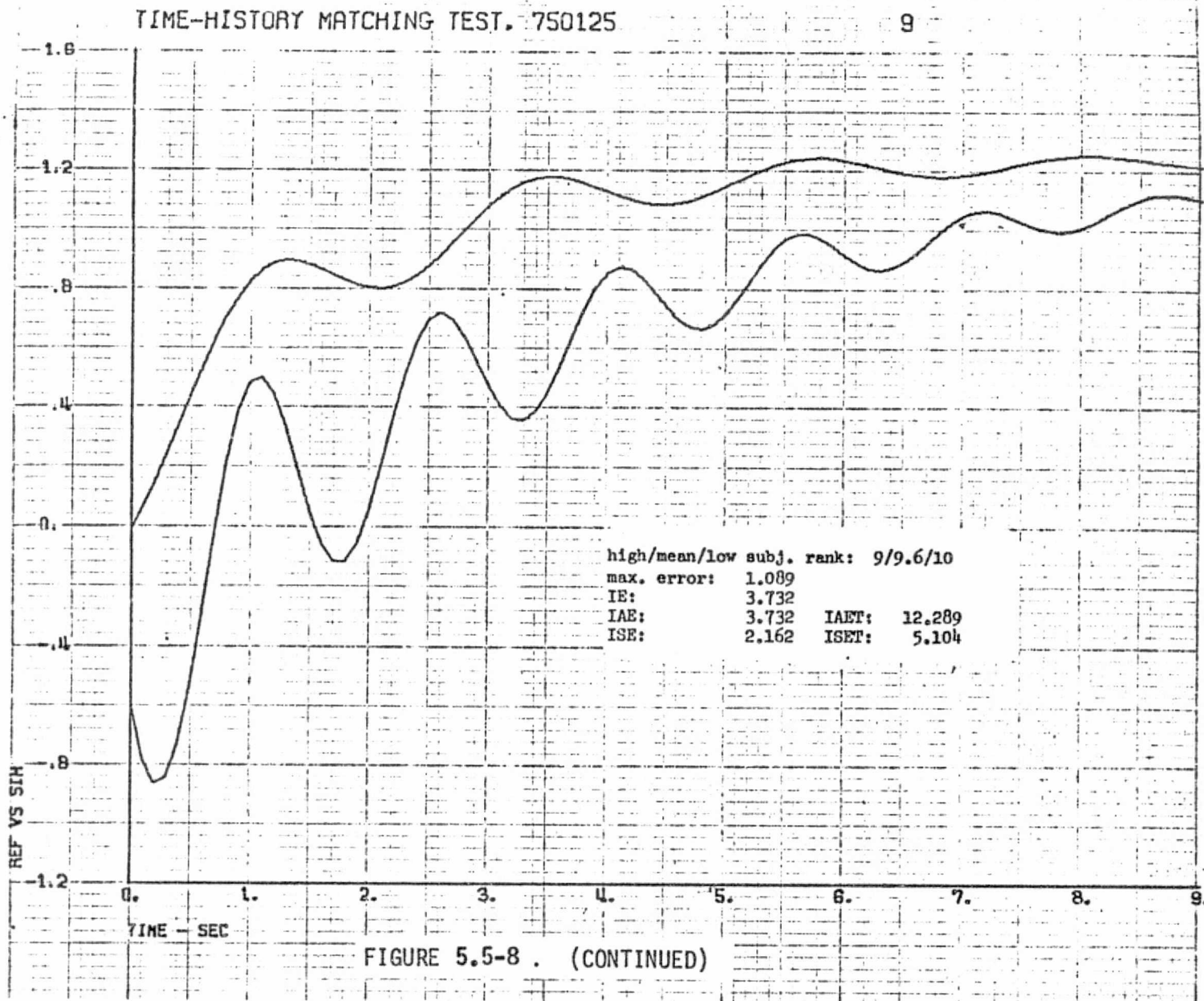


FIGURE 5.5-8. (CONTINUED)

