

Dr. 2110

DOE/CS/51294--01

DE83 014921

Prepared for: U.S. Department of Energy

DOE/CS/51294-01
Dist Category UC 96

**Assistant Secretary for Conservation and Solar Energy
Office of Transportation Programs
Washington, D.C. 20585**

**Near-Term
Electric Test Vehicle
Phase II — Final Report**

Prepared by:
General Electric Company
Schenectady, N.Y. 12301
Under Contract No. DE-AC03-76CS51294

October 1980

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.

**It has been reproduced from the best
available copy to permit the broadest
possible availability.**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Report Annex

Annex A to this report contains a complete list of all drawings for the Electric Test Vehicle (ETV-1) developed under this contract. Copies of the annex may be obtained from the Department of Energy's Technical Information Center at the following address:

**Department of Energy
Technical Information Center
Customer Services Branch
P. O. Box 62
Oak Ridge, Tennessee 37830**

Copies of the drawings listed in Annex A are available for purchase also at the above address.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
EXECUTIVE SUMMARY	E-1
Vehicle Subsystem	E-2
Electrical Drive Subsystem	E-7
Battery Subsystem	E-13
1 INTRODUCTION	1-1
Program Management	1-1
Program Objectives	1-7
Technical Approach	1-8
Technical Results	1-8
Vehicle Subsystem	1-9
Electrical Drive Subsystem	1-10
Battery Subsystem	1-11
2 SYSTEM ANALYSIS AND DESIGN.	2.1-1
WBS 2.1 Requirements Review and Analysis	2.1-1
WBS 2.2 System Modeling and Performance Prediction	2.2-1
WBS 2.2.1 Description of Program	2.2-1
Modeling and Simulation Techniques	2.2-2
WBS 2.2.2 Summary of Results	2.2-3
WBS 2.3 System Design and Specifications	2.3-1
WBS 2.3.1 General System Description	2.3-1
WBS 2.3.2 Summary of System and Subsystem Specifications	2.3-1
WBS 2.3.3 Summary of Interface Specifications and Drawings.	2.3-2
WBS 2.3.4 Special Studies	2.3-2
Battery Compartment Heating and Cooling	2.3-2
Alternate Designs to Improve Vehicle Range	2.3-4
Electrical Drive Subsystem (EDSS) Cooling	2.3-5
Battery Emergency Disconnect System.	2.3-5
Effects of Battery Life as a Function of Equalization Charge	2.3-6
Battery Life Above 100 °F Ambient Temperature Operation	2.3-6
Implementation of Ground Fault Interrupter	2.3-6
Hydrogen Safety During Battery Charging and Motoring	2.3-6
Electrical Hazard Analysis	2.3-6
Projected Life Study on Electrical Drive Subsystem (EDSS) Components	2.3-7
WBS 2.3.5 System Wiring Diagrams and Interface Drawings.	2.3-7
Interface Meetings	2.3-13
WBS 2.4 Design Reviews.	2.3-13
WBS 2.5 Safety and Reliability Analysis	2.5-1
WBS 2.6 Electromagnetic Compatibility/Electromagnetic Interference Tests	2.6-1
Summary	2.6-1
Test Facilities	2.6-1
Conclusions	2.6-1

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Page</u>
3	SUBSYSTEM ANALYSIS AND DESIGN 3.1-1
WBS 3.1 Vehicle Subsystem	3.1-1
Introduction	3.1-1
WBS 3.1.1 Body Structure	3.1-3
Basic Packaging	3.1-3
Aerodynamic Development	3.1-5
Structural Design	3.1-7
Static Design Criteria	3.1-7
Dynamic Design Criteria	3.1-8
Crashworthiness Prediction (computer model)	3.1-15
Design Verification	3.1-18
Glazing	3.1-18
Interior Trim	3.1-22
Seat and Shoulder Belt Restraint System	3.1-25
Vehicle Shipment	3.1-25
Battery Hoist Design	3.1-26
Battery Tray Design	3.1-27
WBS 3.1.2 Chassis	3.1-30
Introduction	3.1-30
Front Suspension and Steering	3.1-30
Rear Suspension	3.1-31
Ride and Handling	3.1-31
Tires and Wheels	3.1-33
Brakes	3.1-34
Final Drive	3.1-40
Bumpers	3.1-45
WBS 3.1.3 Air Handling and Electrical System	3.1-45
WBS 3.1.3.1 Heater and Defroster	3.1-45
Windshield Wiper and Washer	3.1-49
PCU Blower	3.1-51
Purge Blower	3.1-51
Power Connectors	3.1-51
Concealed Headlamp System	3.1-51
WBS 3.1.3.4 Instruments, Controls, and Interior Lighting	3.1-53
Instrument Panel and Controls	3.1-53
Steering Column Components and Controls	3.1-59
Interior Lighting	3.1-61
Electrical Loads and Circuit Design	3.1-61
Electrical Loads - 12 V	3.1-61
Circuit Design	3.1-61
Motor Compartment	3.1-61
Instrument Panel	3.1-63
Body Wiring	3.1-64
Battery Tunnel System	3.1-64
WBS 3.1.5 Vehicle Design and Fabrication	3.1-71
WBS 3.2 Electrical Drive Subsystem	3.2-1
WBS 3.2.1 Parameter Optimization	3.2-1
Vehicle Parameter Variations	3.2-3
Battery Resistance Variation	3.2-4

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Page</u>
3	
SUBSYSTEM ANALYSIS AND DESIGN (Cont'd)	
WBS 3.2.2 Control Strategy and Sensors	3.2-5
Drive Control Methods	3.2-5
Rating Philosophy	3.2-5
Fuel Gauging	3.2-8
Battery Charging	3.2-11
WBS 3.2.3 Drive Motor	3.2-13
Results	3.2-14
Variety of Designs Developed for Evaluation	3.2-15
Appraisal of Other Motor Design Types	3.2-16
Fabrication	3.2-17
WBS 3.2.4 Armature Chopper	3.2-21
General Description	3.2-21
Armature Chopper Selection	3.2-23
WBS 3.2.4.1 Detailed Description of Armature Chopper	
Electronics	3.2-25
Armature Chopper Power Circuit	3.2-25
Dual Armature Base Drive	3.2-28
Armature Card 1	3.2-30
Armature Card 2	3.2-33
Armature Card 3	3.2-35
WBS 3.2.5 Field Chopper/Battery Charger	3.2-61
WBS 3.2.5.1 Field Chopper/Battery Charger	3.2-61
Function	3.2-61
Operating Principle	3.2-61
Battery Charging Mode	3.2-62
Field Chopping Mode	3.2-62
Circuit Description	3.2-63
Power Circuit	3.2-63
Control Circuit	3.2-70
Hardware Implementation	3.2-76
Circuit Data	3.2-76
Operating Waveforms	3.2-81
WBS 3.2.5.2 Logic Power Supply (LPS)	3.2-95
Function	3.2-95
Operating Principle	3.2-95
Circuit Description	3.2-96
Hardware Implementation	3.2-105
Circuit Data	3.2-115
Operating Waveforms	3.2-118
WBS 3.2.5.3 On-Board Charger Power Unit	3.2-120
WBS 3.2.6 Microcomputer Control	3.2-124
WBS 3.2.6.1 Microcomputer Functions	3.2-124
WBS 3.2.6.2 Propulsion Control	3.2-124
Propulsion Control Description	3.2-124
System Analysis	3.2-126
Hybrid Computer Simulation	3.2-129

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Page</u>
3	SUBSYSTEM ANALYSIS AND DESIGN (Cont'd)
WBS 3.2.6.3 Drive Sequencing	3.2-133
Description of I/O Signals	3.2-133
EV Sequence Diagram	3.2-135
WBS 3.2.6.4 Hardware Design	3.2-141
CPU Board	3.2-141
I/O Board	3.2-145
Interface Board	3.2-150
DC-DC Converter Board	3.2-153
WBS 3.2.6.5 Microcomputer Packaging	3.2-153
WBS 3.2.6.6 Microcomputer Software	3.2-157
System Description	3.2-157
Function Descriptions	3.2-159
Propulsion Control Function	3.2-166
Drive Sequencing Function	3.2-170
State Table	3.2-171
State Transition Processor	3.2-172
State Transition Request Routines.	3.2-173
Action Routines	3.2-173
Table Translator Program	3.2-174
Battery Charge and Fuel Gauge Functions	3.2-174
Determination of BVEX Flag	3.2-174
Charging Fuel Gauge Calculation	3.2-176
Motoring Fuel Gauge Calculation	3.2-177
Signal Monitoring Functions	3.2-179
I/O Functions.	3.2-179
Data Storage	3.2-179
ROM Organization	3.2-180
Appendix 3.2.6.6	3.2-182
WBS 3.2.7 Accessory Charger	3.2-183
Function	3.2-183
Operating Principle	3.2-183
Circuit Description	3.2-184
WBS 3.2.8 Drive Test Instrumentation	3.2-196
WBS 3.2.9 Transistor Power Module	3.2-199
Available Transistors	3.2-199
Power Darlington Chip.	3.2-200
Power Darlington Substrate	3.2-202
Thermal Resistance and Thermal Cycling.	3.2-203
Power Module	3.2-210
High Current Testing	3.2-213
High Current Test Yield	3.2-215
WBS 3.2.10 Electronics Packaging Subcontract	3.2-217
WBS 3.3 Battery Subsystem.	3.3-1
WBS 3.3.1 Battery Component Design	3.3-1
WBS 3.3.2 Tooling Development.	3.3-9
WBS 3.3.3 Battery Fabrication	3.3-10

TABLE OF CONTENTS (Cont'd)

<u>Section</u>		<u>Page</u>
3	SUBSYSTEM ANALYSIS AND DESIGN (Cont'd)	
	WBS 3.3.4 Development Testing	3.3-10
	WBS 3.3.5 Technical Support	3.3-12
	Charging	3.3-12
	Battery Temperature Control	3.3-13
	Regenerative Braking	3.3-13
	Fuel Gauge	3.3-14
	Battery Mathematical Model	3.3-15
	Hydrogen Gas Generation	3.3-15
	Accessory Battery and Charger	3.3-17
	Maintenance Schedule	3.3-18
	Connectors, Connector Shields, and Cabling	3.3-18
	External (to the battery) Watering/Venting System	3.3-20
4	TEST AND EVALUATION	4.1-1
	WBS 4.1 Synopsis of Master Test Plan	4.1-1
	Integrated Vehicle Tests	4.1-1
	Structural Safety Tests	4.1-2
	Vehicle Subsystem Tests	4.1-2
	Electrical Drive Subsystem Tests	4.1-2
	Battery Subsystem Tests	4.1-3
	Support and Special Test Equipment	4.1-3
	Documentation	4.1-4
	WBS 4.2 Special Test Equipment and Facilities	4.2-1
	Voltage Measurements	4.2-1
	Current Measurements	4.2-2
	WBS 4.3 Mule Car 30 mph Barrier Test	4.3-1
	Barrier Test Instrumentation	4.3-2
	Results	4.3-2
	WBS 4.4 Electrical Drive Subsystem Tests	4.4-1
	Tests Performed	4.4-1
	Microcomputer Tests	4.4-1
	Propulsion/Sequencing Control	4.4-2
	PCU Tests	4.4-2
	Electrical Drive Subsystem Tests	4.4-3
	WBS 4.6 Integrated Vehicle Performance Tests	4.6-1
	Objective	4.6-1
	Scope	4.6-1
	Tests	4.6-1
	Range on SAE J227a Schedule D Driving Cycle	4.6-1
	Range at Constant Speed	4.6-2
	Maximum Speed on Level Road	4.6-2
	Acceleration on Level Road	4.6-2
	Gradability	4.6-2
	Sustained Speed on 5% Grade	4.6-2
	Grade Climbing Ability	4.6-2
	Instrumentation	4.6-3
	For Performance Testing	4.6-3

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Page</u>
For Charging Propulsion Batteries	4.6-4
Test Facilities	4.6-4
Oval Test Track	4.6-4
Straightaways	4.6-4
Ride and Development Road	4.6-4
Dynamic Handling Facility	4.6-6
Highlights of ETV-1 Performance Results	4.6-6
Test Data and Results	4.6-9
Summary of ETV-1 Performance Test Results	4.6-44
Battery Gauge Calibration/Range Test	4.6-45
Test Results Discussion	4.6-46
 5 MANUFACTURING STUDY	 5-1

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
E-1	Photograph of Electric Test Vehicle	E-1
E-2	U.S. Department of Energy Near-Term Electric Vehicle Program - GE/Chrysler Vehicle	E-3
E-3	Front Suspension Schematic	E-4
E-4	Rear Suspension Schematic	E-4
E-5	Mule Car (shown during jacking test).	E-5
E-6	ETV Mule Car - 3/4 Frontal - Prior to Barrier Impact	E-6
E-7	ETV Mule Car - 3/4 Frontal - After Barrier Impact	E-6
E-8	Advanced dc Drive Subsystem	E-7
E-9	Power Conditioning Unit (PCU) with Covers	E-8
E-10	Microcomputer	E-9
E-11	Armature Chopper Power Circuit	E-9
E-12	Power Module	E-10
E-13	Field Chopper/Battery Charger - Power Circuit.	E-11
E-14	Microcomputer Block Diagram	E-12
E-15	Simplified State Sequencing Diagram	E-12
E-16	Cutaway View of EV2-13 Propulsion Battery	E-14
1-1	DOE Organizational Elements	1-2
1-2	Relationship of the General Electric Company to DOE Electric Vehicle Program	1-3
1-3	General Electric Electric Vehicle Program Organization	1-4
1-4	Chrysler Task Force Organization for the Near-Term Electric Vehicle Program - Phase II	1-6
1-5	Final Body Design	1-10
1-6	Packaged PCU	1-12
1-7	Packaged Microcomputer	1-12
1-8	Design Features of the EV2-13	1-13
2.1-1	ETV Specification Tree	2.1-1
2.1-2	ETV Interface Specification/Document Tree	2.1-2
2.2.1-1	Overall System Model	2.2-2
2.2.1-2	Propulsion Battery Model	2.2-3
2.2.1-3	Chopper Model	2.2-3
2.2.1-4	Motor Model	2.2-4

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
2.2.2-1 Energy Flow Model for GE-ETV on J227a Schedule D – Performance Prediction Model	2.2-6
2.2.2-2 Energy Flow Model for GE-ETV at Constant 25 mph – Performance Prediction Model	2.2-6
2.2.2-3 Energy Flow Model for GE-ETV at Constant 35 mph – Performance Prediction Model	2.2-7
2.2.2-4 Energy Flow Model for GE-ETV at Constant 45 mph – Performance Prediction Model	2.2-7
2.2.2-5 Energy Flow Model for GE Near-Term EV J227a Schedule D – Performance Prediction Model (W_{GVW} - 3920 lb)	2.2-9
2.2.2-6 Energy Flow Model for GE Near-Term EV Constant 25 mph – Performance Prediction Model (W_{GVW} - 3920 lb)	2.2-10
2.2.2-7 Energy Flow Model for GE Near-Term EV Constant 35 mph – Performance Prediction Model (W_{GVW} - 3920 lb)	2.2-10
2.2.2-8 Energy Flow Model for GE Near-Term EV Constant 45 mph – Performance Prediction Model (W_{GVW} - 3920 lb)	2.2-11
2.2.2-9 Energy Flow Model for GE Near-Term EV Constant 55 mph – Performance Prediction Model (W_{GVW} - 3920 lb)	2.2-11
2.3.1-1 ETV System Block Diagram.	2.3-1
2.3.5-1 Vehicle Wiring Diagram	2.3-9
2.3.5-2 System Interconnection Diagram	2.3-11
2.5-1 Results of Lurch Mode Test No. 1	2.5-2
2.5-2 Results of Lurch Mode Test No. 2	2.5-3
2.5-3 Results of Lurch Mode Test No. 3	2.5-3
2.6-1 Radiated Guide	2.6-1
2.6-2 Magnetic Field Levels	2.6-3
3.1-1 Front View of Near-Term Electric Vehicle	3.1-1
3.1-2 Rear View of Near-Term Electric Vehicle	3.1-2
3.1.1-1 Packaging Comparison – Rear Section View.	3.1-3
3.1.1-2 Packaging Comparison – Side View Section	3.1-4
3.1.1-3 Plan View – Chassis and Drive Subsystem.	3.1-4
3.1.1-4 Battery Support Frame	3.1-6
3.1.1-5 3/8 Clay Wind Tunnel Test (left side forward of windshield)	3.1-6
3.1.1-6 3/8 Clay Wind Tunnel Test (3/4 left rear view)	3.1-7
3.1.1-7 Graphic Representation of Sections Evaluated – 3/4 Left Front View.	3.1-10

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>		<u>Page</u>
3.1.1-8	Graphic Representation of Sections Evaluated – 3/4 Right Rear View	3.1-10
3.1.1-9	NASTRAN Modeling Flow Chart	3.1-13
3.1.1-10	NASTRAN Finite Element Graphic Representation	3.1-14
3.1.1-11	NTEV Mule Car Torsional Rigidity Test	3.1-14
3.1.1-12	MINIBASH Flow Diagram	3.1-15
3.1.1-13	Rate Crush Factors	3.1-16
3.1.1-14	MINIBASH Model – 30 mph Frontal Impact	3.1-17
3.1.1-15	MINIBASH Model – 30 mph Rear Impact	3.1-18
3.1.1-16	MINIBASH Plot – 30 mph Frontal Impact	3.1-19
3.1.1-17	MINIBASH Plot – 30 mph Rear Impact	3.1-19
3.1.1-18	Mule Car Battery Tunnel and Battery Pack Assembly	3.1-20
3.1.1-19	Mule Car Structural Twist Test	3.1-20
3.1.1-20	Mule Car Structural Beam Test	3.1-21
3.1.1-21	Mule Car Emergency Jacking Test.	3.1-21
3.1.1-22	Door Glazing Operating Mechanism	3.1-23
3.1.1-23	Glazing Forming Operation.	3.1-23
3.1.1-24	NTEV Interior Trim Sketch	3.1-24
3.1.1-25	NTEV Instrument Panel and Front Seat Interior Trim.	3.1-24
3.1.1-26	NTEV Rear Seat Interior Trim	3.1-25
3.1.1-27	NTEV Shipment Tie-down Points	3.1-26
3.1.1-28	Battery Pack Servicing Hoist – Full Down Position.	3.1-27
3.1.1-29	NTEV Battery Pack Servicing Hoist – in Servicing Position	3.1-28
3.1.1-30	NTEV Battery Tray and Retaining Rings	3.1-28
3.1.2-1	Front Suspension	3.1-30
3.1.2-2	Rear Suspension	3.1-31
3.1.2-3	Graphic Representation of Rear Suspension Finite Element Model .	3.1-32
3.1.2-4	Graphic Representation of Steady-State Yaw Response.	3.1-32
3.1.2-5	Graphic Representation of Transient Yaw Response	3.1-33
3.1.2-6	Brake System Performance and Balance Analysis (computer input) .	3.1-35
3.1.2-7	Stopping Distance vs Pedal Effort Graph	3.1-36
3.1.2-8	Brake System Performance Graph	3.1-36
3.1.2-9	Brake Effectiveness Curve	3.1-37

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.1.2-10 Regenerative Brake System Schematic	3.1-38
3.1.2-11 Typical Metering Valve Performance Curve.	3.1-39
3.1.2-12 Regenerative Brake Torque/Differential Pressure vs Input Curve .	3.1-39
3.1.2-13 Coastdown Motor Torque vs Speed	3.1-40
3.1.2-14 Phase I Drive System Schematic	3.1-41
3.1.2-15 Phase II Drive System Schematic	3.1-41
3.1.2-16 NTEV Transmission Partially Assembled	3.1-42
3.1.2-17 NTEV Transmission Test Setup	3.1-43
3.1.2-18 Transmission Endurance Test Cycle in Final Drive Laboratory. . .	3.1-44
3.1.2-19 NTEV Transmission Dynamometer Test Cycle Trace	3.1-44
3.1.3.1-1 Heater Temperature Verification Test Results	3.1-46
3.1.3.1-2 Defroster Compliance	3.1-47
3.1.3.1-3 Warmup Test Results - Composite.	3.1-48
3.1.3.1-4 Heater Control	3.1-49
3.1.3.1-5 Federally Required Wipe Area	3.1-50
3.1.3.1-6 Power Conditioning Unit/Motor Cooling System	3.1-51
3.1.3.1-7 Headlamps Raised.	3.1-53
3.1.3.2-1 NTEV Instrument Panel	3.1-54
3.1.3.2-2 Instrument Cluster Visibility Study	3.1-55
3.1.3.2-3 Final Cluster Configuration	3.1-55
3.1.3.2-4 Flexible Printed Circuit Board	3.1-57
3.1.3.2-5 Multifunction Control Stalk	3.1-60
3.1.3.2-6 Interface Harness Diagram	3.1-63
3.1.3.2-7 Tray-Mounted Female Receptacle - Front	3.1-66
3.1.3.2-8 Tray-Mounted Female Receptacle - Rear.	3.1-67
3.1.3.2-9 Tunnel-Mounted Male Receptacle - Front	3.1-68
3.1.3.2-10 Tunnel-Mounted Male Receptacle - Rear	3.1-69
3.1.3.2-11 Multi-Pin Connector-Body Mounted	3.1-70
3.1.5-1 Work Flow Diagram - Clay Model Through Design and Die Models .	3.1-72
3.1.5-2 NTEV Body Draft	3.1-73
3.1.5-3 NTEV Die Model Stack - Front View.	3.1-74
3.1.5-4 NTEV Die Model Stack - 3/4 Right Side	3.1-74

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>		<u>Page</u>
3.1.5-5	NTEV Die Model Stack – Rear View	3.1-74
3.1.5-6	Work Flow Diagram – Final Drawings Through Complete Body . . .	3.1-75
3.1.5-7	NTEV Underbody, Surface Plate, and Fixtures – 3/4 Front View . .	3.1-76
3.1.5-8	NTEV BIW Build – Side View	3.1-76
3.1.5-9	NTEV BIW Build – Rear View	3.1-77
3.1.5-10	NTEV Underbody – Front Portion	3.1-78
3.1.5-11	NTEV Underbody – Rear Portion	3.1-78
3.1.5-12	NTEV Motor Compartment	3.1-79
3.1.5-12a	NTEV Body Side Aperture Panel Assembly in Subassembly Fixture .	3.1-79
3.1.5-13	NTEV BIW Complete	3.1-80
3.1.5-14	Work Flow Diagram – Vehicle Assembly	3.1-81
3.1.5-15	NTEV Front Fascia	3.1-82
3.1.5-16	NTEV Transmission Installation	3.1-83
3.1.5-17	NTEV Motor Compartment	3.1-83
3.1.5-18	NTEV Instrument Panel, Seats, and Door Trim	3.1-84
3.1.5-19	NTEV Body Complete	3.1-84
3.2.1-1	Battery Energy – Field Flux Performance on J227a Urban Cycle . .	3.2-3
3.2.1-2	Vehicle Sensitivity Study	3.2-4
3.2.1-3	Battery Resistance Sensitivity Study	3.2-5
3.2.2-1	Torque Control Schemes	3.2-6
3.2.2-2	Overall Control Strategy Block Diagram	3.2-7
3.2.2-3	Torque Envelope	3.2-8
3.2.2-4a	Percent Capacity vs Battery Pack Voltage – 10 A	3.2-9
3.2.2-4b	Percent Capacity vs Battery Pack Voltage – 30 A	3.2-10
3.2.2-4c	Percent Capacity vs Battery Pack Voltage – 50 A	3.2-11
3.2.2-4d	Percent Capacity vs Battery Pack Voltage – 75 A	3.2-11
3.2.2-4e	Percent Capacity vs Battery Pack Voltage – 100 A	3.2-12
3.2.2-5	Typical Battery Charging Current Profile	3.2-12
3.2.2-6	Microcomputer Battery Charging	3.2-13
3.2.3-1	Motor Capabilities and Current Requirements	3.2-15
3.2.3-2	Motor Armature	3.2-17
3.2.3-3	Motor Field	3.2-18

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.2.3-4 Motor	3.2-18
3.2.3-5 Motor Outline	3.2-19
3.2.3-6 Connection Diagram.	3.2-20
3.2.4-1 Two Quadrant Single-Phase Chopper.	3.2-21
3.2.4-2 Armature Chopper - Microprocessor Interface	3.2-22
3.2.4-3 Interface Electronics	3.2-22
3.2.4-4 Candidate Armature PCU's (single quadrant)	3.2-23
3.2.4-5 Multiphase Chopper Maximum Input Harmonics	3.2-24
3.2.4-6 Total Weight of Series-Reactors vs Chopper Frequency for Various Peak-to-Peak Ripple Currents and Number of Phases . . .	3.2-25
3.2.4-7 Armature Chopper Power Loss	3.2-26
3.2.4.1-1 Typical Stalled Rotor Current 100 A/cm (zero at two divisions from bottom) Time: 1 ms/div	3.2-28
3.2.4.1-2 Typical Current Limited Motor Current 100 A/cm (zero at two divisions from bottom) Time: 5 ms/div	3.2-28
3.2.4.1-3 Typical dc Input Voltage and Current Measured at input to PCU . .	3.2-29
3.2.4.1-4 Transistor Collector-Emitter Voltage and Base Current	3.2-29
3.2.4.1-5 Transistor Collector-Emitter Voltage and Base Current at Turnoff. .	3.2-29
3.2.4.1-6 Base Drive Waveform	3.2-30
3.2.4.1-7 Base-Emitter Voltage and Base Current at Transistor Turnoff . . .	3.2-31
3.2.4.1-8 Base-Emitter Voltage and Base Current at Transistor Turnoff . . .	3.2-31
3.2.4.1-9 PWM Modulator Performance.	3.2-32
AC Power Circuit and Interconnection with Power Conditioning Unit Schematic	3.2-37
Dual Armature Base Drive Schematic	3.2-39
Armature No. 1 Schematic	3.2-41
Armature No. 2 Schematic	3.2-43
Armature No. 3 Schematic	3.2-45
Electric Vehicle Armature Base Drives.	3.2-47
Armature Chopper Card #1, Component Side	3.2-49
Armature Chopper Card #1, Lead Side	3.2-51
Armature Chopper Card #2, Component Side	3.2-53
Armature Chopper Card #2, Lead Side	3.2-55
Armature Card No. 3, Component Side	3.2-57
Armature Card No. 3, Lead Side	3.2-59

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.2.5.1-1 Field Chopper/Battery Charger	3.2-61
3.2.5.1-2 Idealized Waveforms	3.2-63
3.2.5.1-3 Power Circuit	3.2-65
3.2.5.1-4 Battery Charge Idealized Waveforms	3.2-67
3.2.5.1-5 Turnoff Circuit	3.2-68
3.2.5.1-6 Q4 Turnoff Waveforms.	3.2-69
3.2.5.1-7 Reset Circuit.	3.2-71
3.2.5.1-8 Control Circuit, Battery Charge Section	3.2-73
3.2.5.1-9 Control Circuit, Field Chopper	3.2-74
3.2.5.1-10 Schematic of Logic Section.	3.2-77
3.2.5.1-11 Field Chopper/Battery Charger Hardware	3.2-79
3.2.5.1-12 Control Circuit Card	3.2-80
3.2.5.1-13 Turnoff Circuit Card Layout	3.2-81
3.2.5.1-14 Reset Card Layout	3.2-82
3.2.5.1-15 Power Circuit Hardware - Side 1	3.2-83
3.2.5.1-16 Power Circuit Hardware - Side 2	3.2-84
3.2.5.1-17 Circuit Interconnections	3.2-85
3.2.5.1-18 Q4 Waveforms	3.2-87
3.2.5.1-19 Q4 Waveforms	3.2-87
3.2.5.1-20 Q4 Collector Current	3.2-87
3.2.5.1-21 Q4 Base 1 Current	3.2-88
3.2.5.1-22 Q4 Collector-to-Emitter Voltage	3.2-88
3.2.5.1-23 Turnoff Waveforms	3.2-88
3.2.5.1-24 Battery Current	3.2-89
3.2.5.1-25 Battery Current	3.2-89
3.2.5.1-26 Q4 Base 1 Current	3.2-90
3.2.5.1-27 Collector-Emitter Voltage	3.2-90
3.2.5.1-28 Battery Current	3.2-90
3.2.5.1-29 Battery Current	3.2-91
3.2.5.1-30 AC Line Waveforms	3.2-91
3.2.5.1-31 Q4 Waveforms	3.2-92
3.2.5.1-32 Q4 Waveforms	3.2-92
3.2.5.1-33 Q4 Waveforms	3.2-92

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.2.5.1-34 Q4 Collector Current and T4 Reset Current	3.2-93
3.2.5.1-35 Q4 Collector Current and T4 Reset Current	3.2-93
3.2.5.1-36 TP6 Voltage and Q4 Collector Current	3.2-94
3.2.5.1-37 Field Current Turnon	3.2-94
3.2.5.1-38 Field Current Turnoff	3.2-94
3.2.5.2-1 LPS Block Diagram	3.2-95
3.2.5.2-2 Transient Filter, Chopper Regulator, Storage Capacitor, and Crowbar	3.2-97
3.2.5.2-3 Simplified Inverter Schematic	3.2-98
3.2.5.2-4 Inverter Schematic	3.2-99
3.2.5.2-5 Output Section Schematic	3.2-101
3.2.5.2-6 Control Section Schematic	3.2-103
3.2.5.2-7 Internal Power Supply	3.2-107
3.2.5.2-8a LPS Control Logic Board (Component Side).	3.2-109
3.2.5.2-8b LSP Control Logic Board (Lead Side).	3.2-110
3.2.5.2-9a LPS Inverter Board (Component Side)	3.2-111
3.2.5.2-9b LPS Inverter Board (Lead Side)	3.2-112
3.2.5.2-10a LPS Output/Chopper Board (Component Side)	3.2-113
3.2.5.2-10b LPS Output/Chopper Board (Lead Side).	3.2-114
3.2.5.2-11 LPS Interconnection Diagram	3.2-115
3.2.5.2-12 CRD #2476 Connections	3.2-116
3.2.5.2-13 Q8 Waveforms	3.2-118
3.2.5.2-14 Q9 Base Drive	3.2-118
3.2.5.2-15 40 V Square Wave Output	3.2-119
3.2.5.2-16 Collector Currents of Q19 and Q23	3.2-119
3.2.5.2-17 Waveform at Common Cathode Connection of D33 and D34.	3.2-120
3.2.5.2-18 LM555 Output	3.2-120
3.2.5.3-1 On-board Charger Power Unit (OBCPU)	3.2-121
3.2.5.3-2 On-Board Charger Power Unit Electrical Schematic	3.2-123
3.2.6.2-1 Block Diagram of the Drive Control System	3.2-125
3.2.6.2-2 Operation Modes Diagram Simplified	3.2-125
3.2.6.2-3 Transfer Function Block Diagram of the Armature Chopper Control Loop	3.2-126

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.2.6.2-4 Analog Equivalent Circuit of the Compensator	3.2-127
3.2.6.2-5 Simulation Diagram of Digital Compensator	3.2-129
3.2.6.2-6 Transfer Function Block Diagram of the Field Control Loop. . . .	3.2-129
3.2.6.2-7 Simplified Real Time Simulation of the Drive System.	3.2-131
3.2.6.2-8 Simulation Performance Characteristics in Chopping Mode	3.2-131
3.2.6.2-9 Transient Response in Chopping Mode at $W = 0$	3.2-132
3.2.6.2-10 Simulation Performance Characteristics in Field Control Mode . .	3.2-132
3.2.6.2-11 Transient Response in Field Weakening Mode at $W = 3000$ rpm. . .	3.2-132
3.2.6.3-1 μ P Block Diagram with I/O Signals	3.2-134
3.2.6.3-2 Electric Vehicle Sequence Diagram	3.2-137
3.2.6.4-1 Simplified μ P Diagram	3.2-142
3.2.6.4-2 Schematic - CPU Board	3.2-143
3.2.6.4-3 Microcomputer Memory Map	3.2-145
3.2.6.4-4 Simplified I/O Diagram	3.2-146
3.2.6.4-5 I/O Board Microcomputer Schematic.	3.2-147
3.2.6.4-6 Linear Signal Variation	3.2-150
3.2.6.4-7 Computer Interface Board Microcomputer Schematic	3.2-151
3.2.6.5-1 Microcomputer Boards.	3.2-154
3.2.6.5-2 Printed Circuit Backplane	3.2-155
3.2.6.5-3 Microcomputer Enclosure	3.2-156
3.2.6.5-4 Microcomputer Enclosure Showing Card Access	3.2-156
3.2.6.5-5 Microcomputer with All Boards Installed	3.2-157
3.2.6.6-1 Software Functional Diagram.	3.2-158
3.2.6.6-2 Simplified Structure Chart of Software	3.2-160
3.2.6.6-2a Structure Chart of Software Modules	3.2-161
3.2.6.6-3 Memory Map of Base Page Module.	3.2-163
3.2.6.6-4 Initialization and Background	3.2-164
3.2.6.6-5 Interrupt Service Routines	3.2-164
3.2.6.6-6 Task Timing Diagram (not in scale)	3.2-165
3.2.6.6-7 Real Time Scheduler	3.2-167
3.2.6.6-8 Compensator Block Diagram	3.2-168
3.2.6.6-9 Armature Chopping Control Block Diagram	3.2-169

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.2.6.6-10 Field Weakening Control Block Diagram	3.2-170
3.2.6.6-11 Structure Chart of Sequential Controller	3.2-171
3.2.6.6-12 Functional View of Sequential Controller	3.2-171
3.2.6.6-13 Motoring Fuel Gauge Block Diagram	3.2-178
3.2.6.6-14 Memory Map of ROMs	3.2-180
3.2.7-1 Simplified Circuit Schematic	3.2-183
3.2.7-2 Accessory Charger	3.2-185
3.2.7-3 Power Circuit with Base Drive Board Removed	3.2-188
3.2.7-4a Control Logic Printed Circuit Board Layout (Component Side)	3.2-189
3.2.7-4b Control Logic Printed Circuit Board Layout (Lead Side)	3.2-190
3.2.7-5 Accessory Charger Printed Circuit Board Pin Connections	3.2-191
3.2.7-6 Accessory Charger Circuit	3.2-191
3.2.7-7a CRD #2511 Winding Details	3.2-192
3.2.7-7b Secondary Sheet Winding Dimensions	3.2-192
3.2.7-8 Q1 Quiescent Base Drive	3.2-193
3.2.7-9 I_c of Q1	3.2-193
3.2.7-10 Conditions for Average Charging Current 36 A	3.2-195
3.2.8-1 Drive Test Facility	3.2-196
3.2.8-2 Vehicle Simulation Flywheel Assembly and Detail	3.2-197
3.2.8-3 EV Drive System Test Facility	3.2-198
3.2.9-1 Darlington Transistor in Schematic Cross Section of Chip Before and After Solder Reflow Operation	3.2-200
3.2.9-2 Scanning Electron Micrograph Showing Aluminum Emitter Stripes and Polyimide Copolymer Over the Base Metal Strips	3.2-202
3.2.9-3 Darlington Transistor in Substrate™ Form	3.2-203
3.2.9-4 Heat Flow Pattern from Chip to Heat Sink and Equivalent Thermal Resistance Circuit.	3.2-205
3.2.9-5 Thermal Resistance of the Heat Spreader vs the Fin Area of Heat Sink	3.2-206
3.2.9-6 Stress and Curvature as Functions of Heat Spreader Thickness, for the Silicon Chip (solid line) and the Substrate (dashed line) on Copper	3.2-208
3.2.9-7 DC Common Emitter Current Gain Characteristic of the Two-Stage Darlington Transistor	3.2-208

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>		<u>Page</u>
3.2.9-8	Schematic of the Armature Chopper Circuit.	3.2-209
3.2.9-9a	Top Trace: Base Current as a Function of Time.	3.2-209
3.2.9-9b	Storage Time, t_s , Fall Time, t_f , and ON-state Voltage, $V_{CE(SAT)}$, as Functions of Collector Current	3.2-210
3.2.9-10	Schematic of the Components and Assembly of the Power Hybrid Integrated Circuit	3.2-211
3.2.9-11a	Operation of Two Integrated Circuits in Parallel with a Common Base Drive Voltage, Top Trace: $V_{BE} = 5$ V/cm.	3.2-212
3.2.9-11b	I_C vs V_{CE} During Turnoff, 250 A, Comparing Loose vs Tight Shubbers and Single vs Double Base Operation.	3.2-214
3.2.9-12	Comparison of How 200 A Are Switched in a Pair of Modules When 400 A Are Shared in Parallel or When 200 A Are Forced Through Individually.	3.2-214
3.2.9-13	Energy Dissipated in One Turnoff Transition as a Function of the Current Switched in a Module.	3.2-215
3.2.9-14	Temperature Dependence of Switching for SM-37 Operated as Single (double) Base Device	3.2-216
3.2.9-15	Yield of Modules in High Current Testing.	3.2-216
3.2.10-1	Power Conditioning Unit (PCU)	3.2-217
3.2.10-2	PCU Block Diagram	3.2-219
3.2.10-3	PCU Side 1.	3.2-220
3.2.10-4	PCU Side 2.	3.2-221
3.2.10-5	PC Logic Board Stacking Arrangement	3.2-221
3.2.10-6	Accessory Charger Filter Capacitors	3.2-222
3.3.1-1	Battery Pack Layout	3.3-2
3.3.1-2	Cutaway View of EV2-13 Propulsion Battery	3.3-3
3.3.1-3	Estimated Peukert Curves for Battery Designs A and B (80 °F)	3.3-5
3.3.1-4	Estimated Discharge Curves for Battery Pack at Various Current Rates - Designs A and B (80 °F)	3.3-6
3.3.1-5	Estimated Electrolyte Freezing Temperature as a Function of Depth of Discharge - Designs A and B	3.3-6
3.3.1-6	Propulsion Battery (EV2-13) - External View of Two Types	3.3-7
3.3.1-7	Advantages of Having Two Battery Types: Less Cable is Required, Resulting in (1) Lower Cable Weight (-2 lb) and (2) Lower Circuit Resistance and Inductance	3.3-9
3.3.5-1	Overview of Effect of Temperature	3.3-13
3.3.5-2	Effect of Temperature on Capacity of GE EV Battery - Design A	3.3-14

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>		<u>Page</u>
3.3.5-3	Battery Pack Open-Circuit Voltage vs State of Charge (80 °F) . .	3.3-15
3.3.5-4	EV2-13 Battery Voltage During Constant-Current Discharges at 3 Rates at 80 °F vs State of Charge	3.3-16
3.3.5-5	Peukert Curve for EV2-13 at 80 °F (3 ceil cutoff voltages)	3.3-16
3.3.5-6	Hydrogen Gas Generation During Charging	3.3-17
3.3.5-7	Connector and Cable Top View	3.3-19
3.3.5-8	Section View of Connector on Battery Terminal	3.3-19
3.3.5-9	Venting/Watering System Schematic	3.3-20
4.2-1	Instrumentation Schematic	4.2-1
4.2-2	Sensor and Signal Conditioning Circuitry	4.2-2
4.4-1	Thermal Transient Response Within the Microcomputer Box. . . .	4.4-2
4.4-2	Electrical Drive Subsystem Test Configuration	4.4-3
4.6-1	ETV-1 Performance Test Location - Chrysler Corporation, Chelsea Proving Grounds	4.6-5
4.6-2	J227 A Schedule D Acceleration Segment	4.6-7
4.6-3	ETV-1 Battery Gauge Performance Based on the Time During the Constant 45 mph Range Test on June 14, 1979	4.6-45

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1-1	Contractor Responsibilities.	1-5
1-2	DOE Objectives.	1-7
1-3	Test Results Versus Key Performance Objectives	1-9
2.5-1	Lurch Mode Tests	2.5-2
2.6-1	Test B Radiated Emissions (EMI)	2.6-2
3.1.1	Package Comparisons	3.1-2
3.1.1-1	Luggage Capacity Comparison	3.1-5
3.1.1-2	Structural Areas and Items Targeted.	3.1-8
3.1.1.3	Standard Section Location Definition	3.1-9
3.1.1.4	Justification for Targeted Sections	3.1-11
3.1.1.5	NTEV Minimum Section Properties	3.1-12
3.1.1.6	Glazing Abrasion Test	3.1-22
3.1.1-7	Battery Pack Retention System	3.1-29
3.1.2-1	Ride Frequency Comparison at Two-Passenger Loading.	3.1-33
3.1.2-2	Jounce Travels – MM	3.1-34
3.1.2-3	Drag Torque Comparison Phase I vs Phase II	3.1-42
3.1.3.1-1	PCU Blower Test Data.	3.1-52
3.1.3.2-1	Instrument Cluster Nomenclature and Graphics	3.1-56
3.1.3.2-2	Electrical Loads	3.1-62
3.1.3.2-3	Fuse Chart.	3.1-65
3.2.1-1	Summary of Evaluation Results	3.2-2
3.2.2-1	Drive Component Ratings	3.2-7
3.2.3-1	Motor Data	3.2-14
3.2.6.2-1	Parameters Affecting the System Control Loops	3.2-127
3.2.6.6-1	Distribution of Functions Among Tasks.	3.2-158
3.2.6.6-2	Functions Determined By Mode	3.2-159
3.2.6.6-3	Task 1 Functions	3.2-169
3.2.6.6-4	State Table Linkage Parameters	3.2-175
3.2.6.6-5	Signals Monitored in Tasks 2 and 4.	3.2-179
3.2.6.6-6	ROM Organization	3.2-181
3.2.7-1	Circuit Performance Calculations	3.2-194
3.2.8-1	Disk Numbers and Vehicle Weight Relationship	3.2-198
3.2.9-1	Devices Evaluated in Chopper Circuit	3.2-199

LIST OF TABLES (Cont'd)

<u>Table</u>	<u>Page</u>
3.2.9-2 Summary of Measured Properties of Polyimide Copolymer	3.2-201
3.2.9-3 Effect of Solder Composition on Solder Joint Reliability as Measured by the Thermal Resistance ($^{\circ}\text{C}/\text{W}$)	3.2-206
3.2.10-1 Heat Exchanger Pressure Drop	3.2-218
3.2.10-2 Heat Exchanger Thermal Resistance.	3.2-218
3.3.1-1 Propulsion Battery Goals and Specifications	3.3-1
3.3.1-2 Estimated Weight and Performance of Designs A and B.	3.3-4
3.3.1-3 Estimated EV2-13 Weight and Performance Versus SOW Specifications	3.3-7
3.3.1-4 List of EV2-13 Product Drawings August 22, 1979	3.3-8
3.3.2-1 EV2-13 Tooling	3.3-9
3.3.4-1 Summary of Test Results.	3.3-11
3.3.4-2 Individual Battery Data	3.3-11
3.3.5-1 Charging Information	3.3-12
3.3.5-2 Range of Estimated Hydrogen Generation Volumes	3.3-18
4.4-1 Logic Power Supply Output.	4.4-1
4.6-1 ETV-1 Performance Test Results	4.6-7
4.6-2 ETV-1 Performance Test Results	4.6-44
5-1 1975 Electric Vehicle Costs	5-1
5-2 Consumer Cost and Investment Summary By Category	5-2
5-3 Cost By Category	5-3

EXECUTIVE SUMMARY

This report describes the work performed by the General Electric Company and its subcontractors as part of the Near-Term Electric Vehicle Program. The contract was conducted for the U.S. Department of Energy and technical management was provided by the Jet Propulsion Laboratory, California Institute of Technology. The period of performance for this work was April 1977 through July 1979.

The purpose of this research and development was to develop and deliver to the DOE two advanced experimental electric cars known as Electric Test Vehicles (ETV's). These vehicles incorporate technology improvements to achieve a level of performance substantially better than previous state-of-the-art electric vehicles. Specific objectives were established for vehicle performance, safety, cost, and consumer acceptance. The vehicles were also specified to be suitable for production by the mid 1980's. As detailed in this report, the DOE objectives have generally been achieved. With some further advances in battery technology expected by 1982, all performance and cost objectives can be satisfied. A photograph of the ETV is shown in Figure E-1.



Figure E-1. Photograph of Electric Test Vehicle

The Electric Test Vehicles delivered under this contract were developed as a total system, with careful attention to the interactions between vehicle body and chassis, electrical drive subsystem, and propulsion battery. Beginning with the creation of system specifications, each step of the design and development process was controlled to achieve the best end result. Electrical, mechanical and control interfaces were also carefully analyzed and controlled to insure compatibility between subsystems. As a result of this systems approach, the test vehicles represent a careful balance between sound automotive design, innovative technology, and overall energy efficiency. Utilizing many proven components and adhering to established manufacturing techniques, these vehicles are suitable to serve as preproduction models for further evolutionary development.

General Electric Corporate Research and Development (CRD) served as the prime contractor for this program and was responsible for the overall system design. CRD also developed the complete electrical drive subsystem, utilizing the expertise of several other General Electric components to furnish equipment and engineering services which contributed greatly to a successful design.

The total responsibility for automotive engineering, design, and manufacture of the test vehicles was subcontracted to Chrysler Corporation. Chrysler's Research Office performed the vehicle engineering with support from many other operating departments. Design and fabrication of the test vehicles was subcontracted by Chrysler to Modern Engineering Services, Inc. Modern Engineering performed their design and fabrication work under direct supervision by Chrysler engineers.

Battery subsystem design, fabrication, and test were the responsibility of Globe Battery Division of Globe-Union Inc. The battery subsystem developed by Globe-Union includes an advanced single-point watering system. Globe-Union also provided valuable engineering assistance to General Electric CRD for the development of battery chargers, regenerative braking techniques, and fuel gauging.

Each major subsystem of the Electric Test Vehicle displays new technology developments which contribute to the vehicle's improved performance. This executive summary gives a description of the development process and significant technical accomplishments for each subsystem (Vehicle, Electrical Drive, and Battery).

VEHICLE SUBSYSTEM

Development of the vehicle subsystem began with packaging studies to determine the overall vehicle size, passenger seating dimensions, battery location, and drive train configuration. Seating for four adults was necessary, and passenger comfort was maintained by close adherence to Chrysler's corporate standards for critical seating dimensions. The final seating package comfortably accommodates two 95th-percentile males in front and two 50th-percentile males in the rear seats.

After the basic packaging of the ETV was determined, styling and aerodynamic studies began to define the body shape and appearance. A difficult target was given to the stylists to achieve a product of drag coefficient and frontal area ($C_D A_F$) no greater than $0.53 \text{ m}^2 (5.7 \text{ ft}^2)$. Several basic shapes were investigated using wind tunnel tests on 3/8 scale models. Based on these iterative design and test activities, the body design shown in Figure E-1 was selected. This handsome fastback coupe achieved a drag coefficient (weighted for wind direction) of 0.30 in wind tunnel tests with road trim. Combined with a frontal area of just over $1.76 \text{ m}^2 (19 \text{ ft}^2)$, the excellent aerodynamic design meets all program objectives. Special features of the design which help to achieve such low aerodynamic drag are the smooth, flowing curvature of the front surfaces, an integral air dam, and belly pans to minimize under-car turbulence. Side windows are completely flush with the body surface and contribute to smooth flow around the A-pillar region. Fenders and rear quarters shield the wheel openings to reduce turbulence around the tires, resulting in a "coke-bottle" shape at the sill. A functional rear spoiler and flush rear hatch design also contribute to the slippery shape of the ETV, which has approximately 50% lower drag than any comparable production vehicle.

Several possible locations and mounting methods were investigated for the propulsion batteries. The final position, illustrated in Figure E-2, provides good weight distribution and crashworthiness while minimizing intrusion into the seating space. The batteries

are located along the vehicle centerline in a sealed tunnel which provides excellent structural rigidity. Within the seating area, a single row of batteries is mounted to retain adequate seating comfort and to reduce frontal area. Behind the rear seats, two batteries are mounted outboard on each side. To accommodate this T-section design, a special rear suspension was developed. Mounting of the batteries to the car is accomplished by means of a light aluminum tray which carries the eighteen 6 V modules and is bolted to the battery tunnel from the bottom side. Battery removal and replacement is easily accomplished with the vehicle raised on a service lift, using a battery jack provided with each car.

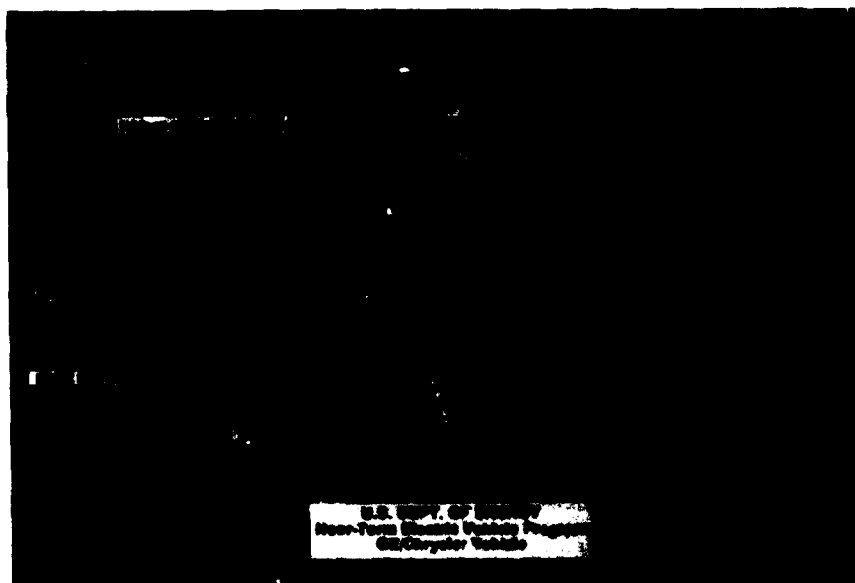


Figure E-2. U.S. Department of Energy Near-Term Electric Vehicle Program – GE/Chrysler Vehicle

An important objective of the vehicle design was to meet all applicable Federal Motor Vehicle Safety Standards (FMVSS), making the ETV's just as safe to operate as conventional cars. To insure meeting the FMVSS requirements, Chrysler Corporation made use of previously-qualified designs wherever possible. Some of the areas where carry-over designs were used include door locks, passenger restraints, instrument panel, steering wheel, and brakes. In those areas where new designs were required such as the main body structure, extensive analyses and testing were performed to demonstrate compliance with the FMVSS regulations.

Efficient packaging of the electrical drive subsystem dictated the use of front wheel drive, with the drive motor positioned transversely to eliminate right-angle gears. Standard production parts from the newly-developed Omni and Horizon vehicles were adapted to the ETV chassis, including the final drive mechanism and front suspension members. To reduce friction losses in the drive train, a new silent chain transaxle unit was developed and tested at Chrysler. Figure E-3 illustrates the compact arrangement of the drive motor, transaxle, steering, and front suspension which resulted from Chrysler's design studies.

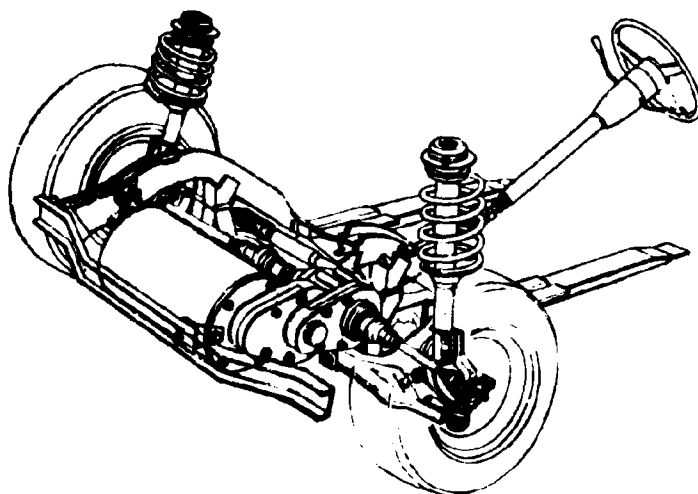


Figure E-3. Front Suspension Schematic

An independent rear suspension system was developed for the ETV, to allow convenient mounting of batteries behind the rear seat. An early version of the rear suspension design is illustrated in Figure E-4. The final design is nearly identical but has fixed mounting points which establish optimum caster and camber as determined by handling tests.

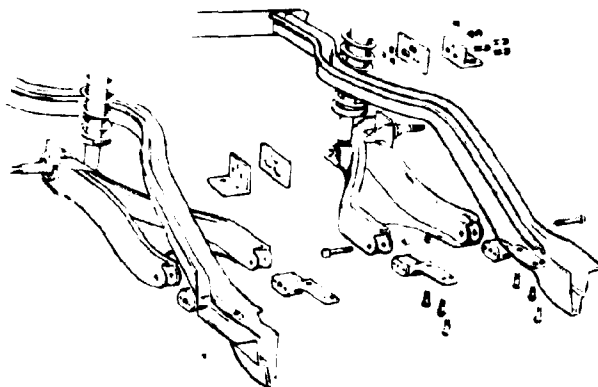


Figure E-4. Rear Suspension Schematic

Successful development of the vehicle subsystem was greatly enhanced by the use of a "mule" car illustrated in Figure E-5. The mule car is a prototype Plymouth Horizon, extensively modified to incorporate front and rear suspension brakes, battery tunnel, and structural refinements designed for the ETV. Developmental tests performed with the mule car included ride and handling evaluations, braking tests, structural twist and beam tests, and jacking tests. These tests were performed using a conventional gasoline engine to propel the car. The mule car was then further modified by removing the gasoline engine

and installing a complete electric drive (some electronic components still under development were replaced by structurally identical mock-ups). The "electric" mule was then subjected to a 30 mph barrier impact to demonstrate compliance with FMVSS requirements for crashworthiness. "Before" and "after" pictures of the 30 mph barrier test are shown in Figures E-6 and E-7. All criteria of FMVSS 204, 212, and 219 were satisfied after this test.



Figure E-5. Mule Car (shown during jacking test)

To enhance the energy efficiency of the ETV, it was necessary to reduce weight wherever possible. However, where structural integrity was concerned no sacrifice of crashworthiness could be tolerated. The difficult trade-offs between light weight, safety, and producibility were carefully examined during the ETV design. The final design employs an efficient unibody structure into which the battery tunnel is fully integrated. High strength, low alloy steel is used in several locations to obtain a high strength-to-weight ratio. External body panels such as the doors, hood, and fenders are heat treated aluminum. Aluminum is also used for hood and door inner panels and in-door guard beams. Side and rear windows are Lexan[®], while the windshield is conventional safety glass. Through efficient design and the selected use of lightweight materials, a total curb weight of 1506 Kg (3320 lbs) was achieved. This weight, while representing a significant accomplishment, could be further reduced given additional development time. Special chassis components, tires, and drive motors could be developed (for example) but these were not feasible within the given contract schedule. By the mid-1980's a weight reduction of 45 Kg (100 lbs) could be achieved. This would result in a range improvement of 3 Km (≈2 miles) in urban driving.

[®]Registered trademark of General Electric Company for polycarbonate resin



Figure E-6. ETV Mule Car - 3/4 Frontal - Prior to Barrier Impact



Figure E-7. ETV Mule Car - 3/4 Frontal - After Barrier Impact

ELECTRICAL DRIVE SUBSYSTEM

The basic configuration of the electrical drive subsystem was selected from several alternates considered during Phase I of the Near Term Electric Vehicle contract. This study showed that a separately-excited dc motor with electronic armature and field controls would provide the best combination of efficiency, performance, and production cost for a near term all electric vehicle. For maximum range in stop-and-go driving, the car would utilize regenerative braking to recover kinetic energy. An on-board battery charger integrated with the drive subsystem was specified. New technology developments called for in the drive electronics included the use of high power transistors for armature and field controls, and an on-board microcomputer to provide flexible programmed control of the entire electrical subsystem.

During the Phase II contract, the advanced dc drive subsystem shown in Figure E-8 has been implemented. This was an entirely new design which incorporates several state-of-the-art improvements. All objectives previously established for the drive subsystem have been met, resulting in smooth flexible control of the vehicle speed and torque under all driving conditions. Maximum battery current is limited to 400 A for improved range performance. Due to the high efficiency of the drive subsystem, total energy consumption on the urban driving cycle is less than 0.25 kWh/km (0.4 kWh/mile).

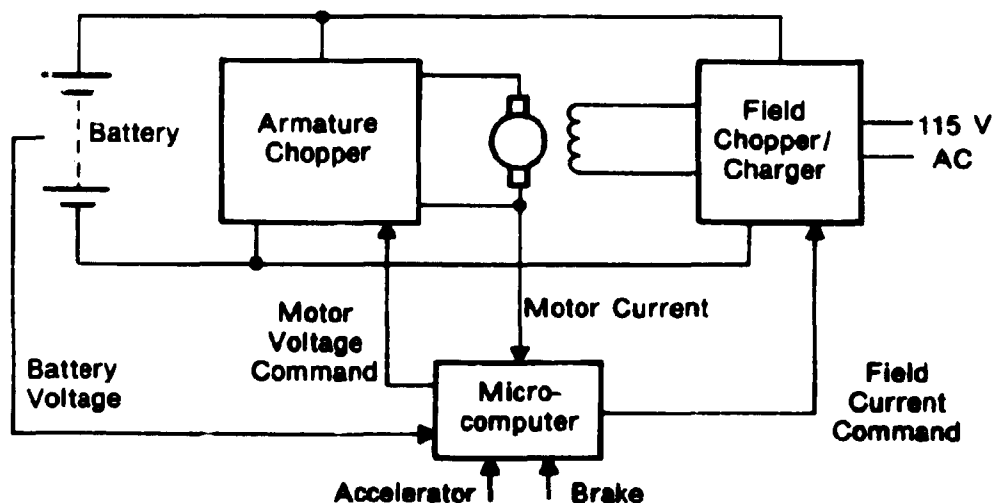


Figure E-8. Advanced dc Drive Subsystem

A first step in designing the electrical drive subsystem was to specify dc motor characteristics. More than 20 candidate designs were evaluated by CRD based on preliminary design data from General Electric's DC Motor and Generator Department (DCM&G). The selected motor design is a four-pole separately-excited machine, nominally rated 15 kW continuous at 96 V dc. The speed range for field control is nominally 2:1, from 2500 to 5000 rpm. This motor design gave the maximum urban range of all designs evaluated during computer simulation studies conducted at CRD. Maximum rated motor speed of 5000 rpm corresponds to a vehicle speed of 96 km/hr (60 mph). The control strategy involves armature speed control from 0 to 48 km/hr, and field control from 48 to 96 km/hr.

When operating in the field control mode, the motor armature is connected directly to the propulsion battery and losses in the armature controller are eliminated by a bypass contactor.

New electronic circuitry was developed at CRD for the motor controls, battery chargers, and microcomputer which comprise the electrical drive subsystem. The functional units which make up the control electronics include a bidirectional armature chopper, a combined field chopper/battery charger, an accessory battery charger, a logic power supply, and the microprocessor controller with associated signal conditioning circuits. Built-in current, voltage, and temperature sensors are provided for measuring critical control parameters. All of these electronic functions are packaged into two compact units known as the Power Conditioning Unit (Figure E-9) and the Microcomputer (Figure E-10). A third small package (not shown) contains the circuit breaker, line filter, and relays associated with the on-board battery charger 115 V ac power supply. All elements of the electrical drive subsystem were designed for maximum efficiency, and fail-safe controls were implemented to improve overall system reliability. Key functions of the drive electronics are briefly described in this summary. For additional details the reader should consult Section 3.2 of the Final Report.



Figure E-9. Power Conditioning Unit (PCU) with Covers

The armature chopper (Figure E-11) provides continuous control of motor voltage and current in the speed range from 0-48 km/hr. Bidirectional control is provided, allowing the drive motor to operate either as a motor (supplying drive torque) or as a generator (supplying recharge energy to the propulsion battery) without reversing the field connections.

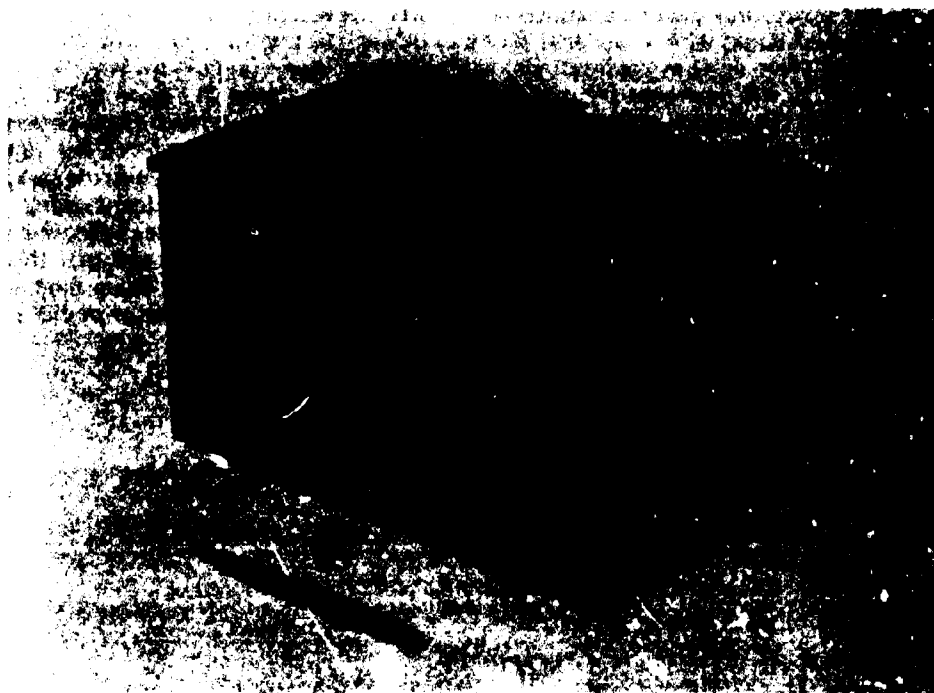


Figure E-10. Microcomputer

Maximum rated armature current is 400 A in motoring and 200 A in the regenerative braking mode. Continuous rating of the armature chopper is 175 A, which corresponds to rated continuous power for the drive motor.

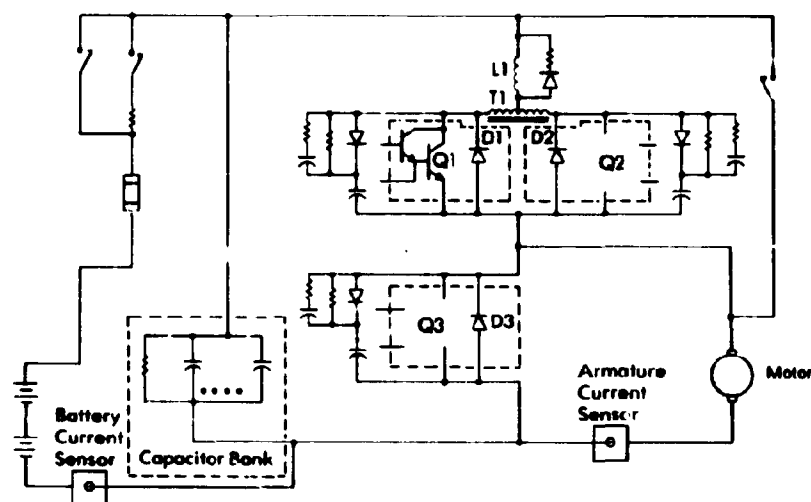


Figure E-11. Armature Chopper Power Circuit

Transistor power modules of a unique design were developed for the armature chopper circuit. Beginning with a General Electric Power Darlington transistor developed at CRD for earlier drive system applications, several proprietary techniques were employed to develop the high power low-cost transistor module which is shown in Figure E-12. This module contains two Darlington transistor chips and a fast recovery power diode packaged for maximum power dissipation. Two of the modules shown are used to control the 400 A motoring current in the armature chopper while a single identical module controls up to 200 A of regenerative current. A similar module of lower power rating (containing only one transistor) is used in the field chopper/battery charger. The General Electric integrated power modules used in the electrical drive subsystem are about one half the size and weight of competitive devices. Based on production cost studies, these modules could be built for less than one fifth the cost of previously available transistor devices of the same rating.



Figure E-12. Power Module

The field chopper/battery charger (Figure E-13) is a high frequency transistor chopper which operates in either of two modes. During motoring and regenerative braking, the field chopper supplies a regulated current to the motor field. Above base speed of the motor, this field current is controlled by microcomputer commands to regulate the motor speed and torque in response to the accelerator setting. When operating as a battery charger, the chopper circuit operates under microcomputer control to furnish a regulated charging current for the propulsion battery. A maximum charging current of 24 A is available at room temperature from a 115 V ac, 30 A power line input. Operating at

a frequency of about 15 kHz, the field chopper/battery charger achieves an operating efficiency of 93% at full load. Power factor and power line harmonics are maintained within recommended levels by means of line filters. The battery charger will operate from either a 15 A or 30 A power circuit, and a detector circuit is provided to limit charging current to the appropriate value for each source.

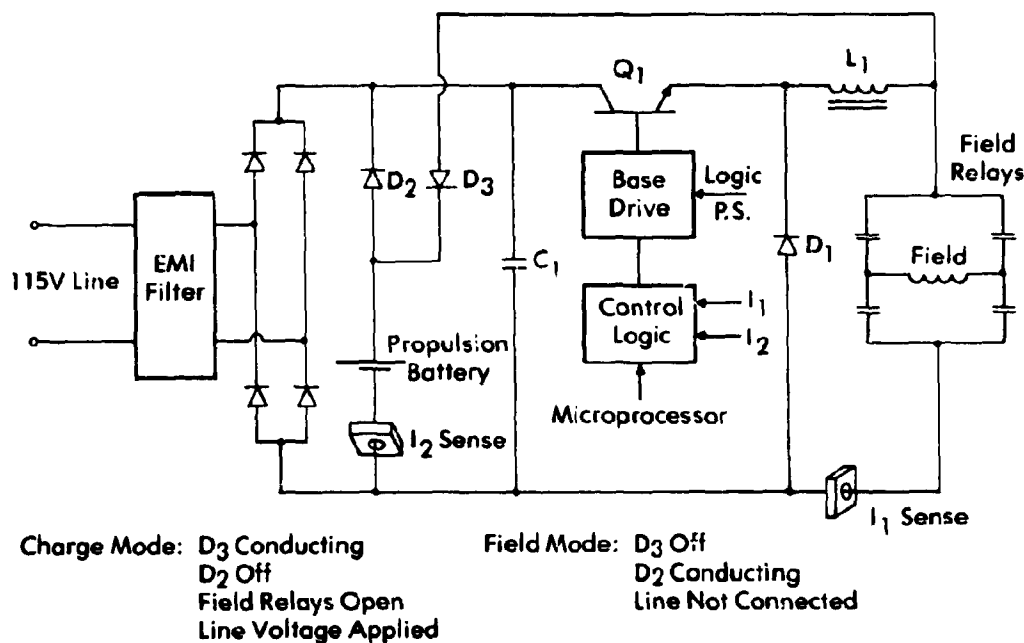


Figure E-13. Field Chopper/Battery Charger – Power Circuit

At the heart of the electrical drive subsystem is a microprocessor-based controller which receives all driver commands, system status inputs, and sensor signals. Operating on these input signals, the microcomputer (Figure E-14) generates output commands which control the operation of the armature and field choppers and the battery charger. In addition to providing real-time closed-loop control of the propulsion subsystem, the microcomputer also controls battery charging, calculates battery state-of-charge, and drives a fuel gauge display on the instrument panel. Other computer-generated displays are a "drive activated" lamp, a "motor overspeed" lamp, and a "charging" lamp.

The microcomputer is a unique design for this application, based on the Intel 8080A microprocessor and associated peripheral chips. Signal conditioning and interface circuits included within the microcomputer provide A to D and D to A conversion, noise filtering, and optical signal isolation to achieve noise-free operation with the high power chopper circuits in the Power Conditioning Unit. Military-grade integrated circuits are employed throughout the microcomputer to insure stable operation over the ambient temperature range encountered in the vehicle. As a further precaution against electrical noise and high temperatures, the microcomputer is located in the passenger compartment behind the instrument panel.

Software design of the microcomputer is based on a finite-state machine architecture in which each valid state represents a well-defined operating mode of the vehicle.

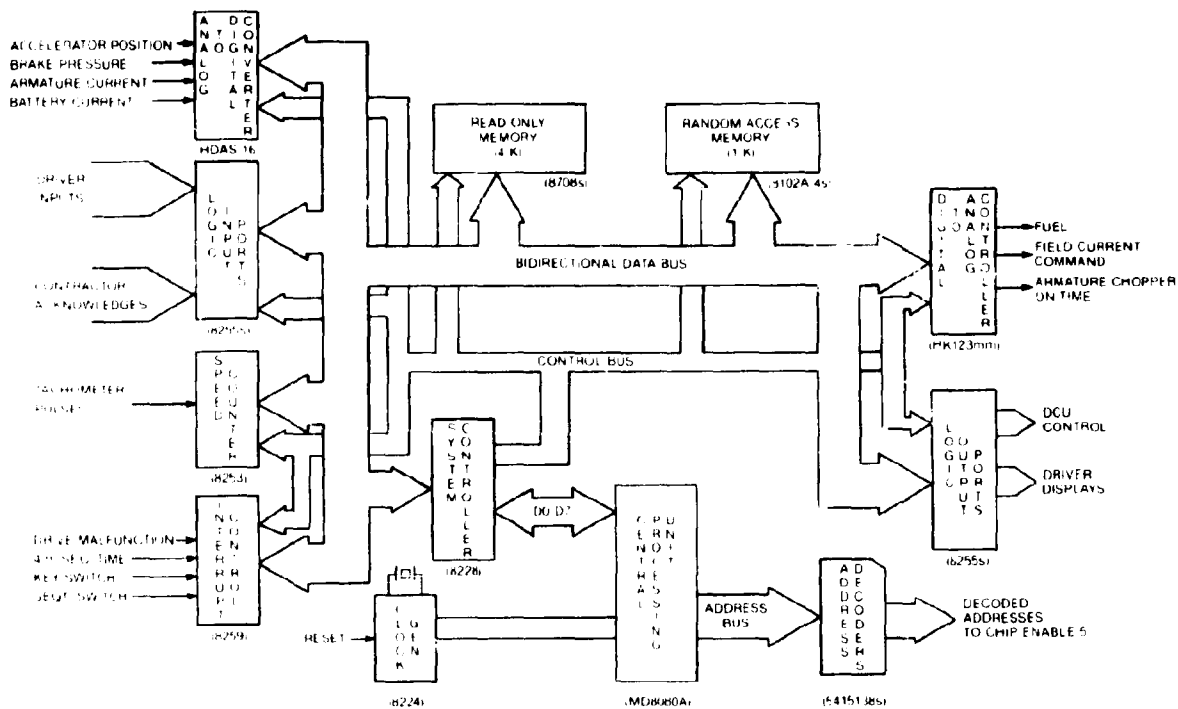


Figure E-14. Microcomputer Block Diagram

This concept is illustrated in Figure E-15 which shows in simplified form the possible transitions between operating states. To control the sequencing of these states, and to perform the real time processing functions of the computer, a set of modular software routines is employed. These program modules operate under control of an executive program. All programs are stored in read-only memory (ROM) which provides reliable error-free operation in the vehicle environment.

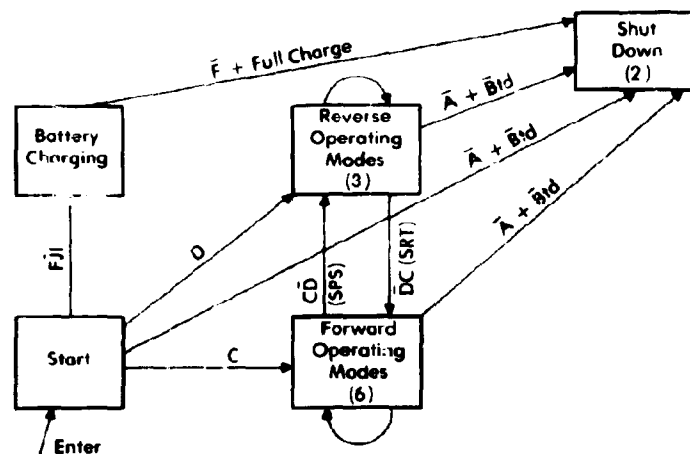


Figure E-15. Simplified State Sequencing Diagram

Operation of the electrical drive subsystem is completely automatic and effortless for the driver. Controls are similar to a conventional car, and only the presence of certain unique displays would indicate that the ETV is an electric car. Battery charging is equally effortless — the driver simply plugs in the battery charger to a 115 V ac source and selects either the normal (daily) or equalizing (weekly) charge mode. Once charging is initiated, the microcomputer will automatically regulate the charging current to maintain battery voltage within prescribed limits. A temperature-compensated control loop automatically adjusts the limit voltage as a function of battery voltage.

BATTERY SUBSYSTEM

The greatest single factor which limits the range and performance of any electric vehicle is its propulsion battery. Critical performance requirements for the battery include energy density (stored watt-hours per pound of battery weight), power density (maximum power output per pound), and cycle life (usable number of deep-discharge cycles). Production cost is also important, since battery replacement is a controlling factor in the total life-cycle cost of the vehicle. Based on studies performed during the Phase I contract, an improved lead-acid battery was specified to power the ETV. This selection was made because the lead-acid battery would provide the best combination of energy density, power density, cycle life, and manufacturing cost available within the time frame of this program.

Globe-Union Inc. was selected by General Electric to develop the improved vehicle batteries required for the ETV. Globe-Union has been active for many years in research and development of lead-acid batteries for vehicle propulsion and offered a number of design innovations for this application. Based on previous development results, design goals of 37.5 Wh/kg, (17 Wh per pound), 220 W/kg (100 W per pound) (instantaneous peak), and a life of 500 deep-discharge cycles were specified. These goals have been met by the EV2-13 battery developed under this contract.

The EV2-13 battery, illustrated in Figure E-16, incorporates many special design features which contribute to its superior performance and life characteristics. These are briefly summarized here with additional details in the body of the Final Report.

The EV2-13 battery uses flat-plate electrodes, with 13 plates per cell. Each plate contains a lead/antimony grid onto which the active material is applied in paste form. The plates used in the EV2-13 have several special characteristics including:

- A radial grid design which minimizes lead weight while providing uniform current density
- Large plates with near-optimum aspect ratio, resulting from 90 degree rotation of the cell alignment
- Low-antimony grid alloy to reduce water consumption

Other features of the EV2-13 battery which improve its performance are the following:

- Optimized positive-to-negative active material and electrolyte-to-active material ratios
- Additional energy storage volume by means of a high-rise cover design

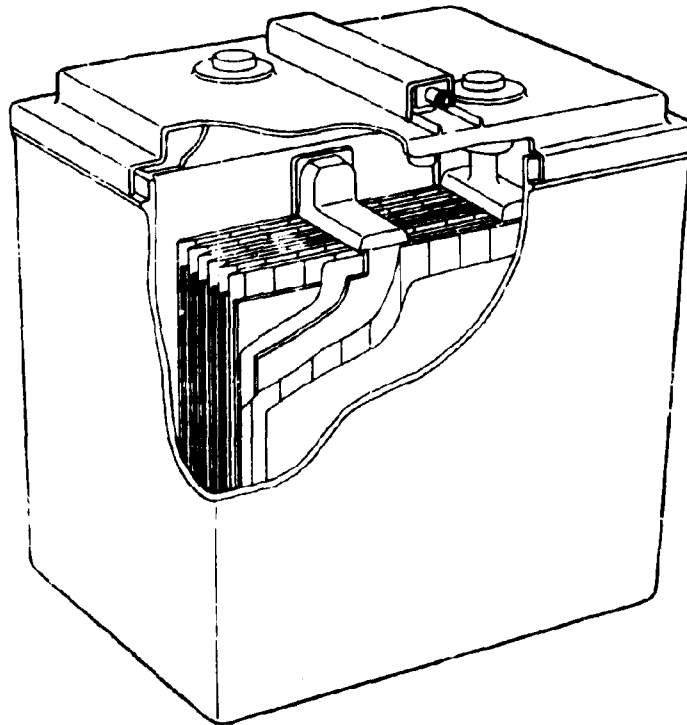


Figure E-16. Cutaway View of EV2-13 Propulsion Battery

- Thin-wall, heat-sealed polypropylene container
- Low-resistance, through-partition intercell connectors
- Envelope separators with glass mats for long battery life

By combining all of these features in a carefully balanced design, the EV2-13 achieves an energy density of 37.5 Wh/kg (17 Wh/lb) which is more than 25% higher than typical golf-cart batteries. This improved battery also has a high usable power density, ranging from 181 W/kg (82 W/lb) at full charge to 90 W/kg (41 W/lb) at 80% discharge. While no extended tests have been made to measure cycle life, it is anticipated that 500 cycles to 70% depth of discharge can be attained. For shallower depths of discharge the cycle life will be even greater. Thus, it is reasonable to expect a range of 18,300 to 80,450 km (30,000 to 50,00 miles) from one set of batteries.

COST AND CONSUMER ACCEPTANCE

Cost goals for a production version of the ETV were stated by the Department of Energy (DOE) as follows: An initial price of \$5000 and a life-cycle cost of 15¢/mile. These figures were based on 1975 dollars, and a production volume of 100,000 vehicles per year was specified as the basis for estimating a consumer price.

An analysis made by the contractor team established a probable 1980 sales price of \$8520 for a production version of the ETV, based on a volume of 300,000 vehicles per year. This price is equivalent to \$6430 in 1975 dollars. While this estimated sales price

is higher than the goal established by DOE, it does not seem unreasonable for a vehicle that offers reliable urban transportation which is not affected by petroleum shortages or price escalations. Direct fuel costs for the production car would be very low — approximately 1.2¢/km (2¢/mile) at an electrical energy cost of \$0.05/kWh.

Total cost of operating the production electric car over a ten-year period is estimated at 11¢/km (18¢/mile) in 1975 dollars, based on 16,000 km (10,000 miles) of driving per year. A major factor in this life cycle cost is the cost of battery replacements. According to DOE goals the operating life of lead-acid batteries should be increased from 500 cycles in 1980 to at least 800 cycles by 1985. If this improvement can be achieved, the life cycle cost of a production electric vehicle will be reduced significantly from present estimates.

Consumer acceptance of the production version should be good, due to its attractive styling, excellent ride and handling qualities, and ease of operation. Limited range and performance capabilities may be an obstacle to immediate acceptance of electric cars, but the growing popularity of diesel cars in 1980 indicates that buyers will sacrifice some performance to obtain improved fuel economy.

Considerable effort has been expended to make the ETV-1 a safe vehicle to operate and service. Among the areas which have received special attention are the following: accident avoidance, crash worthiness, electrical safety, and electromagnetic compatibility. Accident avoidance capability and crashworthiness have been assured by compliance with all Federal Motor Vehicle Safety Standards, and by subjective testing of vehicle dynamics in simulated accident-avoidance situations. Electrical safety is achieved by isolation of the 108-volt battery system from the vehicle body, and by the use of protective measures including interlock switches to avoid accidental contact with the 108-volt power supply. Tests have been conducted to verify that the ETV-1 does not generate dangerous levels of electromagnetic interference and does not malfunction when exposed to normal levels of stray radiation.

The quest to develop a practical electric car is one of the most challenging problems facing the nation's scientists and engineers. The Department of Energy's Near Term Electric Vehicle Program has spurred the search for a solution, and the ETV-1 electric vehicle — equipped with tomorrow's technology — has passed an important milestone on the road to this goal. This program is one of the steps being taken by DOE to stimulate the ultimate large-scale commercialization of electric vehicles and thereby reduce U.S. dependence on petroleum.

Section 1

INTRODUCTION

PROGRAM MANAGEMENT

The activities described in this report were carried out by the General Electric Company and its subcontractors under a contract with the U.S. Department of Energy (DOE). This work is part of the Near-Term Electric Vehicle Program being administered by DOE in accordance with Public Law 94-413, the Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976. Management responsibility for the Near-Term Electric Vehicle Program is within the Division of Transportation Energy Conservation under the Assistant Secretary for Conservation and Solar Energy. Dr. H.L. Stadler and P.J. Brown are the DOE Program Manager and Deputy Program Manager, respectively, of the overall NATIONAL ELECTRIC & HYBRID VEHICLE PROGRAM of which this Near-Term Electric Vehicle Program is a major element.

R.S. Kirk and G.J. Walker are the DOE Program Director and Program Manager, respectively, of this Near-Term Electric Vehicle Program. General Electric's contract was administered by the San Francisco Operations Office of DOE with J. La Grone as Manager. The organizational relationships within DOE are shown in Figure 1-1.

Technical management of the General Electric contract was the responsibility of the Jet Propulsion Laboratory (JPL) of Pasadena, California. Mr. Thomas A. Barber is Manager of the Electric and Hybrid Vehicle Systems R&D Project at JPL. The Contract Technical Manager for General Electric's contract was Mr. T.A. Almaguer.

Within the General Electric Company, primary responsibility for the Near-Term Electric Vehicle Program was assigned to Corporate Research and Development (CRD), at Schenectady, New York. Mr. E.A. Rowland was the Program Manager. The relationship of CRD to other elements of the General Electric Company is shown in Figure 1-2.

The General Electric program organization for the Near-Term Electric Vehicle Program is shown in Figure 1-3. Project leaders within GE/CRD are identified in this figure along with Project Managers for each major subcontractor. Also shown in Figure 1-3 are other departments of General Electric who contributed to the design and development of the Electric Test Vehicles (ETV). Table 1-1 provides an explanation of the roles performed by each contractor under this contract.

The Chrysler Corporation played a major role in the electric vehicle program, with responsibility for design and development of all vehicular systems, fabrication and assembly of the Electric Test Vehicles, and performance of integrated vehicle tests. The key members of Chrysler's program staff are identified in Figure 1-4. Also identified in this figure is Chrysler's design and fabrication subcontractor, Modern Engineering Services of Detroit, Michigan.

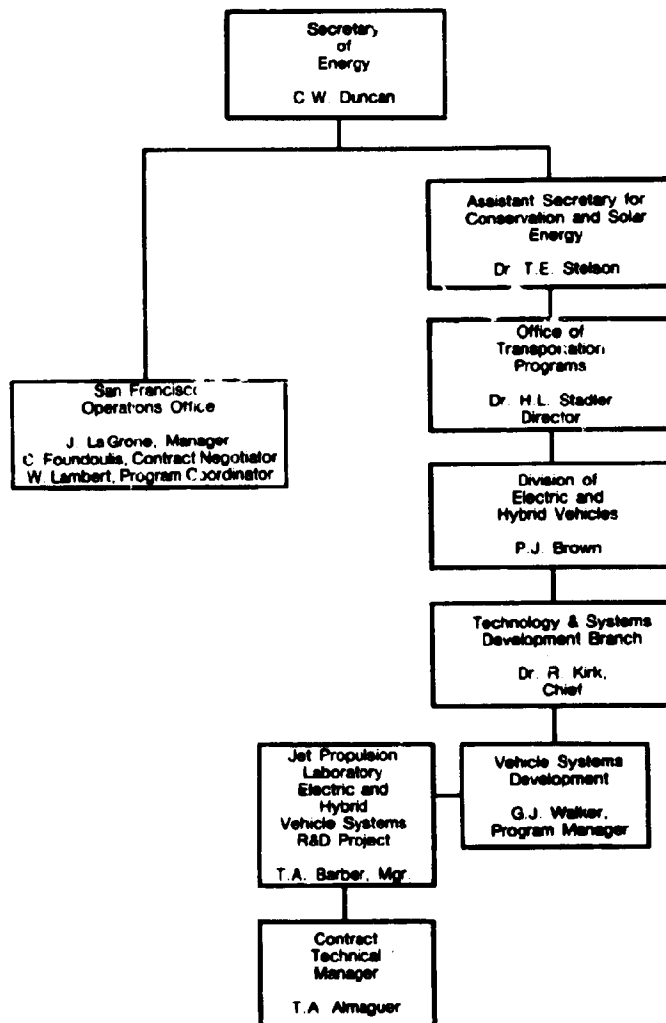


Figure 1-1. Relationship of the General Electric Company to DOE Electric Vehicle Program

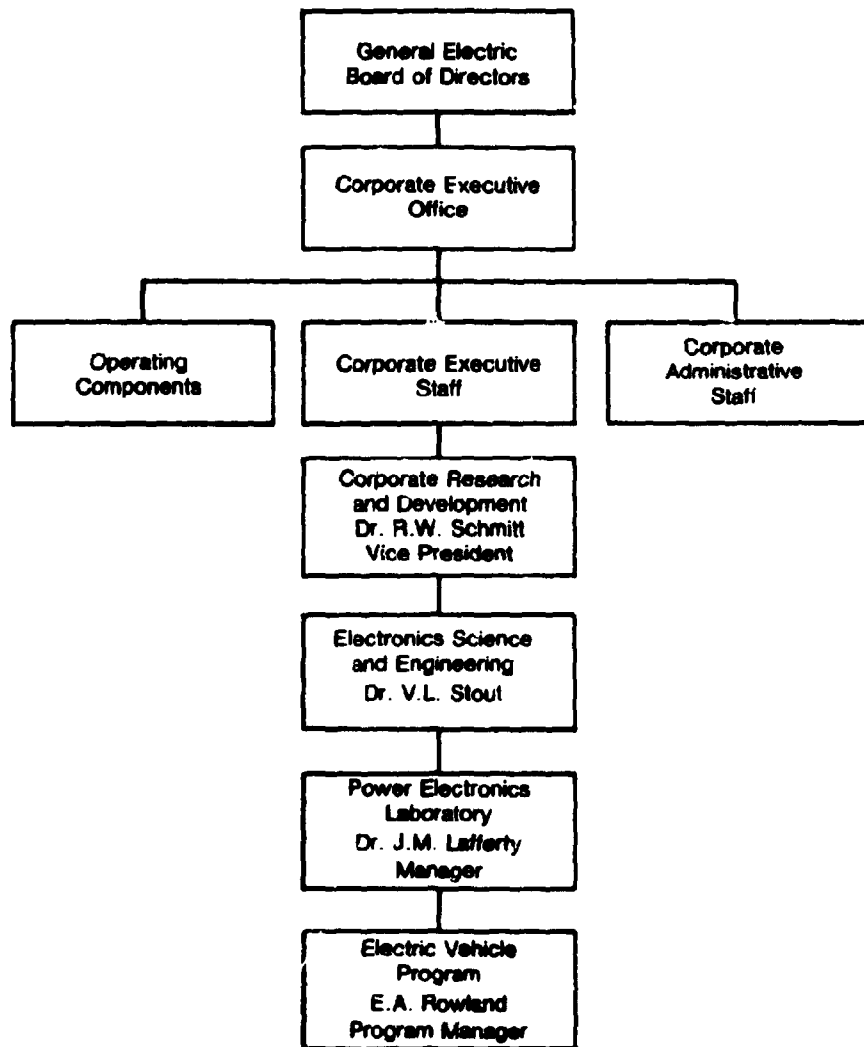


Figure 1-2. Relationship of the General Electric Company to DOE Electric Vehicle Program

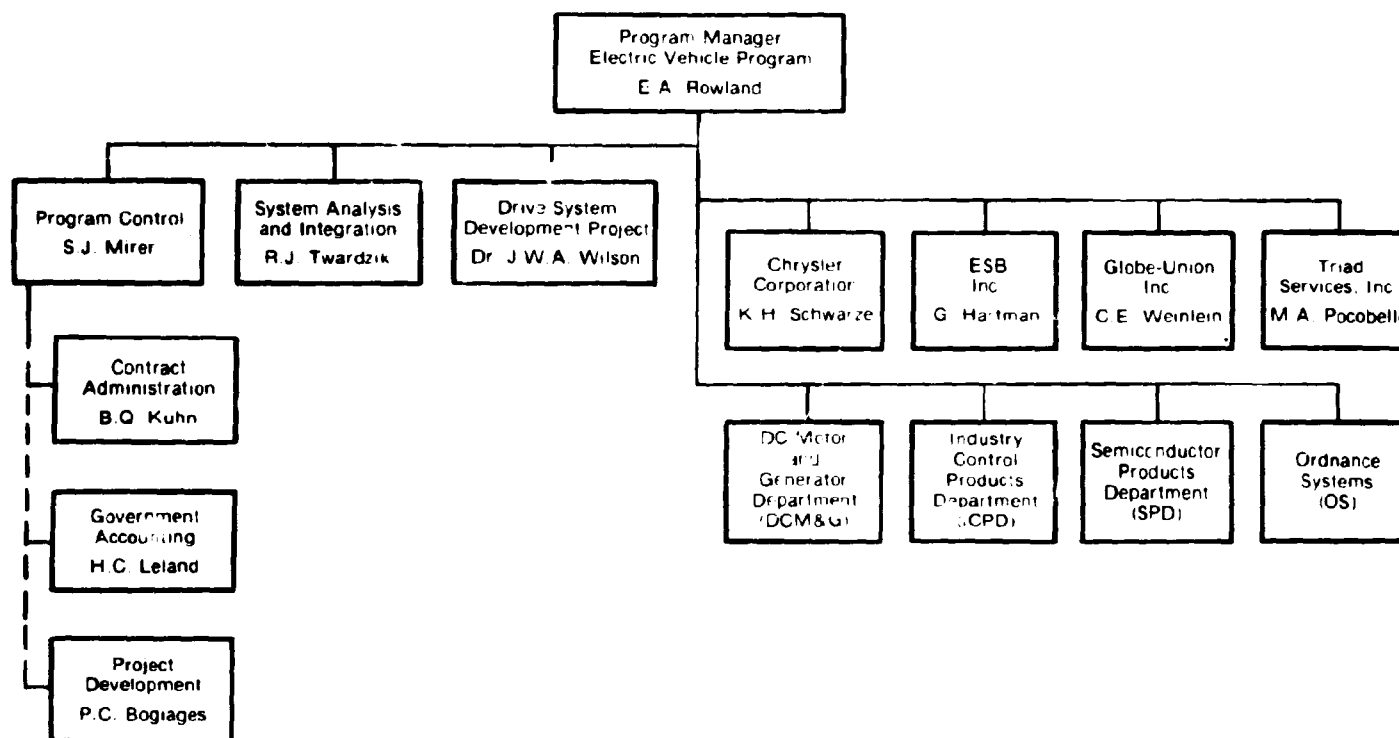


Figure 1-3. General Electric Electric Vehicle Program Organization

TABLE 1-1
CONTRACTOR RESPONSIBILITIES

<u>Contractor</u>	<u>Role in Program</u>
General Electric/CRD	● Prime Contractor & System Integrator ● Development of Electrical Drive Subsystem ● Development of Power Transistor Modules
Chrysler Corporation	● Development of Vehicle Subsystem ● Vehicle Fabrication and Assembly ● Integrated Vehicle Testing
ESB, Inc.	● Consultant, Battery Modeling and Regenerative Braking
Globe-Union, Inc.	● Development of Lead-Acid Battery ● Battery Subsystem Integration ● Battery Fabrication and Testing
Triad Services, Inc.	● Phase I Vehicle Design ● Consulting, Phase II
General Electric/DCM&G	● Design of DC Drive Motor ● Drive Motor Fabrication & Testing
General Electric/ICPD	● DC Contactors & Controls ● Consulting, Motor Controllers
General Electric/OS	● Mechanical & Thermal Design ● Packaging of Drive Subsystem Electronics
General Electric/SPD	● Power Transistor Fabrication

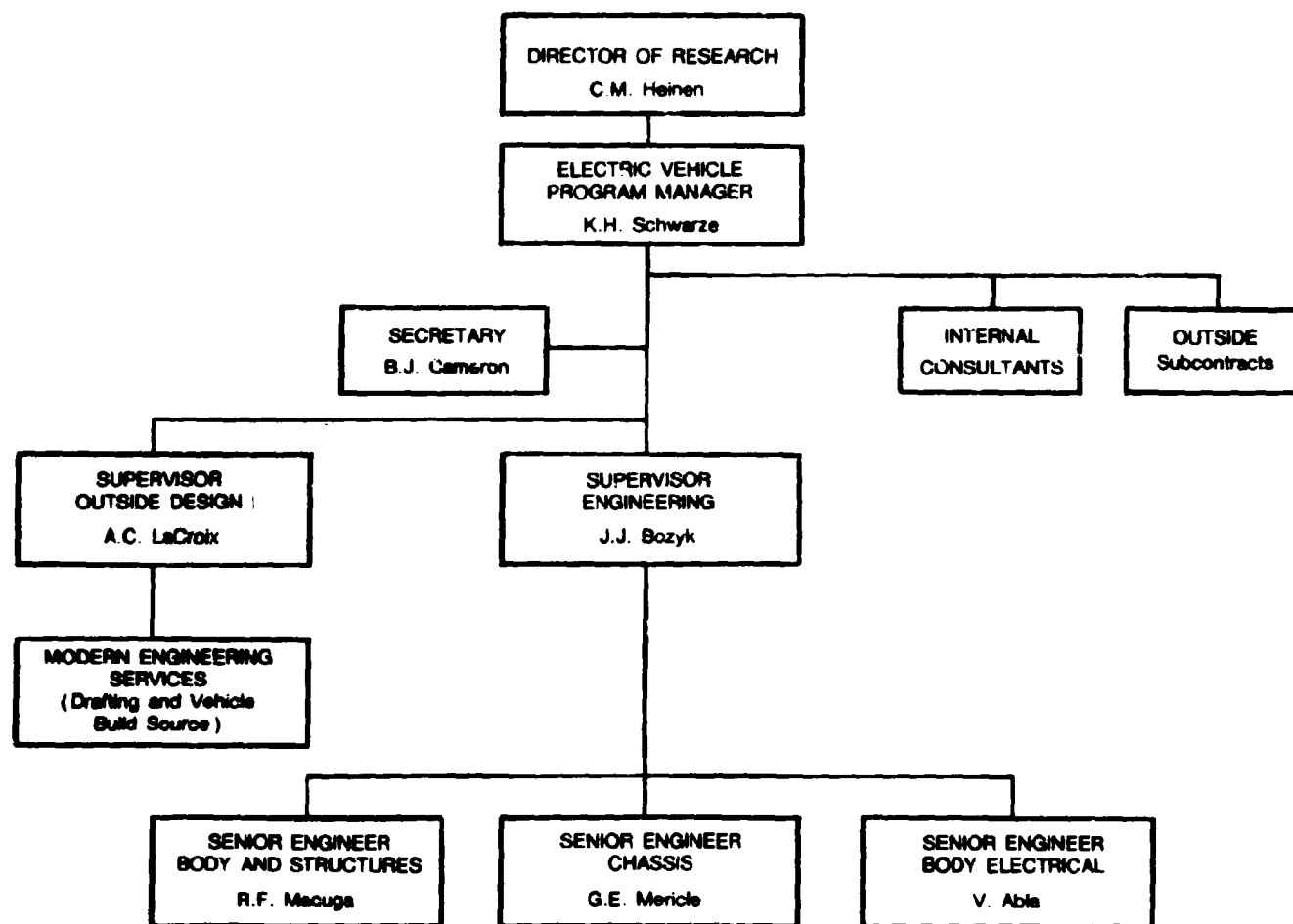


Figure 1-4. Chrysler Task Force Organization for the Near-Term Electric Vehicle Program — Phase II

PROGRAM OBJECTIVES

The general objective of the Near-Term Electric Vehicle Program is to confirm

1. That, in fact, the complete spectrum of requirements placed on the automobile (e.g., safety, producibility, utility) can still be satisfied if electric power train concepts are incorporated in lieu of contemporary power train concepts, and
2. That the resultant set of vehicle characteristics are mutually compatible, technologically achievable, and economically achievable.

The approach to meeting this general objective is focused on the design, development, and fabrication of complete electric vehicles incorporating, where necessary, extensive technological advancement.

The program described in this report has resulted in the development and delivery to DOE of two Electric Test Vehicles (ETVs) incorporating technology improvements for energy-efficient operation. The Electric Test Vehicles were designed to meet the DOE Near-Term Objectives shown in Table 1-2 and will be amenable to mass production in the early 1980s.

TABLE 1-2
DOE OBJECTIVES

Parameter	Near-Term DOE Objectives
Minimum passenger capacity	4 adults
Maximum curb weight, lbs	Open
Minimum urban range (J227B), miles	75
Maximum initial cost, projected, 1975	5000
Minimum life, miles	100,000
Minimum life, years	10
Maximum life-cycle cost, projected in 1975 dollars/mile	0.15
Cost of energy in dollars/kWh	0.05
Maximum electric recharge energy in urban driving, kWh/mile	0.5
Maximum recharge time, hr (115 volts, 30 ampere service)	6
Minimum top passing speed, mph	60
Minimum top cruising speed, mph	55
Minimum accessories	Heater/defroster, on-board charger
Safety features	FMVSS requirements at time of contract
Minimum unserviced park duration, day	7
Maximum years till production ready	5
Maximum critical materials required	Few
Minimum acceleration (0-30 mph), sec	9
Minimum merging time (25-55 mph), sec	18
Sustained speed on 5% one-mile grade, mph	50
Maximum scheduled maintenance, dollars/mile	0.02
Minimum ambient temperature range, °F	-20 to +125
Interior noise	Minimum
Turning and braking	No power assist required

Specific DOE vehicle performance and characteristic objectives for this program are presented later in this section under "Technical Approach." These objectives define a four-passenger car similar in concept to today's subcompact vehicle, which is widely used for urban transportation and commuting service. The driving mission for this car is specified by means of the Society of Automotive Engineers J227a (Schedule D) driving cycle, which is representative of urban stop-and-go driving.

The electric car resulting from this program was to be suitable for future production at a cost comparable to conventional (internal combustion engine) autos. When produced in quantities of 100,000 or more per year, the electric car should be available at a consumer price equivalent to \$5000 in 1975 dollars. Life cycle cost was not to exceed \$0.15/mile, on the basis of a ten-year life-span and 10,000 miles of operation per year.

Performance objectives specified for the electric car included a range of 75 miles in simulated urban driving, acceleration from 0 to 30 mph in nine seconds, and a top speed of 60 mph. Hill-climbing capability on a one-mile-long grade was to be sufficient to maintain 50 mph on a 5% grade. To meet these performance requirements an improved lead-acid battery which delivers an energy density of 17 Wh/lb was developed. Significant improvements in design and efficiency were required, to meet these performance objectives, as compared with present commercially available vehicles.

TECHNICAL APPROACH

The specific technical approach which was implemented in the General Electric Electric Test Vehicle included the following design features which were identified as key requirements by DOE.

- **Regenerative Braking** - The vehicle utilizes regenerative braking to recover electrical energy during periods of deceleration.
- **Integrated Propulsion Control/Charging** - Onboard electronics are provided for battery charging, and the charger function is integrated with propulsion control electronics to minimize size, weight, and production cost.
- **Microprocessor Control** - A microprocessor is utilized to provide on-line supervisory control of the electric propulsion subsystem, including acceleration, cruise, and regenerative braking modes. In addition, the microprocessor provides monitoring and control functions associated with operator displays, warning indicators, battery charging, and emergency overrides.
- **Transistorized Controls** - DC chopper controls for the vehicle drive motor armature and field were implemented with high power transistors developed to meet the vehicle power requirements and operating environment. Packaging of power transistors was accomplished in a manner that is amenable to future low-cost production.
- **Integrated Power Modules** - An objective of the General Electric design program was to furnish integrated power modules for both armature and field choppers. These modules consist of high-current, low-cost transistors packaged and bonded directly to a heat sink for simple plug-in or bolt-down replacement.

TECHNICAL RESULTS

The Integrated Test Vehicles developed under this contract demonstrate new levels of performance for electric passenger vehicles. Most of the performance objectives established

by DOE have been met during early performance testing. Test results versus key performance objectives are illustrated in Table 1-3. With continued improvements in battery technology, all of these performance goals are expected to be met by 1982 (the target date for production vehicles employing the technology developed here).

TABLE 1-3
TEST RESULTS VERSUS KEY PERFORMANCE OBJECTIVES

Parameter	DOE Objective	Test Results
Passenger capacity	4 adults	4 adults
Curb weight	open	3320 lb (1509 kg)
Energy consumption in urban driving	0.5 kWh/mile	0.36 kWh/mile [calculated]
Passing speed	60 mph	70 mph (112 km/hr)
Cruising speed	55 mph	55 mph (88 km/hr)
Acceleration, 0-30 mph	9 seconds	9 seconds
Acceleration, 25-55 mph	18 seconds	20 seconds [See Section 4.6]
Speed on 1 mile 5% grade	50 mph	47 mph (75 km/hr)
Urban range (SAE J227/D)	75 miles	74 mi (118 km)

Technological improvements have been realized in all major subsystems of the Electric Test Vehicle, contributing to its overall excellent performance. A summary of the major technical accomplishments is presented in this section. Further details can be found in later sections of this report.

Vehicle Subsystem

Major accomplishments in the vehicle subsystem design include lightweight, low aerodynamic drag, low rolling resistance, excellent ride and handling characteristics, and full compliance with Federal Motor Vehicle Safety Standards (FMVSS) as specified at the time of contract award. Vehicle weight was reduced by means of computer-aided design techniques, careful selection of sheet metal alloys and gauges, extensive use of aluminum in exterior body panels, and substitution of Lexan® for glass in side and rear glazing. Total vehicle weight less batteries is 2243 lb, only 27 lb more than a comparable 1979 subcompact (Plymouth Horizon/Dodge Omni sport coupe). Total vehicle curb weight with batteries is 3320 lb. This figure could be further reduced by development of lightweight chassis components, and such developments should be considered for future production vehicles.

Low aerodynamic drag was achieved by extensive wind tunnel testing and shape modification to obtain a yaw-weighted drag coefficient (C_D) of 0.30. Frontal area (A_F) was also reduced, to 19.3 ft², resulting in an effective area ($C_D A_F$) of 5.8 ft². This figure represents nearly a 50% reduction in drag as compared to similar production vehicles, and accounts for a significant range improvement on the urban driving cycle. The final body design is shown in Figure 1-5.

Several brands of steel-belted radial tires were tested to select those with the lowest rolling resistance. A further reduction in rolling resistance was achieved by means

®Registered trademark of General Electric Company for polycarbonate resin



Figure 1-5. Final Body Design

of the special low-loss transaxle developed specifically for this vehicle. The transaxle utilizes a double-reduction silent chain drive with no right-angle gears. Based upon coastdown tests, the overall rolling resistance is estimated at 11 lb (force) per 1000 lb of vehicle weight.

Excellent ride and handling qualities combined with good braking performance have been demonstrated during performance testing of the Electric Test Vehicle. The ETV drives and handles at least as well as most contemporary subcompact cars, as judged by the reactions of several experienced drivers.

Compliance with the 1977 FMVSS has been achieved with only one minor exception. An exception was made to FMVSS-205, to allow the use of Lexan plastic glazing which does not fully comply with regulatory requirements for abrasion resistance. With continued development of abrasion-proof coatings, Lexan is expected to meet the Federal standards. Weight and aerodynamic styling advantages of the plastic windows will encourage their use in future production vehicles.

Electrical Drive Subsystem

The electrical drive subsystem exhibits a number of significant technological improvements as compared to previous electric vehicle drives. Increased efficiency and flexibility of operation are achieved by means of the separately-excited dc drive motor, transistorized armature and field choppers, integrated transistor power modules, and an on-board micro-computer controller. A very effective regenerative braking method provides increased vehicle range in stop-and-go driving. An efficient on-board charger is integrated with the field chopper electronics, resulting in a minimum size and weight penalty to the vehicle.

The separately-excited dc motor drive was selected as offering the best combination of performance, cost, and efficiency for a near-term test vehicle. The motor used has

a full load efficiency of 90% and a speed control range of more than 2:1 under field control. Low speed control of motor voltage and current is performed by a transistorized armature chopper. This electronic chopper operates over a frequency range from 100 Hz to 2000 Hz and performs regenerative braking as well as motoring control for speeds below 30 mph. Peak efficiency of the armature chopper is approximately 97%. Above 30 mph, motor voltage and current is controlled by a transistorized field chopper. In the field control mode, the armature chopper is bypassed to eliminate losses in the armature circuit. This control strategy results in a very efficient drive subsystem which requires only 0.35 kWh of energy per mile to propel the ETV over the J227a Schedule D driving cycle.

The integrated power transistor modules developed for this contract represent a major improvement over any similar device which was previously available. High power Darlington transistors are packaged using proprietary materials and techniques to achieve a small lightweight module with very high power switching capability. In the armature chopper, two of these compact modules control a peak power of 40 kilowatts to the drive motor. A further advantage of the GE-developed power modules is their suitability for mass production, at costs as low as 1/10th the price of presently-available power devices with similar ratings.

An on-board microcomputer in the ETV employs an INTEL 8080A microprocessor chip combined with standard peripheral devices as well as custom signal conditioning and interface circuits. Optical coupling is used to isolate the microcomputer logic from high power circuits in the drive subsystem, thus providing a high degree of noise immunity. "Firmware" controls all programmed operations in the microcomputer, using read-only-memory (ROM) chips with a capacity of 4096 bytes of storage. All driver commands are processed by the microcomputer to provide smooth flexible control of mode selection and sequencing, torque and speed control, regenerative braking, and battery charging.

Packaging of the drive subsystem electronics was executed by General Electric's Ordnance Systems utilizing techniques adapted from prior military electronics experience. The packaged units are illustrated in Figure 1-6 (PCU) and 1-7 (Microcomputer).

Battery Subsystem

Globe Battery Division of Globe-Union, Inc. was selected by General Electric to develop the improved lead-acid battery which powers the Electric Test Vehicle. This improved battery, designated as Model No. EV2-13, achieves an energy density of 17 Wh/lb with a design life of 500 deep-discharge cycles. Compared to standard vehicle batteries previously available, the EV2-13 represents a 25% improvement in both energy density and cycle life. A further development by Globe-Union for this program is a single-point watering and venting system which allows the battery to be watered without removal from the vehicle. During battery charging, the integral venting system safely evacuates hydrogen from the batteries through flame arrestors.

Significant design features which contribute to the EV2-13's improved performance are a thin wall polypropylene case with high-rise cover, large flat-plate electrodes, envelope separators, and welded through-partition connectors. The plates of the EV2-13 are rotated 90° from their traditional placement, allowing thirteen large plates to be used in each cell as opposed to 19 smaller plates which would be used in a standard deep-discharge (golf-cart) battery. These larger plates have a more nearly optimum aspect ratio, which contributes to improved performance. Another factor in improved energy density is the use of a radial grid construction to minimize the weight of lead required for efficient current collection and distribution within the electrodes. Proprietary computer-aided design techniques were employed by Globe-Union in the development of these grids. Many of the special design features of the EV2-13 are illustrated in Figure 1-8.



Figure 1-6. Packaged PCU

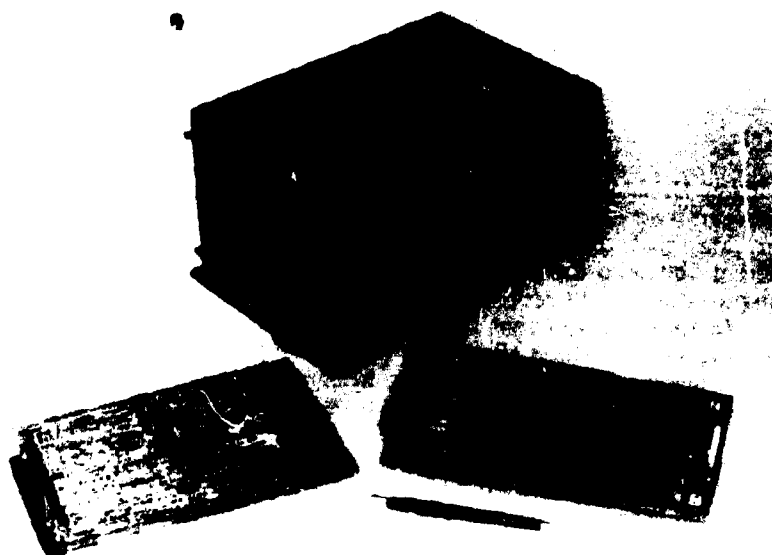
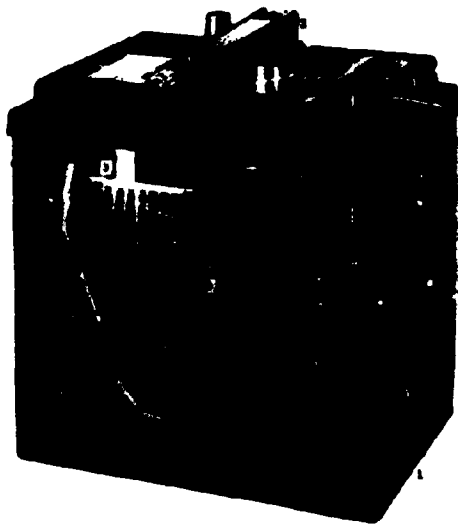


Figure 1-7. Packaged Microcomputer



**EV2-13 12V-ACID
RECHARGEABLE BATTERY**

- 6 Volt
- 27.5 kg (60 lb)
- Maintenance-Free, Computer-
- Designed Cell Geometry
- Low-Resist and High-Speed
- Models

FEATURES

1. Thin, Lightweight, Durable Polypropylene Container and Cover Mechanically Folded for a Leak-Proof Assembly
2. Single-Point Venting System with Battery Venting
3. Low-Resistance, Through-the-Partition Inter-cell Welds
4. High-Efficiency, Computer-Designed Radial Grids
5. Optimized Active Materials
6. Submersible Polyethylene Envelope Separators with Glass Mat

Figure 1-8. Design Features of the EV2-13

Section 2

SYSTEM ANALYSIS AND DESIGN

WBS 2.1 REQUIREMENTS REVIEW AND ANALYSIS

The system design was initiated with a review of the Phase I design, the DOE Near-Term Performance Objectives, and the Phase II Statement of Work requirements. The initial baseline system requirements are shown in Table 1-2.

A specification tree was developed which allocated system requirements to four major subsystems: Vehicle, Electrical Drive, Battery, and Support Equipment. The specification tree is depicted in Figure 2.1-1. As shown, each major subsystem is further broken down into major components or groups, with a specification sheet developed for each.

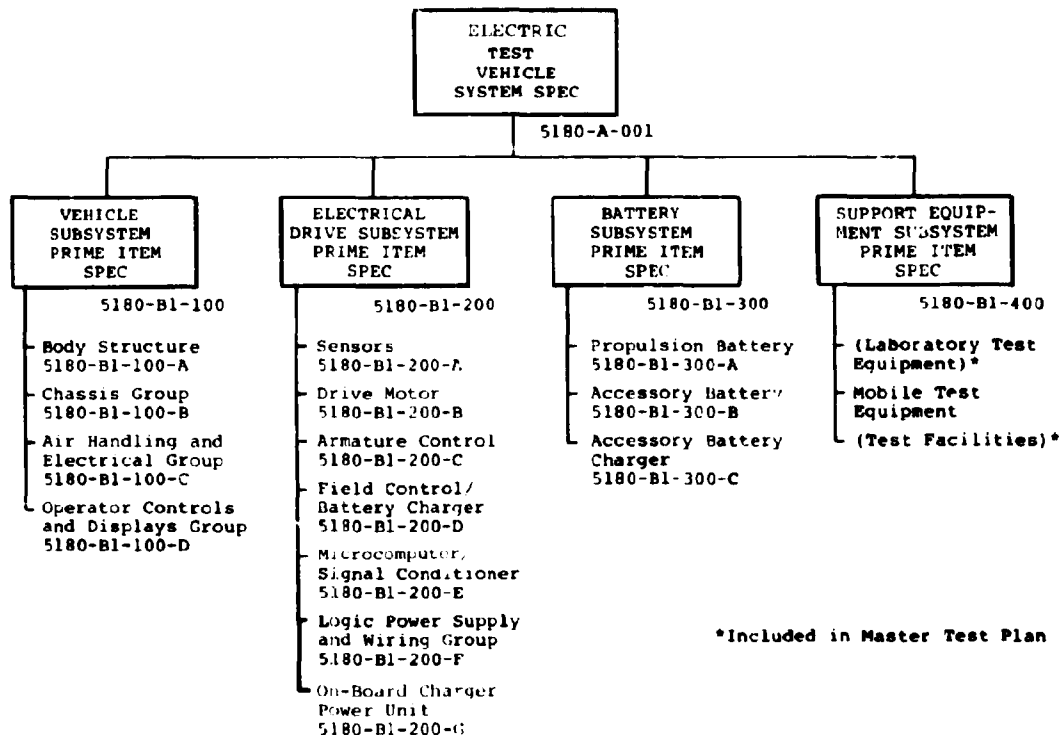


Figure 2.1-1. ETV Specification Tree

In addition to the above, an interface matrix was developed delineating major interface requirements between subsystems. This matrix resulted in the development of an interface specification tree and subsequent interface specifications. The interface specification tree is shown in Figure 2.1-2. A working group on vehicle design trade-offs was initiated consisting of the Lead Systems Engineer and representatives from both Chrysler and Globe-Union. A Weight Control Specification and Power Loss Control Specification were generated and were used as a formal means of controlling these parameters and as a prime input for design trade-off decisions.

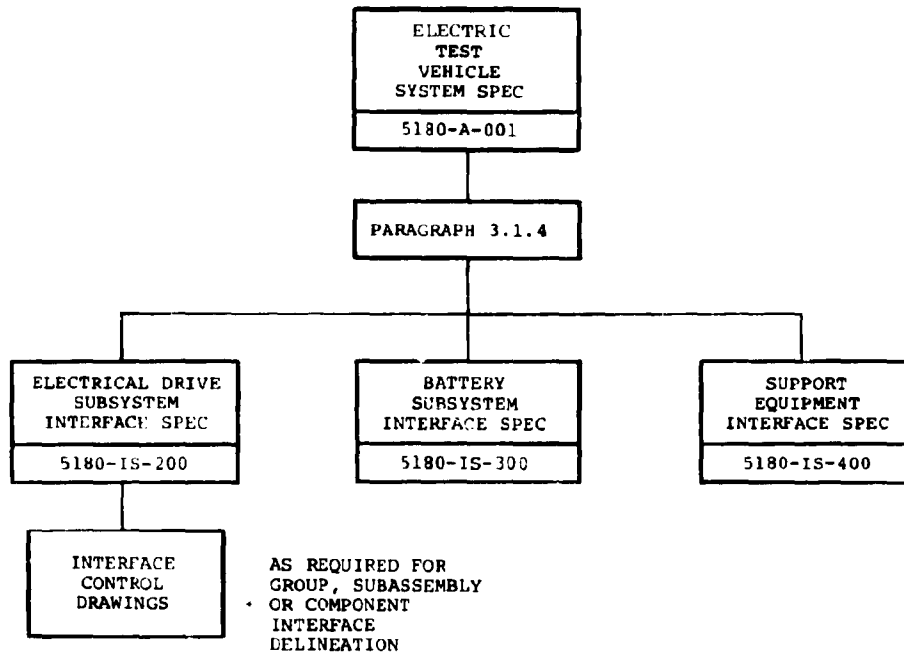


Figure 2.1-2. ETV Interface Specification/Document Tree

WBS 2.2 SYSTEM MODELING AND PERFORMANCE PREDICTION

WBS 2.2.1 Description of Program

Programs are available for simulating a variety of performance tests, including SAE J227a driving cycles. Five basic types of simulations are possible:

1. Vehicle range on SAE J227a driving cycle. Schedules B, C, and D can be simulated.
2. Vehicle range at any constant velocity from 5 to 55 mph (or higher, if desired).
3. Time to accelerate from 0 to 30 mph or 0 to 60 mph. (Conversely, program will define power profile to achieve 0 to 30 mph in specified time.)
4. Time to accelerate from 25 to 55 mph, or other specified velocities. (Conversely, program will define power profiles to achieve 25 to 55 mph in specified time.)
5. Maximum speed achievable on a specified grade. (Conversely, program will define power profile to maintain a specified speed on a specified grade.)
6. Maximum gradeability

A great deal of flexibility is available in the existing programs to accommodate a wide variety of vehicle parameters. The following parameters can be entered or changed independently:

- Vehicle test weight
- Wheel rolling radius
- Final drive ratio
- Aerodynamic drag coefficient (C_D) and frontal area (A_F)
- Number of transmission speed ranges (gears)
- Speed ratio for each gear
- Rolling resistance drag coefficients (k_1, k_2, k_3)
- Wheel inertia
- Transmission/final drive efficiency
- Motor design parameters (as defined by motor model)
- Battery design parameters (as defined by battery model)
- Electrical losses in drive train (as defined by armature and field chopper models)
- Auxiliary power losses (including logic power, accessories, and ventilating blowers)

A number of output (print) options are available for each simulation, depending upon the information desired. For example, when the J227a Schedule D range test is run, a single cycle printout can be obtained which shows the calculated values of motor current and voltage, battery current and voltage, etc., at each second during the cycle. An alternate print mode displays snapshots of each variable at specified points during each cycle, and records the number of cycles (as well as distance traveled) for one continuous driving mission. Since the main use of this program is design optimization, a record of vehicle losses is made during each simulation to account for the energy consumed by each system component.

Another feature of the program is that a regeneration mode can be simulated in the J227a cycle. The regeneration mode occurs during the coastdown phase of the cycle to provide internal combustion engine "feel," and during the braking phase to simulate both electrical and hydraulic braking. During regeneration, the motor acts as a generator with losses modeled in a fashion similar to the motoring phase.

Modeling and Simulation Techniques

Vehicle performance during a simulated driving segment is determined by solving a series of equations which mathematically define the response of the vehicle subsystems to each calculated set of operating conditions. For example, to determine the vehicle range on the J227a Schedule D driving cycle, the computer program would step through the following calculations:

- Specify vehicle speed versus time according to stored Schedule D velocity-time coordinates.
- Compute vehicle propulsion loads for each time increment (aerodynamic drag, rolling resistance, etc.).
- Compute motor torque and speed required at each time increment to achieve the specified velocity or required acceleration.
- Compute drive subsystem voltages, currents, and power losses at each time increment.
- Compute instantaneous values of battery current and terminal voltage.
- Calculate from the battery discharge model the fraction of battery capacity consumed during each time interval.
- Repeat the above steps until the battery is completely discharged, calculating the total distance traveled during the mission.

The mathematical models which are used to represent the vehicle and drive subsystems are represented by blocks in the overall system model of Figure 2.2.1-1. A brief description of the individual models will be presented.

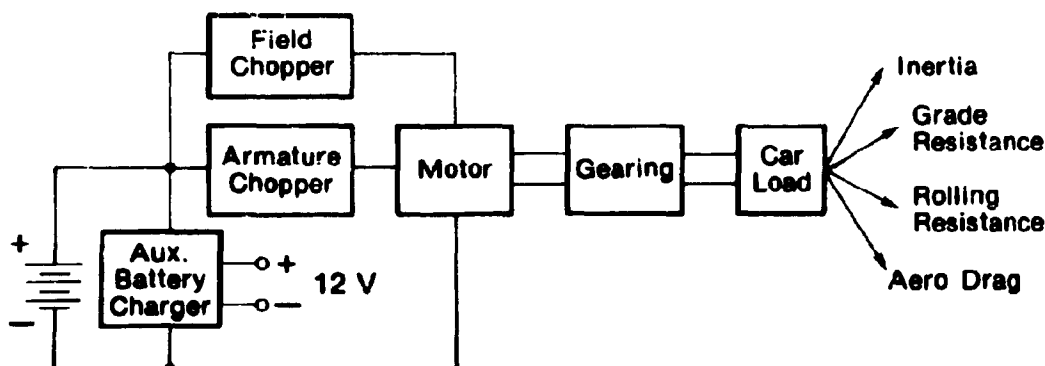


Figure 2.2.1-1. Overall System Model

The propulsion battery is modeled as shown in Figure 2.2.1-2. This is a very simple representation, whereas the equations which describe the battery behavior are quite complex. However, the figure does illustrate the basic concept. The battery consists of a voltage source (E_B) supplying current through a variable resistance (R). The value of R is determined by battery state-of-discharge, represented by S . During regeneration, current flow to the battery is reversed and the battery state-of-charge is increased (state of discharge, S , is decreased).

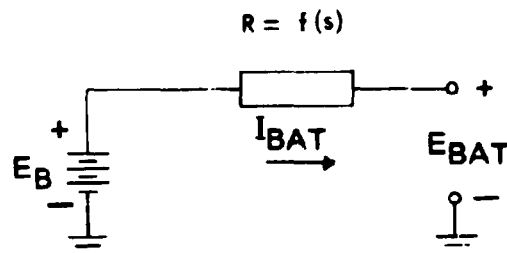


Figure 2.2.1-2. Propulsion Battery Model

Speed and torque of the electric vehicle drive motor are controlled by means of armature and field choppers. Each of these chopper devices is modeled as shown in Figure 2.2.1-3. Here the chopper is represented as a variable-ratio dc transformer which converts the battery voltage to a lower value as required to achieve proper motor excitation. Ignoring chopper losses, Power Out = Power In, so that $V_M \cdot I_M = E_{Battery} \cdot I_{Battery}$. In the actual armature chopper model, internal losses are accounted for by means of fourteen equations which are solved for each time step.

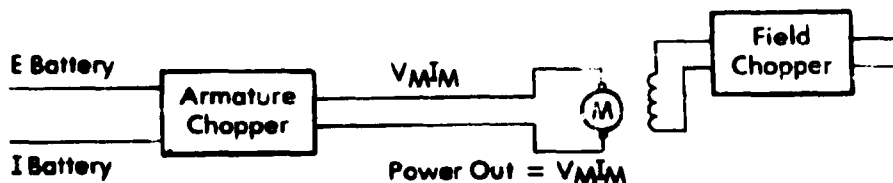


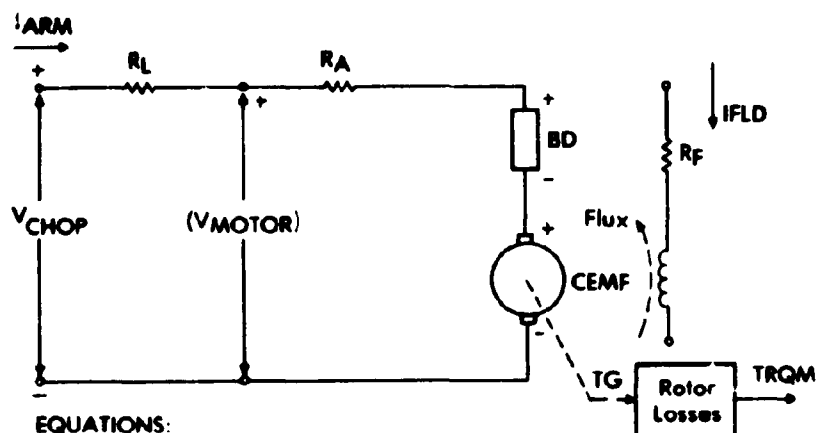
Figure 2.2.1-3. Chopper Model

Figure 2.2.1-4 illustrates the model used to represent a dc separately excited drive motor. The equations which define rotor speed, torque, and motor losses are shown; these equations constitute the actual model used by the computer to predict motor performance during each time interval.

The remaining models for the electric vehicle are quite simple and do not merit a detailed description. Over a period of more than two years the accuracy of these models has been refined, and new components have been modeled as the need has been identified.

WBS 2.2.2 Summary of Results

The initial system-modeling mathematical model was developed for the Parameter Optimization Project and used to select the optimum dc drive motor design. Boundary values for key vehicle parameters (weight, A_F , C_D , F_{RR}), were selected and used to



EQUATIONS:

$$\text{Armature Loop: } V_{CHOP} = CEMF + BD + I_{ARM}(R_A + R_L)$$

$$CEMF = KV \cdot RPM \cdot FLUX$$

Rotor Power Loss:

$$\text{Core Loss: } WCL = WCL1 (RPM/1000)^{1.5}$$

$$\text{Friction: } WF = WF1 (RPM/1000)$$

$$\text{Windage: } WDG = WDG1 (RPM/1000)^3$$

$$\text{Stray Load Loss: } WLL = 1\% \text{ of Power Out}$$

$$\text{Torque: } TG = I_{ARM} \cdot KT \cdot FLUX$$

Figure 2.2.1-4. Motor Model

determine sensitivity of the motor design to variations in vehicle design. The results of this effort were presented at the Preliminary Design Review (PDR) and documented in Task Report SRD-77-160, WBS 3.2.1 - Parameter Optimization, dated 31 October 1977.

The initial Performance Predictions of the Near-Term Electric Vehicle were made using the EV-108 battery model and a regeneration technique that used no friction brake blending during the braking mode, resulting in very high armature currents. Armature currents of this magnitude result in high battery currents which, in turn, would adversely affect battery life.

The initial range performance results and vehicle parameters are summarized as follows:

Range J227 D cycle	61 miles
Range 25 mph cruise	117 miles
Range 35 mph cruise	131 miles

Range 45 mph cruise	104 miles
$C_D A_F$	5.7 ft ²
F_{RR} (rolling resistance)	0.009 lb/lb

In response to a concern expressed at the PDR, a brief analysis of the performance trade-offs associated with shifting transmissions was performed. The results indicated a potential range performance improvement of less than 1% on the J227a Schedule D cycle if realistic values of transmission efficiency are used. This analysis was documented in a letter report dated October 14, 1977.

Globe-Union provided an estimate of the performance of the improved EV2-13 battery, which was modeled analytically and incorporated into the program. The regeneration model was revised to incorporate regeneration during the coastdown phase of the J227a Schedule D cycle and electrical and hydraulic brake blending during the braking phase. The battery charging currents used during both phases were adjusted to acceptable values based on data provided by Globe-Union. The new battery model also reflected full discharge to 1.3 volts per cell as the criterion for termination of the cycle. The effective frontal area ($C_D A$) was increased to 5.8 ft², based on scale-model wind tunnel tests.

The following additional modifications were made to the Performance Model:

- Updated and more detailed modeling of the armature chopper losses
- Decrease in field chopper efficiency from 95 to 90%
- Improved drive motor performance based on design optimization
- Inclusion of updated power requirements of the logic power supply, accessory charger, and armature and field contactors
- Inclusion of transmission overall efficiency of 96%
- Optimized acceleration profile (constant I_{BAT})

The range performance and vehicle parameters resulting from the above updates are summarized as follows:

Range J227a Schedule D	71 miles
Range 25 mph cruise	129 miles
Range 35 mph cruise	146 miles
Range 45 mph cruise	124 miles
$C_D A_F$	5.8 ft ²
F_{RR} (rolling resistance)	0.009 lb/lb

Energy flow models were developed for the Integrated Test Vehicle (ITV) for the J227a Schedule D driving cycle and constant speeds of 25, 35, and 45 mph. These are shown as Figures 2.2.2-1 through 2.2.2-4.

As a result of an IDR Action Item, the acceleration segment of the J227a Schedule D driving cycle was modified to simulate a linear acceleration. Using this profile and restricting motor current to the present design limit resulted in a significant range

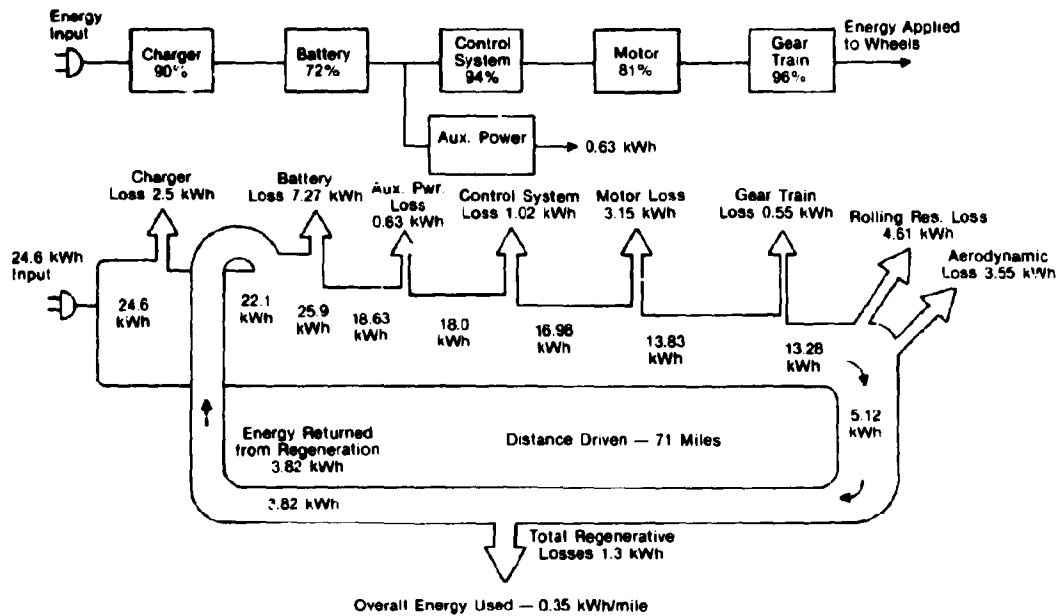


Figure 2.2.2-1. Energy Flow Model for GE-ETV on J227a Schedule D - Performance Prediction Model

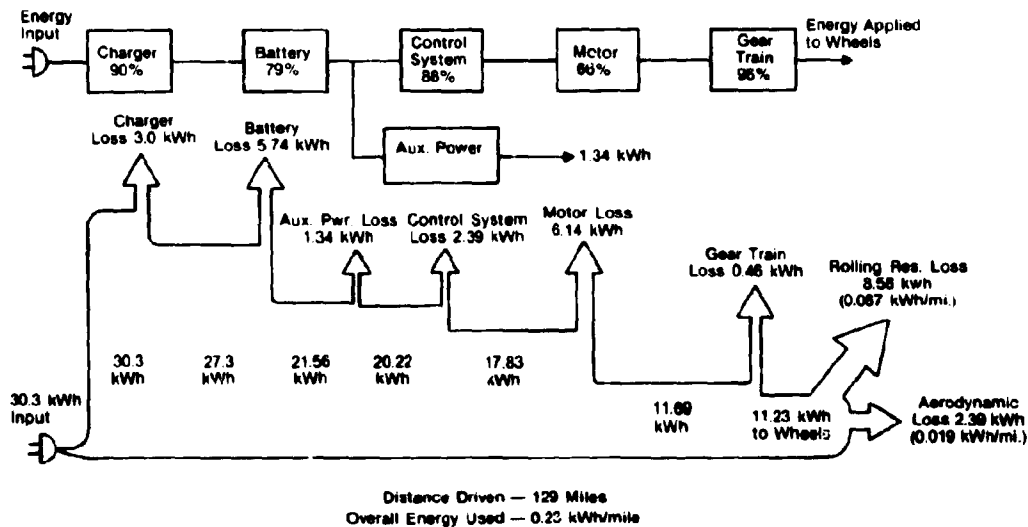


Figure 2.2.2-2. Energy Flow Model for GE-ETV at Constant 25 Mph - Performance Prediction Model

decrease. A letter report dated February 23, 1978 was written detailing General Electric's position on establishing an arbitrary constraint on the velocity versus time profile during this acceleration segment. As a result, JPL requested that the acceleration profile in the performance model be simulated to provide a repeatable constant I_{BAT} acceleration, cycle to cycle. This request has been implemented in the model.

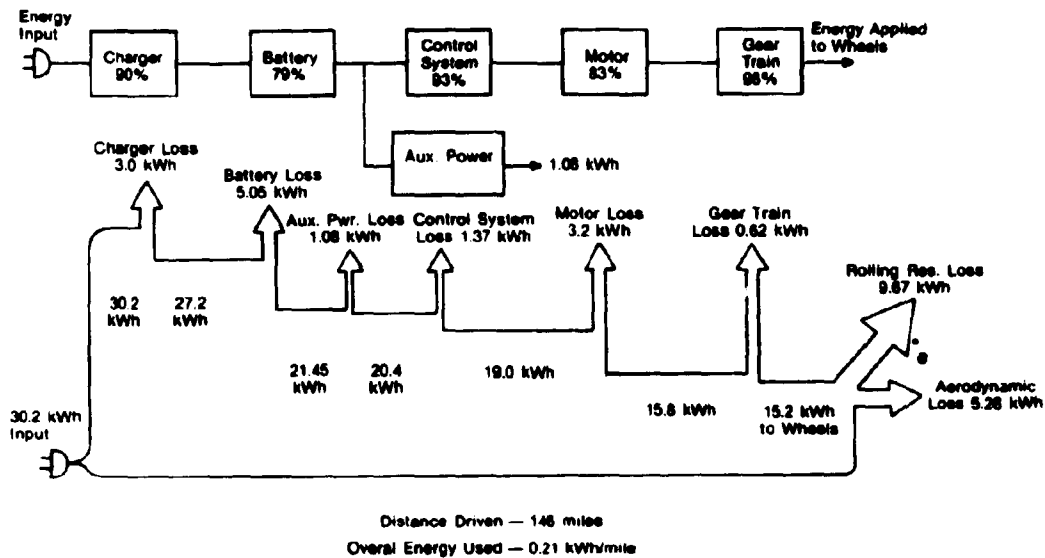


Figure 2.2.2-3. Energy Flow Model for GE-ETV at Constant 35 Mph — Performance Prediction Model

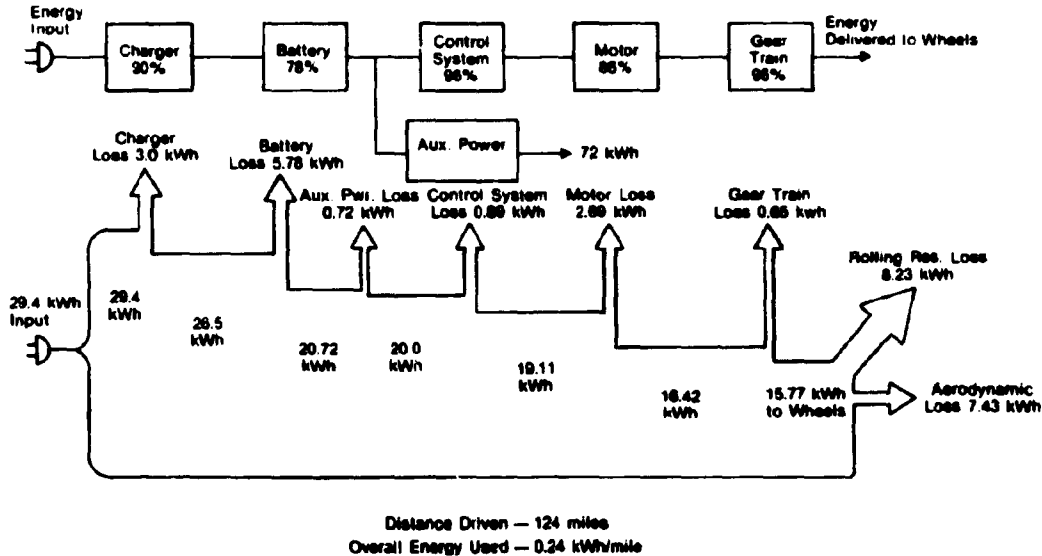


Figure 2.2.2-4. Energy Flow Model for GE-ETV at Constant 45 Mph — Performance Prediction Model

Globe-Union provided up-to-date performance data on the EV2-13 batteries based on cell tests of the batteries. This data is referenced in Table 3.3.1-3. The battery model in the Performance prediction model was updated, based on this data and resulted in the following range prediction:

Range J227a Schedule D	72 miles
Range 25 mph cruise	109 miles
Range 35 mph cruise	120 miles
Range 45 mph cruise	100 miles
Range 55 mph cruise	75 miles
$C_D A_F$	5.89 ft ²
F_{RR} (rolling resistance)	0.009 lb/lb

Upon completion of the first vehicle, the weight estimate was revised from 3751 lb gross vehicle weight to 3920 lb gross vehicle weight. The increased weight was due to a number of vehicle subsystem changes which occurred during the final design and build of the vehicle. Changes to the estimated subsystem weights are tabulated below:

Subsystem	Best Estimate	Updated Weight
Vehicle Subsystem	1668	1872
Battery Subsystem	1138	1120
Electrical Drive Subsystem	345	328
	3151	3320
Payload		
	600	600
	3751 lb	3920 lb

The Performance Prediction model was updated based on the new weight estimates. Range as well as other performance parameters based on the new weight are tabulated below:

Parameter (600 lb payload)	Result
Range J227a Schedule D	69 miles
Range 25 mph cruise	106 miles
Range 35 mph cruise	117 miles
Range 45 mph cruise	97 miles
Range 55 mph cruise	73 miles
0-30 mph acceleration; 0% discharged battery pack	8.9 seconds
0-30 mph acceleration; 60% discharged battery pack	9.2 seconds
25-55 mph acceleration; 0% discharged battery pack	17.6 seconds
25-55 mph acceleration; 60% discharged battery pack	19.8 seconds

5% grade (max. velocity); 0% discharged battery pack	54 mph
5% grade (max. velocity); 60% discharged battery pack	50 mph
Maximum gradability; 0% discharged battery pack	17%
Maximum gradability; 60% discharged battery pack	17%

A performance prediction run was performed using a 300 lb payload. This resulted in a range of 75 miles on the J227a Schedule D urban driving cycle. Energy Flow Models were developed for the 600 lb payload (gross vehicle weight of 3920 lb) and are included as Figures 2.2.2-5 through 2.2.2-9.

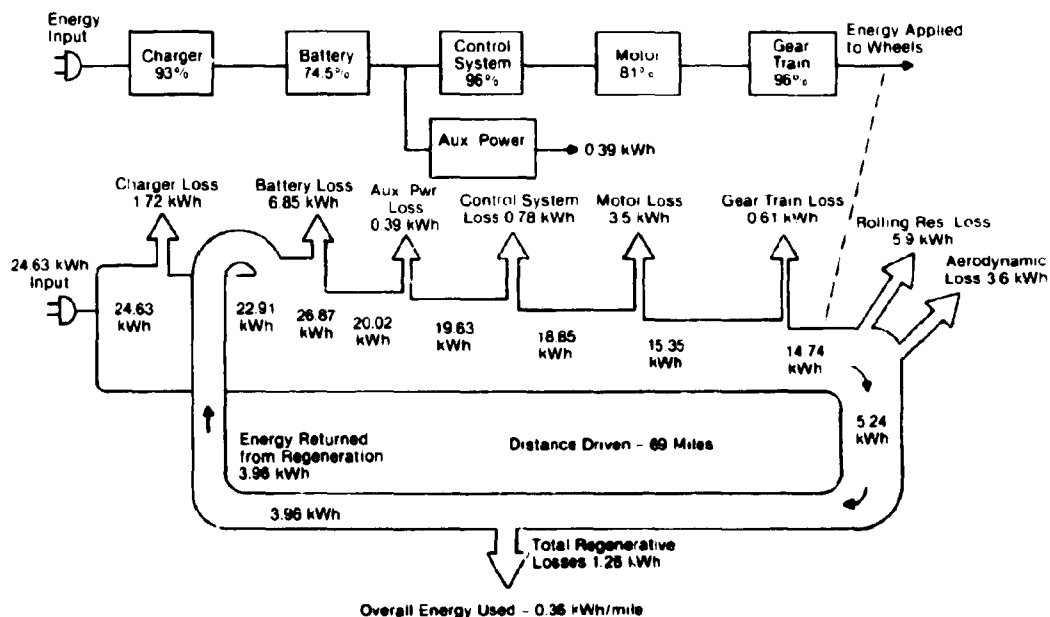


Figure 2.2.2-5. Energy Flow Model for GE Near-Term EV J227a Schedule D - Performance Prediction Model (W_{GVW} - 3920 lb)

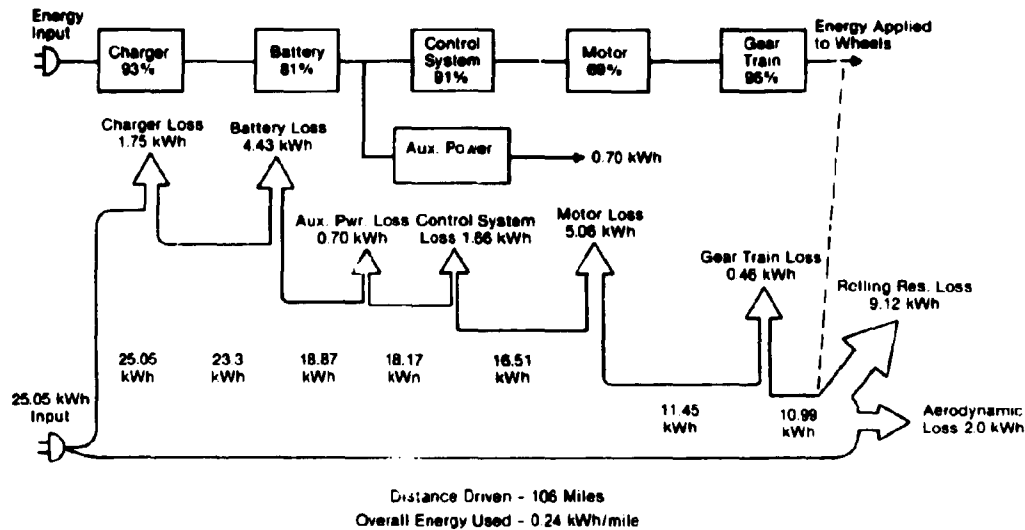


Figure 2.2.2-6. Energy Flow Model for GE Near-Term EV Constant 25 mph - Performance Prediction Model (W_{GVW} - 3920 lb)

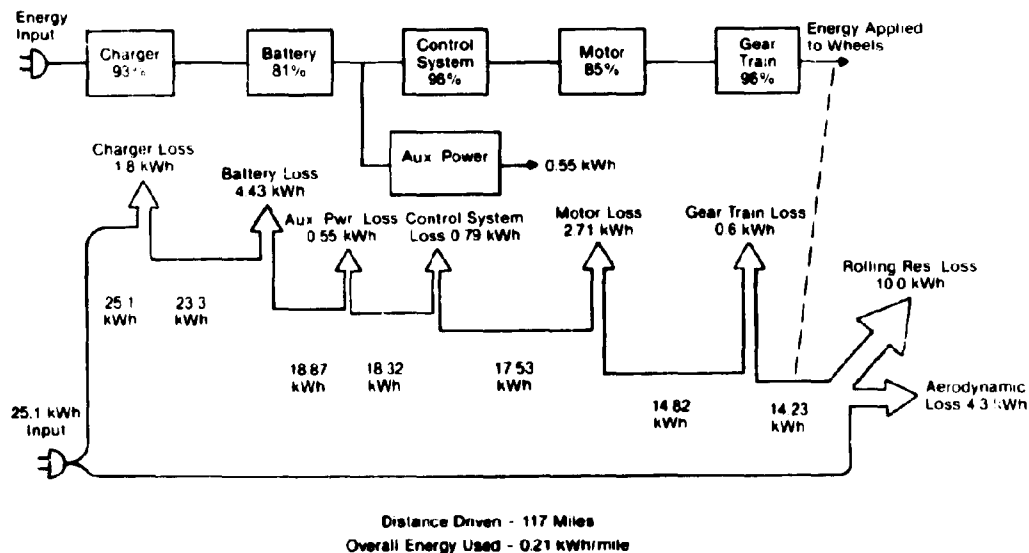


Figure 2.2.2-7. Energy Flow Model for GE Near-Term EV Constant 35 mph - Performance Prediction Model (W_{GVW} - 3920 lb)

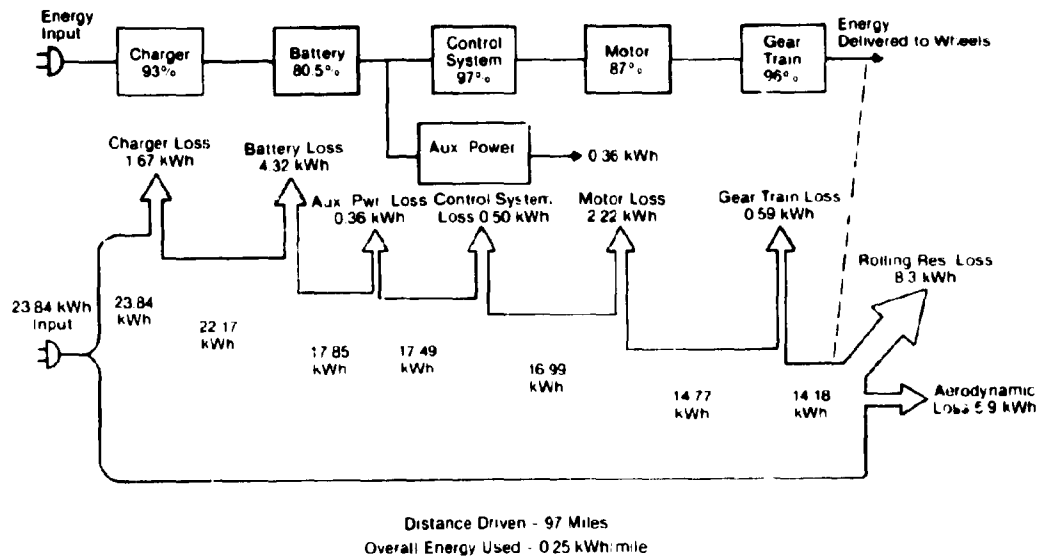


Figure 2.2.2-8. Energy Flow Model for GE Near-Term EV Constant 45 mph - Performance Prediction Model ($W_{GVW} - 3920 \text{ lb}$)

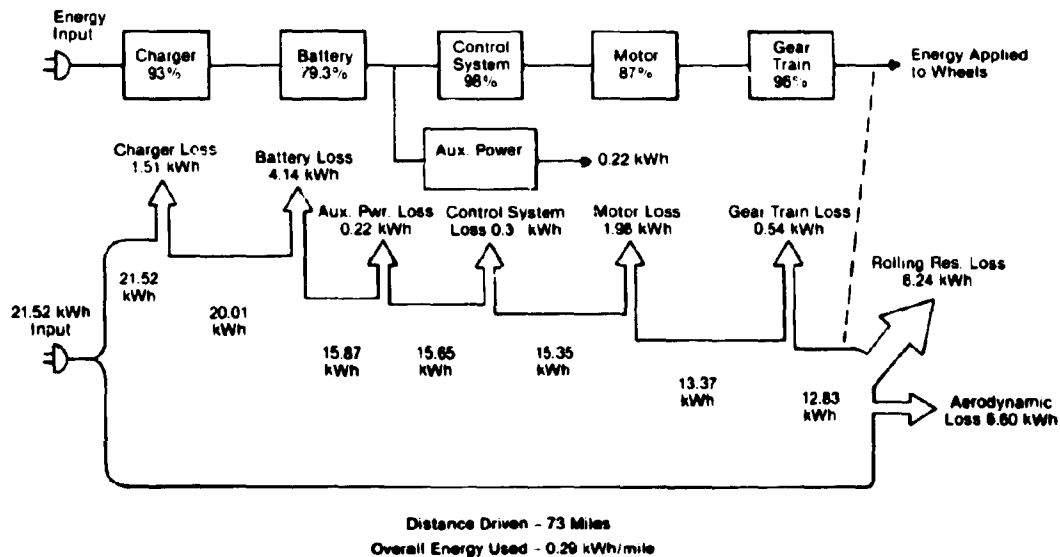


Figure 2.2.2-9. Energy Flow Model for GE Near-Term EV Constant 55 mph - Performance Prediction Model ($W_{GVW} - 3920 \text{ lb}$)

WBS 2.3 SYSTEM DESIGN AND SPECIFICATIONS

WBS 2.3.1 General System Description

The Electric Test Vehicle is an all-electric subcompact vehicle designed to carry up to four passengers in a suburban driving environment. The ETV system block diagram is depicted in Figure 2.3-1.

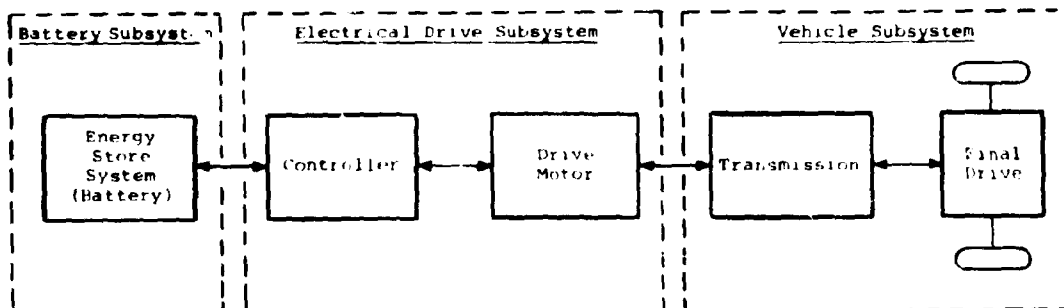


Figure 2.3.1-1. ETV System Block Diagram

The principal system elements are the Battery Subsystem, the Electrical Drive Subsystem, and the Vehicle Subsystem. The Battery Subsystem includes 18 propulsion batteries and their venting/watering system, propulsion battery wiring, the 12 V accessory battery, and the accessory battery charger, which is physically located in the power conditioning unit (PCU). The Electrical Drive Subsystem includes the PCU, which contains the armature controller, field control/battery charger, logic power supply, and the accessory battery charger. The drive motor, microcomputer/signal conditioner, on-board charger power unit, and differential pressure transducer amplifier and exciter (part of the regenerative braking system) are also elements of the Electrical Drive Subsystem. The Vehicle Subsystem is composed of the body structure, chassis, and air handling and electrical groups. The ETV is designed to conform to applicable Federal Motor Vehicle Safety Standards (FMVSS). Other significant system parameters are delineated in the Integrated Test Vehicle System Specification, 5180-A-001.

WBS 2.3.2 Summary of System and Subsystem Specifications

Figure 2.1-1 showed the five major equipment-related specifications of the Electric Test Vehicle. The specifications were developed in general according to the MIL-STD-490 specification format. The top level specification is that for the system. The subsystem specifications have requirements allocated from the system specification. Specifications sheets which form a part of the subsystem specifications define component requirements. In addition to the hardware-related specifications, a weight control specification and a power loss control specification have been developed. Performance against these specifications is tracked on a continual basis. The specifications were useful as a design trade-off decision-making tool since control of the weight and power loss are the key factors affecting vehicle performance. These specifications were issued for the Preliminary Design Review and revised for the Interim Design Review and Critical Design Review.

WBS 2.3.3 Summary of Interface Specifications and Drawings

Section 2.1 (Figure 2.1-2) defined the interface control specification tree. The interface specifications were used to define principal functional interfaces between the Vehicle Subsystem and the Electrical Drive Subsystem, Battery Subsystem, and Mobile Test Equipment. These specifications also served as an integration tool and were structured to define responsibilities and provide visibility of unassigned areas and responsibilities. Interface Control Drawings (ICDs) were documented and contain most of the details of the interfaces.

WBS 2.3.4 Special Studies

As part of the system analysis and design task, a number of special studies have been performed. The most significant ones are:

- Battery compartment heating and cooling
- Alternate designs to improve vehicle range
- Electrical drive subsystem cooling
- Battery emergency disconnect system
- Effects of battery life as a function of equalization charge
- Battery life above 100 °F ambient temperature operation
- Implementation of a ground fault current interrupter
- Hydrogen safety during battery charging and motoring
- Electrical hazards
- Projected life study on electrical drive subsystem components

A summary of the results of the special studies is included in the following sections.

Battery Compartment Heating and Cooling

An analysis was performed of various means of heating electric vehicle batteries, which might be subjected to ambient storage temperatures of -20 °F, in an effort to increase the resulting range. Several methods were considered:

- Battery self-heating just prior to start-up
- Using wall outlet energy via an electric blanket or equivalent
- Using the drive motor thermal energy by passing motor exhaust air over the batteries
- Using waste heat from the hot gas side of the passenger compartment heater

The results of the analysis are summarized below.

- Range of the vehicle relative to its range at 80 °F battery temperature is estimated at 0.4 if no auxiliary heating is used. This is based on long-term storage at -20 °F (more than 5 days). The estimated battery temperature after 24 hours storage at -20 °F is 34 °F, thus resulting in a 0.78

range ratio. The temperature after 48 hours storage at -20°F is 9°F , resulting in a 0.66 range ratio. The estimated temperature after 72 hours storage at -20°F is -7°F , resulting in an estimated range ratio of 0.51. The above data is based on the estimated thermal time constant of the battery pack and assumes a battery pack temperature of 80°F at the start of cold soak. Additional assumptions are one inch of thermal insulation around batteries with thermal conductivity of $0.03 \text{ Btu/hr-ft-}^{\circ}\text{F}$ and no regeneration during coasting or braking until battery temperature is 15°F . (Note: All relative ranges are based on starting with a fully charged battery. The J227a Schedule D driving cycle was assumed.)

- Use of battery energy to heat the battery just prior to start-up is not a promising concept. Relative range after a long-term soak using various approaches for this technique reaches a maximum of 0.5 (as compared to 0.4 with no external heating).
- Use of waste heat from the drive motor is not a promising concept. Relative range using this method is expected to be 0.5 or less. This concept requires air recirculation to achieve temperatures for adequate heat transfer.
- Waste heat from the drive motor and PCU increased the relative range to no more than 0.58. This concept also requires air recirculation to achieve temperatures for adequate heat transfer.
- The concept of using waste heat from the vehicle heater with no air recirculation in the battery compartment resulted in a large variation in the air-side heat transfer coefficient required for battery temperature uniformity. Resultant relative range was approximately 0.55 including heat transfer losses and heater fan motor losses. This assumes one inch of insulation on the sides and bottom of the batteries.
- The concept of using waste heat from the vehicle heater, providing air recirculation, and assuming one inch of insulation on the sides and bottom of the batteries provides a relative range of 0.66 (includes heat transfer losses and heater fan motor losses). This concept also requires a mixer to divert/dilute a portion of the hot exhaust gases from the heater before circulation over the battery pack.
- Use of wall outlet energy and an electric blanket to warm up the batteries to 80°F prior to start-up would, of course, yield no reduction in range compared to the 80°F baseline condition.

The range increase due to battery heating after long-term storage (greater than 5 days) based on the concepts analyzed is not sufficient to compensate for the additional power, weight, and volume requirements of an air circulating system for the preferred concept (waste heat from vehicle heater). A major redesign of the battery pack and enclosure system would be necessary in order to provide a method of insulation and the required air flow paths and is not in the scope of the contract to environmentally condition the battery.

As noted above, short-term storage (one to two days) does not result in a large range reduction because of the thermal time constant of the batteries. Long-term storage (one or more weeks) using the concept of a heating blanket or other thermal source plugged into a 115 V outlet has not been analyzed in detail. However, this concept may require redesign of the battery tray and battery tunnel to provide space around the batteries for heating elements and air circulation.

An analysis was also performed to determine various concepts of cooling the batteries during high ambient temperature operation. Two driving conditions were studied – constant 55 mph cruise and the J227a Schedule D cycle. The goal of the analysis was to use ambient air to hold battery temperatures below 100 °F to prolong battery cycle life.

The results of the analysis are tabulated below for an ambient temperature of 90 °F:

Ventilation Factor	Temperature at End of Driving Cycle (°F)	
	55 mph	J227a Schedule D
No Ventilation	104	112
Maximum Practicable Ventilation	101+	107+

Maximum practicable ventilation of the battery pack for ambient temperatures of 90 °F results in excessive air flow requirements (on the order of 290 lb/min). As with the heating concept, ventilation would require redesign of the battery tray and battery tunnel to allow air flow paths for adequate air movement.

Ambients above 90 °F would, of course, increase the temperatures to which the batteries are subjected. The table below summarizes data of battery temperature at the end of a 55 mph driving cycle and a J227a Schedule D driving cycle with no ventilation.

Driving Cycle	Ambient (°F)	Temperature After Full Cycle (°F)
55 mph	80	94
	90	104
	100	114
J227a Schedule D	80	102
	90	112
	100	122

Based on Globe-Union estimates, the cycle life of typical lead-acid batteries decreases with increased temperature. Quantitative data of the effect of temperature on deep cycle life is not available at this time; however, quantitative data showing the effects of temperature on positive grid corrosion (one of the modes of battery failure) is available. The corrosion rate increases by an order of magnitude when the temperature rises from 90 °F to 120 °F and by another order of magnitude with a temperature increase from 120 °F to 150 °F. In addition, Globe-Union states that the greatest damage would occur during charging at elevated temperatures.

Therefore, unless some cooling (refrigeration) arrangement is available in the vehicle, operation at elevated temperatures above 90 °F ambient will decrease battery life. Because of the excessive ventilation requirements to obtain a nominal reduction in battery temperatures, it is recommended that no action be taken. In addition, it is not in the scope of the contract to environmentally condition the battery.

Alternate Designs to Improve Vehicle Range

Three alternatives were suggested as design options for range improvement of the electric vehicle; a 15 plate battery design, a 120 V battery system, and a hybrid

battery system (108 V lead-acid system with a nickel-cadmium acceleration battery). The results are summarized below:

- The 15 plate battery design has a range improvement potential of ~10%. However, the cycle life of the batteries would be reduced considerably.
- A 120 V battery system provides a potential 7% range improvement. However, the additional two batteries would impact the battery tray design and structure as well as the vehicle structural design.
- The hybrid battery system using a bank of nickel-cadmium acceleration batteries in addition to 18 lead-acid batteries provides a 7% increase in range at a significant cost penalty.

Electrical Drive Subsystem (EDSS) Cooling

Drive motor cooling requirements were determined during the early system design stage since this data was readily available. A review was then held with the electronic equipment (Power Conditioning Unit -- PCU) designers to determine whether cooling should be handled independently for the motor and the electronics or with one fan ventilating both units in parallel or in series. The preferred approach was the series ventilating system. It was decided to ventilate the electronics first in the series chain in order to provide cooling to the electronics at the lowest ambient temperature. Thermostats were selected for the PCU and the motor, so that either unit could demand ventilating air.

Because the port for air entrance into the PCU was in a very tight location, it was determined that drawing air through the PCU into the ventilating fan and then exhausting that air into the motor would be the best mechanical arrangement. Thus, a pull-push configuration was designed. Air is sucked through the PCU, carried in a ventilating duct to the inlet of a ventilating fan, and exhausted into the motor. Air is then forced through the motor and exhausted into the motor compartment.

Battery Emergency Disconnect System

Three types of battery emergency disconnects were considered: a manual "punch to release" type commonly used in electric fork trucks; a manually cocked system requiring an electrical pulse to trip; and a manually cocked system held in electrically which would drop out once voltage was interrupted to a hold-in coil. The three types analyzed were designed to use minimal power in fork truck and EV industry applications. The disconnect requiring power for hold-in was chosen as the preferred concept because it is the most fail-safe and flexible of the three.

The unit selected uses energy in a stored spring to operate the interrupt mechanism. This enables the hold-in power to be used only as a trigger mechanism for the release spring. By having all vehicle interlock circuits in series with the hold-in coil, operation of any one of the interlocks will shut down the 108 V dc. Included in the series interlock system are the microcomputer which will shut down the 108 V under certain conditions, a manual emergency disconnect switch on the dash, a hood switch which removes power when the hood is open, a switch on the PCU terminal cover, and switches at the rear of the car actuated by access panels to either the battery or the vent/fill systems. In addition to the emergency disconnect which operates on the negative side of the battery, a main fuse is used on the positive side of the battery so that by operating the switch and removing the fuse, the battery would be completely disconnected. A hold-in coil within the on-board charger power unit was also added across the emergency disconnect switch to remove 115 V ac power from the car.

Effects of Battery Life as a Function of Equalization Charge

Globe-Union stated that it is not desirable to charge batteries to 100% state of charge on a daily basis. As the battery nears 100% state of charge, electrolysis of water increases significantly. This has a number of adverse effects. The gas bubbles (H_2 and O_2) generated decrease battery capacity and life by tearing small particles of active material from the plates. During excessive gassing, the expander in the negative plates can be moved mechanically or be chemically destroyed by nascent hydrogen, thus resulting in negative plates with decreased porosity and capacity. The equalization charge (100% battery pack charge) is recommended to be performed once following each series of seven daily charges.

Battery Life Above 100 °F Ambient Temperature Operation

(See Section 3.3)

Implementation of Ground Fault Interrupter

The use of a 60 Hz, 115 V power supply in the propulsion battery charger on board the ITV required that consideration be given to the possibility of electric shock resulting from 60 Hz current leakage to ground. A Ground Fault Current Interrupter (GFCI) was implemented in the vehicle with an appropriate power contactor to achieve the performance of a "cord connected" GFCI. Leakage currents in excess of six milliamperes trip the GFCI.

Hydrogen Safety During Battery Charging and Motoring

Globe-Union's study results are covered under Section 3.3. The electric vehicle battery tunnel is provided with a purge fan which runs continually during motoring and charging. This fan is a backup to the semiautomatic watering/venting system provided in the vehicle. In addition to the above, the Operation and Maintenance Manual includes a warning that "when charging the ETV in a closed area such as a garage, positive ventilation to the outdoors must be maintained."

Electrical Hazard Analysis

- AC System Interlocks - 115 V ac for battery charging is connected through a receptacle located behind the front license plate. The power ground connects to the car frame. The other power leads go to ac disconnect contactors located in the on-board charger power unit. AC is only connected to the PCU if power is applied to the onboard charger receptacle. Otherwise, a relay remains open and no connection is made. In addition, an interlock daisy-chain circuit is used which requires that all interlocks are enabled in order to enable the relay. If any of the interlocks are interrupted, the relay will drop out, disconnecting power.
- 108 V dc System Interlocks - In general, 108 V dc protection is by two means: an interlock system which ties into the quick disconnect switch (QD) and a 500 A fuse which is located at the rear of the car. The QD switch and the fuse are installed on opposite ends of the battery pack to prevent a shock hazard when the battery bank is removed from the car. The QD switch is tied into an interlock system which disconnects the 108 V dc when the hood is open or the terminal cover installed over the input

terminals to the PCU is removed. Additionally, other interlocks are provided by the microcomputer and the operator's emergency power-off hand switch. Removal of access covers at the rear of the battery to access the fuse or the vent/fill system also operates the QD disconnecting the PCU from the battery bank. This also disconnects the charging system should the car be in a charge or equalizing mode.

- In addition to the interlocks, additional safety protection is provided by routing the motor leads directly from the motor to the PCU, eliminating the need for terminals or connectors. Other safety features provided include a seat switch which prohibits driving the vehicle unless the driver's seat is occupied and an interlock which prevents driving when the ac power cord is not disconnected from the vehicle.

Projected Life Study on Electrical Drive Subsystem (EDSS) Components

EDSS parts lists were screened to identify possible limited life parts. Projected life data for these parts was obtained and evaluated. After screening, the following components were investigated: accelerator potentiometer, pressure transducer and solenoid valves (part of regenerative braking system), power conditioning unit contactors, drive motor, and power modules. The results of the study indicated that only the drive motor brush life is a concern requiring periodic maintenance checks of brush wear. The Operation and Maintenance Manual specifies inspection of the brushes every six months and replacement every two years.

WBS 2.3.5 System Wiring Diagrams and Interface Drawings

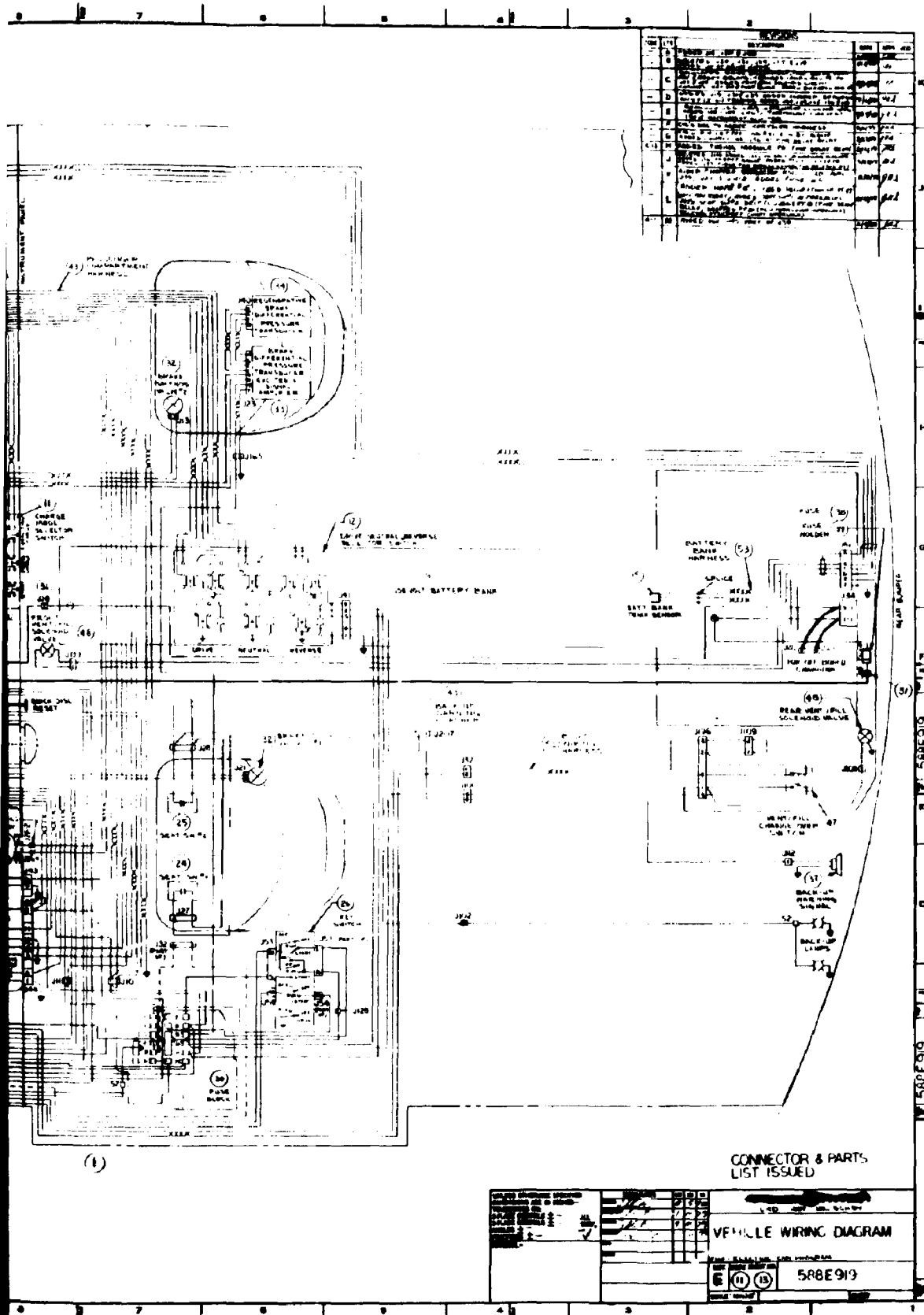
Two main drawings were made to depict overall system wiring. The Vehicle Wiring Diagram, drawing No. 588E919, shown in Figure 2.3.5-1, was made as a point-to-point diagram representing the layout of components in the vehicle. The System Interconnection Diagram, drawing No. 588E923, shown in Figure 2.3.5-2, identifies signal names, wire color, and pin numbers in a block diagram format.

The following wiring diagrams were prepared:

- Motor Compartment Harness
- Passenger Compartment Harness
- Power Conditioning Harness
- Motor Compartment Wiring Harness - 12 V
- Instrument Panel Harness - 12 V
- Body Wiring Harness - 12 V
- Battery Tray Wiring
- Vehicle Wiring Assembly - 12 V

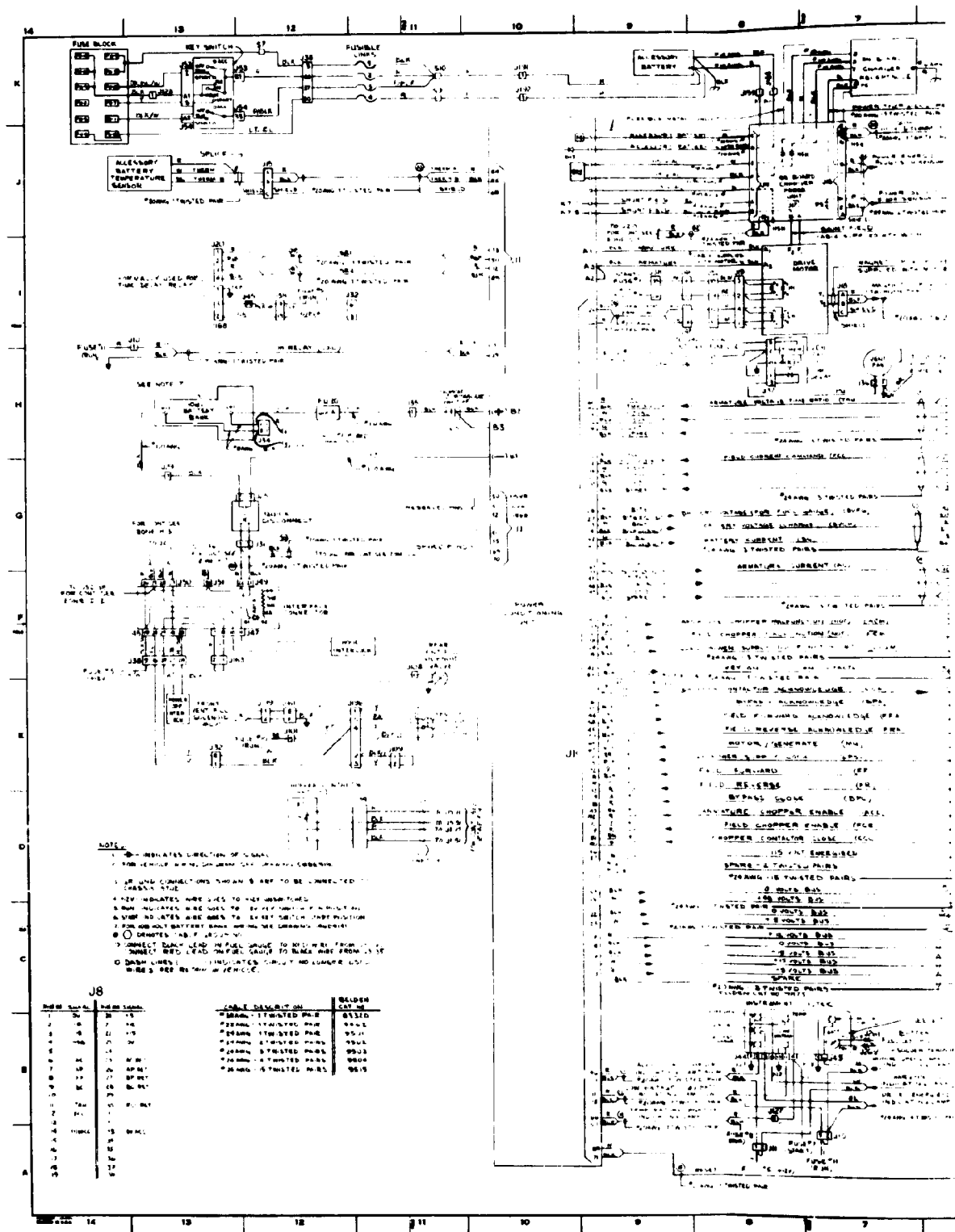
A series of individual diagrams were also prepared to simplify and segregate portions of the system, particularly in relationship to interface items such as the accelerator controls, brake controls, etc. These diagrams are:

- The Safety and Vent/Fill Interlock diagram - shows the arrangement of the various interlock switches which can remove 108 V dc power from the



3.5-1. Vehicle Wiring Diagram
2.3-9

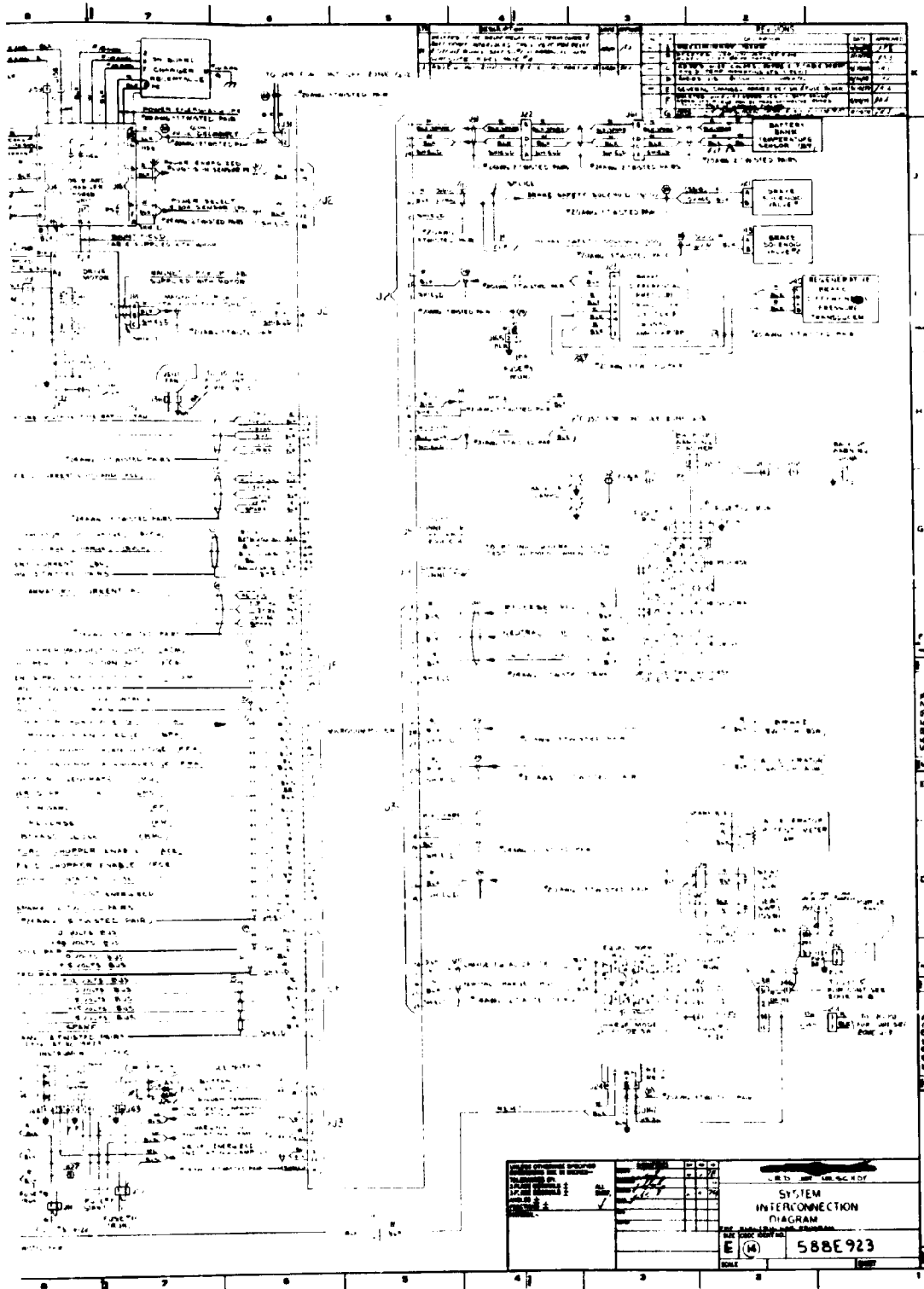
Reproduced from
best available copy



Reproduced from
best available copy

Figure 2.3.5-2. System Interconnection

2.3-11/12



System Interconnection Diagram

Reproduced from
best available copy

2.3-11/2

PCU. Interlocks are provided on the hood, PCU terminal cover, battery connector access panels, and vent/fill controls, etc. A 115 V ac control relay was added to the circuits so that operation of any of these interlock switches would also deactivate or disconnect 115 V ac power should it be plugged in inadvertently.

- The 108 V dc battery bank wiring diagram – depicts the various interfaces for General Electric, Chrysler, and Globe-Union.
- The 12 V wiring diagram for special fans and displays – shows the various instrument displays and techniques for ventilating the drive system components. The diagram also illustrates the purge air flow for the battery bank.
- The hand control circuits diagram – consolidates various microcomputer control circuits showing command signals from either the drive/neutral/reverse mode selector switch or from the charge mode selector switch.
- The foot control circuits diagram – depicts brake blending and accelerator controls.
- Another diagram – shows 115 V ac, logic power supply, temperature sensors, and seat switch circuits.

Interface Meetings

Early in the program, interface meetings were conducted to determine circuit and component responsibilities for Chrysler, General Electric, and Globe-Union. In general, it was decided that Chrysler would specify and furnish all 12 V components using automotive components as much as possible and that General Electric would specify 108 V dc components and 115 V ac components as well as logic power components and special sensors. Some items, such as the 108 V dc main connector for the battery bank, were specified electrically by General Electric and for packaging reasons, selected by Chrysler.

Interface meetings were held to solve interface problems as they occurred. Results of these meetings were documented and resulted in workable interface drawings.

WBS 2.4 DESIGN REVIEWS

Three design reviews were conducted by the Jet Propulsion Laboratory to verify that subsystem designs were compliant with the specifications and that proper consideration was given to safety and operability of the deliverable vehicles.

Preliminary Design Review	9/15/77
Interim Design Review	2/1/78
Critical Design Review	6/15/78

WBS 2.5 SAFETY AND RELIABILITY ANALYSIS

Vehicle safety analysis was performed under three basic headings:

- Safety characteristics of the vehicle under normal operating conditions categorized into vehicle operation, vehicle charging, and vehicle maintenance. Operational characteristics included electromagnetic compatibility (EMC) and electromagnetic interference (EMI). EMC/EMI tests will be performed on the completed vehicle and will be reported under WBS 4.6.
- Safety characteristics during operating, charging, and maintenance under the assumption that failure of elements of vehicle hardware has in fact occurred.
- Safety characteristics and potential hazards of the vehicle associated with or resulting from vehicle collision.

The results of the safety and reliability analyses are contained in a detailed Safety Report (SRD-78-199) issued on 15 January 1979.

In summary, design analyses, performance simulations, component tests, and laboratory tests indicate compliance with performance goals. Performance validation is discussed in WBS 4.6 Integrated Vehicle Tests. The vehicle has been designed for compliance with applicable Federal Motor Vehicle Safety Standards (FMVSS) and National Highway and Traffic Safety Administration (NHTSA) safety requirements for electric vehicles. Compliance with FMVSS relative to the 30-mph barrier test is reported under WBS 4.3.

A failure mode effects analysis (FMEA) has been performed on the Electrical Drive Subsystem – armature chopper, field chopper/charger, logic power supply, and microcomputer. The analysis revealed no category 1-A failure modes which have no fall-back mode for recovery. Category 1-A failure modes are defined as critical failures resulting in loss of vehicle control. The results of the FMEA is documented in the Safety Report (SRD-78-199).

A laboratory test was conducted to verify that the drive subsystem will clear a fault current in the drive motor circuit quickly enough to prevent a "lurch" of the vehicle. The drive subsystem was tested under "worst case" conditions, i.e., motor at zero rpm, full field current of 10.6 A, batteries fully charged, and by-pass contactor closed to simulate a transistor short. The main power contactor was located out of the PCU during these tests to preclude damage to the PCU and also to allow the use of a contactor with arc coolers. The following tests were performed and results are indicated in Table 2.5-1.

Contactors without arc coolers and the vehicle wheels would have moved a few revolutions (although at a relatively slow acceleration rate). Using a contactor with arc coolers, the short circuit current was interrupted successfully with little damage to the contacts, and the equivalent vehicle movement would have been minimal (a maximum of a third of a wheel revolution at a low acceleration rate). In either case, the driver could have applied the brakes of the vehicle to stop any further movement after sensing the failure.

The main power contactor with arc coolers has been mounted outside the PCU. This will prevent any damage to the PCU in the event of arcing. (Space limitations prevented installation of arc coolers on the main power contactor previously in the PCU.)

TABLE 2.5-1
LURCH MODE TESTS

Test No.	Contactor	Results
1	Standard main power contactor with used contacts (no arc coolers).	Motor moved 1 1/2 revolutions in ≈ 7 sec. Edge of contacts melted. (see Figure 2.5-1).
2	Standard main power contactor with new set of movable contacts (no arc coolers).	Motor moved 11 revolutions in a time > 15 sec. (Equivalent to ≈ 2 rotations of vehicle wheels.) The contactor spewed vaporized metal (see Figure 2.5-2).
3	New main power contactor with arc coolers	Motor moved 1 1/2 revolutions in ≈ 7 sec. Center of contacts melted (see Figure 2.5-3).
4	Test No. 3 repeated	Motor moved 1 1/2 revolutions in ≈ 7 sec. No added damage to contacts.



Figure 2.5-1. Results of Lurch Mode Test No. 1

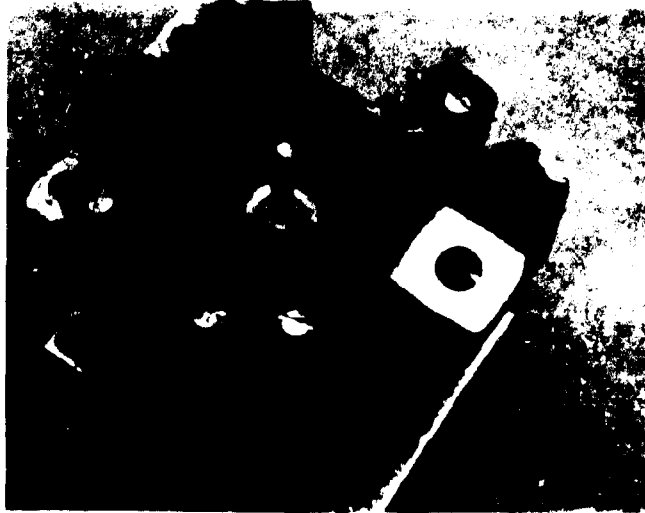


Figure 2.5-2. Results of Lurch Mode Test No. 2



Figure 2.5-3. Results of Lurch Mode Test No. 3

Based upon the results of the analyses and tests performed, the vehicle is considered entirely suitable for operation by trained personnel in a proving ground environment.

WBS 2.6 ELECTROMAGNETIC COMPATIBILITY/ELECTROMAGNETIC INTERFERENCE TESTS

Summary

The objective of the electromagnetic compatibility/electromagnetic interference (EMC/EMI) tests on the DOE ETV-1 vehicle was to determine the degree of conformance of the vehicle with the environmental EMC/EMI requirements of the system specification. These tests would provide reasonable assurance that ETV-1 would not operate in a manner which could be considered hazardous as a result of external environmental RF fields. In addition, the tests would characterize the vehicle EMI emissions and susceptibility to environmental radio frequency fields.

Test Facilities

The EMC/EMI tests were performed on July 10 and 11, 1979 in a shielded room facility located at Bendix Aerospace, Ann Arbor, Michigan.

Conclusions

EMI - EMISSIONS (Radiated). The radiated guidelines (Figure 2.6-1) are exceeded by an estimated 20 dB at some frequencies above 30 MHz as shown in Table 2.6-1. This level corresponds to present-day ignition systems.

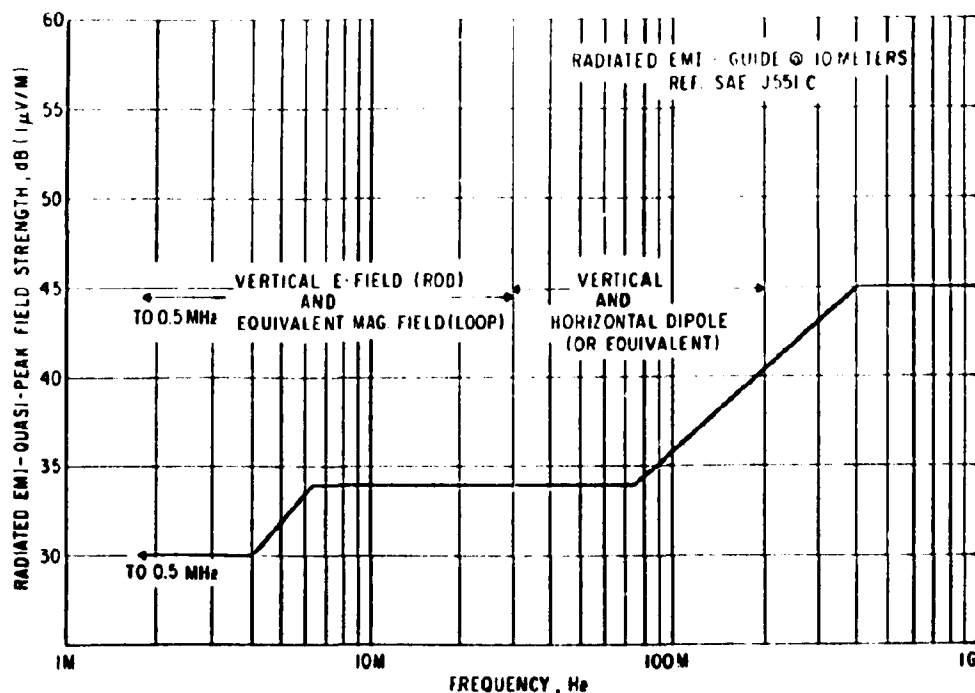


Figure 2.6-1. Radiated Guide

TABLE 2.6-1
TEST B RADIATED EMISSIONS (EMI)

Configuration (b) Mode iii & iv			
FREQUENCY MHZ	EMI FIELD STRENGTH dB (1 μ V/m)		ESTIMATED GUIDE @ 1 m
	ACNA	A,C,R	
35	45.5	75.5	54
50	40.0	65.0	54
60	51.5	74.5	54
90	34.7	49.7	55
100	55.6	65.6	56
120	47.2	72.2	57
150	54.1	59.1	58
200	56.6	66.6	61
240	58.2	58.2	62
300 } 1000 }	NO DISCERNIBLE EMI WAS MEASURED OR RECORDED		

ACNA - Accelerator not activated

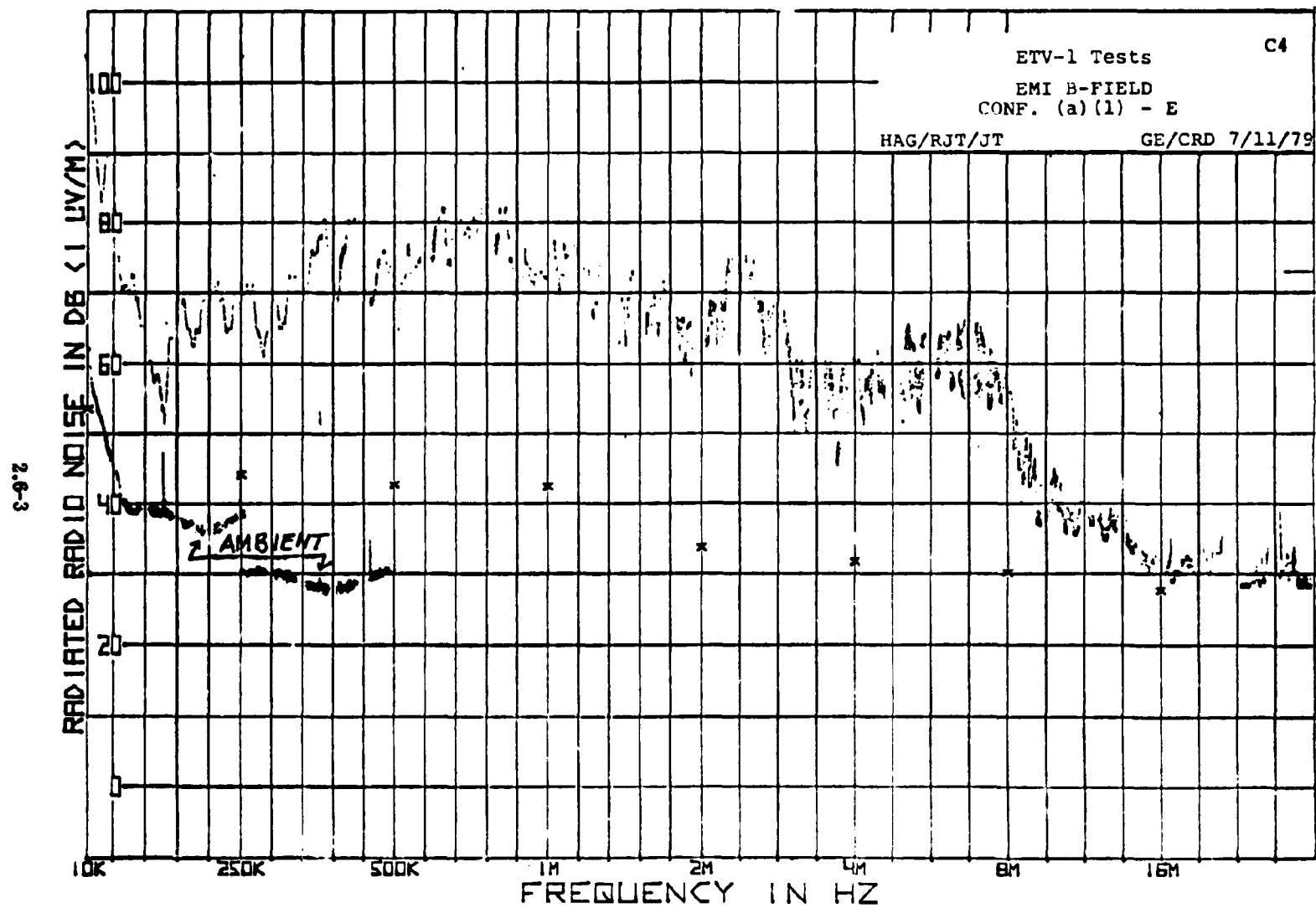
A,C,R - Accelerate, Coast, Regenerate

The magnetic field levels recorded in Figure 2.6-2 indicate values of 80 dB above 1 μ V/m at 1 m distance, which is about 10 dB over the guideline at 10 m when the 10 m value of 30 dB (μ V/m) is translated to 1 m utilizing the inverse square rule.

Slight interference to AM broadcast receivers in cars in very close proximity to ETV-1 might be anticipated as a result of the observed levels.

EMC - Susceptibility. The identified response of the ETV-1 to radio frequency fields in the 140 MHz portion of the spectrum occurs at field strength levels less than the level of 50 V/m listed in the system specification.

This may be interpreted as follows: there are a number of authorized mobile radio services which operate in the band of 140 to 155 MHz. Typical power levels are less than 100 W, except for the Amateur Radio Service which may go up to 2000 W maximum effective power. Although we do not have measurements to define the precise near fields from a 100 W transmitter, field strengths from 20 to 50 V/m from 1 to 3 m distance from a 100 W vertical antenna at 140 MHz must be anticipated. Therefore, it is possible that the effects noted in the EMC tests can occur on the highway. The speed could be affected or the main contactor could drop out in the presence of a passing car equipped with an operating 100 W 150 MHz transmitter.



The impact on the ETV-1 drive system electronic hardware when under high current and load conditions is unknown. Due to the possibility of damage to the electrical drive subsystem, the EMC susceptibility tests were not performed under high current and load conditions.

Section 3

SUBSYSTEM ANALYSIS AND DESIGN

WBS 3.1 VEHICLE SUBSYSTEM

Introduction

The Phase II Near-Term Electric Vehicle represents the state-of-the-art in automobile design. The sleek aerodynamic styling is attractive and contemporary in appearance and contributes significantly to the attainment of the range performance goals. The front air dam, contoured door glazing, shaped side paneling, and rear spoiler are all functional features that were sculptured and refined in the Chrysler wind tunnel. These features are illustrated in Figures 3.1-1 and 3.1-2. The flush glazing, concealed headlamps, low drag outside rearview mirror, full-belly pan, and low frontal area combined with the other features to produce a low $C_D A$ of 5.8 ft². The vehicle comfortably seats four passengers and provides storage space behind the rear seat for groceries, luggage, or other cargo. Batteries are distributed in between the seats and rear cargo area and centered in the side view between the front and rear wheels to give superior vehicle handling characteristics. Package comparisons are shown in Table 3.1-1.

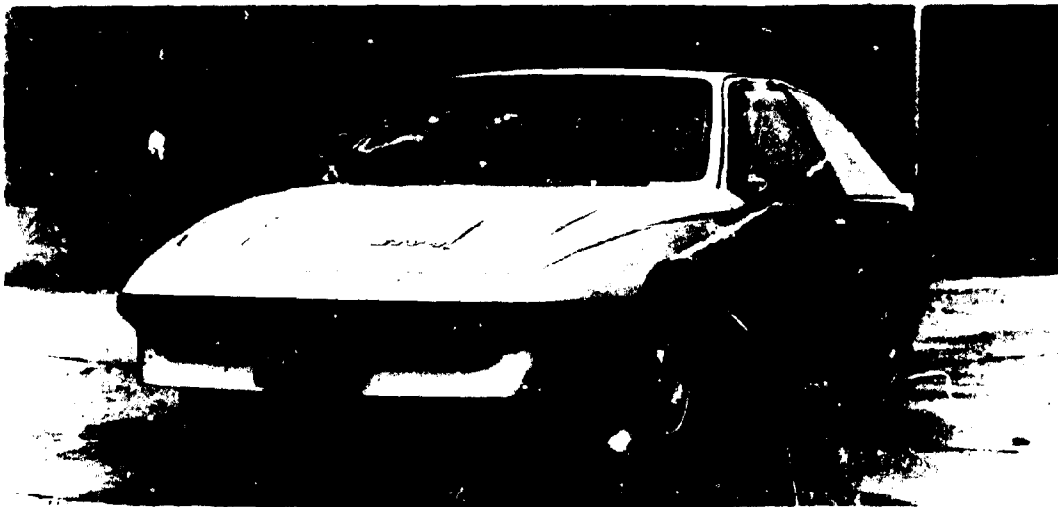


Figure 3.1-1. Front View of Near-Term Electric Vehicle

Chassis features include front wheel drive, independent front and rear suspension, rack and pinion steering, and low rolling resistance steel-belted radial tires. Braking is provided by combining the regenerating electric drive at the front with a four-wheel diagonal split hydraulic braking system. Power from the motor is transmitted to the wheels through a two-stage chain reduction drive transaxle.

Extensive use of lightweight materials, including aluminum, various plastics, and high-strength low-alloy steels, helps to offset the mass of lead-acid batteries used to power the vehicle.



Figure 3.1-2. Rear View of Near-Term Electric Vehicle

TABLE 3.1-1

PACKAGE COMPARISONS

	1979 Monza Notchback 2 Dr. Coupe	1979 Pinto 2 Dr. Sedan	1979 Omni Hatchback 2 Dr. Hardtop	Phase II Electric
Overall Length	4551.68 mm (179.20 in)	4338.32 mm (170.80 in)	4386.58 mm (172.70 in)	4302.76 mm (169.40 in)
Wheelbase	2463.80 mm (97.00 in)	2400.30 mm (94.50 in)	2456.18 mm (96.70 in)	2489.20 mm (98.00 in)
Front Track	1391.92 mm (54.80 in)	1397.00 mm (55.00 in)	1422.40 mm (56.00 in)	1422.40 mm (56.00 in)
Rear Track	1361.44 mm (53.60 in)	1417.32 mm (55.80 in)	1412.24 mm (55.60 in)	1412.24 mm (55.60 in)
Overall Width @B-Pillar	1661.16 mm (65.40 in)	1762.76 mm (69.40 in)	1676.40 mm (66.00 in)	1668.78 mm (65.70 in)
Curb Weight	1179 kg (2599 lbs)	1208 kg (2664 lbs)	1023 kg (2256 lbs)	1503 kg (3315 lbs est)
Overall Height	1264.92 mm (49.80 in)	1285.24 mm (50.60 in)	1305.56 mm (51.40 in)	1310.64 mm (51.60 in)

The Near-Term Electric Vehicle is specifically designed to meet all of the requirements of the Federal Motor Vehicle Safety Standards (FMVSS) that were in effect at the time of the contract in April 1977, with the exception of the side and rear window glazing. Lightweight polycarbonate with an anti-abrasive coating was used to save weight. Particular attention has been paid to minimizing those hazards that are peculiar to electric cars; i.e., battery acid spillage and electrical shock hazards in the event of a collision.

WBS 3.1.1 Body Structure

Basic Packaging

A thorough review of the Phase I design revealed several areas where repackaging of the passenger area and the electric drive motor could achieve significant improvement in aerodynamic drag, crashworthiness, and customer acceptance.

Placement of the batteries in the center tunnel is appropriate for proper weight distribution for ride and handling and barrier crash performance. The double row arrangement in the Phase I car results in an unnecessarily wide, high frontal-area configuration.

Figure 3.1.1-1 shows a rear section view of the passengers and battery packaging. The view to the left of the centerline shows the passenger raised to clear the wide battery tunnel. The right half of the drawing shows the single row battery tunnel and its effect on improving the seating comfort and maintaining the head room in spite of a lower vehicle roof.

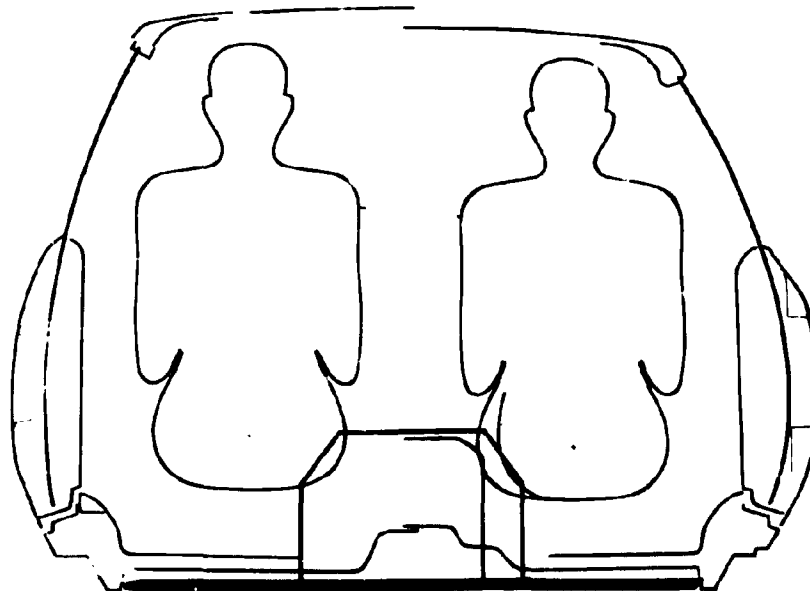


Figure 3.1.1-1. Packaging Comparison – Rear Section View

Figure 3.1.1-2 shows the side view seating and the motor compartment packaging. A plan view of the chassis and drive subsystem is shown in Figure 3.1.1-3.

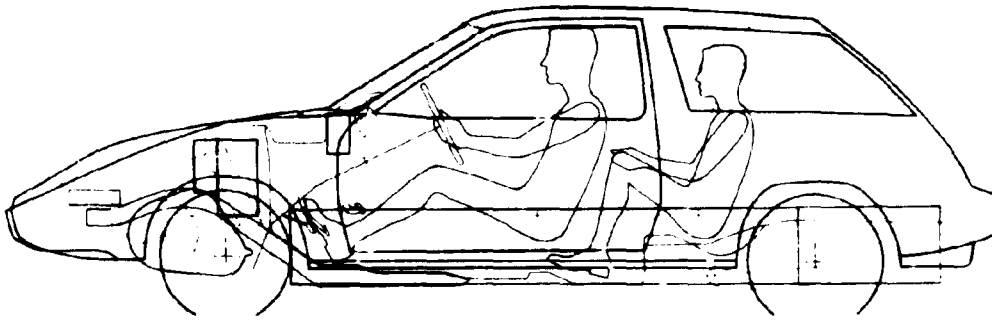


Figure 3.1.1-2. Packaging Comparison – Side View Section

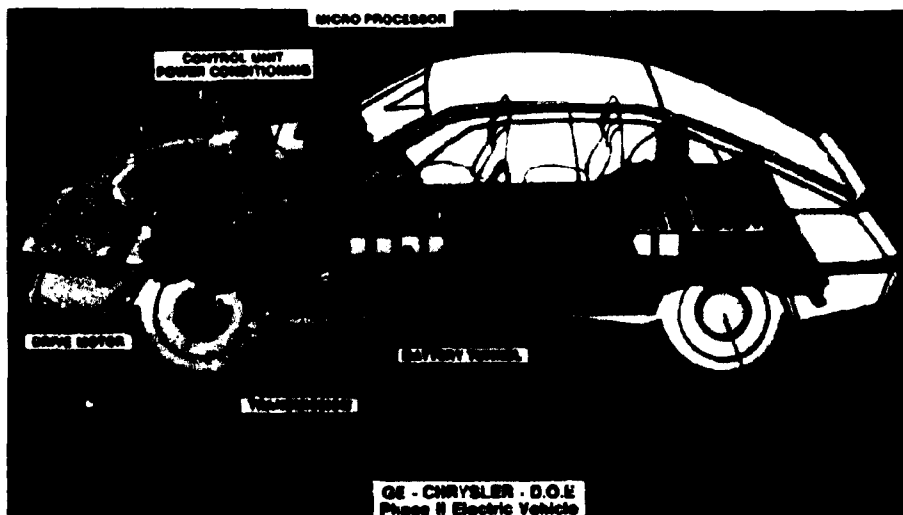


Figure 3.1.1-3. Plan View – Chassis and Drive Subsystem

The Phase I fore and aft positioning of the traction motor would not meet the 30 mph barrier impact requirements. It did not provide a load path nor sufficient crush space to absorb the dissipation of the kinetic energy. Positioning the motor in a transverse configuration low in the motor compartment (Figure 3.1.1-2) provided a direct load path for the batteries into the motor and finally into the barrier. A transverse mounted motor provides an additional benefit by eliminating the inefficiency of the right angle hypoid or bevel gear set since the motor and drive axis are parallel.

The Phase I design used a seating arrangement with the rear passengers facing backward to achieve the aerodynamic objective. This same objective was met by revising the seating package to provide for all passengers to face forward. The vehicle comfortably seats two 95th-percentile males in the front and two 50th percentile males in the rear.

Luggage storage of the Near-Term Electric Vehicle is approximately 0.1925 cu m (6.8 cu ft) and is located all of the rear seat above the battery storage compartment. This volume does not include the space above the lower edge of glass. As shown in Table 3.1.1-1 the luggage capacity of the Near-Term Electric Vehicle compares favorably with mass-produced subcompact vehicles. The luggage capacity was determined in accordance with the procedure established in the SAE Recommended Practice -- SAE J1100, Section 8.

TABLE 3.1.1-1
LUGGAGE CAPACITY COMPARISON

Passenger Car (Year, Make, Model)	Luggage Capacity (ft ³)	(m ³)
1979 Monza Two-Door Coupe	6.6	2.0
NEAR-TERM ELECTRIC VEHICLE	6.8	2.1
1979 Pinto Two-Door Sedan	8.7	2.6
1979 Omni/Horizon Two-Door Hatchback	10.5	3.2

The Phase I roller mounted battery tray was determined to be structurally redundant and subsequently was changed to a bolted-in-place battery pack. Eighteen six-volt batteries are arranged in a "T" shape as shown in Figure 3.1.1-4 supported by a light-weight aluminum frame to retain the batteries during rollover and 30 mph barrier impact. The battery pack is lifted into place using a modified commercial lift table and secured with 22 uniformly loaded bolts around the periphery of the battery tray. Roller mounted batteries result in substantial weight penalties. In a mass-produced electric vehicle for public use, batteries should not have to be serviced (by removal) more frequently than at six-month intervals.

Aerodynamic Development

Once the basic packaging task was completed, a number of styling themes were evaluated for esthetic value and aerodynamic drag. These selections included a square-back station wagon and a modified fastback sedan. The basic station wagon design was slightly superior to the sedan for a frontal air flow vector, but it deteriorated drastically in the real world condition of a cross wind. The final design of the Near-Term Electric Vehicle was accomplished by actually sculpturing the 3/8 scale clay models in the Chrysler Wind Tunnel. Figure 3.1.1-5 and 3.1.1-6 are typical flow study pictures.

Areas that required detailed attention to achieve a laminar (or attached) flow were the windshield glass, A-pillar, door glass, front fascia and air dam, wheel openings, side glass-to-rear pillar transition, and rear spoiler. Flush windshield and side windows, as well as a full underbody pan, contribute significantly to the drag coefficient reduction effort. The final design, with windshield wipers, side view mirror, four passenger load, and license plates, yielded a yaw corrected drag coefficient of 0.030. The resultant corrected frontal area product of $C_D A$ is 5.8 ft².

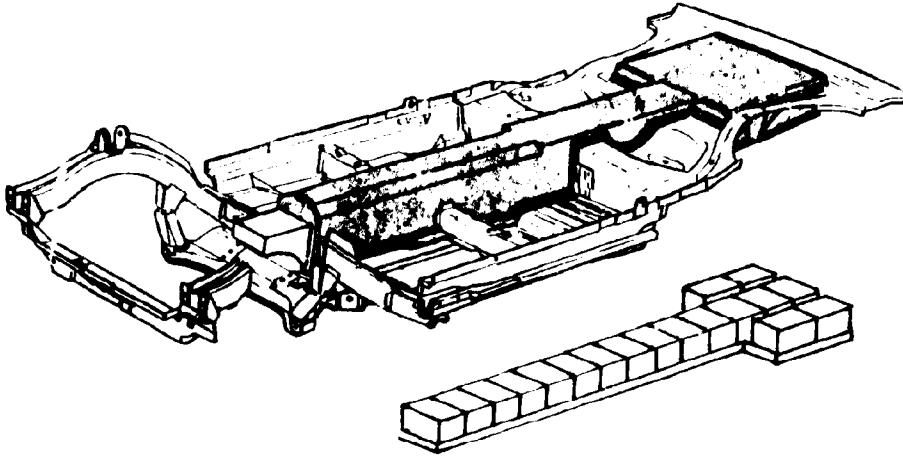


Figure 3.1.1-4. Battery Support Frame

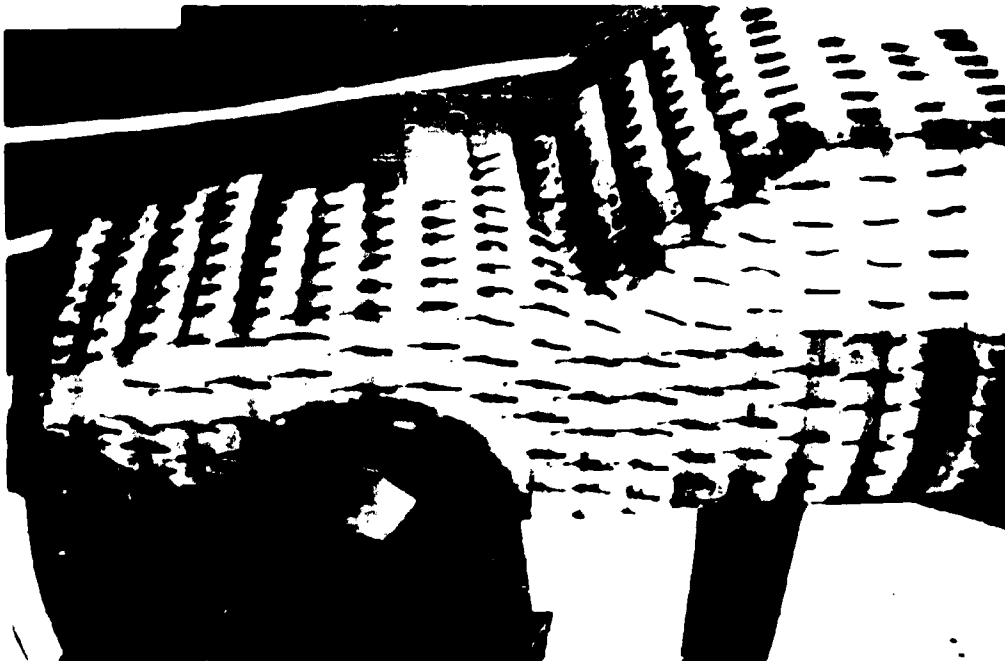


Figure 3.1.1-5. 3/8 Clay Wind Tunnel Test
(left side forward of Windshield)

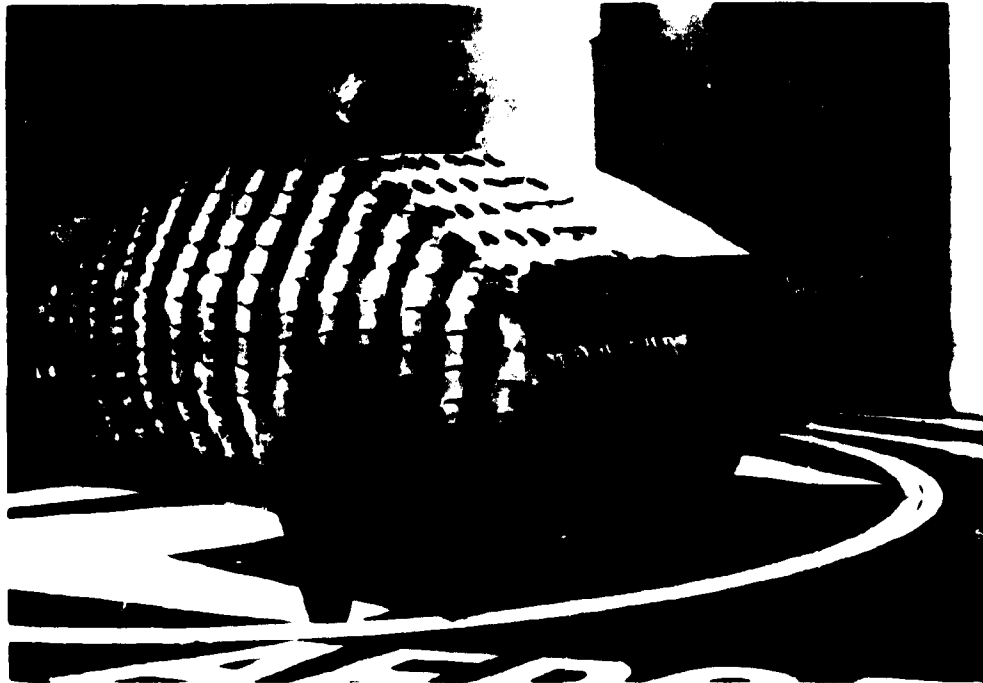


Figure 3.1.1-6. 3/8 Clay Wind Tunnel Test
(3/4 left rear view)

Structural Design

The basic unitized body structure is patterned after the 1978-79 Chrysler Omni/Horizon vehicles. The main side elevation load-bearing members in these vehicles are a two cell truss including the front longitudinal and fender, rear longitudinals and quarter, the side sills, roof rails, and A, B, and C Pillars. Lateral structural integration is obtained by joining the side elements with floor pan, crossmembers, front and rear roof headers, and the roof panel into a full unitized welded body.

The electric car has a self-sustaining third main structural member, the battery tunnel, which extends the full length of the passenger compartment. This member supports the weight of the batteries and uniformly distributes the load into the body truss system. An aluminum honeycomb impact structure protruding into the motor compartment serves to absorb energy during a frontal impact, thus reducing damage to the battery tunnel.

Static Design Criteria

Given the varied structural requirements placed upon an automotive body and the complex nature of this structure, simple calculations cannot be used to compute the strength and design criteria for each element of that structure. Sophisticated techniques, such as finite element modeling of the entire vehicle, were applied. These techniques require a basic reference point. Previous Omni/Horizon analysis data and test results were utilized as a guide in calculating the needs of the new design.

A proprietary computer program called SST (Structural Section Targets) was used to establish these design criteria. Basic information, including values of various sectional

properties for selected elements from the referenced design and necessary correction factors based on the size, weight, and test requirements, constitute the input data. From this the program generated a set of the required sectional properties for the new design. This targeting system was used in developing minimum section properties for the electric vehicle.

Shown in Table 3.1.1-2 is a list of the vehicle body elements checked, and Table 3.1.1-3 defines the location of each targeted section. Figures 3.1.1-7 and 3.1.1-8 illustrate graphically the location of the various sections, while Table 3.1.1-4 lists the dynamic and static load justification for each targeted section. Table 3.1.1-5 tabulates the minimum section property requirements for the Near-Term Electric Vehicle.

Dynamic Design Criteria

After the basic structural parameters were defined, the structural integrity of the vehicle under full-load conditions was confirmed by application of the NASTRAN

TABLE 3.1.1-2
STRUCTURAL AREAS AND ITEMS TARGETED

Section Number*	Description	I'X'X	IZZ	IM'N	K	ZXX	ZZZ	ZC
1	Windshield Header	X		X				X
2	A-Pillar Upper Min	X	X					X
3	A-Pillar at Belt	X	X			X	X	X
4	A-Pillar Lower	X	X		X			
5	Cowl Box Center	X			X			
6	Sill	X			X			
7	Roof Rail		X	X				X
9	Roof Bow	X		X				
10	Door Frame at Belt	X	X	X	X			
11	B-Pillar Lower	X	X		X	X		
12	B-Pillar at Belt	X	X		X	X		X
13	B-Pillar Upper Min	X	X		X			X
14	Backlite Heater	X		X				
15	C-Pillar Upper Min	X	X		X			
16	C-Pillar at Belt	X	X		X			
17	Upper Deck Center	X		X				
18	Deck Drain Trough		X	X				

NOTE: Door Beam (8), Front Rail (20), and Rear Rail (19) metal thicknesses and section sizes are determined with the thin wall buckling analysis "SERCRIP."

*Detailed descriptions of these elements are provided in Table 3.1.1-3.

TABLE 3.1.1-3
STANDARD SECTION LOCATION DEFINITION

Section Number	Section Name	Remarks
1	Windshield Header	Centerline section cut parallel to fore-aft direction in a vertical plane.
2	A-Pillar Upper	True radial section of the minimum size of A-Pillar upper located just below transition to roof rail and windshield header.
3	A-Pillar at Belt	True radial section representing maximum size of A-Pillar upper located just above transition to cowl top and A-Pillar lower.
4	A-Pillar Lower	True radial section cut at the lower hinge mounting position.
5	Cowl Box Center	Centerline section cut parallel to fore-aft direction in a vertical plane.
6	Sill	Section cut parallel to inboard-outboard direction in a vertical plane through the center of door opening.
7	Roof Rail	Same as 6.
9	Roof Bow	Same as 1.
10	Door Frame at Belt	True radial section located at belt. (Just above attachment to door - represents minimum section).
11	B-Pillar Lower	Same as 4.
12	B-Pillar at Belt	True radial section representing maximum size of B-Pillar upper located at belt just above transition to B-Pillar lower. If the pillar is discontinuous at this location and the discontinuity represents a minimum section, the section is taken through the discontinuity.
13	B-Pillar Upper	True radial section representing minimum size of B-Pillar upper located just below transition to roof rail.
14	Backlite Header	Centerline section cut parallel to fore and aft direction in a vertical plan.
15	C-Pillar Upper	True radial section representing minimum size of C-Pillar upper located just below the transition to the roof rail and rear header.
16	C-Pillar at Belt	True radial section representing maximum size of C-Pillar upper located just above the belt.
17	Upper Deck	Same as 1.
18	Deck Drain Trough	True radial section representing minimum deck drain trough size.

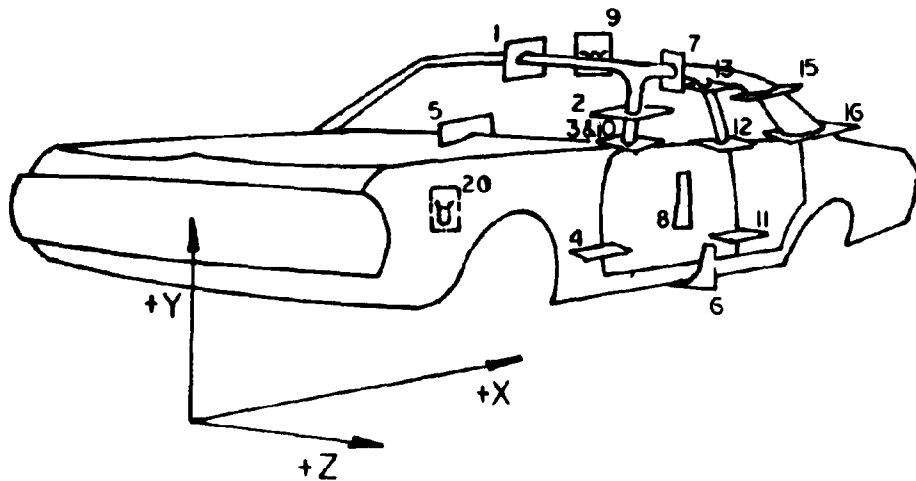


Figure 3.1.1-7. Graphic Representation of Sections Evaluated - 3/4 Left Front View

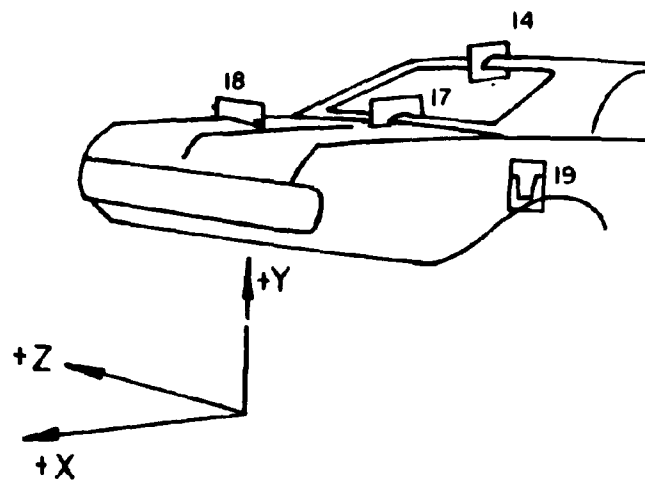


Figure 3.1.1-8. Graphic Representation of Sections Evaluated - 3/4 Right Rear View

TABLE 3.1.1-4

JUSTIFICATION FOR TARGETED SECTIONS

Section Number	Section	Section Property	Section Justification
1	Windshield Header	IXX	Vertical shake (Dynamic Load) (D)
		IMIN	Vertical shake (D)
		ZU	Roof crush (static load) (S)
2	A-Pillar Upper Min	IXX	Lateral shake (door vertical with (D)(S) door full open)
		IZZ	Fore and aft shake (door vertical (D)(S) with door near closed)
		ZU	Roof crush (S)
3	A-Pillar at Belt	IXX	Lateral shake (door vertical with (D)(S) door full open)
		IZZ	Fore and aft shake (door vertical (D)(S) with door near closed)
		ZX	Side impact (S)
		ZU	Roof crush (S)
		ZZ	Front impact (S)
4	A-Pillar Lower	IXX	Lateral shake (door vertical (D)(S) with door full open)
		IZZ	Fore and aft shake (D)
		K	Door check strap (S)
5	Cowl Box Center	IXX	Vertical shake (D)
		K	Torsional stiffness (S)
6	Sill	IZZ	Door bearing stiffness (S)
		K	Torsional stiffness (S)
7	Roof Rail	IZZ	Bending stiffness (D)(S)
		IMIN	Bending stiffness (S)
		ZU	Roof crush (S)
8	Roof Box	IXX	Bending stiffness (S)
		IMIN	Bending stiffness (S)
10	Door Frame at Belt	IXX	Bending at belt (below sill loading) (S)
		IZZ	Bending stiffness (S)
		IMIN	Bending stiffness (below sill loading and pivot bending) (S)
		K	Torsional stiffness (S)
11	B-Pillar Lower	IXX	Same as 1 (S)
		IZZ	Same as 11 (S)
		K	Same as 11 (S)
		ZX	Same as 11 (S)
12	B-Pillar at Belt	IXX	Same as 11 (S)
		IZZ	Same as 11 (S)
		K	Same as 11 (S)
		ZU	Same as 11 (S)
		ZX	Side impact, lateral shake (S)
13	B-Pillar Upper Min	IXX	Door vertical with door full open (S) (4 door only)
		IZZ	Door vertical with door near closed (S) (4 door only)
		K	Rear door check strap (4 door Only) (S)
		ZU	Roof crush (S)
14	Backlite Header	IXX	Lateral shake (D)
		IMIN	Vertical shake (D)
15	C-Pillar Upper Min	IX	Lateral shake (D)
		IZZ	Fore and aft shake (D)
		K	Twist rigidity of roof (S)
16	C-Pillar at Belt	IXX	Same as 14 (D)
		IZZ	Same as 14 (D)
		K	Same as 14 (D)
17	Upper Deck Center	IXX	Vertical stiffness (S)
		IMIN	Vertical stiffness (S)
18	Deck Drain Trough	IZZ	Vertical stiffness (S)
		IMIN	Vertical stiffness (S)

Reproduced from
best available copy

TABLE 3.1.1-5

NTEV MINIMUM SECTION PROPERTIES

Section Number	Section	I _{xx}		I _{zz}		I _{min}		K		Z _{xx}		Z _{crush}		Z _{min}	
		NTEV Target	L24 Target	NTEV Target	L24 Target	NTEV Target	L24 Target	NTEV Target	L24 Target	NTEV Target	L24 Target	NTEV Target	L24 Target	NTEV Target	L24 Target
1	Windshield Hdr	0.059	0.039			0.041	0.027					0.071	0.076		
2	A-Pillar Upper	0.246	0.189	0.135	0.104							0.115	0.115		
3	A-Pillar at Belt	0.328	0.252	0.461	0.354					0.161	0.167	0.116	0.134	0.230	0.239
4	A-Pillar Lower	0.751	0.316	2.679	1.102			0.646	0.395						
5	Cowl Box Center	0.745	0.521					0.197	0.288						
6	Sill			2.144	1.640			2.111	1.579						
7	Roof Rail			0.354	0.158	0.253	0.113					0.089	0.083		
9	Roof Bow	0.008	0.006			0.008	0.006								
13	B-Pillar Upper	0.280	0.171	0.483	0.295			0.149	0.114			0.099	0.091		
12	B-Pillar at Belt	0.342	0.209	0.534	0.326			0.209	0.219	0.188	0.155	0.229	0.210		
11	B-Pillar Lower	2.321	1.243	4.249	2.276			1.814	1.205	0.747	0.671				
18	Deck Drain Trough			0.038	0.032	0.008	0.007								
16	C-Pillar at Belt	0.340	0.295	0.538	0.467			0.186	0.145	0.162	0.171				
14	Backlite Heater	0.380	0.333			0.105	0.092								
10	Door at Belt	I _{yy} = 0.060		0.013		0.030		0.0601							

structural analysis computer program shown in Figure 3.1.1-9. A graphic representation of the subsequent finite element model of the vehicle structure (Figure 3.1.1-10) shows the individual plate, beam, and shell elements.

Deflection rates of the structure when bending and torsional loads applied were of primary concern. These values were calculated and "normalized" in terms of the vehicle wheelbase to facilitate comparison with other "baseline" vehicles.

The beam rigidity was determined to be 243,122 lb/in/ft and the torsion rigidity 69,184 ft-lb/in/ft - both meet the goals established in the Preliminary Design Review. Laboratory testing of the mule car established that test values were approximately 10% higher than calculated. Figure 3.1.1-11 illustrates the test procedure used to determine the torsional rigidity of the mule car.

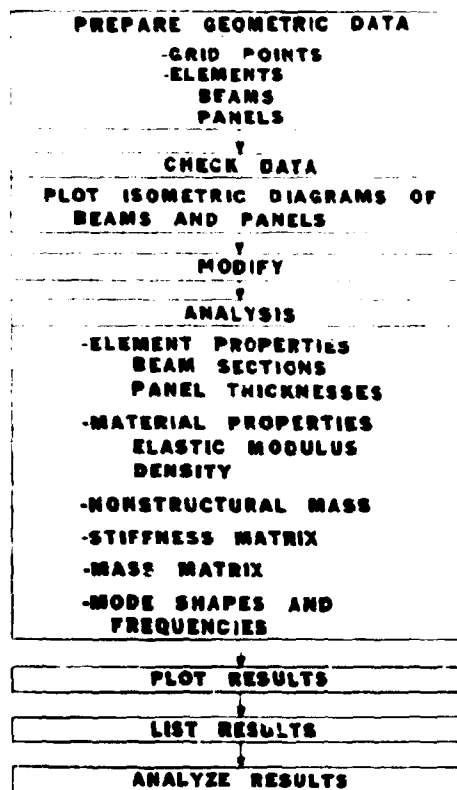


Figure 3.1.1-9. NASTRAN Modeling Flow Chart

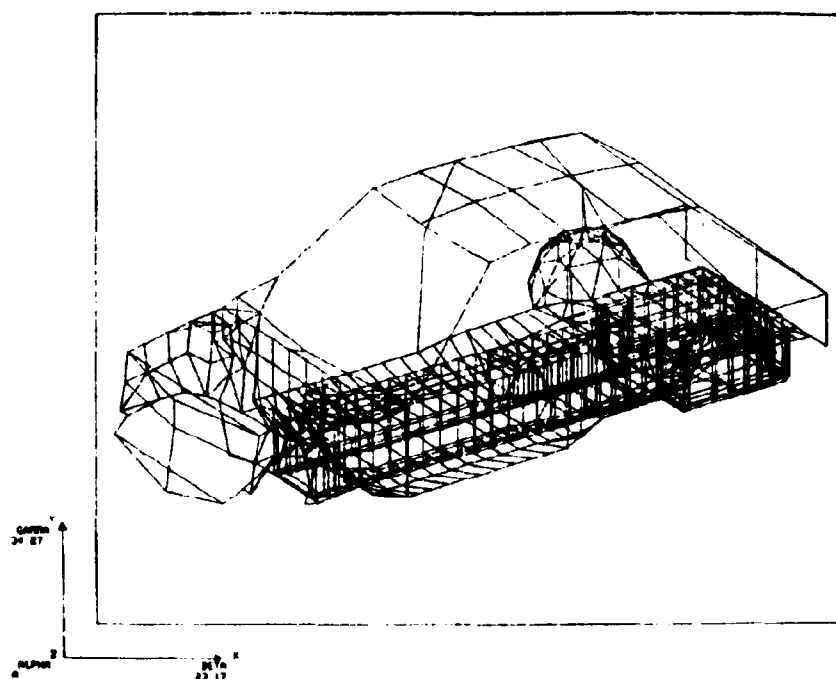


Figure 3.1.1-10. NASTRAN Finite Element Graphic Representation



Figure 3.1.1-11. NTEV Mule Car Torsional Rigidity Test

Crashworthiness Prediction (Computer Model)

In addition to the demands of normal over the road operation the body structure must provide compliance with the federally mandated safety standards (FMVSS).

A computer simulation program (MINIBASH) developed by Calspan Corporation was used, with their concurrence, to predict both front and rear end high speed barrier impact test performance. The program utilizes static crush data (load deflection properties) from a known complete vehicle and/or individual components to make predictions about dynamic barrier impacts. This modeling method is used to determine the structural design requirements. Using Chrysler's engineering expertise, the required static crush load-deflection curves were estimated. The total crush and vehicle deceleration profile were then developed based upon these estimated values. Figure 3.1.1-12 provides a graphic illustration of the process.