5.5-22



TIME-HISTORY MATCHING TEST, 750125

10

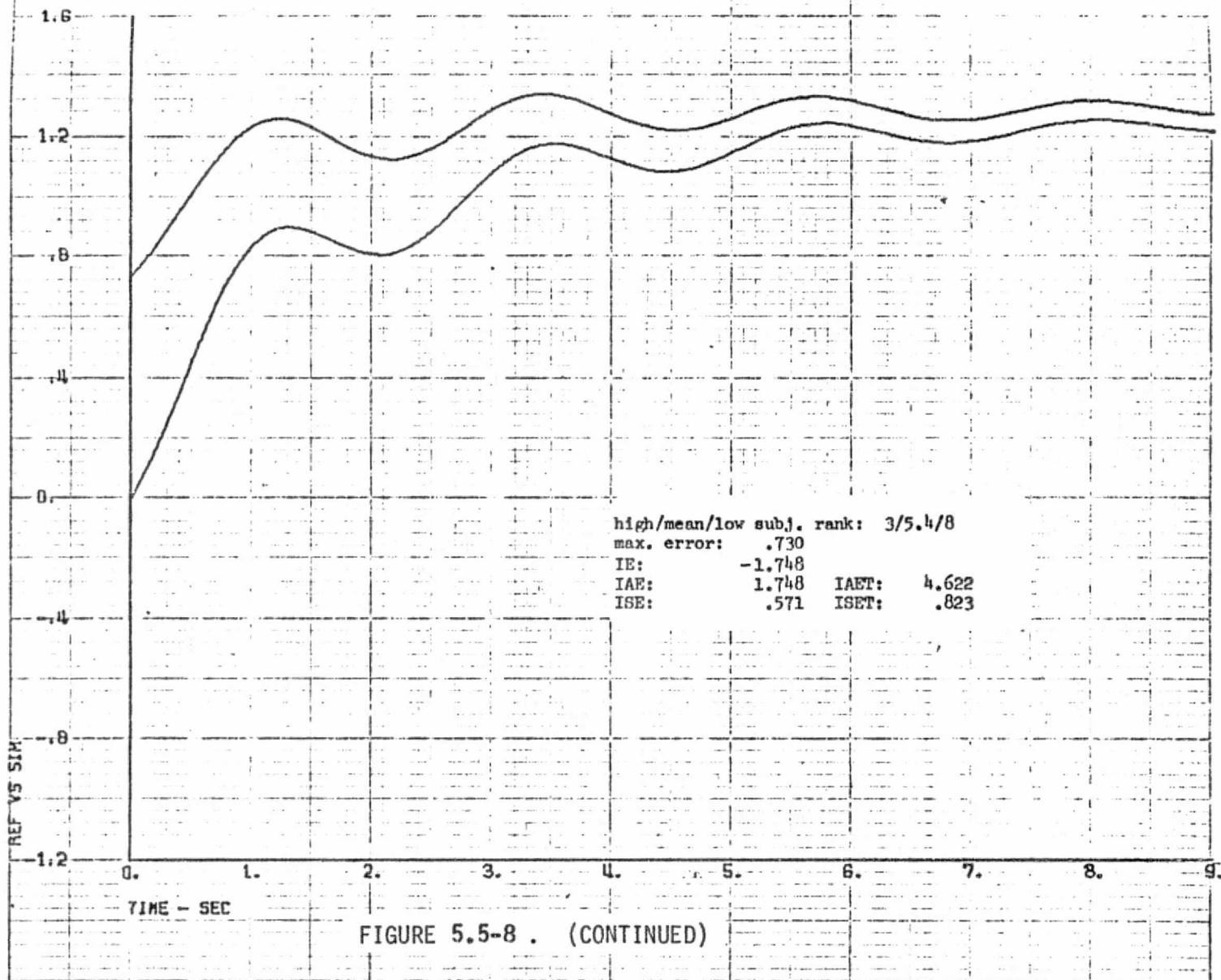


FIGURE 5.5-8 . (CONTINUED)

1. This experiment will take you only a few minutes.
2. The attached plots represent ten attempts to match a given "reference" data time-history with a simulation program. On each plot, the reference and simulation time-history data are plotted on the same axes. Your task is to evaluate (rank) how well the ten simulation trails succeeded in matching the reference data.
3. Spread out the time-history plots so that you can easily see and compare all of them. The plot which, in your judgement, shows the best match between the two curves should be ranked 1; the next best ranked 2; and so forth down to the worst match, which should be ranked 10.
4. Take your time; look them over. When you are sure of your ranking, mark each plot with its assigned ranking in the top right corner; circle it. Then staple the entire set together and return to P. B. Schoonmaker, E917, Beta.
5. To maintain standard experimental conditions, please do not discuss the experiment with anyone until it is completed.
6. Thank you for your cooperation.

FIGURE 5.5-9 . INSTRUCTION SHEET DISTRIBUTED TO SUBJECTS IN EXPERIMENT.

5.5.3.2 Subjective Comparison of Time-History Data

Table 5.5-1 summarizes the subjective ranking data for all ten subjects. As would be expected, the greatest unanimity is shown for the best and worst matches, with considerable scatter for the intermediate cases. Scatter would probably be lower in a real application, where the context of the data was known, and hence the relative importance of various response attributes would be better understood.

Table 5.5-2 compares the subjective rankings accorded by subjects in the high and low experience groups. The low-experience data seems to show slightly greater scatter, and some significant individual differences in ranking. As an objective measure of the comparability between the two groups, we use the "rank correlation" given by

$$r = 1 - \frac{6 \sum d_i^2}{N(N^2-1)}$$

where d_i = the difference between the two groups' mean ranks for the i^{th} case
 N = the number of cases (10)

For these data, $r = 0.962$, which is quite high (r is always between plus and minus one). Overall, then, the differences between the two groups are not important for these data. Differences with respect to individual criteria will be evident in the following discussion.

5.5.3.3 Comparative Ranking for Simple Criteria

Table 5.5-3 shows the numerical values and resulting ranking for each of the simple objective comparison criteria: maximum error, and the five integral transformations previously listed. The ten-subject mean subjective ranking (MSR) is also shown for convenient comparison. The IE criterion must be converted to absolute value (AIE) to make any sense at all; and as expected, it shows some wide departures from the results for the other criteria. Note that IAE and ISE gave the same objective ranking for these data.

Table 5.5-4 summarizes the comparison of subjective and objective ranking for the simple mismatch criteria and the mean objective rank (MOR), using the rank correlation algorithm previously shown. Correlation values are shown for all subjects, and separately for the high and low experience groups. As expected,

TABLE 5.5-1 . SUBJECTIVE RANKING OF EXPERIMENT DATA

CASE	RANKING BY INDIVIDUAL SUBJECTS										RANK SPREAD		
	"High" Experience					"Low" Experience					High	Mean	Low
	1	2	3	4	5	6	7	8	9	10			
1	9	9	10	9	9	10	9	9	10	10	9	9.4	10
2	2	2	2	2	2	2	2	2	1	2	1	1.9	2
3	5	7	8	6	6	5	6	7	5	8	5	6.3	8
4	8	5	5	8	7	8	4	4	2	5	2	5.6	8
5	7	6	7	7	8	7	8	8	6	7	6	7.1	8
6	4	3	3	3	3	4	3	3	4	3	3	3.3	4
7	1	1	1	1	1	1	1	1	3	1	1	1.2	3
8	6	4	4	4	5	6	7	5	7	4	4	5.2	7
9	10	10	9	10	10	9	10	10	9	9	9	9.6	10
10	3	8	6	5	4	3	5	6	8	6	3	5.4	8