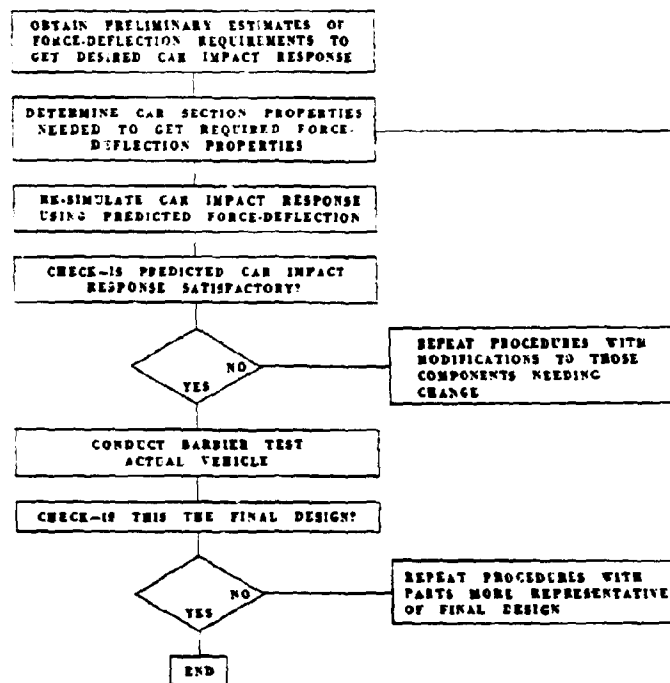


Figure 3.1.1-12. MINIBASH Flow Diagram

The following is a brief summary of the MINIBASH logic and dynamic rate factors:

MINIBASH is a general dynamic impact math model, written in BASIC language that can be used for barrier and car to car impact simulations. A general math model consisting of up to 10 masses and 20 resistances can be simulated in this program. A nonlinear static force deflection table can be specified for each resistance, with one of four dynamic magnification factors applied. The four dynamic rate factors which are shown in Figure 3.1.1-13 are explained as follows:

- None; no rate factor applied
- Linear; $F_{dyn} = \left[(F_{stat} 1.0 + 0.000568(XR)) \right]$
- Log; $F_{dyn} = F_{stat} \left[1.27228 + 0.0197 \ln(XR) \right]$
- Expon; $F_{dyn} = F_{stat} \left[1.0 + \left(\frac{XR}{40.4L} \right)^{1/5} \right]$

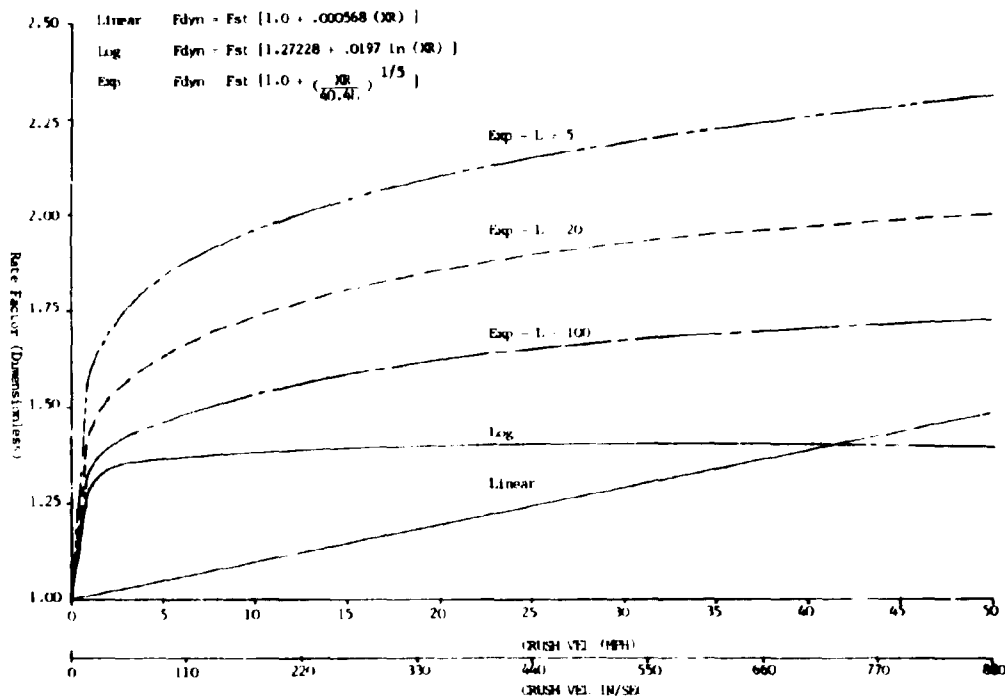


Figure 3.1.1-13. Rate Crush Factors

The displacements, velocities, and accelerations are calculated at each time increment and printed at each print interval for each mass in the system. The static and dynamic force, crush of each resistance, and the sum of the forces is also calculated and printed.

Minibash solution provides the following results:

- The new mass displacement from previous displacement, velocity and acceleration:

$$X_{new} = X_{old} + V_{old} + \frac{A_{old}}{2} \quad (1)$$

Where: X = displacement
 V = velocity
 A = acceleration

- The relative position of all masses and determined crush of each resistance
- The static force of each resistance and applied specified dynamic rate factor for dynamic force in each resistance
- Sums up the dynamic loads on all the masses and calculates acceleration (A);

$$A_{\text{new}} = \frac{F_{\text{dyn}}}{M} \quad (2)$$

- The velocity (V) for all masses:

$$V_{\text{new}} = V_{\text{old}} + \frac{(A_{\text{new}} + A_{\text{old}}) t}{2} \quad (3)$$

Equations (1), (2), and (3) define the system for each time increment. The above steps are repeated for each time increment.

The Near-Term Electric Vehicle frontal impact math model is composed of five masses and six resistances. The rear impact model is composed of only two masses and four resistances.

Figures 3.1.1-14 and 3.1.1-15 illustrate the two MINIBASH math models utilized in the development of the Near-Term Electric Vehicle.

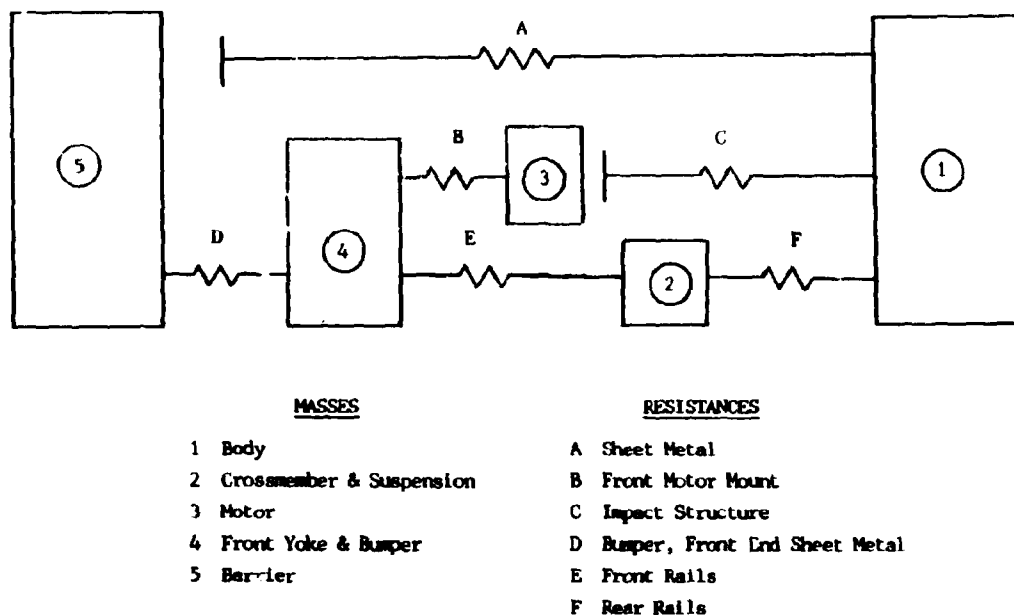


Figure 3.1.1-14. MINIBASH Model – 30 mph Frontal Impact

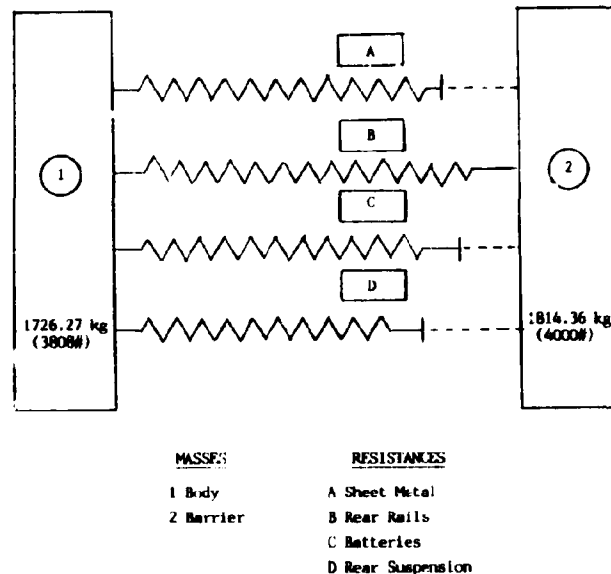


Figure 3.1.1-15. MINIBASH Model - 30 mph Rear Impact

Body displacement velocity, and displacement versus time curves for both the front and rear impact models are displayed in Figures 3.1.1-16 and 3.1.1-17, respectively.

Design Verification

Verification of the body structure and crashworthiness simulations were accomplished by means of a "mule" car. A 1978 Plymouth Horizon was modified to simulate the Near-Term Electric Vehicle body structure and chassis. The battery tunnel and tray are shown in Figure 3.1.1-18. Static loading in beam and twist modes, shown in Figures 3.1.1-19 and 3.1.1-20, was conducted to verify the finite element model analysis. Jacking tests to change tires were also evaluated on the mule car (with full battery load) as shown in Figure 3.1.1-21. A 30 mph front barrier impact was the final verification test of the crashworthiness studies. A detailed discussion is included in WBS 4.3 of this report.

Glazing

All windows of the Near-Term Electric Vehicle are designed to be made of injection-molded polycarbonate, except the windshield. Injection-molded materials provide more freedom for the designer in obtaining a smooth, aerodynamic surface as well as styling character lines. Plastics offer a weight savings. Currently, coated polycarbonate materials for automobile windows do not quite meet the abrasion resistance required by the FMVSS; therefore, hard surface coatings have been developed for both acrylic and polycarbonate materials. Table 3.1.1-6 shows the abrasion test results compared to glass. Development work by the plastics industry indicates that the abrasion requirements may be achieved in the near future.

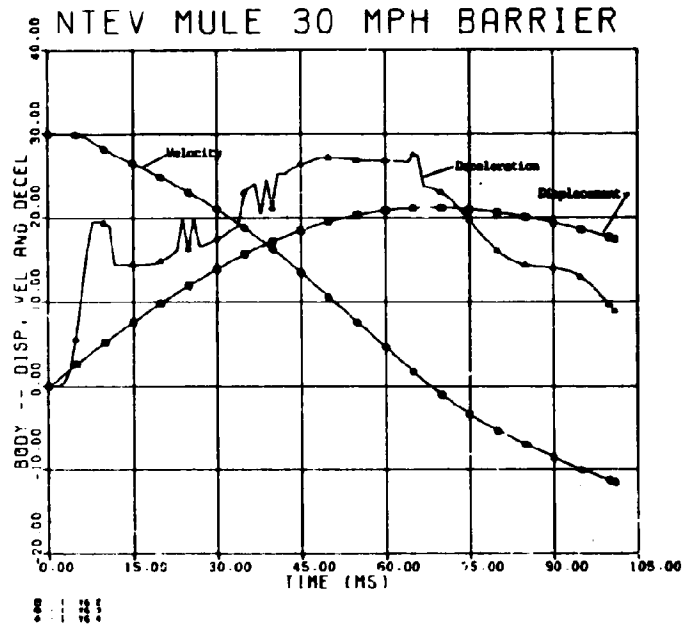


Figure 3.1.1-16. MINIBASH Plot - 30 mph Frontal Impact

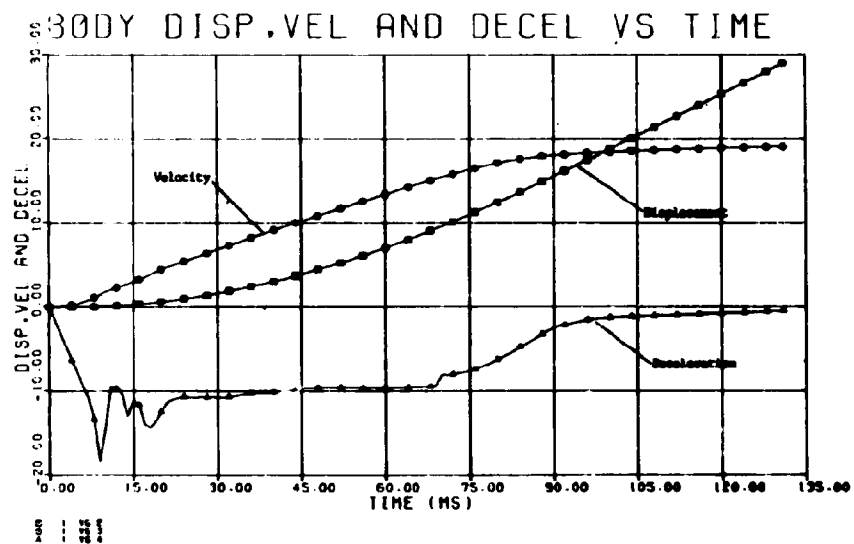


Figure 3.1.1-17. MINIBASH Plot - 30 mph Rear Impact

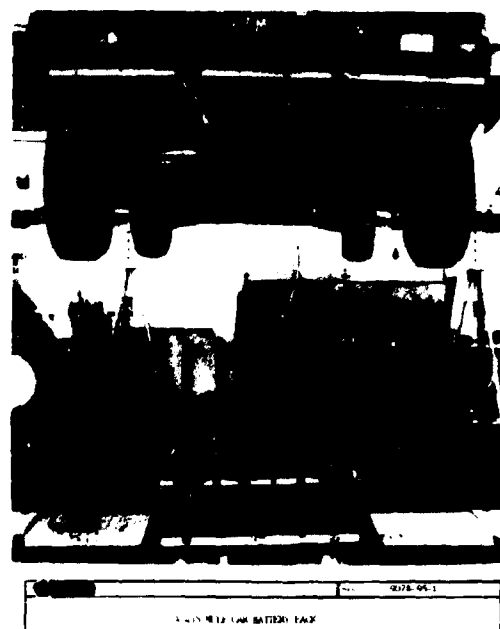


Figure 3.1.1-18. Mule Car Battery Tunnel and Battery Pack Assembly

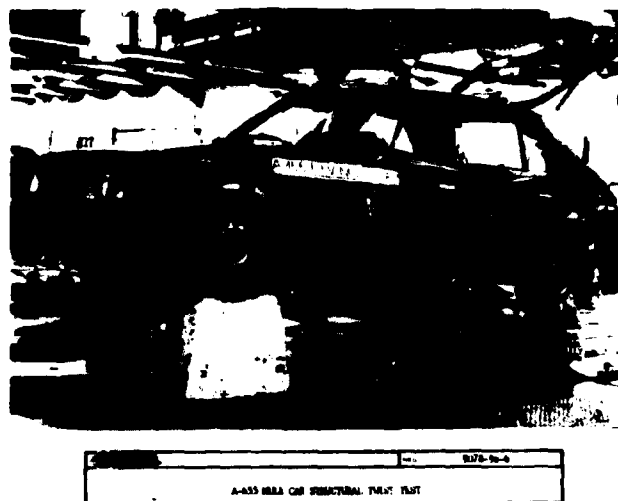


Figure 3.1.1-19. Mule Car Structural Twist Test

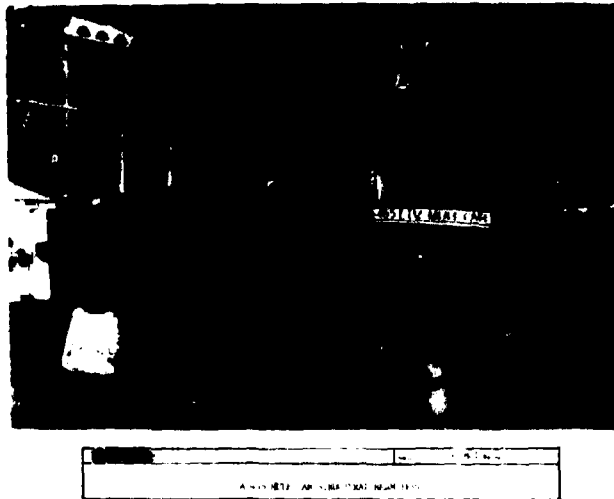


Figure 3.1.1-20. Mule Car Structural Beam Test



Figure 3.1.1-21. Mule Car Emergency Jacking Test

**TABLE 3.1.1-6
GLAZING ABRASION TEST***

ANS-26 Test Procedure No. 18

1000 Cycles with a pair of CF-10
Calibrase wheels with a load of
500 grams on each wheel.

ANS-26 Requirements	Glass	Coated Acrylics	Coated Polycarbonates
Arithmetic mean of light scattered by three abraded specimens shall not exceed 2%.	1%	3-3.5%	5-5.7%

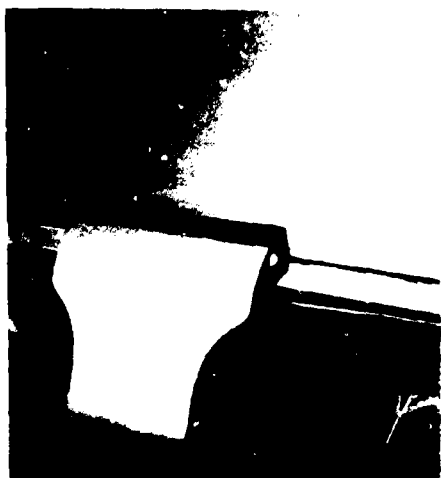
*Reference: American National Standard "Safety Code For Safety Glazing
Materials for Motor Vehicles Operating on Land Highways."

All of the NTEV windows are flush with the adjacent body panels, reducing air turbulence to a minimum. The fixed windows are bonded in place with a structural polyurethane adhesive and the movable door windows and rear hatch window are bonded to concealed steel frames using the same material. The door windows represent a departure from a standard automotive configuration since they do not roll down inside the door. They are hinged at the top instead and open outward at the bottom. An over-center toggle mechanism holds them in either the fully open or closed positions, as shown in Figure 3.1.1-22. This novel approach provides easy access to road toll baskets, parking lot ticket machines, rural mailboxes, etc., and provides a considerable weight savings since it eliminates the internal door hardware associated with conventional windows. The rear hatch window utilizes twin counterbalance air cylinders to balance the window and to hold it open.

As indicated earlier, the windows were designed as injection-molded parts; however, the high cost of tooling such parts dictated that the Near-Term Electric Vehicle parts be made from pressed flat sheet material. Figure 3.1.1-23 shows the end result of forming a heated sheet of plastic over a wood die model. This approach resulted in a significant compromise in optics and loss of character line crispness in the side windows.

Interior Trim

The interior trim of the Near-Term Electric Vehicle is designed to provide a "soft feel," maximum interior space, durability, and premium price class appearance. Cloth and vinyls are used throughout the interior as shown in Figures 3.1.1-24, and 3.1.1-25, and 3.1.1-26.



a) Fully Closed Position



b) Fully Opened Position

Figure 3.1.1-22. Door Glazing Operating Mechanism

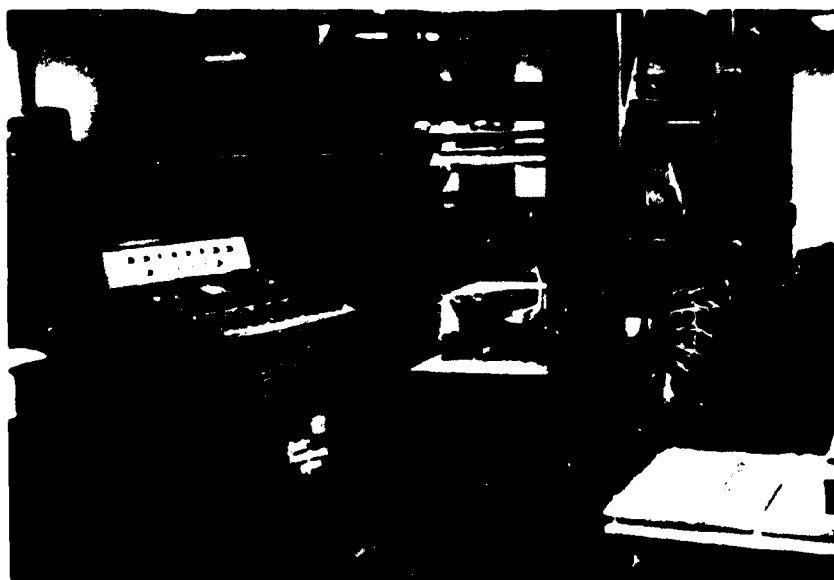


Figure 3.1.1-23. Glazing Forming Operation

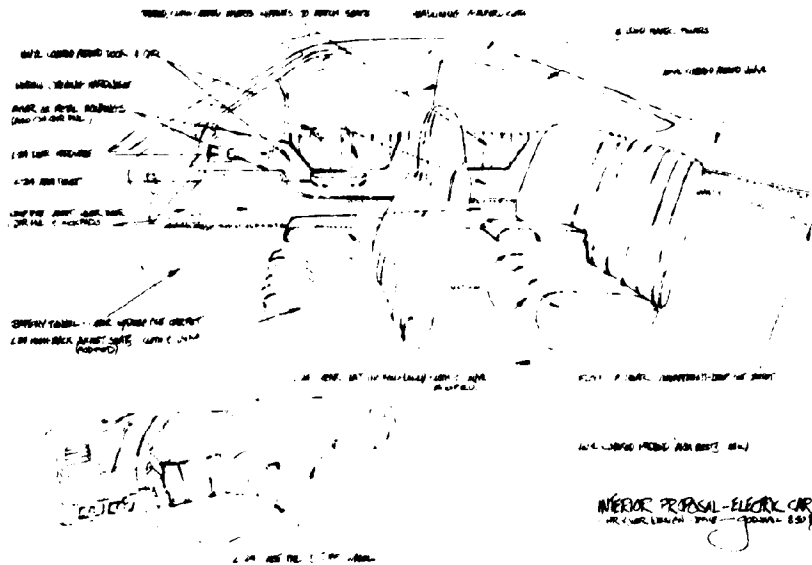


Figure 3.1.1-24. NTEV Interior Trim Sketch



Figure 3.1.1-25. NTEV Instrument Panel and Front Seat Interior Trim



Figure 3.1.1-26. NTEV Rear Seat Interior Trim

The generous use of tweed body cloth on the seats and door trim panels gives a feeling of warmth and luxury, while remaining functional and resistant to the abuse the car will endure as a test vehicle.

The entire floor is covered with heavy duty carpeting while the battery tunnel, door, and quarter trim panels are trimmed with a lighter weight carpeting to save weight. The floor and tunnel are also covered with lightweight sound insulator. Knit headlining was used in the car to save weight.

All the trim materials in the car conform to Federal Motor Vehicle Safety Standard No. 302 - Flammability of Interior Materials - Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Busses.

Seat and Shoulder Belt Restraint System

The unbelt restraint system, while similar to Chrysler mass production vehicles, was designed specially for the NTEV. The retractor is mounted just behind the door, between the quarter inner and outer panels, with the seat belt exiting through a hole in the quarter trim panels. The belt goes through a turning loop on the B-pillar and is bolted through the side sill. The belt tip slides on the seat belt webbing, coming to rest at the outboard base of the seat, where it can be easily reached with a single movement. The outboard anchorages are a carryover from the Omni/Horizon, and the inboard anchorages at the tunnel have been modified.

Vehicle Shipment

Provisions for vehicle retention while being transported by truck and/or rail have been incorporated into the Near-Term Electric Vehicle (see Figure-3.1.1-27). There are

four tie down points – two on each side of the vehicle centerline. The two front tie down locations are forward of the front wheels and the rear locations are behind the rear wheels. The tie down holes are located so that the chains will not project beyond the forward and rearward portions of the front and rear bumpers. The tie down chains also clear all chassis and underbody components by at least two inches.



a) Front



b) Rear

Figure 3.1.1-27. NTEV Shipment Tie-down Points

Battery Hoist Design

The design goal of the battery hoist was to obtain an inexpensive hydraulic power device which would safely raise and lower the 1200 pound (544.3 kg) main battery pack into and out of the vehicle in a palletized manner. Additional design requirements were:

- Mobility
- Infinite adjustment of the table
- Automatically retracted table side stops
- Zero drift of the hoist's table

The hoist for servicing the NTEV battery pack is a derivative of a currently available hydraulic scissor-type lift table. Serviceability/Safety features incorporated into the hoist (see Figure 3.1.1-28) are:

- Portable hand operated lift/lower controls with constant pressure push buttons



**Figure 3.1.1-28. Battery Pack Servicing Hoist
- Full Down Position**

- Swingout screw jacks for leveling and stability
- Retractable battery pack containing devices with roller conveyor deck table top surface
- Pull handle and large diameter wheels for easy mobility

The hoist is powered by a one horsepower 115/230 single-phase 60 Hz motor with starter and is capable of lifting a 2000 lb (907.2 kg) payload in 40 seconds to its full extended height. Figure 3.1.1-29 shows the battery pack servicing hoist elevating the battery pack into position. Certification and acceptance of the hoist was based on cycling a payload of the battery pack weight, plus 25%, several times. No degradation in performance or stability was observed. The hoist's table was also checked for drift at the test load and full extension positions. After a period of 20 minutes, no drift or decrease of the table's elevation was noted.

Battery Tray Design

Packaging of the 18 batteries in the NTEV mule car and prototype vehicles is such that the entire group of batteries can be removed as a single unit from beneath the vehicle. In the plan-view, 14 batteries are located along the centerline of the vehicle from the firewall to the rear crossmember. The four remaining batteries are located two on each side of the center row to form a T-shape configuration (see Figure 3.1.1-4). The battery tray assembly is of ladder-type construction utilizing corrosion protected heat-treated aluminum alloys to minimize weight (see Figure 3.1.1-30). The tray is also designed for in-place or fully supported loading so that the maximum deflection between battery supports does not exceed 0.060 in. (1.52 mm) during 3 g vertical loading. Therefore, to maintain the structural integrity of the battery tray assembly requires a palletized lift which is removed from beneath the vehicle in a rearward direction. The tray assembly is retained on the vehicle by means of threaded fasteners. Access to the fasteners is from outside the vehicle, thereby eliminating the need to remove any exterior trim for battery servicing.



**Figure 3.1.1-29. NTEV Battery Pack Servicing Hoist
—in Servicing Position**

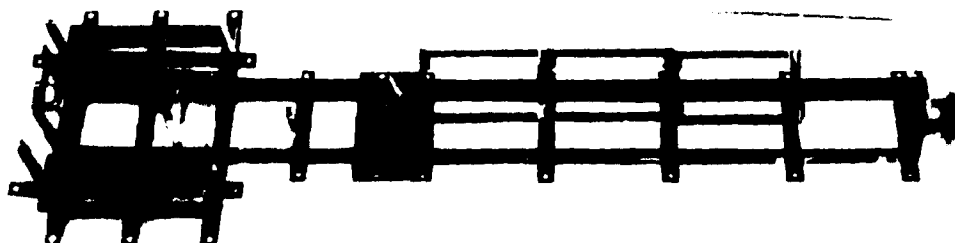


Figure 3.1.1-30. NTEV Battery Tray and Retaining Rings

Removal of the batteries from beneath the vehicle was selected in lieu of the frequently used sliding drawer concept because the rear crossmember must remain intact to provide structural integrity to the underbody of the vehicle. Also considered was the weight penalty for introducing a roller system and associated hardware. A teflon slide system was also investigated, but no record of performance for automotive applications was available as there would be a problem of keeping the teflon tracks dirt free. Table 3.1.1-7 illustrates the various battery tray retention systems evaluated. The full aerodynamic underbody shield, when installed, completes the battery tray assembly and protects the batteries from the environment.

TABLE 3.1.1-7
BATTERY PACK RETENTION SYSTEM

System Description	Total System Weight (kg) Increase	Body Weight	Tray & Hardware Weight	Equipment Required to Remove Power Supply Tray Assembly	Modifications to Body	System Advantages	System Disadvantages	Battery Pack Servicing Time Estimate
Tray assembly bolted to vehicle	Base	Base	Base	(1) Side operated twin-post hoist (2) Body tie-down mechanism to keep vehicle level (3) Movable palletized hoist to transport tray assembly	Localized reinforcements at attaching points	(1) Lightest system (2) Positive attachment to body (3) Minimal cost	(1) Overhead removal of tray assembly (2) Alignment of tray assembly to vehicle (can be dowel pinned to minimize alignment error)	2
Tray assembly mechanically attached to vehicle	1.8	4.2	(2.4)	Same as above	Localized reinforcements at latching mechanism	(1) Release system easily operated when load is supported (2) Minimal hardware removal	Same as 1 and 2 above (3) Difficult synchronization of operating hardware (4) Visual inspection upon engagement	1
Rolling rail and mechanism bolted to vehicle	11.8	10.6	1.3	(1) Body tie-down mechanism to level track system (2) Movable pallet to transport tray assembly	(1) Rear end ride-up and relocation (2) Removable grille on lower deck panel	Does not require vehicle to be elevated to service power pack	(1) Heaviest system (2) Most expensive (3) Difficult track alignment and attachment of tracks to vehicle (4) Bumper system removal required (5) Lower deck panel grille removal required	3

Reproduced from
best available copy

WBS 3.1.2 Chassis

Introduction

The basic packaging studies of the Near-Term Electric Vehicle called for front-wheel drive, full independent suspension, and a compatible steering system. Program objectives established a requirement for a regenerative braking system, a low-loss mechanical drive train and a functional aerodynamic bumper system. In many cases these requirements were similar to those encountered during the design and development of Chrysler's Dodge Omni/Plymouth Horizon family of subcompact cars. Engineering studies confirmed that many chassis components could be used directly in the Near-Term Electric Vehicle design, saving many hours of design, development, and testing as well as thousands of dollars in tooling and fabrication costs.

Front Suspension and Steering

The front suspension used on the Near-Term Electric Vehicle is the same as the Omni/Horizon and is shown in Figure 3.1.2-1. The system uses an integrated shock absorber and coil spring unit, or strut, a steering knuckle, and a lower control arm to position and control the wheel. The steering knuckle also acts as a bearing carrier for the drive shaft. Noise and vibration isolation is accomplished by the use of elastomeric bushings at the attachments points to the body. The lower control arm bushings were also designed to provide fore and aft compliance at the tires to keep ride harshness to a minimum. Internal friction and wear in the struts was reduced by inclining the spring axis to offset the side loading inherent in the strut type suspension. An anti-roll bar attached to the lower control arms completes the system.

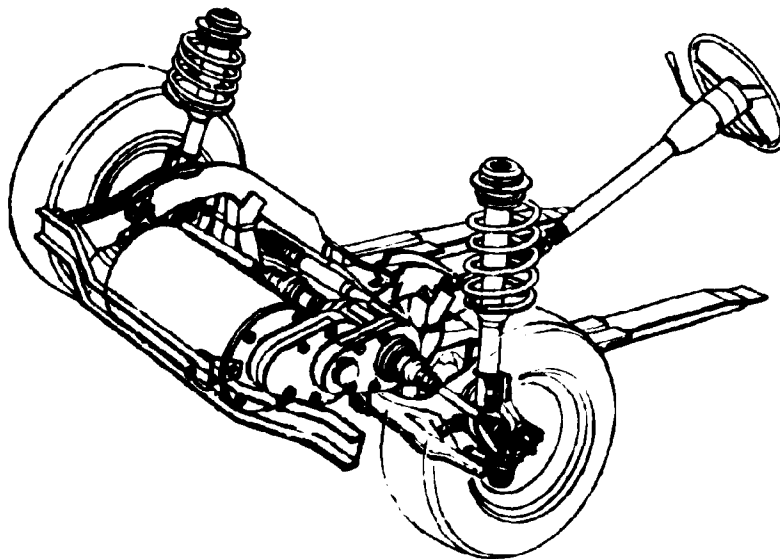


Figure 3.1.2-1. Front Suspension

The rack and pinion steering system developed for the Omni/Horizon provides precise directional control for the driver and requires little effort, even during parking maneuvers. Sealed tie rod ends eliminate the need for periodic relubrication of these components.

Rear Suspension

The packaging requirements for the battery subsystem dictated an independent rear suspension. Analysis of the vehicle dynamics by means of a four degree freedom computer model (SEMIND) resulted in the application of the trailing arm system shown in Figure 3.1.2-2. Finite element analysis of the rear control arm was performed to insure its integrity under the various loading conditions to which it would be subjected. The model is illustrated in Figure 3.1.2-3.

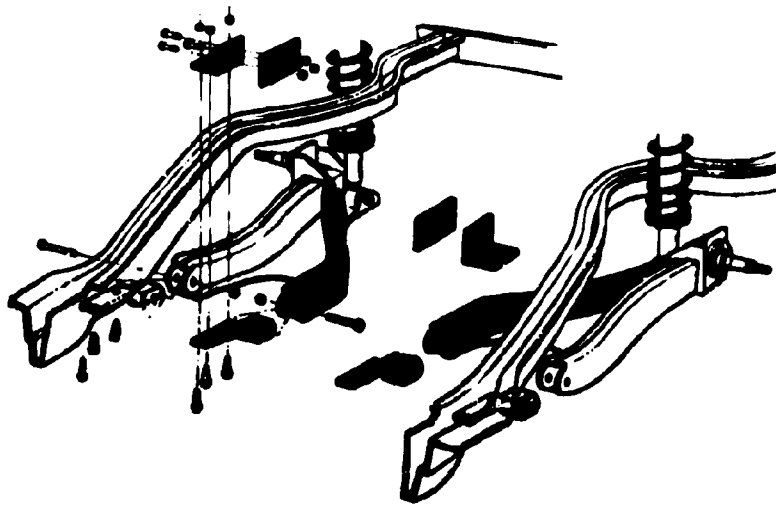


Figure 3.1.2-2. Rear Suspension

Ride and Handling

Dynamic response of the vehicle to various road and/or driver inputs is very difficult to predict analytically because of the complex nature of the interacting elements, particularly the driver. However, analytical models can be used to narrow the range of suspension parameters with final determination being made by means of a test vehicle.

A number of studies show some correlation between vehicle yaw response to given inputs and a driver's subjective rating of the handling characteristics. The Research Safety Vehicle Program, sponsored by the Department of Transportation, defined transient and steady-state yaw response specifications. Figures 3.1.2-4 and 3.1.2-5 show the predicted steady-state and transient yaw response of the Near-Term Electric Vehicle within the acceptable limits as defined in the Research Safety Vehicle Phase II Contract Number DOT-HS-5-01214.

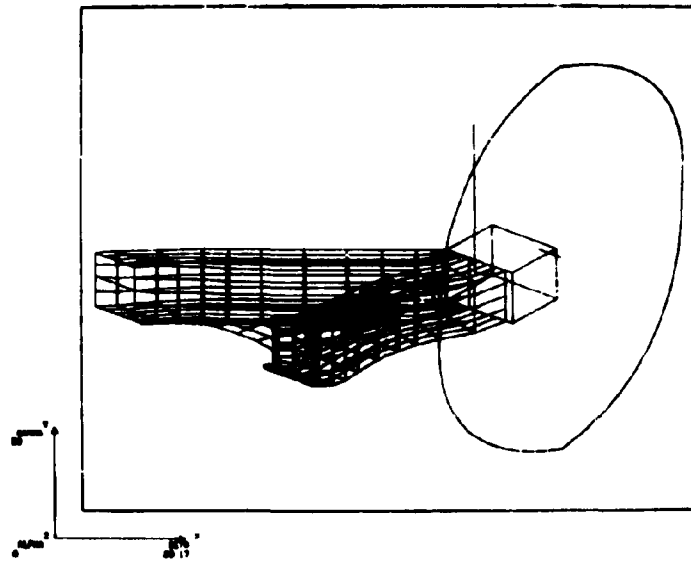


Figure 3.1.2-3. Graphic Representation of Rear Suspension Finite Element Model

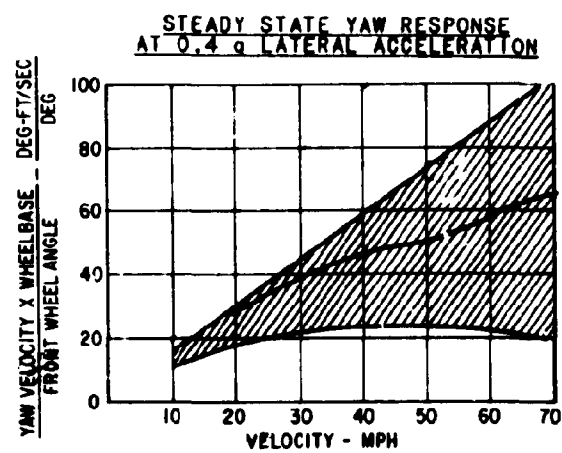


Figure 3.1.2-4. Graphic Representation of Steady-State Yaw Response

Reproduced from
best available copy

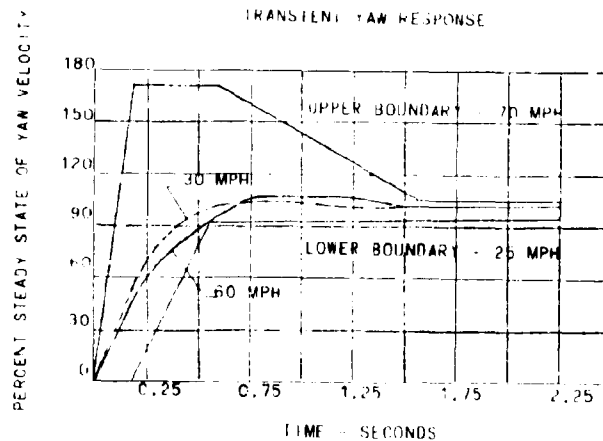


Figure 3.1.2-5. Graphic Representation of Transient Yaw Response

Provisions were made in the suspension attachments of the mule car to adjust the trailing arm pivot axis location and the toe and camber of the rear wheel spindle. The final rear suspension geometry determination was the result of an iterative subjective evaluation process.

Final subjective evaluations by Jet Propulsion Laboratory and General Electric and Chrysler personnel verified that ride and handling characteristics of the Near-Term Electric vehicle are comparable to vehicles of similar size currently being marketed in the United States. Ride frequency and suspension jounce travel comparisons are shown in Tables 3.1.2-1 and 3.1.2-2.

Table 3.1.2-1
RIDE FREQUENCY COMPARISON AT TWO-PASSENGER LOADING

Vehicle	Front Frequency (Hz)	Rear Frequency (Hz)
NTEV	1.19	1.20
Chevrolet Vega	1.26	1.66
Ford Pinto	1.38	1.74
Plymouth Volare	1.16	1.31
Dodge Omni	1.27	1.33

Tires and Wheels

Low rolling resistance tires were solicited from several manufacturers and a number of comparison tests were run at Chrysler's Chelsea Proving Grounds. Omni/Horizon

Table 3.1.2-2
JOUNCE TRAVELS - MM

		Curb		Design		GVW	
		Free	Full	Free	Full	Free	Full
NTEV	- Front	55.3	87.3	35.6	67.6	27.7	59.7
	- Rear	40.8	75.9	24.8	59.9	-0.9	34.2
VW Rabbit	- Front	25.0	74.0	-1.0	48.0	-5.0	44.0
	- Rear	60.0	95.0	36.0	71.0	-23.0	12.0
Dodge Omni	- Front	80.8	112.8	60.3	92.0	57.9	89.6
	- Rear	86.5	121.5	46.0	81.0	10.6	45.6

vehicles were used for coast down force required determinations which were run according to an Environmental Protection Agency approved procedure. The various tires were also screened for vehicle ride and handling characteristics on the mule car. The tires selected for application to the Near-Term Electric Vehicle are P175/75R13 Extra Load steel-belted radials manufactured by the Goodyear Tire and Rubber Company. With the tires inflated to the specified pressure of 29 psi front and 41 psi rear, the vehicle rolling resistance coefficient was determined to be 0.01114 lb/lb.

The coefficient was determined by measuring the total force required and subtracting the aerodynamic factor. Therefore, it includes losses generated in the tires, wheel and axle bearings, seals, the differential, and some of the transmission losses.

Wheel selection criteria included weight, aerodynamic losses, dimensional compatibility with the vehicle, and durability. It soon became apparent that the only type of wheels that meet all of these criteria were made of cast aluminum. A number of OEM and aftermarket wheels were screened for the first three items and the two most likely choices were subjected to a series of Chrysler standard wheel durability tests. The wheel selected for use on the car is a specially machined unit manufactured by Dunlop in France.

Brakes

Vehicle braking is accomplished through a dual mode system. A conventional hydraulic system is combined with an electric system that uses the traction motor as a retarder. The resulting energy generated is used to recharge the propulsion batteries, extending the vehicle range.

The hydraulic system was designed to meet the applicable portions of FMVSS 105(75) without utilizing any regenerative capability. The system was modeled and analyzed using a proprietary computer program. The input data is shown in Figure 3.1.2-6.

Figure 3.1.2-7, which shows stopping distance plotted vs pedal effort, indicates that the brake system exceeds FMVSS requirements. Figures 3.1.2-8 and 3.1.2-9 show the relationship of deceleration to pedal effort and line pressure. The Omni/Horizon system is the basis for the Near-Term Electric Vehicle system, with changes made to the master cylinder, pedal linkage, and rear wheel cylinders to accommodate the difference in vehicle weight and distribution. The brake system was subjected to limited testing at Chrysler's Proving Grounds using the mule car and an Omni ballasted to the N-TEV estimated weight distribution to verify compliance with FMVSS 105(75).

CHRYSLER CORPORATION
SPECIAL VEHICLE PRNG DEPT - 3540

RAMA R. VENKATAPERUMAL

(04/30/79 - 10.53.00.)

BRAKE SYSTEM PERFORMANCE AND BALANCE ANALYSIS

ELECTRIC CAR	
VEHICLE DATA	NOTES
VEHICLE SPEED... VS 60.000	
FRONT AXLE WEIGHT ... WF 1020.000	
REAR AXLE WEIGHT ... WR 1005.000	
HEIGHT OF CG. ... CG 15.000	
WHEEL BASE ... WB 99.000	
EFFECTIVE TIRE RAD ... ETR 11.052	
ROAD TO TIRE COEFF ... RWI 1.070	
ACTUATION DATA	
ACTUATION SYST TA MANUAL	
OVERALL PEDAL RATIO OPR 7.750	
M/CYL SIZE AND TYPE MST CY 0.07500	
BOOSTER SIZE AND TYPE BGT	
MEETING VALVE VMH,VMC,VMM NOT USED	
PROP VALVE ... VPC,VPS NOT USED	
WHEEL BRAKE DATA	
FRONT BRAKE DESC FRD SLDR1.49	
FRT BRK DRN/PCL-SCL RAD FER 1.662	
FRT BRK WHL/CLPR DIA FCD 1.010	
FRT BRK LINING PRI/DR FLP AXD7161	
FRT BRK LINING SEC/IR FLS AXD7161	
REAR BRAKE DESC RRD 177.9X1.10	
RR BRK DRN/PCL-SCL RAD RER 1.017	
RR BRK WHL/CLPR DIA RCD 1.760	
RR BRK LINING PRI/DR RLP CW2339	
RR BRK LINING SEC/IR RLS CW2339	

Figure 3.1.2-6. Brake System Performance and Balance Analysis (computer input)

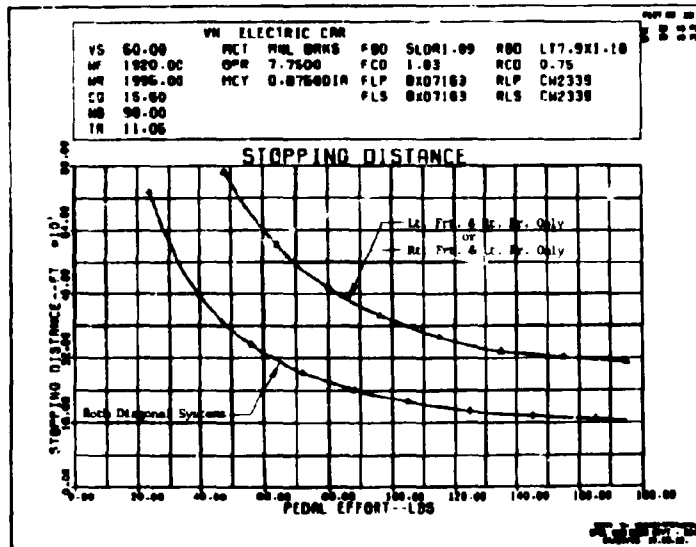


Figure 3.1.2-7. Stopping Distance vs Pedal Effort Graph

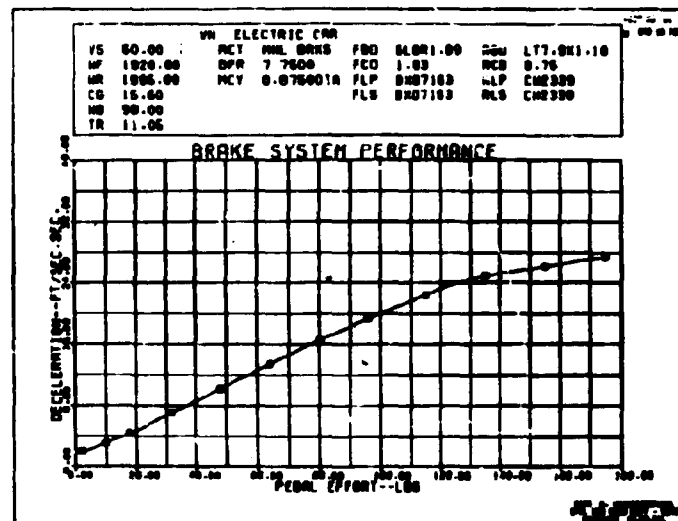


Figure 3.1.2-8. Brake System Performance Graph

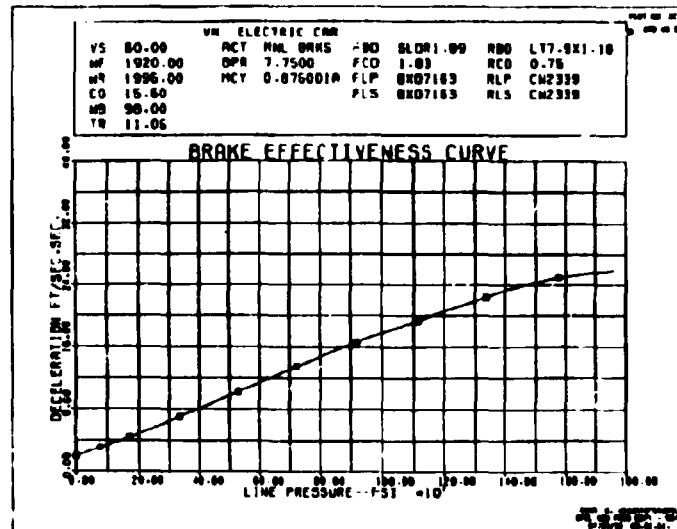


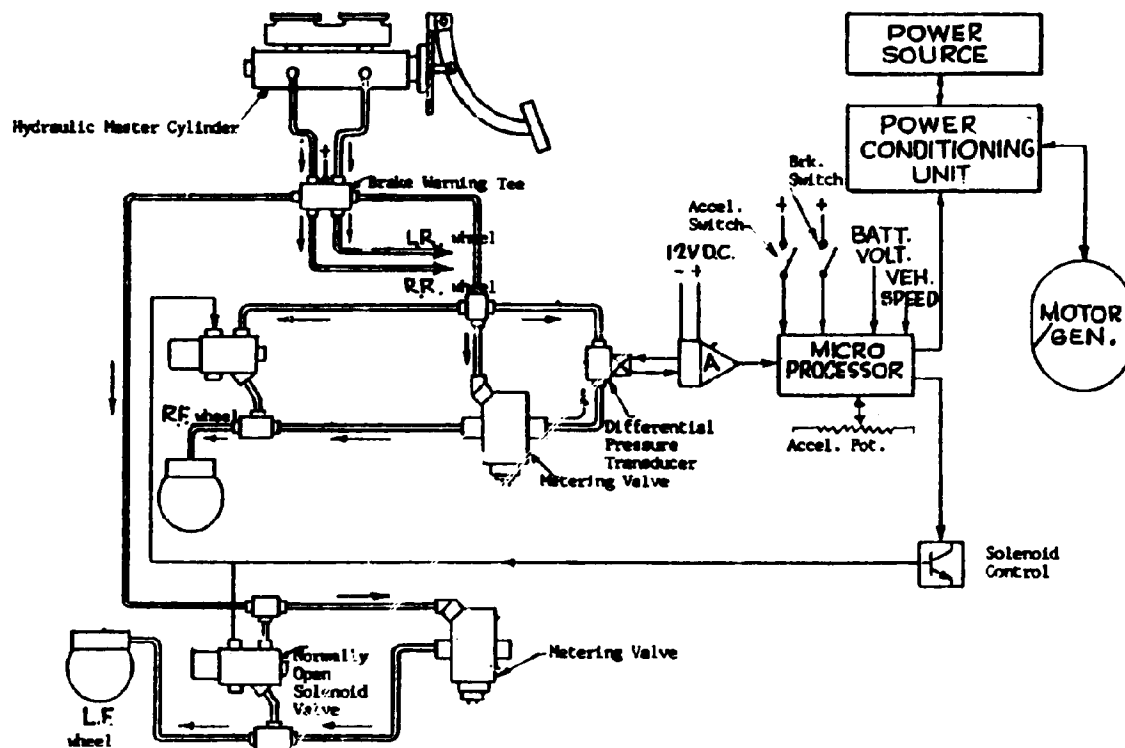
Figure 3.1.2-9. Brake Effectiveness Curve

The parking brake consists of a pedal mechanism actuating a tension cable to the rear brakes. A similar system was successfully evaluated on the mule car chassis on a 32% grade in both uphill and downhill attitudes at the Chelsea Proving Grounds. A warning buzzer that sounds if the driver attempts to leave the car without setting the brake has been incorporated as a safety feature since the transmission does not have a park pawl feature.

The regenerative brake system, shown in schematic form in Figure 3.1.2-10, is designed to blend with the hydraulic system so that the driver will not be able to discern a change in mode during normal operation. Approximately 70% of the braking effort, up to a maximum deceleration rate of 6 ft/s/s, is provided by the motor/generator; the remaining 30% is provided by the brakes at the rear wheels. Deceleration rates from 6 to 16 ft/s/s are handled by the blending of regenerative and hydraulic braking with full hydraulic braking occurring at rates above 16 s/s.

The key element in the blending system is the metering valve which functions as a variable pressure regulator. A typical response curve (Figure 3.1.2-11) shows how output pressure varies with input pressure. With the solenoid valve closed, pressure to the front brake cylinders is suppressed by the metering valve. Since brake torque and, therefore, vehicle retarding force, is proportional to pressure, the amount of regenerative braking torque required from the electrical drive subsystem is proportional to the pressure difference between the input and output of the metering valve as shown in Figure 3.1.2-12. A differential pressure transducer transmits this data to the microcomputer which in turn commands the appropriate regenerative braking torque from the motor.

The solenoid valve (Figure 3.1.2-10) is included in the system as a failsafe device to bypass the metering valve and apply full master cylinder pressure to the front as well as the rear brakes. This is desirable if, for some reason, regenerative torque is not available when demanded by the microcomputer. During emergency braking the valve is a



BRAKE BLENDING NORMALLY (OPEN SOLENOID VALVE TRUTH TABLE

KEY

- (ASW) Accelerator Pedal: '0' not applied; '1' applied
 (BSW) Brake Pedal: '0' not applied; '1' applied
 (V_{BATT}) Battery Voltage: '0' not at limit; '1' at limit
 (V_{SPD}) Vehicle Speed: '0' at rest; '1' greater than 5 mph
 (SV) Solenoid Valve: '0' not energized; '1' energized (open) (closed)

The following table illustrate the modes of solenoid valve (i.e., closed or open) at different combinations of conditions of the above parameters.

<u>CASE</u>	<u>ASW</u>	<u>BSW</u>	<u>V_{BATT}</u>	<u>V_{SPD}</u>	<u>SV</u>	<u>MC RESPONDS TO PROVIDE</u>
1	0	0	0	1	0	Coast down regenerative torque.
2	0	1	0	1	1	Regenerative brake torque
3	1	1 or 0	0	1 or 0	0	Drive torque.
4	1 or 0	1 or 0	1	1 or 0	0	Drive torque but not regenerative torque.

Figure 3.1.2-10. Regenerative Brake System Schematic

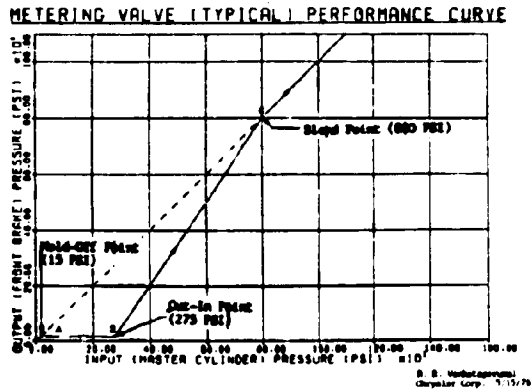


Figure 3.1.2-11. Typical Metering Valve Performance Curve

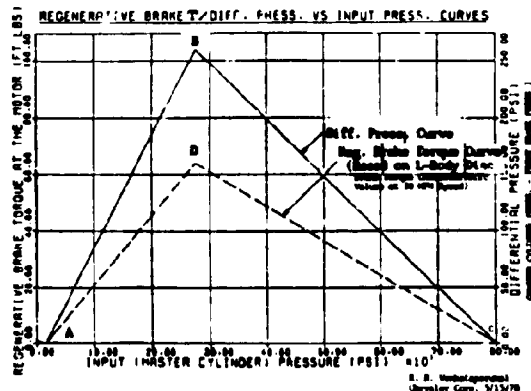


Figure 3.1.2-12. Regenerative Brake Torque/Differential Pressure vs Input Curve

redundant failsafe since the metering valve output pressure is the same as input pressure or deceleration rates above 16 ft per sec. Patent application for the regenerative blending system has been applied for (Case No. S51,240).

Throttle/Potentiometer Control

The vehicle speed modulation control is achieved through the conventional accelerator pedal. The design goal is to closely simulate internal combustion (i.e.) engine accelerator pedal response to the operator. This is accomplished by modifying the production Omni/Horizon linkage and using it to actuate a linear potentiometer whose output (0 to 10 V dc) is linearly dependent upon accelerator pedal position. The output from the potentiometer is one of the drive command inputs to the microcomputer which calls for drive torque (see Figure 3.1.2-10, Cases 3 & 4). A microswitch is also in series with the potentiometer. This microswitch is closed when the accelerator pedal is not depressed and prevents small extraneous inputs from the potentiometer that may occur because the mechanical zero and electrical zero do not coincide.

The accelerator pedal also demands motor braking torque when it is released and the brake pedal is not applied (see Figure 3.1.2-10 Case 1). This motor braking torque is to simulate i.e. engine closed throttle coastdown braking. This is accomplished by the microcomputer by sensing the signals from the accelerator pedal microswitch and the brake pedal switch. The ideal coastdown torque, based on actual coastdown tests of an Omni/Horizon vehicle, is shown in Figure 3.1.2-13.

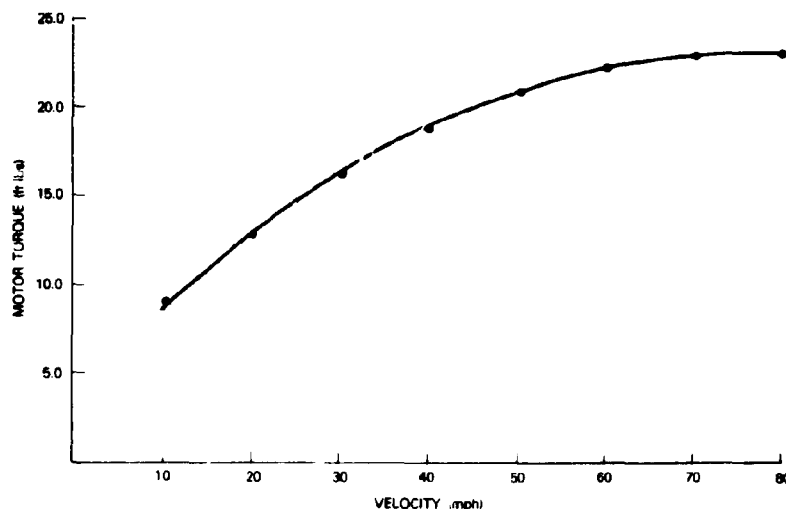


Figure 3.1.2-13. Coastdown Motor Torque vs Speed (Corrected for 3600 lb Vehicle Weight)

Final Drive

Initial performance analysis by General Electric indicated that a multiple ratio transmission would not be required due to the favorable torque characteristics of the electric drive motor. The Phase I vehicle utilized a fore and aft direction for the motor shaft, which required transmitting the drive torque through intersecting shafts. Analysis of the transversely mounted drive motor indicated that a significant reduction in drag torques could be realized due to eliminating thrust loads and secondary bearing reactions associated with intersecting shaft gear sets. The elimination of these loads permits the use of ball and needle bearings rather than tapered roller bearings on some of the shafts. Figures 3.1.1-14 and 3.1.1-15 show schematics of the Phase I and Phase II drive systems and Table 3.1.2-3 compares the constant drag torques for the two drive systems.

Several drive motor speeds vs. transmission ratio vs. range studies were made resulting in a decision to use a 5000 rpm top speed drive motor. The final drive ratio of 5.48/1 was determined by equating motor rpm (5000), vehicle speed (60 mph), and tire size. The final tire size selection results in 912 wheel revolutions per mile.

Morse "HY-VO" chain drives are used to transmit power from the motor to the differential since they are inherently quieter than gears, are highly efficient, and result in reduced transmission drag losses because the side thrust associated with helical gears is eliminated. Vehicle ground clearance requirements at the differential dictated the maximum sprocket size that could be used resulting in a two-stage speed reduction. The differential is an Omni/Horizon unit modified to accept the second-stage sprocket. Figure 3.1.2-16 shows the transmission partially assembled.

The final design and fabrication of the transmission took place at Chrysler's New Process Gear Division in Syracuse, New York. The first unit produced was successfully endurance tested on a drive train inertia dynamometer in Chrysler's Final Drive Laboratory. The test setup is illustrated in Figure 3.1.2-17.

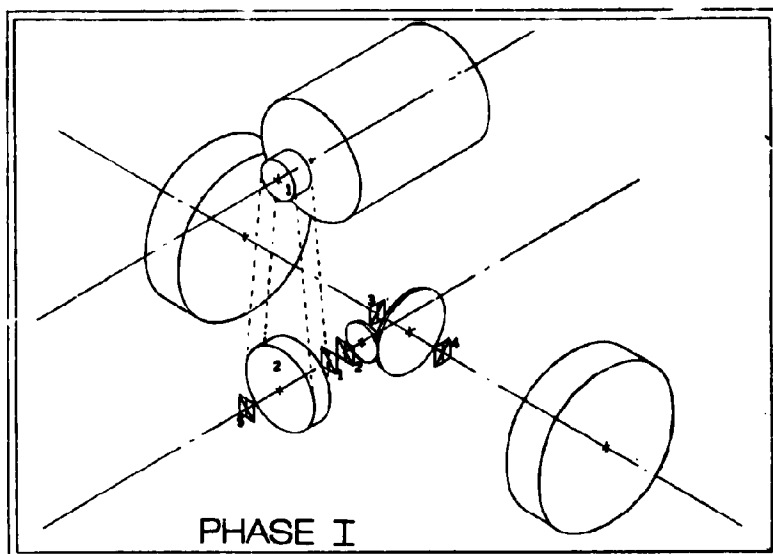


Figure 3.1.2-14. Phase I Drive System Schematic

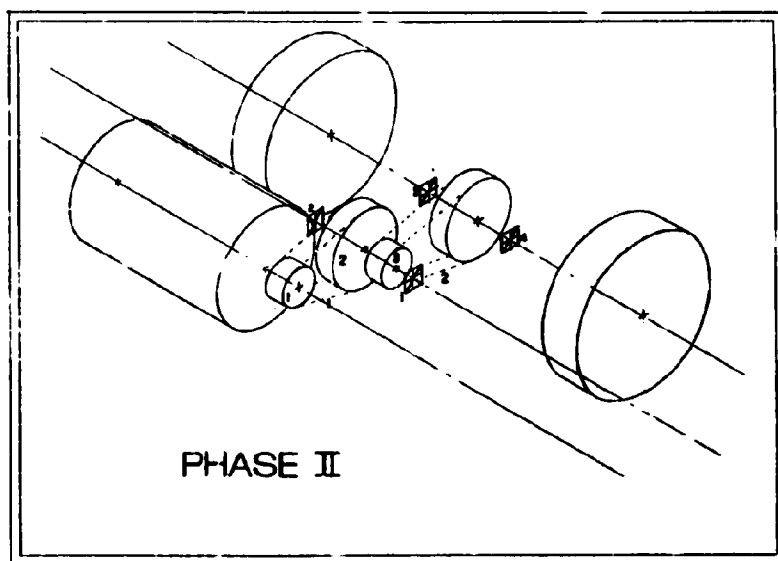


Figure 3.1.2-15. Phase II Drive System Schematic

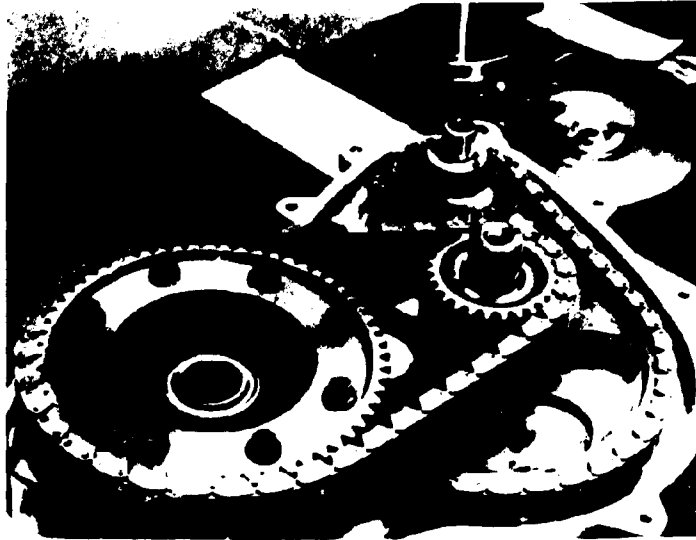


Figure 3.1 2-16. NTEV Transmission Partially Assembled

Table 3.1.2-3

DRAG TORQUE COMPARISON PHASE I VS PHASE II
(from empirical data drag torques)

Phase I			Phase II		
Brg. No.	Brg. Type	Torque	Brg. No.	Brg. Type	Torque
1 & 2	Tapered roller	11.61 in-lbs	1 & 2	Ball	Zero
3	Tapered roller	6.5 in-lbs	3	Tapered roller	4.5 in-lbs
4	Tapered roller	6.5 in-lbs	4	Tapered roller	4.5 in-lbs
5	Roller	Zero	—	—	—
TOTAL		24.61 in-lbs	TOTAL		9.0 in-lbs

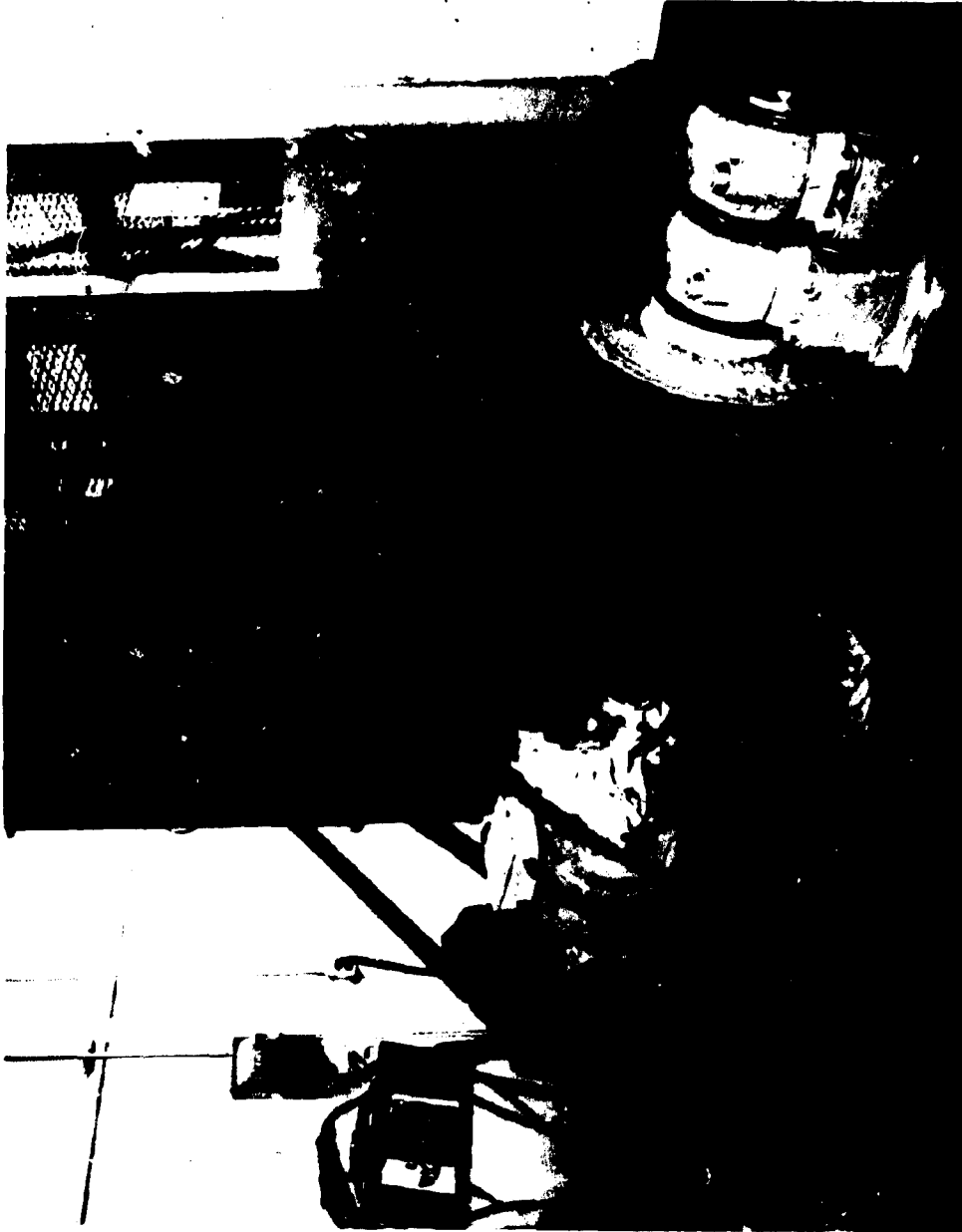


Figure 3.1.2-17. NTEV Transmission Test Setup

The test cycle, which is shown in Figure 3.1.2-18, was derived from the standard test used by Chrysler for conventional drive trains. A total of 4400 cycles were completed, involving ten days of continual running. Figure 3.1.2-19 is a typical trace of motor speed, armature current, and voltage plotted against time for one test cycle.

NTEV TRANSMISSION DYNAMOMETER TEST CYCLE

1. Wide open throttle acceleration to 60 mph.
2. Coast to 20 mph with regenerative braking to simulate engine braking.
3. Wide open throttle acceleration to 40 mph.
4. Regenerative brake to 5 mph using 130 ft-lbs torque.
5. Auxiliary brake to stop.
6. Hold 0 (0) mph for five seconds.
7. Repeat steps one through six.

Figure 3.1.2-18. Transmission Endurance Test Cycle in Final Drive Laboratory



Figure 3.1.2-19. NTEV Transmission Dynamometer Test Cycle Trace

Two deficiencies were noted at the post test inspection. One of the mounting brackets developed a fatigue crack and the motor armature shaft spline exhibited considerable wear. The mounting bracket has been redesigned to eliminate the stress riser that caused the fatigue crack and an extreme pressure lubricant has been specified for application to the drive spline to reduce the wear which was attributed to fretting corrosion.

The remainder of the final drive system components, including the drive shafts, universal joints, bearings, seals, etc., are standard Omni/Horizon units.

Bumpers

The vehicle bumper systems have been designed to comply with the property protection requirements of FMVSS 215. Concealed inside the "soft" fascias at either end of the car is an energy management system consisting of an aluminum beam and two hydraulic absorbers. The fascias, which are made of a flexible polyurethane material by means of the reaction injection molding technique, provide the smooth, continuous exterior surface required for the aerodynamic performance of the car. During an impact the fascia deflects elastically and the concealed beam transmits the impact force to the two absorbers where the energy is dissipated. The absorbers contain gas springs that automatically reset the system after an impact. Per the safety standard, the bumpers are designed to handle impact speeds up to 5 miles per hour.

WBS 3.1.3 Air Handling and Electrical System

WBS 3.1.3.1 Heater and Defroster

Passenger compartment heating and windshield deicing are accomplished by means of a gasoline-fueled heater system. Consideration was given to utilizing waste heat from the motor and power control unit and also to direct electric resistance heating using the propulsion battery as an energy source, but both these approaches were rejected upon final determination of the heating requirement. Compliance with Federal Motor Vehicle Safety Standard 103 covering windshield defrosting requires a heater capacity of 21,000 Btu's. Waste heat from the motor is inadequate, and direct resistance heating would seriously reduce the range of the car.

A commercially available, gasoline-fired, diesel engine preheater is coupled with the Omni-Horizon passenger compartment heat exchanger and air distribution system. The addition of a micro-switch to the standard heater control allows the driver a full range of fan speeds and mode selection. Because the battery tunnel affects the air flow through the car, a minor modification was made to improve the driver comfort and air distribution. Measurement of the external temperature of the combustion unit assured that no excessive or potentially dangerous temperatures existed. The test results are shown in Figure 3.1.3.1-1.

Cold room testing of the heater system in a prototype vehicle verified compliance with Federal Motor Vehicle Safety Standard 103, Heater and Defrosting Systems. The test results are shown in Figure 3.1.3.1-2 for the defroster system and Figure 3.1.3.1-3 for the heater performance.

The fuel tank is located under the floor, forward of the rear axle, with the fill point behind the rear license plate. The filler neck accepts any conventional gasoline pump nozzle for convenient filling at a gasoline station. The capacity of the tank

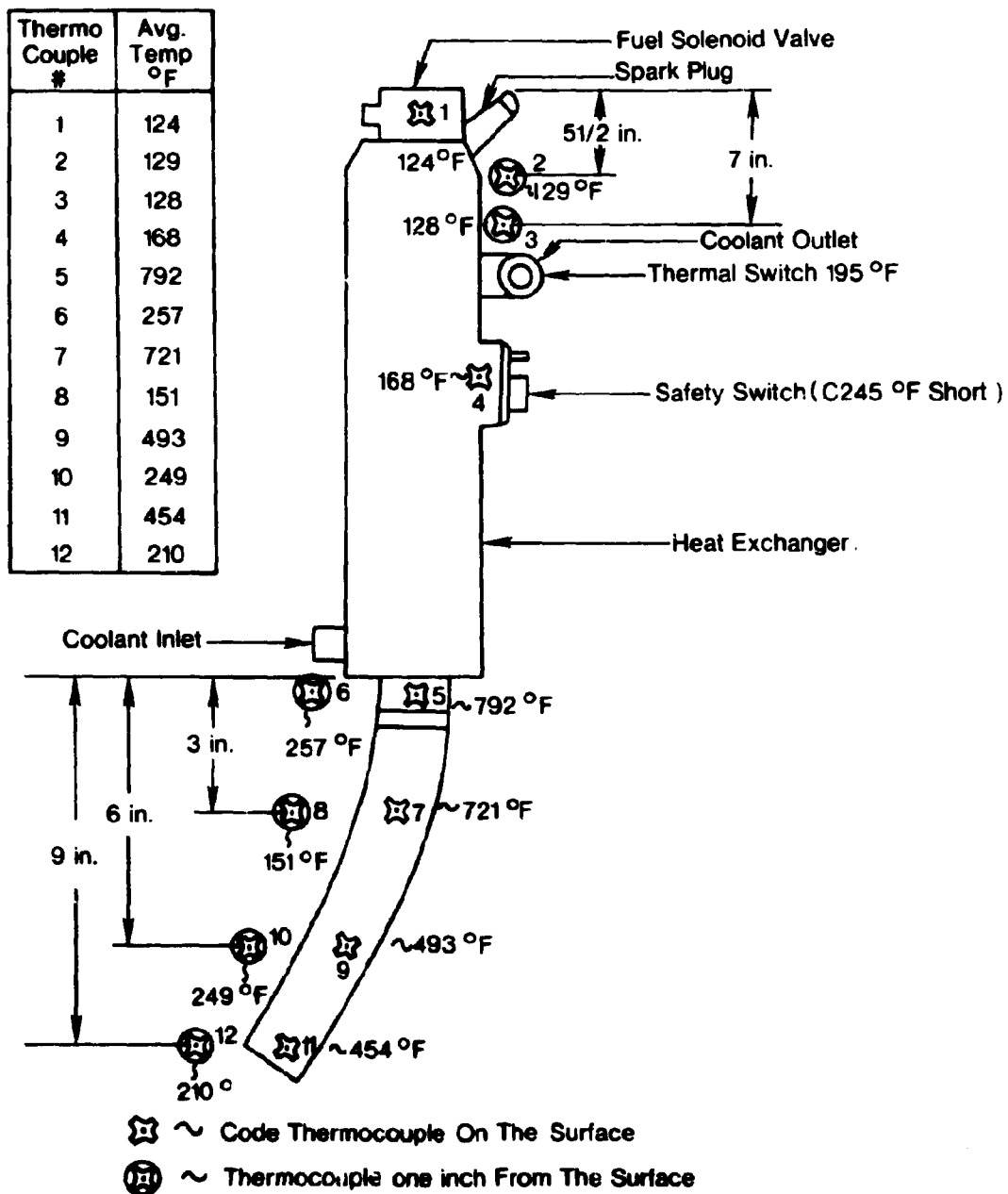


Figure 3.1.3.1 -1. Heater Temperature Verification Test Results

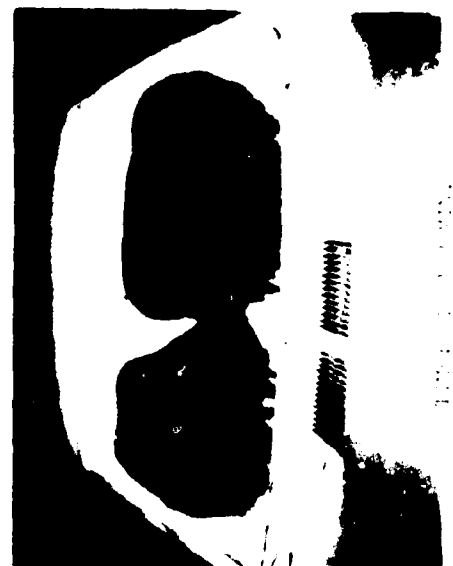
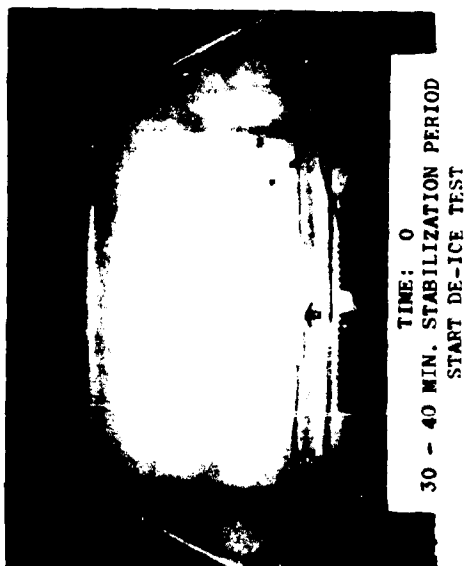
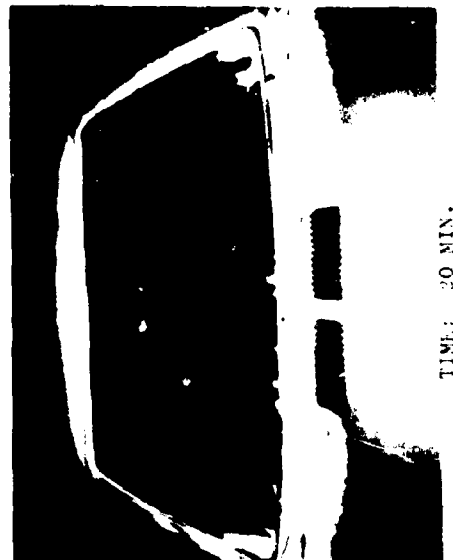
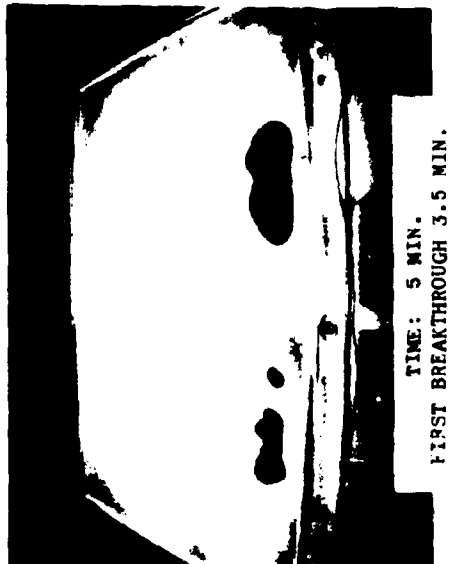


Figure 3.1.3.1-2. Defroster Compliance

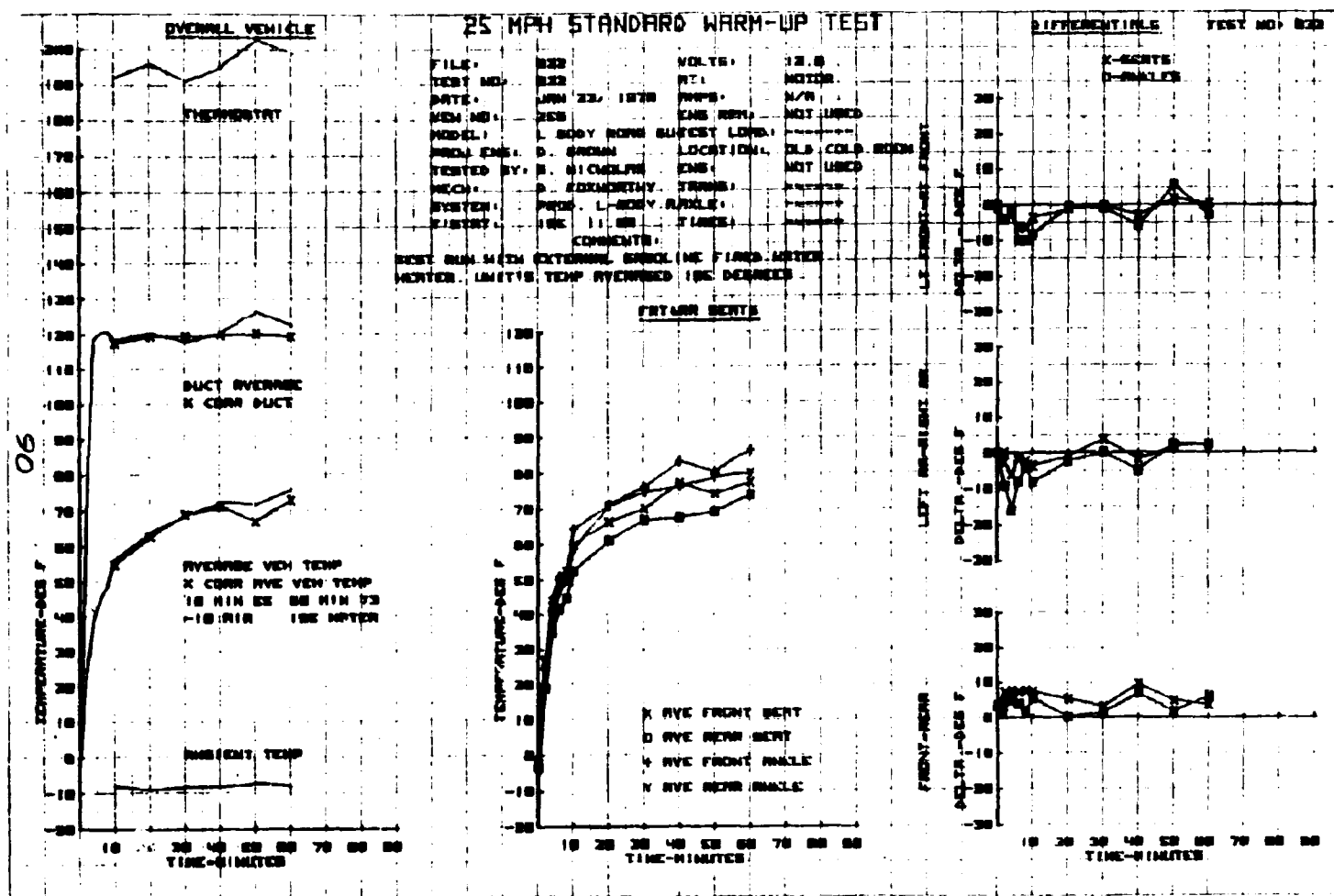


Figure 3.1.3.1-3. Warmup Test Results - Composite

is 0.8 gal. A float switch in the gasoline tank connected to a light emitting diode (LED) on the heater control panel indicates when the fuel supply drops to approximately one quart (Figure 3.1.3.1-4).

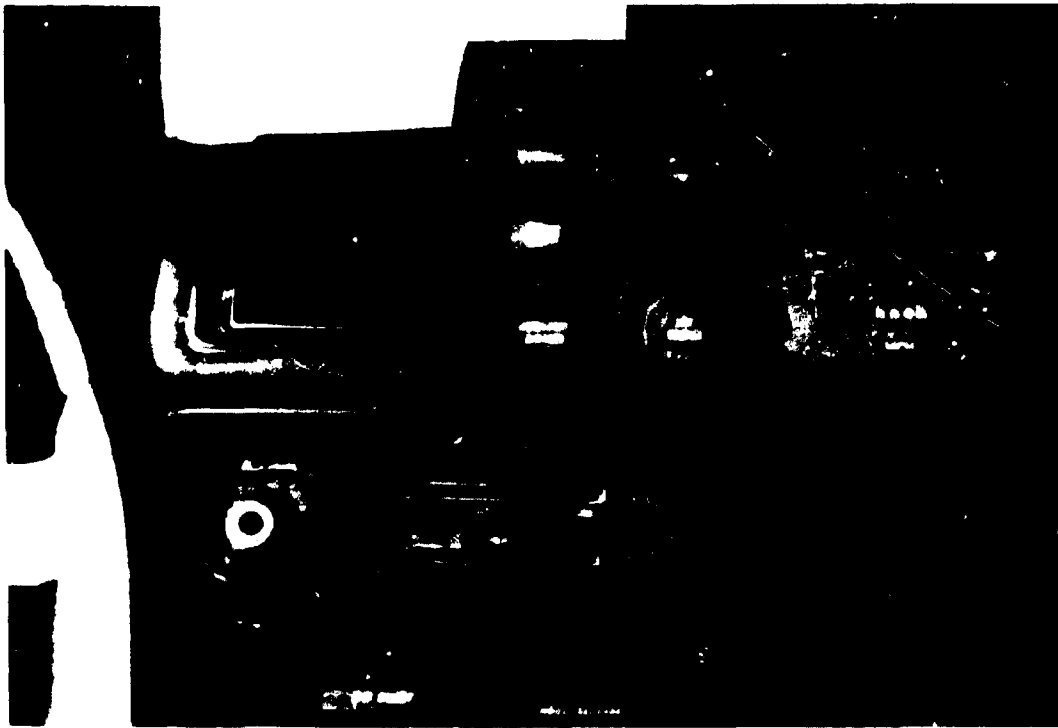


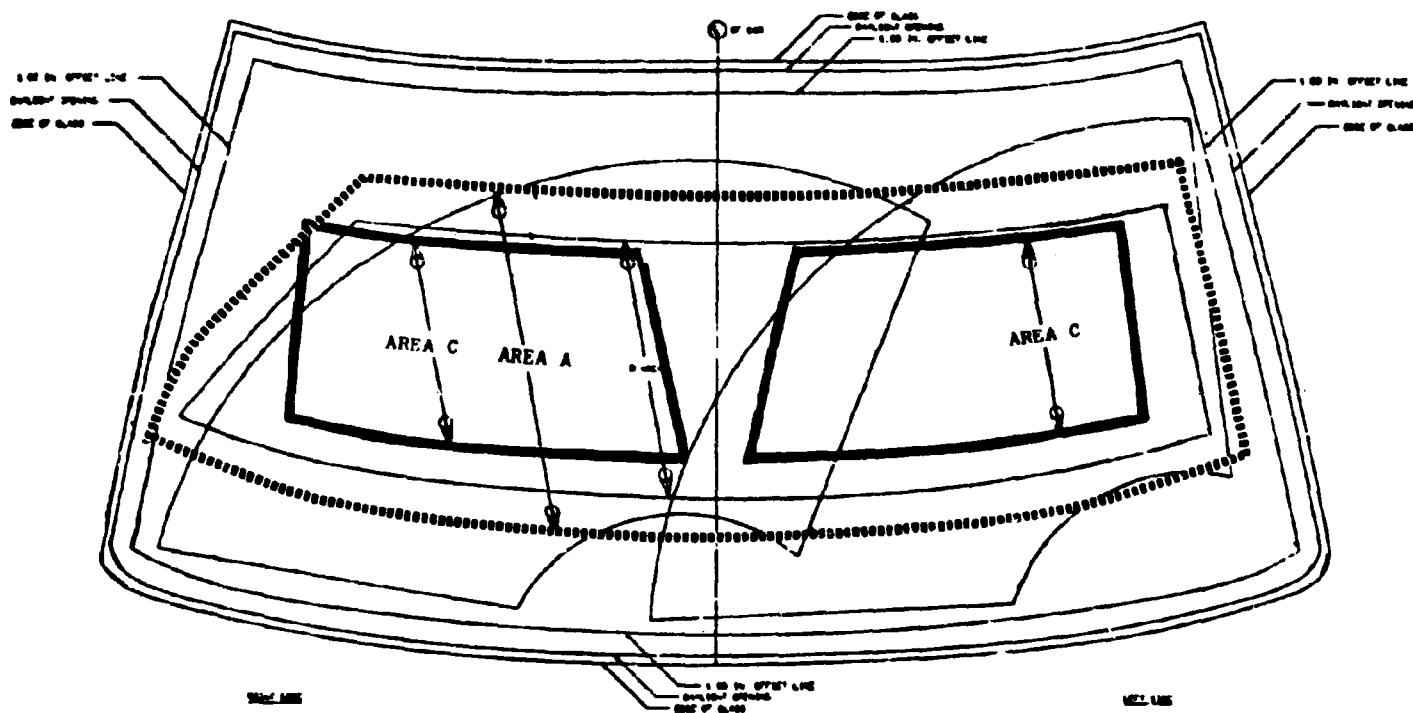
Figure 3.1.3.1-4. Heater Control

Windshield Wiper and Washer

The windshield wiper system used on the Near-Term Electric Vehicle is the same as that used on the Omni/Horizon. The system used a two-speed nonreversing electric motor that completes the wipe cycle when the switch is turned off. The blades park in the lowest portion of the wipe pattern.

Analysis of the system by means of a proprietary computer program verified compliance to FMVSS-104 as shown in Figure 3.1.3.1-5.

The windshield washer system uses a high-speed, electrically driven, impeller pump mounted on a lightweight bag reservoir. The washer nozzles are dual jet units placing four distinct streams on the windshield, assuring good clearability at all vehicle speed.



<u>Position</u>	<u>Area</u>	<u>Goal</u>	<u>Time (Min.)</u>
Driver	C	80% Clear	20
Passenger	C	80% Clear	25
Entire W/S	A	95% Clear	40

Figure 3.1.3.1-5. Federally Required Wipe Area

PCU Blower

The packaging requirements for the power conditioning unit and the drive motor dictated an external blower system that ultimately resulted in the application of a push-pull system as shown in Figure 3.1.3.1-6. Cooling analysis for the system was performed by General Electric, and the requirement of 130 ft³/min at a two-inch static pressure was obtained. Various blower and motor combinations were evaluated with respect to power consumption, weight, and air flow before the final selection was made. The test results are shown in Table 3.1.3.1-1.

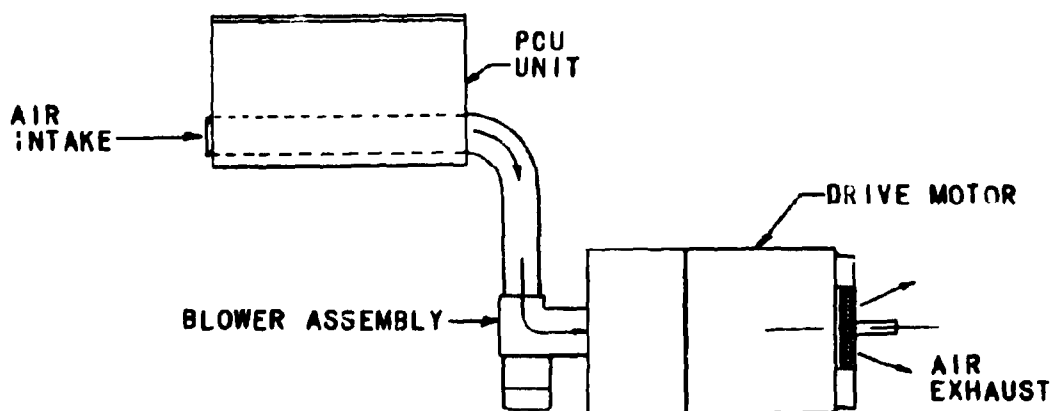


Figure 3.1.3.1-6. Power Conditioning Unit/Motor Cooling System

Purge Blower

Initial analysis by Globe-Union indicated that high charge and discharge currents could possibly result in the presence of hydrogen gas within the battery tunnel even though the system was designed to be sealed. A complete study of the system indicated that a small purge blower changing the air once per minute would meet the venting requirements. A small rear defroster motor mated to a standard one-inch wheel was selected, and, as a further safety measure, the motor was made explosion proof by adding additional seals.

Power Connectors

Packaging requirements for the battery system dictated that the battery connectors be nonlocking. Many vendors were solicited for comparative data, and the various connectors were screened for current capacity and mounting considerations. The connectors selected for application to the Near-Term Electric Vehicle are the J-H 8007 series manufactured by the J-H Service Company of Indiana. The female receptacles were modified by the vendor to reduce the insertion and separating force to meet the NTEV system requirements.

Concealed Headlamp System

Attainment of the low aerodynamic drag objective dictated the use of a concealed headlamp system. A fixed lamp system with transparent fairings was rejected

TABLE 3.1.3.1-1
PCU BLOWER TEST DATA

Small Heater Motor (2,400 rpm) - G.I.			
	<u>I</u>	<u>P Stat</u>	<u>ft³/min</u>
	5.8 A	2.00 in. H ₂ O	72
	6.4	1.54	112
	6.8	1.34	127
Large Motor (3,800 rpm Prestolite) - P/L			
	5.4 A	1.88 in. H ₂ O	74.5
	6.4	1.83	104.0
	7.9	1.57	142.0
Medium Motor (2,900 rpm) - ULV			
	7.4 A	2.42 in. H ₂ O	83.2
	8.0	1.94	110.0
	8.0	1.43	146.5
Medium Motor (4 turns removed from each field winding) - ULV-A			
	9.8 A	2.30 in. H ₂ O	113
	10.4	2.08	135
	10.6	1.90	148
	10.9	1.67	162
Medium Motor (2 turns removed from each field winding) - ULV-B (Selected for Use)			
	8.2 A	2.60 in. H ₂ O	96.3
	9.6	1.82	143.3
	10.2	1.44	162.1

since it was impractical to retract the coverings as required by Federal standards. The final system design uses an electric motor at each headlamp to raise the lamps to the proper position (Figure 3.1.3.1-7). A handwheel on the motor shaft provides for manual opening of the lamps as required by FMVSS-112. Special low power quartz-halogen lamps were used to reduce power consumption and extend the vehicle range.

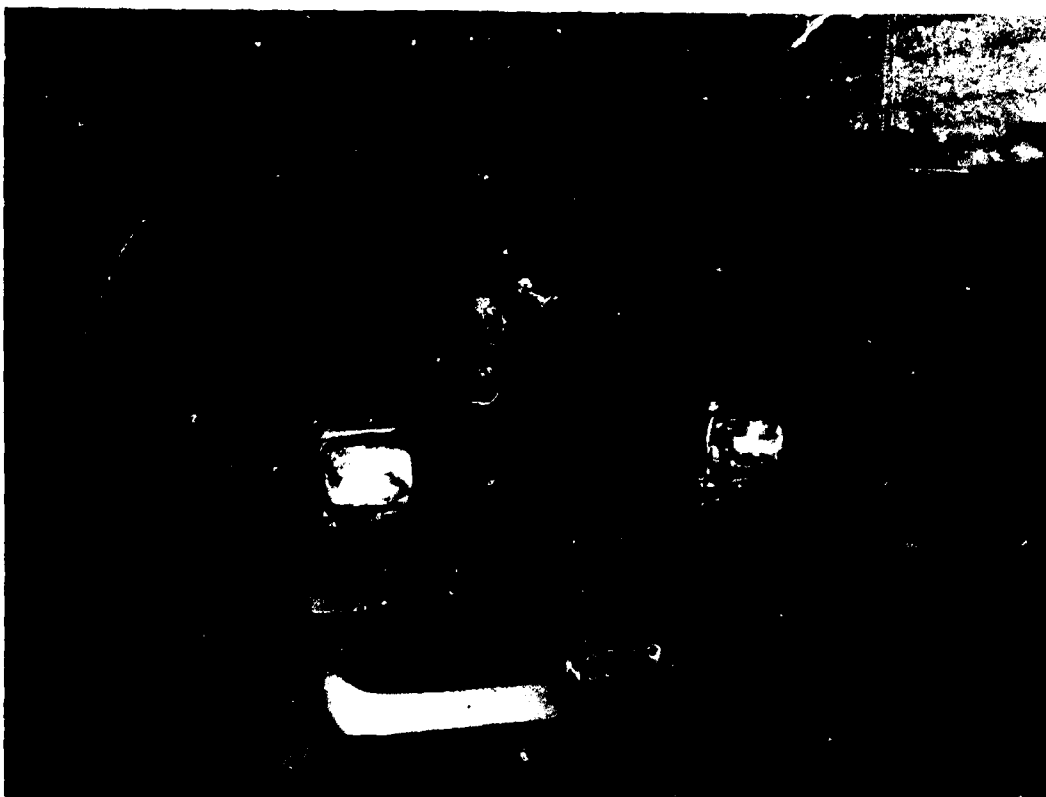


Figure 3.1.3.1-7. Headlamps Raised

WBS 3.1.3.4 Instruments, Controls, and Interior Lighting Instrument Panel and Controls

The instrument panel, which is made of lightweight injection-molded plastic, is very similar to panels used in conventional internal combustion engine vehicles. There are, however, some very distinct differences. The same holds true for the operator controls. A number of factors were considered during the design of the panel and controls, including, but not limited to, aesthetics, visibility, serviceability, hand control reach, cost manufacturability, and various Federal Motor Vehicle Safety Standards.

The NTEV panel instruments, controls, and components are shown in Figure 3.1.3.1-1 and are described in the following paragraphs.

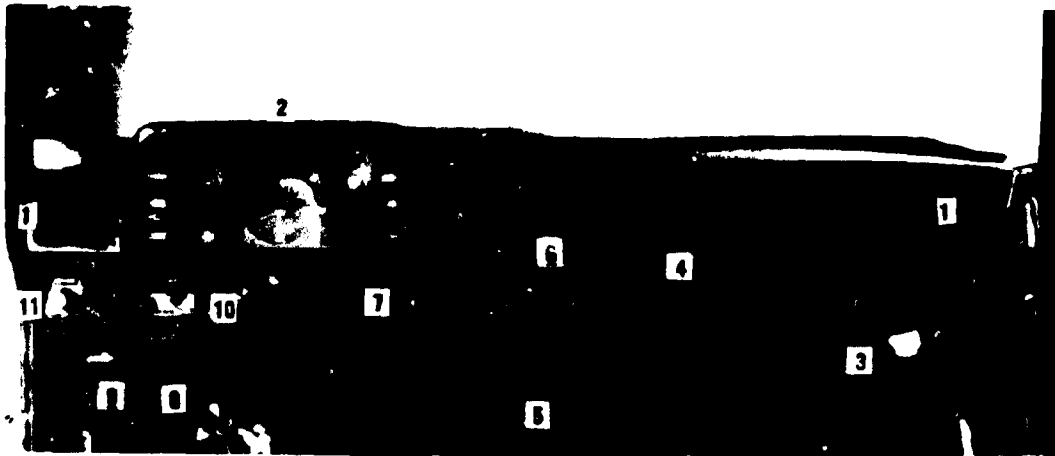


Figure 3.1.3.2-1. NTEV Instrument Panel

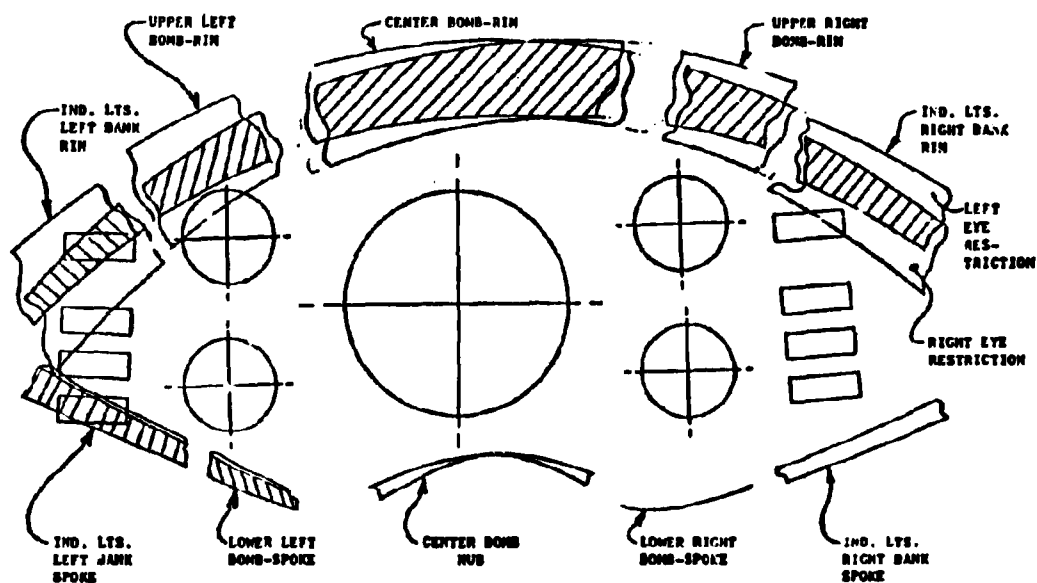
1. Upper Level Air Outlets. Outlet ventilation is through two panel-mounted outboard-vaned outlets which are operator controlled for direction. Total ventilation is 140 to 160 ft³/min at a car velocity of 30 mph with the windows open.
2. Instrument Cluster. Federal Standard MVSS-101 mandates that turn signals, high-beam, brake, and seat belt indicator lights be packaged in the visual regions of the 95th percentile driver as defined by the S.A.E. standard. Compliance is achieved through utilization of computerized cluster studies which project the steering wheel image onto the panel and cluster (Figure 3.1.3.2-2).

This figure highlights regions restricted from left or right eye vision, as well as from areas restricted from both eyes (cross-hatched area). Because cluster components are mounted on at least seven different surfaces, a computer study was required for each respective plane. Illustrated in Figure 3.1.3.2-3 is the final cluster configuration with nomenclature and graphic information listed in Table 3.1.3.2-1.

After considerable trade-off studies of miniature, subminiature lamps, and LEDs, the standard #158 two candle power bulbs were selected for application in the following area: illumination, charging, drive energized, high beam, brake warning, and turn signal light. Special two candle power #557 flashing bulbs are used for warning lamps unique to the NTEV.

Instrument cluster circuitry was designed, and a new flexible Mylar printed circuit board was developed (Figure 3.1.3.2-4). Incorporated into the cluster was a 250° full sweep Faria meter movement to serve as a battery gauge. To ascertain the remaining range per battery charge a trip odometer was added to the speedometer.

3. Glove Box. A small glove box provides storage space for vehicle registration papers, maps, etc.



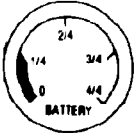
NOTE: CROSS HATCHED SECTIONS REPRESENT THE VISION AREA RESTRICTED FROM BOTH EYES.

Figure 3.1.3.2-2. Instrument Cluster Visibility Study



Figure 3.1.3.2-3. Final Cluster Configuration

TABLE 3.1.3.2-1
INSTRUMENT CLUSTER NOMENCLATURE AND GRAPHICS

System	Symbol	Location	Lens Color	Nomenclature Color	Description 85 mph 140 Km/h
1 Speedometer	Omni/Horizon				
2 Odometer and Trip Odometer	Omni/Horizon				
3 Motor/PCU Over Temp Warning	TEMP	Upper Left Bomb	Red	White	Corporate Lettering
4 Battery Low Voltage Warning	LOW VOLTAGE	Lower Left Bomb	Amber	White	Corporate Lettering
5 Motor Over Speed Warning	MOTOR SPEED	Upper Right Bomb	Red	White	Corporate Lettering
6 Battery Energy Remaining Gauge		Lower Right Bomb	Black Dial	White Graphics Red Danger Zone Orange Pointer	250° Faria Gauge, Corporate Lettering, Red Zone Between 0 and 1/4 Full Range (Increments of 0, 1/4, 2/4, 3/4, 4/4, and the word "Battery" on the dial.)
7 Head Lamp High Beam Indicator	HIGH BEAM	Right Wing Third Window	Blue (Corp.)	White	Corporate Lettering
8 Right Turn Signal Indicator		Right Wing Second Window	Green (Fed.)	White Arrow	Symbol
9 Seat Belt Warning Light	FASTEN BELTS	Right Wing Upper Window	Red (Fed.)	White	Corporate Lettering
10 Brake Warning	BRAKE	Right Wing Bottom Window	Red (Fed.)	White	Corporate Lettering
11 Main Battery Charging Indicator	CHARGING	Left Wing Upper Window	Blue	White	Corporate Lettering
12 Left Turn Signal Indicator		Left Wing Second Window	Green (Fed.)	White	Corporate Lettering
13 Drive Energized Indicator	DRIVE	Left Wing Third Window	Amber	White	Corporate Lettering
14 Accessory Charger Malfunction Warning	ACCESSORY CHARGER	Left Wing Bottom Window	Red	White	Corporate Lettering

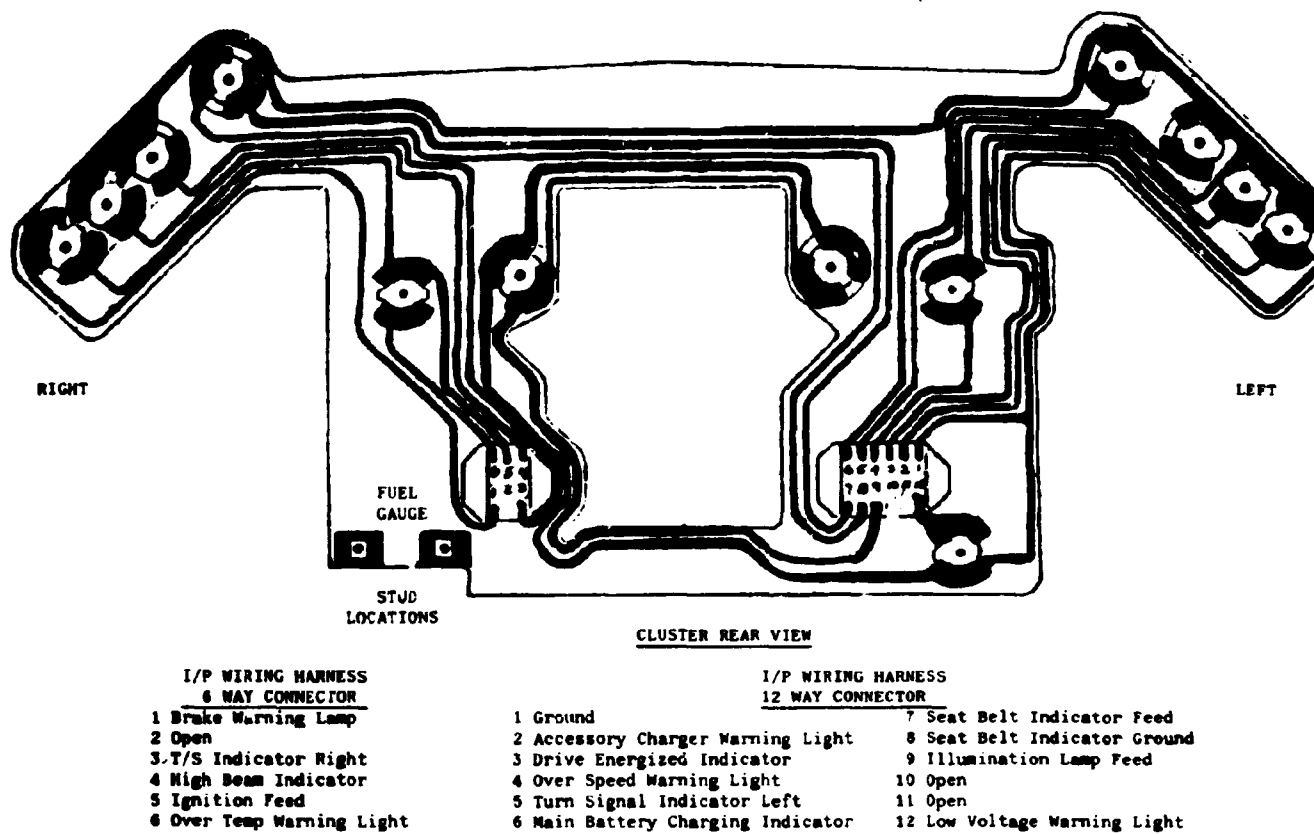


Figure 3.1.3.2-4. Flexible Printed Circuit Board

4. Charge Model Selector Switch (CMSS). After evaluation of various electro-mechanical switches, a multipushbutton switch was selected to actuate the propulsion battery charging system. Functionally, the switch includes the two charging modes normal and equalization, either mode selected by depressing the proper pushbutton followed by depressing the spring-loaded start pushbutton to activate the charging cycle. Charge cycle commencement is indicated by lighting of the charging signal in the instrument cluster.
5. Ash Tray and Lighter. These are standard Omni/Horizon components.
6. Drive, Neutral, Reverse Switch (DNR). Essentially, the same process was used in selecting the drive mode selector switch as was used for the CMSS.

A three-button illuminated switch is used to select drive, neutral, or reverse operating modes.

When depressed, the pushbutton is illuminated. In addition, the indicator in the cluster is also illuminated when either the drive or reverse pushbuttons are depressed. Another feature of the reverse function is a buzzer mounted in the rear of the car that sounds to alert both drivers and pedestrians to the rearward motion of the vehicle. This feature was incorporated due to the low level of vehicle noise when in the neutral mode prior to the backup maneuver.

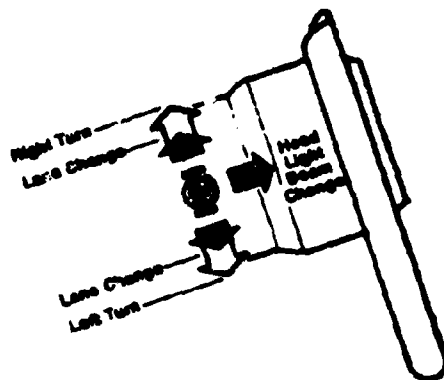
7. Power Off Pushbutton. The power off pushbutton and switch is one of several safety interlock switches used throughout the vehicle to deactivate the 108 V propulsion system. It is located on the instrument panel to the left of the DNR switch and is easily accessible to the driver for emergency use.
8. Hood Release Cable. There is specially designed flexible steel housing with wire core to actuate a hood release mechanism. A "T" handle with a bezel is located to the left of the steering column on the lower skirt of the instrument panel.
9. 108 V DC QUICK DISCONNECT SYSTEM (QD). The QD is composed of a 12-V coil which holds in a 108-V latching disconnect switch. The system also includes a mechanical cable system, microswitch, indicator and panel-mounted bezel. Basically, the NTEV is powered up with 108 V when the driver pulls the panel-mounted, spring-returned "T" handle and mechanical cable which resets the disconnect via a mechanical linkage system. When the "T" handle has been pulled the required distance to initiate the latching function, the bezel light comes on momentarily indicating 108 V is available to the drive system.
10. Heater Control. An Omni/Horizon heater control assembly incorporating the heat, defrost, temperature control, and fan functions was modified by adding a microswitch and LED to it. The microswitch activates the gasoline combustion system when the mode lever is moved from off to heat or defrost. The LED indicates a low fuel condition in the gasoline storage tank. Heater operation is discussed in greater detail in another section of this report.

11. **Headlamp Switch.** The headlamp switch is a production Omni/Horizon unit with added circuitry for headlamp door motors and warning buzzers. When pulled to its first position, the parking, tail, side marker, license plate, and instrument panel lights are illuminated. Headlight door motors and lamps are activated when the knob is pulled to its second position. Panel and cluster illumination brightness is controlled by rotation of switch knob in either direction.

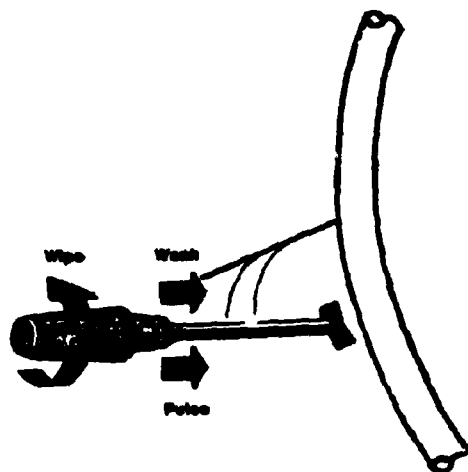
Steering Column Components and Controls

The production Omni/Horizon steering column contains the ignition key switch, multifunction control lever, hazard warning flasher switch, and the horn switch. A brief discussion follows on each item.

1. **Key Switch.** The column-mounted key switch has five positions. Accessory allows electrical component operation with drive system deactivated. The lock position permits key removal after depressing the small button, thus locking steering wheel in place. Off unlocks the steering wheel but does not energize drive system. On activates the drive system and permits electrical accessory operation. The last position has been modified to be utilized as a bulb check position. Also included in this column system is a key in buzzer which is activated when the door is opened without the key removed from the switch.
2. **Multifunction Control Lever.** This standard Omni/Horizon unit containing the turn signals, wiper switch, pulse wiper, washer switch, and headlamp beam selector switch is located on the upper left side of the steering column (Figure 3.1.3.2-5). Each function will be briefly described:
 - **Turn Signals.** Arrows on each side of the instrument cluster flash to indicate proper operation of the front and rear turn signal lights.
 - **Windshield Wipers and Washers.** The wipers and washers are operated by the control lever by rotating the handle to select the desired wiper speed. The washers are activated when the handle is pushed toward the steering column.
 - **Pulse Wiper Feature.** With the wiper switch in the off position, the pulse feature allows the driver to activate the wipers by pushing the handle toward the steering column. The wiper will operate only as long as the handle is held in.
 - **Headlight Beam Selector.** Pulling the lever toward the steering wheel switches the headlights from high to low beam.
3. **Hazard Warning Flashers.** The flasher switch is on the right side of the steering column, just behind the steering wheel. Pulling the switch causes the front and rear directional signals to flash intermittently.
4. **Horn.** The horn is a four-point contact switch located in the center of the steering wheel and activates the horn when depressed.



Side View



Side View - Tilted

Figure 3.1.3.2-5. Multifunction Control Stalk

Interior Lighting

The interior lighting package was minimized for electrical load reduction and includes only a dome lamp and steering column key switch lamp.

Electrical Loads and Circuit Design

Electrical Loads - 12 V

The electrical load parameters were tabulated and analyzed to establish the requirements for the 12 V battery (Table 3.1.3.2-2). Because of variable summer versus winter duty cycles, various scenarios were constructed to allocate these loads between the 12 V battery and the General Electric accessory charger. The worst case scenario is a rainy night with the headlights on high beam, the heater on defrost mode, and the windshield wipers operating. Summations of this load were: summer cycle, 32.24 A, winter cycle 42.74 A. Certain components, such as indicator lights, were not included in the load summation because of their extremely short and intermittent usage.

Allocation of loads resulted in the selection of a 22 Ah U1-9 Globe-Union battery and an accessory charger output rating of 36 A. A ten-pound weight savings in the battery was realized by taking this approach instead of a conventional Starting Lighting Ignition (SLI) battery.

The battery and accessory charger are interfaced with the microprocessor and become an integral part of the vehicle start and drive system.

Circuit Design

The Chrysler portion of the vehicle circuits was divided into four zones or systems: the Motor Compartment, Instrument Panel, Body, and Propulsion Battery Wiring.

Motor Compartment

The motor compartment schematic illustrates the vehicle 12 volt system and numerous interface areas with GE harnesses as shown in Figure 3.1.3.2-6 Block diagram. Inherently, a vehicle body structure poses harness routing problems which were alleviated by specialized automotive components. Two such components are the interface connector and the 40-way bulkhead disconnect.

The interface connector, located on the left fender side shield, was a major interface point between the 12 V car system and the GE drive system components. Brought together at this connector are circuits from the power conditioning unit, motor thermostats, vent and purge fans, and other areas, thus allowing diverse systems and circuits to be tested, evaluated, analyzed, and serviced effectively.

The second important component is the 40-way bulkhead disconnect located in the upper left corner of the dash. It serves as a physical and electrical bridge between the motor compartment harness and the remaining vehicle and General Electric harnesses.

TABLE 3.1.3.2-2
ELECTRICAL LOADS

Item		Amperes	Summer Duty Cycle	Winter Duty Cycle
1	Tunnel Purge Fan	1.50	1.50	1.50
2	Drive Motor Cooling Fan	8.00	8.00	--
3	GE Power Supply	7.50	(Deleted 10-22-77)	--
4	Heater Blower Motor Pass. Corp.	8.00		8.00
5	Gas Heater Combustion Motor-Eng. Comp.	10.50		10.50
6	Windshield Wiper Motor	5.50	4.20	4.20
7	Windshield Washer Motor	3.00	--	--
8	Cigar Lighter	7.50	--	--
9	Fuel Gauge	0.0006	--	--
10	Cluster Warning & Indicator Lamps			
	a. Brake	0.24		
	b. Seat belt	0.24	--	--
	c. Seat belt Buzzer	0.20	--	--
	d. Hi-Beam	0.24	0.24	0.24
	e. Drive Energized	0.24	--	--
	f. Main Battery Charging	0.24	--	--
	g. Overspeed	0.24	--	--
	h. Over Temperature	0.24	--	--
	i. Low Voltage	0.24	--	--
	j. Turn/Hazard	0.48	--	--
11	Instrument Pan. ' & Interior Lamps			
	a. DNR Switch	0.20	--	--
	b. Heater Control Lamp	0.20	0.20	0.20
	c. Dome Lamp	0.95	--	--
	d. Cluster Illumination (2)	0.48	0.48	0.48
	e. Turn Signal/Hazard Flasher	0.24	--	--
	f. Ign. Key Lamp	0.24	--	--
12	Exterior Lamps			
	a. Headlamps (2)	10.20	10.20	10.20
	b. Tail Lamps (2)	1.12	1.12	1.12
	c. Parking Lamps (2)	4.20	4.20	4.20
	d. Stop Lamps (2)	0.30	0.30	0.30
	e. Backup Lamps (2)	0.67	--	--
	f. Side Marker Lamps (2)	0.67	0.67	0.67
	g. License Plate Lamp (1)	0.33	0.33	0.33
13	Horn	6.00	--	--
14	Horn Relay	0.70	--	--
15	108 V QD Relay	0.80	0.80	0.80
16	H/L Door Motors (2)		Intermittent	
17	Backup Buzzer		Intermittent	
18	Key In Buzzer	0.20	--	--
TOTAL		--	32.24	42.74

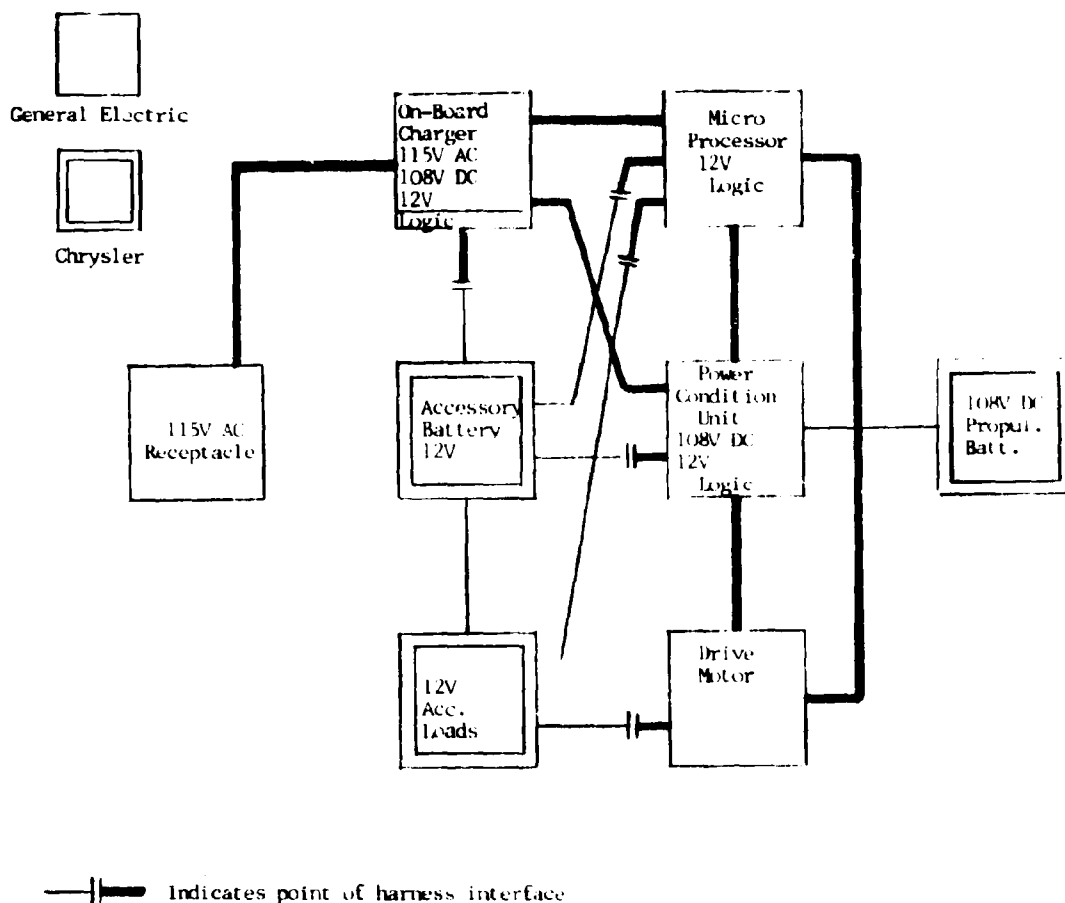


Figure 3.1.3.2-6. Interface Harness Diagram

Instrument Panel

The instrument panel harness ties together all the functional operator-controlled items, display systems, and lighting systems. Several key components interconnected by this harness are the body half of the 40-way disconnect, fuse block, ignition key switch, drive mode selector switch, and the charge mode selector switch. Circuits requiring automotive fuse protection are routed to a modified Omni/Horizon fuse block containing 12 glass automotive fuses and mounting provisions for safety-related relays, buzzers, and flashers. Location of this fuse block is under the plenum floor to left of the steering column. Determination of commonly fused circuits were based on summer/winter, day/night duty cycles which included a wide variation in the environmental parameters of temperature, humidity, rain, snow, and road conditions (Table 3.1.3.2-3).

The ignition key switch is located on the steering column in the standard Omni/Horizon position.

Drive and charge mode selector switches, both panel-mounted near the center of the car, are similar in appearance but dissimilar in function control. Selection of the drive, neutral, or reverse function is accomplished by depressing the required pushbutton. Charging of the propulsion battery bank is accomplished, after inserting the charge cord into its mating receptacles, by selecting the initiating type of charge (normal or equalization), depressing one of the pushbuttons, and then depressing the spring return start pushbutton. The complete charging cycle is then automatically controlled by the microcomputer.

Body Wiring

The body wiring harness provides for interior and exterior lighting and services as an interconnect for the battery tray system.

Battery Tunnel System

The battery tunnel wiring system includes: the drive system main power cable, connectors, and fuse; the water fill/gas vent control valves; the battery tunnel ventilation fan; a propulsion battery temperature sensor, and provisions for measuring the open-circuit voltage of each of the 18 propulsion batteries.

The two cylindrical pin connectors are used to couple the propulsion battery to the drive system wiring. These units are located at opposite ends of the battery pack with the female receptacle mounted on the tray, as shown in Figures 3.1.3.2-7 and 3.1.3.2-8 and with the male plug mounted on the inside of the tunnel, as shown in Figures 3.1.3.2-9 and 3.1.3.2-10. The connectors mate passively when the battery pack is lifted into position in the car. This arrangement minimizes the electrical shock hazard for service personnel.

Since a common manifold is used for filling the batteries with water and for venting the hydrogen gas given off by the batteries, a pair of solenoid valves are used to change the operating mode from venting to water fill. The valves are actuated by removal or installation of the water-fill connector cover at the rear of the car. Removal of the cover also opens the battery quick disconnect switch for safety. Reinstallation of the cover returns the system to the ventilation mode. Even though the vent manifold is a closed system, a small purge fan mounted at the forward end of the tunnel provides 15 to 25 ft³/min of ventilating air flow through the tunnel.

Wiring for the forward solenoid valve, the battery temperature sensor, and the individual battery voltage measurements are terminated at the rear of the battery tray in the multipin connector (Figure 3.1.3.2-11). The mating connector, which is manually assembled after the battery pack is installed in the car, is part of the body wiring harness.

**TABLE 3.1.3.2-3
FUSE CHART**

Cavity	Fuse Size	Usage
1	3AG 5	Purge Fan, Vent Fan Relay
2	3AG 5	Instrument Panel Illumination Lamp
3	SFE 20	Hazard Flashers
4	SFE 20	Head Lamp Door Relay, Horn, Horn Relay, Park, Tail Lamps, Side Lamps, License Lamp
5	SFE 20	QD Interlock Circuit, Ignition Lamp, Key in Buzzer, Dome Lamp, Cigar Lighter, Brake Lamp, PCU/Micro Battery Feed, Switch Relay
6	3AG 30	Heater Blower - Passage, Heater-Blower Combination Heater Fuel and Water Pump
7	3AG 3	Overtemp Warning Lamp - Bulb Check
8	3AG 3	PCU/Motor Overtemp Thermostats
9	3AG 5	Cluster Warning Lamps, Regenerative Brake Feed
10	SFE 20	Backup Lamps, Backup Buzzer, Fill/Vent Solenoids, Turn Signal Flasher
11	3AG 5	Seat Belt Buzzer, DNR Switch Illumination Lamp, Heater System Relay, PCU/Micro Ignition Feed, Heater Fuel Lamp
12	3AG 15	Purge Fan, Vent Fan



Figure 3.1.3.2-7. Tray-Mounted Female Receptacle - Front



Figure 3.1.3.2-8. Tray-Mounted Female Receptacle - Rear

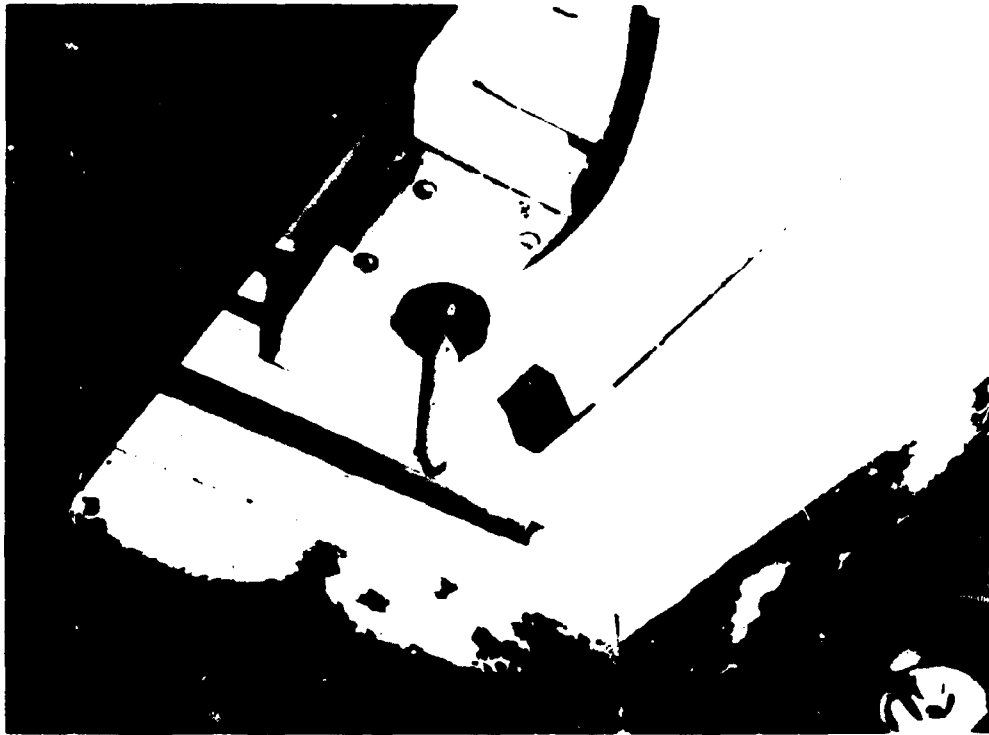


Figure 3.1.3.2-9. Tunnel-Mounted Male Receptacle -Front



Figure 3.1.3.2-10. Tunnel-Mounted Male Receptacle - Rear

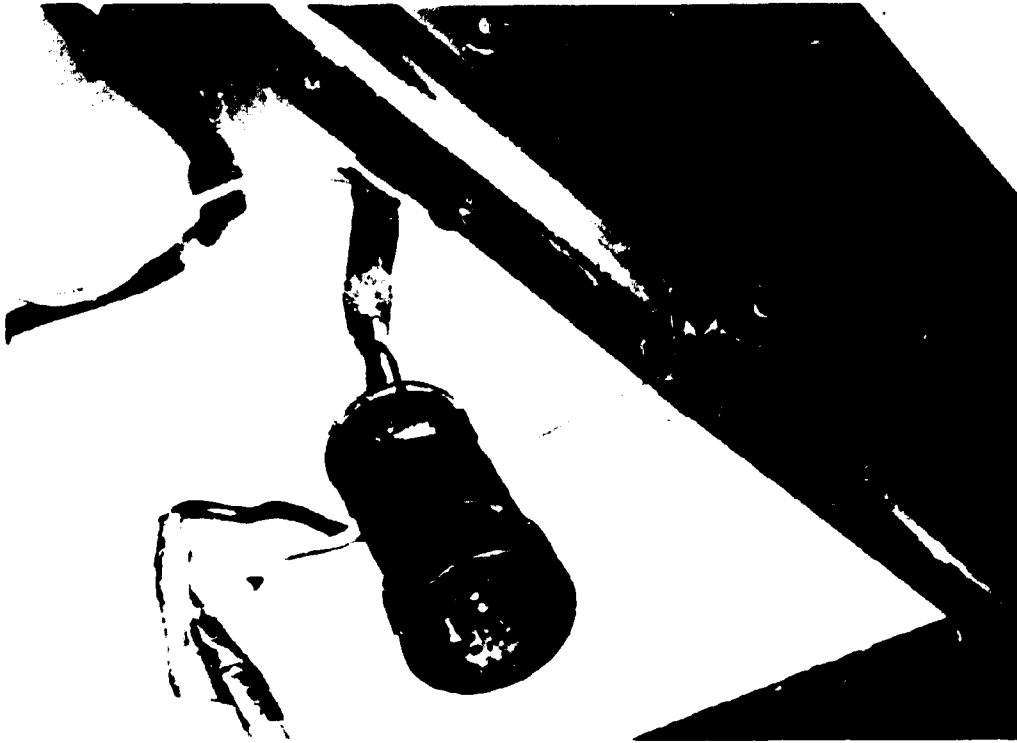


Figure 3.1.3.2-11. Multi-Pin Connector-Body Mounted

WBS 3.1.5 Vehicle Design and Fabrication

Due to the extensive new model engineering program within Chrysler, it was decided to subcontract the actual vehicle design and fabrication outside the corporation with Chrysler supplying the supervisory leadership and technical support personnel. Actual styling, modeling, wind tunnel development, structural and suspension analysis, and heater-defroster design and tests, were done within the Chrysler Research and Development Center. An internal task force of key senior engineers and supporting staffs was established to accommodate the engineering tasks and direct the outside design and building activities. Each senior engineer was also responsible to order all unique parts from various component suppliers and to make sure they arrived on time.

The subcontract to design and fabricate the Near-Term Electric Vehicle was awarded to Modern Engineering Service Company of Troy, Michigan. Their responsibility was to design the complete vehicle from the surface lines furnished by Chrysler Styling and incorporate the structural and suspension geometry requirements established by the task force engineers. A full-time Chrysler Engineering Supervisor was assigned to stay on-site to oversee the design activity. Completion of all drawings and a Bill of Material was the responsibility of the subcontractor and are a part of the deliverable items.

The subcontractor was also responsible for completing the die models as furnished by Chrysler, making all the dies and other tooling, and completing the assembly of the vehicle including the traction drive system.

The Near-Term Electric Vehicle is a derivative of Chrysler Corporation's Omni-Horizon front-wheel drive compacts. Many of the major chassis and body parts have been modified or reworked, thereby reducing the number of new parts required for the car and drastically reducing the overall cost of the project. Carryover parts were used in their largest subassembly whenever applicable to facilitate tracking and ease of construction. The remainder of the parts were made for this vehicle using Kirksite dies or brake-press forming techniques.

The major steps involved in designing the Near-Term Electric Vehicle were as follows:

- Create heavy line packaging layouts to locate the passengers, motor compartment components, batteries, etc.
- Create styling renderings.
- Make 3/8 scale clay models from renderings and package drawings.
- Aerodynamically test 3/8 clay model in the wind tunnel.
- Make a full-size clay model.

The work flow diagram from the approved clay model through the design stages are shown in Figure 3.1.5-1. To expedite the flow of engineering information from Chrysler Styling to the subcontractor, a full computer aided design (CAD) program was employed. Once the 3/8 clay model was approved aerodynamically from an appearance standpoint, the CAD program was employed to develop the full-size clay model. Subsequently, once the full-size clay model was completed and approved for appearance, data was taken directly from the final clay model and used to generate a mathematical model of the surface. Subsequently, a full-size, three-view draft was drawn on a "Gerber" drafting machine (Figure 3.1.5-2). Body panel surfaces on the draft were refined manually by

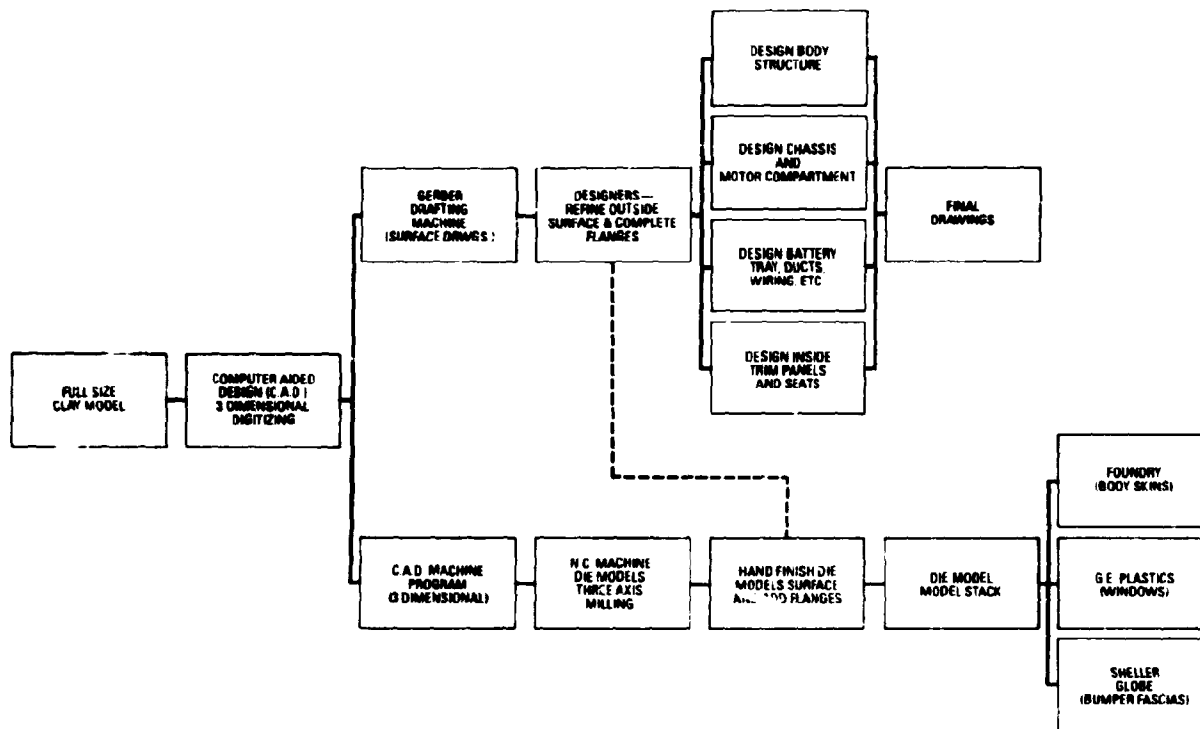


Figure 3.1.5-1. Work Flow Diagram - Clay Model Through Design and Die Models

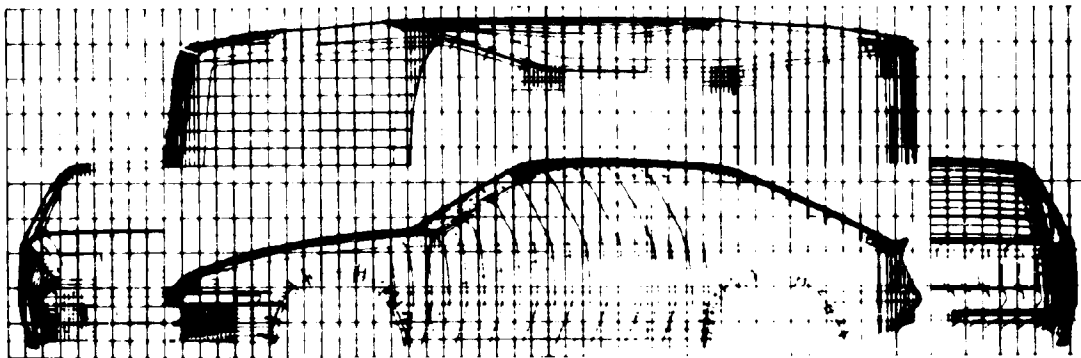


Figure 3.1.5-2. NTEV Body Draft

draftsmen as required. Flanging information was added to the outside panel drawings. The remainder of the vehicle structure, chassis, trim, and electrical designs were made into drawings.

While the designers were working on the layouts, computer programs generated numerical control tapes to machine the three-dimensional die models. A complete die model stack is shown in Figures 3.1.5-3, 3.1.5-4, and 3.1.5-5. Hand finished die models were stacked for approval and subsequently pulled apart and distributed to the Foundry, for Kirksite tooling, General Electric Plastics for side and rear glazing, and Sheller-Globe for bumper fascias.

Male and female plaster molds are made from the die models and provide the shrink factor for the zinc alloy dies. Stamped parts come from these dies. Many parts are also made from zinc alloy forms by hand hammering. Assembly fixture designs are started while dies are being poured. All components are fed into the subassembly and major assembly fixture for final body assembly.

For limited prototype build programs such as the Near-Term Electric Vehicle, each vehicle is built on a grid-lined surface plate utilizing wood assembly fixtures. Figure 3.1.5-6 outlines the essential sequence of events necessary to build the Near-Term Electric Vehicle. Locators and assembly fixtures are first made and set up on the surface plate shown in Figure 3.1.5-7. These fixtures position and hold the component parts in their proper attitude. All body-in-white components are screwed together to verify the dimensional relationships prior to welding. Figures 3.1.5-8 and 3.1.5-9 show a partial body assembly from the side and rear view, respectively.

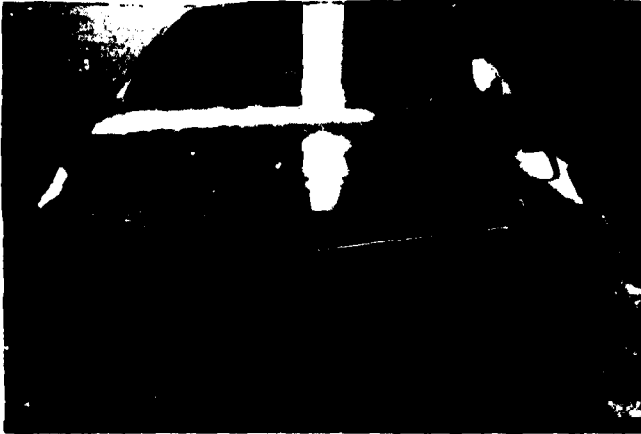


**Figure 3.1.5-3. NTEV Die Model Stack
- Front View**



**Figure 3.1.5-4. NTEV Die Model Stack
- 3/4 Right Side**

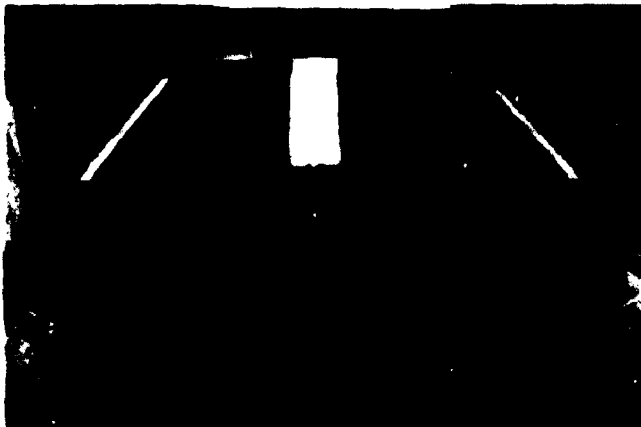


**Figure 3.1.5-5. NTEV Die Model Stack
- Rear View**

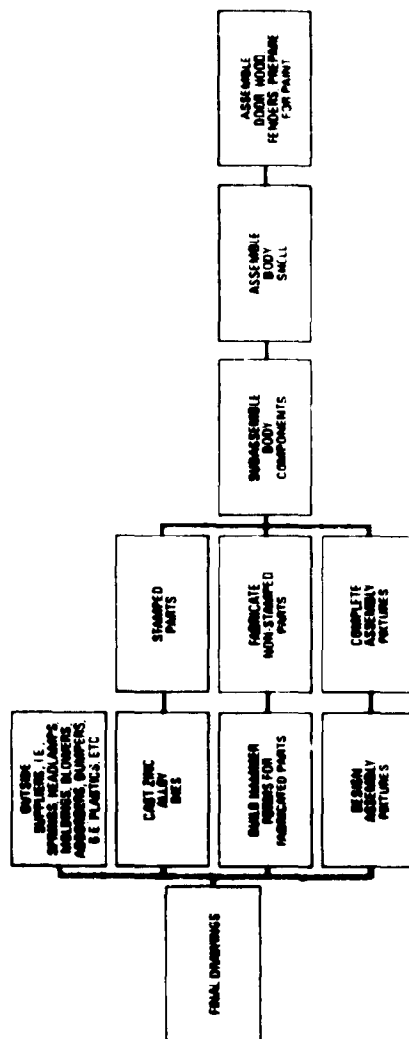


Figure 3.1.5-6. Work Flow Diagram - Final Drawings Through Complete Body



Figure 3.1.5-7. NTEV Underbody, Surface Plate, and Fixtures – 3/4 Front View



Figure 3.1.5-8. NTEV BIW Build – Side View

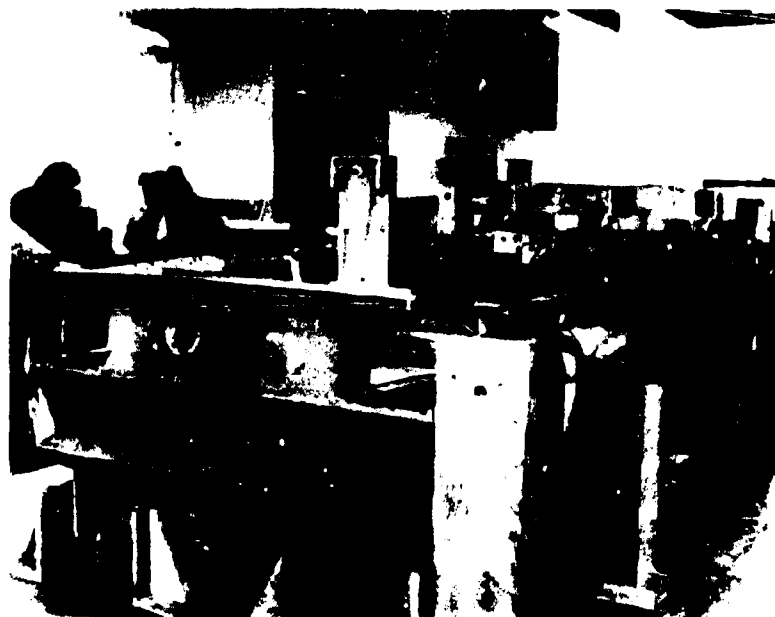


Figure 3.1.5-9. NTEV BIW Build – Rear View

The Near-Term Electric Vehicle underbody is shown in Figure 3.1.5-10 and Figure 3.1.5-11. The motor compartment and the front impact structure, with its Hexcel core, are welded to the front and rear floor pans to complete the underbody assembly (Figure 3.1.5-12).

The side aperture panel subassemblies are put together in their own fixture off line, as shown in Figure 3.1.5-12a, prior to attachment to the underbody platform. The two side aperture panels along with the major cross car structural members, i.e., cowl top, windshield header, backlite header, and lower deck panel assembly are welded to the underbody platform to complete the body shell. Addition of the roof panel completes the body-in-white shown in Figure 3.1.5-13.

Front end sheet metal, i.e., fenders and hood, and the assembled doors-in-white are attached to the body-in-white, completing the body structure of the vehicle. The vehicle then goes to the paint ovens where it undergoes a primer bake cycle of 204°C (400°F) for 30 minutes to age harden the aluminum and the high strength low-alloy steel components. The bake cycle also cures the various sealers used to seal all the welded joints in the car. The body is now ready for applying the corrosion protection and for preparation for painting the body with primer Figure 3.1.5-14 outlines the assembly operations.

*Trademark of Hexcel Corporation



Figure 3.1.5-10. NTEV Underbody - Front Portion

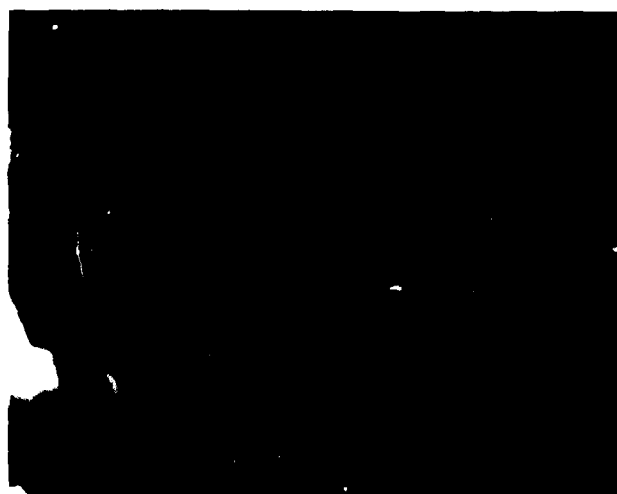


Figure 3.1.5-11. NTEV Underbody - Rear Portion



Figure 3.1.5-12. NTEV Motor Compartment



**Figure 3.1.5-12a. NTEV Body Side Aperture Panel
Assembly in Subassembly Fixture**



Figure 3.1.5-13. NTEV BIW Complete

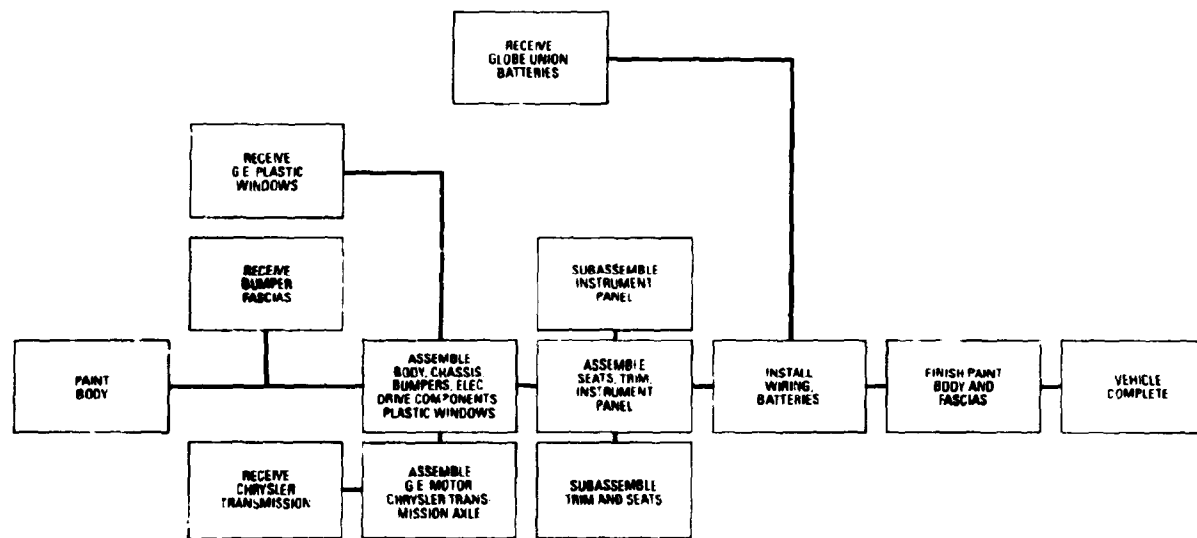


Figure 3.1.5-14. Work Flow Diagram - Vehicle Assembly

After the body is painted with final color, the chassis components are installed. Figure 3.1.5-15 illustrates the installation of the soft front fascia. Figure 3.1.5-16 shows the installation of the transmission and motor assembly into the vehicle. Propulsion system wiring, standard 12 V automobile wiring, interior trim, and operating hardware are installed next. Figure 3.1.5-17 shows the engine compartment after installation of its components, and in Figure 3.1.5-18, the instrument panel, seats, and door trim panels are installed. Glazing, body side molding, and paint striping operations complete the vehicle, as shown in Figure 3.1.5-19.



Figure 3.1.5-15. NTEV Front Fascia



Figure 3.1.5-16. NTEV Transmission Installation

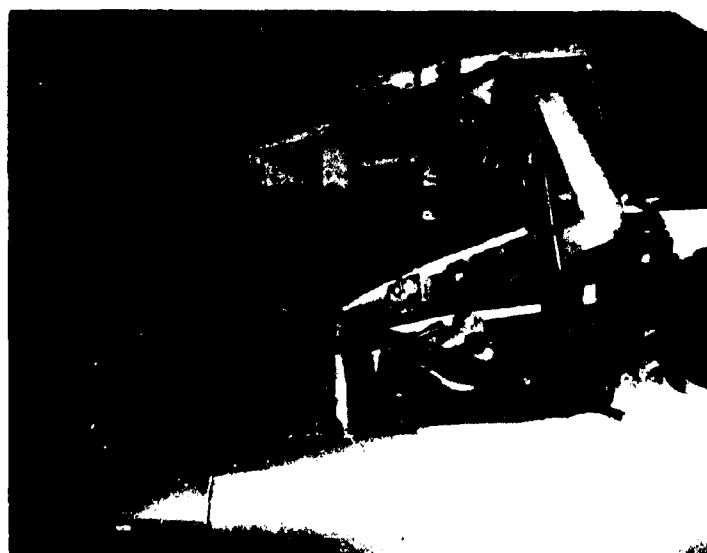


Figure 3.1.5-17. NTEV Motor Compartment



Figure 3.1.5-18. NTEV Instrument Panel, Seats, and Door Trim



Figure 3.1.5-19. NTEV Body Complete

WBS 3.2 ELECTRICAL DRIVE SUBSYSTEM

WBS 3.2.1 Parameter Optimization

The work effort was to evaluate all candidate motor designs submitted by the Direct Current Motor and Generator Department (DCM&G) for suitability on the electric vehicle. The motors have been examined for performance on the J227a Schedule D urban driving cycle and range at a constant 45 mph while also meeting the requirements of 0 to 30 mph acceleration in 9 seconds, 25 to 55 mph acceleration in 18 seconds, and climbing a sustained 5% grade of 1 mile at 50 mph.

The digital computer program which modeled the battery, drive, and vehicle was used to select the motor producing maximum range on the J227a Schedule D cycle. A model of the EV-106 battery was used because the model of the EV2-13 battery, being installed in the vehicle, was not available when this study was conducted.

Because the performance differences between the best performing motors were small, the choice was difficult. The motor selected gave the best performance on the J227a Schedule D urban cycle and remained a leading candidate for all sensitivity studies made for vehicle and battery changes.

The motor selected is designated as General Electric frame size 2366, armature design 2513. The motor is physically designed around the following set of preliminary design parameters:

- Continuous rating 20 hp, 96 V, 2500/5000 rpm speed range
- Shunt wound, 4-pole with commutating poles
- Totally enclosed, blower ventilated
- Shunt field turns = 250
- Voltage constant = 0.050 V/megaline-rpm
- Torque constant = 0.352 lb-ft/megaline-amperes
- Resistance - armature + commutator pole (hot) = 0.0405 ohm
- Resistance - shunt field (hot) = 5.67 ohms
- Approximate weight = 217 lb

Table 3.2.1-1 gives the results for all motors evaluated. For all motor/parameter sets the first step in the analysis was the determination of the optimum field flux to use during the acceleration/deceleration portion of the J227 cycle in the armature contr. 1 region. This was determined by varying the flux level and noting the energy required for one J227 cycle.

Figure 3.2.1-1 shows the results for the selected motor presented in graphical form. The tests were repeated for an 80% discharged battery to verify that there was not a shift in the optimum field flux as the battery lost charge. Figure 3.2.1-1 shows that a flux level of 0.95 megaline is optimum for the J227 cycle for both a fully charged and an 80% discharged battery. The normal rated field flux for this machine is 0.72; thus the optimum flux represents a 32% field flux forcing. This in turn represents approximately a 113% field current forcing due to the machine's magnetic structure saturation.

TABLE 3.2.1-1
SUMMARY OF EVALUATION RESULTS

GE DCMC		Speed Range (RPM)	J227A-D		Range @ 45 MPH (Miles)	Motor Wgt (lb)	ARMATURE CURRENT - AMPS							
Frame No.	Armature Design		Cycles	Miles			Fully Charged Battery				40% Discharged Battery			
							SEGI J227	0/30	25/55	5% Grade	SEGI J227	0/30	25/55	5% Grade
2366	2513	2500/5000	54	54.28	78.2	225	209	320	370	327	214	327	413	358
2369	4111	2500/5000	54	53.26	74.7	305	244	411	343	304	247	415	364	322
2369	2513	1250/5000	53	54.01	77.9	280	200	278	413	354	205	287	Not enough torque	
2366	3312	3750/5000	53	52.64	77.3	225	227	769	353	315	230	374	383	339
2368	4511	3000/5000	53	52.07	74.7	260	251	434	343	303	255	435	363	320
2370	2513	1250/5000	52	52.88	74.0	450	208	289	392	340	213	299	438	371
2368	2513	1750/5000	52	52.63	77.8	260	205	300	401	347	410	307	500	400
2368	5711	2500/5000	52	51.55	76.6	260	233	383	357	317	237	381	385	340
2364	2913	2500/5000	50	49.94	77.8	200	225	360	395	344	229	369	485	N.G.
2366	5711	3750/5000	50	49.09	74.3	225	255				258			
2366	4911	3750/5000	50	48.88	72.2	225	271	480	348	301	273	480	366	319
2368	4111	3500/5000	50	48.73	70.5	260	291				293			
2368	3711	3750/5000	47	45.74	70.5	260	319				320			
2364	5711	3750/5000	43	41.82	70.5	200	336				337			
2368	2511	5000/5000	42	40.86	69.0	260	470				472			
2346	4911	5000/10,000	49	48.69	69.2	150	237				240			
2346	4511	6000/10,000	48	47.48	68.4	150	247				252			
2346	4111	6500/10,000	48	47.19	67.4	150	262				265			
2346	3312	5000/10,000	47	47.51	69.7	150	218				223			
2346	2912	5000/10,000	47	47.19	69.4	150	225				231			
2346	3711	6500/10,000	46	45.02	65.0	150	283				285			

(-) Data not calculated due to poor performance of candidate motor on J227 cycle

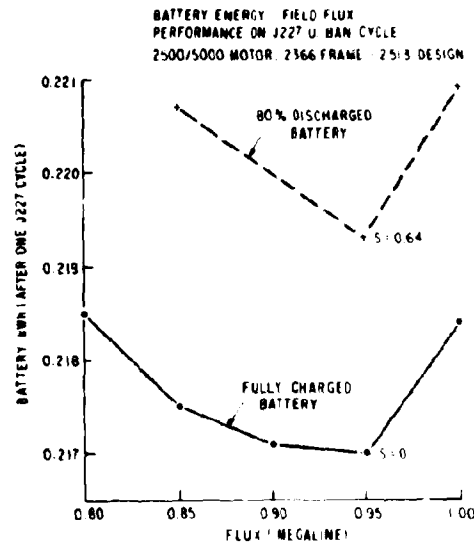


Figure 3.2.1-1. Battery Energy -- Field Flux Performance on J227a Urban Cycle

Vehicle Parameter Variations

In order to assure that the motor selected was suitable for the anticipated range of car parameters, test cases were run for the expected range of parameters. Four candidate motors were selected for this study and their performance calculated for the range of variables shown below.

Aerodynamic Drag

$$F_d = 2.151 * K_1 * A * D * V^2 \text{ (lb)}$$

$$A = \text{Frontal area (ft}^2\text{)}$$

$$D = \text{Drag coefficient}$$

$$V = \text{Velocity (mph)}$$

$$K = \rho/2g = 1.19 * 10^{-3} \text{ at standard atmosphere}$$

Rolling Resistance

$$FR = 1/K_2(W + W_m) (1 + 2.05 * 10^{-3} * V + 2.58 * 10^{-5} * V^2) \text{ (lb)}$$

where W = wgt of car + 300 lb passenger load

$$W_m = \text{wgt of motor}$$

$$V = \text{Velocity (mph)}$$

The range of values for $1/K_2$, W, and $A * D * K$ is shown below

	<u>Min.</u>	<u>Max.</u>
$1/K_2$	0.0101	0.0138
W	2800	3100
$2.151 * K_1 * A * D$	0.01359	0.01689

The results are shown on Figure 3.2.1-2. Within the range of vehicle parameters tested, the chosen motor design is either at the maximum range or within one cycle of the maximum.

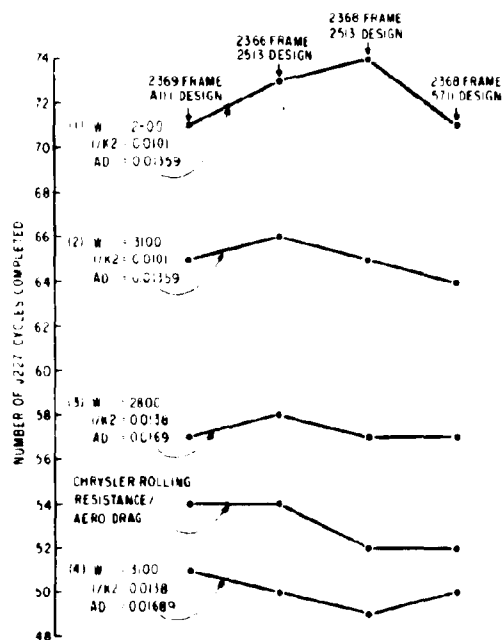


Figure 3.2.1-2. Vehicle Sensitivity Study

Battery Resistance Variation

Preliminary data suggest that the actual battery internal resistance may be less than that obtained in Phase I.* A series of test cases were made for a battery internal resistance of 1/2 that of the model. The results of this change are shown in Figure 3.2.1-3 for the same four candidate motors. Again the 2366 frame, 2513 Design shows a maximum number of cycles for this change.

* "Electric Car Design Tradeoff Studies Report, Phase I," ERDA Contract EY-76-C-03-1294, GE Corporate Research and Development, Schenectady, N.Y., February 10, 1977.

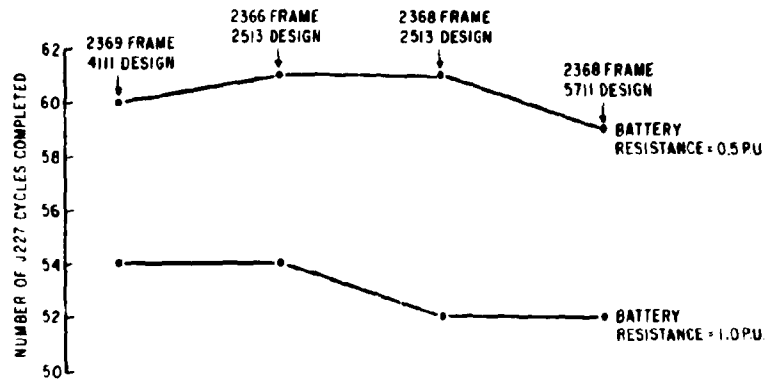


Figure 3.2.1-3. Battery Resistance Sensitivity Study

WBS 3.2.2 Control Strategy and Sensors

This task includes strategy selection relating to (a) drive control methods, (b) rating philosophy, (c) fuel gauging, and (d) battery charging.

Drive Control Methods

The regenerative braking drive requirement favors the selection of a dc, separately excited motor. Motor design evaluation studies conducted under WBS 3.2.1 have resulted in the selection of a motor which operates with armature voltage control from approximately 0 to 25 mph. In the armature control mode, the field current I_f is held constant and I_a is varied by adjusting armature voltage V_a . In the field control mode, V_a is at full value and I_a is adjusted by varying I_f .

The important points relating to this strategy are:

- $T_e \propto I_a$ in armature control (provided I_f is fixed)
- $T_e \propto 1/N$ in field control (provided V_a is fixed)
- $\partial T_e / \partial I_a$ is variable

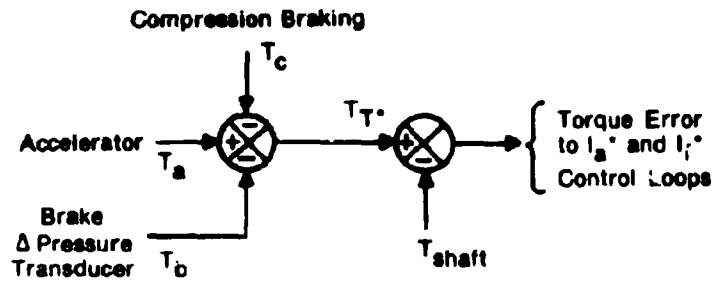
To give the vehicle a constant accelerator pedal "feel" in view of these points, a torque control scheme was selected. Figures 3.2.2-1 (a) and (b) show two possible closed-loop torque control schemes using, respectively, a motor shaft torque transducer and a torque computation circuit. Figure 3.2.2-1 (c) shows an open-loop torque control system, the main feature of which is a nonlinear gain block that processes the armature current command, I_a^* , from the total torque reference. This gain block has an inverse law relationship, $I_a^* \propto 1/I_f$, neglecting saturation. The curve can be modified to include saturation, depending upon the detailed motor design.

The open-loop torque scheme was chosen over the closed-loop schemes on the basis of simplicity and the moderate torque accuracy required by this application.

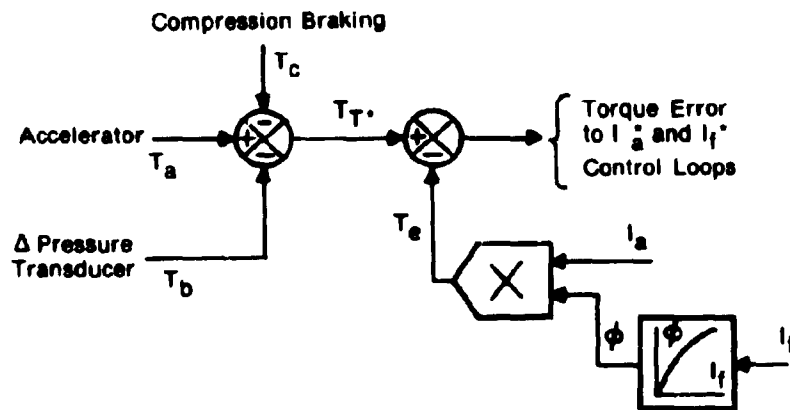
Figure 3.2.2-2 shows a control strategy block diagram.

Rating Philosophy

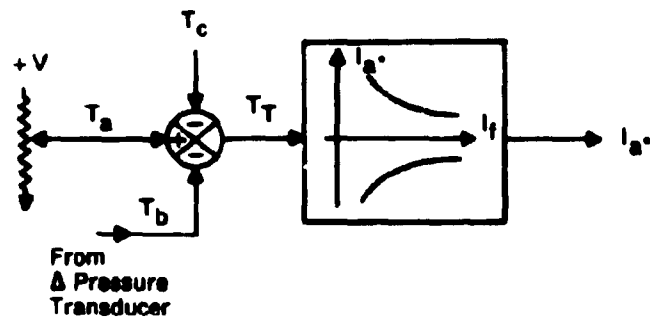
Table 3.2.2-1 and Figure 3.2.2-3 show, respectively, the ratings and torque envelope resulting from the selected control strategy.



(a) Closed-Loop Scheme Using Shaft Torque Sensor



(b) Closed-Loop Scheme Using Computed Torque



(c) Open-Loop Torque Control

Figure 3.2.2-1. Torque Control Schemes

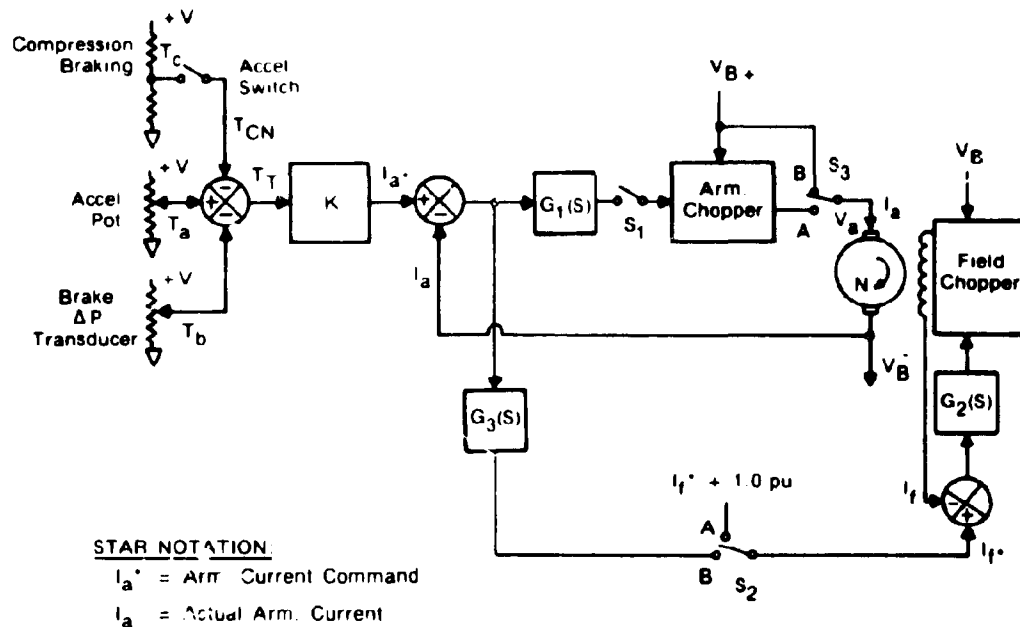


Figure 3.2.2-2. Overall Control Strategy Block Diagram

TABLE 3.2.2-1
DRIVE COMPONENT RATINGS

Armature Chopper	
• Continuous Rating	
Motoring:	$I_A = +200 \text{ A}$, $\tau = 50\%$
Generating:	$I_A = -100 \text{ A}$, $\tau = 50\%$
• Transient Rating	
Motoring:	$I_A = +400 \text{ A}$, $\tau = 50\%$
Generating:	$I_A = -200 \text{ A}$, $\tau = 50\%$
Field Chopper/Charger	
• Continuous Rating	
Field Supply:	$I_f = 10.6 \text{ A}$, $V_f = 53 \text{ V}$ $\phi_{NL} = 0.95 \text{ ML}$
Charging:	$I_B = 24 \text{ A}$, $V_B = 132 \text{ V}$, $T_B = 80^\circ\text{F}$ (30 A line) $I_B = 8 \text{ A}$, $V_B = 132 \text{ V}$, $T_B = 80^\circ\text{F}$ (15 A line)
Motor	
• Continuous Rating:	$I_A = \pm 175 \text{ A}$, $V_A = 96 \text{ V}$, $P_{Sh} = 20 \text{ hp}$

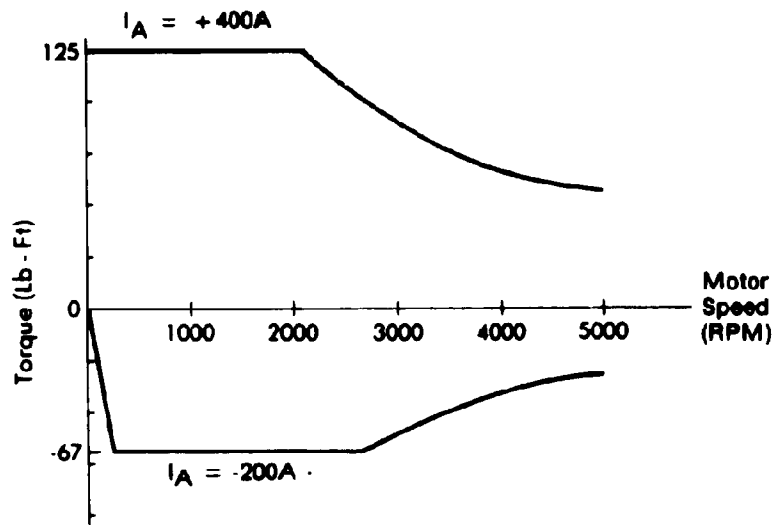


Figure 3.2.2-3. Torque Envelope

Fuel Gauging

The function of fuel gauging is to compute the propulsion battery's state of charge and to display the information on the dashboard meter. The microcomputer receives the battery voltage (BVFG) and battery current (BC) signals for the above computation and gives an output to the fuel gauge ammeter so that the current is proportional to the state of charge. The fuel gauging strategies during drive subsystem operation and battery charging are different and described below.

The fuel gauging computation is inactivated during the regeneration mode of the drive subsystem because no valid strategy has yet been developed. During the motoring condition, the following equation developed by K.R. Kleckner¹ describes the fuel gauging computation:

$$Q = 100 \left[1 - \frac{\text{erf} [10.5 - 0.0025I_B - 0.09578V_B + (6.65/I_B)^{0.5}]}{\text{erf} [2.051 - 0.0025I_B + (6.65/I_B)^{0.5}]} \right]$$

$$= 100 \left[1 - \frac{\text{erf}(x)}{\text{erf}(y)} \right]$$

¹K.R. Kleckner, "Modeling and Testing of Storage Batteries," Paper No. 730251, Paper presented at International Automotive Engineering Congress, January 1973.

where

Q = percent capacity (fuel) remaining at steady discharge rate I_B

I_B = constant current discharge rate (amps)

V_B = pack voltage at I_B (volts)

conditions:

- (1) if $x < 0$, $Q = 100$
- (2) if $\frac{\text{erf}(x)}{\text{erf}(y)} > 1$, $Q = 0$
- (3) $30 \text{ A} < I_B < 400 \text{ A}$

Figures 3.2.2-4(a) through (e) shows curves relating percent capacity (fuel) remaining to battery pack voltage for both experimentally determined and calculated data. The experimentally determined curves were generated by Globe-Union from constant current discharges at the different rates presented. Curve coordinates were determined using a digital voltmeter to monitor a single cell voltage during the discharge and relating that to a calculated percent capacity. The experimentally determined capacities were determined using a 1.3 V/cell cutoff.

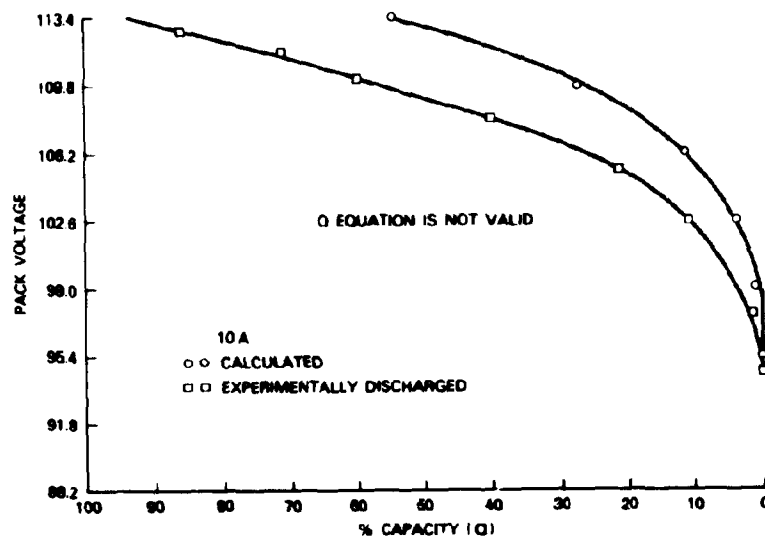


Figure 3.2.2-4a. Percent Capacity vs Battery Pack Voltage - 10A

The EV fuel gauging computation is restricted within the battery current range of 10 A to 100 A, which adequately covers the steady state operation of the vehicle. During fast acceleration the battery current may reach up to 400 A; but the Kieckner equation is not valid for transient battery current.

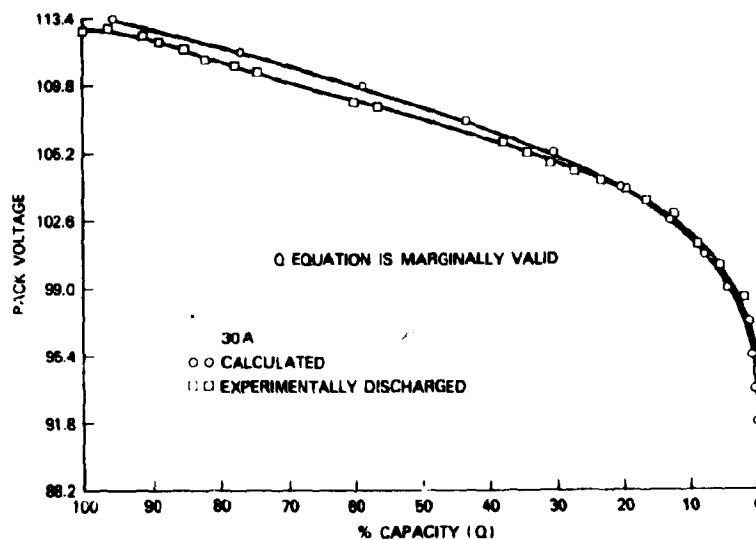


Figure 3.2.2-4b. Percent Capacity vs Battery Pack Voltage - 30A

The fuel gauging computation during battery charging is done by computing the amount of charge placed in the battery and adding it to the state of charge information available in the continuous memory. The basic equation is

$$Q = Q_s + \frac{I_B \Delta t}{C} \times 100 \quad (15)$$

where

Q = state of charge (percent)

Q_s = previous state of charge available in continuous memory

I_B = battery charging current (amps)

Δt = time segment (hours)

C = amp-hr capacity of the battery (171 A-h)

A typical charging current profile is shown in Figure 3.2.2-5.

The amount of charge placed into the battery is given by the shaded area $I_B \Delta t$. When the battery is fully charged at time T , ideally the state of charge should indicate:

$$Q = Q_s + \frac{1}{C} \int_0^T I_B \Delta t \times 100 = 100\%$$

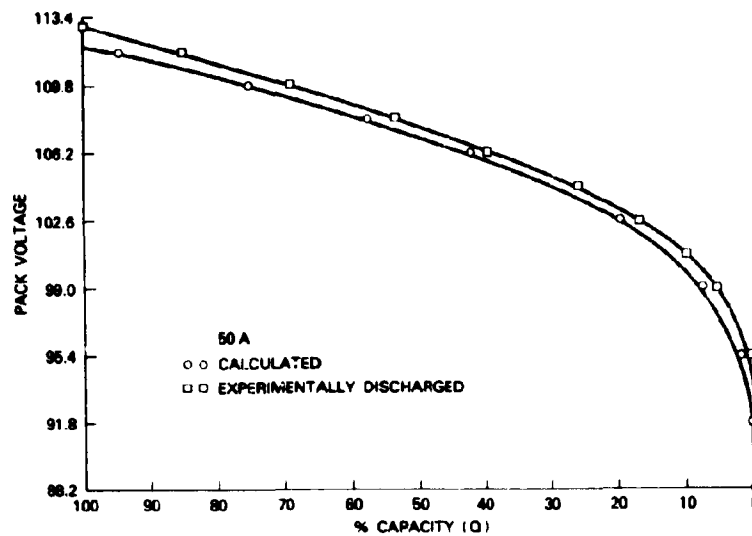


Figure 3.2.2-4c. Percent Capacity vs Battery Pack Voltage - 50 A

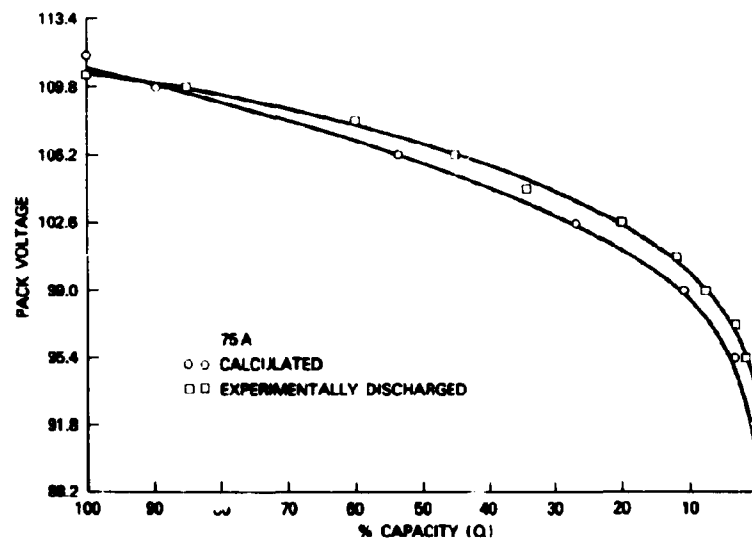


Figure 3.2.2-4d. Percent Capacity vs Battery Pack Voltage - 75 A

Battery Charging

The microcomputer is responsible for controlling battery charging through the field chopper/battery charger unit by placing the charging current command through I_c DAC. The initial charging current is selected according to the receptacle power available. Figure 3.2.2-6 shows the typical battery voltage and current profiles during the

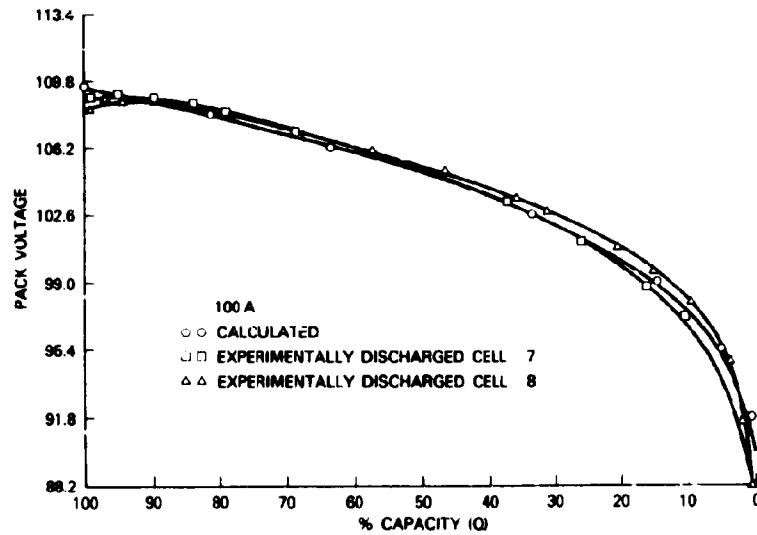


Figure 3.2.2-4e. Percent Capacity vs Battery Pack Voltage - 100 A

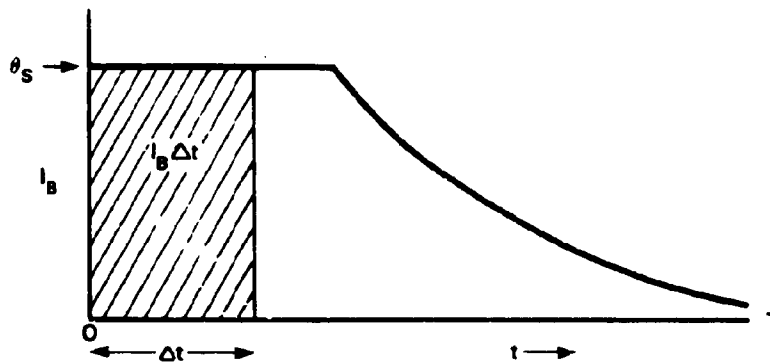


Figure 3.2.2-5. Typical Battery Charging Current Profile

charging condition. Initially, the battery is in the constant current charging mode when the battery terminal voltage continually rises. The permitted peak battery voltage V_B (critical) is a function of temperature and is given by the equation:

$$V_{B(\text{critical})} = N(V_c - KT)$$

where

N = number of cells ($N = 54$)

V_c = cell voltage ($V_c = 2.92\text{V/cell}$)

K = temperature coefficient (0.004 V/°F)

T = temperature (°F)

As the battery voltage reaches the $V_{B(\text{critical})}$ line, the tapered charge mode is entered and the charging current is decremented so that the battery voltage does not exceed $V_{B(\text{critical})}$. The charging is continued so that V_B oscillates between $V_{B(\text{critical})}$ and $V_{B(\text{critical})}-1$ bit values. Over a timed period of five hours the charging current is tapered down to a minimum current of four amperes and terminates if the charge normal switch has been selected. Otherwise, if the charge equalize switch has been selected, the minimum charging current is maintained for an additional five hours. The charge equalization provides an additional booster charge on the battery so that the weakest cells may be fully charged.

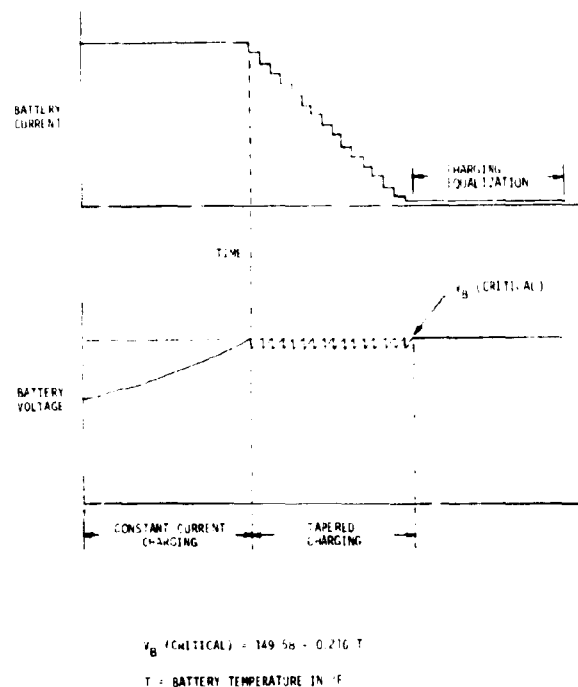


Figure 3.2.2-6. Microcomputer Battery Charging.

WBS 3.2.3 Drive Motor

A separately excited dc motor was chosen by CRD, as described in WBS 3.2.1. Of foremost concern was the selection of the optimum degree of field weakening to be used to accommodate the various drive requirements. The required drive motor capabilities include: continuous, level vehicle operation at all speeds to 60 mph; start/stop service, repeated continuously in accordance with SAE J227a Schedule D; intermittent acceleration from 0 to 30 mph in 9 seconds; and a sustained speed of 50 mph on a one-mile 5% grade. All of these requirements are to be satisfied with acceptable heating and commutation and at the minimum weight consistent with high efficiency.

A speed of 5000 rpm, corresponding to 60 mph, was selected initially. As the study progressed, designs were surveyed to confirm the wisdom of this choice. Consideration was also given to higher speed designs (10,000 rpm), as will be discussed.

A four-pole motor, incorporating a full complement of commutating poles, was given greatest attention. Such a motor affords greatest design flexibility and provides suitable high power density, commutation margin, and thermal capability - particularly at overloads.

Analyses of other dc drive motor types will be discussed later. These include: permanent magnet motor designs, motors having larger and smaller numbers of main poles, and 10,000-rpm designs.

Results

Table 3.2.3-1 gives details regarding the design selected for prototype manufacture. (Design parameters have been modified slightly from preliminary values cited in subsection 3.2.1.)

TABLE 3.2.3-1
MOTOR DATA

NP Rating: 20 hp, 2500/5000 rpm, 96 V, 175 A Cont., Separately Excited at 4.9 A		
Force-Ventilated: 125 cfm (1 in. H ₂ O)		
Winding Resistance: 25 °C		
Armature	0.0189 Ω	
Commutator Field	0.0054 Ω	
Shunt Field	4.3 Ω	
Shunt Field: 330 Turns/Pole		
Winding Inductances:		
	<u>Unsat.</u>	<u>Sat.</u> <u>(FFF @ 3600 A.T.)</u>
Armature + CF	0.52 mH	0.16 mH
Shunt Field	2.3 H	0.21 H
K _T	= 0.352 lb-ft/A Megaline	
K _V	= 0.050 V/rpm Megaline	
WK ²	= 2.2 lb-ft ²	

The selection of the proposed prototype design was the result of careful consideration of more than 20 candidate designs (of various diameters, stackings, and windings), all of which fulfilled the five drive requirements with varying degrees of margin and with varying weights and efficiencies. The design selected provides the maximum range in fulfilling the J227a Schedule D requirements, using the best vehicle and battery information available at the time. The design is close to being optimum, because these duty requirements undergo modification as the result of varying battery and vehicle characteristics.

or stacking, of the designs in this diameter varied more than 2:1. A range of armature turns was considered, resulting in a spectrum of full field speeds between the limits of 1250 (4:1 field weakening) and 5000 rpm (no field weakening). In general, as the full field speed was reduced, the motor size was required to be increased to meet the duty requirements. For a given full field speed, as the motor size increased beyond the minimum size capable of satisfying duty requirements, efficiency improved somewhat. However, when the motor size greatly exceeded the minimum required size by a factor of about 2:1, the increased vehicle weight reduced the vehicle range.

The results of computer runs showed maximum vehicle range on the J227a Schedule D duty with a nominal full field speed of 2500 rpm. With field forcing, the speed is lowered to about 1800 rpm. The motor design limits are primarily the torque required for the 0 to 30 mph in 9 seconds acceleration and for the 50 mph, 5% grade. Because of this, the selected motor exhibits a very moderate temperature rise on the J227a Schedule D urban cycle. Because the design is of ample proportions, commutation duty is not severe.

Computer runs show that a machine with a higher full field speed, although it can be built in a smaller size, is capable of a more limited J227 duty range — even if made oversized. Note, however, that these relations are not highly sensitive. A spread of $\pm 15\%$ as applied to the optimum motor size and optimum full field speed results in a variation in vehicle range of only a few cycles of J227 duty.

Appraisal of Other Motor Design Types

Number of Main Poles. Motor designs built with greater and fewer numbers of main poles were considered. Two-pole designs were substantially heavier and do not offer significant performance advantages to offset the weight penalty. The primary advantages of six-pole designs, as compared with four-pole designs, is a weight reduction of about 15 lbs and an armature circuit resistance reduction of about 10%. Disadvantages include: increased core loss; a poorer stator space factor, resulting from the larger number of poles and coils; and an inherently lower armature circuit inductance, resulting in greater current ripple when operated from a pulse power supply and/or requiring a heavier smooth reactor. Reduced armature reaction per pole allows the use of a smaller air gap, tending to offset the need for more field copper because of the increased number of poles.

Six-pole designs afford less flexibility as to armature winding. In particular, a gap exists between the ratings which can be met with parallel-lap and series-wave winding types. The considered rating bordered on the unavailable range, although it was possible that the optimization process described above for the four-pole designs would have resulted in an acceptable six-pole design. However, it was likely that further investigation would uncover an "optimum" degree of field weakening for a six-pole motor, which would be impractical because of the intrinsic gap in this winding type. For this reason, and because of the near equality of four- and six-pole winding types, a four-pole drive motor was selected for development.

High Speed Motors. Higher speed motor designs were considered, but not judged suitable for maximizing the range of a battery operated vehicle. In particular, five motor designs providing a top speed of 10,000 rpm were evaluated and judged inferior to the 5000 rpm designs described above.

Friction, windage, and core losses of such motors are inherently higher, and, where the armature windings can be shrouded and streamlined, the increased machine losses more than offset the advantage afforded by the weight reduction. The vehicle weight can be reduced about 60 lbs with the use of a motor rated 20 hp, 6000/10,000 rpm. This

figure does not include the increased weight and decreased efficiency likely to be involved in the doubling of the speed-changer ratio.

Permanent Magnet Motors. Permanent magnet excitation of the drive motor offers the obvious advantage of elimination of excitation power. Significant size and weight reductions are foreseeable, particularly with the use of the new cobalt-rare earth magnetic materials now available. A motor design using such magnets developed by the General Electric Company under the trade name Gecor was developed for evaluation by CRD. The machine designed uses approximately 16 lbs of permanent magnet material. Two serious shortcomings are evident.

First, where a permanent-magnet-excited machine using Gecor can be designed for reasonably high airgap flux densities as required for acceptable motor losses during level vehicular operation, a significant flux decrease at severe overloads cannot be avoided — as compared with the flux increase achieved by field forcing with the separately excited machines discussed above. Increased armature current provides the required torque results.

A second shortcoming is the increased motor current associated with peak loading when all of the speed control range is achieved by armature voltage control. Motor currents in the range of 700 A are required, as compared with a maximum current of less than 400 A when using the design selected for prototype manufacture.

Fabrication

Four motors were fabricated with the parameters shown in Table 3.2.3-1. Figures 3.2.3-1, 3.2.3-2, and 3.2.3-3 show the motor armature, motor field, and the assembled motor.

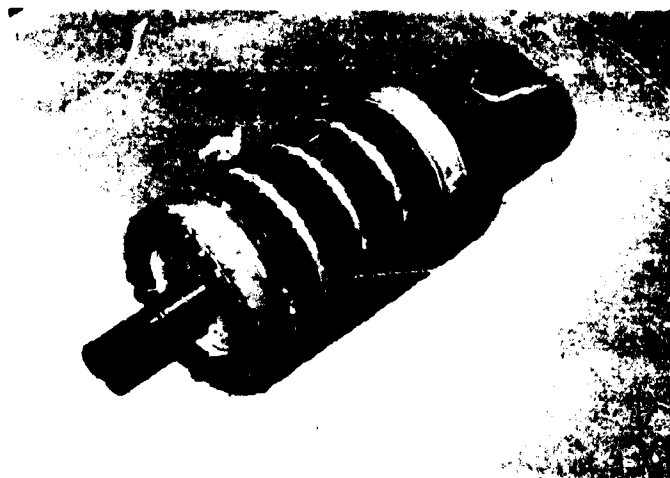


Figure 3.2.3-2. Motor Armature



Figure 3.2.3-3. Motor Field

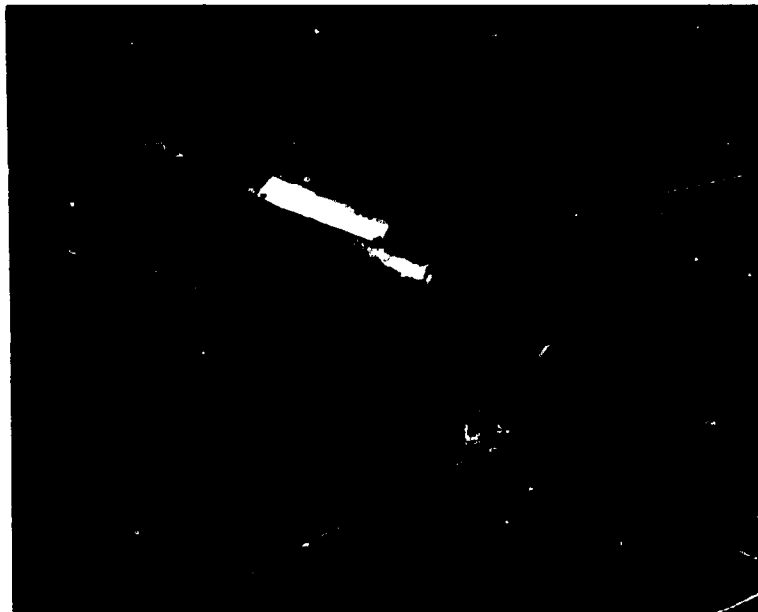


Figure 3.2.3-4. Motor

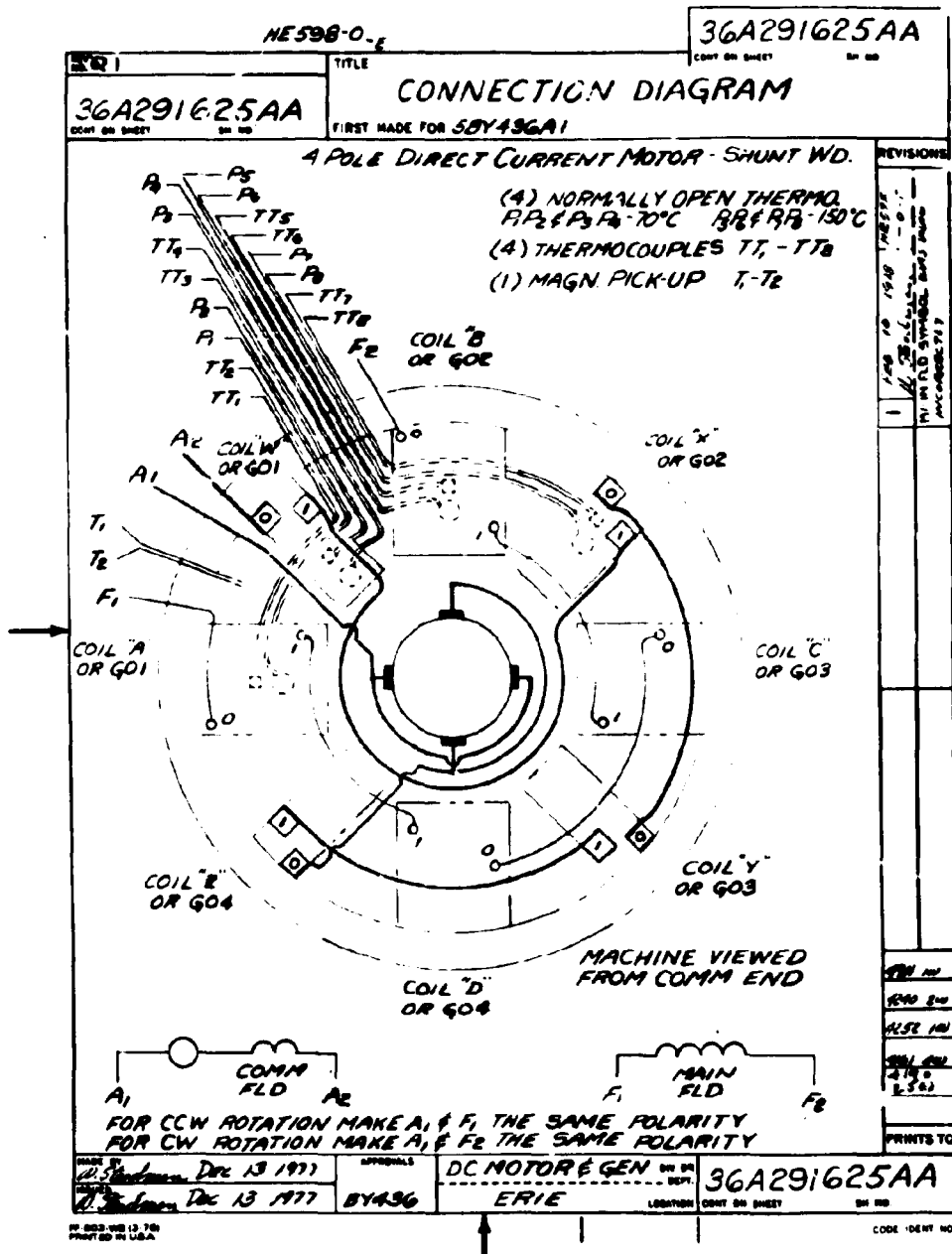


Figure 3.2.3-6. Connection Diagram

WBS 3.2.4 Armature Chopper

General Description

The armature chopper converts the fixed battery voltage into the variable voltage which is applied to the dc motor armature. The armature chopper maximum current ratings are 400 A delivered during motoring and 200 A returned to the battery from the motor during braking. Since power must be delivered in both directions (motoring and braking) a two-quadrant chopper is needed. A simplified diagram of the selected approach is shown in Figure 3.2.4-1. Power Darlington transistor Q2 and diode D2 form the voltage stepdown (motoring) chopper, while power Darlington Q1 and diode D1 form the voltage step-up (braking) chopper. Capacitor C_d provides the low input impedance required by the chopper. The nominal battery voltage E_d is 108 V. Inductor L_a , which smooths the motor current, is actually the motor armature inductance internal to the dc machine. When closed, contactor CC connects the traction battery to the armature chopper.

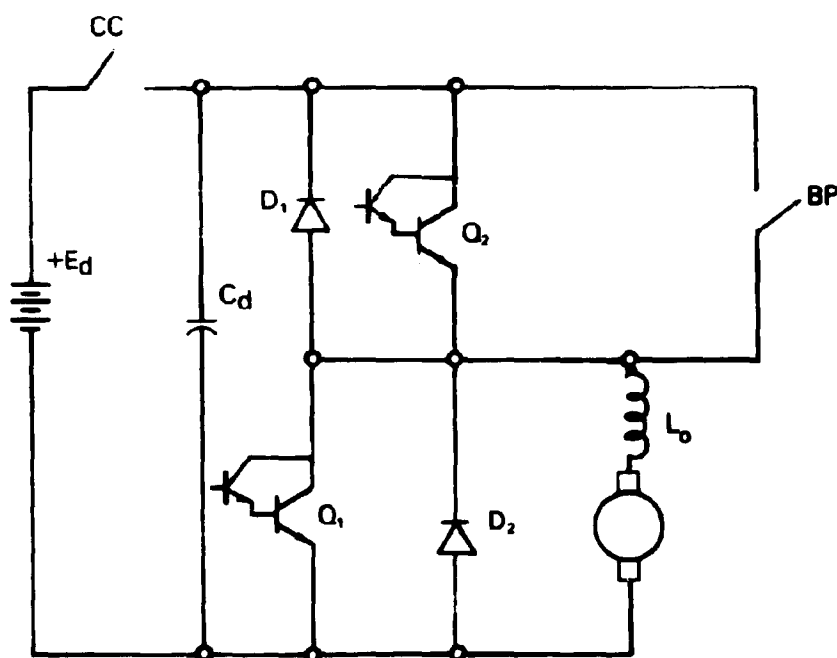


Figure 3.2.4-1. Two Quadrant Single-Phase Chopper

The armature chopper is controlled by the microprocessor. Interface electronics receive the microprocessor commands and control the armature chopper power circuit as illustrated in Figure 3.2.4-2. The interface electronics control the power Darlington base drive circuits which, in turn, switch the power Darlington transistors on and off.

A more detailed description of the armature chopper interface electronics is shown in Figure 3.2.4-3. A local fast-acting current limit provides virtually instantaneous protection against overcurrent for the power Darlington transistors. As seen in Figure 3.2.4-3, several key circuit parameters are sensed to insure proper chopper operation. If one of these parameters indicates a malfunction, an armature chopper malfunction signal is generated which opens the contactor CC, turns off the power Darlington transistors, and sends a signal

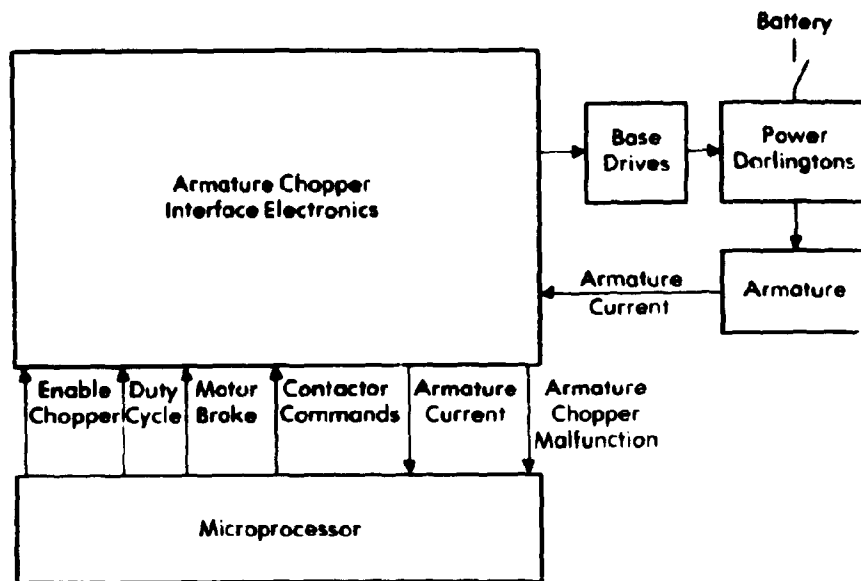


Figure 3.2.4-2. Armature Chopper -- Microprocessor Interface

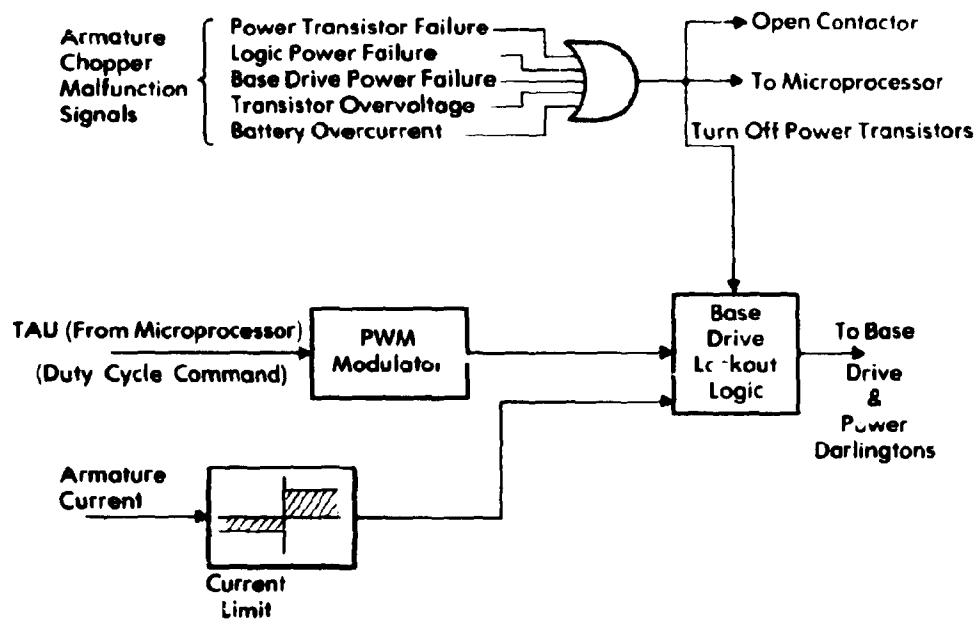


Figure 3.2.4-3. Interface Electronics

to the microprocessor. The PWM modulator in the interface electronics receives a duty cycle command (percent on time for the power Darlington) from the microprocessor and produces an on-off switching signal for the power Darlington. The PWM modulator is a variable pulse width, variable frequency control which implements a constant motor peak-to-peak ripple current control. The chopper frequency varies between approximately

100 to 2200 Hz depending on the duty cycle command. This will be described more thoroughly below.

The approach which has just been discussed was selected from several alternate approaches. The approaches which were considered are discussed below.

Armature Chopper Selection

Figure 3.2.4-4 shows the three alternate motoring chopper arrangements which were considered for the armature chopper. In the single-phase arrangement, an appropriate number of transistors are paralleled in order to switch the total current, while in a multiphase chopper, choppers are paralleled rather than transistors. In the multiphase chopper, the transistor switching is staggered in time so that the chopper input and output ripple frequencies are increased. Figure 3.2.4-5 shows that the multiphase chopper with m phases results in a considerable decrease in input ripple current (and hence rating of the filter capacitor C_d) as the number of phases increases.

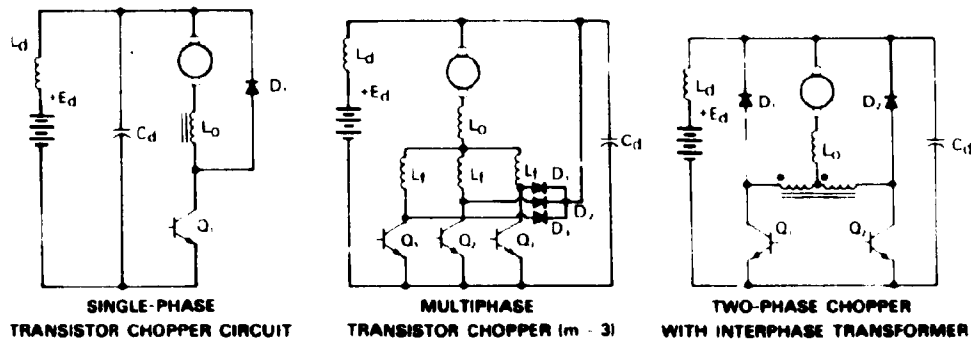


Figure 3.2.4-4. Candidate Armature PCU's (single quadrant)

A disadvantage of the multiphase chopper is that in order for each transistor to carry no more current than it would in a single-phase chopper, the total weight of the reactor L_f , compared with the weight of single-phase series reactor L_{f1} not shown in Figure 3.2.4-4) is given by

$$\frac{W_{m\phi}}{W_{1\phi}} = m^{-1/4} \left[1 + L_o/L_{f1} \right]^{-3/4}$$

where $W_{m\phi}$ is the total multiphase reactor weight and $W_{1\phi}$ is the weight of the single-phase series reactor. Thus, a three-phase chopper has approximately 32% more reactor weight than a single-phase chopper with equal peak transistor currents. However, the chopper output ripple current to the motor and the input ripple current are greatly reduced (the output peak-to-peak ripple decreases as $1/m^2$). In an effort to reduce the weights of the series reactors, a single core can be used, resulting in an interphase transformer arrangement as in Figure 3.2.4-4. However, since it is desirable to run the chopper at relatively low switching frequencies at certain operating points to minimize switching losses (as discussed in more detail below), the interphase reactor weight would be excessive.

Several designs were carried out for both a single-phase and multiphase chopper for various chopping frequencies. The designs are based on equal peak transistor currents.

m = NO. OF PHASES
 f_c = CHOPPER FREQUENCY
 I_0 = AVERAGE OUTPUT CURRENT

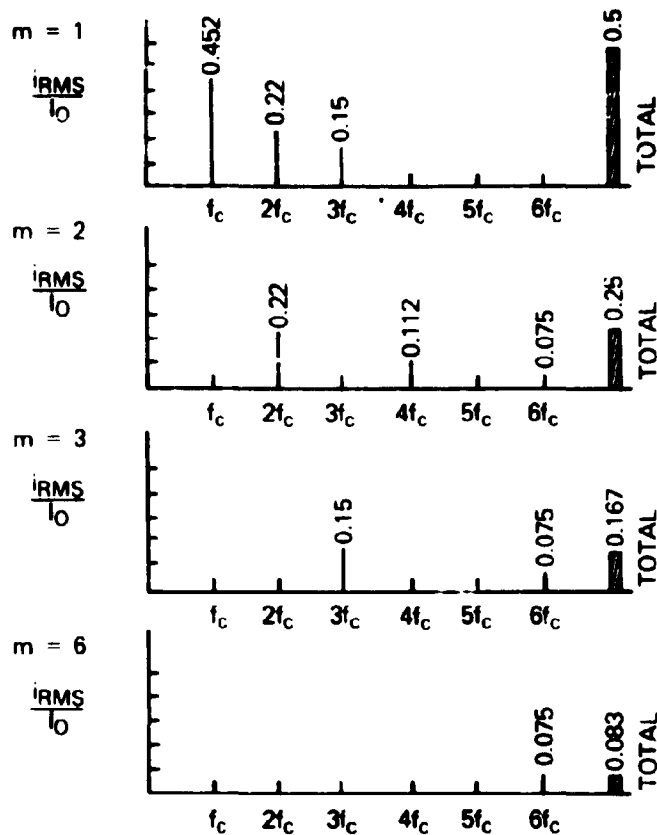


Figure 3.2.4-5. Multiphase Chopper Maximum Input Harmonics

The results in Figure 3.2.4-6 give total reactor weight as a function of unit chopper frequency for two different peak-to-peak ripple currents and for various chopper phases. A transistor chopper with a peak switching frequency of approximately 2000 Hz and with no series reactor was chosen as the minimum weight design. Even with increased input filter requirements for the single-phase chopper (~10 lbs of additional capacitance to handle the increased ripple current), a net savings of 37 lbs resulted compared to a three-phase chopper.

The modulator in the interface electronics operates such that the switching frequency is a parabolic function of duty cycle as shown in Figure 3.2.4-7. This type of control is a constant load ripple control whereby the chopper switches at its highest frequency only when needed (duty cycle = 0.5) to limit the peak transistor current (the maximum output ripple voltage occurs at a duty cycle of 0.5). At duty cycles other than 0.5, the

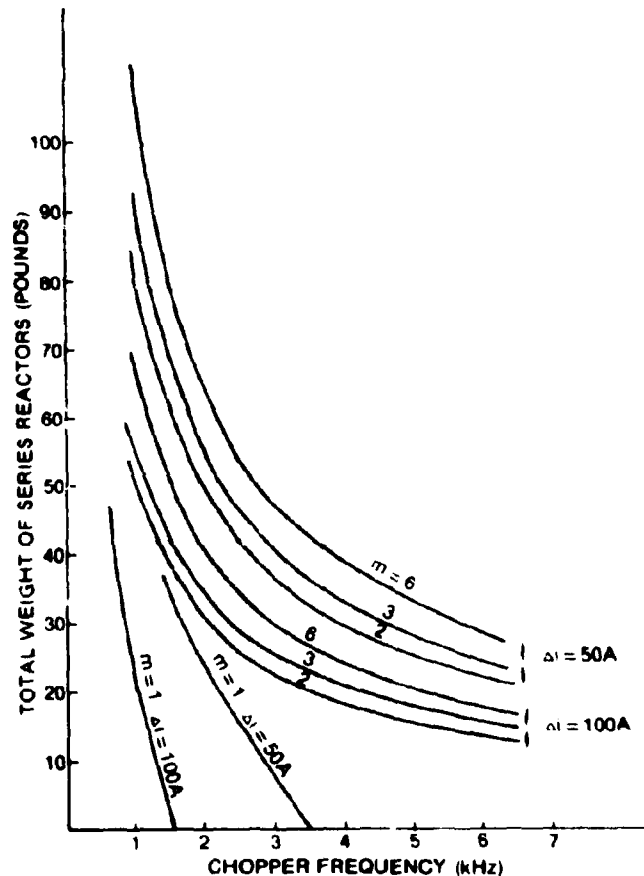


Figure 3.2.4-6. Total Weight of Series-Reactors vs Chopper Frequency for Various Peak-to-Peak Ripple Currents and Number of Phases

switching frequency is reduced to minimize switching losses. Also shown in Figure 3.2.4-7 is the computed chopper power loss as a function of duty cycle and chopper average output current, I_a , for a battery voltage of 100 V. The armature chopper is approximately 95% efficient over most of its operating range.

WBS 3.2.4.1 Detailed Description of Armature Chopper Electronics

(Refer to the detailed schematics at the end of this section during this discussion.)

Armature Chopper Power Circuit

Function. The armature chopper power circuit converts the fixed dc battery voltage into variable voltage to be applied to the dc motor armature. It is a two-quadrant chopper and therefore converts power in either direction (for motoring and braking respectively).

Circuit Description. The dc battery is applied (+BATT, -BATT) to contactor CC which, when closed, connects power to the armature circuit for conversion to variable voltage

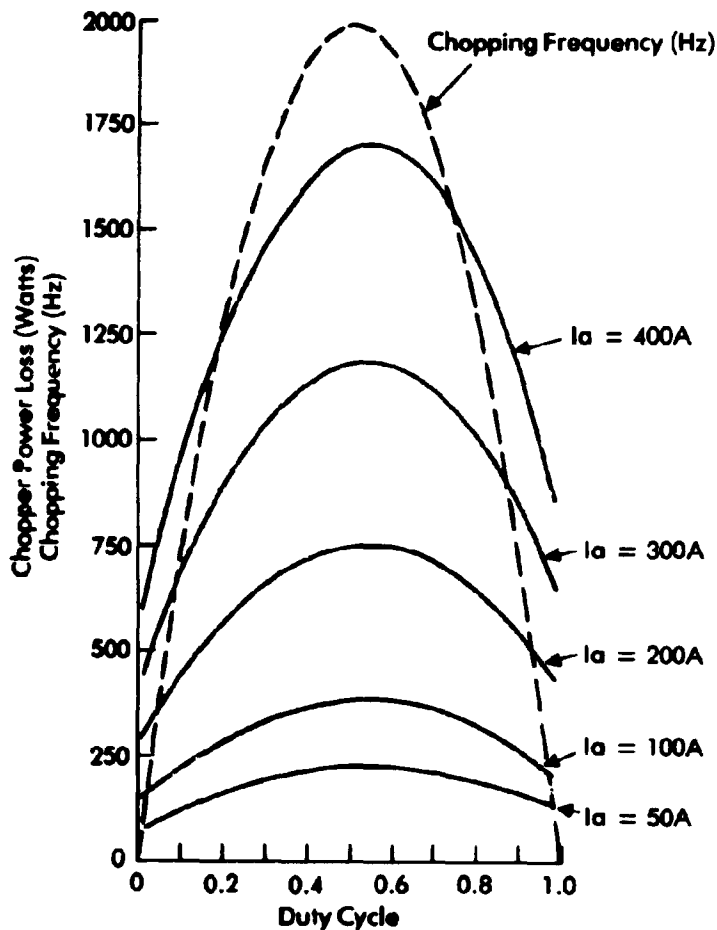


Figure 3.2.4-7. Armature Chopper Power Loss

armature power. The capacitor bank insures a low impedance dc source which is necessary to pass the high frequency (2200 Hz) current pulses drawn by the armature chopper and to reduce excessive voltage transients which would otherwise occur due to the battery cable inductance. In order to reduce the current inrush to the capacitor bank from the battery when the power circuit is first connected, a small relay CBC is first closed, which allows the capacitor bank to charge through R54. Once the bank has charged, CC is closed. R155, R156, R152, and R153 provide voltages proportional to battery voltage and capacitor voltage to the armature logic cards for use in controlling the closure of CC and CBC.

Once CC is closed, variable voltage is supplied by continuously switching parallel transistors Q1 and Q2 from the on to off state which applies an average voltage to the machine of magnitude:

$$E_m = E_d \frac{t_{on}}{t_{on} + t_{off}}$$

where E_m is the machine average voltage, E_d is the battery voltage, t_{on} is the transistor conduction time, and t_{off} is the transistor off time. The resulting motor current is triangular in shape due to the filtering action of the motor armature inductance (see Figure 3.2.4.1-1). When transistors Q1 and Q2 turn off, the inductive motor current circulates through the high-speed power diode in semimodule Q3 until Q1 and Q2 are turned on again. Thus, a rectangular wave of voltage alternating between +BATT and zero is applied to the motor.

When Q1 and Q2 approach the full on condition, contactor BP is closed (bypass mode), placing the battery directly across the motor armature. The armature current is then controlled by field current control.

To achieve electrical braking (regeneration) in the bypass mode, the field current is increased which causes current to flow out of the motor through BP, directly to the battery. When the motor voltage can no longer maintain a value equal to the battery voltage, contactor BP opens and the chopper, operating in the chopping mode, delivers power to the battery as follows.

When Q3 is turned on, the motor is effectively shorted and current builds up due to the machine counter-emf being applied across the motor armature inductance. When the transistor Q3 is turned off, the inductive current which is built up in the armature inductance flows up through the parallel diodes in modules Q1 and Q2 and into the battery. Thus, power is delivered to the battery by repetitively switching transistor Q3 on and off. The average motor voltage is given by

$$E_m = E_d \frac{t_{off}}{t_{on} + t_{off}}$$

where the times t_{on} and t_{off} refer to transistor Q3.

Each power transistor has a turn-off snubber connected from collector to emitter to decrease turnoff dissipation. For example C8 and D7 reduce the rate of rise of voltage across Q1 when Q1 turns off. When Q1 turns on, C8 is discharged through R6 and R7. R12 and C5 act as a snubber across D7 to reduce voltage spikes which are generated when D7 snaps off.

A turn-on snubber is also provided by L_1 , D10, and R15 through R24. When a power transistor turns on, L_1 limits the rate of rise of transistor current and limits the reverse current magnitude resulting from the reverse recovery current in the power module diodes. Diode D10 and resistors R15 through R24 allow a path for the current in L_1 when a power module transistor turns off. The current in inductor L_1 decays to zero in this path. A minimum off time control in the logic circuitry insures that a power module transistor is not turned on until the current in L_1 decays to zero.

Two current sensors are included in the armature chopper section. IS1 measures the battery current for use in fuel gauging. IS2 measures the actual motor armature current for use in the microcomputer current control feedback loop and for instantaneous armature chopper current limit. Resistors R30 and R31 act as a voltage divider and deliver a signal proportional to motor voltage for use in the transistor turnoff monitoring circuit on armature card 1.

The base drive power supplies receive the power via high frequency transformer T1 and T2. Electrolytic capacitors C1, C2, C3, and C4 mounted off the base drive card provide the major filtering for the low-voltage base drive power supplies. The details of the base drive circuits are described in the next section.

Figures 3.2.4.1-1 and 3.2.4.1-2 illustrate typical motor current waveforms which are delivered by the chopper to the motor for the stalled rotor condition. In Figure 3.2.4.1-2 the chopper is in local current limit. In this case, each time the motor current reaches approximately 400 A, the power Darlington's are turned off until the current falls approximately 80 A, at which time normal chopping is resumed.

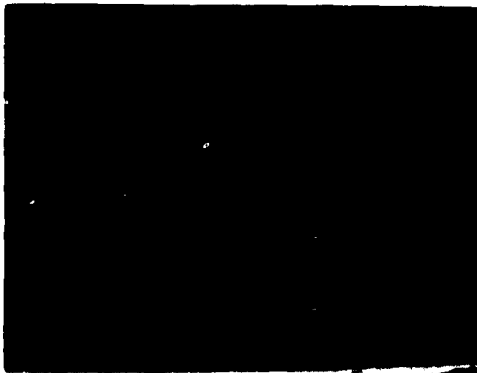


Figure 3.2.4.1-1. Typical Stalled Rotor Current 100 A/cm (zero at two divisions from bottom) Time: 1 ms/div



Figure 3.2.4.1-2. Typical Current Limited Motor Current 100 A/cm (zero at two divisions from bottom) Time: 5 ms/div

Figure 3.2.4.1-3 illustrates typical voltage and current input to the chopper for the case when the chopper is delivering approximately 250 A to a stalled rotor. Figures 3.2.4.1-4 and 3.2.4.1-5 give the collector-emitter voltage and base current waveforms (the base circuit will be discussed in the next section). In Figure 3.2.4.1-5, the voltage spike which results at power Darlington turnoff, is seen as well as the clamping action of power Zener diodes VR1 and VR2 which serve to limit the peak voltage applied to the power Darlington's to tolerable levels.

Dual Armature Base Drive

Function. The dual armature base drive card contains two base drive circuits - one supplies base current to the two parallel power module Darlington transistors while the other supplies base current to the single generating power module Darlington transistor. The base drive circuits are controlled from signals generated on armature card 2.

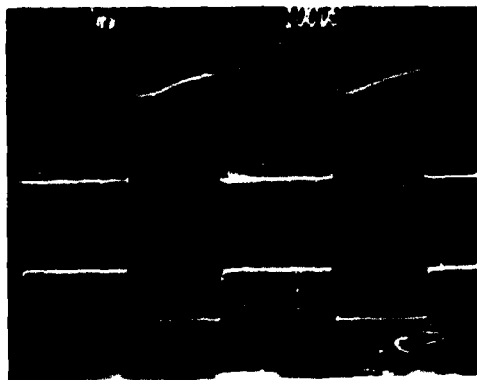


Top: 50 V/cm (zero at center line)

Bottom: 50 A/cm (zero at one line from bottom)

Time: 200 μ s/cm

Figure 3.2.4.1-3. Typical dc Input Voltage and Current Measured at Input to PCU



Top: 50 V/cm (zero at center line)

Bottom: 2 A/cm (zero at one division from bottom)

Time: 100 μ s/cm

Figure 3.2.4.1-4. Transistor Collector-Emitter Voltage and Base Current



Top: 50 V/cm (zero at one division below center line)

Bottom: 2 A/cm (zero at one division from bottom)

Time: 2 μ s/cm

Figure 3.2.4.1-5. Transistor Collector-Emitter Voltage and Base Current at Turnoff

Description of Operation (Numbers in parentheses indicate zones in the circuit schematics). Referring to the schematic diagram for the dual armature base drive card, the operation of the upper base drive circuit will be explained (the two base drive circuits are identical). A positive power supply of +8 V and a negative power supply of -4 V is established by rectifying the output of transformer T1 which obtains its power from an auxiliary winding on the logic power supply (F-10). The positive voltage is filtered by L1 and C2, while the negative voltage is filtered by R3 and C1. Additional filtering is supplied by electrolytic capacitors mounted off the card and connected to base drive card pins 45, 44, and 43 respectively.

To turn a power module transistor on, a 16 mA signal is injected into pins 2 and 3 of the opto-isolator IC (E-9) from armature card 2 via base drive card pins 30 and 31. This current causes the opto-isolator transistor to turn on, which in turn causes Q8, Q7, Q3, and Q1 to turn on and Q6, Q5, Q4, and Q2 to turn off. This action causes approximately 5.5 A to flow out of base drive card pin 47 and to the parallel transistor power modules (approximately 2.75 A to each module). (The current delivered to the single generating module from pin 37 is approximately 2.75 A.) When it is desired to turn the power module transistors off, the 16 mA delivered to the opto-isolator (card pins 30 and 31) is interrupted. This action causes the opto-isolator transistor to turn off, which causes Q8, Q7, Q3, and Q1 to turn off and Q6, Q5, Q4, and Q2 to turn on. These events cause the forward base drive current, delivered out of pin 47, to be interrupted and a negative base drive current pulse to be extracted from the power module Darlington transistors (which appears as current into base drive card pin 28). During the off time, transistor Q2 remains conducting, which applies a steady negative voltage of approximately -4.5 V to the power module Darlington transistor bases.

Figure 3.2.4.1-6 illustrates a typical base current waveform. Figures 3.2.4.1-7 and 3.2.4.1-8 illustrate the current fall (turnoff) and rise waveforms which should be observed at the power module Darlington transistor bases as measured by a Hall effect clip-on current probe. Any significant variations in the current rise and fall times indicate a malfunction.



Base Current to Each Motoring Module:

1 A/cm

10 μ s/cm

(zero at center line, zero at one division from bottom respectively)

Figure 3.2.4.1-6. Base Drive Waveform

Armature Card No. 1

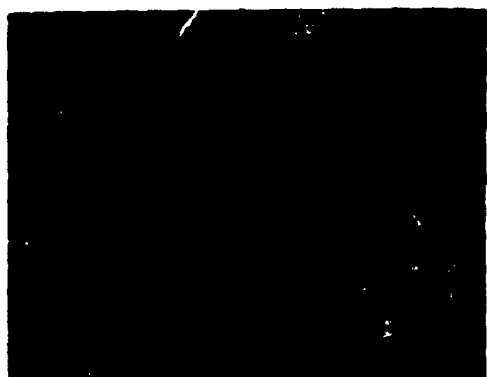
Function. Armature card 1 contains the pulse width modulation (PWM) modulator, current sensor amplifiers, local current limit circuitry, and some fault detection circuitry.



Top: 2 V/cm (zero at one division from top)

Bottom: 1 A/cm (zero at 3 div. from bottom)

Figure 3.2.4.1-7. Base-Emitter Voltage and Base Current at Transistor Turnoff



Top: 2 V/cm (zero at one division from top)

Bottom: 1 A/cm (zero 3 divisions from bottom)

Figure 3.2.4.1-8. Base-Emitter Voltage and Base Current at Transistor Turnoff

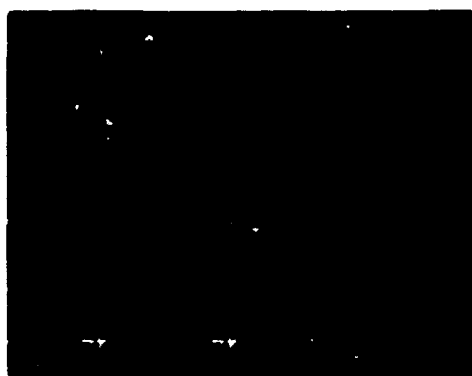
PWM Modulator (B-8) (The numbers in parentheses indicate zones in the circuit schematics.)

A negative-going-triangular waveform is generated at the output of integrator OA4 (and at TP1). This triangular wave is compared with the duty cycle signal, τ , by comparator OA6 which generates the ON-OFF signal which is eventually delivered to the armature base drive card. The duty cycle signal, τ , is received from the microcomputer at card pins 29 and 12 and inverted and filtered by OA3 before being delivered to comparator OA6. The triangular wave is generated with repeated discharge of the integrating capacitor C23 by turning on JFET transistor Q4 each time the integrator output reaches approximately -10 V. This is determined by comparator OA5 and the voltage reference set by potentiometer R53. Multiplier M1, in conjunction with resistors R47 and R48, causes the integration rate and therefore, the frequency, to vary as a function of the τ command. The constant ripple current control which results is such that the maximum modulator frequency of approximately 2200 Hz occurs at a 50% duty cycle ($\tau = 5$ V) while the frequency drops to lower values on either side of $\tau = 50\%$.

The modulator output is applied to AND gate E, pins 5, and 12 (E-6). AND gate E passes either a motoring base drive signal (IC-E pin 13) depending on the logic command received at card pin 26. Other signals at the input to IC-E may inhibit base drive signals from being sent as will be discussed below. The performance of the PWM modulator is illustrated in Figures 3.2.4.1-9a, b, and c.



a. 50% Duty Cycles



b. 15% Duty Cycles



c. 75% Duty Cycles

Triangle: TP1 output voltage
(card 1)

Straight line: Duty cycle input voltage
(pin 29, card 1)

Bottom: TP5, card 2

Figure 3.2.4.1-9. PWM Modulator Performance

Armature Current Amplifiers (F-10, F-9). A +7 volt power supply for the armature current sensor is generated by Zener diodes D1 and D2 (G-11). The differential output of the armature current sensor is received at card pins 36 and 26 and amplified by differential amplifier OA1 (the output of which appears at TP4). The output of OA1 is used in the instantaneous current limit circuitry to be described below and is also applied to isolation amplifier IA1, the output of which is delivered to the microcomputer to be used in the armature current control loop.

Current Logic (F-7). The current logic has two functions. First, it prevents the motoring power transistors from being gated when the motor current is in the generating direction

(i.e., when i_a exceeds approximately 33 A in the generating direction). This function is accomplished by OA8, which inhibits base drive via pin 2 of IC-E. Conversely, when the motoring current exceeds approximately 33 A, the generating power transistors are prevented from being gated by OA7, acting in conjunction with pin 10 of IC-E.

The second function of the current switching logic is to inhibit the transistor turn-off monitoring circuit (C-5) via gate G (pin 5 and 12) when the current drops below approximately 33 A. This action is needed since the transistor turnoff monitoring circuit would inadvertently indicate a fault at near zero armature current (proper operation of this circuit depends on continuous armature current). Thus, the current logic enables the transistor to monitor the circuit only after continuous armature current is assured.

Current Limit (F-6). A local fast-acting current limit is provided in addition to the microcomputer current feedback control loop. If the armature current exceeds approximately 415 A motoring current, OA9 changes state and holds off the power transistors independent of the microcomputer command until the armature current falls below approximately 335 A, at which point the armature current again will follow the armature current command from the microcomputer. The action of OA10 is the same for the generating case, except that the peak current limit value is set at approximately 240 A peak. The outputs of OA9 and OA10 go off card and return to card pin 26, inhibiting power transistor base current through pins 4 and 11 on IC-E (E-6).

Battery Current Amplifiers (D-9, D-10). The outputs from the battery current sensor are input to card pins 21 and 37 and amplified by OA2. The output from OA2 goes off card (card pin 28-30) as an overcurrent shutdown signal for the armature chopper. The output of OA2 is also amplified by isolation amplifier IA2 and sent to the microcomputer to be used for fuel gauging.

Transistor Turnoff Monitoring Circuit (C-5). This circuit checks to see if a power module Darlington transistor, which has been commanded to turn off, has indeed turned off. If a turnoff has not been accomplished, a fault signal is delivered from either pin 1 or 13 or IC-G (C-4). The function is accomplished by sensing the motor-to-ground voltage which alternately switches from zero to positive battery voltage as the power module transistors switch. OA11 alternately switches from logic high to logic low as the transistors switch. The output of OA11 serves to prevent the outputs of IC-G from sending a shutdown signal if the power module transistors have turned off properly. Since the power transistors will not immediately turn off when commanded due to their minority carrier storage times, the shutdown signal is temporarily blanked by a 50 μ s pulse coming in on card pin 7 or 25 each time a transistor turnoff command is given. If, after that time, OA11 is not in the proper state (i.e., a power module transistor has failed to turn off), a shutdown signal is sent out on card pin 24 or 8, which opens the armature contactor. As stated earlier, this shutdown signal is completely disabled by the current logic (F-7) if the armature current is less than approximately 32 A, because proper indication by OA11 of the state of the power transistors depends on continuous armature current.

Armature Card 2

Function. Armature card 2 contains the circuitry which interfaces the PWM modulator with the base drive circuitry, several fault detection circuits and opto-isolators which receive the motor/generate signal and the armature chopper enable signals.

Base Drive Interface Circuitry (F-6 through F-8). The power module on/off signal from the PWM modulator is received at card pins 7 and 24 and input to IC-A. The signal is inverted, filtered, and inverted again by IC-A. Note that only one input to IC-A should

be commanding positive power transistor base current at any one time (i.e., only pin 1 or 5 of IC-A should be positive). To insure against simultaneous motoring and generating transistor conduction (which will short the battery bank), flip-flop B is used which will not allow IC-B pin 9 and 6 to be low (i.e., positive base current) simultaneously.

Since a power module transistor will not turn off instantaneously when it is commanded due to its minority carrier storage time, a delay is built in which prevents the opposite power transistor from turning on until the off-going device is insured of being in the off condition. This is accomplished by monostable multivibrators OS#1 and OS#2 (G7 and F7) which inhibit the opposite gate B from requesting a positive base current for approximately 50 μ s after each transistor turnoff command.

The output of each monostable is also coupled back to pins 3 and 9 of IC-A respectively through diodes. This connection acts as a constant power Darlington transistor off-time control ($\approx 50 \mu$ s). This constant power Darlington transistor off-time allows time for the turn-on snubber in the power circuit to reset for the next turn-on for all operating conditions. The monostable outputs on pin 7 and 9 of IC-I are delivered to card pins 44 and 45 for use on card 1 in the transistor turnoff monitoring circuit. The base drive signals are amplified by Q8 and Q7 (G-6) and Q10 and Q9 (F-6) respectively which deliver current to the opto-isolators on the base drive card.

Opto-Isolators (F-9). The opto-isolators located at F-9 interfacing the microcomputer motor/generator and armature chopper, enable commands to the armature chopper.

Contacting Control (B-5). The opto-isolators at B-5 receive their commands from the microcomputer and cause the main contactor (CC) or the bypass contactor (BP) to close via the coil drives on card 3.

Capacitor Bank Charging Sense (G-4). The comparator at G-4 senses the battery voltage and the capacitor bank voltage and inhibits the contactor CC from being closed until these two voltages are approximately equal (i.e., until the capacitor bank is charged).