TABLE 5.5-2 . SUBJECTIVE RANKING FOR DIFFERENT EXPERIENCE GROUPS

CASE	RANK SPREAD					
	"High" Experience			"Low" Experience		
	High	Mean	Low	High	Mean	Low
1	9	9.2	10	9	9.6	10
2	2	2.0	2	1	1.8	2
3	5	6.4	8	5	6.2	8
4	5	6.6	8	2	4.6	8
5	6	7.0	8	6	7.2	8
6	3	3.2	4	3	3.4	4
7	1	1.0	1	1	1.4	3
8	4	4.6	6	4	5.8	7
9	9	9.8	10	9	9.4	10
10	3	5.2	8	3	5.6	8

TABLE 5.5-3. OBJECTIVE RANKING FOR SIMPLE CRITERIA

CASE	MSR	MISMATCH VALUE/RANK						RANK SPREAD		
		E_{max}	AIE	IAE	IAET	ISE	ISET	High	Mean	Low
1	9.4	0.879 9	0.422 4	2.948 9	11.203 9	1.411 9	4.286 9	4	8.17	9
2	1.9	.153 2	.618 6	.618 2	1.789 3	.065 2	.147 2	2	2.83	6
3	6.3	.753 8	1.781 9	1.792 8	5.931 7	.620 8	1.161 7	7	7.83	9
4	5.6	.510 6	.406 3	.883 5	1.903 4	.233 5	.293 4	3	4.50	6
5	7.1	.472 5	1.623 7	1.628 6	6.282 8	.432 6	1.328 8	5	6.67	8
6	3.3	.231 4	.206 1	.657 3	1.782 2	.094 3	.178 3	1	2.67	4
7	1.2	.138 1	.270 2	.287 1	.610 1	.023 1	.029 1	1	1.17	2
8	5.2	.187 3	.579 5	.851 4	4.116 5	.099 4	.478 5	3	4.33	5
9	9.6	1.089 10	3.732 10	3.732 10	12.289 10	2.162 10	5.104 10	10	10.00	10
10	5.4	.730 7	1.748 8	1.748 7	4.622 6	.571 7	.823 6	6	6.83	8

the AIE criterion shows the poorest results, and should therefore not be used as an evaluation method.

One apparent difference between the high and low experience groups is evident in their correlations with the time-weighted criteria, IAET and ISET. The low experience group apparently gave higher weight to persistent errors, as shown by the fact that the correlation with IAET was higher than with IAE, and their correlation with ISET was higher than with ISE. This carried through to the all-subjects correlations; but results were mixed for the high experience group.

Overall, the maximum-error criterion seems less useful than any of the integral criteria, and the squared-error criteria seem better than the absolute-error criteria. On the basis of these limited data, then, we would make the following recommendations for simple mismatch criteria:

- (a) Use ISE for cases where initial dynamic response is important, such as visual, motion, and instrument-readout inputs.
- (b) Use ISET for cases where persistent errors are undesirable, particularly variables which lie upstream of integrators in the system.

5.5.3.4 Comparative Ranking for Feature Extraction

The features which were considered potentially important in subjective evaluation of mismatch were initial position, initial slope, and final value of the total response curve, and the frequency, damping, amplitude and phase of the oscillatory component. Even for the simple dynamical system used for this experiment, the oscillation frequency amplitude and phase proved surprisingly difficult to extract. This would seem to indicate that they may be particularly difficult to extract for complex dynamical systems. Therefore, the value of the first peak was used as a rough indicator of the oscillation amplitude, and the time of the first peak as a rough indicator of the initial phase of the oscillatory component of the response.

Table 5.5-5 summarizes the correlation of errors in these response features or attributes with the subjective ranking of the experiment time-history data. All rank correlation values are rather low, indicating that no individual attribute is dominant in the subjective evaluation of fidelity, at least for these data.