Fault Flip-Flop (E-6). The fault flip-flop, if reset (IC-B pin 10 high), opens CC (or prevents it from being closed) and turns off the power module transistors. A signal is also sent to the microcomputer on card pins 19 and 40 (D-3) to indicate the status of the fault flip-flop. The flip-flop is set at power up via IC-H (C-4) and RC timer R115-C53. For test purposes, the fault flip-flop may be set by pushbutton S1 mounted on card 2. Once the fault flip-flop has been reset by a fault, it can only be set by shutting down and powering up again or, for test purposes, by pushing and releasing S1. There are several fault conditions which are sensed and which will shut down the armature chopper (i.e., open CC, turn off the power transistors, and send status to microcomputer). These faults are discussed below.

Total Transistor Voltage (E-8). If the total voltage applied to a power module transistor exceeds approximately 300 V as sensed by comparator OA11, the fault flip-flop is reset.

Battery Overcurrent Shutdown (D-8). If the current from the battery exceeds 500 A, comparator OA12 indicates a fault and resets the fault flip-flop.

Overtemperature Shutdown (C-10). A contact closure between pins 38 and 21 will reset the fault flip-flop and shut the drive down. A thermostat or other contact closure may be used. At present, no signal is input, and jumper E3-E4 is connected. If a signal is to be applied, jumper E3-E4 should be replaced with a 1k Ω , 1/4 W resistor. Gate D at C-10 also receives signals from the transistor turnoff monitoring circuit.

Loss of Base Drive Shutdown (C-8). The 36 V ac winding which delivers power to the base drive circuits is input to card pins 18 and 34, transformed, rectified, and sensed by comparator OA13. If the 36 V is not of proper value, the output of OA13 goes high, resetting the fault flip-flop.

Logic Power Supply Sensor (C-7, C-6, and C-5). The transistor and Zener diode arrays keep Q16 conducting only if the three logic power supply voltages (+12, +15 V) are above tolerable values. If a logic power supply fails, Q16 will be turned off causing the fault flip-flop to reset. Note that the commands to the base drive circuits are routed through transistor Q15 (C-4). Thus, turn-on commands are prevented from being sent to the base drive circuits during power up before the logic power supplies reach their tolerable values. In the event of a logic power supply failure, base drive turn-on signals are immediately interrupted.

Bypass Contactor Closure Inhibit (A-9). When the armature chopper is in the chopping motoring mode, it is desired to inhibit the closure of the bypass contactor if an inadvertent closure command is given. This function is accomplished by monostable L (A-9) which runs in the retriggerable mode. As long as a transistor chopping signal is present on IC-B pin 9 (F-7), the monostable is continuously triggered and remains in the timing mode while pin 9 of IC-L remains low. This signal acting with gate M (IC-M, pin 13) inhibits the bypass contactor from closing. When the chopping signal stops (i.e., when the chopper is full on), the monostable times out and the contactor command can pass through gate M, pin 12.

Inhibit Transistor Turn-Off Monitoring Circuit. When the bypass contactor closes, the transistor turnoff monitoring circuit on card 1 inadvertently registers a fault (the bypass contactor closure appears as a transistor short to this circuitry). Therefore, this fault indication must be inhibited during the time that the bypass contactor is closed and for a short time after the bypass contactor open command is given (to allow for the contactor dropout time). This function is accomplished by IC-L (B-9) and gate M. Whenever a bypass contactor closure command is given, the transistor monitoring circuit is shut down by holding the cathodes of diodes D low (A-10). This line is held low for approximately 675 ms (as determined by IC-L) after the command to open.

Armature Card 3

Function. Armature card 3 contains the contactor coil drivers for contactors CC and BP as well as the coil driver for relay CBC. The battery voltage is also sensed and processed for use by the microcomputer in fuel gauging and battery charging.

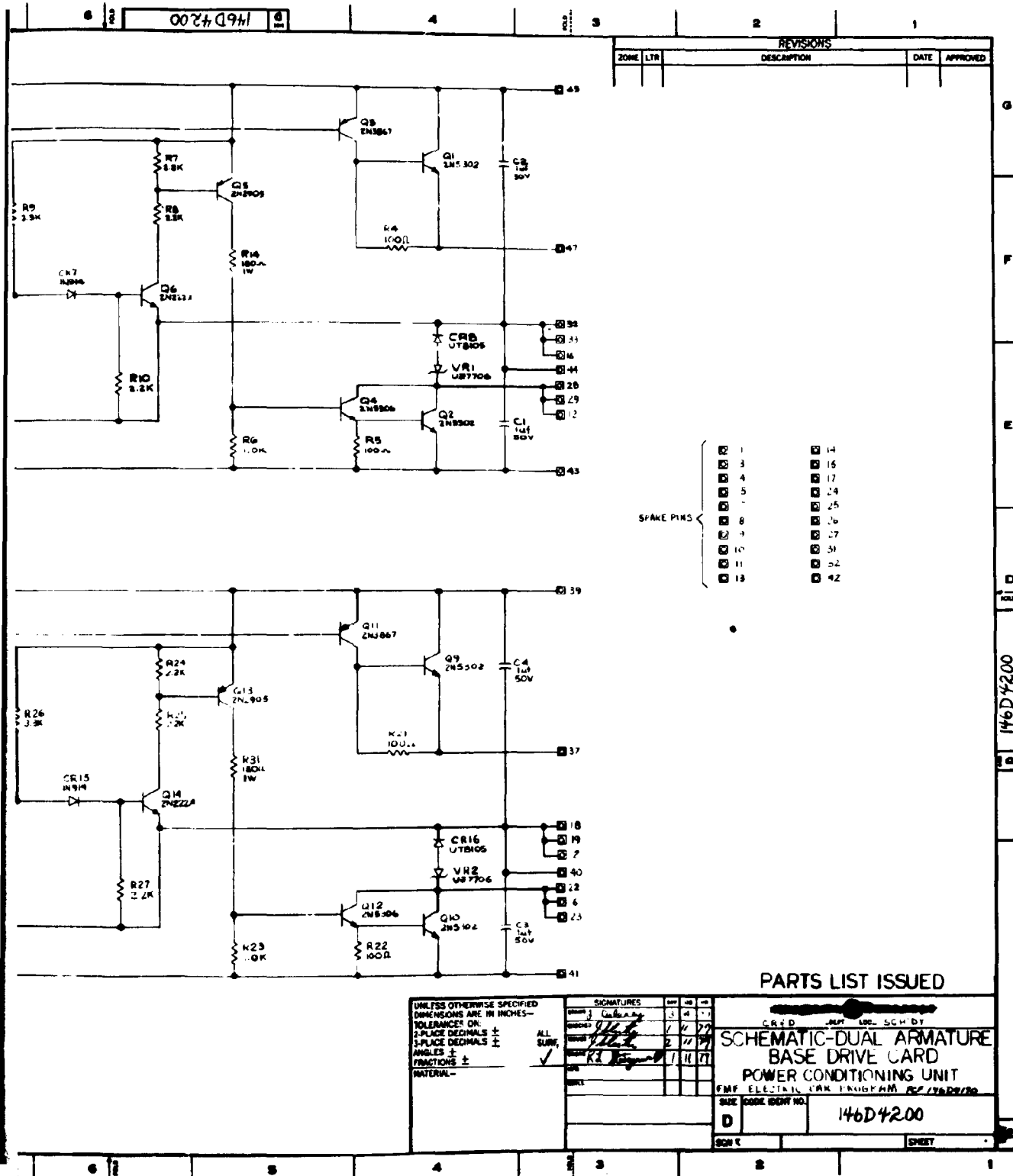
Contactor Drivers (C-7, D-7 and E-7). When turned on, transistors Q22, Q23, and Q24 cause contactors CC, CB, and BP to close, respectively. Each transistor is shunted by a varistor to limit the collector-emitter voltage when the transistor turns off. The gate J performs the logic necessary to perform the capacitor bank charging function (with comparator OA18 on card 2).

Battery Voltage Sensor (E-5). The propulsion battery voltage is divided by voltage divider R135 and R136 and amplified by OA15, the output of which is used in the circuitry described below.

Battery Undervoltage Detector. If the battery voltage falls below approximately 80 V, comparator OA17 turns on Q18, closing relay R, which lights a dash warning light.

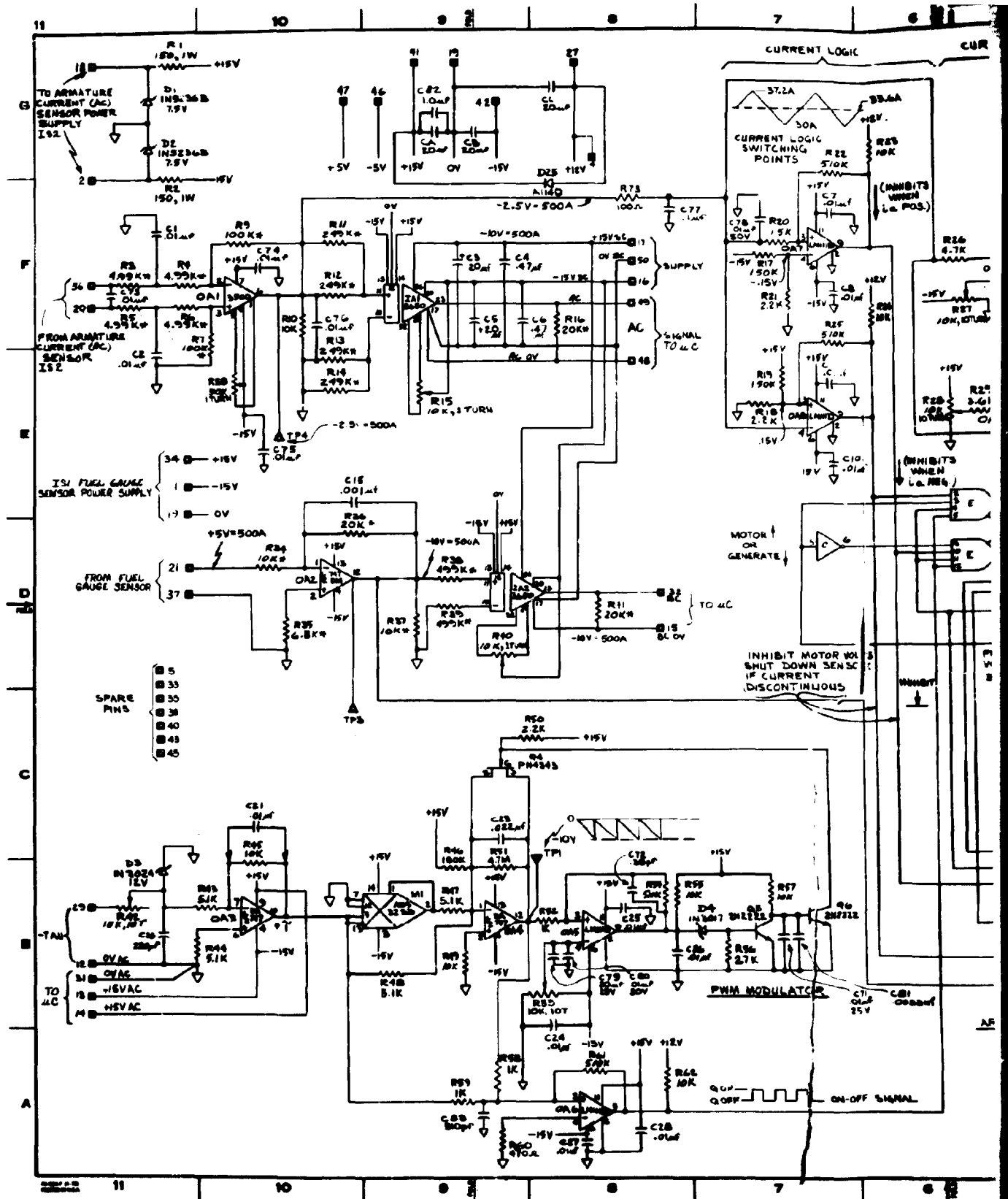
Battery Voltage - Fuel Gauging (E-4). OA16 and IA4 provide the required offset and isolation of the battery voltage signal which is sent to the microcomputer for use in the fuel gauging algorithm.

Battery Voltage - Battery Charging. The required offset and isolation of the battery voltage signal is provided by OA14 and IA3 before being sent to the microcomputer for use in the battery charging algorithm.



ature Base Drive Schematic

3.2-39/40



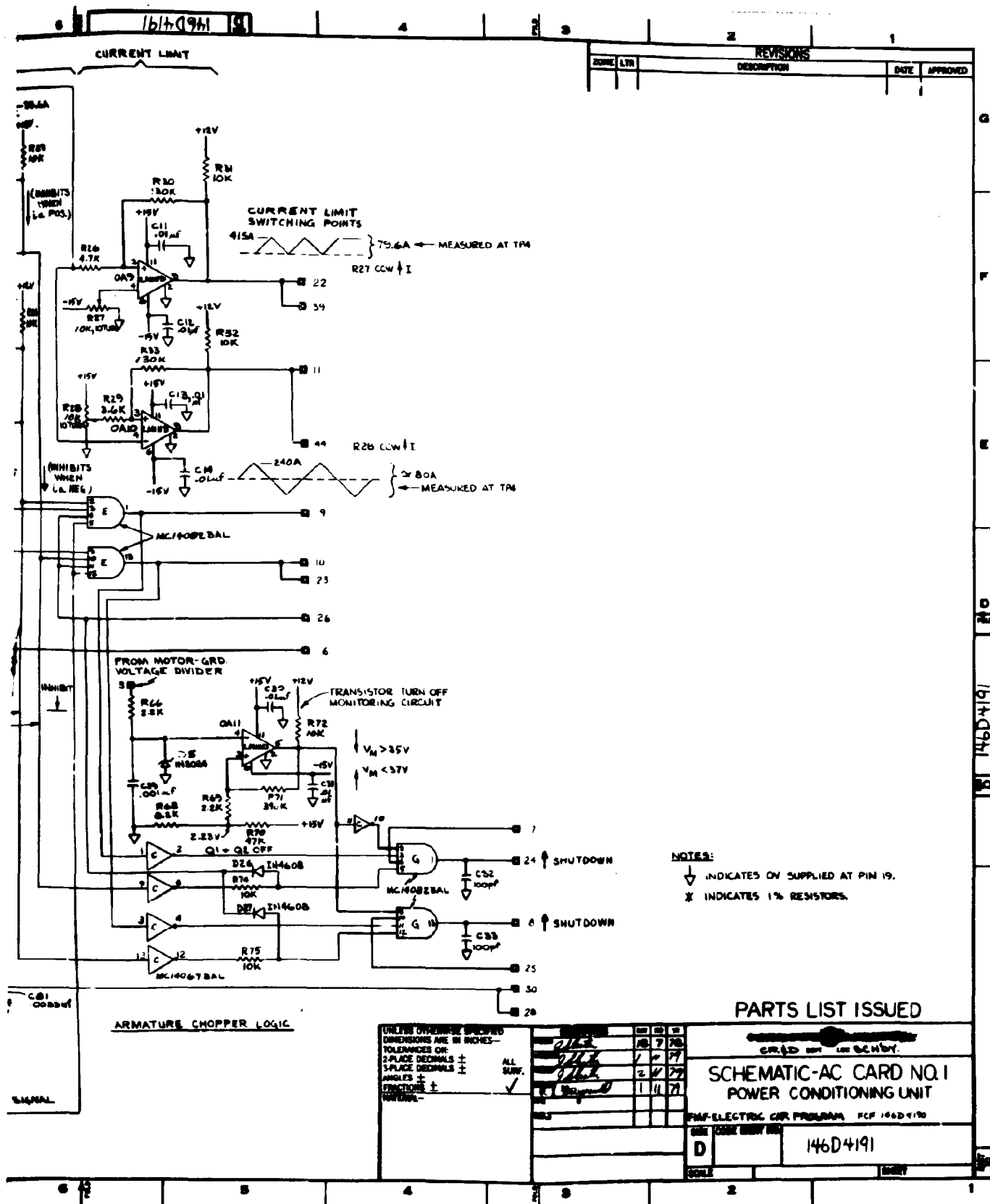


Figure No. 1 Schematic
3.2-41/42

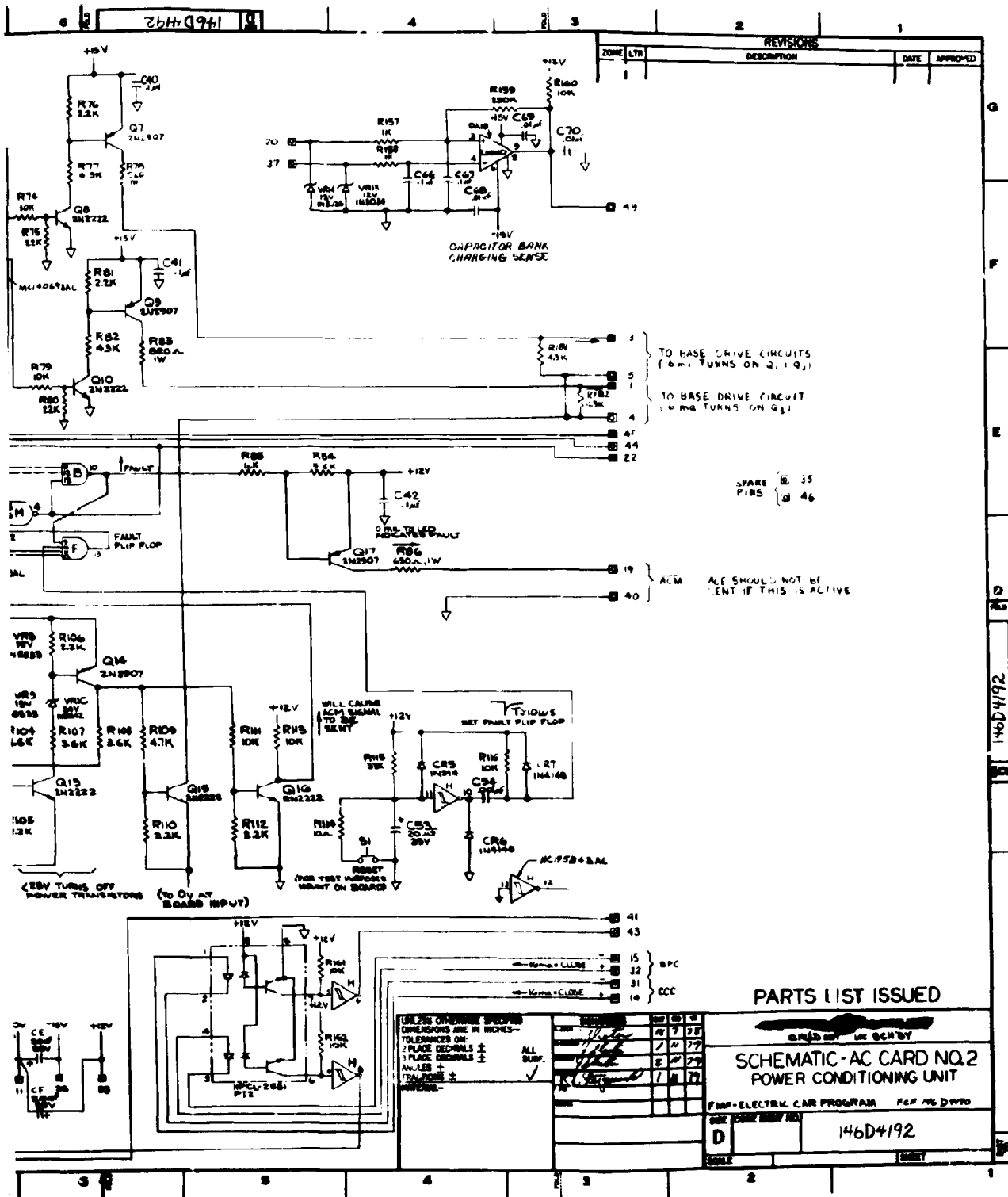


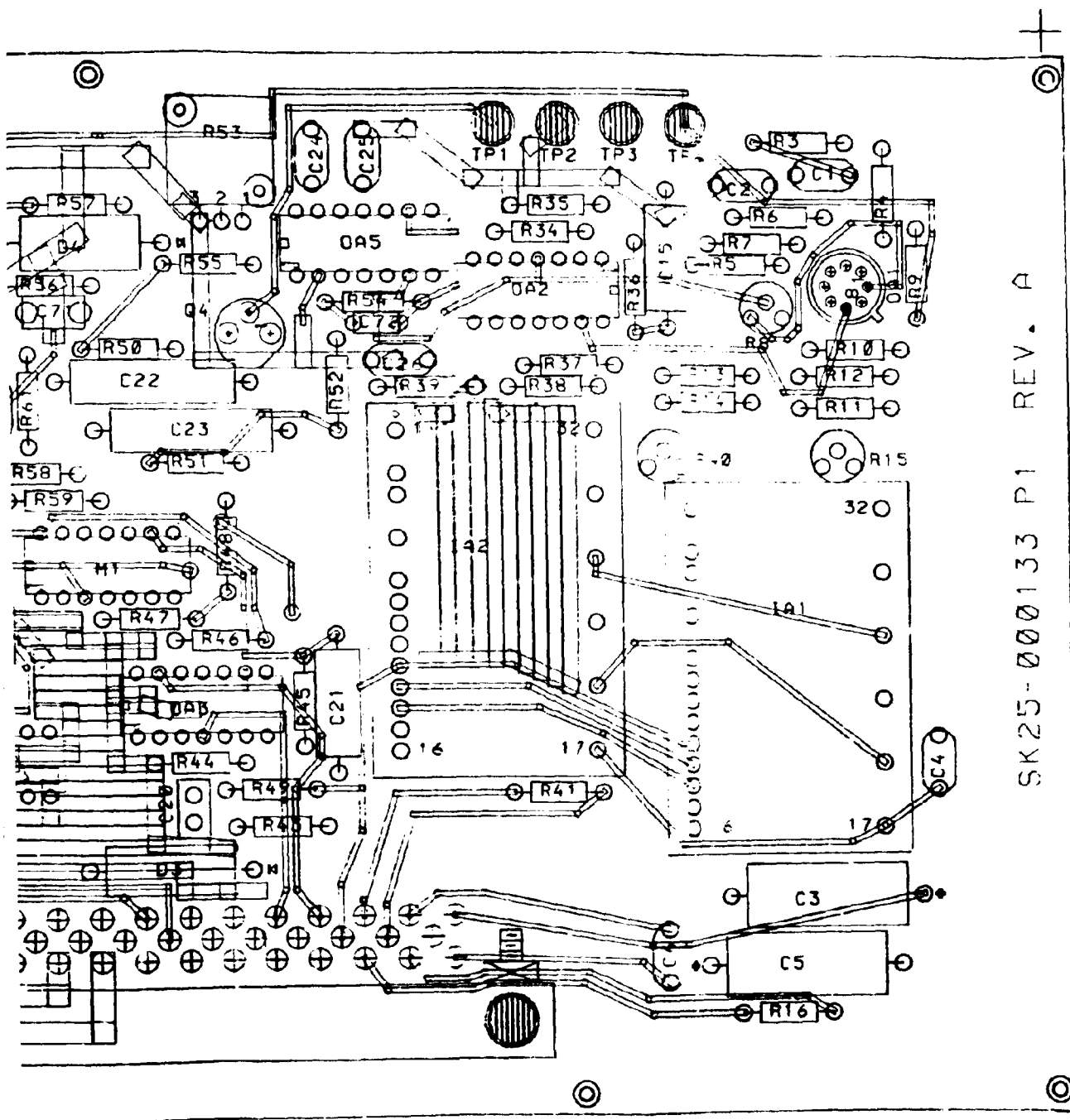
Figure No. 2 Schematic

3.2-43/44



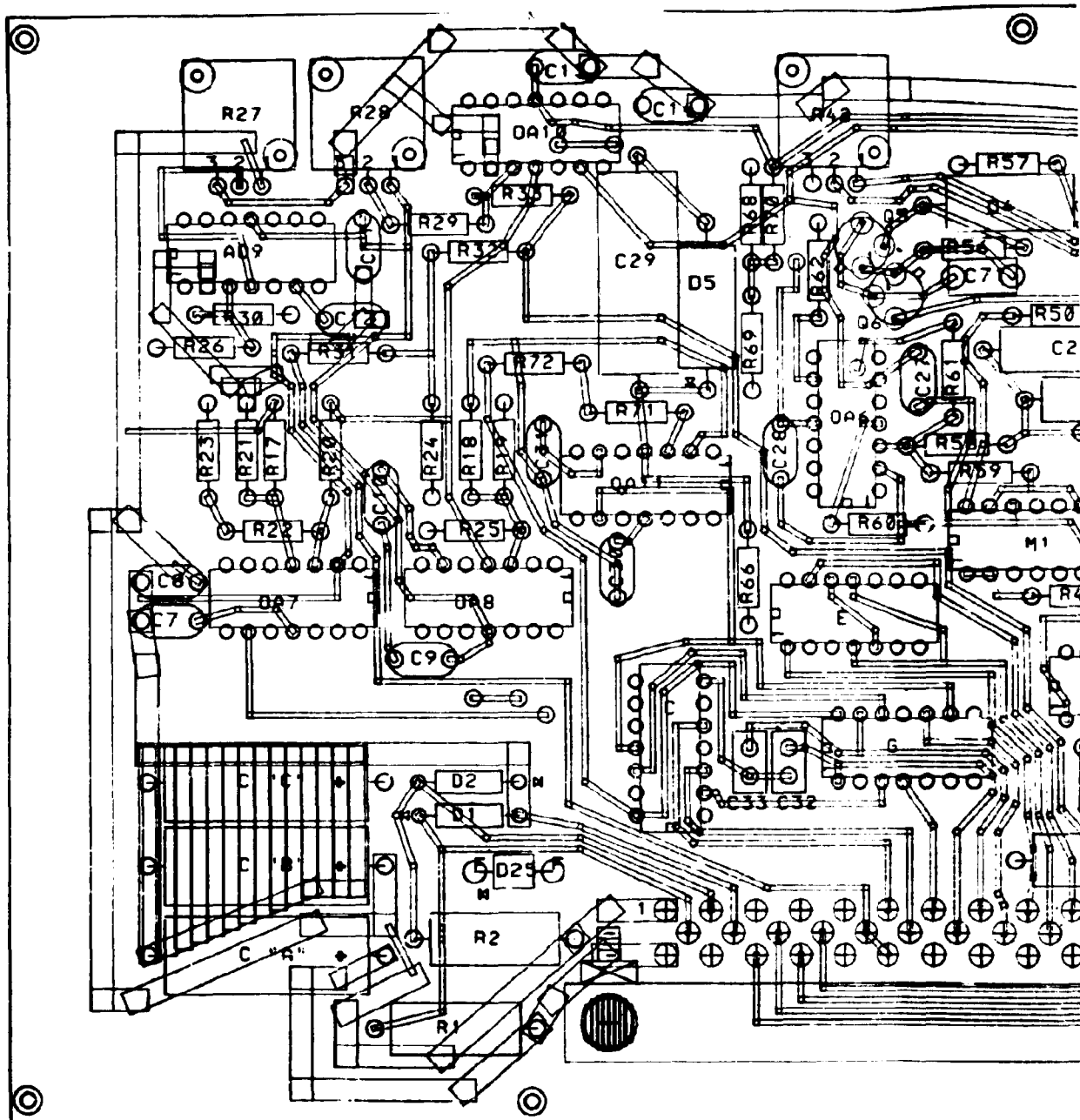
3.2-45/46

3.2-47/48



SK25-000133 P1 REV. A

1 REV A COMP. SIDE



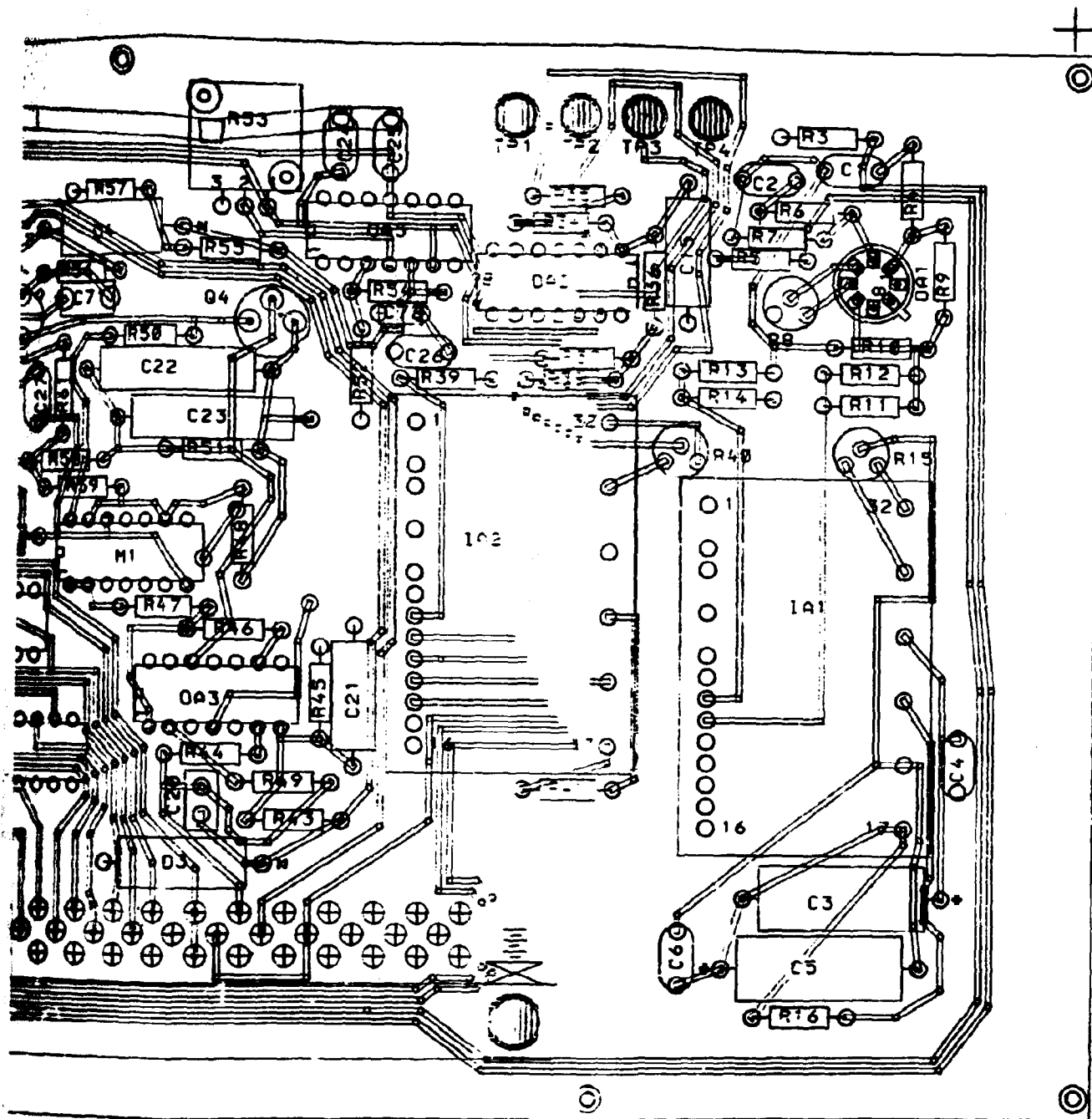
+

SK25-000133 P1 RE

15 DEC 78

Armature Chopper Card No.

3.2-51/52



P1 REV. A LEAD SIDE

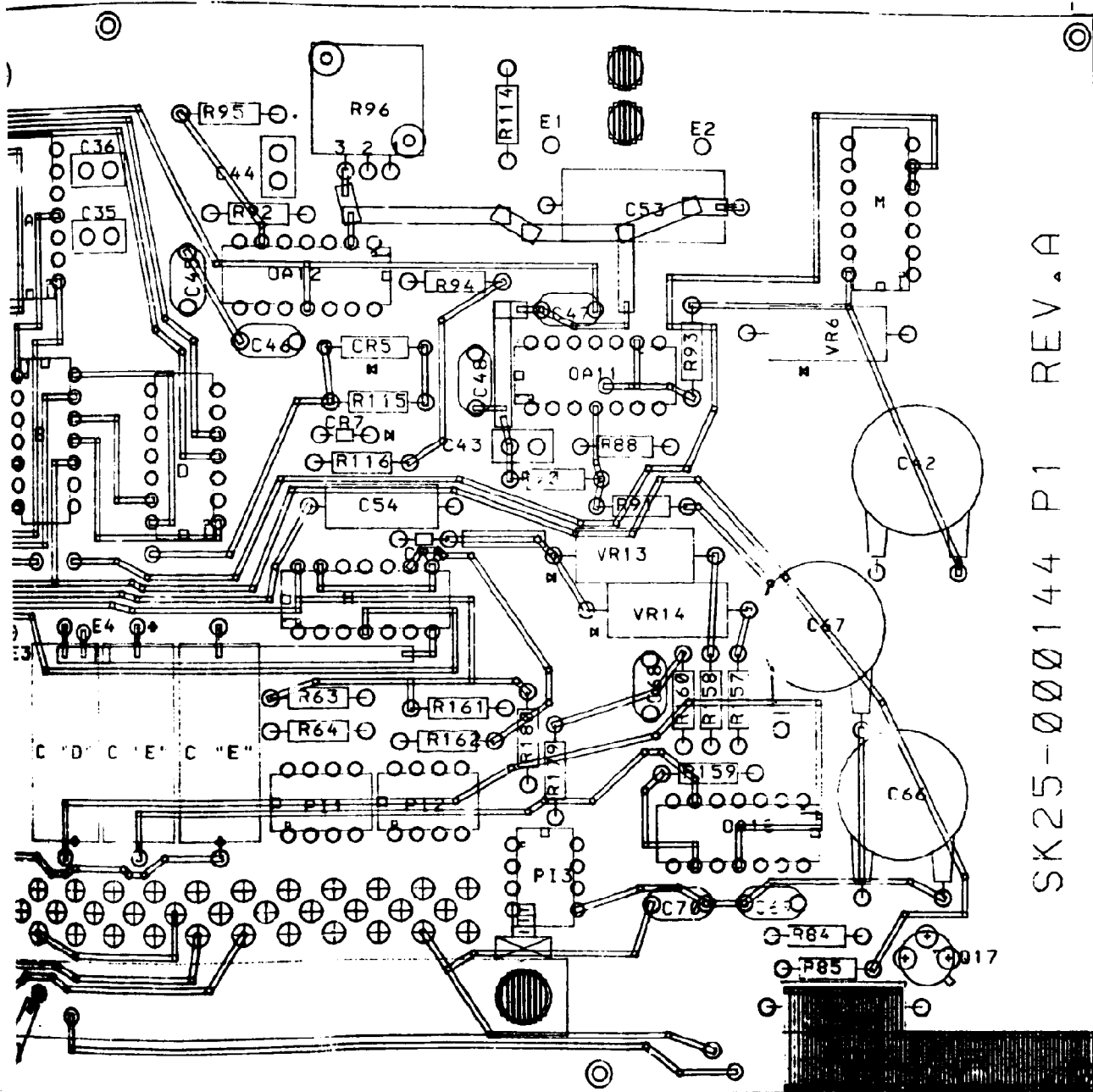
78

Chopper Card No. 1, Lead Side

22-51/51

Armature Chopper Card No. 2,

3.2-53/54

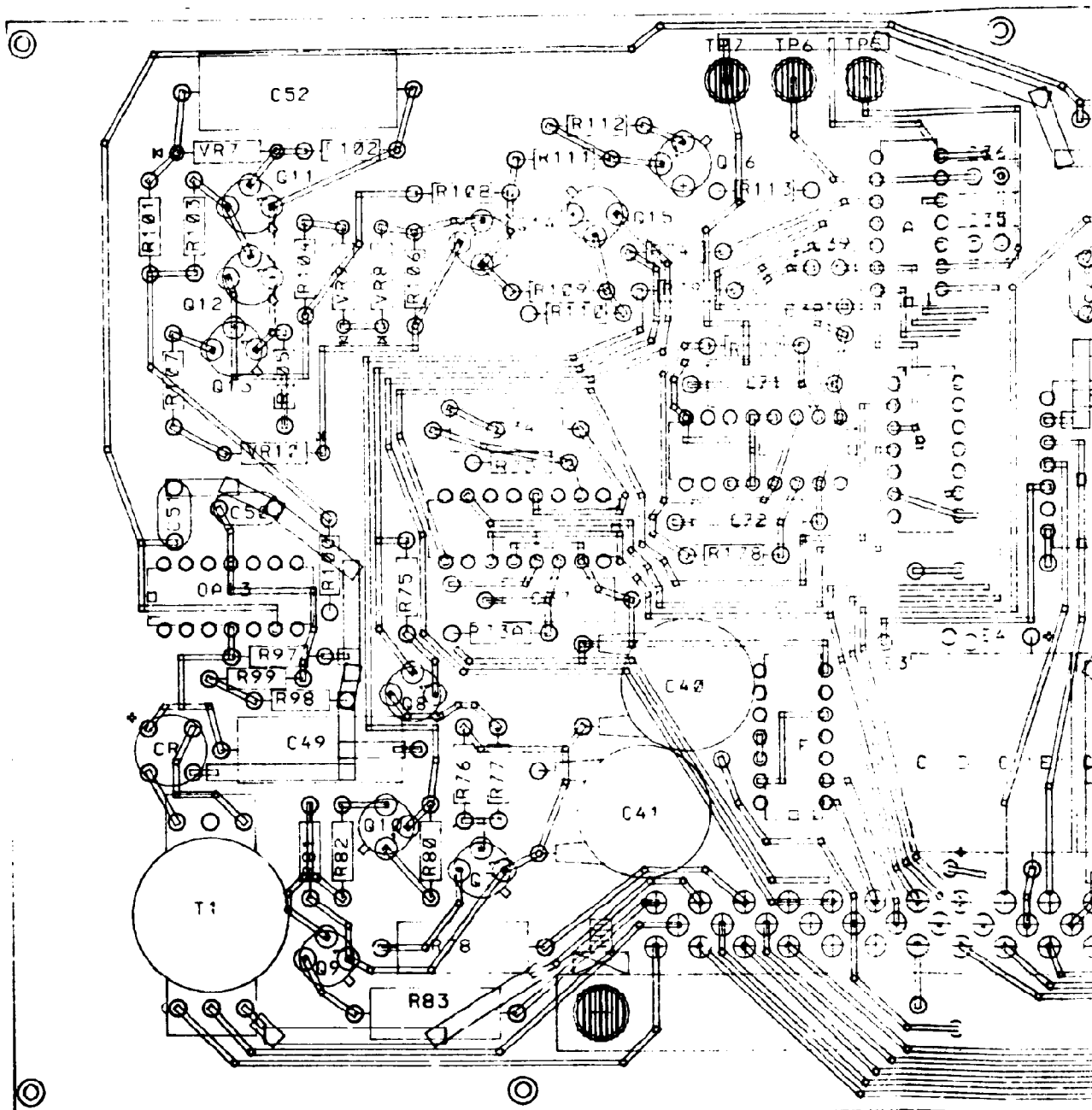


SK25-000144 P1 REV. A

REV. A COMP SIDE

Upper Card No. 2, Component Side

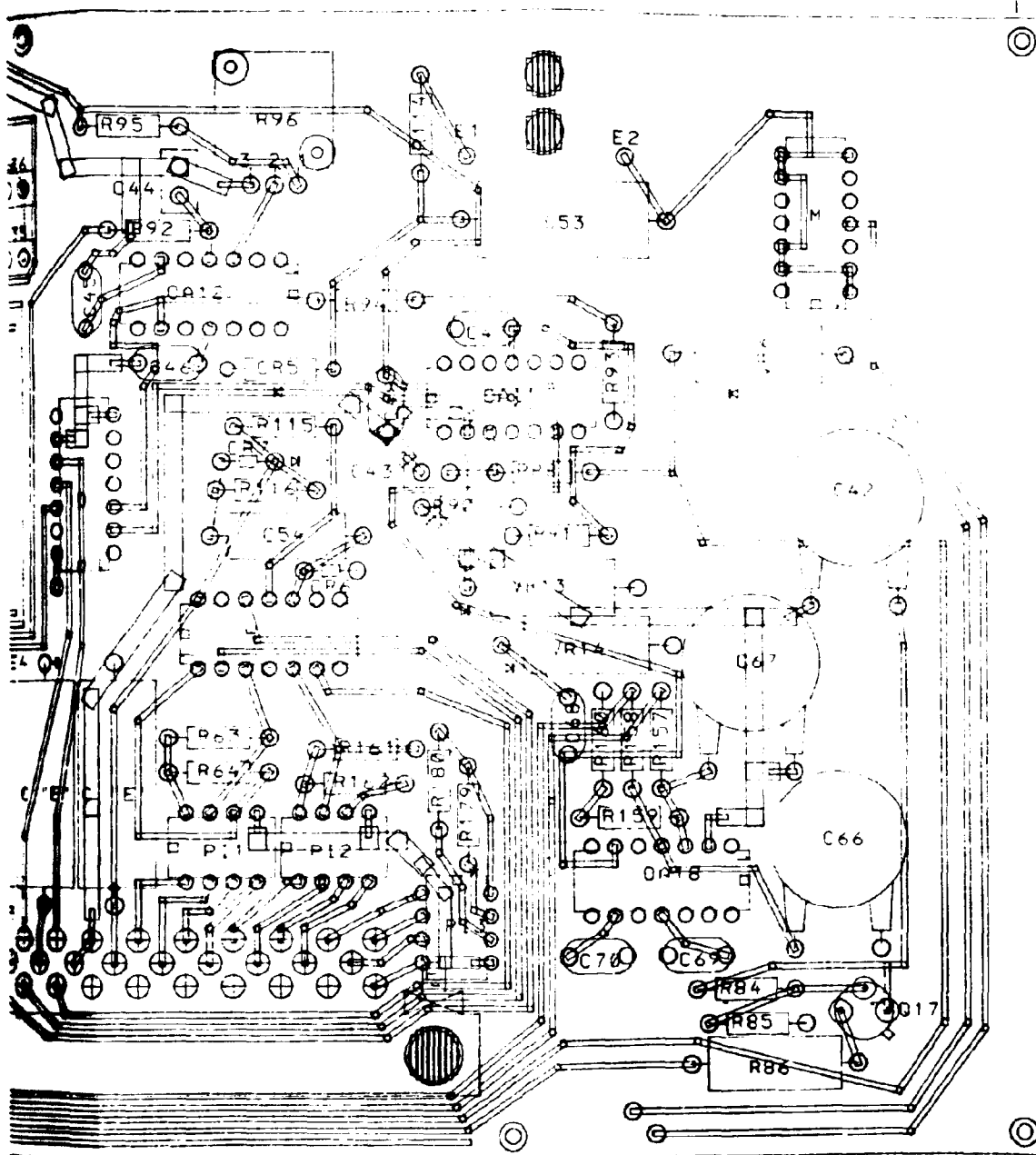
2.2-23/54



SK25-000144 P1 REV

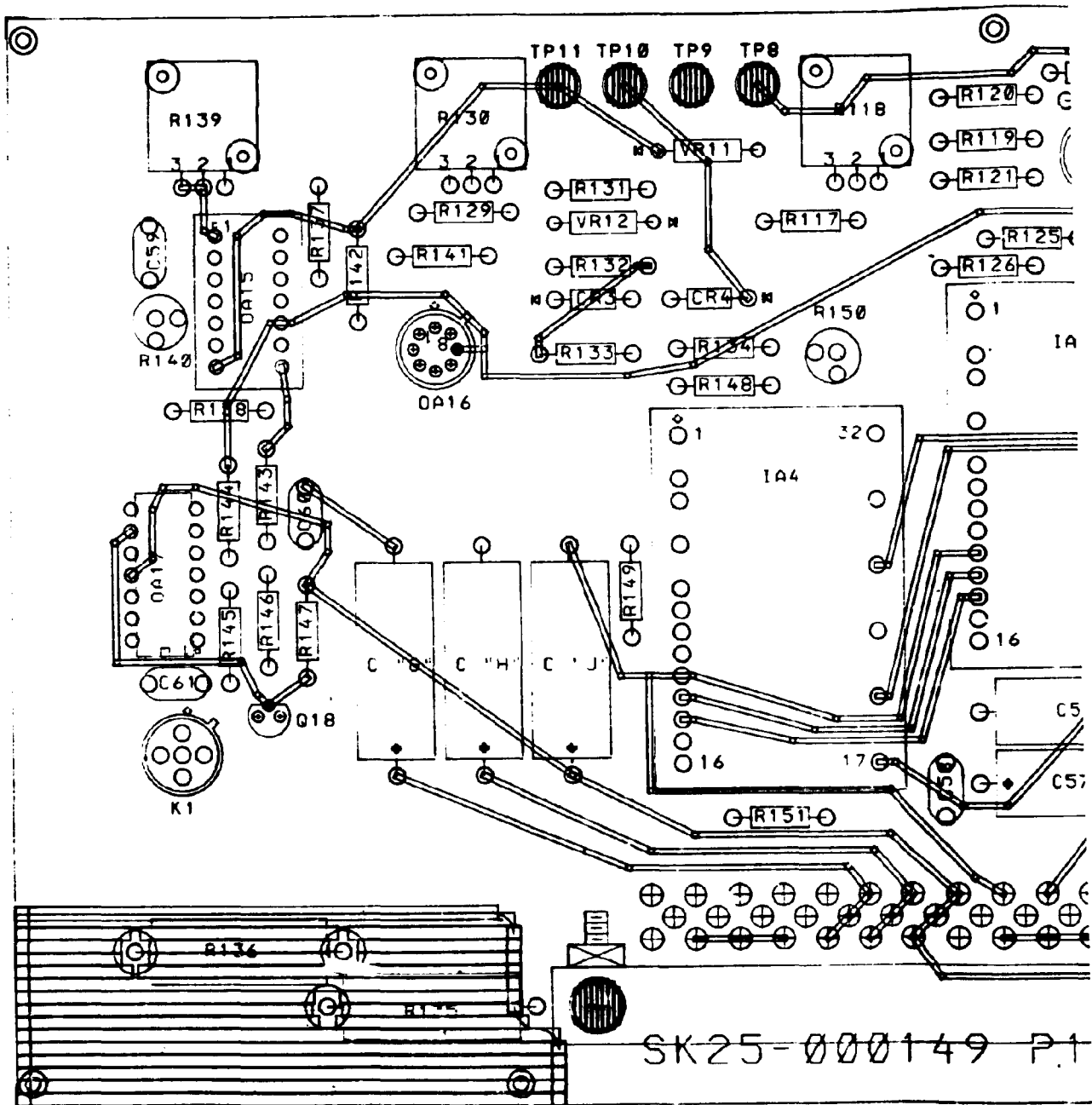
Armature Chopper Card No. 2, I

3.2-55/56



REV A LEAD SIDE

Rev A, Lead Side



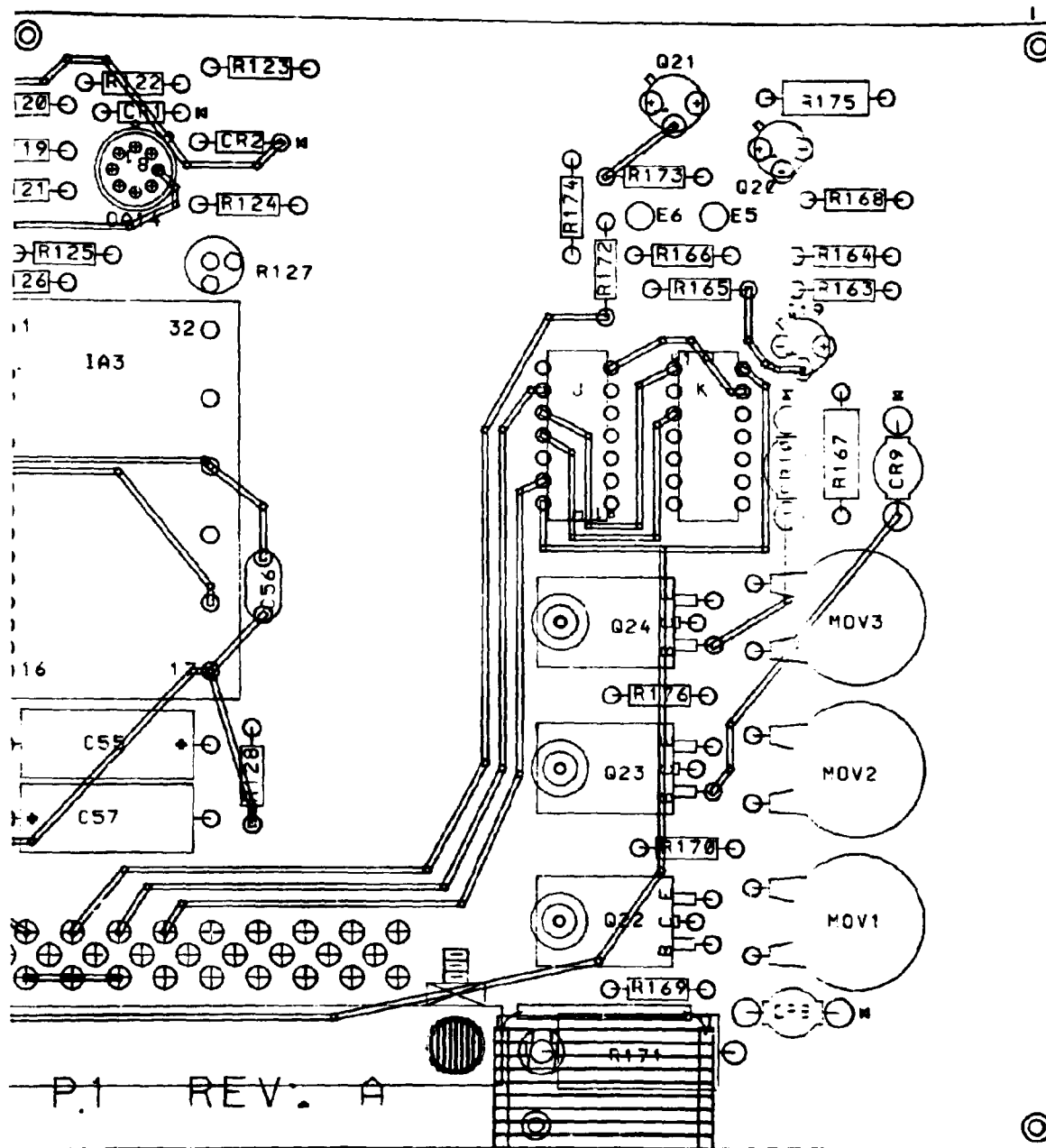
+

SK25-000149 P1 RI

A.C. #3 FINAL

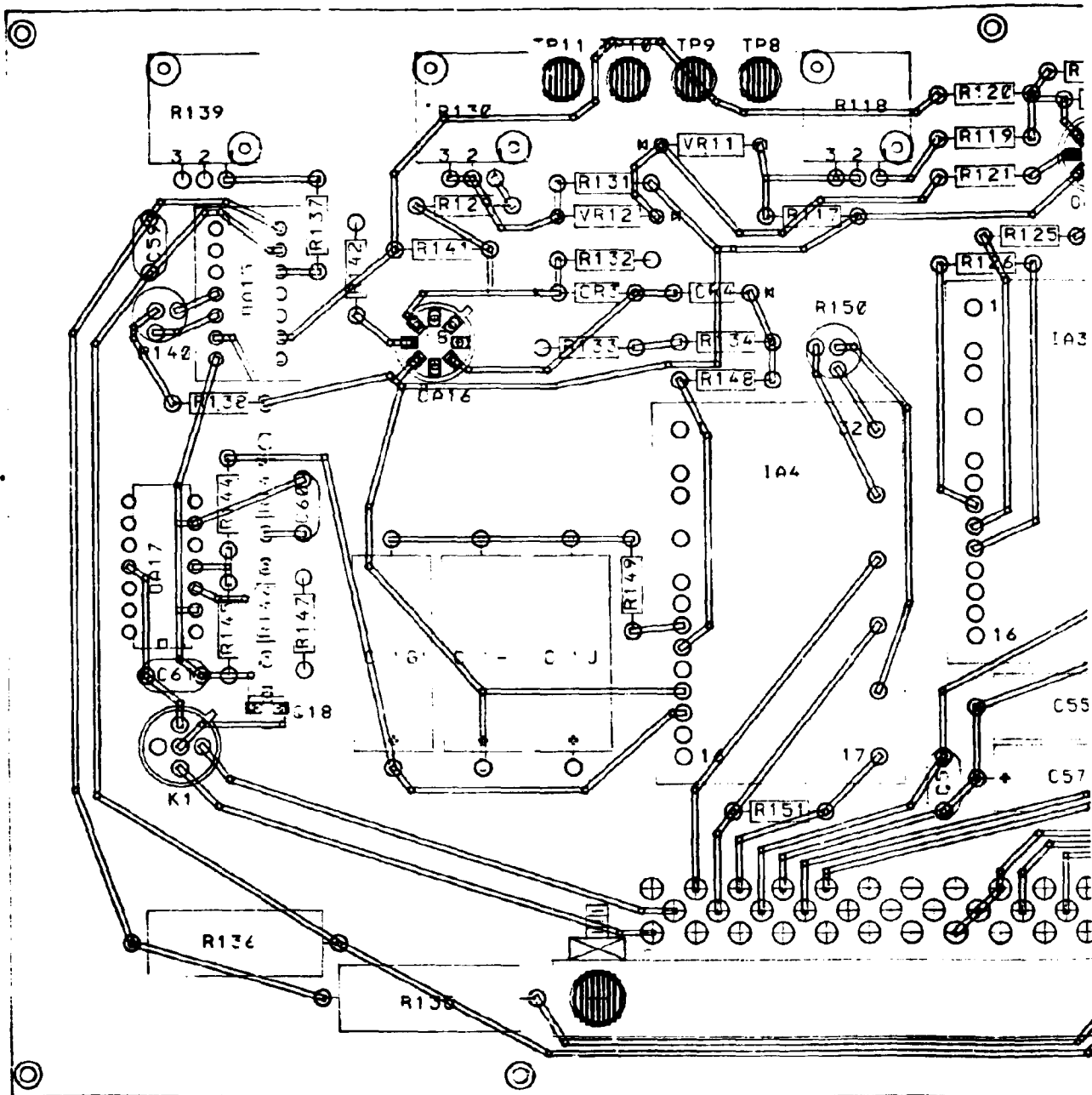
Armature Card No. 3, Comp

3.2-57/51



o. 3, Component Side

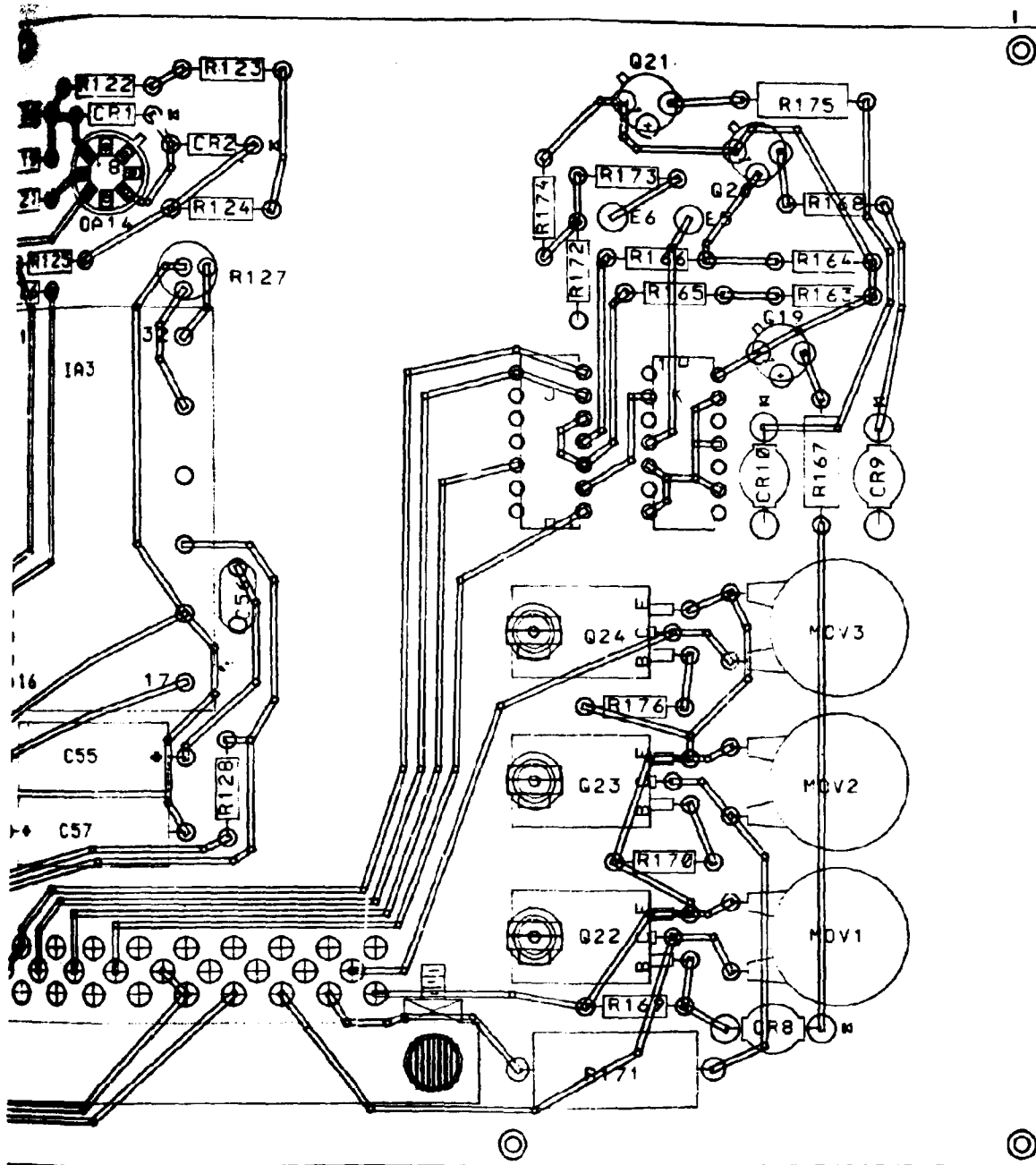
1-57/51



SK25-000149 P1 RE
A.C. #3 - FINAL

Armature Card No. 3, Lea

3.2-59/60



REV. A LEAD SIDE

100%

No. 3, Lead Side

3.3-10/60

WBS 3.2.5 Field Chopper/Battery Charger

WBS 3.2.5.1 Field Chopper/Battery Charger

Function

The field chopper/battery charger (FC/BC) circuitry has been designed to provide the separate functions of on-board propulsion battery charging and propulsion motor field excitation. When the vehicle is parked and connected to an appropriate 115 V service outlet (15 A or 30 A), the vehicle operator can initiate either of two modes of propulsion battery charging under the control of the on-board microcomputer system. The normal charge mode (pushbutton selected) commands 24 A charging current until the battery reaches a predetermined voltage (132 V at 80°C) whereupon current is tapered at constant battery voltage. The equalization mode (pushbutton selected) provides a constant current of about 2 A to the battery.

When the vehicle is underway, the FC/BC supplies field current in the range of 2 to 10.6 A under microcomputer command. Additionally, the FC/BC informs the microcomputer of malfunctions which cause overtemperature or excessive output current.

Operating Principle

A block diagram of the FC/BC circuit is shown in Figure 3.2.5.1-1. The operation of the circuit is as follows.

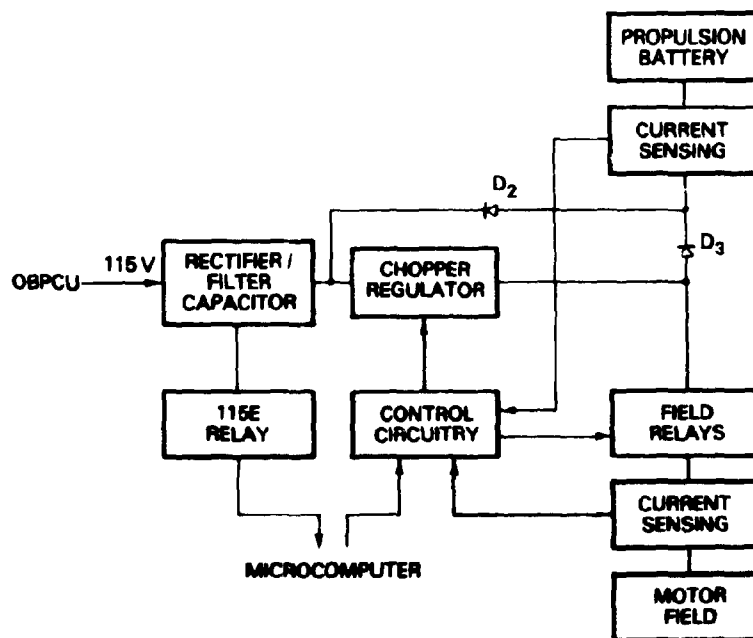


Figure 3.2.5.1-1. Field Chopper/Battery Charger

Battery Charging Mode

The on-board charger power unit (OBPCU) serves as a protective interface between the FC/BC and the ac line. It contains an EMI filter which both helps to suppress line disturbances and to prevent chopper circuit induced noise from reaching the line. Connection of the vehicle's power cord to the ac service supplies 115 V to the rectifier/filter capacitor that feeds full wave rectified dc to the chopper regulator and energizes the 115E relay, which in turn notifies the microcomputer that the ac line is connected. The principal function of the filter capacitor is to provide a path for the high-frequency components of the chopper current, thereby maintaining a relatively constant dc voltage (at chopper frequencies) and assisting in EMI reduction.

The chopper regulator circuit provides a controlled current via D3 to the propulsion battery whenever the full wave rectified voltage is greater than the battery voltage (D2 is reverse biased). When the voltage to the chopper regulator falls below the battery voltage, the input rectifier blocks reverse conduction from the battery through D2. The battery charging current dictated by the microcomputer is controlled by a closed-loop feedback system in the control circuitry which compares the desired value (a voltage from the microcomputer) with a voltage from the battery current sensor.

A threshold modulation scheme is used to control the value of charging current. Referring to the idealized waveforms shown in Figure 3.2.5.1-2, the instantaneous current is constrained to remain between two threshold levels (I_P , I_V , which bracket the desired short time average level (I_{ST}). The long time average value of the current (I_{AV}) is obtained by using the amplified difference between I_{AV} and the desired value of current to control the instantaneous peak current via a comparator having fixed hysteresis. This scheme has several advantages for the present application. First, since the chopper can only supply current during the part of each 120 Hz full wave rectified line cycle where V_{line} exceeds V_{BAT} , it is necessary to get the instantaneous current to increase to its peak value as fast as possible, a situation accomplished by the present scheme. Second, the transient response of the threshold modulator is optimum and closed-loop control is unconditionally stable. Finally, the control scheme is simple in its implementation affording a reduction in circuit complexity, cost, and improved reliability.

The integrator in the control circuit which determines the average value of the battery current has a time constant of approximately 200 ms in order to maintain nearly constant current over a single 8 ms cycle. A peak current limiting circuit is used to prevent collector current from becoming excessive during transient conditions (such as turn-on) while the integrator settles. Since transformer coupling is used to drive the main power transistor (Q_4), the maximum on time permitted for Q_4 is limited. This is accomplished by employing an IC timer configured to be transparent to the drive signal up to the maximum permitted on time. Turn-off is commanded for a minimum duration, permitting the drive transformer core to reset. In the event that excessive current is delivered to the battery, the microcomputer is given a malfunction signal.

Field Chopping Mode

In the propulsion motor field control mode (field chopping mode), the microcomputer commands the field relays (via the control circuitry shown in Figure 3.2.5.1-1) to close as appropriate for forward or reverse excitation, provides a chopper circuit enable signal to the control circuitry, and dictates the magnitude of the field current. The chopper regulator receives energy from the propulsion battery via D2 and controls the current delivered to the field (D3 is back biased). In the field chopping mode, the ac line is disconnected from the OBPCU and the 115E relay is not energized, which prohibits operation of the battery charge control system in the chopper regulator.

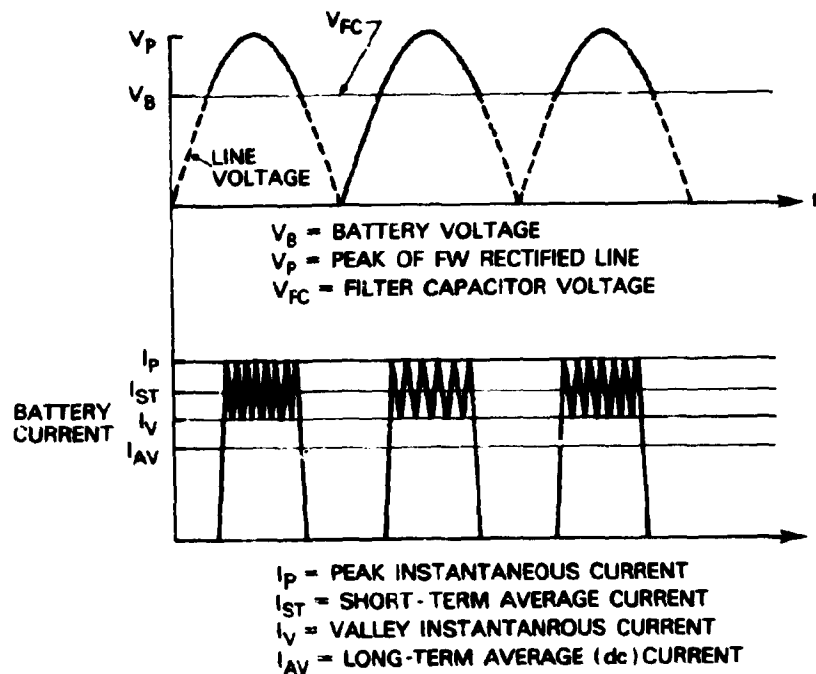


Figure 3.2.5.1-2. Idealized Waveforms

A pulse width modulation scheme is used to control the magnitude of the field current. A voltage proportional to the field current, which is derived from the field current sensor, is compared to the desired value dictated by the microcomputer. The difference is used to determine the duty cycle of the chopper regulator power transistor. The PWM provides a minimum off time to permit resetting of the power transistor base drive transformer. In the event that excessive current is delivered to the field, the microcomputer is given a malfunction signal.

Circuit Description

Power Circuit

Power Section. The schematic of the power circuit section of the power regulator is shown in Figure 3.2.5.1-3. In the battery charge mode, the connection of the 115 V ac line energizes the K₁ relay (115E) via BR2 informing the control circuitry of the connection. Bridge 1 supplies full wave rectified dc to the filter capacitor C19 - C22 which serves as a low impedance path for the high frequency current components of the chopper. Current sensing in the battery charge mode is provided by IS3 located in the negative battery bus. Charge current from the chopper is supplied to the propulsion battery via D11 with diode turnoff snubbing accomplished by L48 and C38. In the field chopping mode, no power is available from the OBPCU (line disconnected), and chopper current is supplied from the battery through fuse F2 via D12.

Control of the power switch transistor Q4 is obtained as follows. A rectangular drive signal to Q13 is received from the chopper regulator and is "high" (Q13 on) for Q4 off and is "low" (Q13 off) for Q4 on. With Q13 on, current in winding N1 of T4 is determined by the supply voltages, diode drops, and R126. The remaining windings experience zero current for their condition. Turnoff of Q13 essentially transfers the current in N1 to N4, which initiates turnon of Q4. As Q4 starts to conduct windings, N3 and N4 act regeneratively to supply a base current which is proportional to the collector current (forced gain equals $N4/N3$ or 50 in this case). Two important advantages of this proportional base drive are low base drive power from the control circuitry and minimum storage time over a wide range of Q4 collector current.

Turnoff of the power switch transistor Q4 is accomplished by turning Q13 back on, which changes winding N2 to a diode drop (CR9) plus the saturation drop of Q13. The "reflection" of this low voltage state to winding N4 causes the current in N4 to be transferred to N2 (N2, N4 are bifilar); with no base drive supplied by N4, the turn-off circuit (discussed later) is activated and clamps the base-emitter junctions of Q4 to a negative voltage for fast turnoff.

After current in winding N3 reaches zero, the stored energy in the core of T4 causes the voltage across all of the windings to reverse. Diodes CR13 and CR9 (and CR10, in turnoff circuit) block and permit the reverse voltage to rise to a high value (limited by winding capacitance) to assist in rapidly resetting the core. Reset for long on times of Q4 is assured by the operation of the reset circuit to be discussed later.

The GE Darlington (Q4) used as the power switch in the FC/BC is capable of very rapid switching and requires snubber circuit protection. Turnoff dv/dt limiting is provided by D13, C23 and R34. The rapid turnoff of D13, which occurs at the peak of Q4's collector voltage, is snubbed by C40 and R50. Turnon snubbing to limit Q4's collector current is accomplished by L_3 , the energy stored in L_3 being absorbed by R36 via D14 and D14's turnoff being snubbed by R49 and C39. The coasting diode snapoff is snubbed by R35 and C37.

Referring to Figure 3.2.5.1-4, current can only be delivered to the battery (when Q4 is on) during that portion of the full wave rectified and filtered input voltage waveform where its magnitude is greater than the battery voltage. Assuming a 115 V line (RMS), 108 V battery and assuming that the line voltage must exceed the battery voltage by approximately 10 V before appreciable battery current can be obtained, a chopping duration of approximately 87° or a battery current duty cycle of 48% can be predicted. Assuming a chopping frequency duty cycle of 40% yields an effective duty cycle of approximately 43%. To obtain 24 A of dc charging current (I_{PC}) would, therefore, require approximately 56 A for the short time average (I_{AV}) during the chopping interval. A peak-to-peak battery current "ripple" of 30 A ($I_P = 71$ A, $I_V = 41$ A) and a coasting inductance of 80 μ H were chosen to accommodate the need for a reasonable maximum frequency at mid-cycle (15 kHz, for reasonable circuit and device switching losses) and a suitably short rise time of battery current at the initiation of each 120 Hz conduction cycle.

As mentioned earlier, the principal function of the filter capacitor C19-C22 is to provide a low impedance path for the high frequency "circulating" components of the chopper current. The capacitance value is a compromise, effecting a trade-off among the variables of voltage ripple, physical size (cost) and impact on line power factor. The 600 μ F capacitor used permits a maximum peak to peak voltage ripple of approximately 10 V at a power factor of 0.82 when supplying rated battery current at rated line conditions and nominal battery voltage.

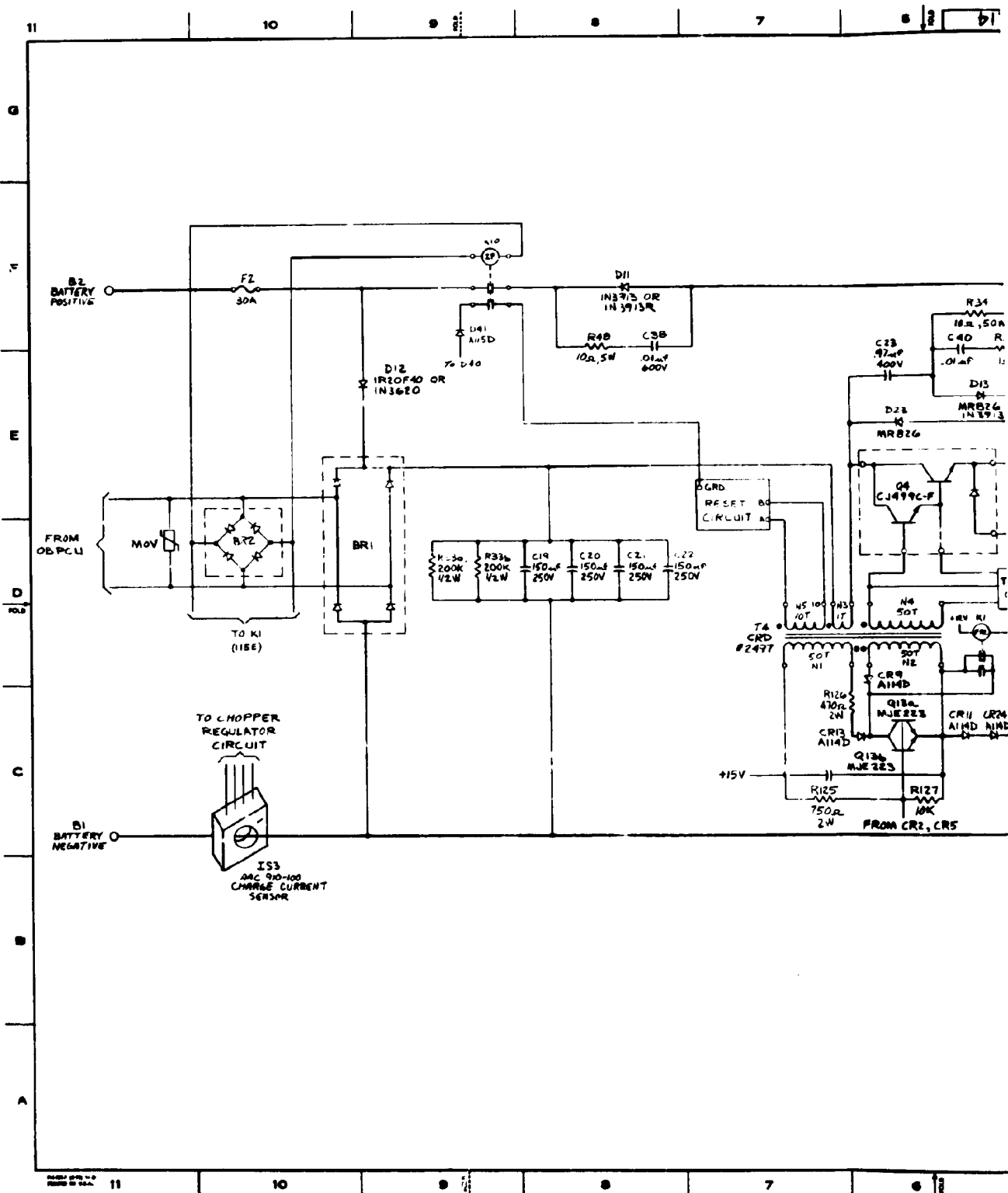
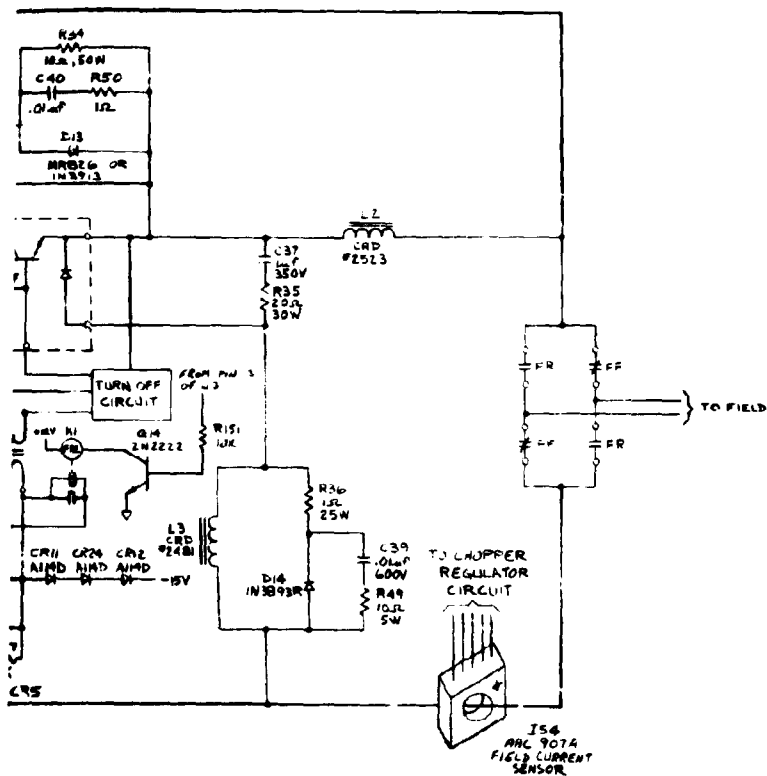


Figure 3.2.5.1-3. Power

3.2-65/66

REVISED		REVISED		REVISED		REVISED	
ZONE	LTR	DESCRIPTION	DATE	APPROVED	DATE	APPROVED	DATE



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 3-PLACE DECIMALS 5-PLACE DECIMALS ANGLES HOLE POSITION HOLE SIZE		SIGNATURES DATE 11/6/72		FIELD CHOPPER POWER CIRCUIT POWER CONDITIONING UNIT 146D4214	
ALL SURF. ✓				D	

Power Circuit

3/4/66

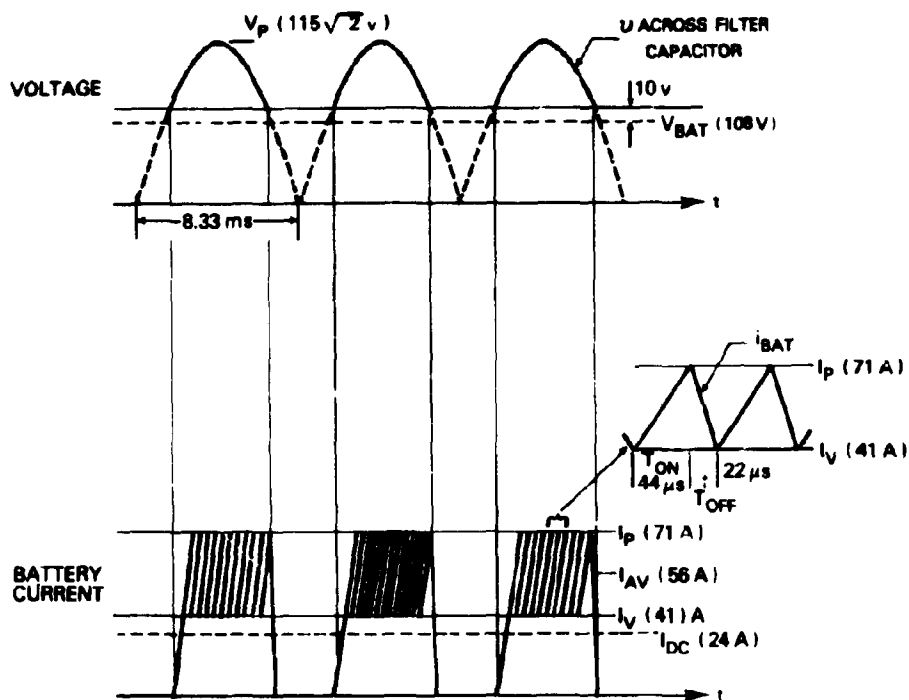


Figure 3.2.5.1-4. Battery Charge Idealized Waveforms

Under the condition of very high armature current in the propulsion motor ($>200 \text{ A}$), it was found that the inductance of the battery cables permitted the voltage supplied to the field chopper to fall below the normal field voltage (on an instantaneous basis), thus turning on diode D11. To prevent this undesirable mode of operation from causing excessive transistor collector current (Q4), it was necessary to insert a normally closed relay contact (operated by FF or FR) in series with D11. This contact is open during field mode.

Turnoff Circuit. The turnoff circuit, shown as a box in Figure 3.2.5.1-4 is illustrated in Figure 3.2.5.1-5. Its purpose is to connect both bases of Q4 to a negative voltage (relative to Q4's emitter) when the voltage across N1 goes negative. This condition results in fast turnoff and helps to prevent noise reinitiating Q4 conduction. The circuit works as follows. Transistor Q4 is first turned on by current from N4 entering B1, exiting the emitter and passing through C16, CR7, CR23, CR10 and back to N4. Initially the voltage across C16 is sufficiently low so that Q10 is off. Capacitor C16 charges until VR12 and Q10 start to conduct (Q10 and VR12 comprise a power Zener), and the voltage across C16 becomes clamped to 8.8V. To turn Q4 off, the voltage across N4 is clamped to a saturation drop by Q13 (Figure 3.2.5.1-3), which reverse biases CR10, CR23 removing forward base drive from Q4. Current from C16 now flows through R130 and into the base of Q14, turning Q14 on and clamping B1 (via CR22) and B2 (via CR8) to the negative capacitor voltage. Stored charge is thus rapidly removed from Q4 for fast turnoff and both bases are clamped to a negative bias voltage. The parallel combination CR22, K147 prevents the oscillation in base current due to base lead inductance, which has been observed with some of the

very fast power Darlington transistors (Q4). Representative waveforms of base current (I_{B1} and I_{B2}) and collector current in turnoff are given in Figure 3.2.5.1-6.

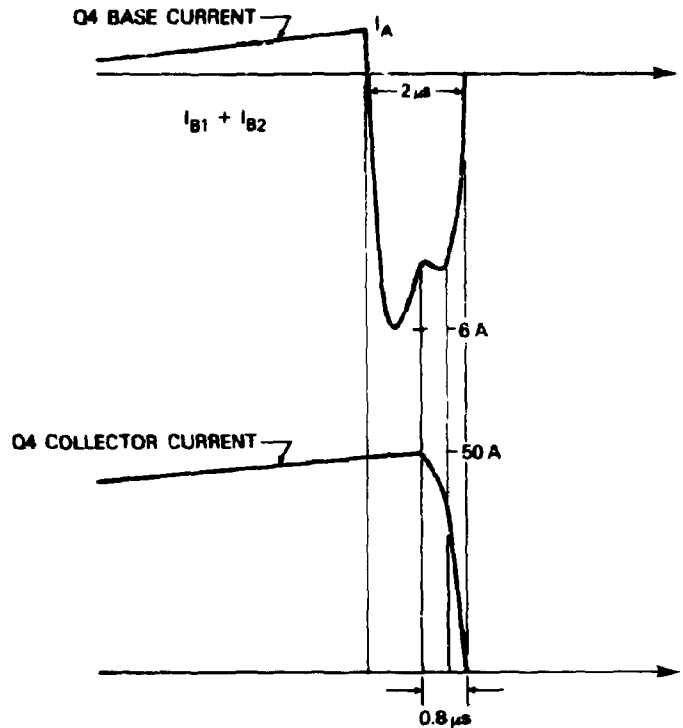


Figure 3.2.5.1-6. Q4 Turnoff Waveforms

Reset Circuit. The reset circuit shown as a box in Figure 3.2.5.1-4 is given in Figure 3.2.5.1-7. Its purpose is to insure the resetting of T4's core at the end of each conduction cycle of the power switch transistor in order to prevent "walking" of the core and consequential saturation when the conduction duty cycle approaches 90%. The circuit operates as follows. The negative 15 V supply provides the reference potential for the circuit. Diodes CR14 and CR15 provide the OR function of the drive signals from the battery charge and field control circuitry while Q1 and CR1 provide the necessary interface level shifting to operate the MC14528B dual one shot. The operating waveforms given in Figure 3.2.5.1-7 show that a delay of 8 μ s (adjustable via R5) is obtained with the first section of the one shot, triggered on the falling edge of the drive signal to Q1. This delay is used to insure that the reset is applied after the power switch turnoff snubber recovers at high power levels, otherwise proper core reset may not be obtained due to snubber current through N3 of T4. The second section of the one shot provides a maximum pulse width of 8 μ s (adjustable via R8), triggered on the falling edge of N_{TP1} . This pulse determines the on time of Q3 - Q4. The peak value of the reset current is held nearly constant by amplifying the voltage across R12 by Q2 and feeding this signal back to pin 13 (reset), resulting in variable pulse width T2. In this manner, for the range of operating conditions encountered (power switch peak current and duty cycle), sufficient volt-second product for core reset is maintained without excessive power dissipation in Q4. Capacitors C4 and C5 provide filtering for closed loop stability and noise reduction.

When the chopper is operated in field mode and is being asked to deliver small currents (~ 2 A), the short on time of the power switch transistor produces relatively little reverse bias voltage across C11 in the turnoff circuit. Under these conditions, the rapid change of reset current can induce turnoff of the power switch transistor. While this mode of operation does not produce transistor failure, it is avoided through the use of C11 at the input of the dual one shot, which eliminates the reset pulse for short chopper on-times.

Control Circuit

Battery Charging Section. The schematic of the battery charge section of the control circuit is shown in Figure 3.2.5.1-8. This circuit provides control of the average value of the battery current, limits the peak instantaneous value, provides an overcurrent signal to the control logic and provides an inhibit function. The instantaneous value of the battery current is sensed by IS3 (5 μ s response time) and presented differentially to op amp U4. The supply voltages for IS3 have been derived using VR1 and VR2 to obtain a nearly zero common mode voltage at the output of IS3. The gain of the differential amplifier, including the internal impedance of IS3, is approximately 10.

Assuming a triangular battery current waveform (65 A peak, 30 A peak-to-peak, 50% duty cycle), the waveform at pin 12 of U4 is shown. The long time average value of the waveform is compared with a control signal reference and difference amplified by U4's second section. The amplified error signal is compared to the peak of the waveform by comparator U8, which has fixed hysteresis determined by R47 and R118. The output of comparator U8 determines the on time of the chopper power switch transistor Q4 via U19 and U18. Thus, controlling the peak value of the current waveform gives the desired control of the long term average value. As a reasonable compromise between speed of response and current droop during the approximately 4 ms chopping duration, the integrating time constant of U4 was chosen as 220 ms (R22, C1). System calibration is effected through adjustment of R111.

To prevent transient operating conditions (such as start up) causing excessive power switch transistor current, the output of U4 (pin 10) is clamped by U20 and VR7 (adjustable by R120) such that the instantaneous collector current cannot exceed 70 A. Pin 12 of R4 is also connected to the logic circuitry via R24 and U12. Should the power switch transistor fail short, current exceeding approximately 90 A will cause a malfunction signal to be directed to the microcomputer (via U7), resulting in power circuit shutdown.

Since the base drive circuitry for the chopper power switch is transformer coupled (T4), a maximum on-time followed by a minimum T4 core reset interval is necessary. This is accomplished by U19, which is transparent to the drive signal from U8 until the on-time exceeds approximately 125 μ s, whereupon U19 changes state for approximately 18 μ s for adequate off-time. Comparator U18 provides the necessary interface to the base drive and reset circuitry with diodes CR5 and CR14 providing the OR function with the field chopper control circuitry. Inhibit is actuated via U19 in response to microcomputer command processed by the control logic section.

Field Chopping Section. The schematic of the field chopper section of the control circuit is shown in Figure 3.2.5.1-9. This circuit provides pulse width modulation control of the dc value of the field current, limits the peak instantaneous transistor current, provides soft start, and provides the inhibit function. The instantaneous value of the field current is sensed by IS4 (40 μ s response time), is amplified by the first section of op amp U2 and is compared to the analog control signal by the second section of op amp U2. Op amp U1 provides a scale factor adjustment and filtering of the analog signal. The error signal at pin 10 of U2 is level adjusted by R109, R145 before being fed to the amplifier input (pin 1) of U16.

10-11/72

Unit 16 is a PWM IC (SG 1524) containing all of the functions necessary to implement a single ended switching regulator. The IC includes a voltage reference, error amplifier, constant frequency oscillator, pulse width modulator, pulse steering logic, dual alternating output switches, and current limiting and shutdown circuitry. Frequency adjustment is obtained via R34 and minimum off-time (referred to the power switch Q4) via R150. Typical adjustments are 130µs on-time, 18µs off-time. Fast inhibit is obtained by pulling down the bases of Q4 and Q3. Upon reinitiation of chopping, soft start is effected by the slow charge of C6 through R43 and CR1.

Due to the logic inductance of the propulsion motor field, the field current is well filtered and displays only about 0.1% ripple at the chopping frequency (~8kHz). Phase shifting to compensate for this output filter pole is accomplished by C3, C34 and R41. Interface of the drive signals (pins 12, 13 of U16) is managed by comparator U17 whose output is ORed with the previously described battery charge circuit by diodes CR2 and CR15. Peak current limiting is provided by comparator U9 which shuts down U16. Peak current adjustment is obtained with RS7.

The positive and negative 14 V supply buses are Zener clamped at IS4 by VR13 and VR14, which provides on-the-board transient protection for all control circuitry connected to these supplies.

Logic Circuit Section. The schematic of the logic circuitry section of the control circuit is shown in Figure 3.2.5.1-10 along with the comparator circuitry used for "housekeeping" functions. The principal function of the logic circuitry is to provide an interface to the microcomputer-generated commands controlling the field chopper/battery charger circuits. Optoisolators provide the isolated link to the input commands 115E, FCE, FF, and FR. Examination of Figure 3.2.5.3-8 permits justification of the following logic relationships:

$$\text{Field Run} = \text{FCE} \cdot (\text{FF} + \text{FR}) + \bar{\text{F}} + \bar{\text{T}} + \bar{\text{SP}}$$

$$\text{FCM} = \text{F} + \text{T} + \text{I}_{\text{CP}} + \text{SP}$$

where, if high

FCE = Field chopper enable

FF = Field forward (field relays provide forward current)

FR = Field reverse (field relays provide reverse current)

F = Field voltage below maximum allowed

T = Temperature below maximum allowed

SP = Spare

FCM = Field chopper malfunction

I_{CP} = Q4 collector current above peak allowed

The field relays are energized in response to logic command by transistors Q5, Q7 or Q6, Q8 as appropriate; MOV's RV1 and RV2 provide inductive energy protection for the transistors. The temperature signal is supplied by a thermal switch. For contingencies, a spare comparator U10 has been enclosed with a view toward battery voltage monitoring. The field comparator U11 has been set to trip at 62 V and reset at 19 V.

Hardware Implementation

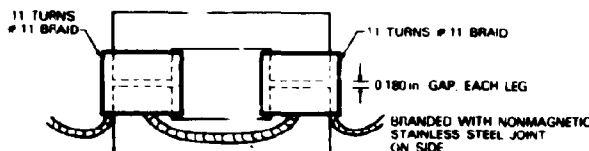
The field chopper/battery charger hardware consists of the control circuit card (Figures 3.2.5.1-11 and 3.2.5.1-12), turnoff circuit card (Figure 3.2.5.2-13), reset circuit card (Figure 3.2.5.1-14), and the power circuit hardware (Figures 3.2.5.1-15 and 3.2.5.1-16) mounted on the PCU casting. The circuit interconnections are shown in Figure 3.2.5.1-17.

Circuit Data

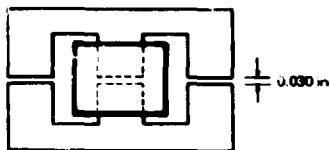
The base drive transformer, coasting inductor and turnon snubber inductor are unique in their design. Transformer and inductor fabrication information are given below.

Coasting Inductor CRD #2523

Core material: Ferroxcube 1F4U, remove one inch of material from each leg



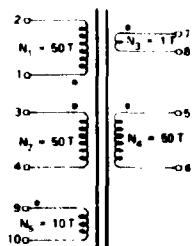
Turnon Snubber Inductor CRD #2481



Core: Ferroxcube EC52-3C8,
double "E" gapped 0.030
in. each leg

Coil: 5 turns of #11 braid

Base Drive Transformer T4, CRD #2497



Core: Ferroxcube 528T400 Toroid

Coils: Distribute uniformly over entire toroid
Coil N_1 is #26

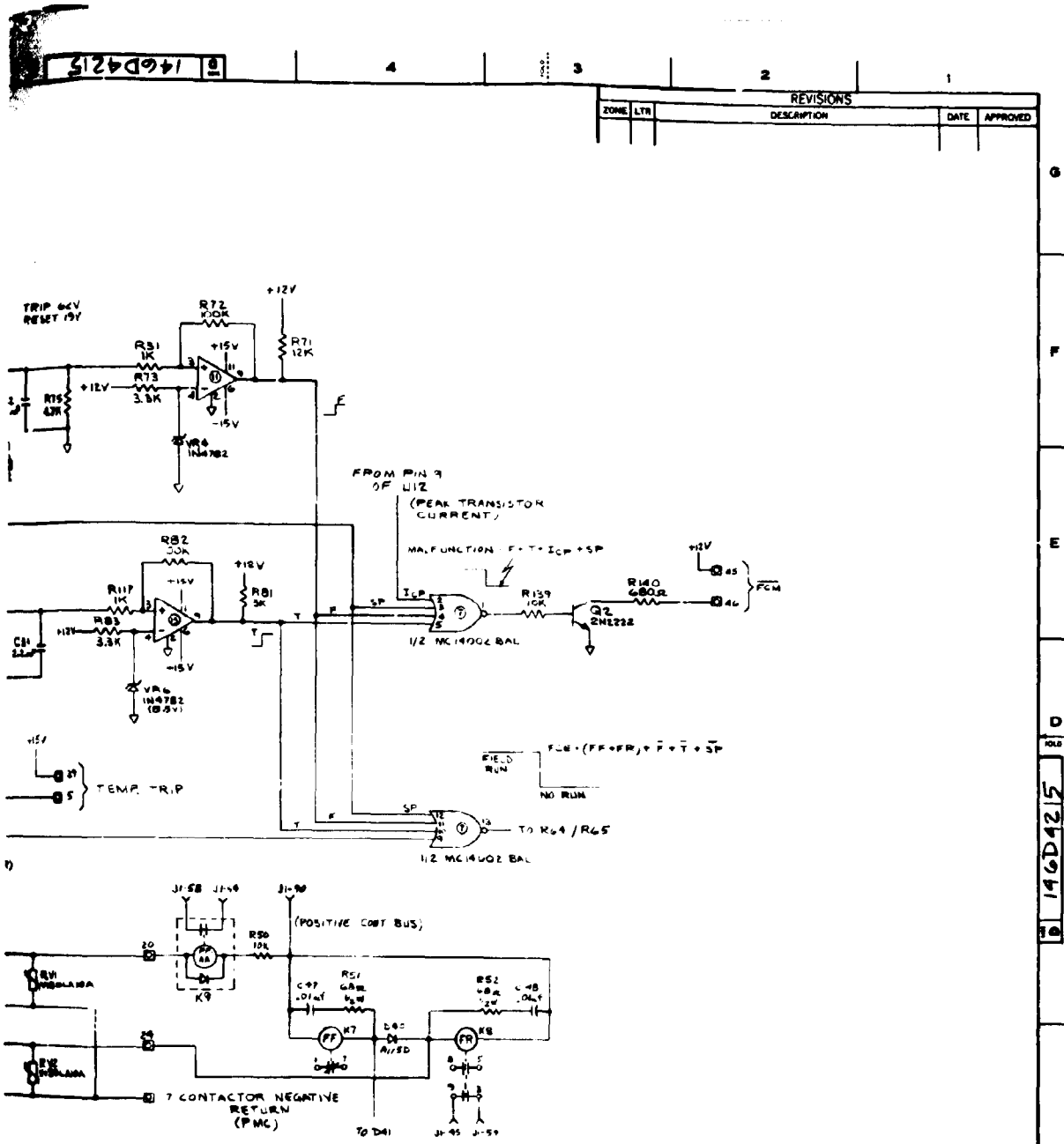
Coil N_2 and N_4 are #21 and bifilar
wound

Coil N_5 is #21

Coil N_3 is one turn of #11 braid

Major Source of Loss. Typical operating power dissipations are given in the table below for certain components of the power circuit. The values were determined using waveforms taken under battery charge conditions with 24 amperes being delivered to the battery from a 120 V line.

Circuit Component	Power Dissipation
R36	6 W
R34	27 W
R35	15 W
Q4	34 W
BRI	19 W
D11	19 W
L2	23 W



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON 2 PLACE DECIMALS ± 3 PLACE DECIMALS ± FRACTIONS ± FRACTIONS ± MATERIAL -		SIGNATURE DATE TIME MATERIAL		CREW DEPT LOC SCH BY FIELD CHOPPER LOGIC CONTROL SECTION POWER CONDITIONING UNIT SIZE CODE IDENT NO. 146D4215 SCALE SHEET	

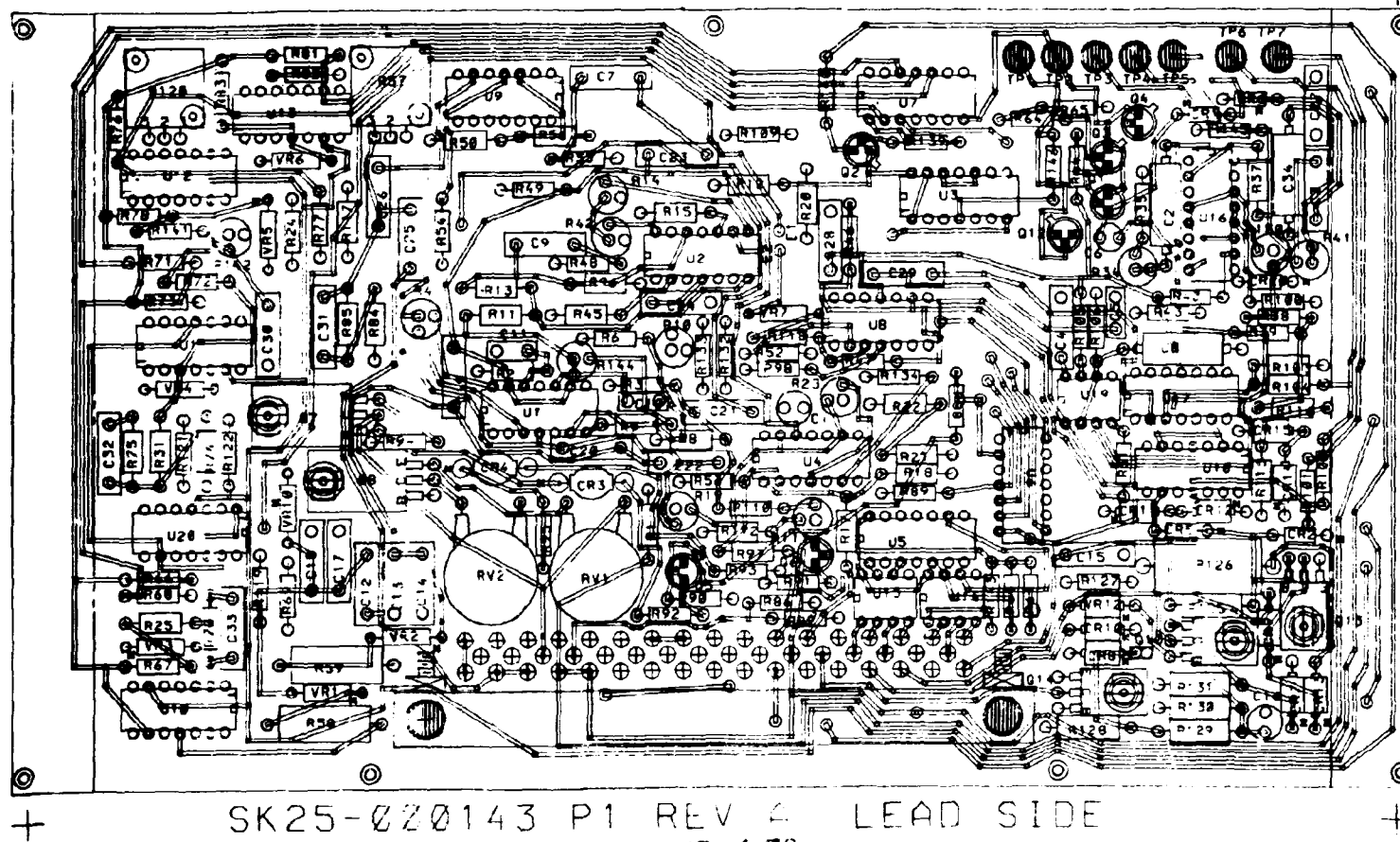


Figure 3.2.5.1-11. Field Chopper/Battery Charger Hardware

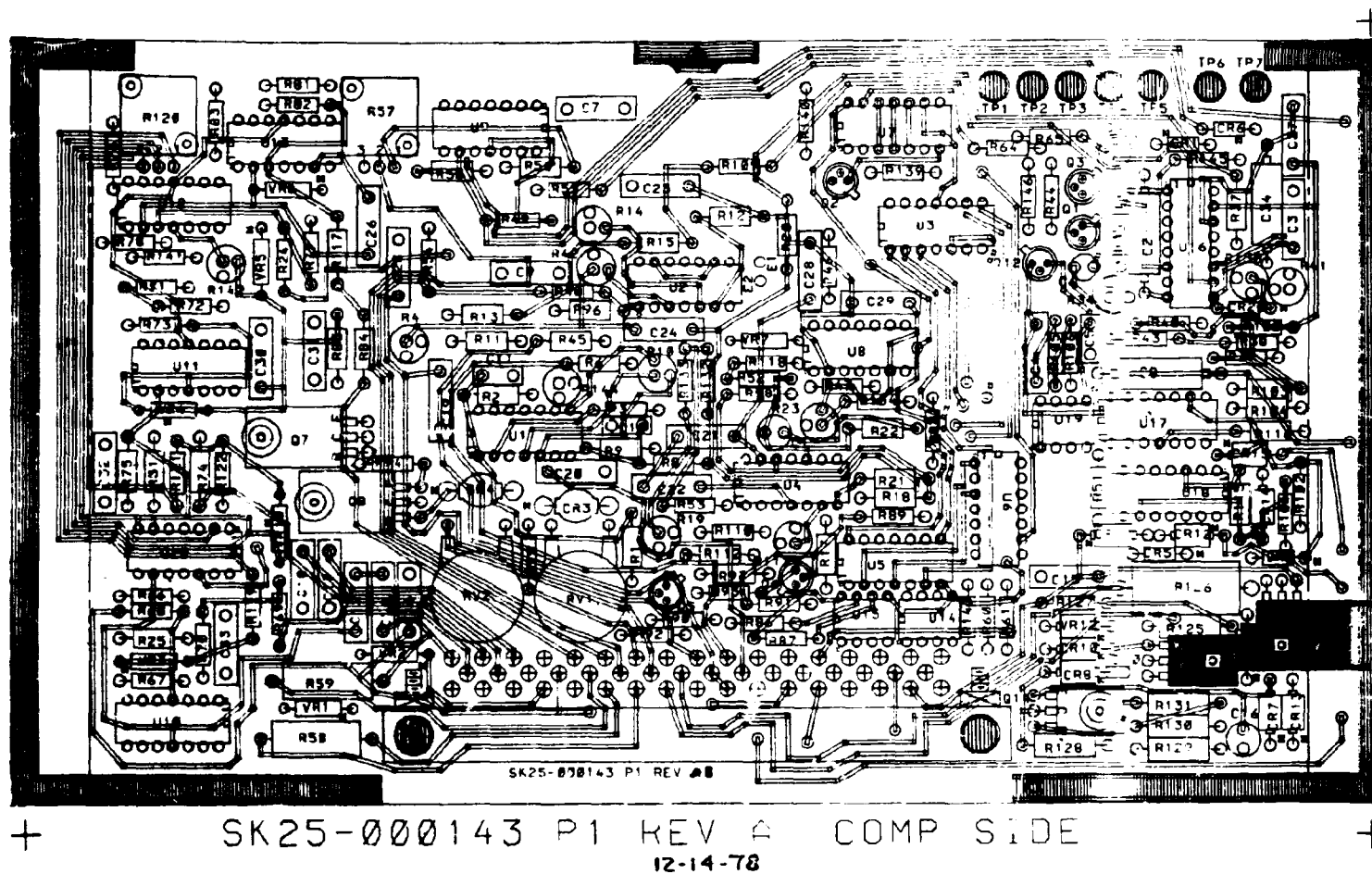
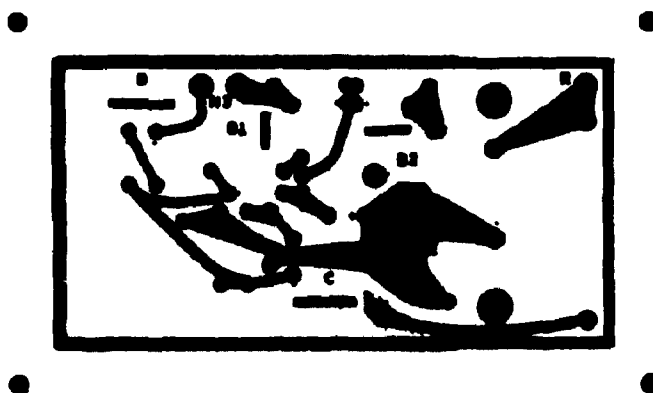


Figure 3.2.5.1-12. Control Circuit Card



Component Side



Bottom side

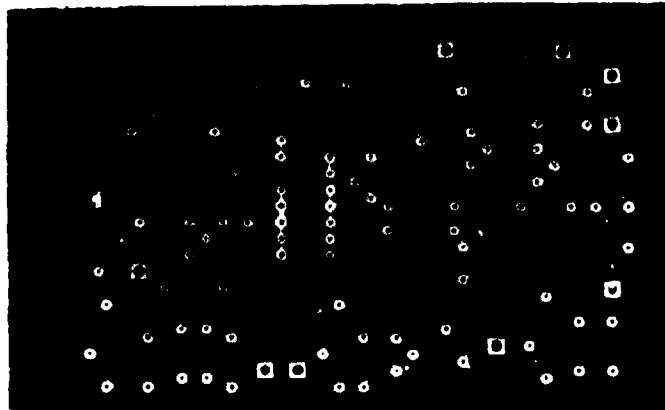
Figure 3.2.5.1-13. Turnoff Circuit Card Layout

Operating Waveforms

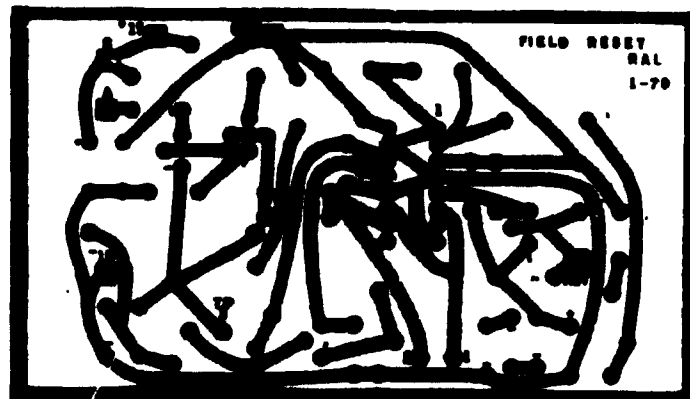
Battery Charging. Figure 3.2.5.1-18 shows collector current, base one current, and collector-emitter voltage of the power switch transistor Q4 in turnoff from the maximum permitted peak collector current of 70 A.

Figure 3.2.5.1-19 shows collector current and collector-emitter voltage of the power switch transistor Q4 in turnon into the condition of 70 A maximum peak collector current. Note the "hump" in the following collector current, typical of the slower Darlington power switch devices at high current levels.

Figure 3.2.5.1-20 shows the power switch transistor Q4 collector current waveform over nearly a complete high frequency chopping cycle for the conditions of maximum permitted collector current of 70 A.



Component Side



Bottom Side

Figure 3.2.5.1-14. Reset Card Layout

Figure 3.2.5.1-21 shows the power switch transistor (Q4) base one current for the conditions given for Figure 3.2.5.1-19. Note the proportionality of base current to collector current and the negative "spike" of turnoff base current.

Figure 3.2.5.1-22 shows the power switch transistor (Q4) collector-to-emitter voltage for the conditions given in Figure 3.2.5.1-20. Note in particular the instantaneous peak voltage of 275 V achieved with 70 A of peak collector current.

Figure 3.2.5.1-23 shows the power switch transistor (Q4) collector current and transformer T4 reset current during turnoff for the conditions of Figure 3.2.5.1-20.

Figure 3.2.5.1-24 shows the battery current with the battery voltage at 119 V, average battery current 22 A, 120 V ac live, 26 A (RMS) live current. This is the maximum average battery current achievable for the given service line at this battery voltage. The peak instantaneous current is limited by the control circuitry to approximately 70 A.

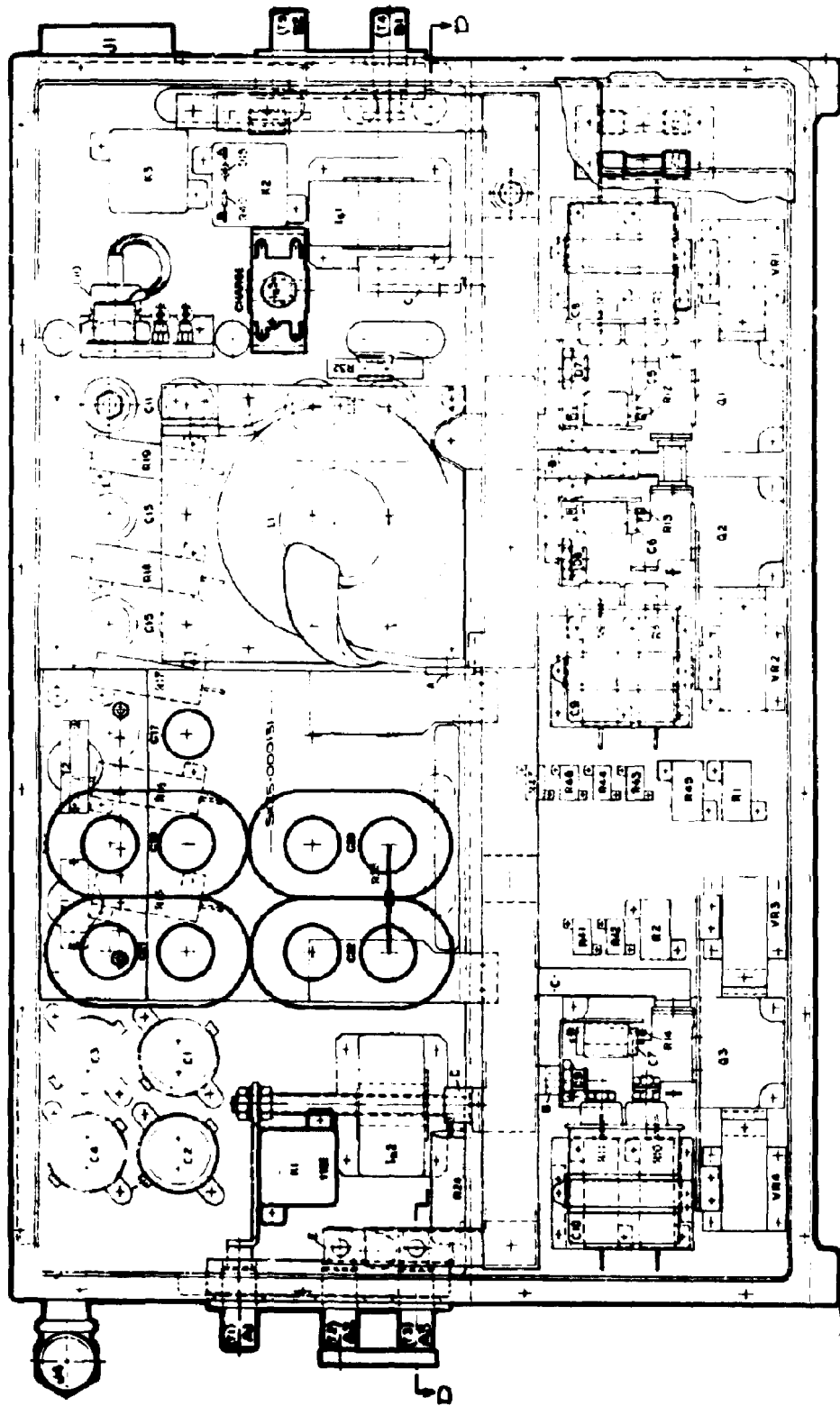


Figure 3.2.5.1-15. Power Circuit Hardware - Side 1

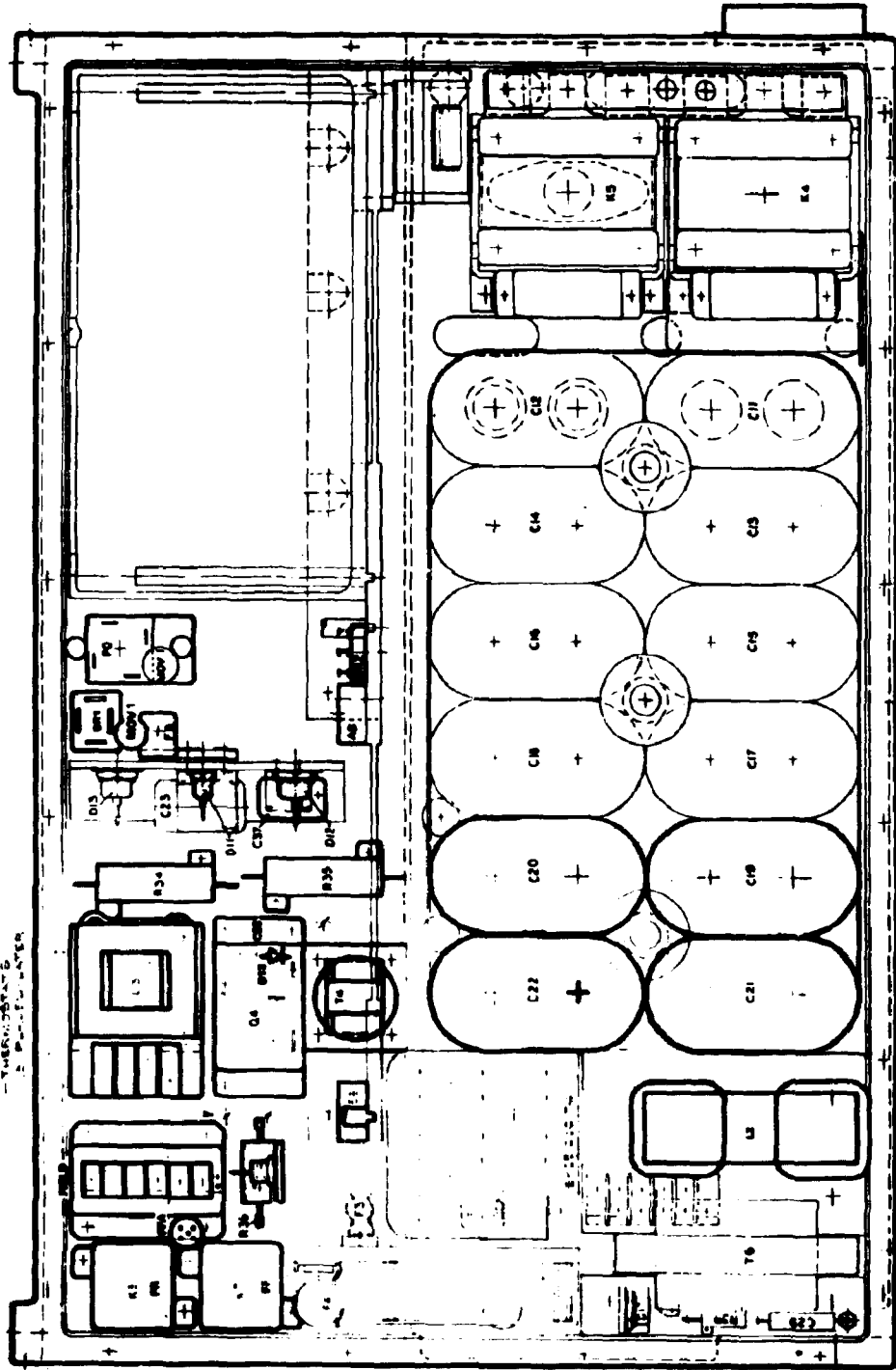


Figure 3.2.5.1-16. Power Circuit Hardware - Side 2



	D	E	F	G
146D4201				

4/86

Top Trace: Base Current
1 A/div
Middle Trace: Collector Current
10 A/div
Bottom Trace: Collector Voltage
50 V/div
Time Base: 1 μ s/div

0-



Figure 3.2.5.1-18. Q4 Waveforms

Middle Trace: Collector Current
5 A/div
Lower Trace: Collector Voltage
50 V/div
Time Base: 0.2 μ s/div

0-



-0

Figure 3.2.5.1-19. Q4 Waveforms

Vertical: 10 A/div
Time Base: 20 μ s/div



-0

Figure 3.2.5.1-20. Q4 Collector Current

Vertical: 1A/div
Time Base: 20 μ s/div

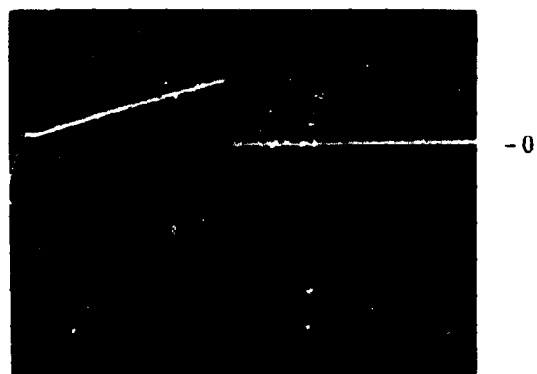


Figure 3.2.5.1-21. Q4 Base 1 Current

Vertical: 50 V/div
Time Base: 20 μ s/div

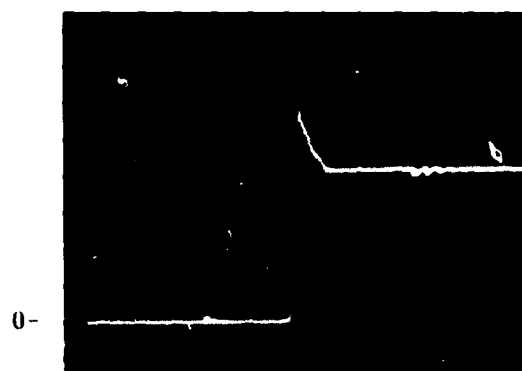


Figure 3.2.5.1-22. Q4 Collector-to-Emitter Voltage

Middle Trace: T4 reset current
1 A/div
Collector Current: 10 A/div
Time Base: 2 μ s/div



Figure 3.2.5.1-23. Turnoff Waveforms

Vertical: 10 A/div
 Time Base: 0.5 ms/div
 $I_{BAT} = 22 \text{ A (dc)}$

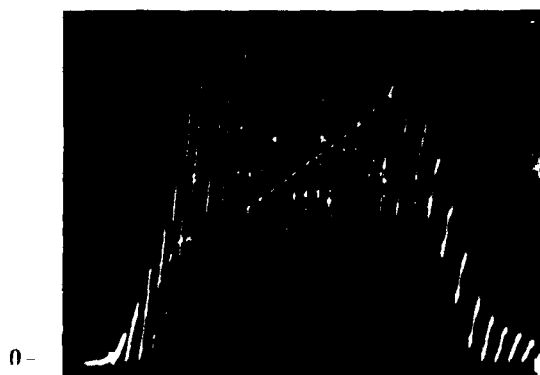


Figure 3.2.5.1-24. Battery Current

Figure 3.2.5.1-25 shows three cycles of the battery charging current for the same conditions given in Figure 3.2.5.1-24.