TABLE 5.5-4. SUBJECTIVE/OBJECTIVE EVALUATION COMPARABILITY FOR
SIMPLE MISMATCH CRITERIA

SUBJECT GROUP	RANK CORRELATION VS. CRITERION						
	E_{max}	AIE	IAE	IAET	ISE	ISET	MOR
High experience	0.919	0.536	0.940	0.931	0.940	0.945	0.931
All subjects	.905	.558	.946	.954	.946	.971	.943
Low experience	.872	.562	.933	.959	.933	.979	.935

TABLE 5.5-5. SUBJECTIVE/OBJECTIVE EVALUATION COMPARABILITY
FOR FEATURE-EXTRACTION DATA

SUBJECT GROUP	RANK CORRELATION VS. ATTRIBUTE						
	Initial Value	Initial Slope	Final Value	Frequency	Damping	First Peak	First-peak Time
High experience	0.451	0.594	0.422	0.749	0.586	0.596	0.400
All subjects	.528	.547	.524	.750	.617	.644	.377
Low experience	.586	.482	.608	.732	.630	.673	.336

For feature extraction to be useful in automatic comparison and evaluation of simulation data, further development will be required in two areas:

- (a) Development of efficient, reliable algorithms for extraction of individual response attributes from time-history data.
- (b) Formulation of a composite performance index -- i.e., a weighted sum of the errors in various response attributes -- which parallels the subjective weighting of experienced simulation engineers.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations compiled from all sections of this report are listed below. The number(s) in parentheses after each item indicate the section(s) in which supporting rationale may be found. The conclusions and recommendations are listed in the order of the section in which first mentioned; no ranking of importance is implied.

1. Simulation validation should be performed by a staff which is organizationally independent of the staff responsible for simulation development (3.0).
2. Simulation validation must be performed at the isolated module level, at intermediate stages of integration, and in the final all-up man-in-loop configuration (3.0, 5.2).
3. Attention should be concentrated upon the "critical" performance parameters of each simulation module in performing simulation validation (4.0, 4.1, 5.3.2).
4. Each of the four types of reference data source -- closed-form solutions, independent math models, existing analysis/simulation programs, and test data -- has particular advantages and disadvantages for simulation validation (4.2).
5. Most simulation modules will require both static and dynamic check cases for thorough validation (4.2.1, 4.7).
6. Libraries of existing simulation routines offer many candidate reference modules for validation. However, modifications will be necessary in many cases (4.2.1.3, 4.7).
7. Driver routines must be developed for module validation exercises: both to provide the inputs representing interfacing modules, and to ensure format compatibility between the reference and simulation data (4.7, 5.1.2, 5.2).
8. The integration/validation sequence for a simulation should be based upon the natural "clustering" structure of strongly-interacting modules. Efficiency will be improved by scheduling module development to be consistent with this module integration/validation sequence (4.8).
9. Early establishment of working interfaces with component and system test groups will help to ensure timely access to appropriate reference data under desired test conditions (4.9).

10. Service routines will be required for printout, plotting, data handling, data comparison, and validation data base management. An early start on the development of these service routines is required to ensure that they will be available when needed (4.10, 4.11, 5.1).
11. For efficient development of the required service routines, "customized" software should be minimized by the early and uniform application of certain standards:
 - a) Data formats and file structures for reference and simulation data files (4.10.2; 5.4).
 - b) Data base management system implementation consistent with CODASYL standards (4.11).
 - c) Module/driver interfacing (using COMGEN or an equivalent support software package) (5.1.2).
12. Hand entry of non-machine-readable reference data into the computer is not recommended. Corresponding simulation data should be output in compatible formats for manual comparison and evaluation (4.10.2).
13. A thorough "make or buy" analysis should be performed before undertaking the implementation of a data base management system for the validation data base (4.11).
14. For all-up simulation validation, use of a "canned man" (pre-recorded manual inputs) is preferable to man-in-loop operation (5.2, 5.3).
15. Efficiency and thorough exercise are the basic criteria for check case design/selection (5.3).
16. For initial validation of a simulation, check cases should be sequenced on the basis of steady expansion of the operational envelope; the opposite approach is recommended for revalidation following modifications (5.3.2, 5.3.3).
17. The acceptable fidelity for a simulation varies with time, as the system being simulated becomes better defined, and more accurate reference data becomes available (5.5).
18. Automated comparison techniques which correlate well with the subjective judgement of experienced simulation engineers are presently available. However, further development of "feature extraction" techniques is recommended (5.5.3).

SECTION 7
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