Vertical: 10 A/div
 Time Base: 2 ms/div
 $I_{BAT} = 22 \text{ A (dc)}$



Figure 3.2.5.1-25. Battery Current

Figure 3.2.5.1-26 shows the base one current for several high frequency chopping cycles near the peak of the battery current waveform. It should be recognized that the amplitude of the negative base current "spike" depends upon several factors including collector current peak amplitude, transistor storage time, and the chopping frequency duty cycle.

Figure 3.2.5.1-27 shows the power switch transistor Q4 collector-to-emitter voltage for the conditions of Figure 3.2.5.1-26.

Figure 3.2.5.1-28 shows battery current for the conditions of 6 A dc supplied, 120 V live. The apparent nonuniformity of chopping across a 120 Hz cycle is due to the relatively fast response of the integrator in the averaging circuit. At very low values of battery current the chopper operates only as often as necessary to maintain the appropriate average value of battery current.

Vertical: 1 A/div
 Time Base: 50 μ s/div
 $I_{BAT} = 22$ A (dc)

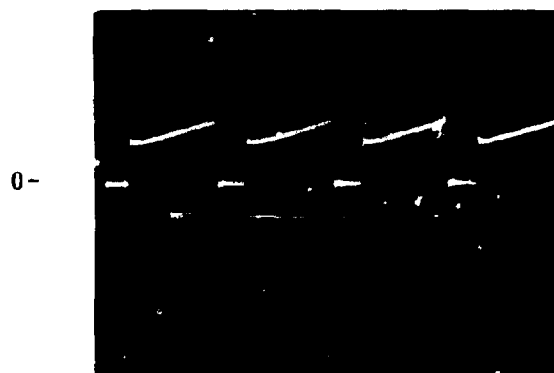


Figure 3.2.5.1-26. Q4 Base 1 Current

Vertical: 50 V/div
 Time Base: 50 μ s/div
 $I_{BAT} = 22$ A (dc)

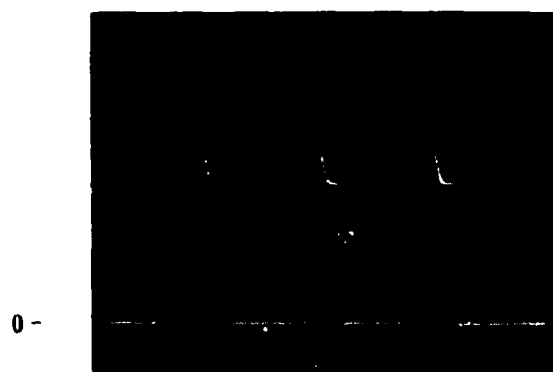


Figure 3.2.5.1-27. Collector-Emitter Voltage

Low Current Condition
 Vertical: 10 A/div
 Time Base: 2 ms/div
 $I_{BAT} = 6$ A (dc)

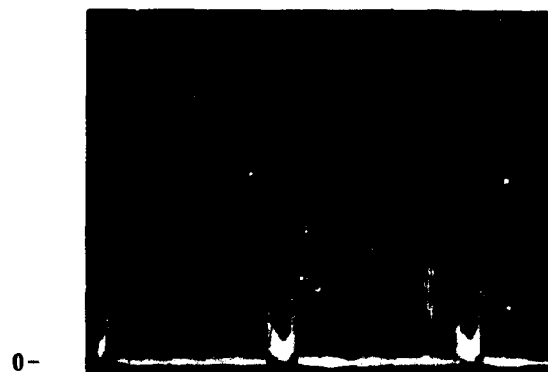


Figure 3.2.5.1-28. Battery Current

Figure 3.2.5.1-29 shows the turnon transient of battery current if the chopper is suddenly enabled. While programmed for other than zero average current the envelope shape of the waveform is due to the time constant of the integrator circuit.

Turnon Transient
Vertical: 10 A/div
Time Base: 50 ms/div

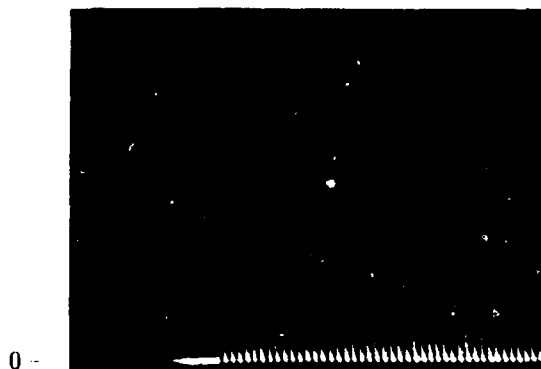


Figure 3.2.5.1-29. Battery Current

Figure 3.2.5.1-30 shows the ac line voltage and current when charging a 119 V battery at 20 A (dc) from a 115 V line, 27 A line current. Battery power was calculated to be 2370 W and input power (from ac line) was 2539 W. Efficiency was calculated to be 93%.

Line Voltage (sinusoidal) Trace:
50 V/div

Line Current: 20 A/div

Time Base: 2 ms/div

$I_{\text{LINK}} = 27 \text{ A rms}$

$V_{\text{LINE}} = 115 \text{ V rms}$

$I_{\text{BAT}} = 20 \text{ A}$



Figure 3.2.5.1-30. AC Line Waveforms

Field Chopping. Figure 3.2.5.1-31 shows typical waveforms of Q4 base current and collector current while supplying the propulsion motor field with rated current (10.6 A).

Figure 3.2.5.1-32 shows the typical waveforms of Q4 base current and collector current while supplying a field current of 5 A. Note in particular by comparison with Figure 3.2.5.1-31 the difference in duty cycle and negative base current "spike."

Figure 3.2.5.1-33 shows the waveforms of Q4's collector current and collector-to-emitter voltage for rated field current (10.6 A) being delivered to the field.

Top: Base I Current 1 A/div
 Bottom: Collector Current 10 A/div
 Time Base: 20 μ s/div
 $I_{\text{FIELD}} = 10.6 \text{ A}$
 $V_{\text{BAT}} = 115 \text{ V}$

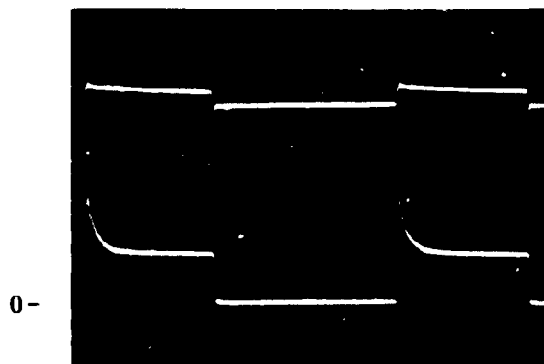


Figure 3.2.5.1-31. Q4 Waveforms

Top: Base I Current 1 A/div
 Bottom: Collector Current
 10 A/div



Figure 3.2.5.1-32. Q4 Waveforms

Top: Collector-Emitter Voltage
 50 V/div
 Bottom: Collector Current 10 A/div
 Time Base: 20 μ s/div
 $I_f = 10.6 \text{ A}$

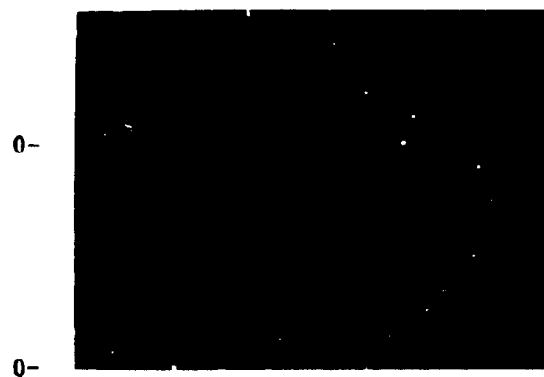


Figure 3.2.5.1-33. Q4 Waveforms

Figure 3.2.5.1-34 shows the waveforms of Q4 collector current and T4 reset current at rated field current. In the vicinity of (and beyond) 50% duty cycle the reset current widens (maximum width approximately 8 μ s) while maintaining 1.25 A peak.

Top: T4 Reset Current 1 A/div
 Bottom: Q4 Collector Current
 10 A/div
 Time Base: 20 μ s/div
 $I_f = 10.6$ A

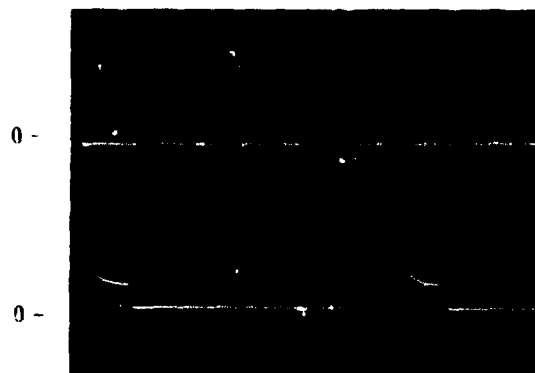


Figure 3.2.5.1-34. Q4 Collector Current and T4 Reset Current

Figure 3.2.5.1-35 shows T4 reset current for short Q4 on time, with Q4 collector current as reference. For short ON times, the reset pulse becomes very narrow (~ 1 μ s).

Top: T4 Reset Current 1 A/div
 Bottom: Q4 Collector Current
 10 A/div
 Time Base: 20 μ s/div
 $I_f = 5$ A



Figure 3.2.5.1-35. Q4 Collector Current and T4 Reset Current

Figure 3.2.5.1-36 shows the signal at TP6 with Q4 collector current as reference for rated field current. In battery charge the signal at TP7 has a similar shape to TP6 in field chopping.

Figure 3.2.5.1-37 shows the field current turnon transient under full-rated conditions. Note the rise time is approximately 160 ms.

Figure 3.2.5.1-38 shows the field current turnoff transient from full-rated current. Note the fall time is approximately one second.

Top: TP 6 Voltage 10 V/div
 Bottom: Q4 Collector Current
 10 A/div
 Time Base: 50 μ s/div
 $I_f = 10.6$ A

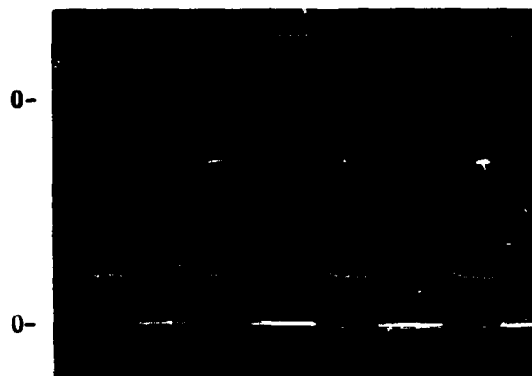


Figure 3.2.5.1-36. TP6 Voltage and Q4 Collector Current

Field Current: 2 A/div
 Time Base: 20 ms/div



Figure 3.2.5.1-37. Field Current Turnon

Field Current 2 A/div
 Time Base: 200 ms/div



Figure 3.2.5.1-38. Field Current Turnoff

WBS 3.2.5.2 Logic Power Supply (LPS)

Function

The function of the logic power supply is to convert the continuously varying main propulsion battery voltage (nominally 108 V dc) into supply voltages required to power the various integrated circuits, sensors, D/A and A/D converters, etc., used in the PCU and microcomputer. The output voltages of the supply are +12 V dc, +15 V dc, +5 V dc, and a 40 V amplitude 25 kHz square wave.

Operating Principle

Figure 3.2.5.2-1 shows a block diagram of the LPS circuit. Operation is as follows:

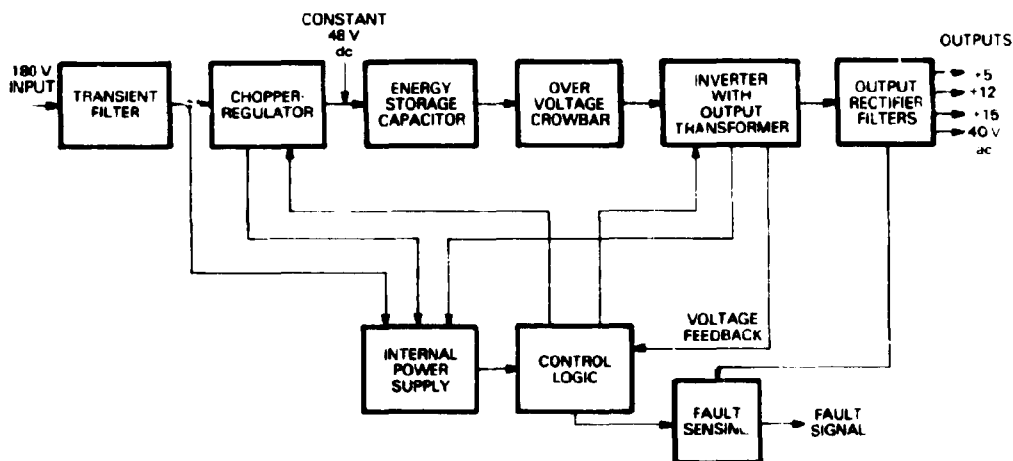


Figure 3.2.5.2-1. LPS Block Diagram

The incoming nominal 108 V supply is filtered by a transient filter to eliminate voltage impulses from the battery voltage waveform. This voltage is then fed to a down-chopper with output generation of a constant nominal 48 V dc voltage across the energy storage capacitor. The output of this capacitor is monitored by an overvoltage crowbar circuit designed to short circuit the terminals of the storage capacitor in the event of a high voltage appearing across those terminals.

The constant 48 V dc is then applied to the input of a half-wave, center-tapped inverter circuit which produces 25 kHz ac power in the primary winding of the output transformer. The voltages on the multiple secondary windings are rectified and filtered to form the required dc outputs. A 40 V amplitude square wave output is also provided for use in the armature chopper base drive circuit.

The control logic for the supply provides the driving signals for the chopper and inverter and also regulates the 48 V dc bus using closed loop negative feedback. Integrated circuits and other circuits within the LPS are powered from an internal power supply that regulates power from the incoming 108 V supply, the chopper regulator, or the inverter output, depending upon operating conditions. A fault sensing circuit monitors conditions in various parts of the supply and produces a fault indication signal when a malfunction is detected.

Circuit Description

The circuit description of the LPS is broken down into functional units as described in Figure 3.2.5.2-1.

Transient Filter, Chopper, Filter Capacitor and Crowbar. Figure 3.2.5.2-2 shows the circuit schematic of the transient filter, chopper regulator, storage capacitor, and crowbar sections of the logic power supply. The incoming 108 V dc is filtered by the L-C filter comprised of L1 and C38. The positive input terminal of the chopper regulator is the collector of power transistor Q8. The combination of Q8 and Q9 in series forms the chopper switching transistor; diode D20 forms the freewheeling diode of the chopper; and the primary winding of transformer Lc4, in conjunction with storage capacitor C24, forms the output filter of the chopper. The constant 48 V dc bus is established across the terminals of C24. The crowbar circuit, centered around the MC3523 integrated circuit, monitors the voltage; should an overvoltage be detected, this integrated circuit will gate on thyristor D21.

Pulses to control the step-down ratio of the chopper are coupled into the circuit by transformer T2. The full wave rectified output of T2 appears with positive polarity at the cathodes of diodes D6 and D7. These rectified pulses are transmitted directly to the base of Q8 by means of diode D13 and resistor R67. Similarly the base drive pulses of Q9 are transmitted to it by diode D12 and resistor R60.

Unlike Q9, the bulk of the base drive of Q8 is provided by regenerative action. The current transformer T1 couples from the emitter circuit to the base circuit of Q8. Current flowing into terminal 1 of T1 causes a secondary current to flow out of terminal 3 and, in so doing, drives current into the base of Q8 and returns to T1 at terminal 4.

The circuitry involving transistors Q7, Q10, and Q11 is used to provide a negative base-to-emitter voltage for Q9 in order to assist in turnoff of that transistor. It is desired to turn off Q9 at the initiation of the zero voltage notches which occur in the waveform appearing at the cathodes of D6 and D7. A local positive supply voltage is generated in capacitor C7 by D11 and R59, and a local negative voltage is generated across C8 by D10 and R63. When a notch begins to appear at the D6/D7 cathode node, the base-emitter junction of Q7 starts to conduct since the voltage on C7 is maintained. With Q7 conducting, Q11 is made to conduct and therefore connects the base of Q9 to the negative supply developed on C8. At this time, the base of Q10 is carrying no current since a voltage notch is also present at the D8/D9 anode node. Therefore, transistor Q10 is not conducting. The negative supply connected to the base of Q9 assists in turning it off. When the notch in the D6/D7 cathode node (and simultaneously in the D8/D9 anode node) disappears, the negative base drive of Q9 must be reversed and the positive base drive reestablished. The absence of a notch at the D8/D9 anode node will cause Q10 to conduct, firmly shorting the base of Q11 and rendering it virtually open circuit. The speedup capacitor, C20, allows this termination of negative base drive to be accomplished before normal positive base drive appears by means of D12 and R60.

The circuit consisting of D14-D18, Q6, and R132 is a power Zener equivalent designed to absorb negative base current of Q8 when this transistor is rendered nonconducting by the action of Q9.

Inverter. The 48 V dc bus established as the storage capacitor (C24 of Figure 3.2.5.2-2) is fed to the input terminals of the inverter section, Figure 3.2.5.2-3.

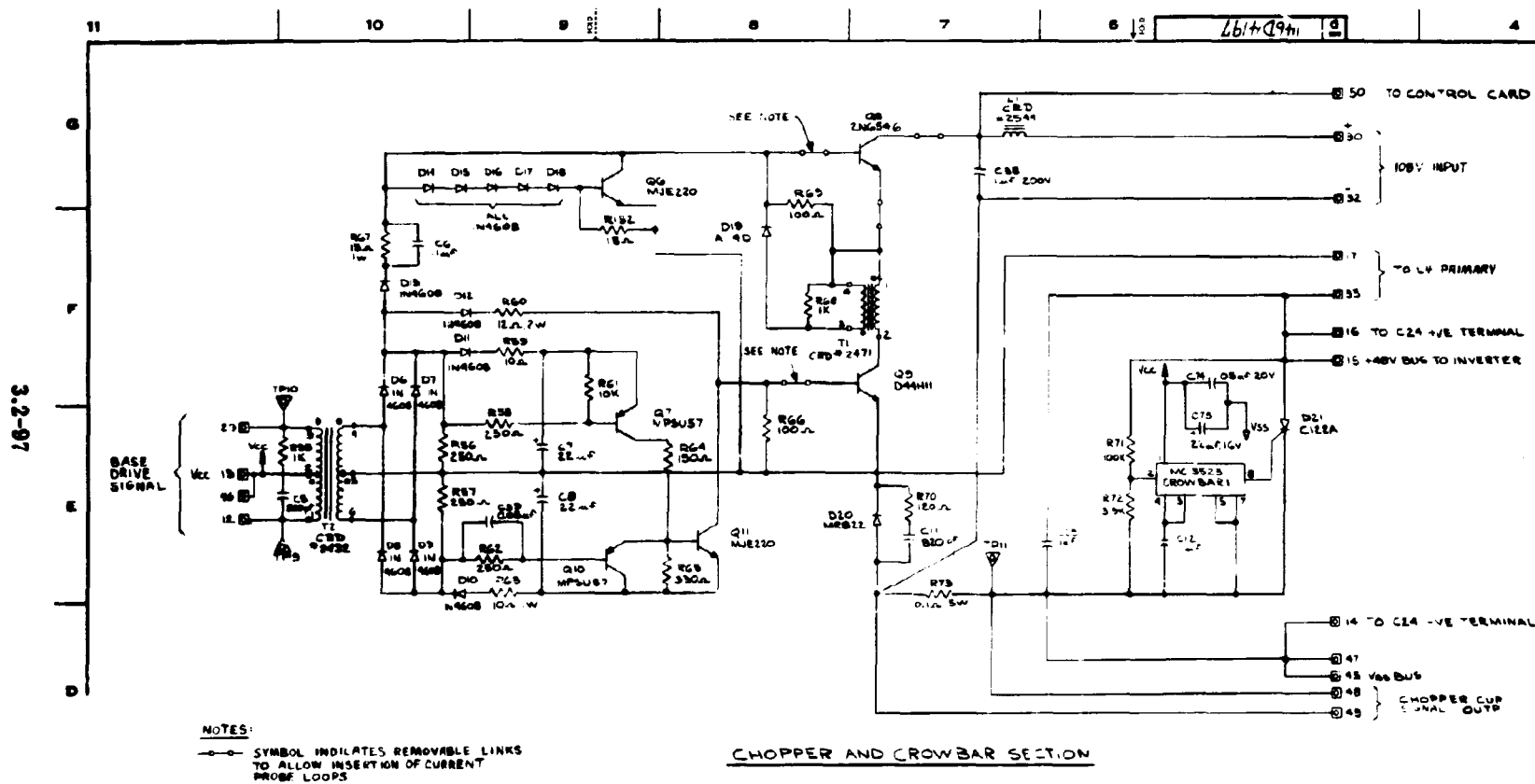


Figure 3.2.5.2-2. Transient Filter, Chopper Regulator, Storage Capacitor, and Crowbar

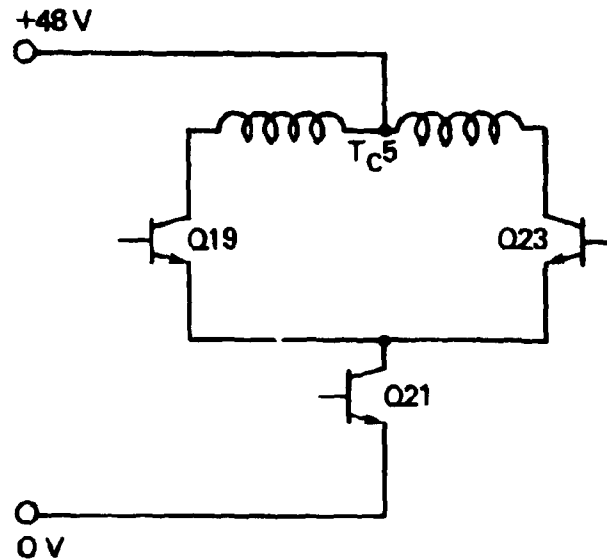


Figure 3.2.5.2-3. Simplified Inverter Schematic

The 48 V supply is applied to the center tap of the primary winding of transformer T_{c5} (secondary windings are not shown in Figure 3.2.5.2-3). Each half of the winding conducts by alternating between transistors Q19 and Q23. The emitters of these transistors are switched by a fast "emitter-switch" transistor Q21. Figure 3.2.5.2-4 shows a complete schematic. As can be seen, each power transistor (Q19 and Q23) has a regenerative base drive provided by current transformers that couple emitter current into the base circuit, T7 and T8. Signal level base drive for Q19 and Q23 is transformer-coupled into the power circuit by transformer T3. Initial base drive for Q19 is provided by D27 and R86, and for Q23, current is provided by D38 and R86. Base drive for Q21, which does not have regeneration, is provided by D33 and D34 acting in conjunction with D37 and R101. Negative base drive for Q21 is provided by the action of Q17, Q18, and Q20 in a similar manner as Q9 was provided with negative base drive in the chopper section described previously. One important difference in this case is the presence of low-valued C19 and the absence of a positive filter capacitor corresponding to C20.

Current transformers T5 and T6 used in conjunction with the "squaring" circuits of Q14 and Q17 respectively, provide a signal which is TRUE when current is flowing in the collector of the appropriate power transistor. These TRUE or FALSE logic levels, corresponding to the presence of main transistor collector current, are fed into the base drive signal path — at power driver PD2 — of the other power transistor so as to inhibit the base drive signal. This cross-coupled, lockout feature prevents noise signals from producing transistor-destroying shoot-throughs which would occur if both Q19 and Q23 were simultaneously conducting. During LPS power-up, the V_{cc} power supply to the PD2 device is inhibited by Q16 until the voltage appearing across R129 has exceeded about 6 V.

Circuitry centered around Monostable MONO 1 performs a current limit function which operates by sensing the voltage developed across shunt resistor R103. Upon detection of an overcurrent, the output of MONO 1 (pin 9), which is normally at logic level 1, changes state to logic level zero and inhibits drive signals to PD2 by means of NAND 3.

7

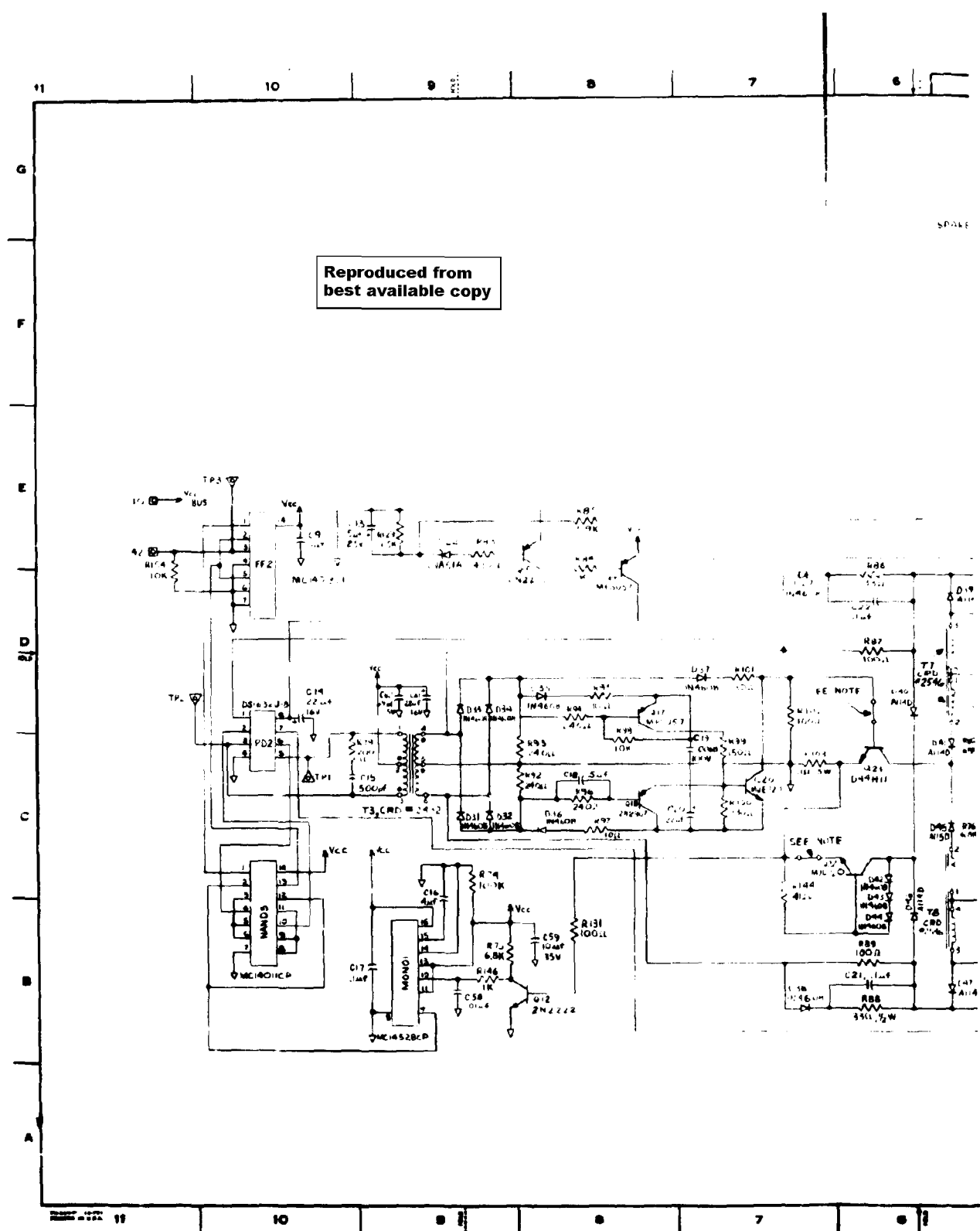


Figure 3.2.5.2-4. Inverter
3.2-99/100

Drive signals to the inverter circuit arrive in the card at pin 42 and are fed to PD2 through FF2 and NAND 3.

Output Section. The circuitry consisting of and connected to the secondary windings of transformer T 5 (CRD No. 2476) is termed the LPS output section and is shown in Figure 3.2.5.3-5. The logic power supply dc outputs of +12 V, +15 V and +5 V are produced by diode rectifying and filtering the voltages appearing at four center-tapped secondary windings. These can be clearly seen in Figure 3.2.5.2-5. A detailed description of the action of each component will not be entered into here. It is important to note that no individual and independent output voltage adjustment is possible with this circuit. The magnitude of the outputs are fixed in relation to each other, but, as will be described later, adjustment can be made to the value of the output voltages as a set.

The voltages generated at transformer secondary terminals 4 and 5, and 6 and 7 are fed to a section of circuitry to be described below. The voltage across terminals 8 and 9 forms the 40 V amplitude square wave output.

Control Section. The circuitry which generates the driving signals for the chopper and inverter section, as well as regulating the 48 V intermediate dc bus, is termed the control section of the LPS and is shown in Figure 3.2.5.2-6.

The heart of this section is a standard LM555 timer, TIMER 1, the output of which (pin 3) is transmitted to the inverter section of the supply to dictate the switching frequency of the transistors Q19 and Q23. The output of this timer is also processed by

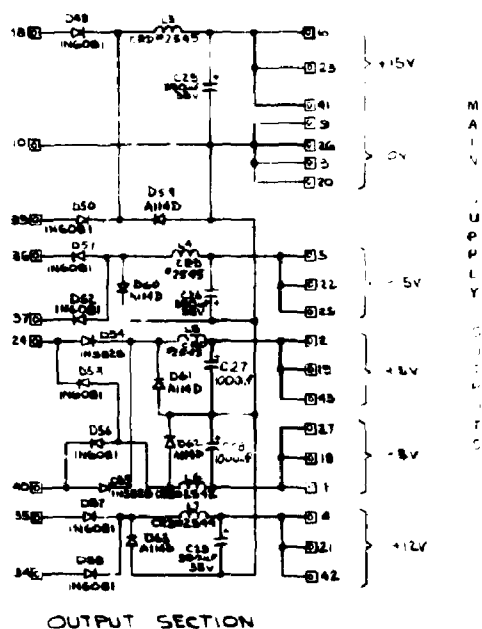


Figure 3.2.5.2-5. Output Section Schematic

comparator COMP 2A, NAND gate 1A, bistable FF1A, gates NAND 1C, NAND 2A, and NAND 1D until amplified in power level by driver PD1 in readiness for being transmitted

to the base drive transformer of the chopper section. This signal is of variable duty cycle ratio, depending upon the magnitude of the incoming 108 V supply to the chopper, and the action of this signal regulates the value of the intermediate 48 V dc bus.

The closed-loop feedback control is a pulse-width modulated (PWM) type of which the main elements are as follows:

1. The voltage command signal is generated at the wiper of potentiometer R14. This voltage adjusts the exact value of the 48 V bus. It is obtained from a special reference voltage supply centered around amplifier AMP 1A with Zener diode D3 as the basic voltage reference.
2. The actual voltage feedback signal is measured by rectifying the output of a secondary winding of the main inverter transformer. The rectified output is filtered and scaled by potentiometer R12 with the ultimate feedback voltage appearing at the wiper of this potentiometer.
3. The error amplifier, operating on the commanded and actual voltage signals, consists of AMP 1B.
4. The triangular waveform carrier generator is one output of TIMER 1 with the appropriate waveform appearing at pins 6 and 2 of this device. The waveform is buffered by AMP 2 A.
5. The PWM modulator consists of comparator COMP 2A. Here the triangular carrier waveform and the amplified analog voltage error are compared against each other to give as an output the basic width-modulated pulse train.

Pulses produced from the five system elements described above are processed by NAND 2A, FF1B, and NAND 1D and are then amplified by power driver PD1, the output of which drives the base drive transformer of the chopper section of the circuit. Driver PD1 is equipped with a power-up delay circuit of a similar type to that used for PD2.

Current is detected in the shunt resistor R73 of the chopper section, and this resistor voltage is amplified by Q1 in Figure 3.2.5.2-6. The difference between the actual current value and the current limit value set by R29 is amplified and filtered by AMP 2B. The output of AMP 2B is compared with the buffered triangular carrier waveform in comparator COMP 2B. If a current limit condition is in effect, notches are generated at the output of COMP 2B which reduce the on-time of the main chopper transistor by acting on the normal voltage-regulated PWM pulse train passing through NAND 1A at pin 1. If no current limit condition exists, the output of COMP 2B is HIGH.

The circuitry associated with amplifier AMP 3 measures the power supply dc output voltages and scales and adds their absolute values. The scaled output (normally 5 V at pin 1 of AMP 3) is compared against a Zener reference by COMP 4, the output of which becomes LOW when the aggregate of the output voltages falls below the threshold level. This threshold setting can be adjusted by the gain potentiometer R130. A LOW at COMP 4 output produces a LOW at pin 7 of isolator OPTO 1, which in turn produces a HIGH at NAND 2B output, energizing the open collector output provided by Q3, which signifies a logic power supply malfunction. Devices AMP 3 and COMP 4 are energized from the main ± 15 V output, not the internal V_{cc} and V_{ss} supplies.

Comparators COMP 1A, COMP 1B, COMP 3A, and COMP 3B perform additional monitoring functions. Their outputs are wired-OR'ed to feed into the fault indication path at NAND 2B. For healthy operation, the inputs of NAND 2B are normally both high.

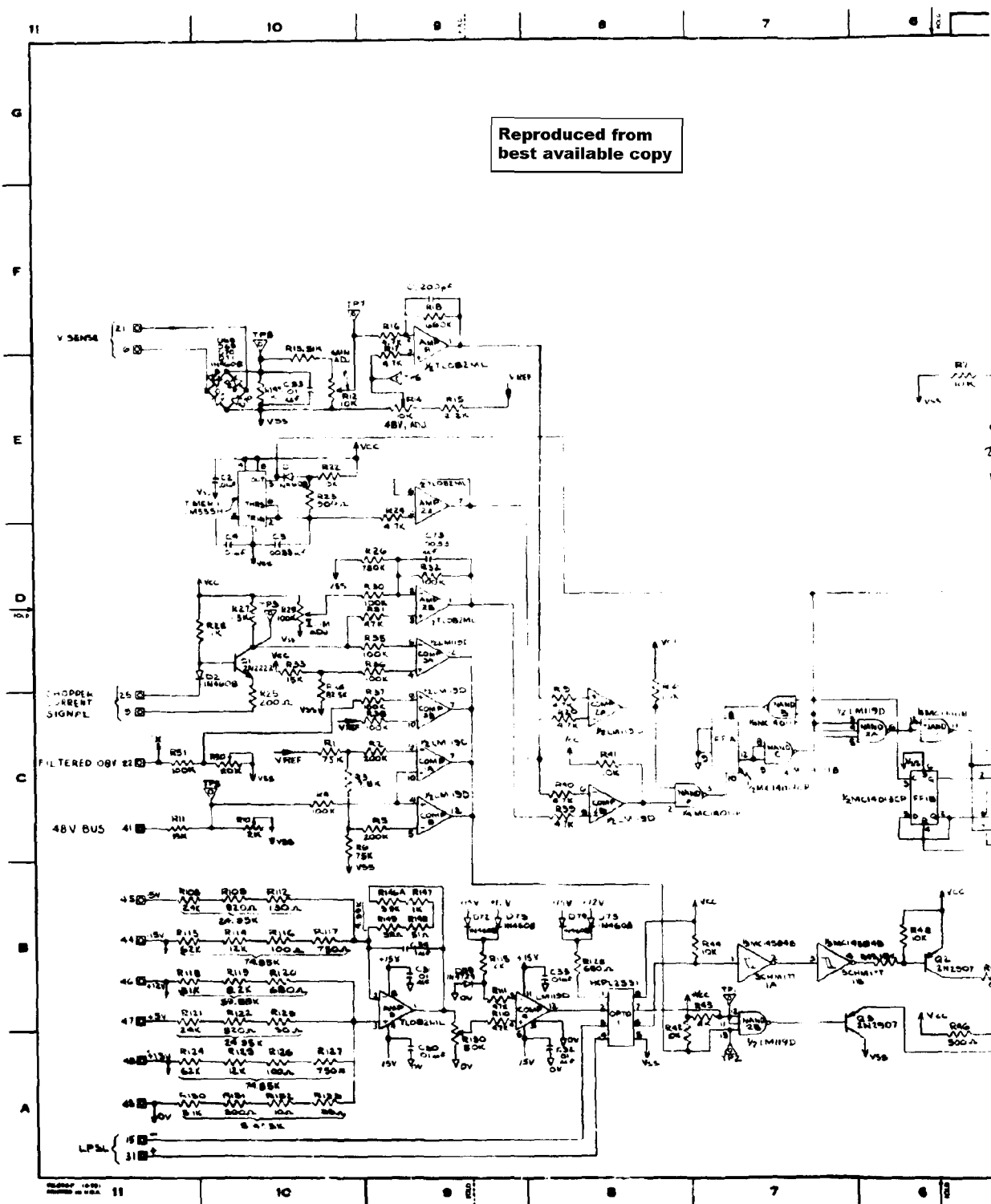
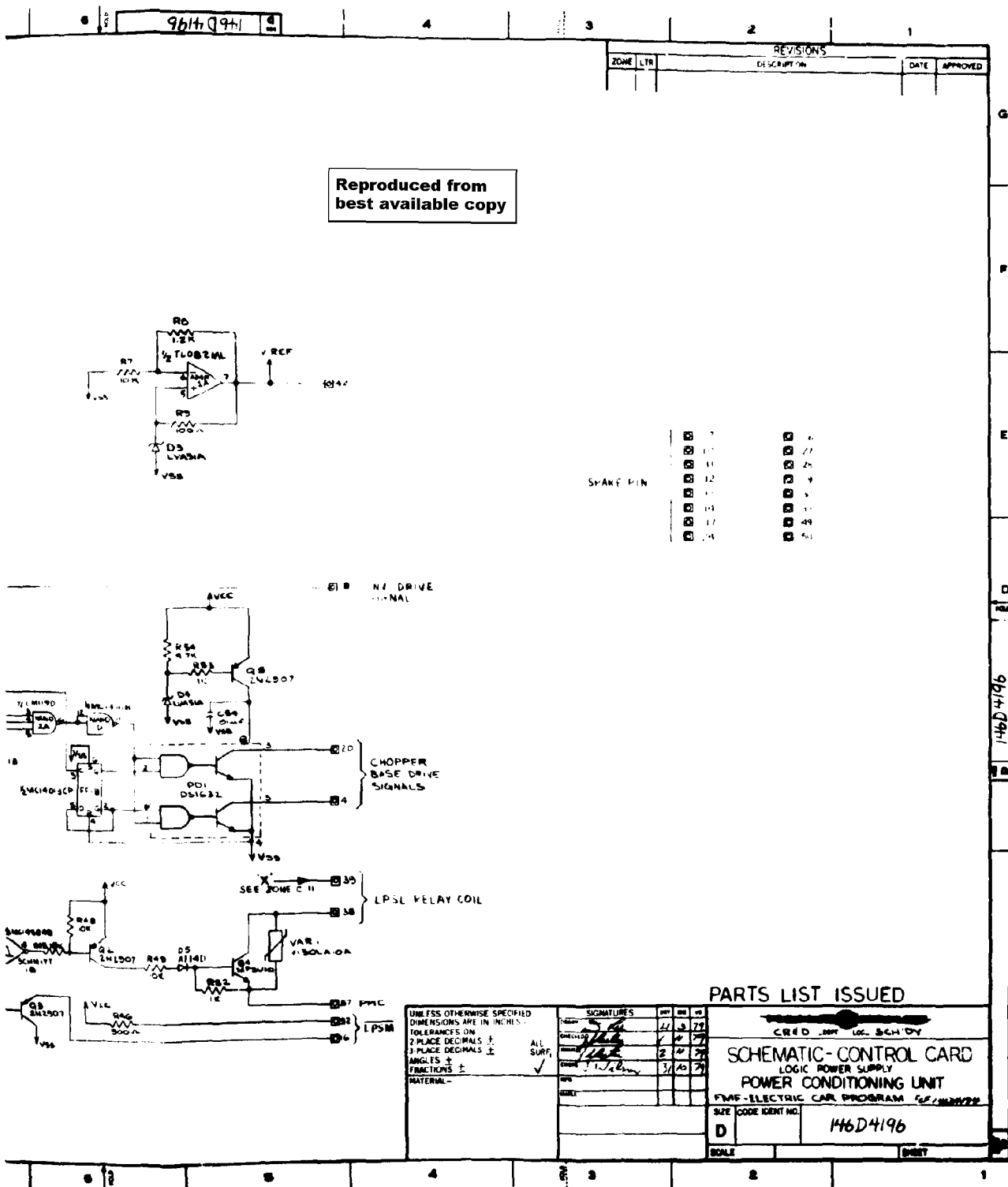


Figure 3.2.5.2-6. Control Sec



3.2-6. Control Section Schematic

3.2-103/104

The circuitry associated with SCHMITT 1, Q2, and Q4 is a relay driver circuit driven by a 16 mA input current and pins 3 and 4 of OPTO 1. This signal controls the state of a KU-type relay (Logic Power Supply Lock) which is connected between card pins 38 and 39.

Internal Power Supply Section. The function of the internal power supply section of the LPS, Figure 3.2.5.2-7, is to provide a nominal +10 V dc supply for use only within the supply for the purpose of powering operational amplifiers, comparators, gates, etc. It is important to note that all operational amplifiers within the supply are operated in a single-sided mode — no negative voltages are used to power these amplifiers, and therefore, all analog control voltages lie between zero and +10 V. V_{CC} and V_{SS} are the symbols assigned to the positive and zero values of this internal supply whereas the designation +15 V, +12 V, +5 V and 0 V are used for the main outputs. Due to transformer and optical isolation, 0 V is not electrically connected within the LPS to V_{SS} .

The operation of the internal supply is centered around the series pass regulator formed by transistor Q29. Unregulated voltages are OR-ed to the collector of Q29 from three possible sources: (a) the secondary winding of the smoothing inductor/transformer of the chopper section, which is transmitted by diode D64, (b) one secondary winding of the main inverter output transformer, which is rectified by diode D67, and (c) voltage transmitted by transistor Q26. Capacitor C41 provides smoothing for these three sources. Transistor Q29 regulates out variation of the average dc voltage on C41 and produces a constant 10 V dc across C43. The basic voltage reference is derived from Zener D66 with transistors Q27 and Q28 forming a stable current source for D66.

The action of the three possible regulator input voltage sources during start-up is critical to safe operation of the LPS. Upon first applying power, the filtered 108 V which is connected to the junction of resistors R136 and R137 is regulated to produce approximately 18 V on C41 by the action of Q25, Q26 and 20 V Zener D63. This is instantaneously converted by Q29 into 10 V dc on C43, and this voltage is sent out into the LPS control circuitry to operate the feedback control mechanism. When the chopper and inverter begin to operate, voltage appears in C41 by virtue of D64 and D67. Voltage also appears on C40 by the rectifying action of D60 on a voltage waveform from a lower secondary tap on the chopper section smoothing inductor/transformer. The voltage thus appearing on C49 acts to switch on transistor Q24, which switches off the Darlington connection of Q25 and Q26, leaving D67 and D64 as the only sources of voltage for charging of C41. This situation remains during normal operation.

Hardware Implementation

The hardware implementation of the LPS consists of six separate parts — three printed circuit boards, two transformers, and one filter capacitor. The three printed circuit board layouts are shown in Figures 3.2.5.2-8, 3.2.5.2-9, and 3.2.5.2-10, the boards being termed the control logic board, the inverter board, and the output/chopper board, respectively.

The two transformers separated from the boards are L 4 (CRD No. 2473) and the main inverter transformer T 5 (CRD No. 2476). The capacitor is the main chopper filter capacitor C24, 4800 μ F, 50 V_W.

Figure 3.2.5.2-11 shows how these six elements are interconnected.

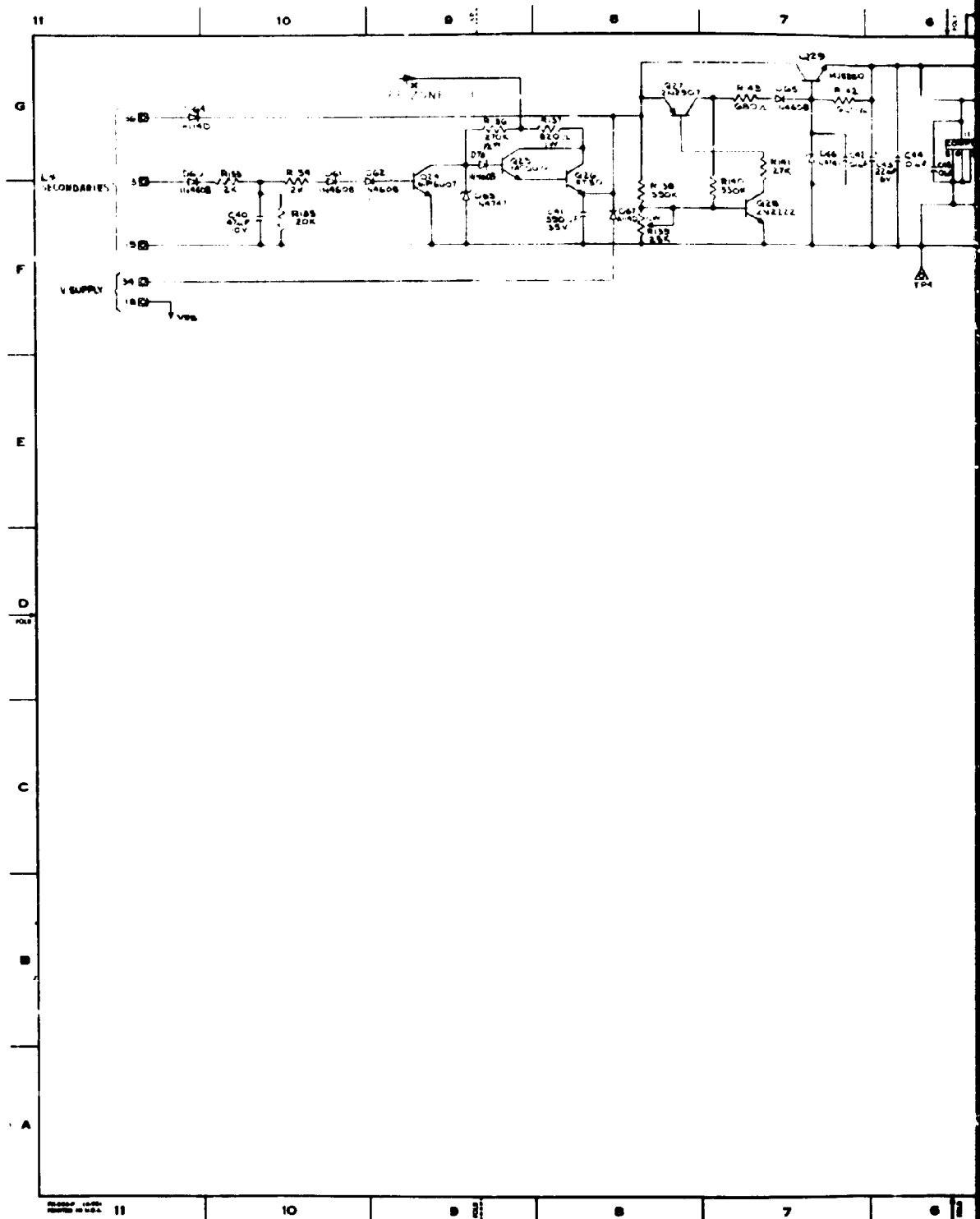


Figure 3.2.5.2-7. Intern

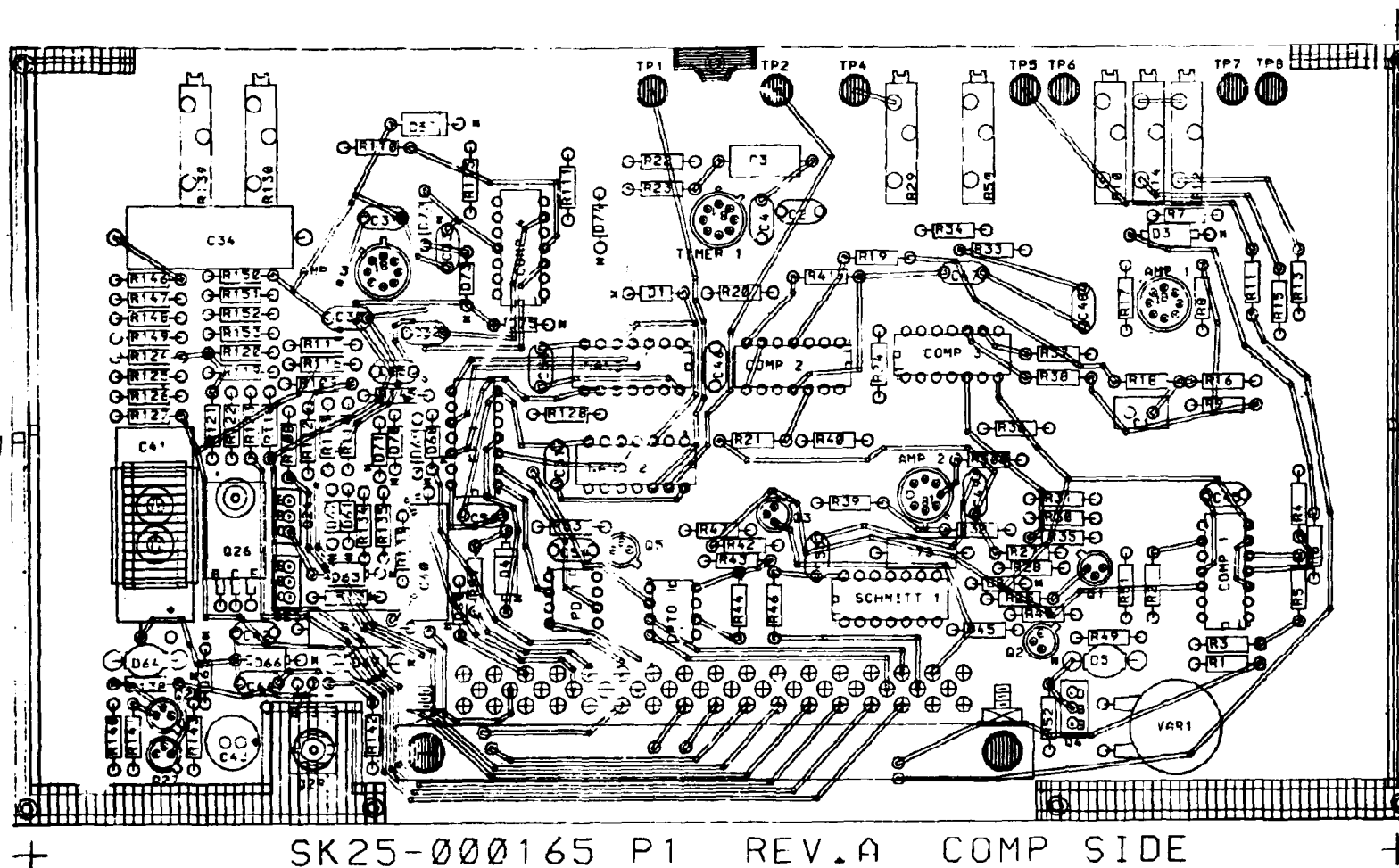
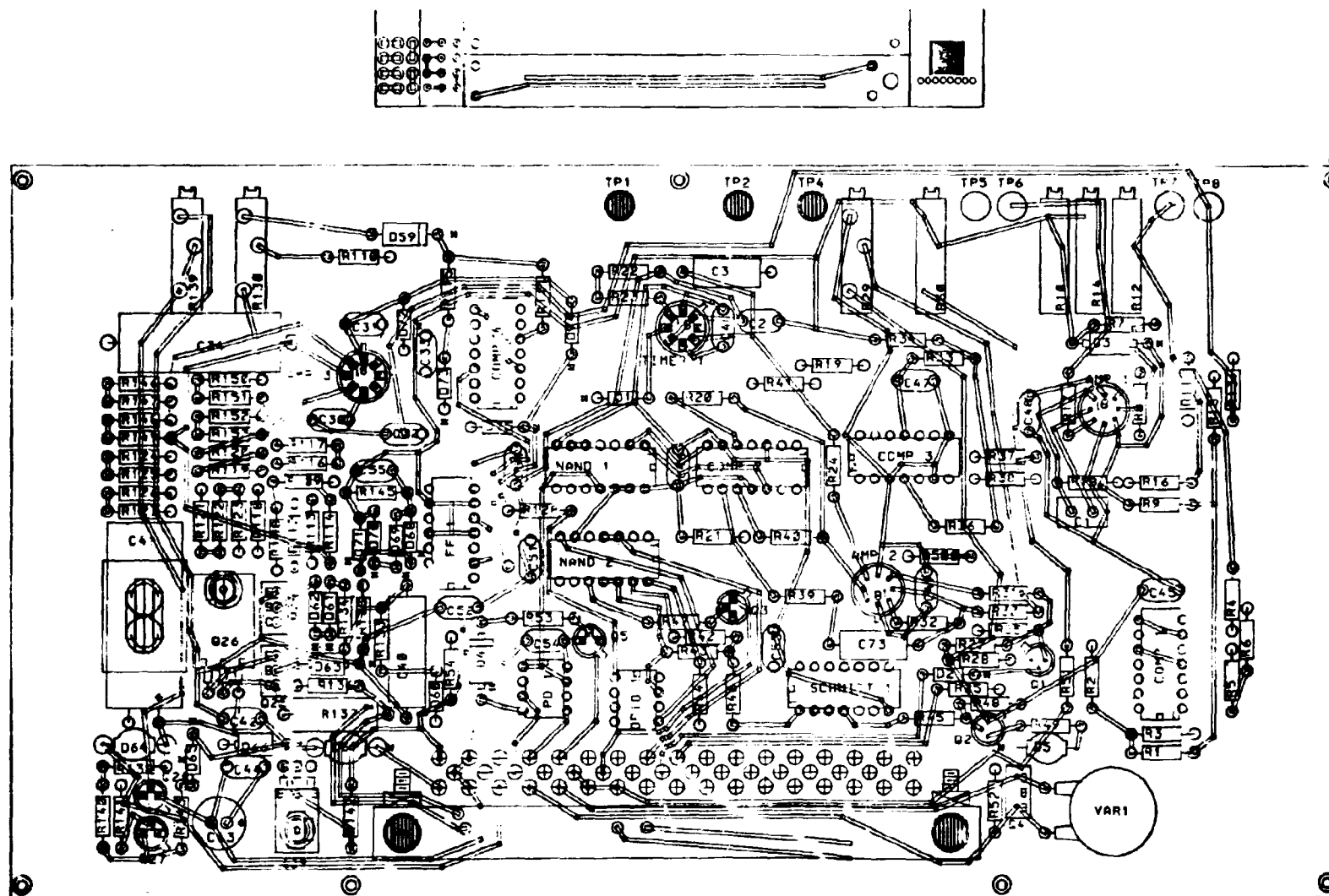


Figure 3.2.5.2-8a. LPS Control Logic Board (Component Side)



SK25-000165 P1 REV. A LEAD SIDE

17 JAN 79

Figure 3.2.5.2-8b. LPS Control Logic Board (Lead Side)

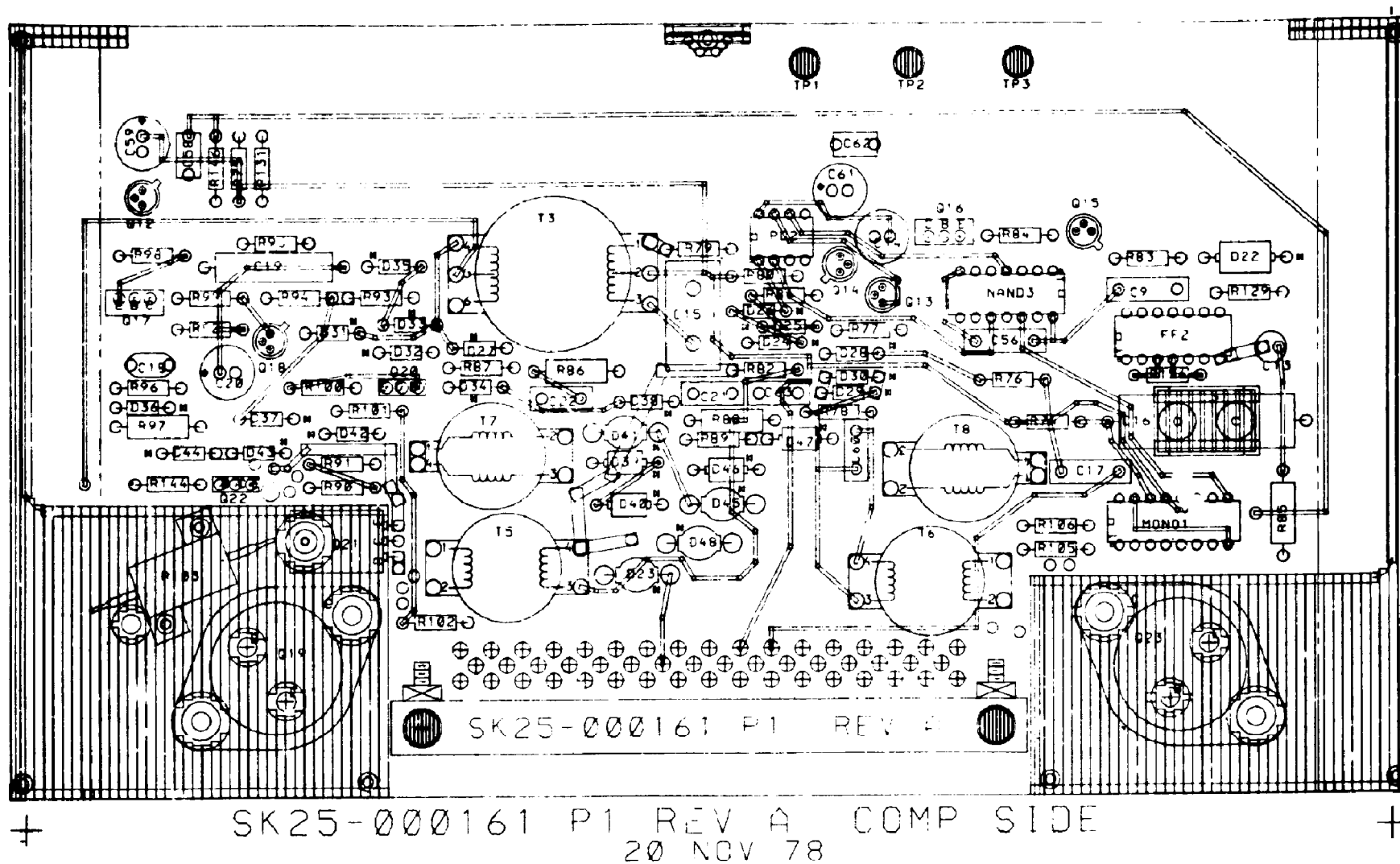
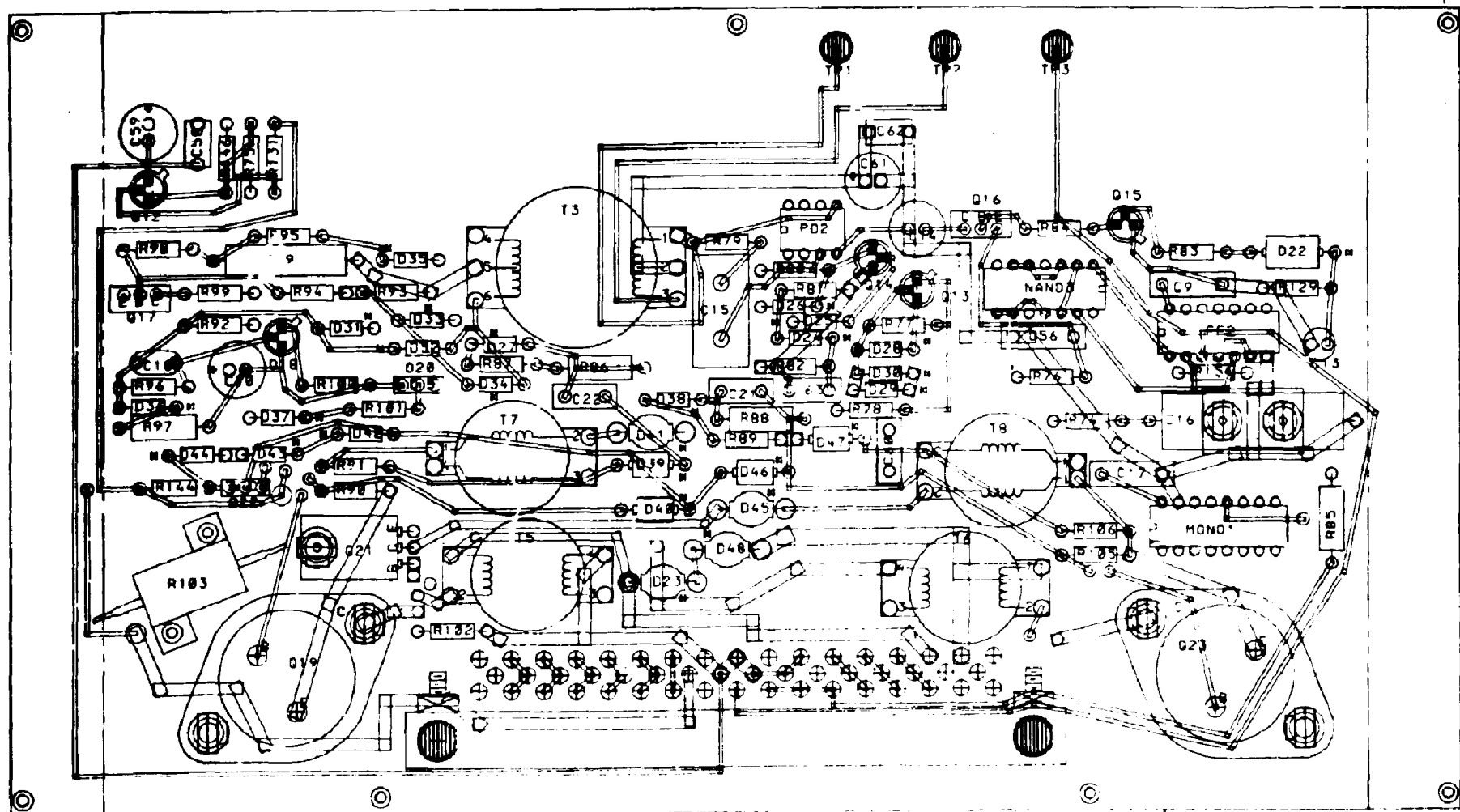


Figure 3.2.5.2-9a. LPS Inverter Board (Component Side)



SK25-000161 P1 REV A LEAD SIDE
20 NOV 78

Figure 3.2.5.2-9b. LPS Inverter Board (Lead Side)

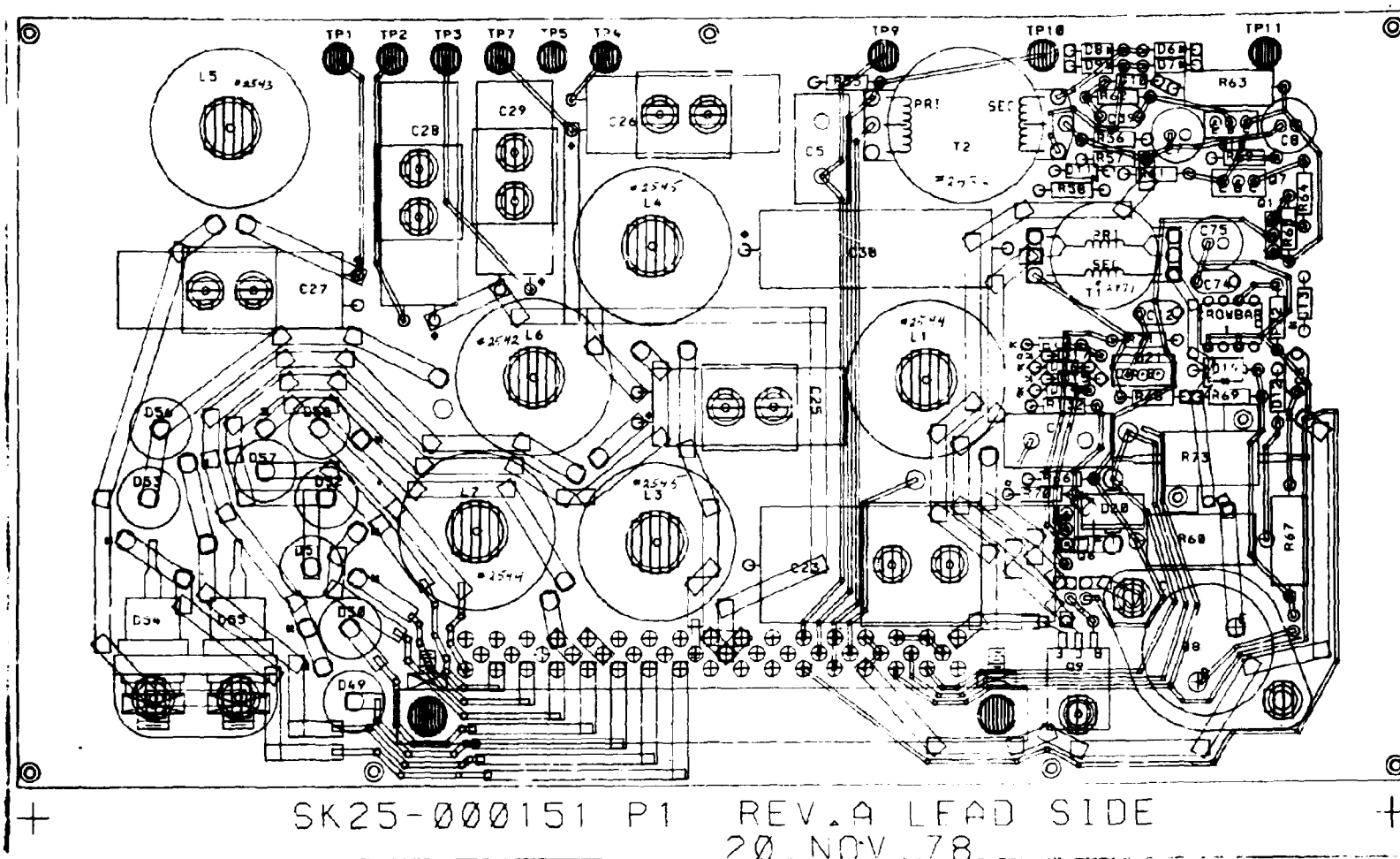


Figure 3.2.5.2-10a. LPS Output/Chopper Board (Component Side)

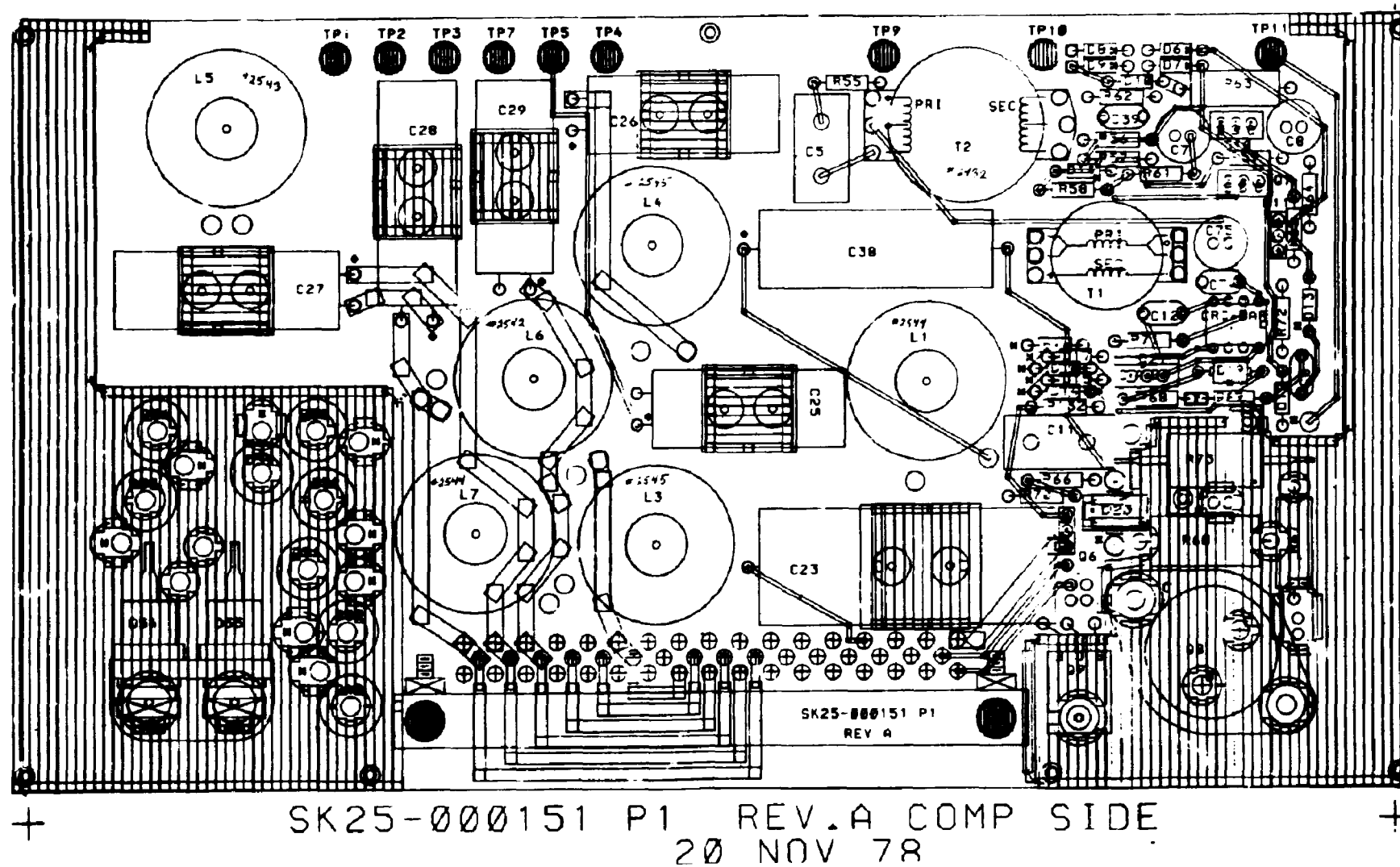


Figure 3.2.5.2-10b. LPS Output/Chopper Board (Lead Side)

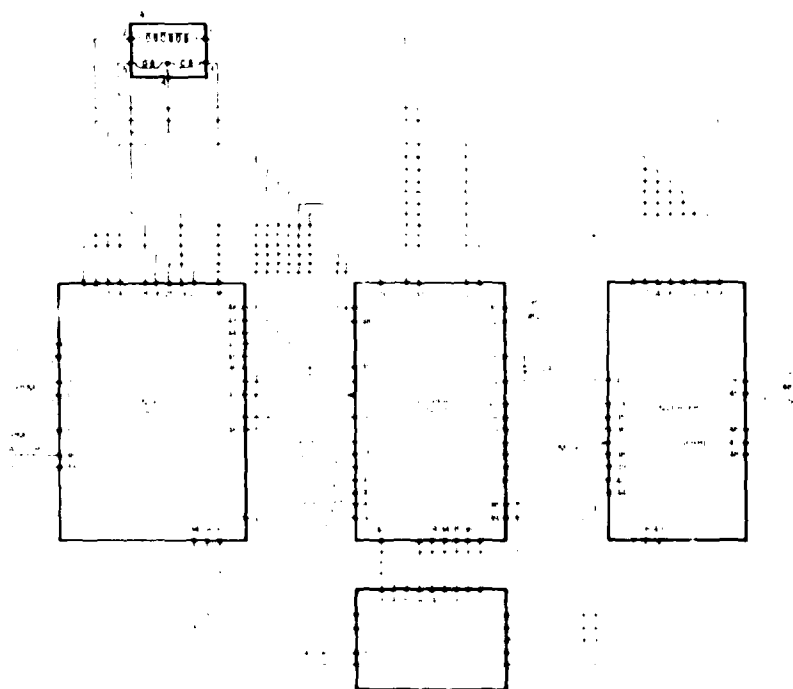


Figure 3.2.5.2-11. LPS Interconnection Diagram

Circuit Data

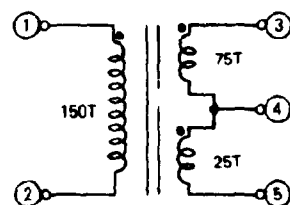
The electrical parts lists supplement the LPS Interconnection Diagram, CRD Drawing No. 146D4194, the LPS Inverter Card, CRD Drawing No. 146D4195, the LPS Control Card, CRD Drawing No. 146D4196, and the LPS Output Card 146D4197. The transformers and reactors used in this supply are unique in their design. The winding details are given here for reference purposes should fabrication of a duplicate component be required.

- CRD #2476

Core: EC52 (See Figure 3.2.5.3-12)

- CRD #2743

Core: EC52



Coil 1: 150 turns #19 AWG wire
Start ①, finish ②

Coil 2: 25 turns #18 AWG wire
Start ④, finish ⑤

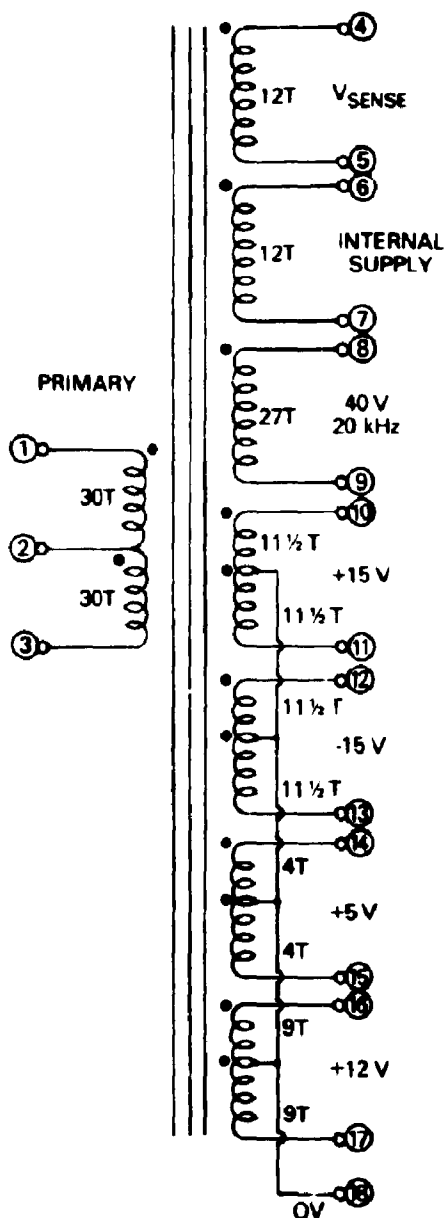
Coil 3: 75 turns #26 AWG wire
Start ③, finish ④

Air gap 0.075 in. per unit, 0.150 in. total. One turn 0.002 in. mylar between Coil 1 and Coils 2 and 3. Cover outer winding with 3-turn Kraft paper.

Reproduced from
best available copy

Secondaries

Winding Data



Layer 1: Six wires #20 AWG arbitrarily numbered 1-6. Start of wires 1,2,3,4 connected together and labeled (14). Wind 4 turns. Finish of wires 5 and 6 connected together and labeled (15). Finish of wires 1,2,3,4 and start of wires 5,6 join together and labeled (18).

Layer 2: Two wires #26 AWG arbitrarily numbered 1,2. Start of wire 1 labeled (4), start of wire 2 labeled (6). Wind 12 turns. Finish of wire 1 labeled (5), finish of wire 2 labeled (7).

Layer 3: Two wires #19 AWG arbitrarily numbered 1,2. Start of wire 1 labeled (1). Wind 30 turns. Finish of wire 2 labeled (3). Start of wire 2 and finish of wire 1 connected together and labeled (2).

Layer 4: Four wires #25 AWG arbitrarily numbered 1,2,3,4. Start of wires 1,2 connected together and labeled (10). Wind 11 1/2 turns. Finish of wires 3,4 connected together and labeled (11). Finish of wires 1,2 and start of wires 3,4 connected to (18).

Layer 5: Four wires #25 AWG arbitrarily numbered 1,2,3,4. Start of wires 1,2 connected together and labeled (12). Wind 11 1/2 turns. Finish of wires 3,4 connected together and labeled (13). Start of wires 3,4 and finish of wires 1,2 connected to (18).

Layer 6: Four wires #23 AWG arbitrarily numbered 1,2,3,4. Start of wires 1,2 connected together and labeled (16). Wind 9 turns. Finish of wires 3,4 connected together and labeled (17). Start of wires 3,4 and finish of wires 1,2 connected to (18).

Layer 7: Two wires #20 AWG arbitrarily numbered 1,2. Start of wires 1,2 connected together and labeled (8). Wind 27 turns. Finish of wires 1,2 connected together and labeled (9).

Figure 3.2.5.2-12. CRD #2476 Connections

- CRD #2471

Core: Indiana General Toroid #F627-8-06

Layer 1: 25 turns #22 AWG: start (3), finish (4)

Layer 2: 5 turns #20 AWG: start (1), finish (2)

- CRD #2432

Core: 2213 P100 3B7 Pot Core

Layer 1: Two wires, #29 AWG, arbitrarily numbered 1,2. Start of wire 1 labeled (1). Wind 50 turns. End of wire 2 labeled (3). End of wire 1 and start of wire 2 connected together and labeled (2).

Layer 2: 0.002 in. copper shield

Layer 3: Two wires, #26 AWG arbitrarily numbered 1,2. Start of wire 1 labeled (6). Wind 25 turns. End of wire 2 labeled (4). End of wire 1 and start of wire 2 connected together and labeled (5).

- CRD #2546

Core: Indiana General Toroid F627-8-06

Layer 1: 40 turns #24 AWG: start (3), finish (4)

Layer 2: 5 turns #18 AWG: start (1), finish (2).

- CRD #2558

Core: Indiana General Toroid F627-8-06

Layer 1: 400 turns #35 AWG: start (3), finish (4)

Layer 2: 5 turns #18 AWG: start (1), finish (2).

- CRD #2541

Core: 2616-3B7 Pot Core

Winding: 20 turns #18 AWG (HF), core gapped with 0.005 in. shim

- CRD #2545

Core: 2616-3B7 Pot Core

Winding: 30 turns #18 AWG (HF), core gapped with 0.005 in. shim

- CRD #2543

Core: 2616-3B7 Pot Core

Winding: 10 turns #16 AWG (HF), core gapped with 0.005 in. shim

- CRD #2542

Core: 2616-3B7 Pot Core

Winding: 40 turns #20 AWG (HF), core gapped with 0.005 in. shim

Operating Waveforms

Chopper Section. Figure 3.2.5.2-13 shows collector and base current waveforms of power transistor Q8 with a dc input voltage of 80 V dc and an input dc current of 0.5 A established by a resistive load connected to the 40 V ac winding.

Top Trace: Collector current
0.5 A/div

Bottom Trace: Base current
0.5 A/div

Time Base: 10 μ s/div



Figure 3.2.5.2-13. Q8 Waveforms

Figure 3.2.5.2-14 shows a waveform typical of base current of the fast "emitter-switch" transistor Q9. Note the substantial negative base drive. The operating conditions match those of Figure 3.2.5.2-13.

Vertical: 100 mA/div

Horizontal: 10 μ s/div



Figure 3.2.5.2-14. Q9 Base Drive

Inverter Section. Figure 3.2.5.2-15 shows a typical voltage waveform of the 40 V ac winding when this winding is loaded with a purely resistive load. The position of the 4 μ s steps superimposed upon the basic square wave varies as a function of load.

Vertical: 20 V/div
Horizontal: 20 μ s/div

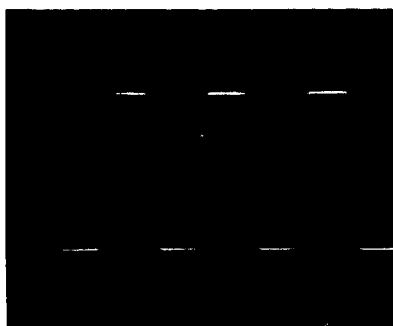


Figure 3.2.5.2-15. 40 V Square Wave Output

Figure 3.2.5.2-16 shows the collector current waveforms of inverter power transistors Q19 and Q23 measured under the operating condition of 80 V dc supply input with the 40 V winding loaded resistively so as to produce an input current from the 80 V supply of 1 A.

Vertical: 1 A/div
Horizontal: 20 μ s/div

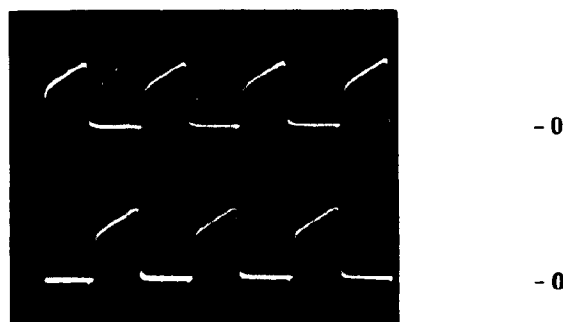


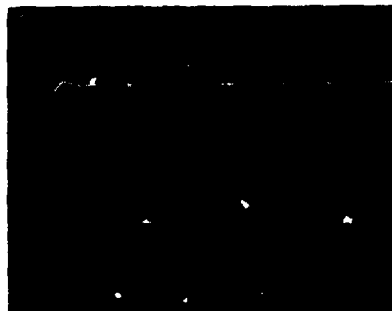
Figure 3.2.5.2-16. Collector Currents of Q19 and Q23

It is important to note the alternating conduction of these transistors and the existence of a dead band between conduction. The waveform of the collector current of Q21 is the sum of the currents of Q19 and Q23.

An important waveform in the base drive circuitry is the waveform appearing at the common cathode junction of D33 and D34. This is shown in Figure 3.2.5.2-17. Of importance in this waveform is the negative notches which operate the base drive of Q21. The waveform at the common anode connection of D31 and D32 is an inverted version of that in Figure 3.2.5.2-17.

Control Section. One of the most important waveforms in the entire power supply is the waveform at the cathode of D1, Figure 3.2.5.2-18, which is the basic clock output of the LM555 timer. This waveform sets the operating frequency of the supply.

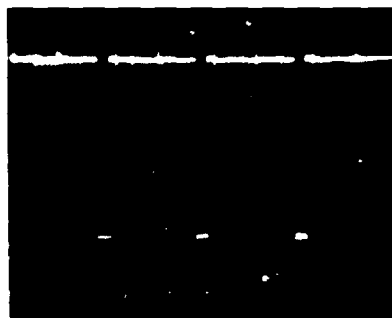
Vertical: 1 V/div
Horizontal: 10 μ s/div



-0

Figure 3.2.5.2-17. Waveform at Common Cathode Connection of D33 and D34

Vertical: 2 V/div
Horizontal: 10 μ s/div



-0

Figure 3.2.5.2-18. LM555 Output

Major Sources of Loss. Typical operating loss figures are given for certain components in the supply. The figures relate to an operating condition of 200 W output total.

<u>Circuit</u> <u>I.D.</u>	<u>Device</u> <u>Type</u>	<u>Typical</u> <u>Loss</u>
Q8	2N6546	10 W
Q9	D44H11	4 W
Q19	2N6546	6 W
Q23	2N6546	6 W
Q21	D44H11	4 W
Q29	MJE220	3 W

WBS 3.2.5.3 On-Board Charger Power Unit

The on-board charger power unit (OBCPU, Figure 3.2.5.3-1) serves as the interface for 115 V ac power with circuit interruption and protection for the drive subsystem. The

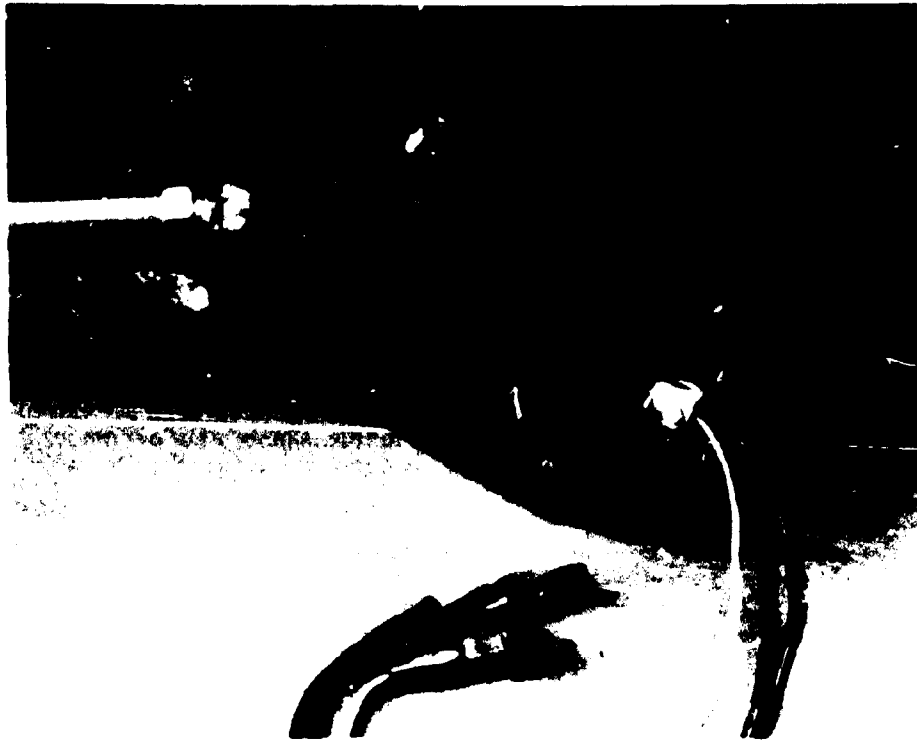


Figure 3.2.5.3-1. On-board Charger Power Unit (OBCPU)

115 V power is used for charging the electric vehicle's batteries while connected to an external power source.

The OBCPU is permanently installed in the car, interposed between the 115 V, 60 Hz power receptacle (located behind the front license plate) and the power conditioning unit (PCU). Its primary functions are as follows.

- Power Contactor – provides the means for interrupting both lines of the 115 V, 60 Hz power through use of the hood interlock switch.
- Ground Fault Current Interruption – a GE ground fault sensing device that provides equipment and personnel protection by sensing excessive leakage current to the chassis and automatically tripping its two pole circuit breakers.
- Electromagnetic Interference (EMI) Filtering – a two-line-to-ground filtering network which serves to reduce electrical noise passing from the car's drive subsystem to the 115 V power mains or to radiate interference to other electrical equipment outside the car. This filter also minimizes the possibility of spurious signals entering the car's drive subsystem by means of the same power mains.
- Interlock Protection – serves to maximize safety by preventing contact with the 115 V ac source by providing a car hood electrical interlock switch which controls the power contactor energization. A further safeguard is provided by means of the power cable plug closing electrical switch contacts when inserted into the main power receptacle.

- **115 V, 15/30 A Charge Sensing** – distinguishes between the available power from the 115 V, 60 Hz utility mains for battery charging. Two different power cords are available for charging from either 15 or 30 A sources. The 30 A cord set is wired to initiate a unique contact closure to the microcomputer circuitry.

The electrical functions of the On-Board Charger Power Unit electrical schematic (Figure 3.2.5.3-2) are discussed in detail as follows:

1. **Primary electrical power (115 V ac, 60 Hz)** is controlled by means of the K3 power relay, a 30 A-rated, 2 PST contactor. This relay also has Auxiliary 1SPST set up contacts which are used to power the battery compartment purge fan during the battery charging operation. The K3 relay is a direct current device powered by means of the rectifier bridge comprised of diodes CP5, 6, 7 and 8. The 115 V ac energy for this bridge is through the car hood interlock contacts of relay K2; operation in this manner provides personal safety by isolating the 115 V ac mains from the Power Control Unit whenever the car hood is opened.
2. **Ground fault interrupter (CB1)** is a two pole current breaker designed to open the circuit when leakage (or unbalanced) electrical currents are detected in excess of approximately 11 mA; such action serves to protect personnel and equipment from excessive leakage current or faulty components.
3. **The 115 V, 15/30 A Charge Sense** is provided by the K1, dc relay, and the associated rectifier bridge is comprised of CR1, 2, 3, and 4; resistor R1 serves to drop the rectified voltage to approximately 24 V dc; Capacitor C1 is connected across the K1 relay to reduce the ac ripple component preventing the chattering or buzzing action of this relay's coil and contacts.

15/30 A charging sense is provided by appropriate wiring of the female plug and of the charge cable. When the 30 A cable is used, the K1 relay and its rectifier bridge become energized. The K1 contacts then close providing a signal to the microcomputer which permits use of the 30 A charging capacity. The lower charge rate of 15 A exists when K1 is left unactivated; this occurs with the appropriate input charging cable/plug wiring arrangement.
4. **Circuit Protection and Radio Frequency Interference Rejection** are afforded by the respective VAR 1 and FL 1 components. The varistor (VAR 1) diminishes transient voltage spikes by offering a low-impedance break-down path to voltages in excess of the 115 V ac main power. The Radio Frequency Interference filter is an inductive-capacitive low-frequency pass filter which serves to bypass high-frequency electrical noise voltages to the electrical ground; this action is bilateral in its function; thus, entrance or exit of spurious RF electrical signals from the electric car is effectively reduced.
5. **Other Circuits.** The OBCPU also serves as a junction point for other electrical circuits; these are: motor field connections, Accessory battery connections, and the Battery Charging "plug is in" switch closure intelligence signal connections to the microcomputer.

Figure 3.2.5.3-2. On-Board Charger Power Unit Electrical Schematic

WBS 3.2.6 Microcomputer Control

WBS 3.2.6.1 Microcomputer Functions

The electric vehicle has a microcomputer-based control system whose functions can be summarized as follows:

- Propulsion control
- Drive sequencing
- Fuel gauging
- Battery charging/equalization
- Diagnostics

WBS 3.2.6.2 Propulsion Control

Propulsion Control Description

A block diagram of the drive control system is shown in Figure 3.2.6.2-1. Essentially, it is a torque-controlled system, where the motoring and regeneration braking torques are commanded by the driver with the accelerator and brake pedals respectively. The main power circuit of the drive system consists of a two-quadrant transistor chopper which modulates the power flow from the battery E_B to the armature of a separately excited dc motor. The transistor T_1 and diode D_2 operate in a quadrant and develop the motoring torque, whereas the transistor T_2 and diode D_1 generate the regeneration torque pumping vehicle energy back to the battery. A bypass contactor (BPC) connects the battery directly across the armature, and the chopper is bypassed in the power circuit. The field current of the motor is supplied through another chopper consisting of transistor T_3 and diode D_3 , but it can be reversed by a set of contactors permitting speed reversal of the motor. The reversible field with the two-quadrant armature chopper permits four-quadrant drive capability of the system.

The command torque of the drive motor translates to the armature current command (I_a^*) which is then regulated by closed loop control. Between zero and base speed of the motor, the armature current (I_a) is controlled by varying the time ratio of the armature chopper, while maintaining a constant field current. With this condition, the developed torque is directly related to the armature current. If the command is transferred from acceleration to braking, the polarity of I_a^* reverses, in turn transferring chopping control from transistor T_1 to T_2 . Near the base speed of the motor, when the time-ratio reaches saturation, the bypass contactor is closed to impress the battery E_B directly across the armature. Over the higher speed range, the field current is regulated to control the armature current in either direction. In this mode, the torque sensitivity is somewhat lower than that in the chopping mode. During the coasting condition of the vehicle, an internally generated current command I_B simulates the equivalent compression braking of a gasoline car.

Figure 3.2.6.2-2 shows the simplified diagram of the operation modes of the vehicle and the possible directions of transition. Since the vehicle speed is restricted in the reverse direction, the field control modes are not permitted.

In Figure 3.2.6.2-1, the area within the dotted line is the domain of microprocessor control. As mentioned before, there are two feedback control loops for armature current control: one in the armature chopping mode and the other in the field control mode.

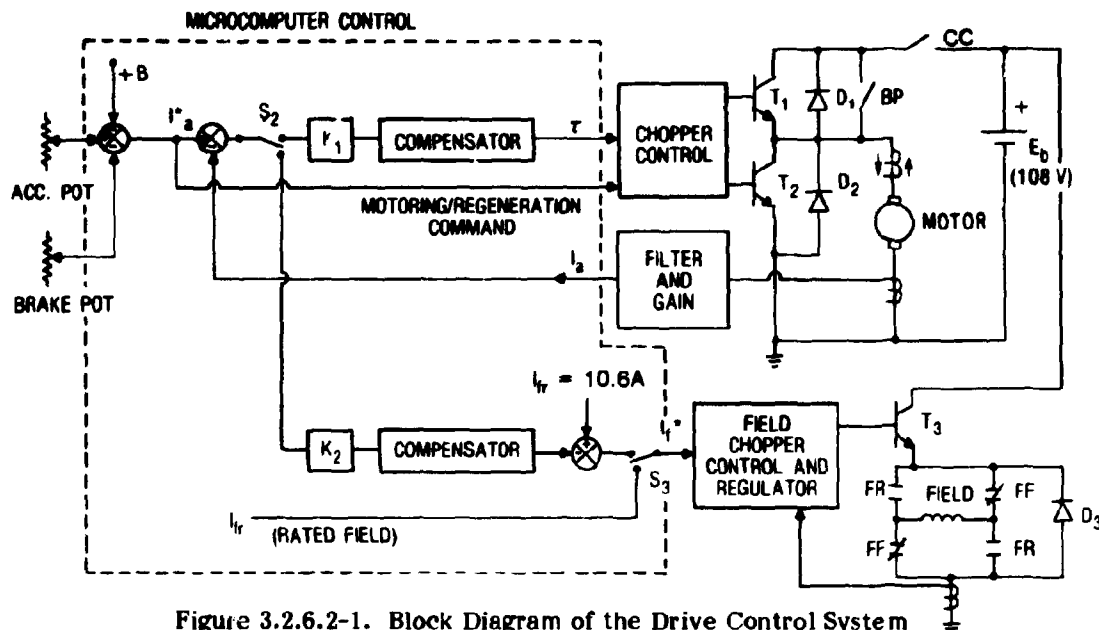


Figure 3.2.6.2-1. Block Diagram of the Drive Control System

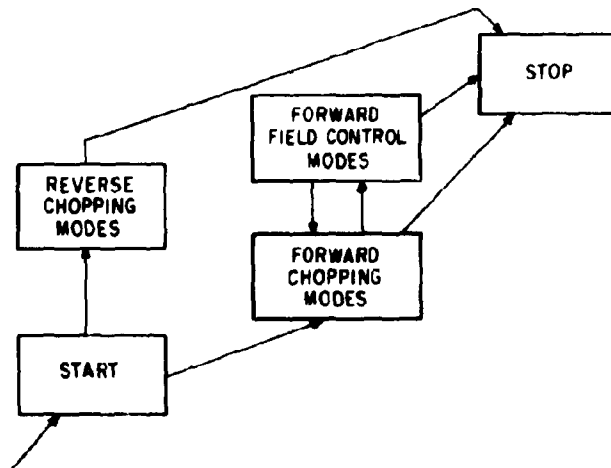


Figure 3.2.6.2-2. Operation Modes Diagram Simplified

In the chopping mode, the command current is compared to the feedback current, and the resulting error signal generates the analog time-ratio signal τ through an amplifier and a compensator. In the field control mode, the signal through the amplifier and compensator subtracts from the rated field current I_r to generate the command i_f^* for the field control circuit. The particular hardware and software partitioning is based on an independent debug and test capability of the microcomputer, armature chopper, and field chopper circuits. In addition, it provides limited drive capability of the vehicle in case of microcomputer malfunction.

System Analysis

As stated before, the microcomputer will have the responsibility of controlling two feedback loops of the propulsion controller, i.e., the armature chopper control loop which provides motoring and regeneration torques in the forward direction and motoring torque in the reverse direction; and the field weakening control loop which provides motoring and regeneration torques in the forward direction. The drive system with high inertia can be considered as a speed control system in the outer loop (by the human operator) and a current or torque controller in the inner loop. Therefore, the static accuracy and dynamic response requirements of the inner-loop are not very stringent. In fact, the torque response of the system should intentionally be made sluggish so that no jerk is developed during acceleration and braking.

Armature Chopper Control Loop. The armature chopper control loop can be modeled as a transfer function block diagram, shown in Figure 3.2.6.2-3. A lag-lead compensator is incorporated in the loop for stabilization. The uncompensated loop gain function can be given as

$$A(s) = \frac{K e^{-T_1 s}}{(1 + \tau_4 s)(1 + \tau_5 s)}$$

where

K = dc loop gain

T_1 = half cycle dead time lag due to chopper

τ_4 = time constant of the armature circuit

and τ_5 = armature current filter time constant.

The approximate values of the parameters affecting the system control loops are given in Table 3.2.6.2-1. The parameters K and τ_4 will vary depending on the battery terminal voltage and armature circuit saturation respectively.

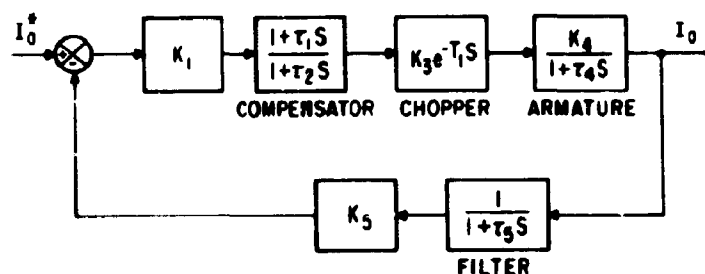


Figure 3.2.6.2-3. Transfer Function Block Diagram of the Armature Chopper Control Loop

The loop should be designed such that in the worst case it remains stable with reasonable overshoot. A Bode diagram of the loop gain function is plotted with nominal values of the parameters and $K = 64$. This results in a crossover frequency $\omega_c \approx 820$ rad/sec

Table 3.2.6.2-1

PARAMETERS AFFECTING THE SYSTEM CONTROL LOOPS

Parameter	Approximate Value
Field inductance L_f	= 171 mH (low current) = 21.13 mH (high current)
Field resistance R_f	= 4.4 Ω (cold) = 5.67 Ω (hot)
Battery internal resistance R_B	= 0.102 Ω (80°F)
Armature resistance R_a	= 0.0454 Ω ($I_a < 250A$) = 0.041 Ω ($I_a > 250A$)
Armature inductance L_a	= 1.1 mH (low current) = 0.024 mH (high current)
Counter emf constant K_b	= 0.05
Torque constant K_t	= 0.352

and the computation of phase margin shows that the loop is highly unstable. Incorporating a lag-lead compensator with $\tau_1 = 0.01$ sec and $\tau_2 = 2$ sec shows that the loop is stable with $W_c \approx 82$ rad/sec and phase margin $\theta_c = 37.7^\circ$.

In the worst case, if K decreases by a factor of 2, the loop becomes more stable at the cost of poorer accuracy and sluggish response time, but these can be tolerated in an EV application.

The analog equivalent circuit of the compensator with op amp is shown in Figure 3.2.6.2-4. Since the microcomputer has to execute the compensator function, it has to be translated into the digital domain.

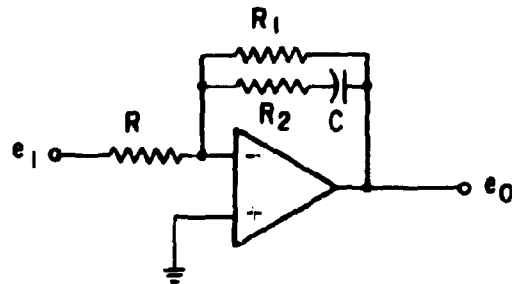


Figure 3.2.6.2-4. Analog Equivalent Circuit of the Compensator

The general state equations of the compensator are:

$$v_c = A v_c + B e_1 \quad (3.2.6-1)$$

$$e_o = C v_c + D e_1 \quad (3.2.6-2)$$

where

$$A = \frac{1}{\tau_2}, B = \frac{1}{\tau_2}, C = \frac{\tau_2 - \tau_1}{\tau_2} \text{ and } D = \frac{\tau_1}{\tau_2}.$$

The state equations in discrete time domain can be given as

$$v_c(kT + T) = G(T) v_c(kT) + H(T) e_1(kT) \quad (3.2.6-3)$$

$$e_o(kT) = C v_c(kT) + D e_1(kT) \quad (3.2.6-4)$$

where

$$T = \text{sampling period, } G(T) = e^{AT} \text{ and}$$

$$H(T) = \left[\int_0^T e^{AT} dt \right] B.$$

By substituting the parameters, the equations (3.2.6-3) and (3.2.6-4) can be written as

$$v_c(kT + T) = e^{\frac{1}{\tau_2} T} v_c(kT) + 1 - e^{\frac{1}{\tau_2} T} e_1(kT) \quad (3.2.6-5)$$

$$e_o(kT) = \frac{\tau_2 - \tau_1}{\tau_2} v_c(kT) + \frac{\tau_1}{\tau_2} e_1(kT) \quad (3.2.6-6)$$

The simulation diagram for equations (3.2.6-5) and (3.2.6-6) is shown in Figure 3.2.6.2-5. In the diagram, $\tau_1 = 0.01$ sec, $\tau_2 = 2$ sec and T = sampling period of the loop. The choice of T depends on the subsystem stability requirement and the basic computation time available. Assuming loop computation time to be approximately one millisecond, the sampling period of four milliseconds will be satisfactory. This will provide three milliseconds for other computations.

Field Weakening Control Loop. The transfer function block diagram of the field control loop is shown in Figure 3.2.6.2-6. The uncompensated loop gain function is given as

$$A(s) = K \frac{W}{(1 + \tau_3 s)(1 + \tau_4 s)(1 + \tau_5 s)}$$

where

$$K = \text{dc loop gain}$$

$$\tau_3 = \text{equivalent field circuit time constant}$$

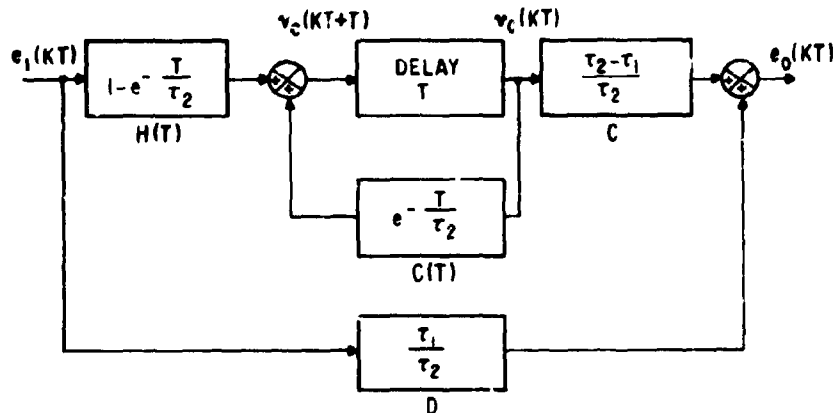


Figure 3.2.6.2-5. Simulation Diagram of Digital Compensator

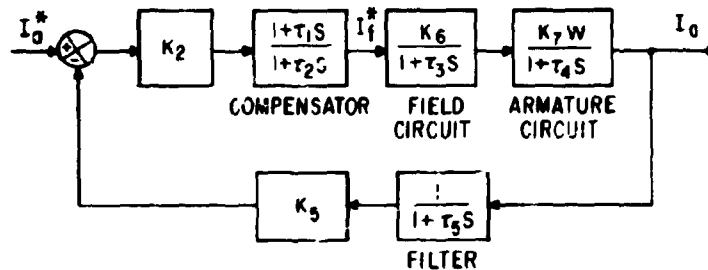


Figure 3.2.6.2-5. Transfer Function Block Diagram of the Field Control Loop

- τ_4 = armature-battery circuit time constant
- τ_5 = armature current filter time constant
- w = motor speed

It is apparent that speed variation will offer a variable gain in the loop and the field saturation will cause considerable amount of nonlinearity. A Bode diagram of the loop gain function is plotted with nominal values from Table 3.2.6.2-1, and it shows that the loop is highly unstable. It is desirable to use the compensator transfer function of the chopper control loop to economize the software development time and memory requirement. After a few iterations, it was found that for a speed variation range of 2:1, $K = 5.76$ will be satisfactory.

Hybrid Computer Simulation

Once the paper design of the feedback control loops was completed a hybrid computer simulation of the drive subsystem was performed. The simulation determined the optimum values of gain, sampling interval, and compensator parameters by iteration, and also verified the digital control algorithm. An EAI 681 hybrid computer was used which essentially consists of an analog computer with logic simulation and a digital mini-computer (PACER 100). The functional components of the drive system that consist of battery, chopper, motor, and vehicle are modeled by mathematical equations which are as follows:

- Battery

$$e_d = E_b - i_a R_B \quad (3.2.6-7)$$

- Motor

$$\text{Armature} \quad N\phi_a = \int (e_d - e_b - i_a R_a) dt \quad (3.2.6-8)$$

$$i_a = f(N\phi_a) \quad (3.2.6-9)$$

$$\text{CEMF} \quad e_b = K_b N\phi_g W \quad (3.2.6-10)$$

$$\text{Field} \quad N\phi_f = \int (E_f - i_f r_f) dt \quad (3.2.6-11)$$

$$i_f = f(N\phi_f) \quad (3.2.6-12)$$

$$\text{Torque} \quad T = K_t N\phi_g i_a \quad (3.2.6-13)$$

- Vehicle

$$T = \frac{1}{C_3} J \frac{dw}{dt} + C_2 W^2 + C_1 \quad (3.2.6-14)$$

The drive subsystem was simulated in analog computer language, and the digital minicomputer control portion was programmed in Fortran with the interface provided by 8-bit AD/DA converters. The time scale factor for the simulation is 50, consequently the Fortran execution delay can be neglected for stability purposes.

Once the time-scaled simulation of the drive subsystem was operating satisfactorily on the hybrid computer, the control was translated into Intel 8080 real time software (described later). The drive subsystem was then simulated in real time and was interfaced with the prototype 8080 control software resident in the microcomputer development system (MDS 800).

Figure 3.2.6.2-7 shows the simplified real time simulation diagram where saturation and armature reaction effects are neglected. Since speed is a slow variable and is outside the control loop, it can be fixed as an independent adjustable variable.

The drive subsystem performance was tested in real time under both static and dynamic conditions. Figure 3.2.6.2-8 shows the steady-state performance in the chopping mode at a preset speed of 1200 rpm. The on-time ratio T_{on}/T is proportional to τ , and it starts with a large initial offset value because of the counter emf of the motor. The small amount of nonlinearity of the curve is due to internal resistance of the battery. Figure 3.2.6.2-9 shows the transient response at the chopping mode with a step input of I^* at a zero initial speed condition. The speed variation is very slow because of large vehicle inertia and virtually does not affect the loop responses. As shown in the figure, the response is underdamped, and the armature current rise time is approximately 200 ms, which is acceptable for the EV drive system. Figure 3.2.6.2-10 shows the steady-state performance in the field control mode and Figure 3.2.6.2-11 gives its step function response. In this mode, the speed affects the loop gain directly, and it is locked to a fixed value for both figures. The approximate computation times in the chopping and field control modes were found to be 800 μs and 1 ms, respectively. The simulation response appears to be quite satisfactory. The successful operation on the hybrid computer with real time software provides confidence for the successful operation of the drive subsystem feedback control loops.

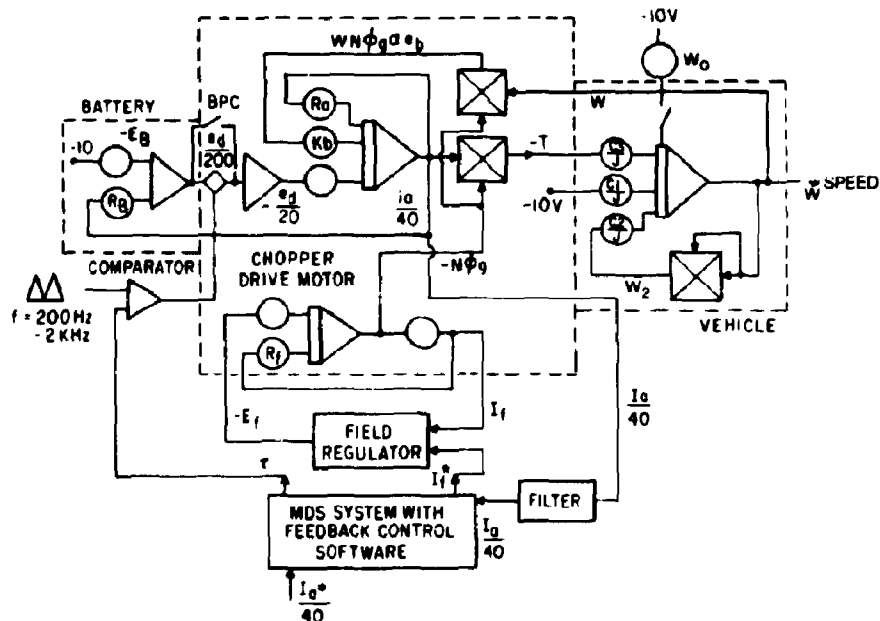


Figure 3.2.6.2-7. Simplified Real Time Simulation of the Drive System

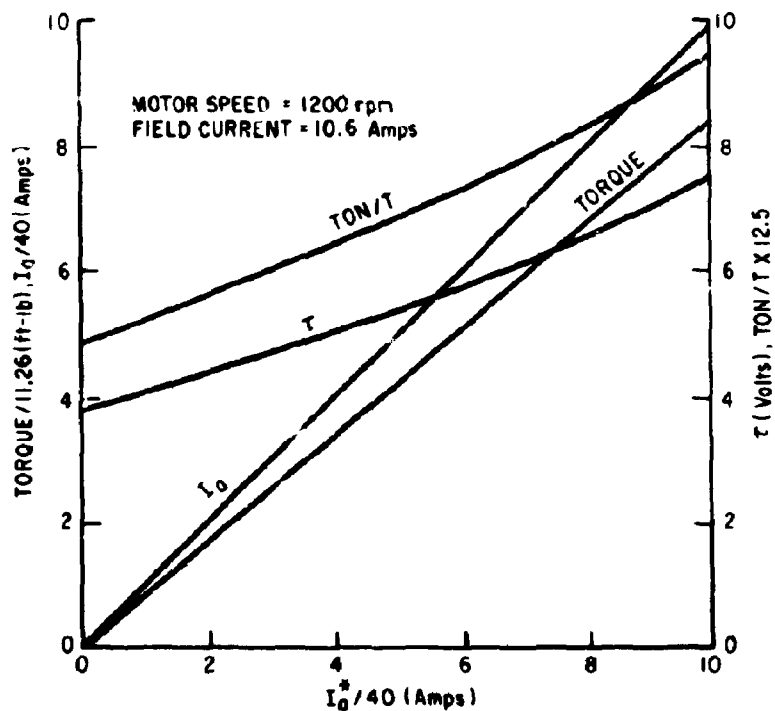


Figure 3.2.6.2-8. Simulation Performance Characteristics in Chopping Mode



Initial $w = 0$

Top: ω (1V = 600 rpm)

Middle: τ

Bottom: I_a (1V = 40A)

Figure 3.2.6.2-9. Transient Response in Chopping Mode at $W = 0$

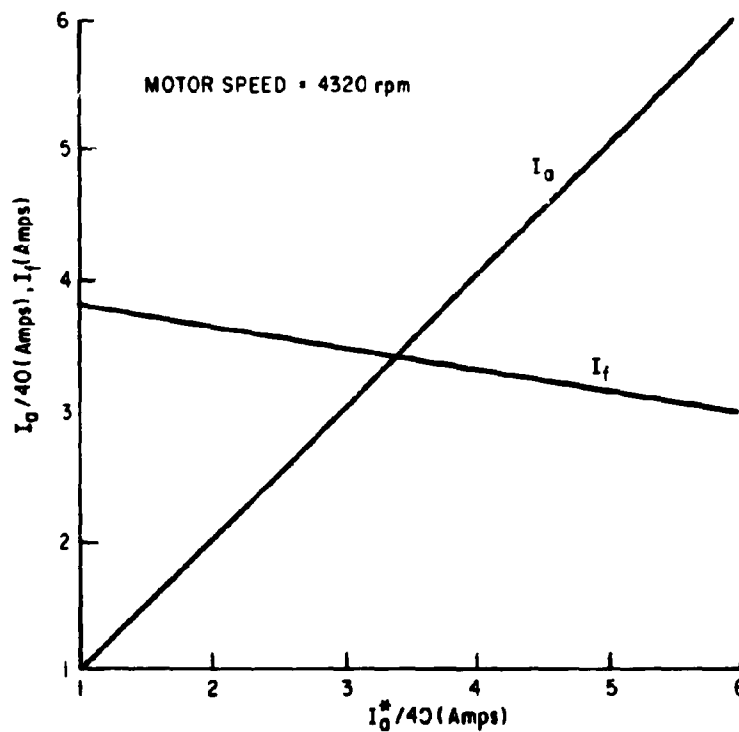


Figure 3.2.6.2-10. Simulation Performance Characteristics in Field Control Mode



Top: I_f (4A/div)

Bottom: I_a (90A/div)

Time Scale 0.5 sec/cm

Figure 3.2.6.2-11. Transient Response in Field Weakening Mode at $W = 3000$ rpm

WBS 3.2.6.3 Drive Sequencing

Drive subsystem sequencing control is a complex function performed by the microcomputer. The various modes of operation of the drive subsystem and the transition between the modes depends on the commands of the driver and the internally generated software signals.

Description of I/O Signals

A block diagram of the microcomputer with the various analogous digital I/O signals is shown in Figure 3.2.6.3-1. A brief description of the signals is as follows:

● Analog Signals

- BVCH - the main battery terminal voltage which indirectly indicates the state of charge of the battery. The signal is used for battery charging and regeneration to hydraulic brake blending.
- BVFG - the battery voltage under normal operating conditions. Good resolution of the signal is available and is used for fuel gauging computation.
- BC - the main battery current signal which is used for fuel gauging computation.
- BT - a signal which represents the battery tunnel temperature. The critical maximum battery voltage is a function of BT and is used for battery charging and brake blending purposes.
- AC - the average dc current flowing in the armature of the propulsion motor. It is used as a feedback signal for armature current control.
- BP - a signal proportional to brake pedal pressure. It relates to command armature current I_a^* for the regenerating condition of the drive system.
- AP - a signal from a pot which deflects proportionally to the accelerator pedal pressure.
- TAU - the analog command signal to the armature chopper and is proportional to the percentage on-time of the chopper.
- FCC - a command signal (I_f^*) to the field current controller.
- FUEL - the signal proportional to the state of charge of the main battery.
- TL - a signal which indicates the various task levels of the microcomputer and their respective time durations.

● Digital Signals

- ASW - a logic signal which becomes "true" when the accelerator pedal is depressed.
- BSW - a logic signal which becomes "true" when the brake pedal is depressed.
- SSW - a logic signal which becomes "true" when the driver is seated.
- KSW - a logic signal which becomes "true" when the car key is turned on.

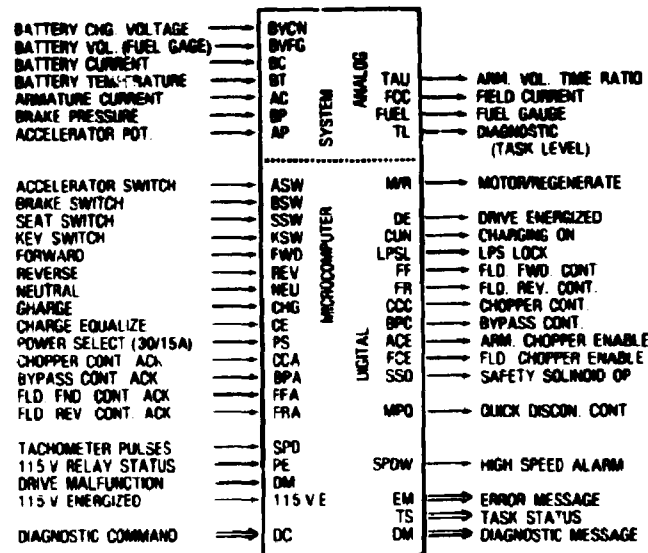


Figure 3.2.6.3-1. μ P Block Diagram with I/O Signals

- **FWD, REV, NEU** - a 3-position switch at the driver's command. By closing the switch, the driver can command the vehicle to move forward or backward or stay in the neutral condition.
- **CHG** - a "true" command in this signal requests the microcomputer to go to the battery charging mode.
- **CE** - a logic signal which commands the microcomputer to go to the charge equalization mode.
- **PS** - a command signal by which the microcomputer recognizes whether the onboard charger ac power supply is 30 A or 15 A. "True" indicates a 30 A source.
- **CCA** - an acknowledge signal of the chopper contactor. When the chopper contactor is closed, it makes CCA = true, indicating that it has closed satisfactorily.
- **BPA** - An acknowledge signal of the bypass contactor. When the bypass contactor is closed it makes BPA = true, indicating that it has closed satisfactorily.
- **FFA, FRA** - a "true" input indicates that the field forward of field reverse contactor, respectively, has closed satisfactorily.
- **SPD** - a train of pulses coming from a variable reluctance type tachometer. The digital speed signal is computed from the pulse train frequency.
- **115 VE** - a "true" signal indicating that the 115 V power supply for battery charging is energized.
- **PE** - signal indicating that the power supply cord for battery charging is mechanically coupled to the car inlet.
- **DM** - a drive subsystem malfunction signal which may arise due to a malfunction in the armature chopper, field chopper, or logic power supply.

- M/G - a "true" output indicating that the drive subsystem is in the motoring mode, and a "false" output indicates the drive system is in the regenerative mode.
- DE - indicates that the microcomputer has been powered up and the drive subsystem is energized.
- CUW - indicates that the microcomputer is in the charging mode.
- LPSL - signal commanding the logic power supply to lock on, once the microcomputer has been powered up by closing KSW and SSW.
- FF, FR - command signal to close field forward or field reverse contactor, respectively.
- CCC - command signal to close the chopper contactor.
- BPC - command signal to close the bypass contactor.
- ACE - enables the armature chopper to operate if the power supply and control signals are available.
- FCE - signal enabling the field chopper as in ACE.
- SSO - a "true" logic signal is amplified and a solenoid relay is energized. This signal helps in brake blending. If the BVCH signal rises beyond a critical value during regeneration, SSO becomes "true," bypassing the brake pedal pressure and cutting out the regeneration completely.
- MPQ - a signal which trips the quick disconnect breaker for a fault in the drive system.
- SPDW - a signal which energizes an alarm if the vehicle speed goes above 60 mph.

EV Sequence Diagram

The complete sequencing of the drive subsystem is shown in Figure 3.2.6.3-2. The various operation modes and submodes (shown as circles) can be summarized as follows:

<u>Mode</u>	<u>Submodes</u>
START	Start, Start Neutral, Forward Neutral, Reverse Neutral
FORWARD CHOPPING	Forward Motoring, Forward Regeneration, Forward Coasting
REVERSE CHOPPING	Reverse Motoring, Reverse Regeneration, Reverse Coasting
FIELD CONTROL	Field Motoring, Field Regeneration, Field Coasting
BATTERY CHARGING	Normal Charge, Taper Charge, Charge Equalize
SHUTDOWN	Shut, Wait
DIAGNOSTIC TESTING	Diagnostic

The motor feedback controlling software corresponding to each submode is executed every 4 ms. In the START mode, the microcomputer power supply is on (after closing KSW and SSW when LPS is latched on), the initialization is complete, and the drive system prepares to go to the FORWARD CHOPPING, REVERSE CHOPPING, FIELD CONTROL, or BATTERY CHARGING mode. In the FORWARD CHOPPING mode, the motor field current is constant (10.6 A), but the armature current varies in polarity and magnitude depending on the command. In the coasting submode, the drive system is required to generate a braking torque of 32 lb-ft, which corresponds to brake bias (BB) = 80 A. As the drive makes the transition to the regeneration submode, BB and BP signals are added with a one-second RAMP for a jerkless transition. The REVERSE CHOPPING mode operates identically with the FORWARD CHOPPING mode, except that the field current is reversed. In the FIELD CONTROL mode, the battery voltage is impressed across the motor armature, and the field current is controlled as explained before. In the field coasting submode, BB = 100 A which corresponds approximately to an average braking torque of 32 lb-ft.

Battery charging may start from high charging or low charging levels depending on the capacity of the 115 V ac household outlet. In the equalization submode, a small charging current (4 A) is applied for five hours to compensate for unequal charging of the cells. The SHUT mode corresponds to the sequential shutdown of the drive system. The DIAGNOSTIC mode is used for troubleshooting the subsystem.

Sequencing. When operating in a submode, the microcomputer periodically (every 20 ms) senses driver command signals, internally generates software parameters, and tries to identify a valid submode transition request. A valid transition request can be expressed in the form of a Boolean function. Once the valid request is identified, the microcomputer performs some action steps before jumping to the new state. All the valid transitions (shown by arrows) and the corresponding requests and actions have been formulated carefully and are summarized in Figure 3.2.6.3-2. A brief description of the sequencing steps follows.

Start → Start Neutral. This is the first transition step if the vehicle is to be driven and occurs after the microcomputer is powered up and initialized. A condition for starting the car is that it should be initially stationary (or moving very slowly), and the drive request switch should be in the NEUTRAL position. The microcomputer checks that the key and seat switches are closed, the neutral switch is on, speed is below 1 mph, and the battery-charging 115 V supply is disconnected before it changes to the start neutral submode.

Start Neutral → Forward Neutral. The driver gives a FORWARD command in this transition. The microcomputer checks the command to make sure that the REVERSE switch and its acknowledge signals are off, which then closes the FF contactor. The microcomputer waits for 60 ms and then checks FFA to be sure that the contactor has closed. Then it closes the CC contactor and switches on the DE light. After waiting for 500 ms, the acknowledge signal is verified, and then changes to the forward neutral submode. If the contactors fail to close, it goes to the WAIT state and gives a malfunction signal at the output. This submode typically is employed when the vehicle is standing at a traffic light. The battery power is impressed across the drive, but the field and armature are not yet energized to conserve battery energy and to prevent lurch mode operation.

Forward Neutral → Start Neutral. In this transition, the driver closes the NEUTRAL switch which makes the chopper and field forward contactors trip off and switches off the DE light.

Forward Neutral → Forward Motoring. The driver now presses the accelerator pedal, which closes the ASW switch. The microcomputer first enables the field chopper and then establishes the rated 10.6 A current. After a delay of 260 ms to be sure that full field current is flowing, the microcomputer enables the armature chopper in the motoring mode, senses the accelerator pot, and establishes the armature current. The DE light is turned off when the vehicle is in the driving condition. In this submode, the motor torque is established, but the vehicle may or may not be in motion.

Forward Motoring → Forward Neutral. The transition will be initiated if the vehicle is not moving and the brake pedal is pressed. In this condition, both the armature and field choppers will be disabled, and the drive will go to the original condition. When the field transistor is off, I_f starts freewheeling through the bypass diode with a large time constant (1.6 sec). A delay time of 3 sec is provided to be sure that the field contactor is not opened when current is flowing.

Forward Motoring → Forward Coasting. If the vehicle is in motion and the driver takes his foot off the accelerator (as well as the brake), this transition is initiated. If the accelerator is pressed again, the system comes back to the original submode.

Forward Motoring → Forward Regeneration. If the vehicle is in motion and the brake is pressed, this transition will be initiated. The regeneration current will be established by the brake pressure which will be added to the coast current ($BB = 80$ A). If the driver uses one foot for both accelerating and braking, the transition will always occur through the coasting submode. The reverse transition will start if the accelerator is pressed. The microcomputer will start sensing AP instead of BP.

Forward Regeneration → Forward Coasting. If the driver removes his foot from the brake (as well as the accelerator), the vehicle will go into the coasting submode. The vehicle will return to the original submode if the brake pedal is pressed again.

Forward Neutral → Forward Coasting. If the vehicle is in the neutral condition, but is gaining speed on a down slope, the forward coasting transition will occur. The reverse transition will occur if the speed is low and the driver's foot is off the accelerator and brake. The action steps in both transitions are identical to those of FORWARD MOTORING.

Forward Neutral → Forward Regeneration. These transitions are identical to the previous one, except that the driver has his foot on the brake.

Forward Motoring → Field Motoring. If the vehicle is speeding up in the forward direction with the driver's foot on the accelerator, field motoring transition will initiate. As the motor approaches the base speed and the motor voltage reaches the battery voltage, the bypass contactor will close. However, before closing, contactor TAU is locked at 100% to prevent transients. The delay of 360 ms prevents faulty transition for underdamped oscillation of TAU in the chopping mode. With an additional delay of 120 ms for contactor closing, the microcomputer checks the acknowledge signal and then goes to the new submode. If BP fails to close and $TAU < 100\%$, the drive returns to the motoring mode.

Field Motoring → Forward Motoring. Forward motoring transition will start if the vehicle is slowing down from a higher speed and the field current exceeds the rated value. A delay of 200 ms is provided to prevent faulty mode transition in case the field current is underdamped in the field control mode. When the valid request is identified, the armature chopper with motoring transistor is enabled, TAU is saturated, and is opened. The operation of BPC with the motoring transistor saturated eliminates transient current in

the armature circuit. After a delay of 100 ms, the BPC acknowledge signal is checked, field current is latched to the rated value, and the drive changes to the new submode.

Field Motoring $\rightarrow$ Field Regeneration. If the brake pedal is pressed, the drive goes to regeneration. In this submode, the brake pressure is added to the bias signal to generate the armature current command. The reverse transition is started when the accelerator pedal is pressed.

Field Regeneration $\rightarrow$ Field Coasting. The field coasting transition is similar to the previous one, except that the coasting submode is attained when the operator's foot is off the accelerator and brake pedals.

Field Motoring $\rightarrow$ Field Coasting. This transition is similar to the previous one.

Field Regeneration $\rightarrow$ Forward Regeneration. If the vehicle is slowing down from higher speed with the driver's foot on the brake, the forward regeneration transition is initiated. The field current is checked to be above 10.6 A for 100 ms, the motoring transistor is saturated, and the bypass contactor is opened. Once the contactor opens successfully after a 100 ms delay, the drive goes to the chopping regeneration mode with the rated field current.

Forward Regeneration $\rightarrow$ Field Regeneration. This transition will be initiated if the vehicle is speeding down a slope in the chopping regeneration condition. Tau is detected to be less than 1% for 360 ms when the chopper is disabled and the vehicle goes to the field control mode. The bypass contactor is closed to complete the transition. If the BPC fails to close, the transition is completed, but armature current is damped to 173 A.

Field Coasting $\rightarrow$ Forward Coasting. The forward coasting transition is similar to the previous one, except that it occurs in the coasting mode.

Constant Charge $\rightarrow$ Taper Charge. After the battery voltage reaches V_B (critical) the taper mode of charging is entered.

Taper Charge $\rightarrow$ Charge Equalize. When taper charging is complete after five hours and equalization is commanded, a transition occurs to the equalization mode where a small current command of 4 A is applied.

Charge Equalize $\rightarrow$ Shut. When equalization is complete, the drive shuts down. The drive will also shut down if the charging command is withdrawn, the 115 V supply is shut off, or the cable is disengaged.

Taper Charge $\rightarrow$ Shut. The microcomputer will shut down if charging is complete, the command is withdrawn, or the 115 V power is removed.

Shut $\rightarrow$ Wait. The wait transition is an orderly shutdown of the drive subsystem by the microcomputer when battery charging is complete or the key or seat switch is turned off at any operation submode. The microcomputer will check I_a and lower it below 6 A in the feedback mode, wait 500 ms, and open the chopper contactor. The microcomputer then disables both the choppers and permits the field current to go to zero before tripping the field contactor. At this point, the logic power supply is turned off and the microcomputer shuts down.

Start → Diagnostic. The diagnostic transition will occur if a logic command exists on the **DEBUG PANEL**.

WBS 3.2.6.4 Hardware Design

The microcomputer hardware on the EV has to operate reliably under extreme temperatures, EMI, shock, and vibration. Therefore, it was decided to custom design the microcomputer using mil spec components. This permits wide ambient temperature variation (-55°C to $+125^{\circ}\text{C}$) and prevents premature failure of the components. The hardware consists of three wire wrap boards which are housed in a shielded aluminum box with the option of utilizing a fourth board. A brief description of the boards is given as follows.

CPU Board

The microcomputer design is based on the Intel 8080A CPU which is an 8-bit NMOS type processor. The selection of the 8080A-based computer is primarily due to availability of mil spec components, the reputation of 8080 for reliability, and the availability of technical expertise within General Electric when the project was started.

A simplified CPU diagram is shown in Figure 3.2.6.4-1 and a detailed diagram of the CPU board is given in Figure 3.2.6.4-2. The microprocessor set consists of standard LSI chips which are the 8080A (CPU), 8224 (clock generator) and 8228 (system controller). The 16-bit address bus and 8-bit data bus are buffered respectively by a pair of 8212 and 8216 chips. The data bus at the output of the buffer is pulled up by 2K resistors which will present a RST instruction for recovery from any noise-induced, nonexistent memory. The application and diagnostic programs are stored in 4K-UV erasable EPROMS (8708), but an additional 1K space is left for memory expansion. The 1K-RAM supports the application and diagnostic programs and provides storage as a ring buffer for on-line software parameters.

A memory map of the computer, including the I/O, is shown in Figure 3.2.6.4-3. A gap is provided between the blocks of ROM, RAM and I/O memory which permits future expansion and avoids misdirection due to noise. Memory address decoding is carefully formulated to provide noise immunity. A serial interface (8251) with variable baud rate generator is provided to have communication with the TTY or CRT console for diagnostic purposes. The three parallel 8-bit ports of the (8255) chip interface with the debug panel and are used for diagnostic purposes.

ADDRESS	ASSIGNMENT	SIZE
0000H - 13FFH	READ ONLY MEMORY	5 K
4000H - 4FFFH	UNUSED	—
5000H - 53FFH	RANDOM ACCESS	1 K
5400H - 7FFFH	UNUSED	—
8000H - 801FH	I/O	32
E000H - E00FH	DIAGNOSTIC I/O	16

Figure 3.2.6.4-3. Microcomputer Memory Map

The port A is bidirectional which either receives or generates the diagnostic command and the port B sends the diagnostic message output to the data acquisition system through the buffer chip 54LS241. The port C generates the diagnostic strobe signals. The programmable counter (8253) consists of three 16-bit binary counters, one of which is used for speed computation. It receives clock pulses from the tachometer and counts for a definite time to construct the digital work proportional to the speed signal.

Continuous Memory. The function of continuous memory is to retain the fuel gauge information when the vehicle is shut down and to use it for updating the fuel gauge reading during the battery charging operation. The hardware consists of an 8-bit CMOS type shift-register, which is powered by the 12 V auxiliary battery and is isolated from the microcomputer in the input and output by optically coupled isolators. While writing the information in the memory, the 8 bits are held at input CMDAT and are serially strobed by clock pulses at input CMCLK. While reading, the 8-bit word is obtained serially at output CMOUT by the clock pulses.

I/O Board

The simplified I/O diagram is shown in Figure 3.2.6.4-4. The I/O board schematic shown in Figure 3.2.6.4-5 essentially consists of analog and digital hardware which communicate with the outside world. The functional components can be briefly described as follows.

Digital I/O. The logic input signals (described in Figure 3.2.6.3-1) are accepted by the three ports of the 8255 chip (HS) through interface electronics which are shown in a separate diagram. Some of the signals are intentionally duplicated to provide convenience in software manipulation. The logic output signals are distributed in the C-port of the chips EN or ER. The ports A and B of ER are connected to two DACs located in the debug panel, and these are used to monitor software parameters. The A port of EN receives diagnostic commands from the debug panel.

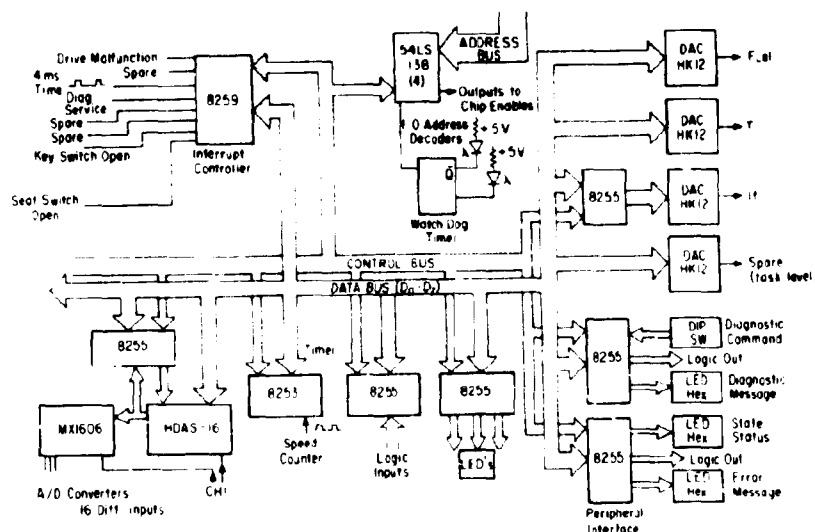


Figure 3.2.6.4-4. Simplified I/O Diagram

DACs. There are four DACs of 0 - 10 V for outputting the analog signal voltages. DAC-4 is a spare, but is normally used to monitor software task levels. The DACs have 12-bit resolution, but TAU, FUEL, and the spare DACs only use 8-bits by grounding the 4 LSB bits. Each bit then corresponds to a $10/(2^8 - 1) = 39.2$ mV analog signal. The FCC DAC is used with 12-bit resolution (1 bit = 2.44 mV) because of high sensitivity of armature current in the field control mode. In Figure 3.2.6.4-5, latch BX holds the 4 MSB bits of LO byte, whereas the HI byte is injected directly into the data bus.

Data Acquisition System. A 62-pin hybrid integrated analog data acquisition system (HDAS-16) is used, which can accept up to 16 differential analog signals with the aid of an external multiplexer. The system package consists of a 16-bit analog multiplexer, an instrumentation amplifier, a sample and hold circuit, an ADC, and a 12-bit tri-state register.

The analog signals are unipolar and bipolar of 0 - 10 V magnitude which can be sampled at random with the maximum acquisition plus conversion time of 20 μ s. The digital signals are used with 7-bit resolution (1 bit = 78.7 mV) with MSB as the sign bit. The 12-bit resolution is used only for calibration purposes. The MUX address input, output, and other control signals are interfaced through the 8255 chip D2.

Analog Interface Electronics. The analog input signals are processed to convert them to correct polarity and magnitude and are fed to the input with heavy noise filtering.

BVCH, BVFG, BP, BC. The interface op/amp input and feedback parameters are selected such that polarity inversion is provided with a scale factor of 1:1. The circuit provides an input noise filter of $\tau = 40$ ms in cascade. An extra 0.01 μ f ceramic disc is paralleled with 1 μ f to eliminate high frequency noise.

AC. The input signal is received from the motor armature current sensor and is filtered with $\tau = 4$ ms to attenuate the ripple content. The time constant plays an important part in the stability of the armature current control loop.

AP. A 10K accelerator pedal actuated potentiometer is impressed with -6.2 V across the Zener, and the variable pot voltage is fed at the input. The op/amp gain factor is 1.8 to convert to a 0 - 10 V signal at the output. The Thevenin resistance of the pot can be neglected because of high series resistance (100K).

BT. The channel senses the battery tunnel temperature such that a linear signal variation is obtained between 0 to +10 V for the temperature variation of -30°C to +50°C. Figure 3.2.6.4-6 (a) shows the linear thermistor network which sends a signal to the interface circuit with the following relationship:

$$\frac{E_o}{E_{in}} = MT + b$$

where

$$M = -0.0068517/^{\circ}\text{C}$$

$$b = 0.653229 \text{ at } T = 0$$

and $T = \text{temperature in } ^{\circ}\text{C}$

E_{in} is obtained from a Zener regulator through an op/amp voltage divider. For $E_{in} = 6.2 \text{ V}$, $6.81/20 = 2.11 \text{ V}$ and the range of T between -30°C to +50°C, the E_o curve is plotted in Figure 3.2.6.4-6 (b). E_o is amplified and biased an appropriate amount so as to get 0 to +10 V at the input of the data acquisition system. A clamping Zener of 10 V is connected across the amplifier to prevent overvoltage in case the thermistor network is removed.

4 ms Clock. This clock generates an "interrupt" signal for the microcomputer every 4 ms. This is the basic time interval for the highest priority task (feedback loop computation). Time intervals for lower priority tasks are multiples of 4 ms and are generated by software. The timer consists of two monostables regeneratively coupled to generate the waveform shown. A start strobe pulse is injected from a decoder to prevent any initial latch-up.

Watchdog Timer. This monostable is strobed every 20 ms by the microcomputer to indicate the satisfactory operation of the core hardware. A green LED (located on the debug panel) indicates satisfactory operation, whereas unsatisfactory operation is indicated by a red LED mounted on the I/O board.

Interrupt Controller. The Intel 8259 chip is a programmable interrupt controller which can accept 8 priority level interrupt signals. The signals are accepted at any time and stored in a request register. Individual requests can be masked by software commands. The interrupt signals, according to priority, are summarized as follows:

- IR0 - drive system malfunction signal (highest priority)
 - IR2 - 4 ms clock
 - IR3 - key switch
 - IR4 - seat switch
 - IR6 - diagnostic service interrupt
- } To shut off the drive system

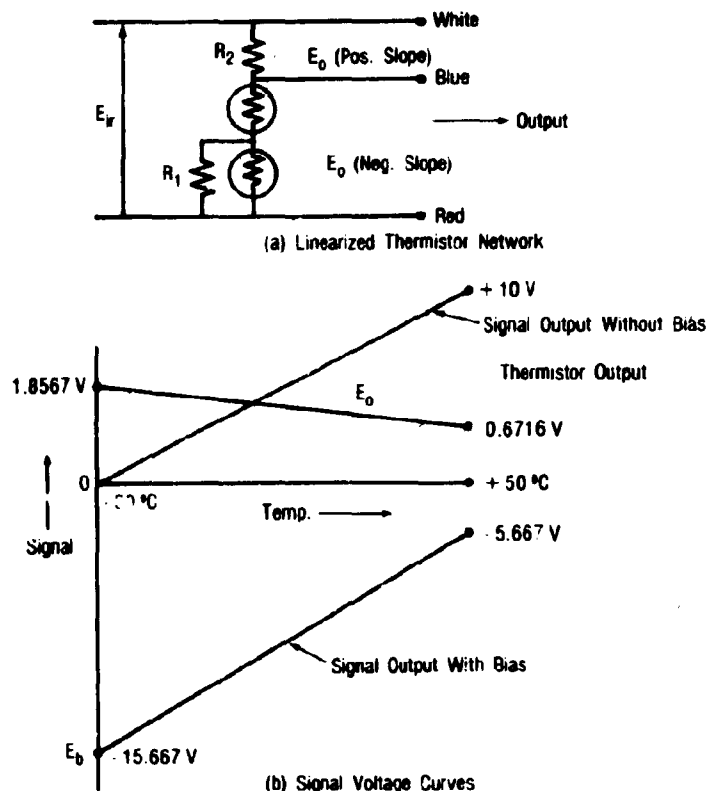


Figure 3.2.6.4-6. Linear Signal Variation

Interface Board

The function of the computer interface board is to optically isolate, debounce, and to condition and/or level shift signals leaving and entering the digital sections of the microcomputer. Figure 3.2.6.4-7 shows a schematic of this board. A more detailed description follows.

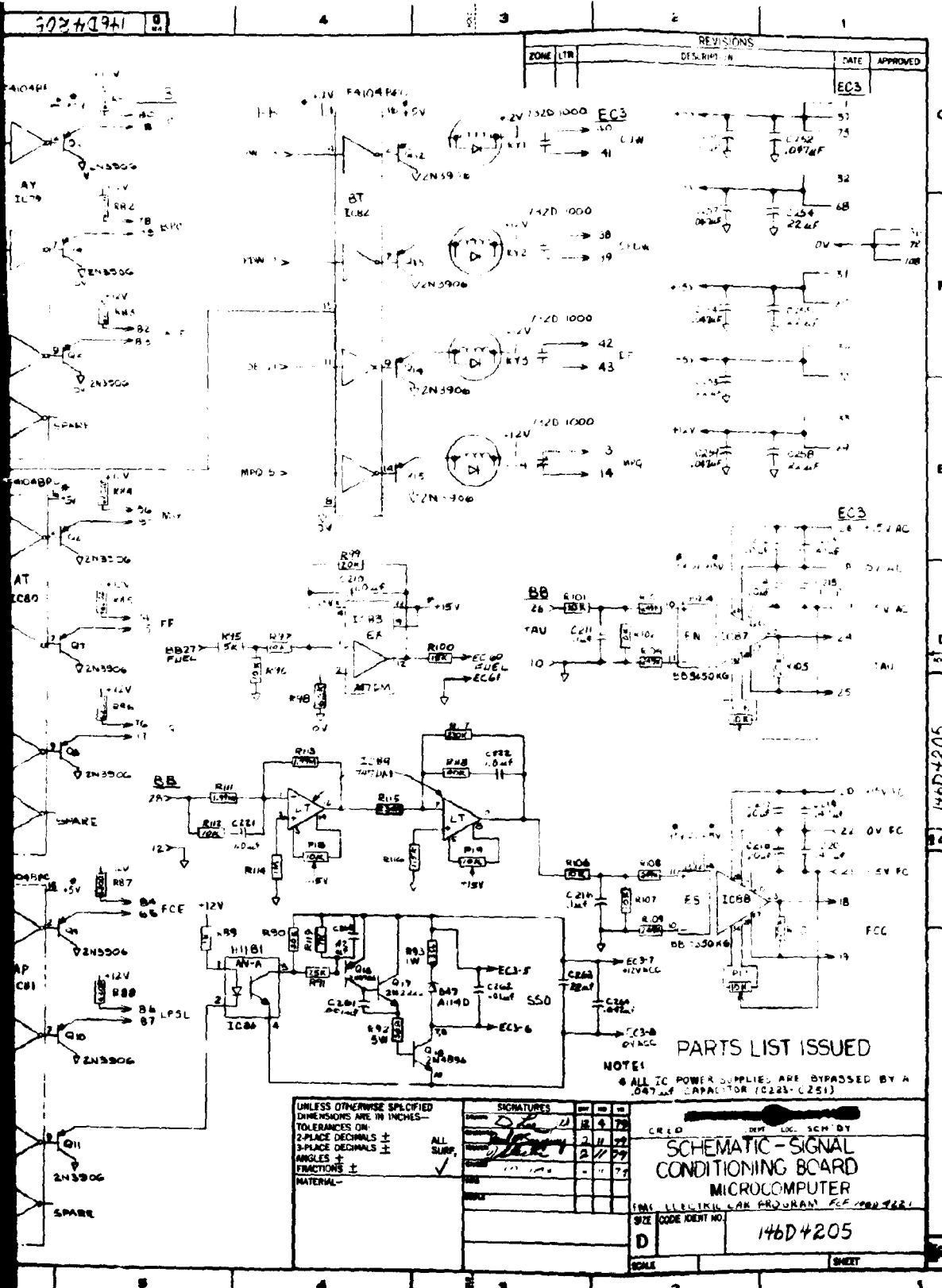
Debounce Circuits. Integrated circuits IC73, IC74, IC75, and IC76 are Motorola MC14490 hex debouncer circuits. These circuits eliminate switch or relay contact bounce voltages from the incoming switch or relay actions.

Level Shift Circuits. Integrated circuits IC79, IC80, IC81, and IC82 are Fairchild F4104 quad level shifter circuits which shift 0 - 5 V logic level outputs to 0 - 12 V logic level outputs in readiness for transmission to the PCU or dashboard. The SSO signal which operates the dual brake blending solenoids is also level shifted by this method. The transistor amplifier circuitry to drive the solenoids consists of Q16, Q17, and Q18 and associated components. The circuitry centered around bistable IC85 inhibits the F4104 devices during power-up.

Optical Isolation Circuits. The two propulsion control analog outputs of the microcomputer are the armature chopper duty cycle command (TAU) and the field current command (FCC). These signals are optically isolated by amplifiers IC87 and IC88 respectively before transmission to the PCU.



3.2-154/52



Microcomputer Schematic

Reproduced from
best available copy

Logic signal inputs, which are isolated in this card, are the three malfunction – not signals which are isolated by IC67, IC68, and IC69 before being inverted by the Schmitt Triggers of IC70 and being AND-ed by IC71.

Conditioning Circuits. Two naturally isolated signals do not require isolation, level shift, or debounce functions. The signal from the motor pulse tachometer, SPD, is an incoming approximate sine wave signal which is squared up by comparator IC78. The output analog voltage, representing battery state-of-charge, is filtered by IC83 before being transmitted to the dashboard gauge.

DC-DC Converter Board

The following components need a power supply with good regulation which was originally believed to be beyond the capability of the logic power supply.

<u>Power Supply</u>	<u>Regulation</u>	<u>Component</u>	
+5 V	0.25 V	8259 8253	(Registers of DACs and DAS)
15 V	0.5 V	DACs DAS	

For this reason, the dc-dc converter board was designed and fabricated to receive +48 V input from the LPS. However, the LPS output provides the above regulation in the field application. So the converter board has been removed from the microcomputer box. An option exists to install the board, if required.

WBS 3.2.6.5 Microcomputer Packaging

The EV microcomputer controller hardware consists of the three boards shown in Figure 3.2.6.5-1, plus the optional board. All four boards are 6 in. x 9 in. and are drilled to accommodate standard IC socket spacings. V_{CC} and ground busses are 0.1 in. wide copper. The boards are populated with Augat 500 series gold plated wire wrap IC sockets, conforming to Mil Std-202 methods 204 and 213. Interconnections are wire-wrapped with No. 30 AWG Kynar insulated wire. Interconnections are made on a semiautomatic wire wrap system which provides reliable connections and reproducibility.

The four microcomputer boards are partitioned as follows.

CPU Board

- 8080A standard interface chip set (8080A, 8228, 8224)
- Read only memory (8708's)
- Random access memory (2102A-4's)
- Address decoders (54LS138's)
- Continuous memory

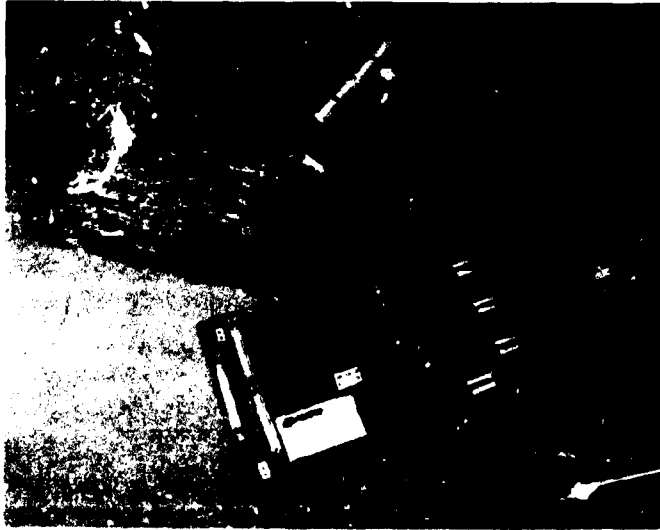


Figure 3.2.6.5-1. Microcomputer Boards

- Tachometer pulse counter (8253)
- Diagnostic I/O
 - serial I/O (8251)
 - parallel I/O (8255)

Input/Output Board

- Analog input signal conditioning (747)
- Analog/digital converter-multiplexer (HDAS-16 mm)
- Digital/analog converter (HK12BMM)
- Digital I/O (8255)
- Interrupt controller (8259)

Signal Conditioning Board

- Logic output drivers (4104)
- Logic input filters (MC14490)
- Analog output isolators (BB3650KG)

DC to DC Converter Board

- +48 V to ± 5 V @ 0.3% regulation converter
- +48 V to ± 15 V @ 0.3% regulation converter

A double-sided printed circuit backplane, shown in Figure 3.2.6.5-2, provides power supply bussing, data control bus routes, EV system logic I/O, and diagnostic I/O interconnections. All boards are connected to the backplane through Mupac type 3612261 108 contact edge connectors. Signal runs are 0.020 in. wide and V_{cc} and ground busses are

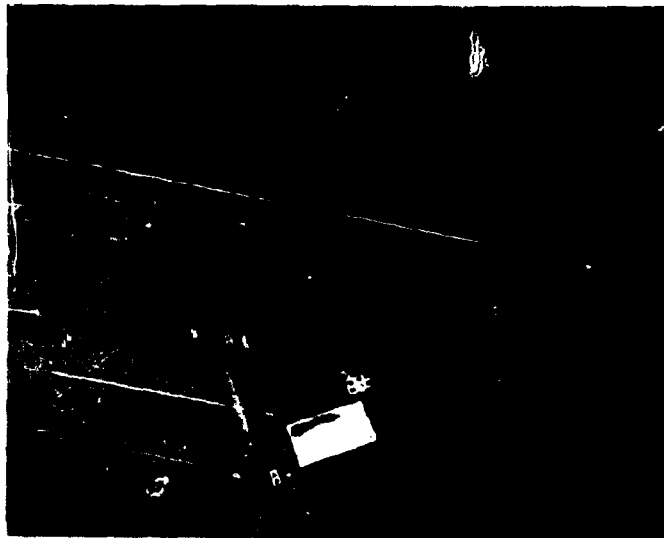


Figure 3.2.6.5-2. Printed Circuit Backplane

0.175 in. wide, 3 oz copper. Signals are routed from the Mupac edge connectors to rows of gold over nickel plated wrap pins, and connections are made with Berg type 47746 contacts to the external connectors. Analog input signal wires are routed directly from the external connectors to a Cannon 37 contact D subminiature rectangular connector mounted on the top of the I/O board. Two 3M 34 contact flat cable connectors carry the signals which flow between the I/O board and the signal conditioning board.

The external connectors shown mounted on the box in Figure 3.2.6.5-3 are Cannon type D*MA with crimp type removable contacts conforming to Mil-C-24308. I/O signals are grouped as follows:

- J2 - Motor Compartment I/O
- J3 - Passenger Compartment I/O
- J5 - Power Conditioning Unit I/O
- J6 - Power Supply Inputs
- J8 - Test Connector
- J9 - Diagnostic Connector

The microcomputer enclosure shown in Figures 3.2.6.5-4 and 3.2.6.5-5 is made of 0.05 in. thick anodized aluminum. Card guides are riveted to the inner walls of the box and provide firm fastening for the boards. The outside dimensions of the enclosure are 11 x 8 x 6-1/2 in., with 0.687 in. tabs on the top, running the entire width to facilitate mounting behind the glove box in the vehicle passenger compartment.



Figure 3.2.6.5-3. Microcomputer Enclosure

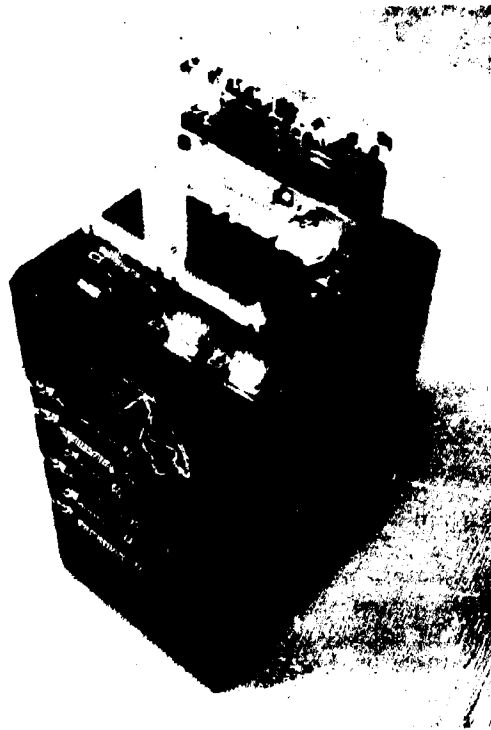


Figure 3.2.6.5-4. Microcomputer Enclosure Showing Card Access

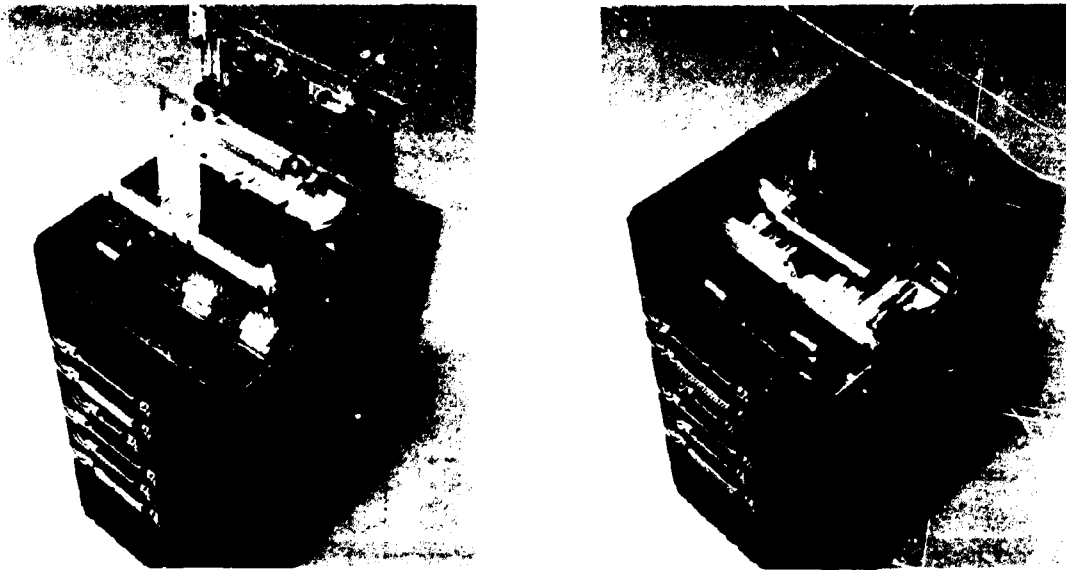


Figure 3.2.6.5-5. Microcomputer with All Boards Installed

WBS 3.2.6.6 Microcomputer Software

The software subsystem contains about 50 modular units and provides real time control of the electric vehicle drive. The software is based entirely in 8080 assembly language so that a time critical four millisecond sampling interval can be met. The software is packaged in four 1024 byte, Read Only Memories (2708 ROM) and is structured to permit modification and replacement of a single ROM chip.

Different design tools have been employed with the software design depending upon the function to be implemented. The propulsion control and fuel gauge functions which are calculation intensive are described with signal flow diagrams. The logically complex drive sequencing is described and implemented using a state diagram technique derived from finite state machine theories. Inter-module structuring is described by use of structure charts, and finally, at the module level flow charts are used only when required by the complexity of a procedure. In general, the modules have been structured so that each is functionally simple and requires no more than three pages of listing each (see Figure 3.2.6.6-1).

System Description

The software subsystem may be partitioned into three major blocks as shown in Figure 3.2.6.6-1. In addition, a fourth optional block includes limited diagnostics. Each block communicates through the hardware interface to a portion of the drive subsystem. As shown in Figure 3.2.6.6-1, all feedback regulation of the motor is performed within the propulsion control block. The drive sequencing block is interconnected to the driver commands and consists of a logical structure to ensure smooth and safe drive sequencing. The monitor and warning block obtains battery parameters and a speed quantity for use by the sequencing block and to provide a variety of vehicle dashboard displays.

Because the software executes in real time, the functions are organized into four scheduling tasks as shown in Table 3.2.6.6-1. Each task corresponds to a particular scheduling time interval over which it is completed. Thus, for instance, Task 1 is repeated 60 times for each time that Task 4 executes.

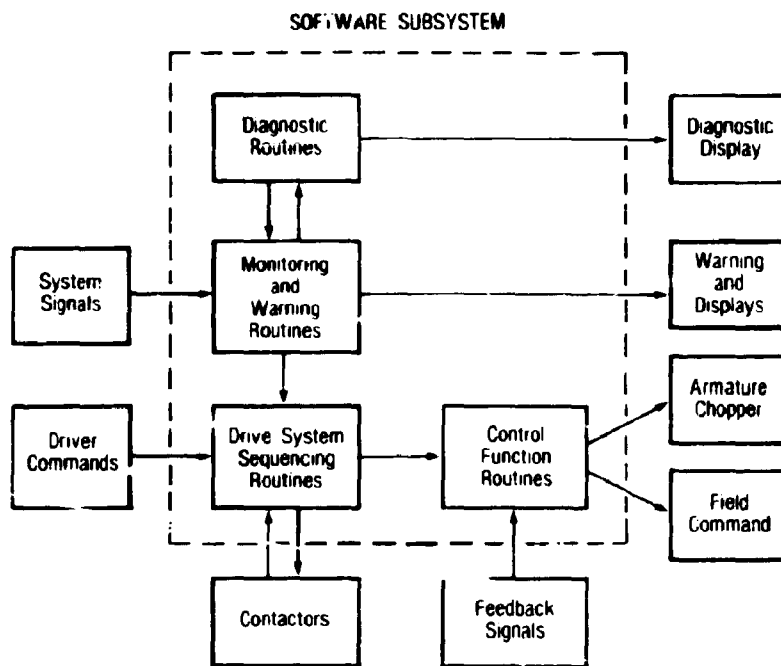


Figure 3.2.6.6-1. Software Functional Diagram

TABLE 3.2.6.6-1

DISTRIBUTION OF FUNCTIONS AMONG TASKS

Task No.	Scheduling Interval	Functions	External Signals Sampled
1	4 ms	● Propulsion control	● Armature current
2	20 ms	● Drive sequencing ● Charge fuel gauge ● Signal monitor	● Accelerator pedal ● Brake pressure ● All logic inputs
3	60 ms	● Tachometer	● Speed counter
4	240 ms	● Charging control ● Motoring fuel gauge ● Battery monitor ● Speed monitor ● Diagnostic service	● Battery voltages, current, and temperature

The monitoring functions are spread throughout Tasks 2, 3, and 4 depending upon the time constant of the signal to be monitored. The slowest changing signals are the battery parameters, and so most battery-related functions are in Task 4. The determination of speed is accomplished by summing tach pulses over a fixed 60 ms time interval. All other signals are sampled every 20 ms; and, likewise, the sequencing function is scheduled at the same time interval.

Not all functions are active at the same time but are only selected as required for the mode of vehicle operation. There are four primary modes of operation:

- Neutral
- Armature Chopping Propulsion
- Field Weakening Propulsion

Table 3.2.6.6-2 summarizes those functions which are determined by mode. Note that some functions are always active such as the Drive Sequencing or Speed Monitor. It is the Drive Sequencing function which in fact determines the mode of operation and commands the selected mode through the data variable MODE SELECT WORD. Each Task then uses the MODE SELECT WORD for selection of the proper function to execute.

TABLE 3.2.6.6-2
FUNCTIONS DETERMINED BY MODE

Mode	Task 1	Task 2 (Signal Monitor)	Task 4 (Battery Monitor)
Neutral	Sample Armature Current	None	None
Charge	None	EV Clock Charge Fuel Gauge	Charge
Armature	Armature Control	Tau Monitor	Motoring Fuel Gauge
Field	Field Control	I_f^+ Monitor	Motoring Fuel Gauge

Figure 3.2.6.6.2-2 presents a simplified view of the essential software structure and Figure 3.2.6.2-2a presents a complete structure chart of all the modules.

Function Descriptions

Interrupt Structure. The base page module is located in program memory from 0 to 178H and contains five interrupt handling routines. The hardware interrupts from the 8259 priority interrupt controller are received in a table between 40H and 60H. Locations 0 to 40H are used for software-initiated service routines utilizing the RST n instruction. Figure 3.2.6.6-3 presents a memory map of the base page and identifies the organization of service routines.

The interrupts directly or indirectly initiate all activity within the software structure. The 4 ms clock interrupt provides a fundamental time interval to the Real Time

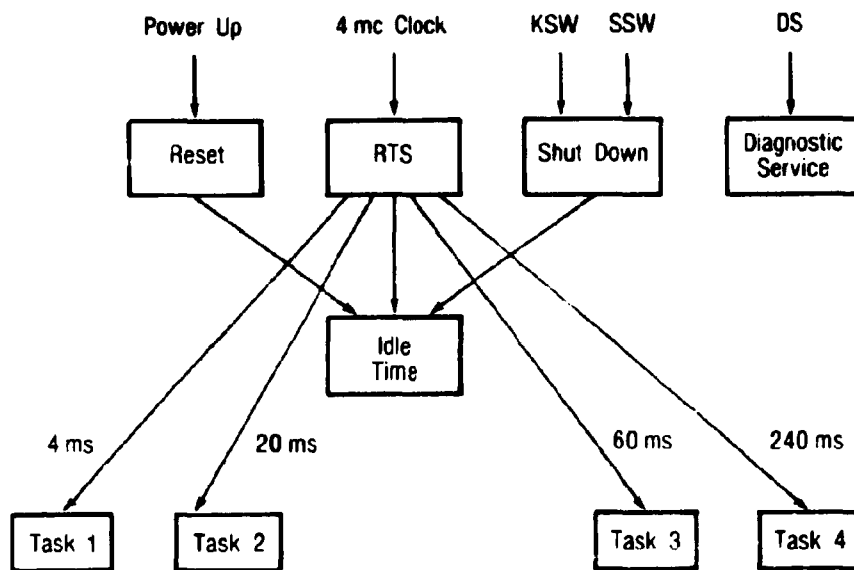


Figure 3.2.6.5-2. Simplified Structure Chart of Software

Scheduler. As a consequence, each task is scheduled (or called by the Real Time Scheduler) according to its associated scheduling interval: 4 ms, 20 ms, 60 ms, or 240 ms. A reset interrupt is triggered by the supply voltage power-up and initiates initialization of both hardware and software. The malfunction line, the key switch, or seat switch initiate an ordered shutdown of the drive subsystem.

Reset Initialization Routine. The RESET INITIALIZATION routine contains three sections (see Figure 3.2.6.6-4) and has three points of entry.

- A RESET occurs automatically with the power-up of power supply voltages and this routine is entered from location OOH. A complete hardware and software initialization is performed with program execution falling into the BACKGROUND section.
- A warm reset (WRMRST) entry is provided for soft recovery from errors or after any shutdown routine has been executed.
- The BACKGROUND section is executed when no other interrupt is being serviced. It contains idle time counters and monitors the watchdog timer to detect a clock failure. Should the 4 ms clock fail, then an error code is issued and a warm reset is executed in an attempt to recover from the failure.

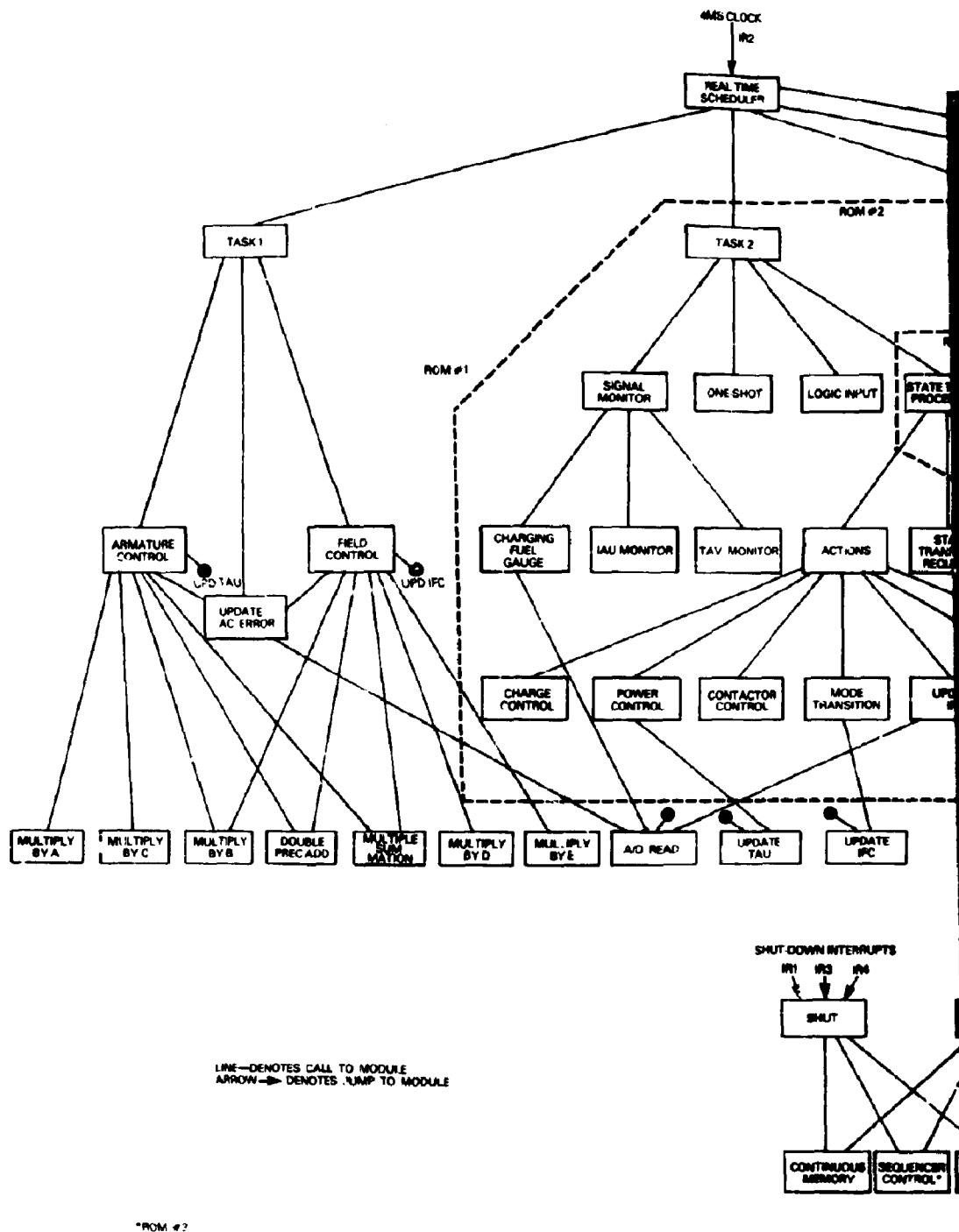


Figure 3.2.6.6-2a. Structure Chart of S

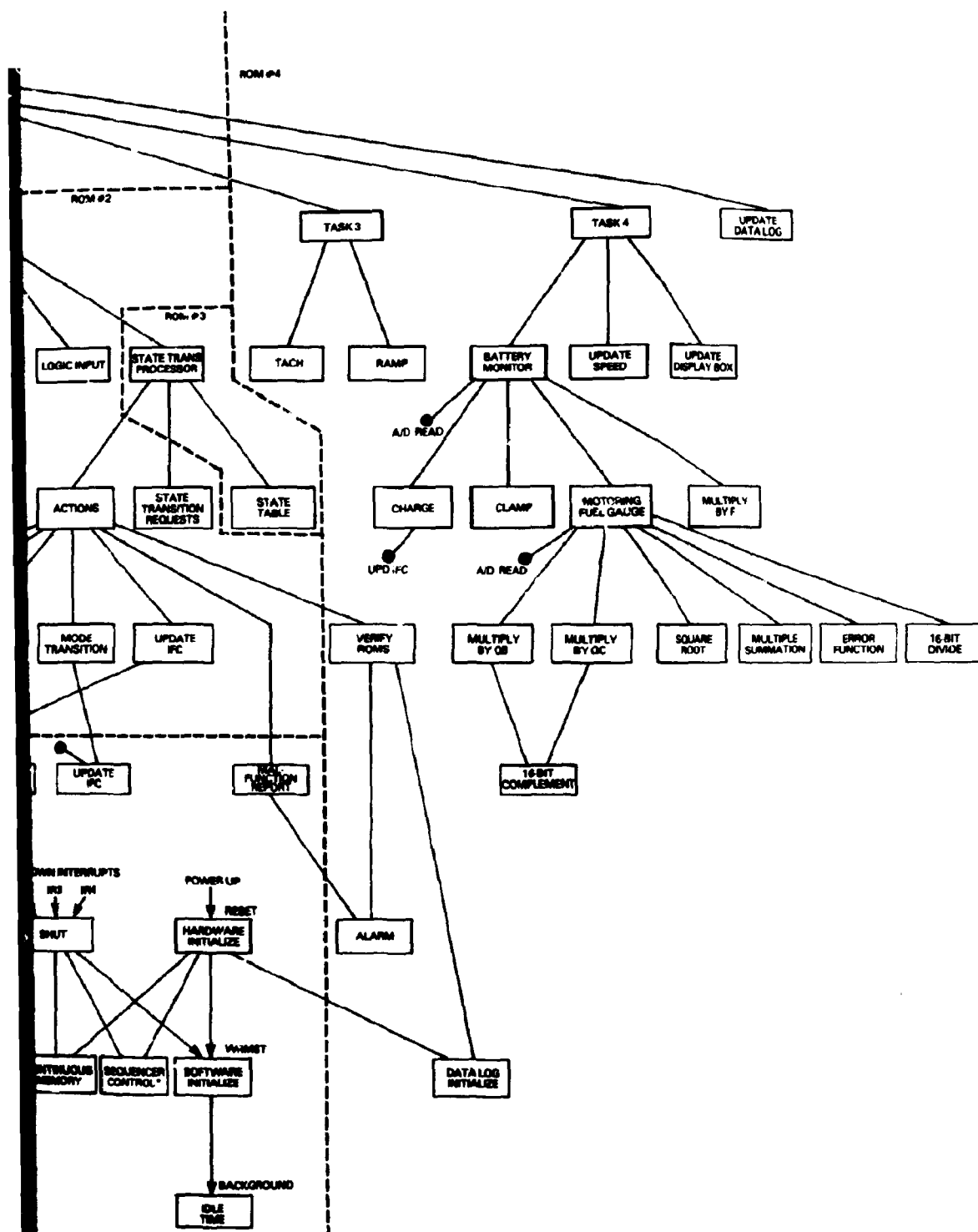


Figure 1-1: Block Chart of Software Modules

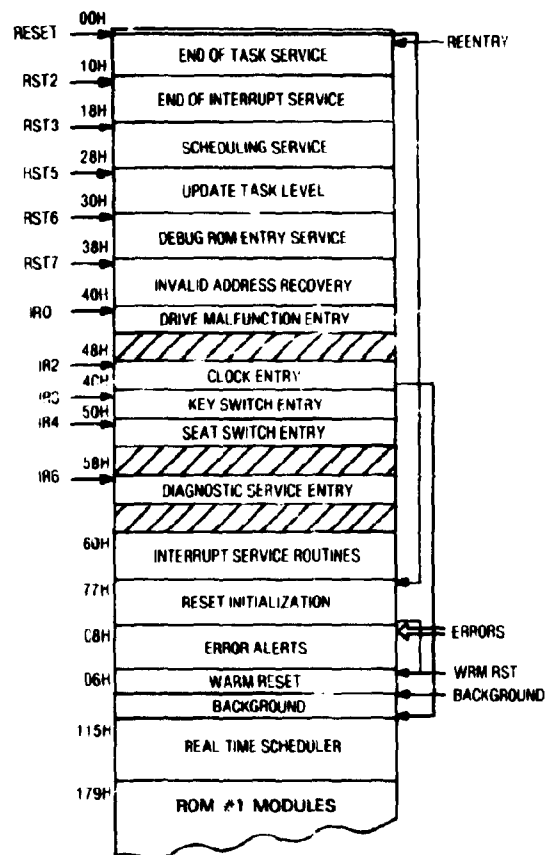


Figure 3.2.6.6-3. Memory Map of Base Page Module

Interrupt Service Routines. The interrupt service routines for shutdown or diagnostics are shown in Figure 3.2.6.6-5. The shutdown interrupts IR3 and IR4 merely call a module in the sequencing function, which forces a transition to the SHUT state. Similarly, the drive malfunction interrupt IRO calls a different module in the sequencing function which also (under present implementation) forces a transition to the SHUT state. Then, because the sequencing function may have been interrupted, a warm reset is executed to ensure that the SHUT state is entered. The diagnostic service interrupt IR6 is provided to enable servicing of a keypad. The keypad service routine would be executed if the DEBUG ROM is in place.

Real Time Scheduler. The real time scheduler serves as an executive routine which schedules each of the four tasks according to its priority and time interval. Each task (except Task 1 is scheduled over a time interval (T_i) that is an integer multiple (N_i) of the time interval of the task of next higher priority. The relationship may be expressed:

$$T_{(i+1)} + 1 = N_i T_i \quad (i = 1, 2, 3) \quad (3.2.6.6-1)$$

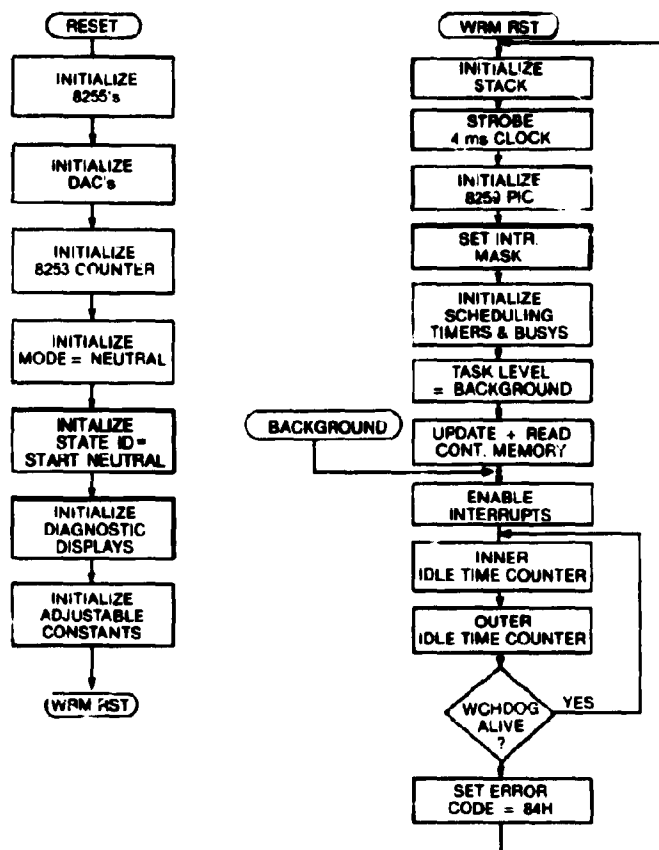


Figure 3.2.6.6-4. Initialization and Background

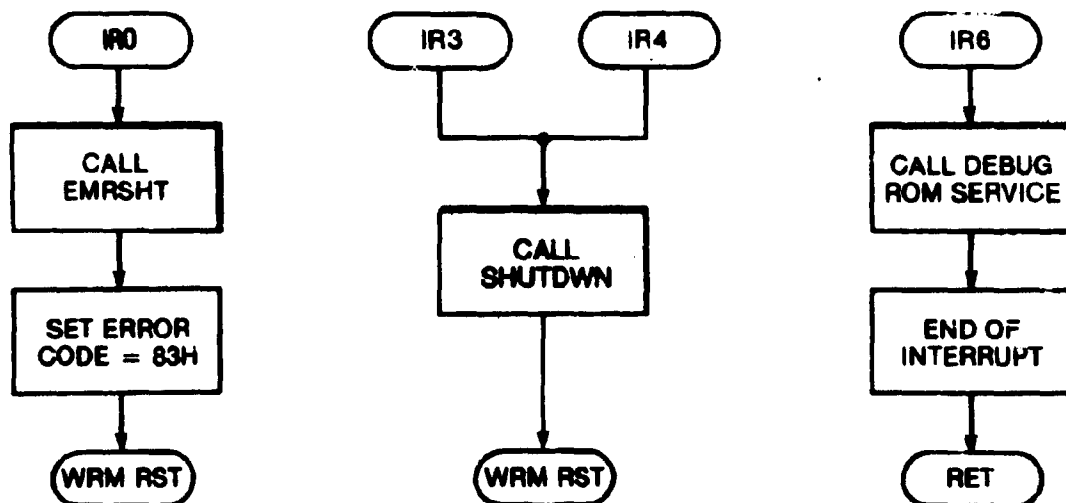


Figure 3.2.6.6-5. Interrupt Service Routines

where

$$T_1 = 4 \text{ ms}$$

$$N_1 = 5$$

$$N_2 = 3$$

$$N_3 = 4$$

For example, Task 4 would have its time interval derived from Task 3 as follows:

$$T_4 = N_3 T_3 = 4 \cdot 60 \text{ ms} = 240 \text{ ms}.$$

The procedure for scheduling a task is the same for all tasks so that a single routine accessible by a 'RST 3' is used along with parameters to identify the particular task. The theory of operation proceeds as follows. Task 1 is always scheduled. Associated with each of the other tasks is a counter which counts the number of time intervals of the next higher task. When the counter reaches the time out value of N_i as defined in Equation 3.2.6.6-1, then the task is called. When all tasks have been scheduled, the scheduler falls through into the background.

A task timing diagram, as shown in Figure 3.2.6.6-6 provides a means of describing the task executions graphically. Each line segment or task level corresponds to the duration of execution time required by the associated task. As for example, Task 1 always completes execution every 4 ms before a lower priority task may start or resume execution. Task 2 is suspended once as indicated by marker 1, whereas Task 4 is suspended three times as indicated by markers 2, 3, and 4.

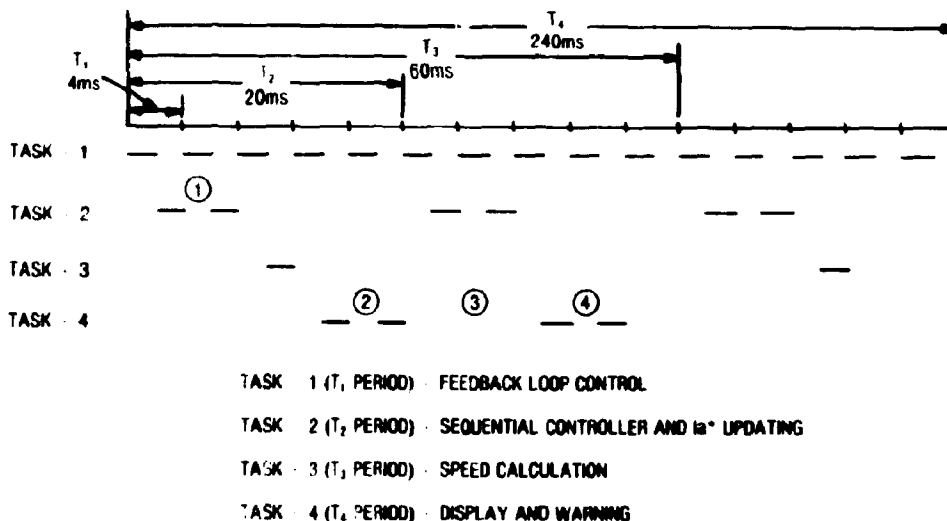


Figure 3.2.6.6-6. Task Timing Diagram (not in scale)

A task timing diagram is generated by the scheduler for display on an oscilloscope. Five different voltage levels are associated with the four tasks and background. The

scheduler maintains a "Task Activity" parameter which is sent through the spare DAC. The listing EVBAS5 provides more details.

Figure 3.2.6.6-7 presents a flowchart of the scheduler. The routine is re-entrant and is entered every 4 ms. The data in the suspended task is always preserved on the stack. The data preserved consists of the contents of all registers, the suspended task level, and the A/D multiplexer channel. The last item placed on the stack is the address of the re-entry routine for resuming the suspended task. This means that a RET, when executed, will automatically resume the suspended task.

The scheduler is able to detect when the time for task execution exceeds its scheduling time interval. This would imply that the functions within the task were not completed in their assigned time interval. A busy flag is associated with each task and is raised and lowered as a task executes and completes. Before scheduling a task, its associated busy flag is tested. If it is busy, then an error code is issued and a warm reset executed.

Propulsion Control Function

Task 1 consists entirely of the propulsion control function and is devoted to the feedback regulation of the armature current. As determined previously, the armature current is controlled under two different modes of motor operation: armature chopping and field weakening. According to system studies, each mode requires a lead/lag compensator and gain as follows:

$$\frac{e_o}{e_i} = K \frac{1 + \tau_2 s}{1 + \tau_1 s}, \quad (3.2.6.6-2)$$

where

$$\tau_1 = 0.01 \text{ and } \tau_2 = 2$$

The compensator has been implemented in terms of two difference equations for solutions by the software. The gain, K, is different between the two modes and a sampling interval, T, is fixed according to the Task 1 scheduling interval so that

$$T = 0.004 \text{ sec}$$

As derived earlier, the difference equations may be simplified and restated to include the gain constant:

$$v_c(KT + T) = \beta v_c(KT) + k\alpha e_i(KT) \quad (3.2.6.6-3)$$

$$e_o(KT) = v_c(KT) + k\gamma e_i(KT) \quad (3.2.6.6-4)$$

where

$$\alpha = \left[\frac{\tau_2 - \tau_1}{\tau_2} \right] \left[1 - e^{(-T/\tau_2)} \right] = 0.001988$$

$$\beta = e^{(T/\tau_2)} = 0.998$$

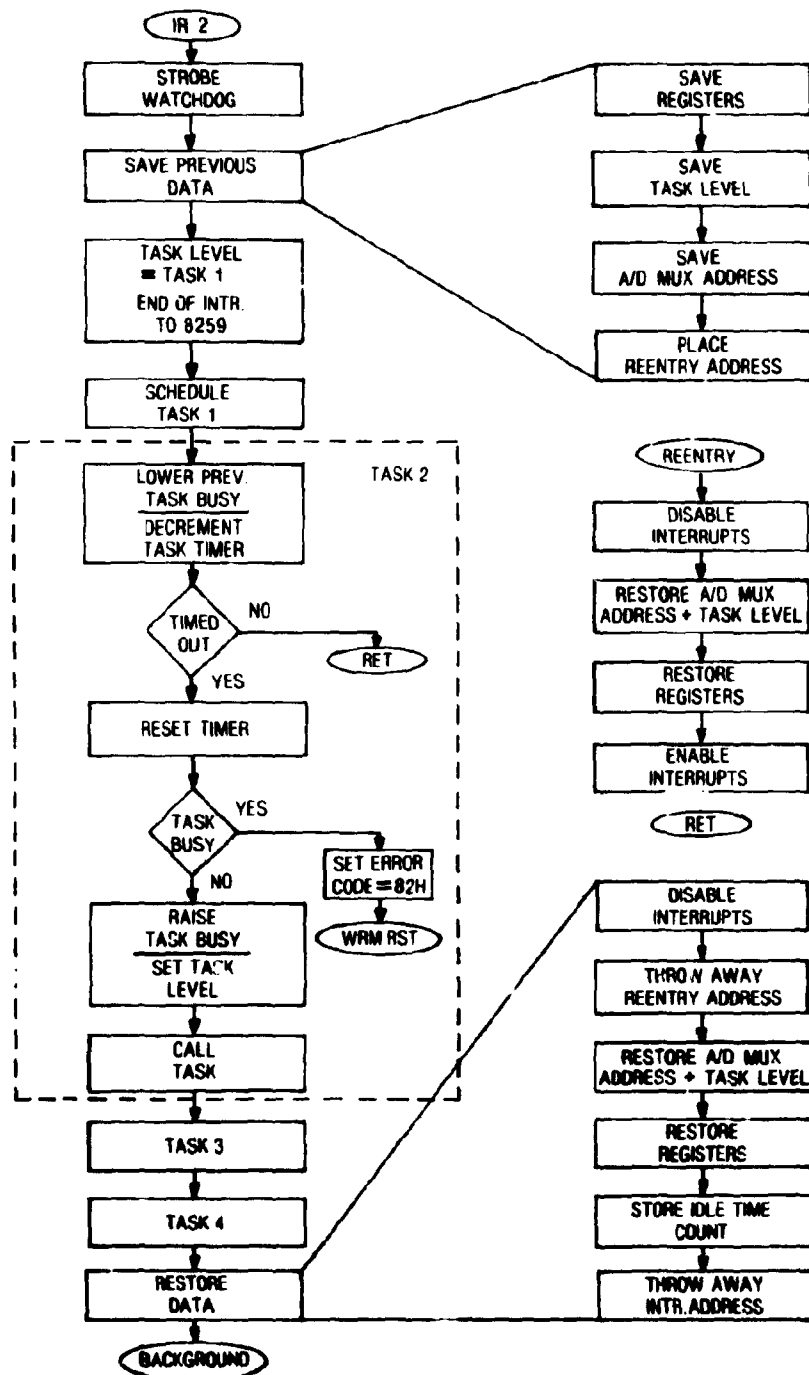


Figure 3.2.6.6-7. Real Time Scheduler

$$\gamma = \tau_1 / \tau_2 = 0.005$$

k = gain constant

A block diagram of the simplified compensator is shown in Figure 3.2.6.6-8.

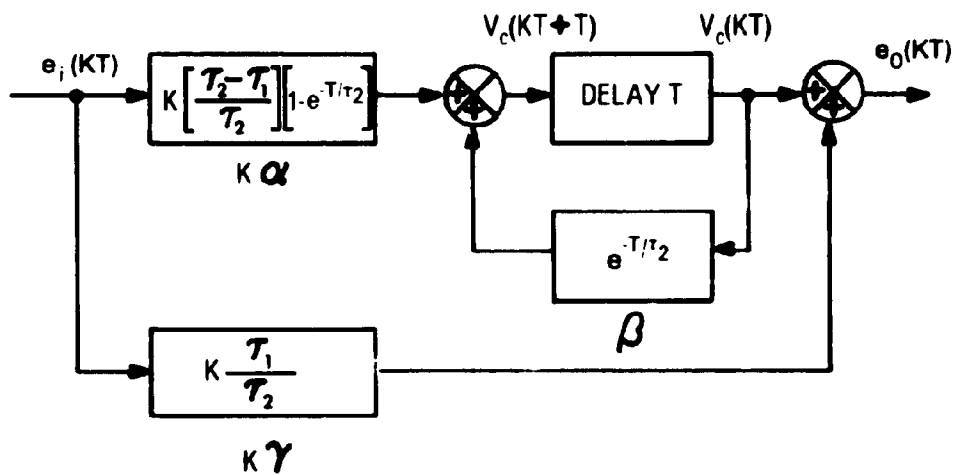


Figure 3.2.6.6-8. Compensator Block Diagram

The difference equations contain a storage element as represented by the delay block in the compensator block diagram. At start-up time, $V_c(T)$ must contain some initial value. That initial value must be loaded by software to a value which prevents a start-up transient. The initial value will depend upon the mode and whether the motor is motoring or regenerating.

The propulsion control function may operate in any one of six modes as determined by the sequential controller function. Table 3.2.6.6-3 identifies each of the six possible modes as specified through the "Mode Select Word." The value of the Mode Select Word may range from 0 to 7 with each value corresponding to a specified mode of operation. The Mode Select Word is used as an index into a jump table which makes reference to each of six entry addresses.

Armature Chopping Control Module. The armature chopping module is shown in Figure 3.2.6.6-9 as a signal flow block diagram. Each block or summing point corresponds to a lower level module. The data flowing between modules is passed by register although each signal may be stored in RAM for monitoring purposes. Each signal is labeled on the diagram and may be found in the propulsion control data section. The signals labeled with R are for diagnostic reasons only.

This module has two entry points. The first entry point enables initialization of the storage element VK to a preset value. The value of the MODE SELECT WORD is incremented by one so that initialization is performed only once. The second entry

TABLE 3.2.6.6-3
TASK 1 FUNCTIONS

Mode	Mode Select Word	Task 1 Function
Neutral	0, 1	Sample armature current
Armature	2	Initialization
Chopping	3	Armature chopping control
Field	4	Initialization
Weakening	5	Field weakening control
Charge	6, 7	No operation

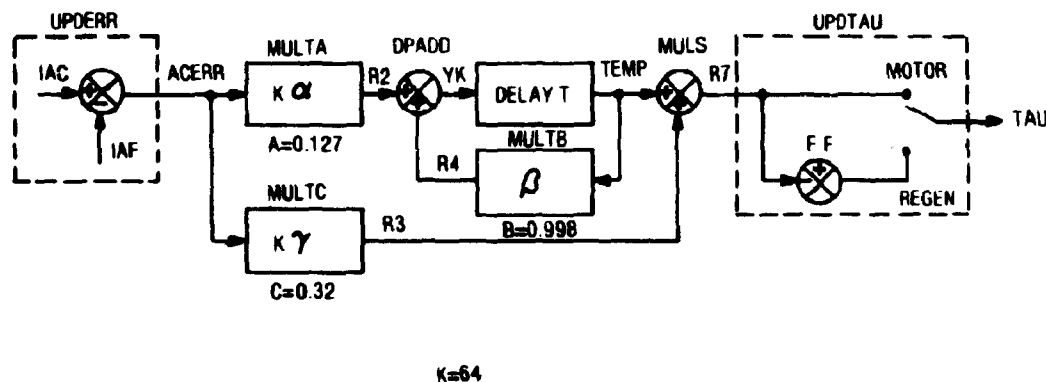


Figure 3.2.6.6-9. Armature Chopping Control Block Diagram

point then provides armature chopping feedback regulation. An error signal is sampled from between the command (IAC) and actual (IAF) armature current. Note that the command (IAC) is generated by the sequencing function. The error receives gain and compensation and is sent as τ , the pulse width modulation percentage on-time. Regeneration is indicated when IAC has a negative value and the M/G signal is set to REGEN. During regeneration, the value of τ must be inverted because it stands for percentage off-time.

Field Weakening Control Module. The field weakening control module is shown in Figure 3.2.6.6-10 as a signal flow block diagram. The structure and signal flow is identical to the armature control module, except the output of the compensator produces a value for the field current command (IFC).

Like the armature control module, there are two entry points with one for initialization. The second entry point provides feedback regulation. The output of the compensator is always subtracted from the rated value of field current. The value sent as IFC is then clamped to some minimum positive value.

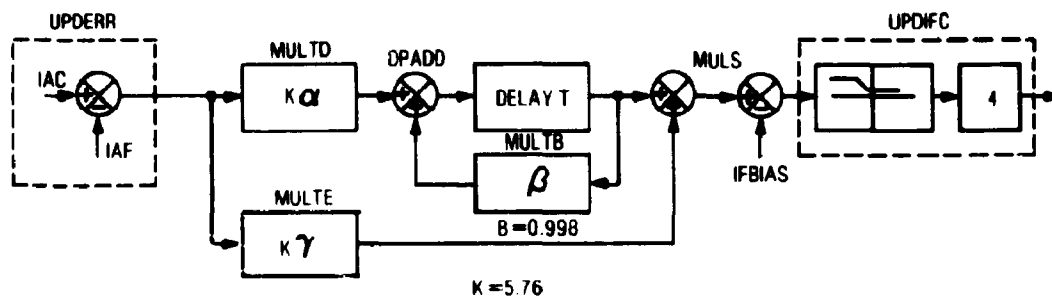


Figure 3.2.6.6-10. Field Weakening Control Block Diagram

Drive Sequencing Function

The sequential controller provides necessary drive subsystem interlocks and smooth transitions between the various modes of vehicle operation. As the sequential controller operates the drive subsystem, it shifts between the various states contained within its State Table. Each of 28 states in the State Table is associated with different modes and submodes of vehicle operation. The responsibility of the sequential controller then is to monitor various driver commands and vehicle parameters and to select appropriate transitions between the available states in the State Table (which is also called a Transition Table)

Figure 3.2.6.6-11 presents the essential structure of the sequential controller. Logical control has been effectively separated from data manipulation. Logical control is handled by the State Transition Processor as it executes transitions between the various states represented in the Transition Table. Then through the Action routines associated with particular transitions, control lines are actuated. Control may consist of directly commanding a device external to the controller or commanding, through an internal parameter, a task executing in software.

Transliterator functions are also required for the State Transition Processor. Each transliterator function monitors for a particular event and raises a flag when the event occurs. For instance, a software comparator detects when TAU, the command value sent to the armature chopper, has reached a maximum value, and as a result a flag is raised. As shown in Figure 3.2.6.6-12 the State Transition Processor may only examine logic flags or logic combinations.

The transliterator functions are distributed throughout the system and may be included within a task which produces the parameter to be monitored. The following transliterator functions are provided:

- Motor Command (I_f^* and τ) Monitor
- Armature Current (I_a) Monitor
- Speed Monitor
- Battery Monitor
- Programmable Software One-shot.

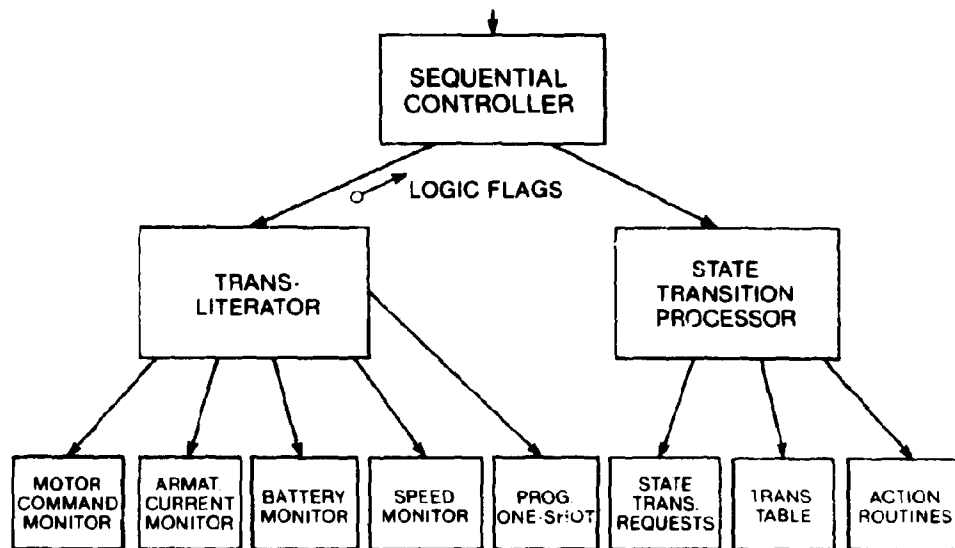


Figure 3.2.6.6-11. Structure Chart of Sequential Controller

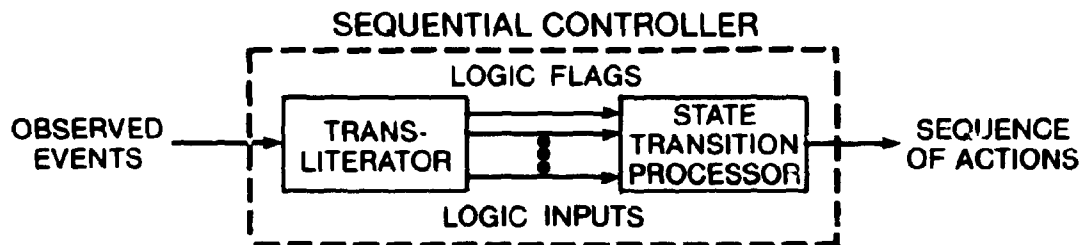


Figure 3.2.6.6-12. Functional View of Sequential Controller

The programmable software one-shot provides a delay which can be set to a multiple of 20 ms and after a time-out a flag is raised. In the remaining sections, the various components of the sequential controller are defined in further detail.

State Table

The State Table contains a Finite State Machine representation of the sequencing activity. The selected method to represent the FSM is with a modified Right-Linear Grammar. The table is specified directly in terms of the modified Right-Linear Grammar, and a translator program generates the proper table format for incorporation into the controller software. In this section the form of the modified Right-Linear Grammar is defined.

The modified Right-Linear Grammar is composed of three elements.

- A predefined set of states (or modes)
- A predefined set of StateTransition Request (STR) words (or Boolean expressions)
- A predefined set of Actions

Furthermore, each element is actually an address label. The address labels for the STR words and Actions are entry addresses into a corresponding module. For the states the address labels correspond to locations within the Transition Table.

Permissible transitions are defined between states by listing a set of productions after each state according to the following format:

STATE-n $\rightarrow$ STR (ACTION) . . . STATE-n

where the bracket indicates that an action need not be included. In the modified Right-Linear Grammar there is a second state called a Meta-state. The Meta-state is represented in the same way as a state but may be intermingled optionally in any number with a list of actions. The Meta-state provides the capability for a delay on condition within the environment of the Real Time Scheduler. The Meta-state must have its transitions defined in a special manner as follows:

<meta-state-n> $\rightarrow$ STR (ACTION) . . . <STATE>

where the following strict limitations apply:

- The action list may not include a Meta-state.
- The right hand side of a production may include either a State or Meta-state but not both.

As an example consider the following productions:

<NEU> $\rightarrow$ GO (CLOSE FF) <CLOSFF> <FWD>
 $\rightarrow$ α <NEU>
 <CLOSFF> $\rightarrow$ NOTMO <CLOSFF>
 $\rightarrow$ FFA
 $\rightarrow$ α (REPORT) <WAIT>

The Sequential Controller starts in the NEU state and when the State Transition Request word GO is true, the associated transition is executed or else it loops in the neutral state. The action CLOSEFF closes the Field Forward contactor and sets the software one-shot for a delay long enough for the contactor to close. Next, the meta-state CLOSFF is entered, and the Sequential Controller loops back upon the CLOSFF meta-state every 20 ms until the delay is over. Then the FWD state is entered after the FFA acknowledge signal is verified as being true. If FFA is not true then a malfunction is reported and the transition is aborted.

State Transition Processor

The State Transition Processor executes a transition to a new state every 20 ms where 20 ms is the scheduling time of the Sequential Controller. The activity of the State Transition Processor for each cycle may be summarized as follows:

- Fetch a pointer into the State Table.
- Execute a set of State Transition Request routines (specified in the Transition Table) until a transition is requested.
- Push a set of Action routines onto the stack. (There may be none.)
- Make the associated transition to a new state. (Move the pointer to another state in the Transition Table, and set the State Identification Number to reflect the new state.)

The State Transition Processor uses the following variable storage:

- **STPTR** State Pointer is a pointer directed into the Transition Table and always points to a state production.
- **MSPTR** Meta-state Pointer is a pointer directed into the Transition Table and always points to a Meta-state production.
- **STATID** State Identification Number identifies with a unique value the present state or meta-state. A state is indicated when the MSB=0, and a meta-state is indicated when the MSB=1 (Most Significant Bit).

State Transition Request Routines

State Transition Request Routines are modules executed by the State Transition Processor. There is a State Transition Request for each logical combination of driver commands and internal parameters that must be examined. For each cycle of the sequential controller (20 ms) a particular series of State Transition Request Routines as specified in the Transition Table are executed until a state transition is executed.

In general, each STR routine may examine some logic combination of the driver commands or internal parameters. When a STR routine is executed, it determines if a particular logic combination is TRUE. Special program conventions are employed such that the zero flag is to be set according to the following conditions:

- **ZF=0** A state transition is not requested because the logical combination of the selected input parameters is FALSE.
- **ZF=1** A state transition is requested because the logical combination of the selected input parameters is TRUE.

In summary, each STR routine performs a test for a particular logic combination, and if the combination is TRUE then the zero flag (ZF) is set to one in order to initiate a state transition.

Action Routines

The Action routines are modules referenced in the State Table and may be executed as a part of a transition. Normally, an Action routine either commands a device external to the controller, or commands a software task through an internal parameter. For instance, the Mode Select Word is used to command the Propulsion Control function in Task-1. Then an Action routine executed by the sequential controller selects a possible mode of operation through this internal parameter.

Table Translator Program

The Table Translator program translates the modified Right-Linear Grammar into a State Table which is usable by the State Transition Processor. In addition, certain linkage parameters are added for use by the State Transition Processor. The translation procedure is relatively straightforward though tedious, and to avoid human error, a Table Translator program on the Microcomputer Development System automatically performs the translation before assembly. Only a specification of the Table Translator is given and not a detailed description of the program itself.

The Table Translator program takes as input a modified Right-Linear Grammar as defined previously. In addition, the following conventions apply:

- A semicolon (;) must precede comments.
- Provide a prologue at the beginning which includes Externals for the STR and Action routines, and a Public defining the start state.
- States are denoted by placing :STATE on the line preceding the grammar.
- Meta-states are denoted by placing :META-STATE on the line preceding the grammar.
- An END placed at the end of the grammar terminates translation.

The format of the Transition Table requires four types of linkage parameters:

- Production Link. The production link provides a byte count pointing to the next production. When the State Transition Processor is using the table and an STR routine does not request a transition, then a production link points to the next production and a new STR routine to be executed.
- Action Count. The Action count specifies a count (added by one) of the number of actions to be executed in a particular transition.
- State Address. An absolute address referring to the location of a particular state in the State Table.
- State Identification Number. A unique valued number associated with each state in the State Table.

Table 3.2.6.6-4 summarizes information which is encoded into the four types of linkages.

Battery Charge and Fuel Gauge Functions

Both functions are selected according to the mode of vehicle operation as reflected in the "Mode Select Word." Table 3.2.6.6-2 summarizes when either of the functions are active. The Charge function (as defined in Section 3.2.2) is executed by the BATMON module in Task 4. There are two different fuel gauging algorithms (as defined in Section 3.2.2) which are selected according to motoring or charging. As shown in Table 3.2.6.6-2 the Charge Fuel Gauge function is executed by the SIGMON module in Task 2 and, the Motoring Fuel Gauge function is executed by the BATMON module in Task 4.

Determination of BVEX Flag

The battery voltage is monitored in all modes of operation so that it does not exceed a peak value, V_B (critical). A flag BVEX (Battery Voltage Exceeded) is set when V_B (critical) is exceeded and is needed so that:

- Regeneration may be inhibited during braking.
- Battery current is tapered during battery charging.

TABLE 3.2.6.6-4
STATE TABLE LINKAGE PARAMETERS

Table Linkage Parameters	Description	
	MSB = 0	MSB = 1
State Address	Address pointing to a state production	Address pointing to a Meta-state production
State Identification	Identifies a state	Identifies a Meta-state
Production Link	Relative pointer to next production	The production pointed to must be accepted and a transition executed
Action Count	Number of actions in transition	Forces a transition to the state pointed to by the State Pointer (used in a Meta-state production)

The equation for V_B (critical) as derived in the previous Section is

$$V_B \text{ (critical)} = 157.68 - 0.216 \text{ T volts}$$

where

$$T = \text{temperature (}^{\circ}\text{F)}.$$

The temperature sensor has the following relationship to bits sampled:

$$T = 1.125 \bullet BT - 22 \text{ }^{\circ}\text{F}.$$

where

$$BT = 0 - 127 \text{ bits.}$$

Combining equations yields

$$V_B \text{ (critical)} = 162.4 - 0.243 \bullet BT$$

The charge battery voltage sensor has the following relationship to bits sampled:

$$V_B = 0.315 \bullet BVCH + 120 \text{ volts,}$$

where

$$BVCH = 0 - 127 \text{ bits.}$$

Since the BVEX flag is set according to the difference between V_B (critical) and V_B , then the last two equations are subtracted to yield

$$3.17 \left[V_B \text{ (critical)} - V_B \right] = BVCRT - F \bullet BT + BVCH,$$

where

$$BVCRT = 134.6 (=87H),$$

$$F = 0.7725 (= .CCH),$$

and BT and BVCH = 0 - 127 bits.

BVEX flag is set as follows:

$$\text{If } \left[V_B \text{ (critical)} - V_B \right] \geq 0, \text{ then BVEX} = \text{TRUE} \\ \text{ELSE BVEX} = \text{FALSE.}$$

Charging Fuel Gauge Calculation

During charging of the battery, an increment of charge over a fixed interval of time t is calculated by the equation,

$$\Delta Q = IFC \bullet \Delta t,$$

where

ΔQ = increment of charge in Amp-Min

IFC = charging current in Amps,

Δt = sampling interval in Minutes

The total charge is obtained then by successive addition of the incremental charge:

$$Q(t + \Delta t) = Q(t) + \Delta Q,$$

where

Q = total charge.

For display of total charge by the computer, Q must be expressed as bit units rather than Amp-Minutes. Therefore note that the full capacity of the battery is 10,260 A-M and the maximum measurable current is 30 Amps so that

$$10,260 \text{ A-M} = 255 \text{ bits},$$

and

$$30 \text{ Amps} = 255 \text{ bits.}$$

Now ΔQ may be converted to bit representation as follows:

$$\Delta Q = \frac{IFC \cdot \Delta t}{342} \text{ bits}$$

The Δt is a fixed sampling interval and is arbitrarily selected to produce a constant that is easily multiplied times IFC. A constant of 2^{-6} (or 0.04 H) is selected so that

$$\Delta Q = 2^{-6} \cdot IFC,$$

where

$$\Delta t = 5.344 \text{ Minutes sampling interval.}$$

Motoring Fuel Gauge Calculation

The fuel gauge equation described in Section 3.2.2 must be rescaled to allow evaluation in terms of bit units. Consider that the battery voltage and current sensors have the following relationships to bits sampled:

$$I_B = 3.937 \text{ BC Amps}$$

$$V_B = 0.276 \text{ BVFG} + 80 \text{ Volts}$$

where

$$\text{BC and BVFG} = 0 - 127 \text{ bits.}$$

Restatement of fuel gauge equation yields

$$Q = 255 \left[1 - \frac{\text{erf}(x)}{\text{erf}(y)} \right] \text{ bits,}$$

where

$$y = 2.051 - 0.00984 \cdot \text{BC} + \frac{1.299}{\sqrt{\text{BC}}},$$

$$x = y + 0.7866 + 0.0264 \cdot \text{BVFG}$$

The arguments for the error function are to be scaled by a factor of 50 to give a variation from 0 to 100 so that it may be evaluated by means of a 100 point look-up table. In addition, note that full capacity corresponds to 255 bits. The final form of the equation becomes

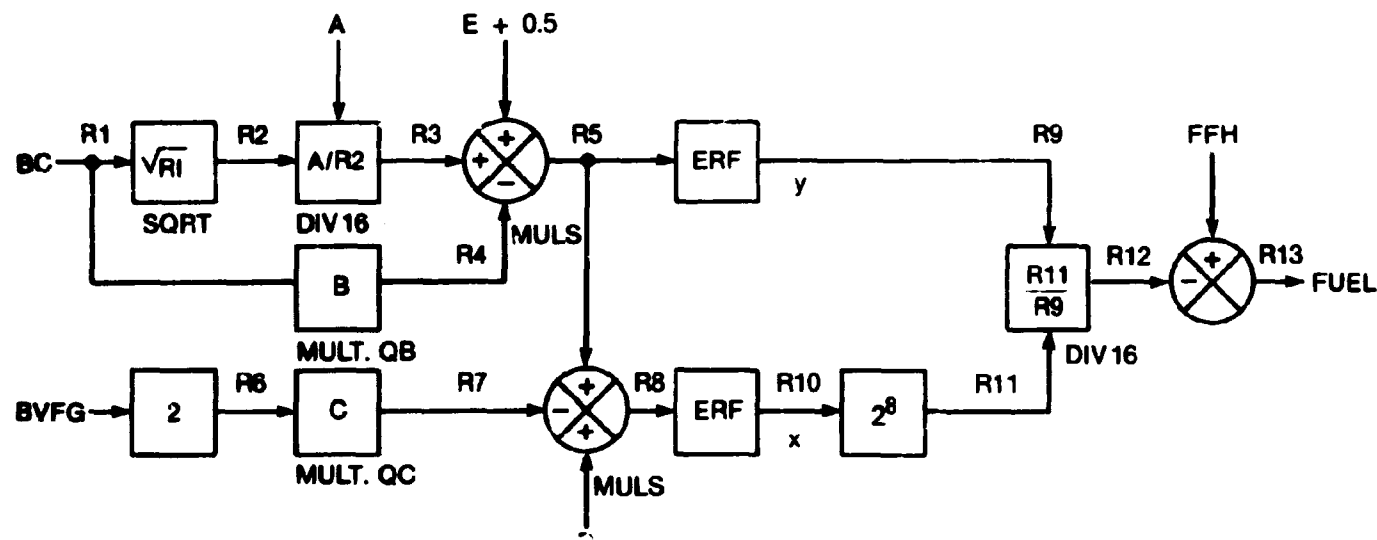
$$Q = 255 \left[1 - \frac{\text{erf}(x)}{\text{erf}(y)} \right] \text{ bits,}$$

where

$$Y = 66 \text{ H} - 0.7DFH \cdot \text{BC} + \frac{41 \text{ H}}{\sqrt{\text{BC}}},$$

$$X = 27 \text{ H} + Y - 0.491 \text{ H} (2 \cdot \text{BVFG}).$$

Figure 3.2.6.6-13 presents a block diagram of the equation as implemented.

**EQUATIONS**

$$(1) R5 = A/\sqrt{BC} - B \cdot BC + E$$

$$(2) R8 = R5 - C \cdot 2 \cdot BVFG$$

$$(3) FUEL = FFH - \frac{2 \cdot ERF(R8)}{ERF(R5)}$$

CONSTANTS

$$A = 41H$$

$$B = 0.7DFH (= 0.49213_{10})$$

$$C = 0.A91H (= 0.6599_{10})$$

$$D = 27H$$

$$E = 66H$$

Figure 3.2.6.6-13. Motoring Fuel Gauge Block Diagram

Signal Monitoring Functions

Signals may be monitored either at a sampling interval of 20 ms or 240 ms. The fast-changing signals, IAF, TAU, and IFC, are monitored by SIGMON in Task 2. The remaining signals, which include all battery parameters and speed, are monitored by BATMON and UPDSPD in Task 4. Both SIGMON and BATMON monitor different signals depending upon the mode of operation as reflected in the MODE SELECT WORD. Table 3.2.6.6-5 summarizes the signals monitored.

TABLE 3.2.6.6-5
SIGNALS MONITORED IN TASKS 2 AND 4

MODE	MODE SELECT WORD	TASK 2 (20 MS) (SIGMON)	TASK 4 (240 MS) (BATMON)
Neutral	0,1	IAF	BT, BVCHG
Armature	2,3	IAF, TAU	BT, BVCHG, BC, BVFG
Field	4,5	IAF, IFC	BT, BVCHG, BC, BVFG
Charge	6,7	IAF, IFC	BT, BVCHG, BC, BVFG

I/O Functions

In general, I/O signals are handled by the bottom layer of modules in the software structure. In most cases, each I/O signal is handled by only a single module. In this manner, only a single module need be affected by a signal modification in hardware.

A single A/D module is used to sample and filter any of the seven analog input channels. Likewise, a single logic input module samples and filters the three logic input ports every 20 ms. For the speed signal, a tachometer pulse count is sampled and stored every 60 ms in a three element ring buffer for filtering by the speed monitoring module UPDSPD in Task 4. The continuous memory is handled by a single module both for input and output of a data byte. The logic and analog output signals are handled individually by modules within a function responsible for controlling a signal. On the logic outputs, the software utilizes the bit SET/RESET capability of the Intel 8255 peripheral chip.

Data Storage

The RAM is organized to provide common data for the software subsystem. All interfunction and most intermodule data communication passes through preassigned locations in RAM. In general, RAM is organized to contain three varieties of parameters:

- Filtered external I/O logic and analog signals
- Internal logic (flags) and analog parameters
- Status and control parameters

The listing 'EVRAM' provides individual descriptions of each parameter.

ROM Organization

The software is packaged in four 1024-byte Erasable Programmable Read Only Memories (2708) and is organized into the Task groupings. In addition, a fifth EPROM is available as a spare but has been used to contain software handlers for driving a special test fixture, the Debug Panel. Refer to Figure 3.2.6.6-14 and Table 3.2.6.6-6 for further details about the organization.

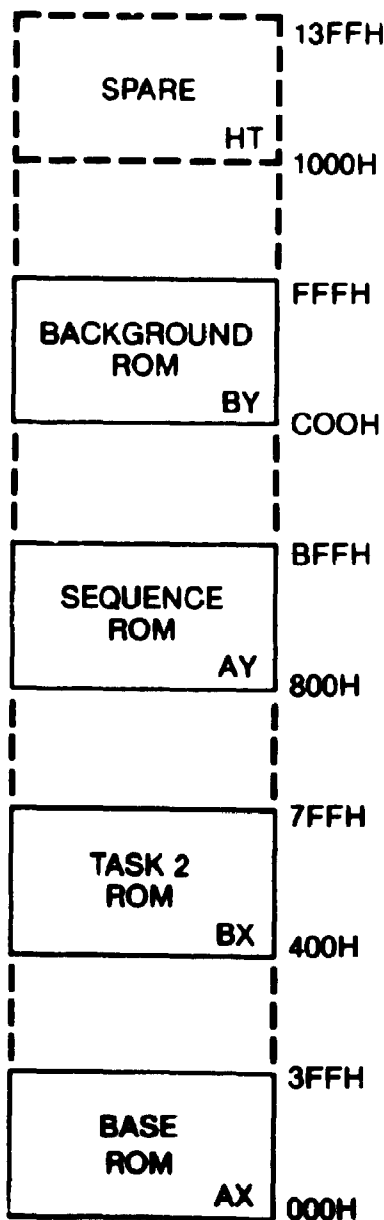


Figure 3.2.6.6-14. Memory Map of ROM s

TABLE 3.2.6.6-6
ROM ORGANIZATION

Number	Location	Name	Description
1	AX	Base	Contains the Base page module and Task 1
2	BX	Task 2	Contains all of Task 2 except the sequencer
3	AY	Sequencing	Contains the State Table and State Transition processor
4	BY	Background	Contains Tasks 3 and 4
5	HT	Spare	May be used to drive a special test fixture

Each ROM is labeled in the upper seven bytes with three fields of information:

3 bytes 3F9 - 3FB	General Electric symbol
3 bytes 3FC - 3FE	date code of creation
1 byte 3FF	ROM check sum for verification of content integrity.

In addition, below these bytes there are linkages to modules which are referenced externally.

Appendix 3.2.6.6-1

	ANALOG OUT	<u>UPDATE INTERVAL</u>
TAU		4 ms
FUEL		240 ms
JFC (or FCC)		4 ms
SPARE		4 ms
ANALOG IN		
BVCH		4 or 240 ms
BVFG		240 ms
BT		240 ms
BC		240 ms
AC		4 ms
BP		20 ms
AP		20 ms

WBS 3.2.7 Accessory Charger

Function

The accessory battery charger provides the electrical interface between the (nominal) 108 V propulsion battery system and the (nominal) 12 V battery system. The accessory charger is designed so as to duplicate the terminal characteristics of a conventional IC engine-driven alternator.

Operating Principle

Figure 3.2.7-1 shows a simplified circuit schematic of the charger. The incoming 108 V supply is fused by a 20 A fuse, F_{C3} , the function of which is to avoid possible damage to wiring should transistor Q_1 fail shorted.

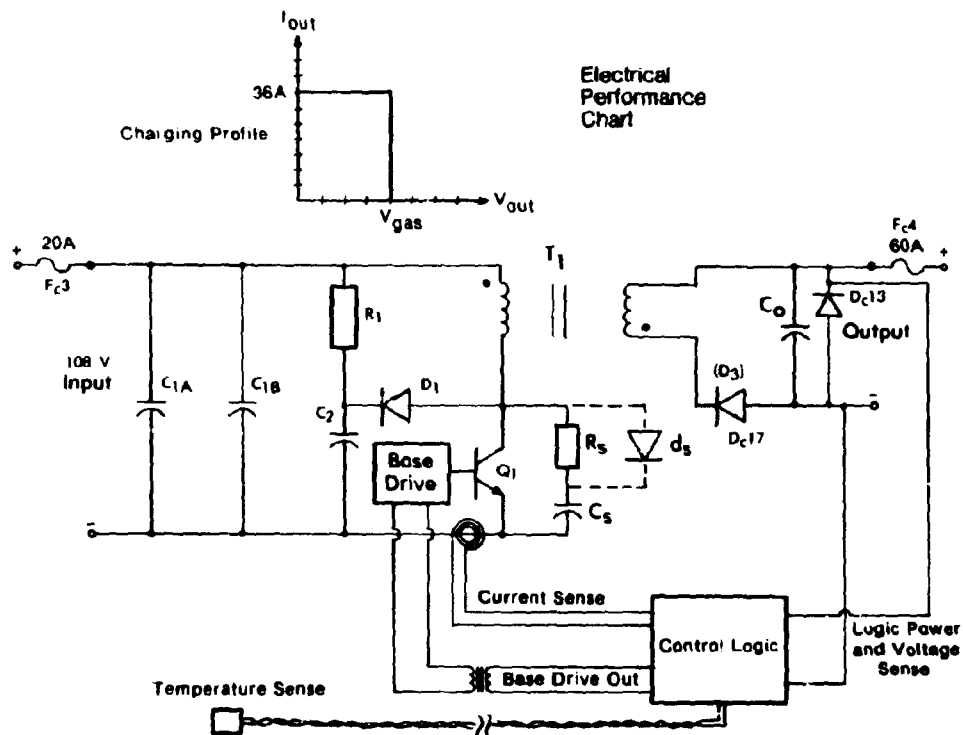


Figure 3.2.7-1. Simplified Circuit Schematic

Capacitors C_{1A} and C_{1B} initially filter the supply. However, it was discovered that during simultaneous operation of the armature chopper, these capacitors draw dangerously high ripple current; and they were, therefore, disconnected from the circuit. The accessory charger now relies upon the field chopper and armature chopper filter capacitor banks to provide the filtering of the disconnected capacitors C_{1A} and C_{1B} .

Transistor Q_1 and the primary winding of transformer T_1 are connected in series across the 108 V source. Components R_1 , C_2 and D_1 act as a voltage clamp. If Q_1 is

made to conduct, current in the primary of T1 grows at a rate di/dt given by $di/dt = V/L_p$ where V is the applied voltage and L_p is the inductance of the primary winding.

During this current growth, diode D₁₇ in the secondary circuit of the transformer is reverse biased and, hence, no secondary current flows. When Q1 is switched off, the magnetic energy stored in the core of T1 is transferred to the secondary of T1 and causes a decaying current to flow in D₁₇ and, therefore, into the 12 V battery connected across the output terminals.

If Q1 is switched on and off again, another pulse of energy is transferred from the primary to the secondary of T1. By repeating the on-off action of Q1 at a high frequency, a continuous stream of pulses (or dc with superimposed ripple) are generated in the output winding. Capacitor bank, C₀, provides a low impedance shunt path for ripple current, while the dc component is delivered to the 12 V battery. Fuse F₄ and diode D₁₂ protect the circuit from failure of D₁₇ and improper connection of the 12 V battery respectively.

In Figure 3.2.7-1, the block labelled "Control Logic" performs the control function for the power circuit described above. This is a signal level circuit which measures the output voltage of the charger circuit and maintains that voltage within the limit required to safely charge the battery. This voltage limit is determined by the temperature of the battery, which this circuitry also senses. The emitter current of Q1 is also sensed (not including snubber discharge current) in order to provide a current limit function to protect Q1. The main output of the control logic is a pulse train, amplified by the circuitry labelled "Base Drive" (Figure 3.2.7-1), and then becomes the base current for Q1.

The logic power supplies for the control logic circuitry and for the base drive amplifier are derived entirely from the 12 V battery at the output of the charger.

Circuit Description

Figure 3.2.7-2 shows a complete schematic of all accessory charger circuitry, except the temperature sensor located externally to the PCU. It includes the control logic circuitry, the power circuit, and the base drive circuit.

Control Logic. Important sections of the control logic circuitry are:

1. The V_{cc} generator, coordinates H1-2-3, generates a stable 9.3 V dc (nominal) voltage by regulating down the voltage of the accessory battery. The V_{cc} generator circuit provides the power supply voltage for the IC's and other circuits in the charger. The voltage V_{cc} is determined by Zener D15 and is regulated by series pass transistor Q9. Relay RY2 has its contacts in series with the input to the V_{cc} generator. The coil of RY2 is energized by the 12 V output of the main drive system and, thus, the accessory charger will be operational only when the main logic power supply is operational. The V_{cc} generator will give zero volts output unless the input voltage is greater than approximately 10 V.
2. The V_{ref} generator, coordinates O2-3, generates a fixed voltage of 5.5 V dc at pin 7 of A1B. This voltage is set by the Zener diode D12.
3. The main timer circuit, coordinates H10-11, is used to generate waveforms that determine the operating frequency of the charger. The circuit is built around an LM555 timer IC. The pulse train output appears at pin 3 of TM1 and consists of pulses 33 μ s in duration with a repetition frequency of 20 kHz. This pulse train

Reproduced from
best available copy

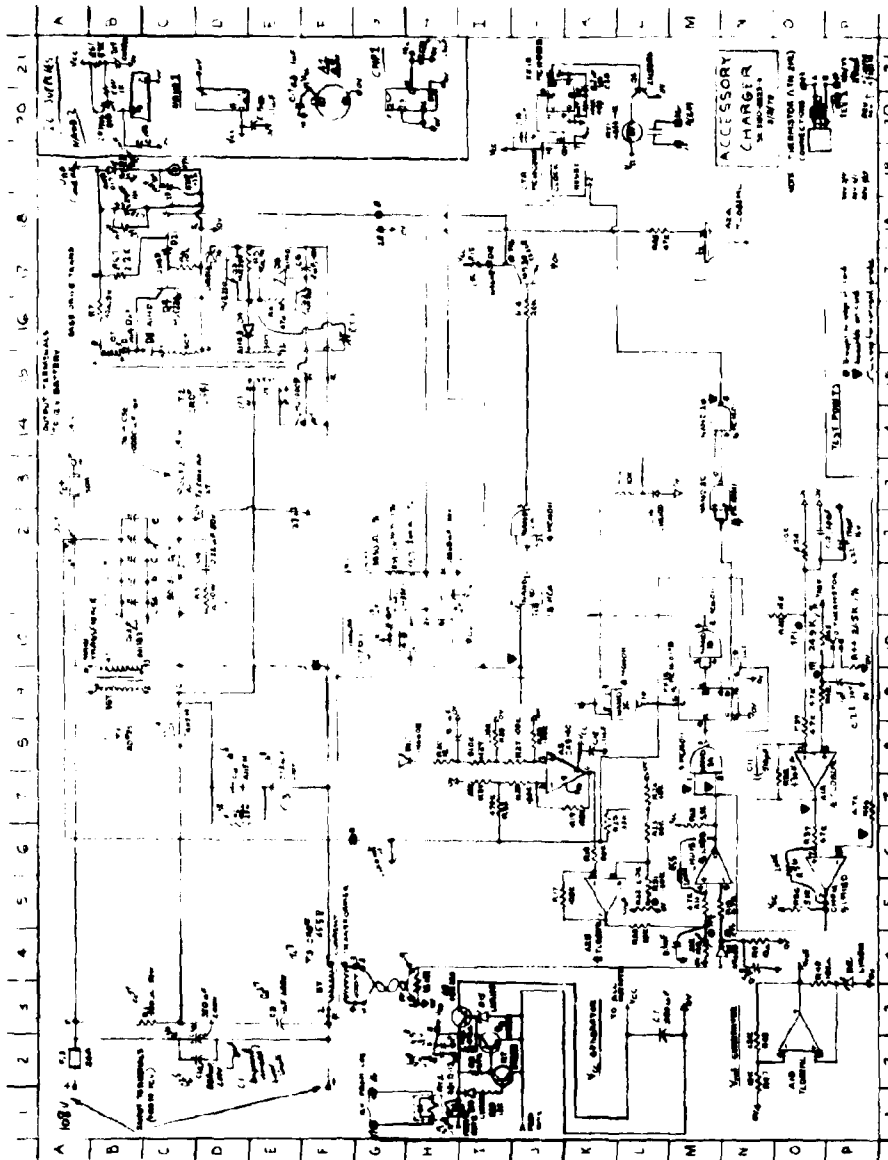


Figure 3.2.7-2. Accessory Charger

passes through NAND 1D and NAND 2A to Q5 and, hence, off the control logic circuitry to the base drive circuitry. If the system is in either voltage limit or current limit modes, the basic 33 μ s pulse width is reduced by the action of the signal at pin 13 of NAND 1.

4. The pulse width reducer circuitry is centered around bistable FF1A, coordinates M9. Output $\bar{Q}$ (pin 2) is set low by a high on input S. If no voltage or current limit conditions exist, input R is always low; thus, $\bar{Q}$ is always high, allowing the pulse train from TM1 to pass through NAND 1D unaltered. If a voltage or current limit condition exists, a low will occur once per cycle at the reset input of FF1A which inhibits the end of the pulse passing through gate NAND 1D. This, in turn, limits the peak current through the transistor Q1 or limits the output voltage.

5. The over-current detection circuitry centers around comparator CMP1B, coordinates M6. The waveform of transistor current derived from pulse transformer T3 located in the power circuit is compared at CMP1B with a dc value, determined by the setting of the current limit potentiometer R12 and the output of amplifier A2B. If the actual current instantaneously exceeds the set value, the output of CMP1B becomes low, FF1A is reset, and the pulse at NAND 1D terminates immediately, which is reflected in the immediate switching-off of main transistor Q1.

The current limit setting is intended to act on the average output current. In order to do this by regulating conditions on the primary side of the transformer, it is necessary to adjust the peak current limit in the main transistor Q1 in response to changes of the average voltage of the 12 V accessory battery and to change in the average value of the incoming 108 V battery voltage. Circuitry of A3 and A2B provides this feature.

6. The voltage limit circuitry operates using the average value of the output, not instantaneous values as with the current limit circuitry. In this circuit, a signal proportional to the desired voltage limit is established across capacitor C41, coordinates P9. This voltage is temperature modulated by the influence of the linear thermistor network connected in series with resistor R44. The commanded value of voltage is compared with the actual value of voltage, and the error signal is generated at the output of the summing amplifier A1A. This error signal is now compared with a sawtooth waveform generated at the output of A2A, coordinates M17. The comparator used in CMP1A, coordinates P5; and the comparator's pulse output is used to reduce the pulse width of the basic 33 μ s main transistor on-pulse and, therefore, regulate the average output voltage.

7. The fault detection circuitry involves counter CTR1, bi-stable FF1B, and relay RY1 located at coordinates J, K, L 19-20. This circuit detects malfunctions within the charger, the most likely being failure of transistor Q1 with the subsequent blowing of input fuse F_{C3}. When this occurs, the counter is not continually reset by the action of pulses from pin 4 of NAND 2B; and counter output Q₇ (pin 3) becomes high, thereby setting FF1B $\bar{Q}$ output at a logic low which, in turn, illuminates the accessory charge malfunction light on the dashboard of the vehicle.

Base Drive Circuitry. This is the circuitry shown at the upper right of Figure 3.2.7-2. The function of this circuitry is to convert the voltage pulses appearing at the collector of Q5 of the control logic circuit into current pulses in the base circuit of Q1.

The heart of the base drive circuit is the transformer T2, CRD #2541, used to isolate the control logic circuitry from the power circuitry and to provide regenerative base drive for Q1.

When Q5 is not conducting, Q4 is caused to conduct with R57 as the base drive source. With Q4 conducting, current is established in the 10-turn winding of T2. When Q4 is extinguished, current is induced into the base circuit of Q1 by transformer action. When base current begins to flow in Q1, collector current also begins to increase, which couples back into the 50-turn base winding by means of the 2-turn collector winding. This coupling from the collector to base constitutes regenerative base drive. To extinguish Q1, Q4 is driven on and D4 stops conducting. Negative base drive to assist in turn-off is provided by C6 and associated components.

Relay RY3 is used to delay application of base current to Q1 until the logic circuit has stabilized during power-up. The power supply to the base drive board is the unregulated output voltage. This voltage is instantaneously applied when RY2 is energized, but RY3 is delayed in energizing due to the R-C network feeding the coil. Similarly, RY3 is delayed in dropping-out due to charge stored on its parallel coil capacitor.

Power Circuit. The function of the power circuit components (shown in Figure 3.2.7-2 upper left) has already been described under the heading "Operating Principle" and therefore is not described here.

Circuit Layout. The three portions of the circuit are implemented in the PCU as follows:

1. Most power circuit components are mounted on an L-bracket attached to the PCU casting. The input and output capacitor banks are mounted vertically next to the L-bracket. The capacitors are four-terminal feedthrough types (low inductance) and are held at each end with small printed circuit boards. The output of the power circuit passes from the PCU by means of the flexible umbilical and the on-board charger power unit.
2. The base drive circuit is mounted on a printed circuit board supported on stand-off spacers attached to the power circuit L-bracket. This places the base drive circuit in close proximity to the main transistor Q1, as is desired to minimize noise pickup.
3. The control logic circuitry is mounted on one printed circuit board, which is inserted in the card stack.

Figure 3.2.7-3 shows a photograph of the power circuit and base drive board. (Drawing No. SK25-000170 covers component identification and placement.) Relay RY3 and its associated delay circuitry were not installed on this board at the time of the photograph.

Figure 3.2.7-4 shows a drawing of the control logic printed circuit board layout, and Figure 3.2.7-5 summarizes the pin connections to this card.

Figure 3.2.7-6 summarizes the interconnection of the three circuit sections and also defines the type of wiring interconnecting each section (twisted pair or twisted trio).



Figure 3.2.7-3. Power Circuit with Base Drive Board Removed

Winding data for the custom-made GE transformers is:

- CRD #2511 — Winding and construction details for this transformer are shown in Figures 3.2.7-7a and -7b.

- CRD #2541

Core:	846T 250 - 3C8 Toroid (Ferroxcube)	
Windings:	50 Turns	#22 AWG
	30 Turns	#25 AWG
	10 Turns	#25 AWG
	2 Turns	#16 AWG Teflon Insulated

- CRD #2558

Core:	Toroid F627-8-06 (Indiana General)
Windings:	Layer 1, 400 Turns, #35 AWG
	Layer 2, 5 Turns, #18 AWG

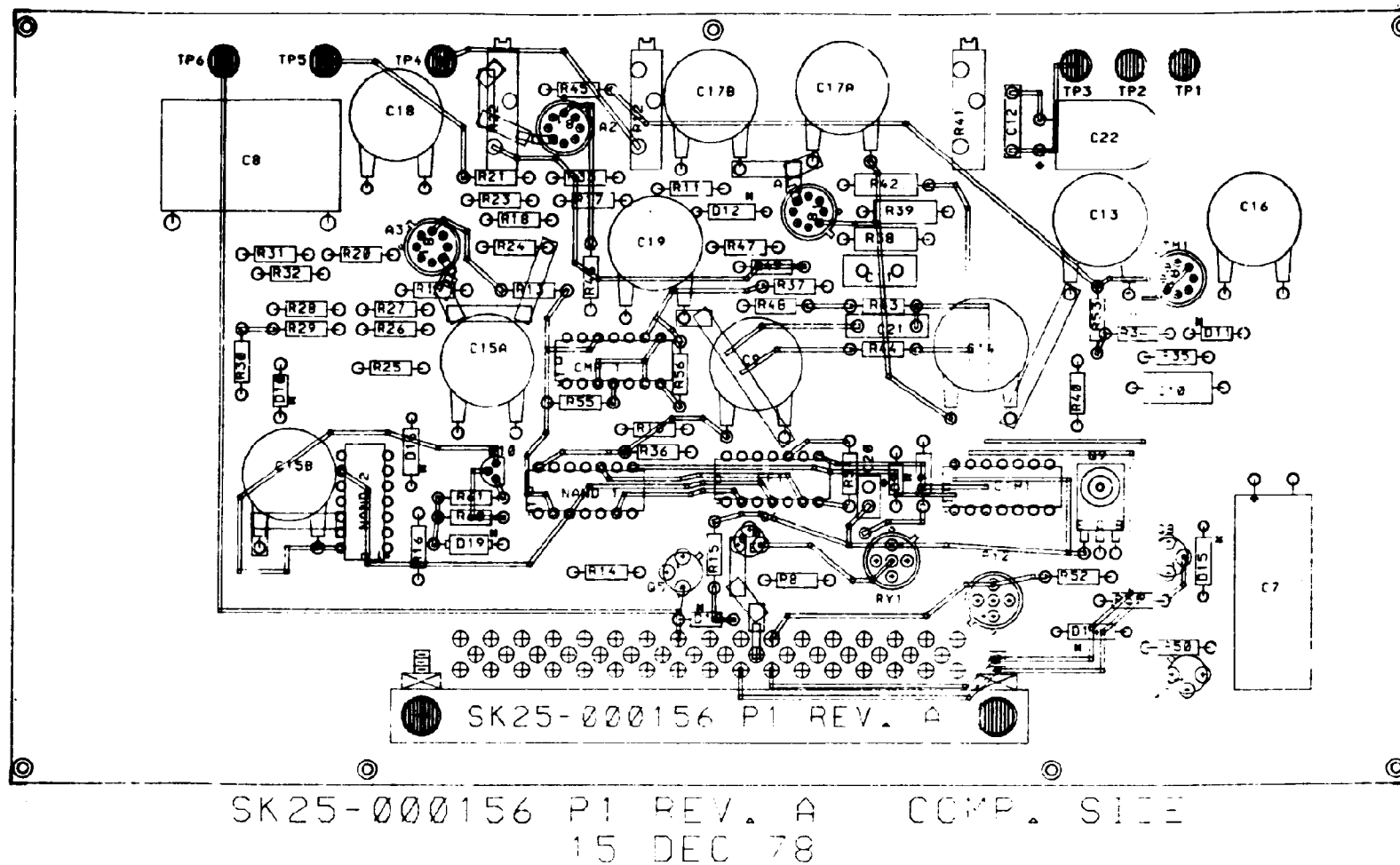
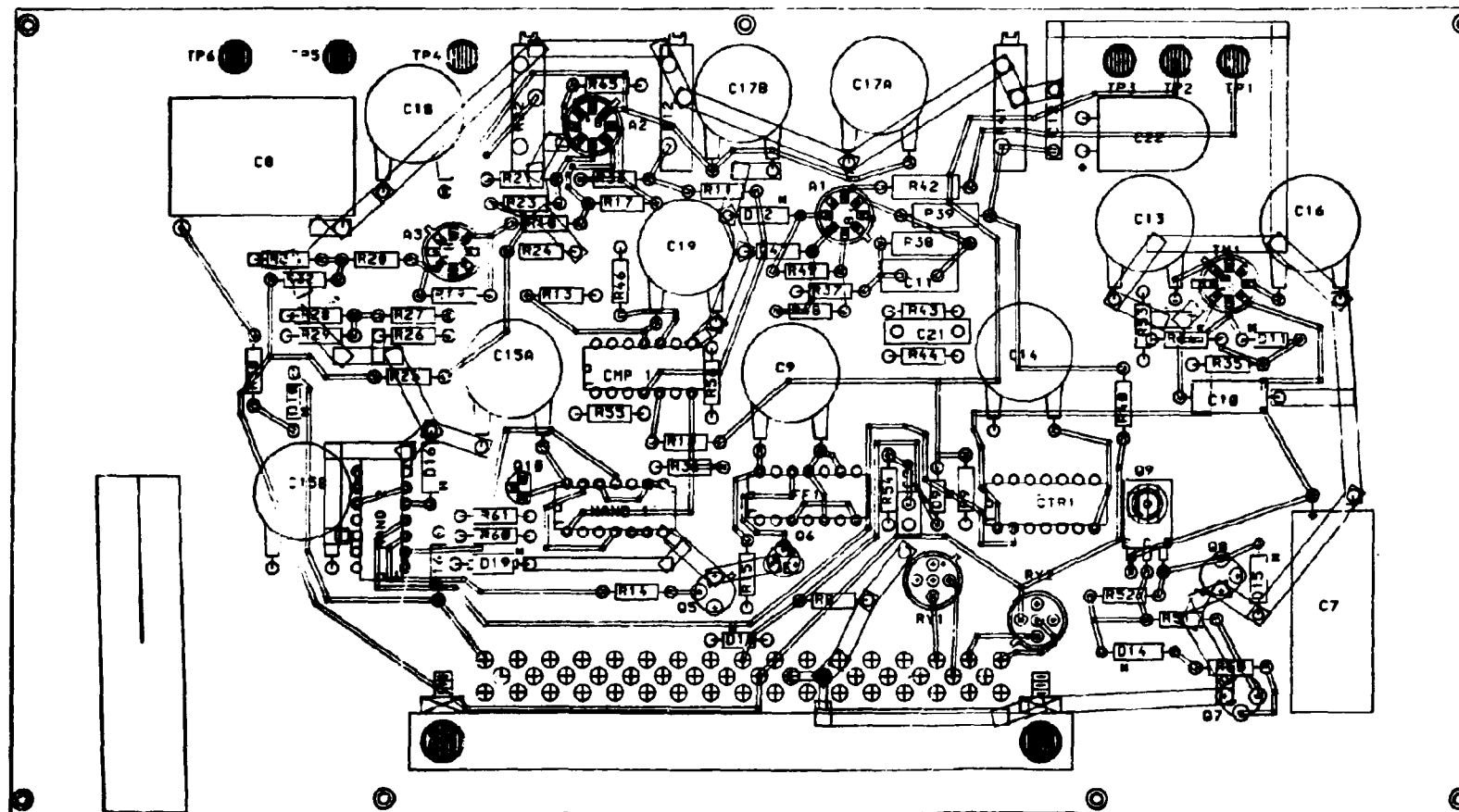


Figure 3.2.7-4a. Control Logic Printed Circuit Board Layout
(Component Side)



SK25-000156 P1 REV A LEAD SIDE
15 DEC 78

Figure 3.2.7-4b. Control Logic Printed Circuit Board Layout
(Lead Side)

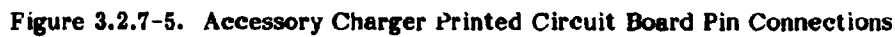


Figure 3.2.7-9 shows a typical Q1 collector current waveform.

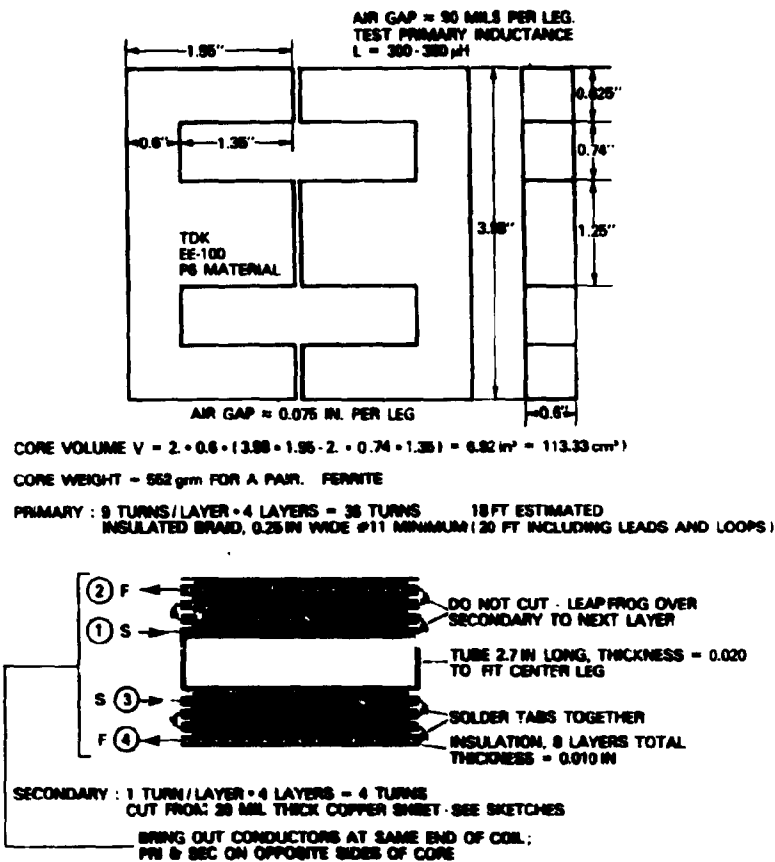


Figure 3.2.7-7a. CRD #2511 Winding Details

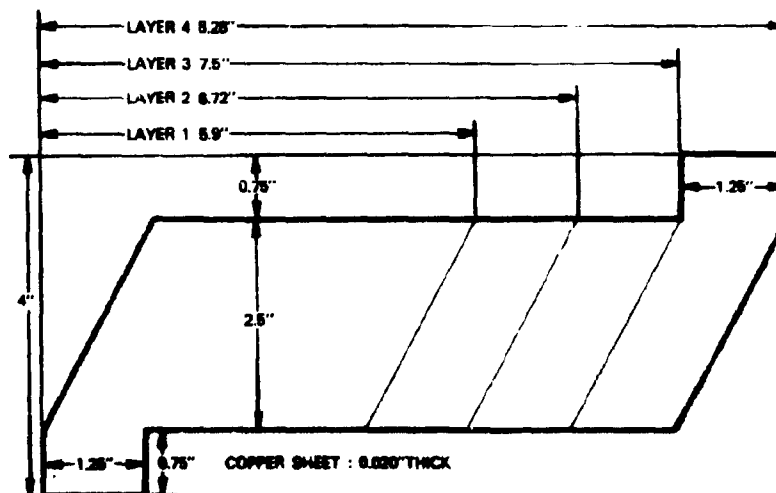


Figure 3.2.7-7b. Secondary Sheet Winding Dimensions



Figure 3.2.7-8. Q1 Quiescent Base Drive



Figure 3.2.7-9. I_c of Q1

Useful calculated circuit performance is given in Table 3.2.7-1.

TABLE 3.2.7-1

CIRCUIT PERFORMANCE CALCULATIONS

V_B (V)	V_{TP} (V)	I_{TP} (A)	I_{C5} (A)	$\eta\%$	P_T (W)	Operating Point
60	250	17.8	56.9	81.6	22.0	$T_A = 125^\circ\text{F}$ $I_O = 36.0\text{ A avg.}$ $P_O = 488\text{ W}$
80	260	15.9	50.1	82.8	17.1	
100	275	15.0	46.1	83.4	14.3	
120	293	14.5	43.7	83.5	12.5	
140	312	14.2	42.2	83.4	11.2	
160	331	14.1	41.4	83.2	10.3	

Symbols:

- V_B = Incoming average battery voltage
- V_{TP} = Peak voltage on Q1
- I_{TP} = Peak current in Q1
- I_{C5} = RMS current in output capacitor bank
- η = Circuit efficiency
- P_T = Transistor loss (Q1)
- T_A = Ambient temperature
- I_O = Average charger output current
- P_O = Power output

Figure 3.2.7-10 shows a calculated operating area of the charger as a function of ambient temperature and input battery voltage for a constant average output current of 36 A.

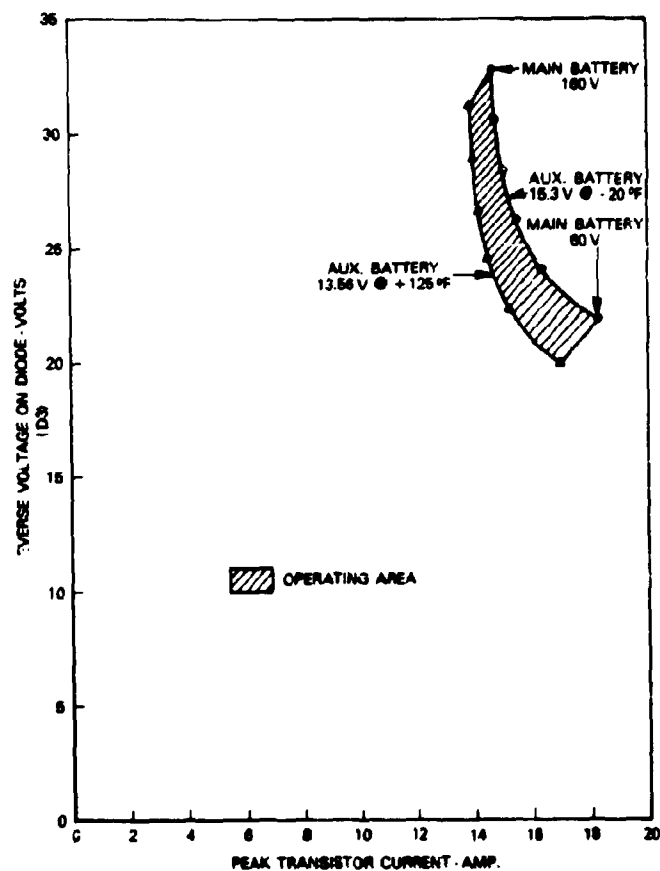


Figure 3.2.7-10. Conditions for Average Charging Current 36 A

WBS 3.2.8 Drive Test Instrumentation

The object of this General Electric-funded task was to construct a drive system test facility for an evaluation of the Electrical Drive Subsystem prior to its installation in the vehicle.

A sketch of the facility is shown in Figure 3.2.8-1. The heart of the system is a custom-designed flywheel shown in operating detail in Figure 3.2.8-2. The flywheel is designed to operate at speeds of up to and including 5000 rpm. The two outer flywheel disks are removable so that different vehicle weights may be simulated. The relationship between numbers of disks and vehicle weight is shown in Table 3.2.8-1.

Other components of the system are:

- A load generator, used in conjunction with a resistor load bank and field controller to simulate the aerodynamic drag and rolling resistance of the vehicle. The system also simulates the force of gravity if the negative gravitational thrust is less than the forward positive thrust of the drive subsystem. An example of this is hill-climbing when the vehicle is always moving forward.
- A torque transducer, used to provide a torque signal for the recording equipment.
- A bracket to which the motor of the drive under test is mounted.
- Signal processing circuitry to amplify, attenuate, filter, average, and isolate (in various combinations) the input signals.

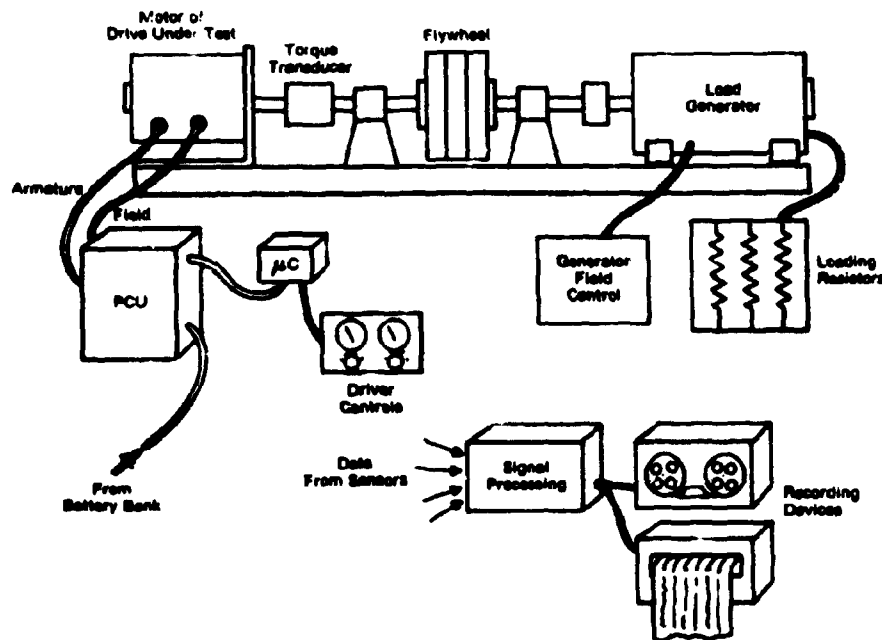


Figure 3.2.8-1. Drive Test Facility

Figure 3.2.8-2. Vehicle Simulation Flywheel Assembly and Detail

TABLE 3.2.8-1
DISK NUMBERS AND VEHICLE WEIGHT RELATIONSHIP

Flywheel Configuration	Equivalent Vehicle Mass (lb)
Main Section	2932
Main Section plus One Disk	3665
Main Section plus Two Disks	4398

- Sensors (not shown in Figure 3.2.8-1 except for the torque transducer) to measure quantities such as battery current and voltage, motor armature current and voltage, motor field current and voltage, and PCU and motor temperatures.
- Recording devices, such as an instrumentation tape recorder or a chart recorder.

Figure 3.2.8-3 shows a photograph of an EV drive system test facility similar to that actually used for ETV-1 drive subsystem testing.

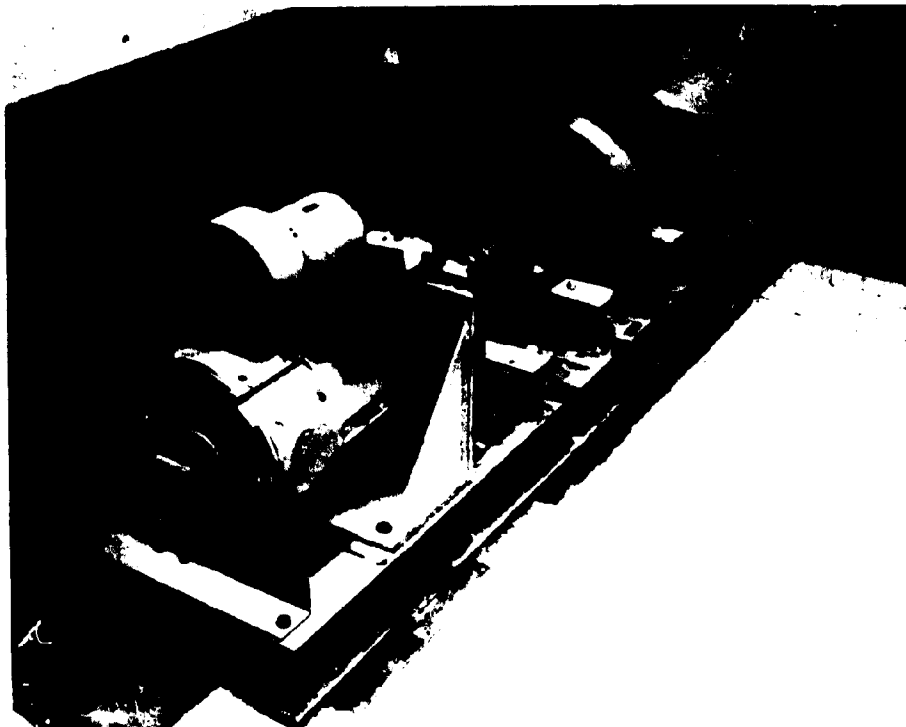


Figure 3.2.8-3. EV Drive System Test Facility

WBS 3.2.9 Transistor Power Module

Available Transistors

In May 1977, letters were sent to and information solicited from both foreign and domestic vendors of power transistors and rectifiers with products that might be suitable for the needs of the armature and field choppers. The devices evaluated in the armature circuit are listed in Table 3.2.9-1. Based on the requirements of the armature chopper, and a need for the transistors and diodes to be compatible with integrated power module technology, it became evident that the only suitable candidate transistors were the Power Tech PT4502 and the General Electric monolithic power Darlington transistors. Furthermore, it was seen that the General Electric transistor had significantly higher current handling capability and current gain than the PT4502, and was therefore selected for the module design.

TABLE 3.2.9-1

DEVICES EVALUATED IN CHOPPER CIRCUIT

DEVICE	MANUFACTURER	MANUFACTURER'S RATINGS			MAX, I _C PK TESTED	CASE
		I _C DC (A)	I _C PK (A)	V _{CEO} (V)		
PT 7511	Power Tech	50	90	200	110	T063
PT 4502	Power Tech	60	110	325	100	T0114
PT 4500	Power Tech	100	150	200	100	T0114
Low Voltage Power Darlington	GE			200	180	
High Voltage Power Darlington	GE			300	200	Flat Base Module
RSD-751	EVC	100	300	450	160	
WT GEX	Westcode	120		450*	150	Flat Base
2SD648	Toshiba	400		300	400	Press Pak

*V_{CER}

The General Electric power Darlington transistor features a metal contact system and a method for dielectric isolation that results in the improved performance of the device whether it operates in a discrete form or in a hybrid integrated circuit. These features are accompanied by substantial reductions in the weight and the volume of the packaged electronic function. The hybrid integrated circuit has two features that distinguish it from an integration of discrete components.

- All the elements in the circuit are on a common heat spreader.
- All electrical connections and voltage isolation are made internal to the package.

The electronic function in this case is a dc to dc converter or "chopper." The chopper is designed to control the torque and speed of the dc drive motor of an electric car and delivers 450 A of armature current. The circuit consists of two monolithic Darlington transistors in parallel with a fast recovery diode. Before the transistors are mounted onto a heat spreader, they are fabricated into Subcrete[®] transistor form. This allows for testing of the individual units which are then suitably matched for parallel operation.

Power Darlington Chip

The transistor consists of a two-stage Darlington monolithically integrated on a 1.7 cm² silicon chip. With a common emitter current gain (h_{FE}) in the range 200 to 1000 at a collector current (I_C) of 200 A, it requires a low current base drive that is provided directly by the power supply of the logic circuit. This eliminates the need for intermediate stages and reduces the complexity of the power integrated circuit. To minimize excessive junction leakage currents (I_{CEO}) that can result from the high gain, resistors are connected in shunt across the emitter base junctions of both stages. The silicon resistors are monolithically integrated, as shown in Figure 3.2.9-1. The resistor (R_1) across the driver stage of the Darlington, besides reducing I_{CEO} , controls the turnoff base current of the output transistor. With R_1 in place, high switching speeds are achieved without the use of a bypass diode. The designed value of R_1 is a compromise between the frequency response of the transistor and its threshold to failure due to second breakdown.

The base and emitter regions of this planar epitaxial structure have a multilevel metal interconnection system. It differs significantly from earlier work in the use of a different copolymer polyimide which exhibits excellent adhesion and moisture resistance because of disiloxane radicals incorporated within the polymer molecule. The molecular structure may be represented by the following general formula:

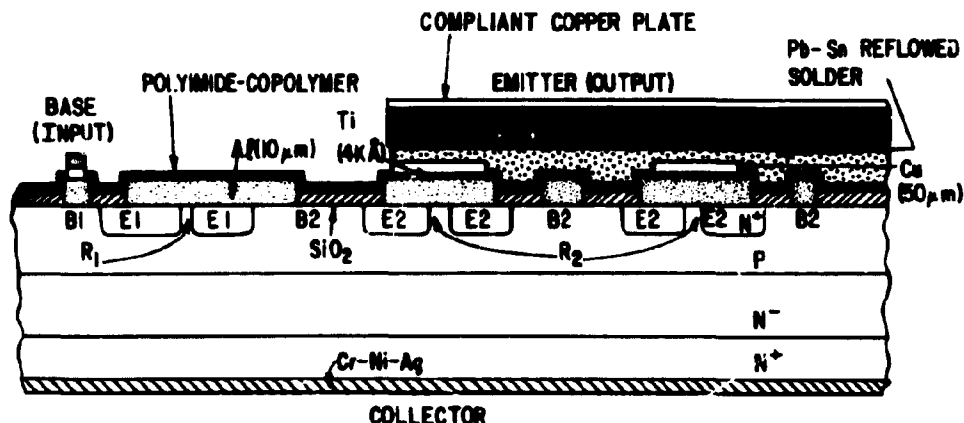
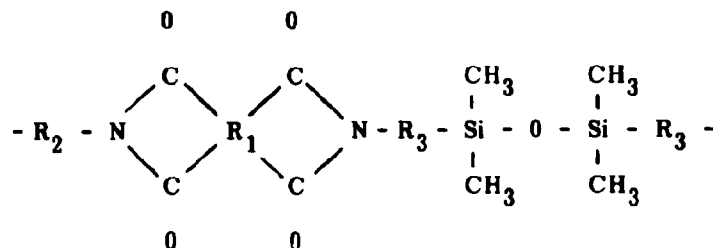


Figure 3.2.9-1. Darlington Transistor in Schematic Cross Section of Chip Before and After Solder Reflow Operation

[®] Registered trademark of the General Electric Company



where R_1 is an aromatic radical and R_2 and R_3 are aliphatic or aromatic radicals.

This material, as is the case for other polyimides, is applied in the form of a precursor polyamic acid solution which is imidized by heating to $\sim 200^\circ\text{C}$. During this process, the disiloxane sections of the molecule become chemically bonded to surface silanols on the silicon wafer, accounting for strong adhesive characteristics and moisture resistance of such coatings. Pertinent physical characteristics of the polyimide copolymer are shown in Table 3.2.9-2.

TABLE 3.2.9-2

SUMMARY OF MEASURED PROPERTIES OF POLYIMIDE COPOLYMER

Characteristic Dielectric Strength (1 - 2 μm thickness)	Measurement 400 to 500 V/ μm
Dielectric constant	3.0
Bulk resistivity	10^{17} ohm-cm @ 25°C 10^{13} ohm-cm @ 200°C
Surface charge on n-type silicon	$1.8 \times 10^{11} \text{ cm}^{-2}$
Water vapor permeability*	59×10^{-9}

* unit is $\frac{\text{cc of vapor @ RTP} \times \text{cm}}{\text{sec} \times \text{cm}^2 \times \text{cm Hg} \Delta p}$

As employed here, the polyimide copolymer films serve two important functions. First, they serve as a solder mask defining those areas of the chip which are to be solder bumped. Second, they serve as a dielectric layer protecting the interdigitated base fingers of the output transistors on the chip, permitting the attachment of an electrode to the entire surface of the emitter. This eliminates the need for bonding pads and substantially reduces the size of the silicon chip.

A summary of the chip processing is as follows:

1. Following the high temperature diffusion steps, contact windows are defined and 10 μm of aluminum is vapor plated and etched to remove metal from all areas other than the base and emitter contact regions.
2. Polyimide copolymer is applied and patterned using photolithographic processing.
3. Thin films of Ti (2000 $\text{\AA}$) and Cu (5000 $\text{\AA}$) are then evaporated overall to form a conducting layer for electroplating. Conventional photoresist is applied and processed to open once again the areas that are exposed in step 2.
4. Cu and Pb-Sn solder are electroplated in succession. The plating occurs in the regions where photoresist has been removed.
5. The resist is stripped and the thin evaporated layers of Ti and Cu are etched away. This leaves solder bumped regions in the emitter of the output and the base of the driver. The wafers are then scribed into individual chips. Figure 3.2.9-2 shows a scanning electron micrograph of a section of the solder bumped power Darlington chip.



Figure 3.2.9-2. Scanning Electron Micrograph Showing Aluminum Emitter Stripes and Polyimide Copolymer over the Base Metal Strips

Power Darlington Subcircuit

The power Darlington subcircuit is shown in Figure 3.2.9-3. The chip has a solderable metallization of Cr-Ni-Ag on the collector surface. The beryllia substrate to which the chip is mounted has a copper layer applied to both sides by a direct copper bonding process. The bottom layer of copper permits subsequent solder mounting of the subcircuit.

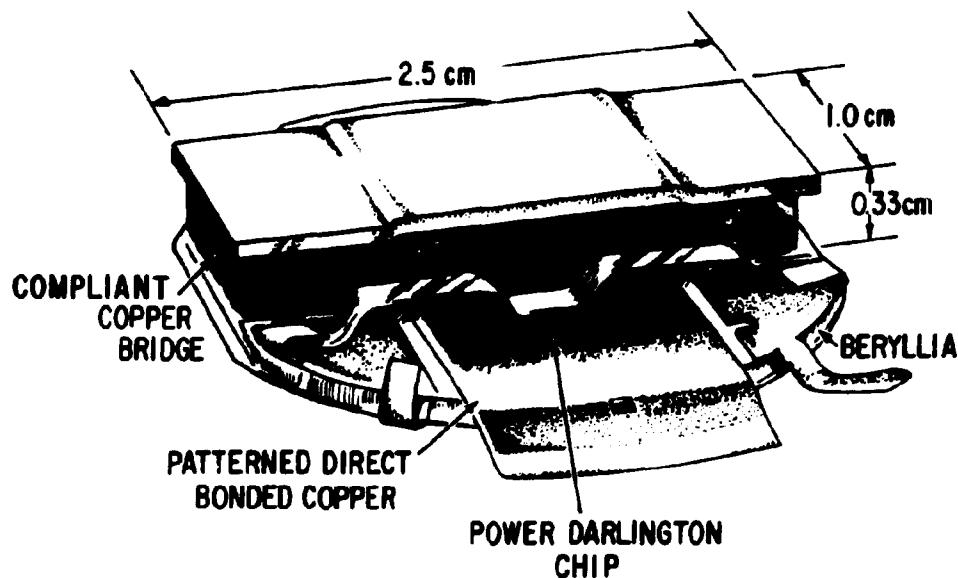


Figure 3.2.9-3. Darlington Transistor in Subcrete™ Form

to a heat spreader or heat sink, while the patterned top layer provides isolated contact pads for the emitter, base, and collector connections. The thermal, mechanical, and electrical properties of the subcrete are discussed in later sections.

The chip is soldered to the central copper stripe on the patterned BeO which serves as a collector contact. A compliant copper strain buffer is soldered to the bumped emitter areas and the larger outboard pads on the BeO substrate. Finally a soldered base contact is made with copper ribbon, and this completes the fabrication of the subcrete.

The compliant copper strain buffer consists of a heavy copper bus to which a large number of separate parallel copper fibers are attached. These are packed to a density of 90% of the bulk but retain their individual freedom. This results in a contact material with electrical and thermal properties approaching those of solid copper but differing significantly in being highly compliant because the individual strands are free to move laterally. Therefore, it serves as an effective thermal stress buffer between Cu and Si which have substantially different temperature coefficients of expansion.

In subcrete form, we have a rugged entity which can be subjected to any electrical tests necessary for matching transistor characteristics for parallel operation. It differs from a final configuration only in the absence of a heat spreader. However, adequate heat capacity exists at the subcrete level to permit tests to full current rating using low-duty cycle pulsed techniques. The complete elimination of contact resistance variations in the subcrete assures that data employed for matching are reliable and results will be repeatable when the subcrete is mounted on a heat spreader.

Thermal Resistance and Thermal Cycling

The thermal analysis of the subcrete mounted on a copper heat spreader was based on an approach in which the heat spreader is treated as a single side convective

cooled fin with a heat transfer coefficient h , mounted on an isothermal heat sink. The chip configuration and equivalent circuit of such an arrangement is shown in Figure 3.2.9-4. The analysis accounts for the effect of both heat spreader parameters such as area, thickness, thermal conductivity, interfacial heat transfer coefficient, and the structure associated with the chip mount. Figure 3.2.9-5 shows the manner in which the total fin resistance varies as a function of fin area for a 1/4 in. thick copper fin with h as parameter. The heated chip area is taken as 1.21 cm^2 which represents the area of the output transistor. To this thermal resistance, that of the chip and its mounting structure are added. This in turn is also considered in two parts, the direct thermal resistance due to heat conduction from the bottom of the chip, and in parallel with this a second shunting resistance due to heat conduction from the top of the chip, and then laterally outward through the heat structure to the heat spreader.

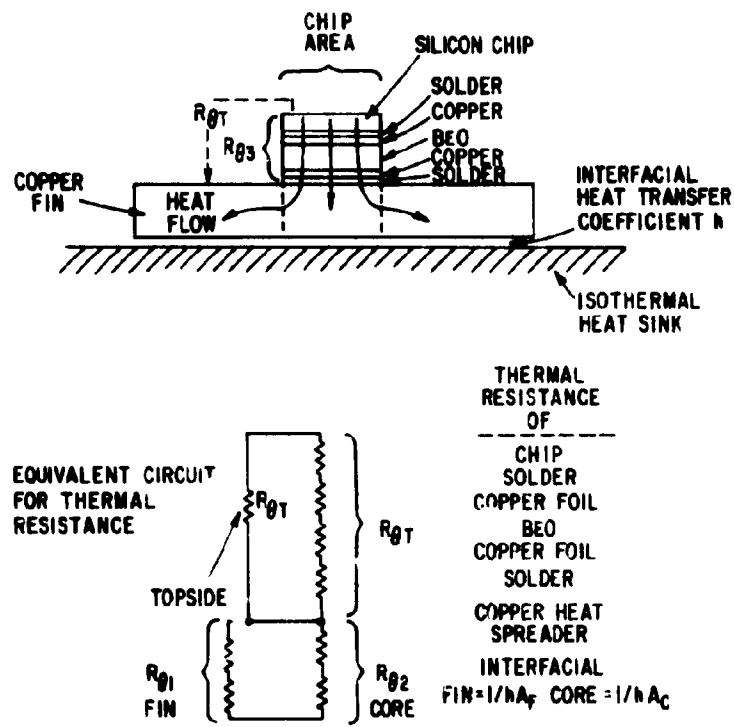
For the case where the subcrete is solder mounted to a heat spreader of 20 cm^2 , with an interfacial heat transfer coefficient of $1 \text{ W/cm}^2 \text{ } ^\circ\text{C}$, the analysis indicates an overall thermal resistance of 0.15°C/W should be achieved with $\sim 20\%$ of the heat flow leaving the top surface of the chip. These results were subsequently verified on functional samples of the transistor by direct measurements of thermal resistance. A method was employed which uses the emitter-base voltage-current characteristic of the output transistors as the temperature sensitive parameter.

The reliability of the solder interfaces were studied by subjecting a number of samples to thermal cycling from -50°C to $+125^\circ\text{C}$, and the thermal resistance was periodically measured (1 hr/cycle). The data from these tests are summarized in Table 3.2.9-3 showing that a high ratio of Pb to Sn is to be recommended for a solder system.

A power cycle test was also performed on the subcrete, mounted on the heat spreader and attached to a water cooled heat sink. The test consisted of dissipating 260 W and letting the emitter base junction of the transistor rise to 92°C where it is held constant for one minute. The junction is then allowed to cool to 20°C and held at this temperature for a minute. The thermal resistance (R_θ) was measured during each turn-on cycle. Over a period of 1000 cycles, there was no measurable change in R_θ .

Mechanical Considerations

In addition to thermal and electrical considerations, another important factor in the design of power devices and hybrid integrated circuits is the control of stress in the semiconductor mounting method. It is desirable that low resistivity electrode materials be used to minimize power dissipation due to lead resistance and to provide effective paths for heat removal from the chip. A restriction in the selection of electrode materials is imposed by the low thermal expansion coefficient of silicon. Because of this, destructive stresses and intolerable distortions can result when silicon is joined directly to higher expansion coefficient metals.



$$R_{\theta TOT} = \frac{R_{\theta 3} R_{\theta T}}{R_{\theta 3} + R_{\theta T}} + \frac{R_{\theta 1} R_{\theta 2}}{R_{\theta 1} + R_{\theta 2}}$$

Figure 3.2.9-4. Heat Flow Pattern from Chip to Heat Sink and Equivalent Thermal Resistance Circuit

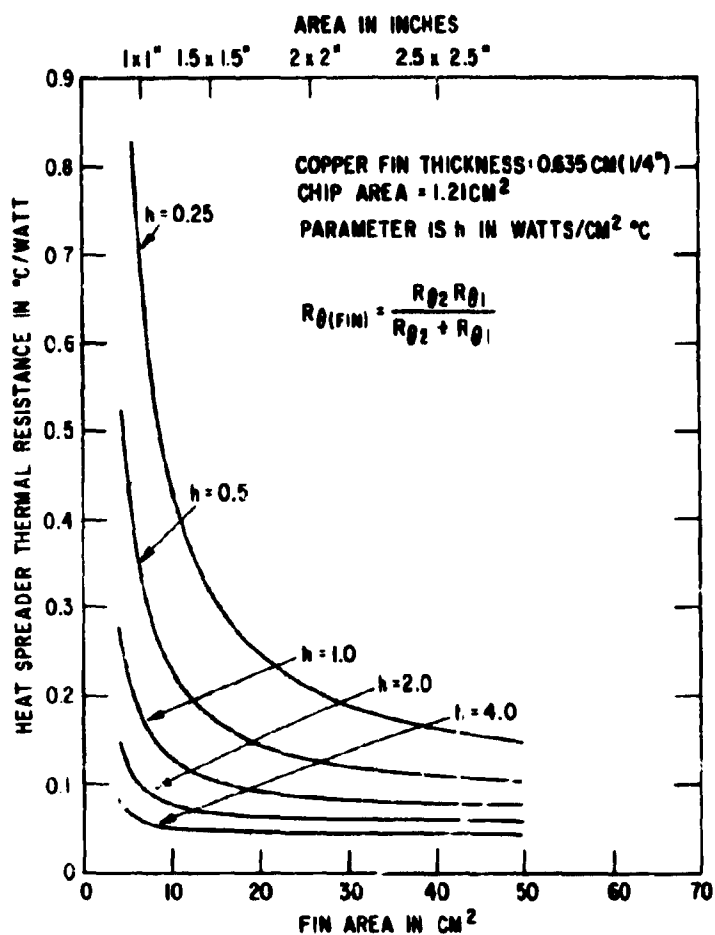


Figure 3.2.9-5. Thermal Resistance of the Heat Spreader vs the Fin Area of Heat Sink

TABLE 3.2.9-3

EFFECT OF SOLDER COMPOSITION ON SOLDER JOINT
RELIABILITY AS MEASURED BY THE THERMAL RESISTANCE (°C/W)

Solder Type	Number of Thermal Cycles -50°C to +125°C				Unit
	0	6	21	84	
62:36:2 Sn:Pb:Ag	0.17	0.30	0.44	Failed	°C/W
92.5:5:2.5 Pb:Sn:Ag	0.16	0.15	0.15	0.16	°C/W

While molybdenum and tungsten are commonly used as mounting structures for silicon because of their relatively low expansion coefficients, heat removal considerations suggest Cu, Ag, and BeO as superior heat sinking materials. The design approach selected for the power Darlington subcrete emphasizes heat removal from the silicon chip. A copper clad BeO disc is used as the basic chip holder which is, in turn, soldered to a copper heat spreader plate. This configuration assures that both BeO and the silicon chip are loaded in compression. Figure 3.2.9-6 shows the results of a computer study of the thermal stresses resulting in such a structure fabricated with Indalloy 151 solder having a melting point of $\sim 300^\circ\text{C}$. The results comparing stresses and bending radius of curvature for a chip mounted directly to copper with subcrete mount employed here are shown as a function of heat spreader thickness. No allowance is made for yielding of any of the materials although this will reduce the stresses in the silicon. In contrast to a direct mount to copper, the subcrete mount reduces stress in the silicon by $\sim 30\%$ and provides a comparable radius of curvature. The principle unknown in this configuration was the fatigue characteristic of the solder system used. To verify the integrity of the solder system in the subcrete, samples were successfully cycled (600 times) over the temperature range -55°C to $+125^\circ\text{C}$.

Electrical Performance

The dc common emitter current gain (h_{FE}) as a function of collector current (I_C) for the Darlington transistor is seen in Figure 3.2.9-7. The dynamic behavior of this device was studied in the chopper breadboard circuit of Figure 3.2.9-8. A typical collector current characteristic during turn-off is shown in Figure 3.2.9-9a. During the period when the reverse base current $I_{B2} \approx 2.4\text{ A}$ is applied, the input transistor is cleared of stored charge. The collector current falls from 230 A to 190 A, and the input stage is turned off. These events occur in the first 1.2 μs after the application of the negative base bias. Following the turnoff of the driver, the base current falls to 0.2 A, and the stored charge is removed from the output stage through the resistor R_1 . The collector current remains unchanged for an additional 1.6 μs , and then falls off in 1.2 μs . This second storage delay suggests that the output stage is in saturation when the Darlington is fully conducting. The measured values of storage time (t_s), fall time (t_f), and ON-state voltage $V_{CE(\text{SAT})}$ as a function of collector current are given in Figure 3.2.9-9b. It is seen that at a collector current of 200 A the measured voltage drop V_{CE} is only 1.6 V. In the present structure, the collector series resistance (R_{C2}) calculated to be 40 m Ω , would produce a voltage drop far greater than seen experimentally. This disagreement between measured and calculated values would suggest that the conductivity of the collector is in fact substantially increased by the injection of holes from the base of this npn structure. The base collector junction must therefore be forward biased in which case the output transistor is in saturation. In the range of 70 to 225 A of collector current, the Darlington transistor gain falls off. As the base drive is constant, the storage time is reduced and fall time increased with increasing collector current.

When bipolar transistors are operated in parallel, they are required to have similar storage and fall times. It then becomes necessary that they have near equal current gain (h_{FE}), base transit time (τ_f), and base turnoff current (I_{B2}). The latter is precisely determined by the magnitude to the monolithic resistor R_1 , and the factors influencing the gain and transit time are controlled during the fabrication of the device. For parallel operation in the integrated circuit, the subcretes are chosen with gains that match within 5%, at the highest level of collector current that device is required to control. Most often it was seen that devices with similar gains at mid-current levels ($\approx 100\text{ A}$) have almost identical I_C versus h_{FE} loci.

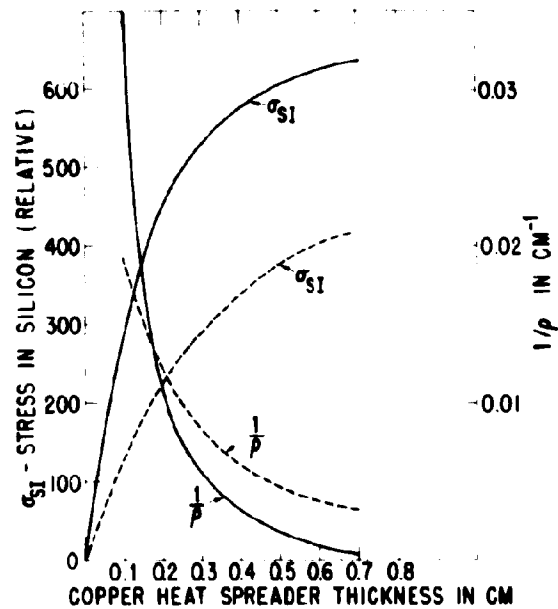


Figure 3.2.9-6. Stress and Curvature as Functions of Heat Spreader Thickness, for the Silicon Chip (solid line) and the Subserete (dashed line) on Copper

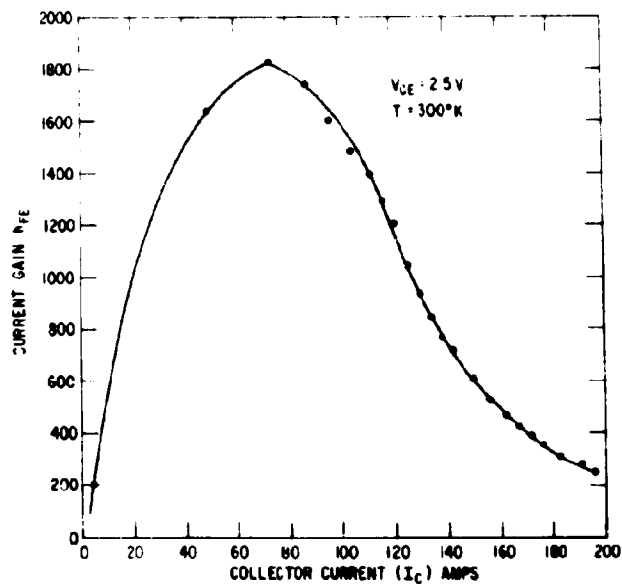


Figure 3.2.9-7. DC Common Emitter Current Gain Characteristic of the Two-Stage Darlington Transistor

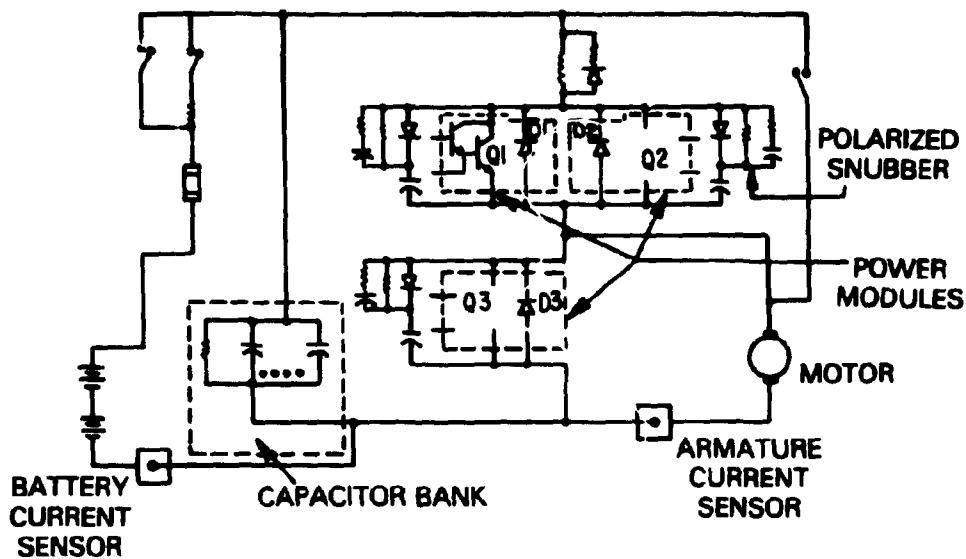


Figure 3.2.9-8. Schematic of the Armature Chopper Circuit. Hybrid circuits Q_1 and Q_2 operate with D_3 during restoring. Circuit Q_3 together with D_1 and D_2 operate during regenerative braking.



Figure 3.2.9-9a. Top Trace: Base Current as a Function of Time. Vertical scale: 2 A/cm and horizontal scale: 1 μ s/cm. Bottom traces: collector current 40 A/cm and collector emitter voltage 50 V/cm as functions of time; horizontal scale: 1 μ s/cm.

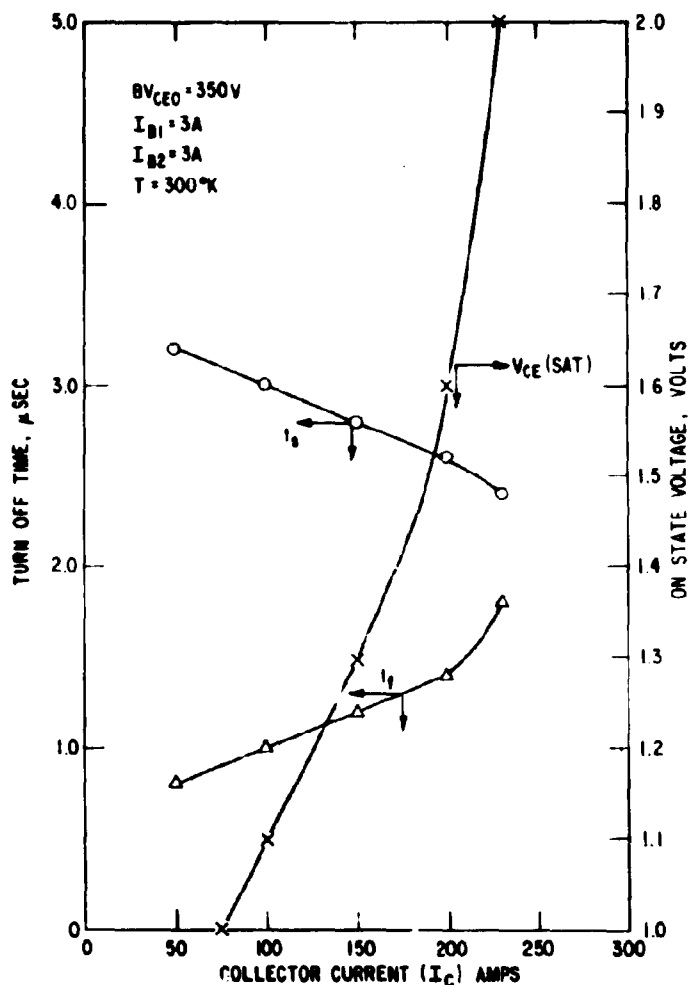


Figure 3.2.9-9b. Storage Time, t_s , Fall Time, t_f , and ON-state Voltage, $V_{CE(SAT)}$, as Functions of Collector Current

Power Module

Assembly

The circuit for the dc converter is comprised of the components shown in Figure 3.2.9-10. The circuit is fabricated by putting together the various elements on the common heat spreader and subjecting the assembly to a single solder reflow operation at $350^\circ C$. The circuit is tested for its dc parameters and then mounted onto the breadboard of the armature chopper. Q_1 , Q_2 , and Q_3 in Figure 3.2.9-8 represent the power modules. Each module consists of two Darlington transistors and a fast recovery diode on a common heat spreader with all the electrode connections made internally. The transistors in the circuits Q_1 and Q_2 along with the diode in Q_3 control the voltage and

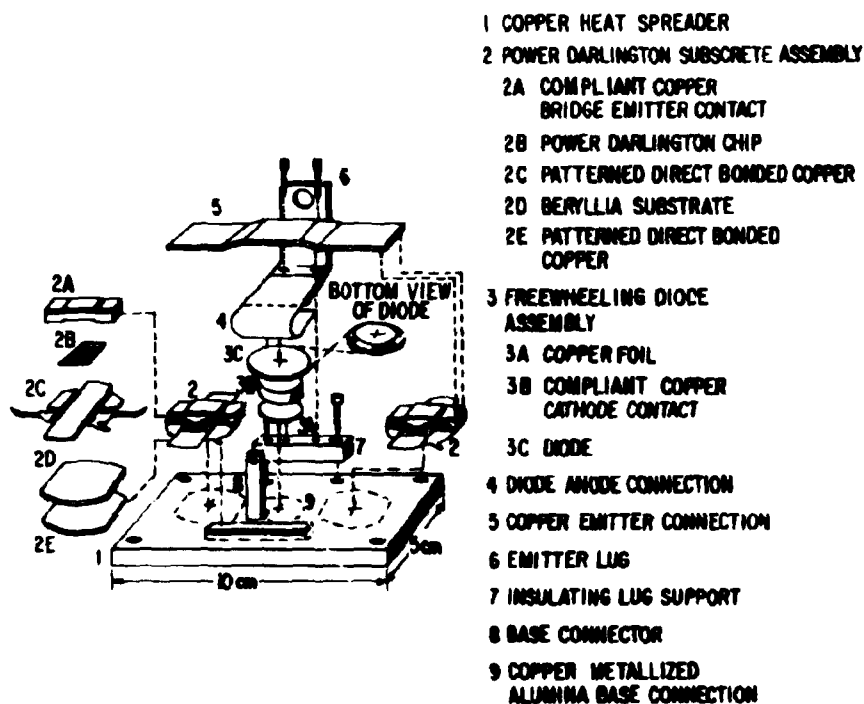


Figure 3.2.9-10. Schematic of the Components and Assembly of the Power Hybrid Integrated Circuit

therefore the torque and speed of the separately excited dc motor. The transistors in Q_3 operate with the diodes in Q_1 and Q_2 for the purposes of regenerative braking. Even though Q_1 and Q_2 are each capable of switching the full load current of 450 A, they were operated in parallel to allow for a substantial margin of safety in the event that the ambient temperature of the heat spreader should exceed 90°C .

Subcircuites are packaged with the chip mounted on BeO, with the structured copper plate on the emitter surface. The subcircuit is tested for voltage, gain, and saturation $V_{CE}(\text{sat})$ characteristics and matched for paralleling in the module. The module consists of two subcircuites and one diode connected internally in parallel with the necessary electrical isolation. The assembly is covered with silicone rubber and encapsulated in epoxy resin. The silicone is used to provide a stress buffer between the epoxy and the rigid lead terminals of the semiconductor devices. The epoxy is then cured at an appropriate temperature.

Armature Chopper

Two modules, or four transistors, must be matched in dc gain for optimum performance in the circuit. It should be pointed out that the requirement to parallel four General Electric Darlington transistors does not come about from the requirement for 400 A of motoring current but from the survival heat sink temperature of 78°C , which may raise the temperature of the copper substrate of the module to 110°C .

Figure 3.2.9-11a shows the parallel operation of two power modules, each with two Darlington subcircuits, driven by a common base current. The full load motor current of 450 A is shared equally both during the ON-state as well as the turn-off period. The criteria applied for the matching of circuits for parallel operation are identical to those used for matching discretes into a circuit. The fall time delay of about a microsecond at 450 A for the integrated circuits, and 220 A for the discrete transistor demonstrates the performance of the monolithically integrated resistor R_1 . This achievement of high speed without the use of a bypass diode, and with only a minimal turn-off base current, enhances the second breakdown capability of the transistor.



Figure 3.2.9-11a. Operation of Two Integrated Circuits in Parallel with a Common Base Drive Voltage, Top Trace: $V_{BE} = 5$ V/cm. Bottom trace: Collector current characteristics, vertical scale 40 A/cm, Collector to emitter voltage 50 V/cm, as functions of time, horizontal scale: 1 μ s/cm.

Field Chopper

The search for a transistor to fill the needs of the field chopper and once again be compatible with power module assembly techniques singled out the Power Tech PT3523. This is a 400 V, 90 A device capable of switching in 1 μ s. However, when the PT3523 was compared with the General Electric power Darlington transistor in the field chopper breadboard, the latter device showed better switching behavior (< 200 ns).

In the battery charging mode, this circuit is required to perform at frequencies ranging from 10 to 20 kHz. Higher speed transistors are therefore necessary. Moreover, it was found that using the General Electric Darlington chip would replace two PT3523's (for a Darlington connection) along with two resistors and a turnoff diode. The field chopper module consists of a General Electric Darlington transistor in parallel with a free-wheeling diode.

High Current Testing

Fifty power modules containing two transistors in parallel and a free-wheeling diode were tested. Test sequences such as the following were used:

h_{FE} at $I_c = 100$ A
 I_L at 300 V blocking
 $I_c = 270$ A, 60 Hz, 25°C
 $I_c = 270$ A, 60 Hz, 100°C
 $I_c = 270$ A, 60 Hz, -30°C

h_{FE} at $I_c = 100$ A
 I_L at 300 V blocking
 $I_c = 250$ A, 2 KHz, 25°C , 1 min
 $I_c = 250$ A, 2 KHz, 60°C , 1 min

Diode test, $I_c = 240$ A, 2 KHz, 75°C

h_{FE} at $I_c = 100$ A
 I_L at 300 V blocking
Matched pair test at $I_c = 450$ A, 60 Hz, 25°C
Matched pair test at $I_c = 450$ A, 60 Hz, 100°C
Matched pair test at $I_c = 450$ A, 60 Hz, -30°C

h_{FE} at $I_c = 100$ A
 I_L at 300 V blocking

The h_{FE} and I_L measurement was repeated after the high collector current measurements, in order to verify that the device was not damaged during the current test. During the high current tests, scope photographs of the collector current and voltage traces and the base voltage and/or current traces were taken. Modules which survived the high current testing are subsequently considered for further testing. Devices which fail in high current testing do so by burnout leading to one shorted emitter (to the collector) section. The testing concentrated on the turnoff transition, because it was judged to be the most critical. Certain general conclusions could be drawn from the high current test results in turnoff.

- A linear I_c vs V_{ce} transition in turnoff is obtained only if both the first and second base are used and a tight snubber is employed. A tight snubber displays a minimum inductance. This is illustrated in Figure 3.2.9-11b.
- The I_c vs V_{ce} transition takes a different course when the semimodule is tested as one of a pair of modules, than if tested alone. This is illustrated in Figure 3.2.9-12. The switching energy increases ~20% when two modules are paired to switch the same total current.
- The energy dissipated in a turnoff transition increases with I_c , the maximum rate of increase being of the order of 0.4 mJ per transition per ampere of collector current. This is illustrated in Figure 3.2.9-13. Further, this switching energy does not greatly vary from module to module. Note that the switching energy per transition is essentially negligible below 50 A collector current.

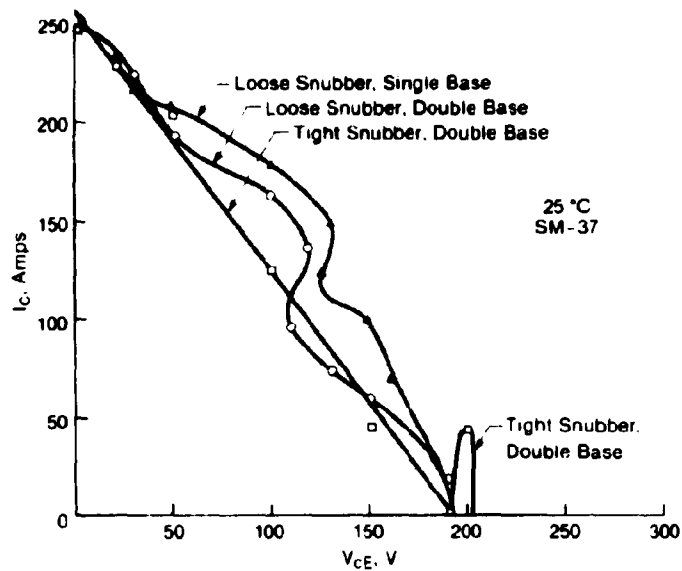


Figure 3.2.9-11b. I_c vs V_{ce} During Turnoff, 250 A, Comparing Loose vs Tight Snubbers and Single vs Double Base Operation

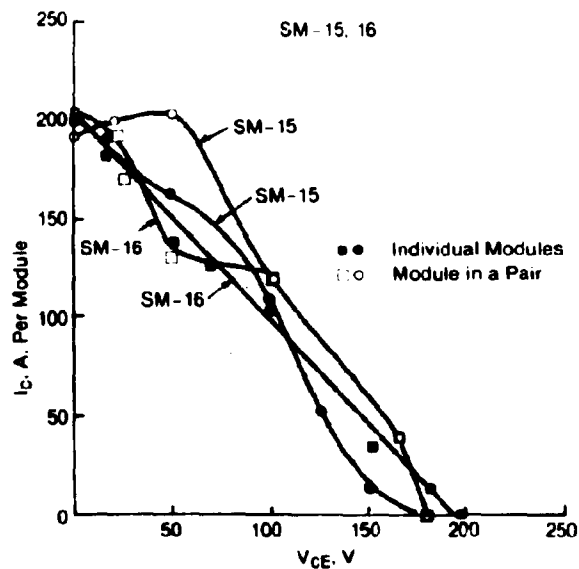


Figure 3.2.9-12. Comparison of How 200 A Are Switched in a Pair of Modules When 400 A Are Shared in Parallel or When 200 A Are Forced Through Individually

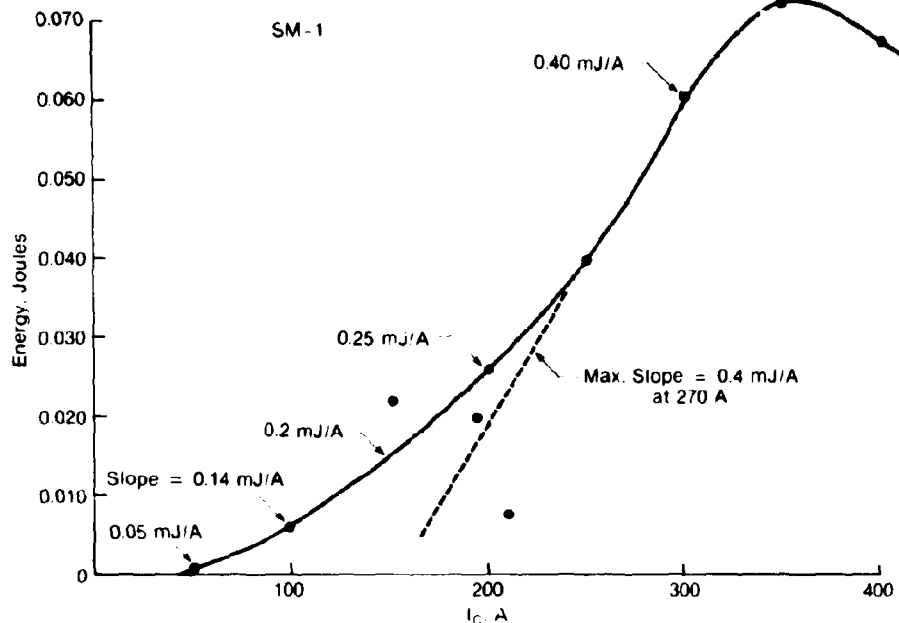


Figure 3.2.9-13. Energy Dissipated in One Turnoff Transition as a Function of the Current Switched in a Module

- The power dissipated in a transition as a function of time after the base current has returned to zero goes through a sharp, cusp-like maximum.
- The location on the time axis of the power cusp depends strongly both on temperature and whether single or double base operation is used. This is illustrated in Figure 3.2.9-14. The switching energy and switching time (location of the power cusp on the time axis) are only 1/2 for double base operation as compared to single base operation. This is principally due to the reduction in storage time for double base operation.
- In $I_c = 200$ A operation, the difference between modules having best and worst case $V_{CE(sat)}$ results in a difference of only 17% in the total power dissipation.

High Current Test Yield

Approximately 50% of the modules tested at $I_c = 250$ A were unaffected and without damage. At lower currents correspondingly more modules survive. The yield as a function of collector current is plotted in Figure 3.2.9-15.

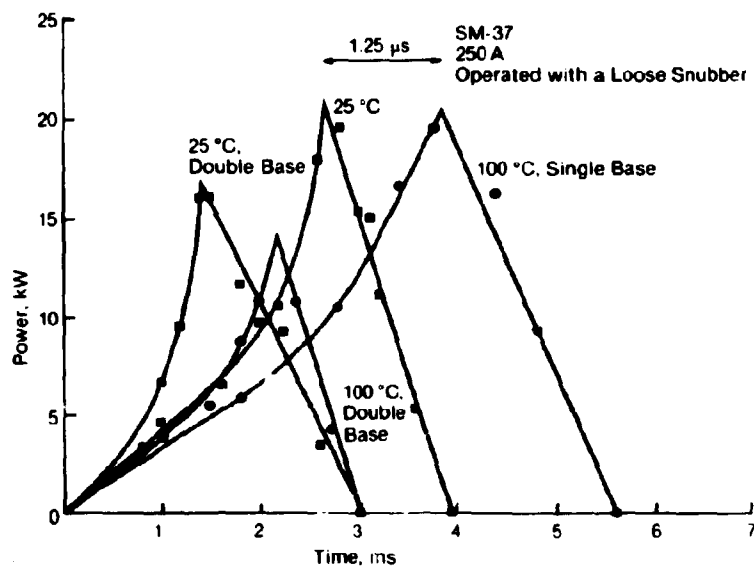


Figure 3.2.9-14. Temperature Dependence of Switching for SM-37 Operated as Single (double) Base Device

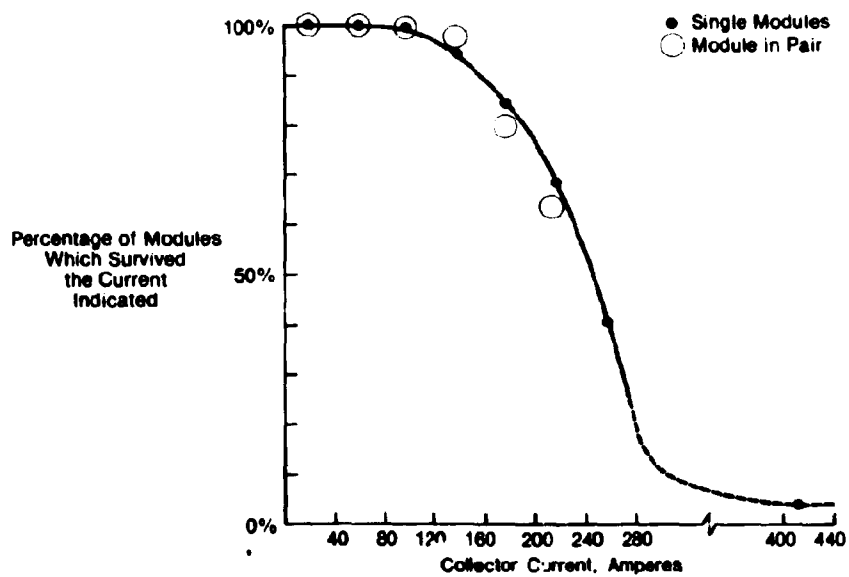


Figure 3.2.9-15. Yield of Modules in High Current Testing

WBS 3.2.10 Electronics Packaging Subcontract

The electronics packaging subcontract was performed by General Electric Ordnance Systems, located in Pittsfield, Massachusetts. The objective of the project was to design the mechanical and thermal aspects of the drive subsystem electronics and to fabricate packaged sets of hardware for the two electric test vehicles.

The power conditioning unit (PCU) contains an armature chopper, field chopper/battery charger, logic power supply, and accessory charger. The microcomputer control unit is packaged separately and has been described in WBS 3.2.6. The PCU has an outward appearance as shown in Figure 3.2.10-1.

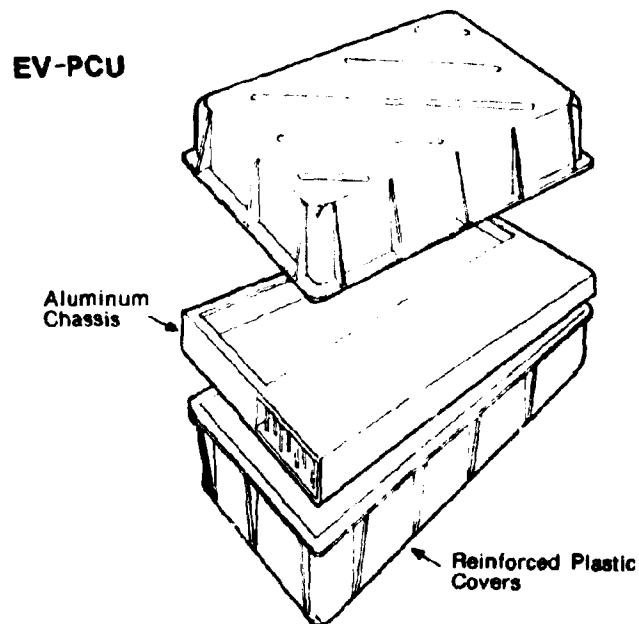


Figure 3.2.10-1. Power Conditioning Unit (PCU)

The unit consists of an aluminum chassis and two reinforced plastic covers. The aluminum chassis is essentially an integral forced-air heat exchanger with a calculated thermal resistance from sink to ambient of 0.024°C/W at a forced-air condition of $125\text{ ft}^3/\text{min}$ having a $1.08\text{ in. H}_2\text{O}$ pressure drop. Tables 3.2.10-1 and 3.2.10-2 show these calculations.

Figure 3.2.10-2 is a simplified functional block diagram showing the interconnection of major components and circuits within the PCU. All components within the PCU are mounted on, but electrically isolated from, the heat exchanger (aluminum casting). Side 1 (Figure 3.2.10-3) of the casting contains the armature chopper power circuit mounted on the air duct and low heat dissipating armature chopper components mounted away from the air duct.

Transistors Q1 and Q2 are a matched pair of motor power transistors and Q3 is the generating power transistor. Grouped around these prime components, in a symmetrical pattern, are the capacitors, resistors, and diodes of the turnon snubber circuits. Also mounted on the air duct are the base drive resistors and two fuses.

TABLE 3.2.10-1
HEAT EXCHANGER PRESSURE DROP



A. TEMPERATURE RISE OF COOLING AIR

$$T_{a_n} - T_{a_m} = q/m C_p = 951 \frac{\text{W}}{\text{ft}^2} \times 0.068 \frac{\text{ft}^3}{\text{min}} \times 7.6 \frac{\text{W-min}}{\text{lb-}^\circ\text{C}}$$

$$= 14.72^\circ\text{C}$$

B. AIR VELOCITY

$$V = \frac{Q}{A} = \frac{1.25 \frac{\text{ft}^3}{\text{min}} \times 1.88 \frac{\text{ft}}{\text{min}}}{0.068 \frac{\text{ft}^2}} = 3327 \frac{\text{ft}}{\text{min}}$$

C. REYNOLDS NUMBER

$$Re = \frac{V D_e}{\mu} = \frac{199,620 \frac{\text{ft}}{\text{hr}} \times 0.131 \frac{\text{ft}}{\text{min}} \times 0.068 \frac{\text{lb}}{\text{ft}^3}}{0.0475 \frac{\text{lb}}{\text{ft-hr}}}$$

$$= 37,436$$

D. PRESSURE DROP

$$H_L = \frac{f L V^2}{D_e 2q} = \frac{12 \times 0.025 \times 9.34 \frac{\text{ft}}{\text{min}} \times (55.4 \frac{\text{ft}}{\text{sec}})^2 \times 0.068 \frac{\text{lb}}{\text{ft}^3}}{0.131 \frac{\text{ft}}{\text{min}} \times 64.4 \frac{\text{ft}}{\text{sec}^2} \times 64.2 \frac{\text{lb}}{\text{ft}^3}}$$

$$= 1.08 \text{ in. H}_2\text{O}$$

WHERE

- T_{a_n} RAM AIR TEMPERATURE
 D_e EFFECTIVE HYDRAULIC DIAMETER
 f FRICTION FACTOR (DEVELOPED FROM MOODY DIAGRAM)

TABLE 3.2.10-2
HEAT EXCHANGER THERMAL RESISTANCE

A. CONDITIONS:

1. 1000 Pins, 0.08" D x 0.9" L
2. AIR FLOW @ 125 cfm (6.1" x 0.9" Duct)
3. Film Temperature = 68.5°C

B. MASS FLOW

$$G = \frac{Q}{A_c} = \frac{125 \times 0.064 \times 60}{0.038} = 12,631 \frac{\text{lb}}{\text{hr-ft}^2}$$

C. HEAT TRANSFER COEFFICIENT: (KRAUS)

$$h = 1.4 \left(\frac{q}{A} \right)^{.28} \left(\frac{C_p}{k} \right)^{.33}$$

$$= \frac{1.4 \times 0.0172 \left(\frac{0.0067 \times 12,631}{0.049} \right)^{.28} \left(\frac{0.241 \times 0.049}{0.0172} \right)^{.33}}{0.0067}$$

$$= 0.0939 \frac{\text{W}}{\text{in. } 2.0^\circ\text{C}}$$

D. EFFICIENCY:

$$mb = .075 \sqrt{h \text{ in.}}$$

$$= 82.9\% \text{ (KRAUSS; CYLINDRICAL SPINE EFFICIENCY)}$$

E. THERMAL RESISTANCE:

$$R = \frac{1}{h \cdot s} = \frac{1}{0.0939 \times 0.025 \times 541} = 0.024 \frac{^\circ\text{C}}{\text{W}}$$

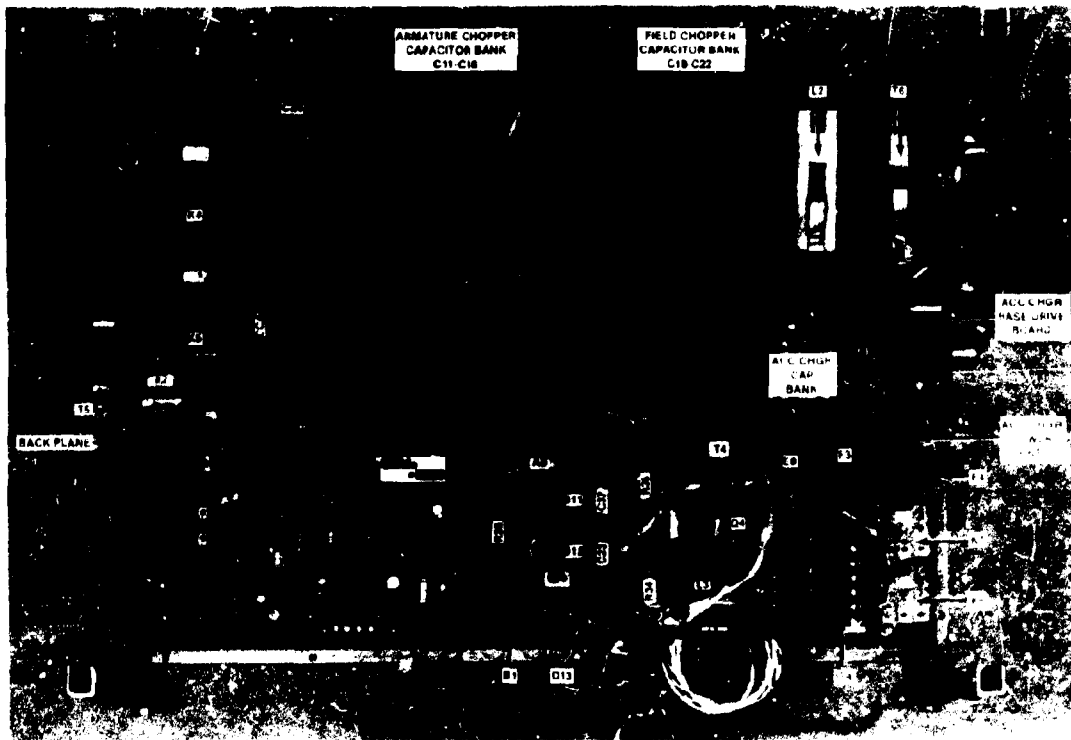


Figure 3.2.10-4. PCU Side 2

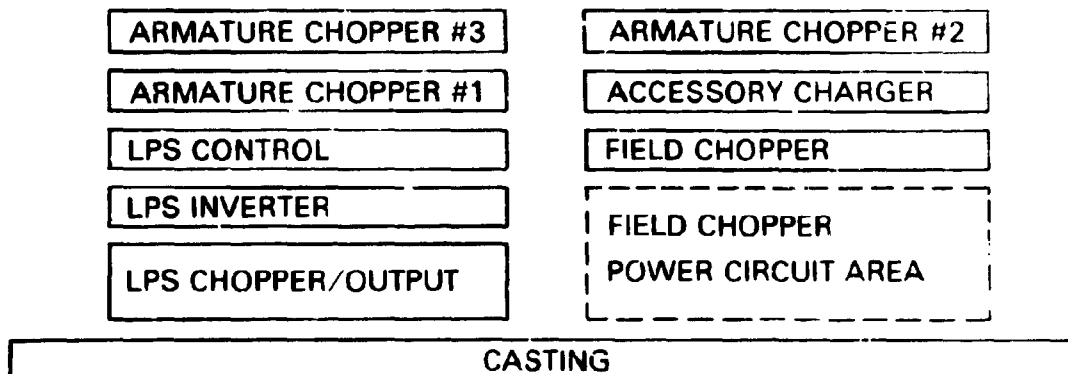


Figure 3.2.10-5. PC Logic Board Stacking Arrangement

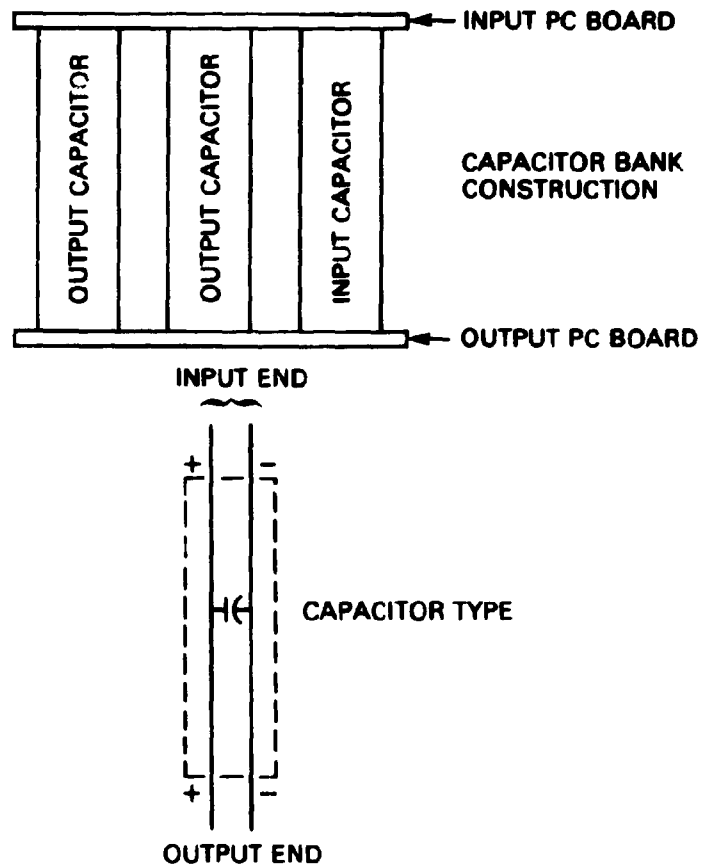


Figure 3.2.10-6. Accessory Charger Filter Capacitors

CONTROL FUNCTION TERMINOLOGY WBS 3.2 ELECTRICAL DRIVE SUBSYSTEM

AC	Armature Current
ACCM	Accessory Charger Malfunction
ACE	Armature Chopper Enable
$\overline{ACM}$	Armature Chopper Malfunction, Not
BC	Battery Current
BPA	Bypass Contactor Acknowledge
BPC	Bypass Contactor Close
BVCH	Battery Voltage Charging
BVFG	Battery Voltage Fuel Gauge
CCA	Chopper Contactor Acknowledge
CCC	Chopper Contactor Close
115E	115 V Energized
FB	Field Battery
FCC	Field Current Command
FCE	Field Chopper Enable
$\overline{FCM}$	Field Chopper Malfunction, Not
FF	Field Forward
FFA	Field Forward Auxiliary
FR	Field Reverse
FRA	Field Reverse Auxiliary
LPSL	Logic Power Supply Lock
$\overline{LPSM}$	Logic Power Supply Malfunction, Not
MG	Motor-Generate
ON	On Relay
OVR	Regulated Voltage
PCU	Power Conditioning Unit
RESET	Reset Relay
SR1	Seat Relay 1
SR2	Seat Relay 2
τ	Tau
+15VR	Regulated Voltage
-15VR	Regulated Voltage
VW	Voltage Warning

WBS 3.3 BATTERY SUBSYSTEM

WBS 3.3.1 Battery Component Design

The design goals and specifications of the EV2-13 propulsion battery are summarized in Table 3.3.1-1.

TABLE 3.3.1-1
PROPULSION BATTERY GOALS AND SPECIFICATIONS

Performance	Minimum	Goal
Performance at 3 h rate, 5.25 V cutoff		
Usable energy (Wh)	970	1031
Weight Energy Density (Wh/lb)	16	17
Volume energy density (Wh/in ³)	1.5	
Peak power density at full charge (W/lb)	100	
Cycle life - 70% depth of discharge at 3 h rate (number of cycles)	500	
Dimension	Maximum size	
Length (in.)	10-3/8	
Width (in.)	7-3/16	
Height (in.)	11-1/8 (but lower at sides of tunnel)	

The battery was designed within the external length and width dimensional constraints of a standard golf car battery (BCI group size GC2). The height dimension was limited by the tunnel design, which allowed for additional height (over that of a standard golf car battery) except near the sides of the tunnel. The battery was to be nominally 6 V. Eighteen batteries would be connected in series to provide a 108 V battery pack. The battery was also to incorporate a semiautomatic, single-point watering system.

Globe-Union investigated two general approaches to maximizing the performance of the lead-acid system within the golf car envelope. The first approach encompassed computer-assisted optimization of the battery design within the existing golf car battery cell configuration and orientation. The optimization program included:

- Grid and top lead efficiency through establishment of minimum weights with ideal lead distribution
- Positive-to-negative active material ratios and total weights
- Electrolyte to active material ratios
- Active material and electrolyte distribution within the cell

The second approach involved not only a complete optimization but also an effort to minimize the plate design restrictions imposed by the conventional golf-car battery

configuration. From previous work on computerized electric vehicle battery design optimization, Globe-Union has determined that there are ideal plate design characteristics. These characteristics include ranges of plate apparent surface area and ranges of width-to-height aspect ratio. Existing golf car battery plates are significantly below the desired ranges in both area and aspect ratio. Ideal aspect ratios and surface areas cannot be achieved within the golf car battery envelope, but improvements in each can be made if the cells are rotated 90 degrees from their normal orientation.

Rotation of the cells by 90 degrees dictated a new terminal location and a 90 degree rotation of the vent strip which is used in this battery for both the venting and watering (water top-off) functions. The relocation of the vent strip had definite advantages for the selected tunnel configuration, which provides for a side-by-side battery layout as shown in Figure 3.3.1-1.

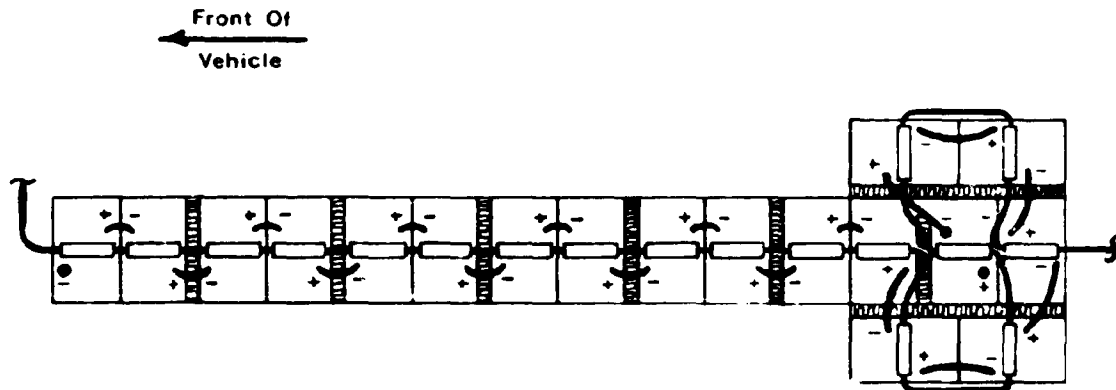


Figure 3.3.1-1. Battery Pack Layout

The 90 degree rotated design was chosen over the conventional layout for two reasons:

- Lighter weight for equivalent performance
- Simplified and lighter plumbing for the watering/vent system

A cutaway view of the EV2-13 is shown in Figure 3.3.1-2. A high-profile cover design was chosen to accommodate increased volumes of active material and electrolyte, which provide additional energy storage capacity. The stepped cover design shown in Figure 3.3.1-2 was necessary in order to provide a high-profile cover which would fit in the battery tunnel.

Other features of the battery can be seen in Figure 3.3.1-2:

- Thin-walled, heat-sealed polypropylene container
- Low-resistance, through-the-partition intercell welds
- Removable vent cap with semiautomatic watering design

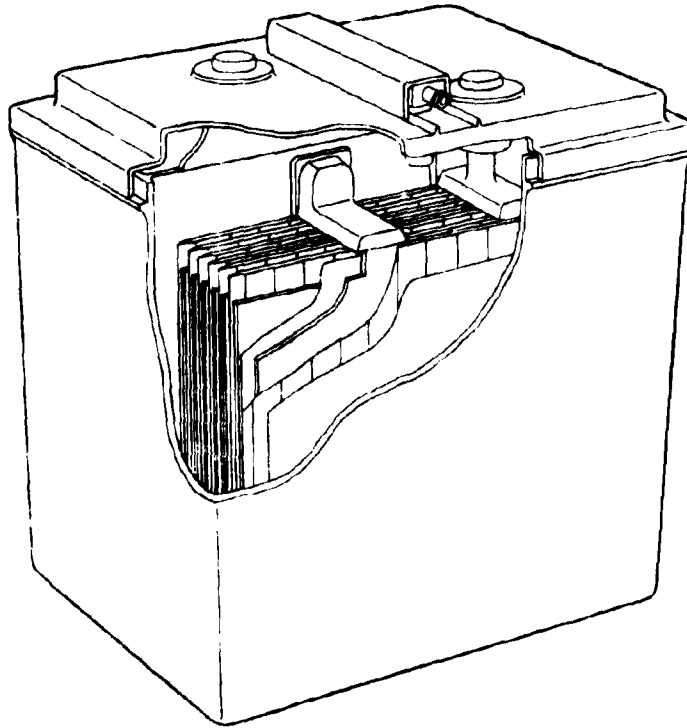


Figure 3.3.1-2. Cutaway View of EV2-13 Propulsion Battery

- Designed so that acid will not leave cell unless battery is inclined more than 30 degrees
- Envelope-type separators with glass mat for long battery life
- Efficient straight-up terminal straps.

Table 3.3.1-2 summarizes the estimated weight and performance for two battery designs. One was designed for maximum weight energy density (Design A), and one for maximum volume energy density (Design B).

Figures 3.3.1-3, -4, and -5 show additional estimated performance characteristics for the two designs. Based on this estimated data, General Electric selected Design A, which was designed under the maximum weight-energy-density philosophy. The advantages of Design A are:

- Lower weight and higher weight energy density (Table 3.3.1-2)
- Better performance at high rates (Figure 3.3.1-4)
- Increased resistance to electrolyte freezing at low temperatures (Figure 3.3.1-5)

TABLE 3.3.1-2
ESTIMATED WEIGHT AND PERFORMANCE OF DESIGNS A AND B

Parameter	Design A Battery with Maximum Wh/lb	Design B Battery with Maximum Wh/in. ³
Battery weight (lb)	59.68	65.82
Performance, 3 h rate, 5.25 V cutoff		
Capacity (Ah)	175.4	180.8
(Wh)	1005.1	1035.8
Weight energy density (Wh/lb)	16.84	15.74
Volume energy density (Wh/in. ³)	1.236	1.274
Performance, 1 h rate, 5.25 V cutoff		
Capacity (Ah)	123.3	127.4
(Wh)	684.3	679.4
Weight energy density (Wh/lb)	11.47	10.32
Volume energy density (Wh/in. ³)	0.842	0.836

Table 3.3.1-3 summarizes the estimated battery weight and performance and compares the estimates with the SOW specifications. The values are close to those for Design A, discussed previously. The differences are due to a design refinement and a more accurate estimate of component weights. As shown in Table 3.3.1-3, it was estimated that all of the SOW specifications could be met or exceeded with the exception of the volume energy density. This is because the specified value was established without consideration for the extra battery volume associated with the semiautomatic watering/venting system.

The 18-battery pack contains ten LHF and eight RHF batteries, as shown in Figure 3.3.1-6. The advantages of having two battery types are illustrated in Figure 3.3.1-7. Table 3.3.1-4 is a complete list of the drawings which comprise the EV2-13 product drawing package.

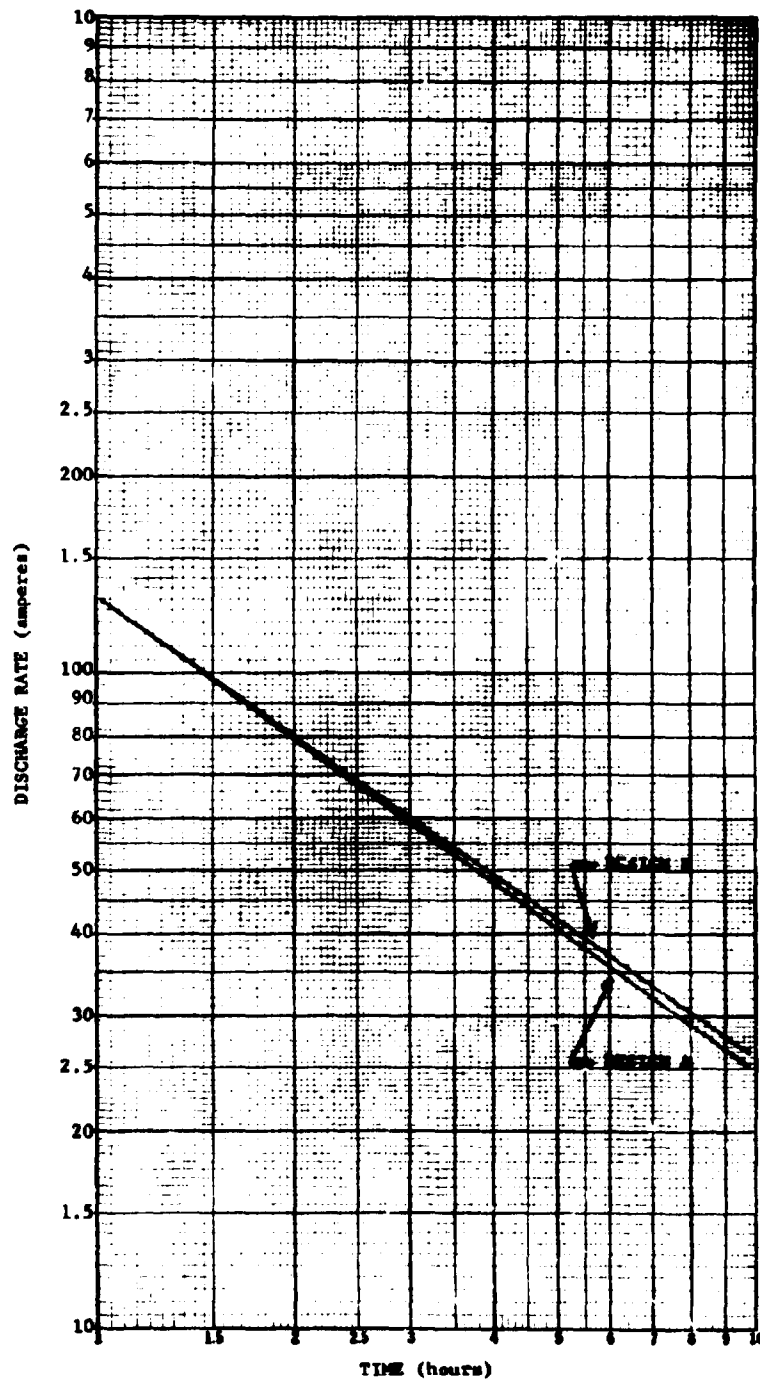


Figure 3.3.1-3. Estimated Peukert Curves for Battery Designs A and B (80°F)

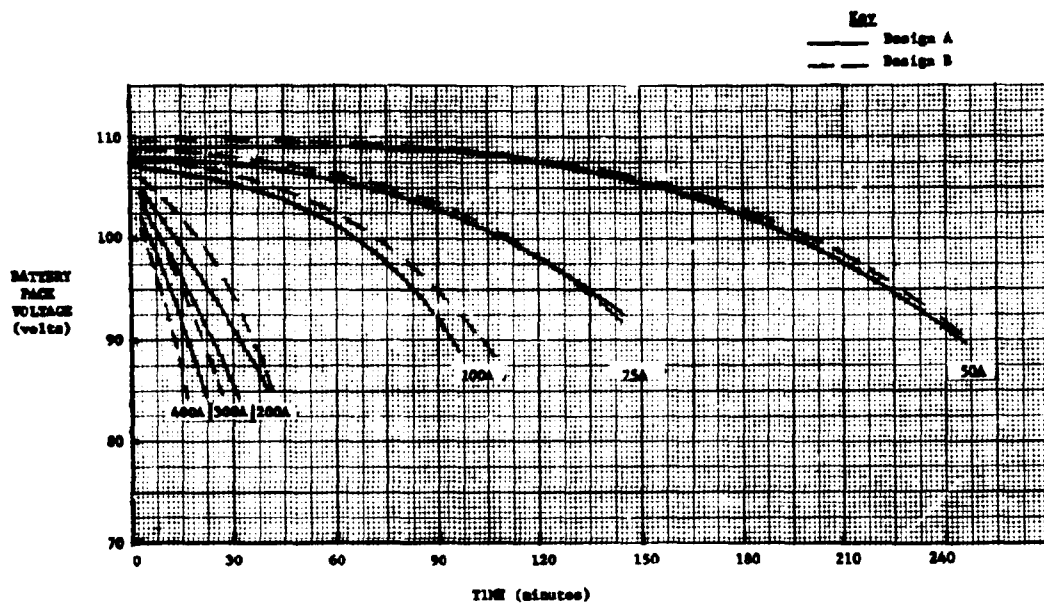


Figure 3.3.1-4. Estimated Discharge Curves for Battery Pack at Various Current Rates - Designs A and B (80°F)

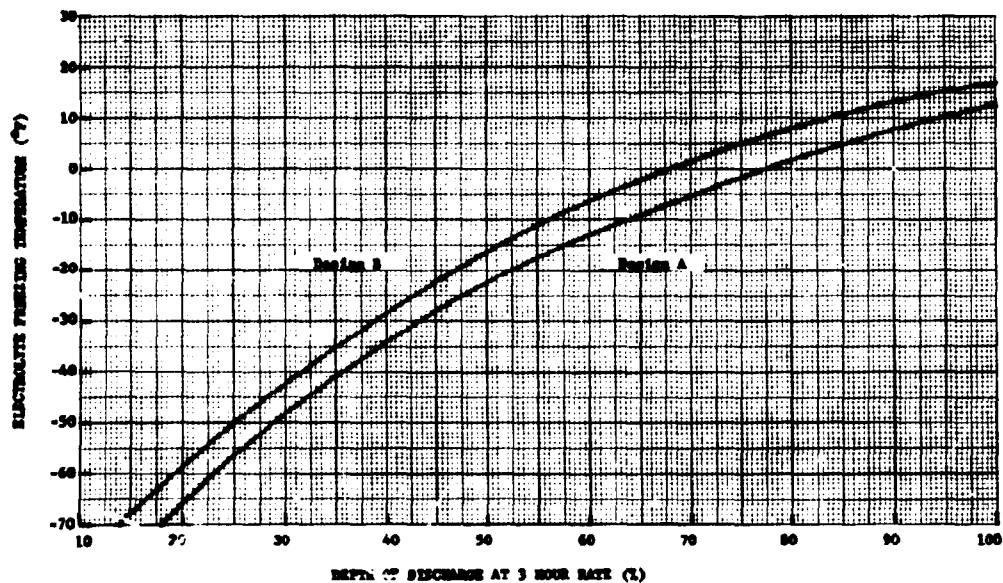
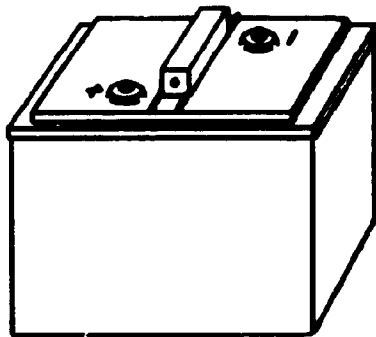


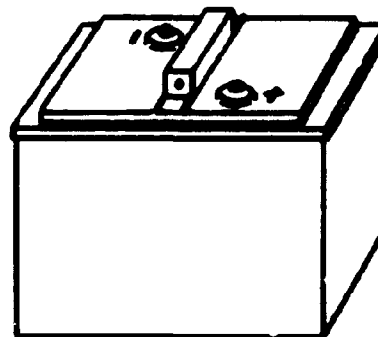
Figure 3.3.1-5. Estimated Electrolyte Freezing Temperature as a Function of Depth of Discharge - Designs A and B

TABLE 3.3.1-3
ESTIMATED EV2-13 WEIGHT AND PERFORMANCE
VERSUS SOW SPECIFICATIONS

Parameter	Estimate	Specification (minimum)
Battery weight (lb)	60.65	
Performance, 3 h rate, 5.25 V cutoff		
Capacity (Ah)	174.1	
(Wh)	997.5	970.0
Weight energy density (Wh/lb)	16.45	16.0
Volume energy density (Wh/in. ³)	1.35	1.5
Performance, 1 h rate, 5.25 V cutoff		
Capacity (Ah)	133.1	
(Wh)	738.8	
Weight energy density	12.18	
Volume energy density	1.00	
Peak power density (W/lb)	100.0	100.0
Cycle life, 70% depth of discharge at 3 h rate (number of cycles)	500.0	500.0



**LEFT-HAND-FRONT
(LHF)**

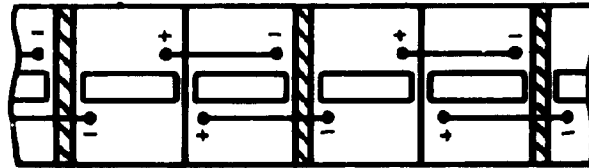


**RIGHT-HAND-FRONT
(RHF)**

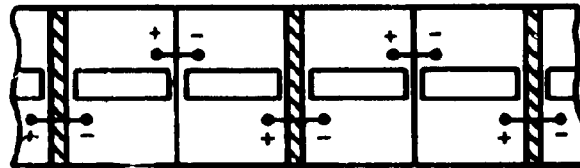
Figure 3.3.1-6. Propulsion Battery (EV2-13) — External View of Two Types

TABLE 3.3.1-4
LIST OF EV2-13 PRODUCT DRAWINGS AUGUST 22, 1979

Drawing Number	Title	Drawing Date	Date of Last Revision
77159-D, sht. 3	Inside negative grid - wire and frame	10/21/77	None
77160-D, sht. 3	Outside negative grid - wire and frame	10/21/77	None
77161-D, sht. 3	General Electric positive grid mold	11/01/77	None
77166-D	General Electric battery assembly	10/10/77	07/18/78
77167-D	Container	10/07/77	03/13/78
77168-D	Cover	10/07/77	08/10/78
77169-D	Vent and watering cap - base	10/12/77	09/03/78
77170-C, sht. 1	Cover - vent and watering cap	10/12/77	08/11/78
77170-B, sht. 2	Cover - top view, vent and watering cap	12/28/77	None
77171-D	Outside negative grid	10/26/77	None
77172-D	Inside negative grid	10/26/77	None
77173-D	Positive grid	10/27/77	None
77174-C	Internal post and strap	10/11/77	08/23/78
77175-B	Envelope separator blank	10/11/77	None
77179-B	Terminal connecting strap	07/18/78	04/26/79
77180-D	Battery connection and water flow	07/18/78	04/26/79
77188-D	EV Battery	11/16/77	08/07/78
77196-A	Terminal post and strap assembly	07/18/78	08/07/78
77202-B	Connector shield	12/15/77	None
78120-A	General Electric (EV) terminal post	08/07/78	None
79070-A	Angle adapter-vent and watering cap	04/26/79	None
79071-A	Modified vent/watering cap for General Electric	04/26/79	None



Cabling With One Battery Type



Cabling With Two Battery Types

**Figure 3.3.1-7. Advantages of Having Two Battery Types:
Less Cable Is Required, Resulting in
(1) Lower Cable Weight (-2 lb) and (2)
Lower Circuit Resistance and Inductance**

WBS 3.3.2 Tooling Development

The tooling and equipment modifications developed for the program are summarized in Table 3.3.2-1.

**TABLE 3.3.2-1
EV2-13 TOOLING**

Container Mold Modifications
Cover Mold
Covering Vent Mold
Watering Vent Heat Seal Tooling
Platen
Backup plate
Spacers
Grid Molds
Grid Trim Tooling
CRS Modifications
Molds
Other
Container Punch Tooling
Cover Heat Seal Platen
Heat Seal Cover Backup Plate
Post Burn Tooling
Paster Tooling
Orifice plate
Feeder modifications
Separator Envelope

WBS 3.3.3 Battery Fabrication

Numerous test cells were fabricated during the months of March through July 1978 for the purpose of obtaining performance data for General Electric before the fabrication of complete batteries. This was possible since most of the tooling required to fabricate batteries was not required to fabricate the cells.

The first set of twenty-two EV2-13 batteries was shipped to General Electric in early December 1978. Prior to shipment, the batteries had been charge-discharge cycled six times.

The second and third sets of batteries (44 batteries total) were shipped to Modern Engineering Service Company (Chrysler subcontractor) in mid-December 1978. Prior to shipment the batteries had one charge-discharge cycle.

At General Electric's request the shipment of the fourth and fifth sets of batteries was delayed until mid-February 1979. On this date 42 batteries were shipped to Modern Engineering Service Co. after having been cycled up to full capacity. Thirty-six batteries from this group were used for the battery packs for the two Integrated Test Vehicles.

At General Electric's request two batteries were shipped to Argonne National Laboratory in mid-February 1979 after having been charge-discharged cycled once.

The total number of batteries delivered under the contract was 110. Of these 62 were LHF and 48 were RHF.

WBS 3.3.4 Development Testing

Cell tests were conducted during the months of April through September 1978.

The Battery Performance Tests were performed in January 1979 according to the Battery Subsystem WBS 3.3 Test Plan. Five batteries were randomly selected from the first group of 15 batteries approved for shipment.

Seventeen conditioning cycles were performed before the testing was initiated. The three-hour discharge was performed first. The batteries were then recharged and subjected to the peak power test.

Table 3.3.4-1 summarizes the test results and compares them to the goals and specifications from Revision C (1/17/78) of the Statement of Work. Cycle life tests were deleted per General Electric's instructions.

**TABLE 3.3.4-1
SUMMARY OF TEST RESULTS**

Performance Parameter	Minimum	Goal	Battery Data	
			Average	Range
Weight energy density (Wh/lb) (3 h rate, 1.75 V/cell)	16	17	17.31	17.08-17.58
Volume energy density (Wh/in ³) (3 h rate, 1.75 V/cell)	1.5		1.41	1.39-1.43
Usable energy/6 V battery (Wh) (3 h rate, 1.75 V/cell)	970	1031	1036	1021-1055
Peak power density (W/lb)	100		112.3	111.1-113.3
Cycle life (number of cycles) (70% depth of discharge, 3 h rate)	500		—	—

As can be seen in Table 3.3.4-1, the specified minimums and goals were exceeded for all performance parameters with the exception of volume energy density. This was because the specified value was established without consideration for the extra volume associated with the watering/venting system. Table 3.3.4-2 contains more detailed data for each of the five test batteries.

**TABLE 3.3.4-2
INDIVIDUAL BATTERY DATA**

Battery Number	Type	Weight (lb)	Initial Specific Gravities			3 Hour Rate (58A) Discharge					Instantaneous Peak Power Density at 10 m sec (W/lb)
			1	2	3	Time to 5.25 Volts (min)	(Ah)	(Wh)	Energy Density Weight (Wh/lb)	Density Volume (Wh/in. ³)	
48053	LHF	60.00	1.283	1.285	1.286	186	179.8	1055	17.58	1.43	113.3
48048	LHF	59.79	1.278	1.280	1.278	180	174.0	1021	17.08	1.39	111.1
48099	RHF	60.41	1.283	1.281	1.279	185	178.8	1049	17.37	1.42	112.6
48095	RHF	59.82	1.281	1.279	1.281	182	175.9	1032	17.26	1.40	112.3
48081	LHF	59.16	1.272	1.276	1.272	180	174.0	1021	17.26	1.39	112.2
Average		59.84				182.6	176.5	1036	17.31	1.41	112.3

Average voltage during discharge=5.869 V
Average temperature during discharge=80.5 °F

WBS 3.3.5 Technical Support

Work performed and reported under the Technical Support task includes work related to a number of areas of investigation, such as battery charging, battery temperature control, regenerative braking, fuel gauge, battery mathematical modeling, hydrogen gas generation, accessory battery and charger, and battery maintenance. All work on the battery connector and cabling system and on the external (to the battery) watering/venting system is also reported under the Technical Support task.

Charging

Most of the charging work performed by Globe-Union was based on Globe's standard golf cart battery (GC2-19) because data was required before EV2-13 cells were available for test.

A number of charging schemes were discussed and recommended for implementing in the onboard charger. Implementation was difficult in some cases; however, a $V_{\text{limit}} - V_{\text{min}}$ charge scheme appeared workable but was later changed to a more implementable scheme and one on which Globe-Union had performed some preliminary testing relative to charge termination. Table 3.3.5-1 delineates the charging scheme.

TABLE 3.3.5-1
CHARGING INFORMATION

Assumptions: 1. Initial current = 24 A 2. Battery temperature during charge in 70-90 °F range	
<u>Daily Charge</u>	<u>Equalization Charge</u>
1. Charge at 24 A until cell voltage limit (V_{max}, in volts) is reached. V_{max} is dependent on battery temperature (T, in °F) as shown below: $V_{\text{max}} = 2.60 + (0.004)(80 - T)$ 2. Then charge for 5 hours at the maximum current allowed by above voltage limit with a sampling interval of 1 second except that the current should not go below 4 A. The voltage may go slightly above the maximum near the end of charge. 3. Estimated total charge time for an 80% discharged pack is 10.3 hours.	1. Every seventh charge should be an equalization charge. 2. Charge at 24 A until temperature-corrected voltage limit (V_{max}) shown at left is reached. 3. Then charge for 10 hours at the maximum current allowed by above voltage-limit with a sampling interval of 1 second except that the current should not go below 4 A. The voltage will go slightly above the maximum near the end of charge. 4. Estimated total charge time for an 80% discharged pack is 15.3 hours.

Battery Temperature Control

Figure 3.3.5-1 provides an overview of the effect of temperature on battery performance. The temperature at which the electrolyte of the EV2-13 will freeze is a function of the concentration of the electrolyte, which is a function of the depth of discharge; the higher the depth of discharge, the higher the freezing temperature. The curve for Design A in Figure 3.3.1-5, which was previously discussed, provides a good estimate of the freezing temperature of the electrolyte as a function of depth of discharge. As shown, electrolyte freezing becomes a concern below 20 °F if the battery is fully discharged at the 3 hour rate.

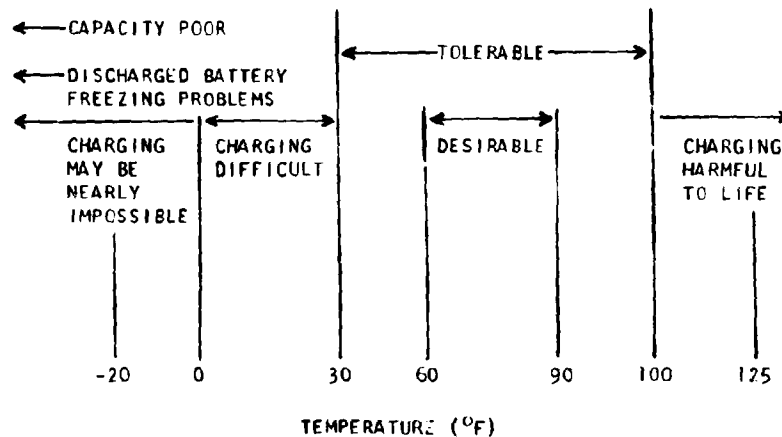


Figure 3.3.5-1. Overview of Effect of Temperature

The effect of temperature on the capacity of the EV2-13 battery can be estimated by referring to Figure 3.3.5-2, which was prepared specifically for Design A. As an example, it is estimated that the battery at 0 °F will be able to deliver 60% of the capacity it could deliver at 80 °F at the one hour rate.

Temperatures in excess of 100 °F, especially during charging, will shorten the cycle life of the battery. Elevated temperatures have a number of adverse effects on battery life. Probably the worst effect is that positive grid corrosion, one of the failure modes for lead-acid batteries, is greatly accelerated at elevated temperatures. For example, in laboratory tests the grid corrosion rate was found to increase an order of magnitude with a temperature increase from 90 to 120 °F. The corrosion rate increased another order of magnitude with a temperature increase from 120 to 150 °F. On the basis of trade-off studies by General Electric, it was decided not to employ active battery temperature control in the Near-Term Electric Vehicle.

Regenerative Braking

Regenerative braking data were generated on EV2-13 cells in July 1978. After testing EV2-13 cells, Globe recommended that the regenerative braking currents be held low enough to keep the cell voltages below 2.60 V at 80 °F. At battery temperatures (T, in °F) other than 80 °F the recommended voltage limit (V_{max} , in volts) is given by the following equation:

$$V_{Max} = 2.60 + (0.004) (80 - T)$$

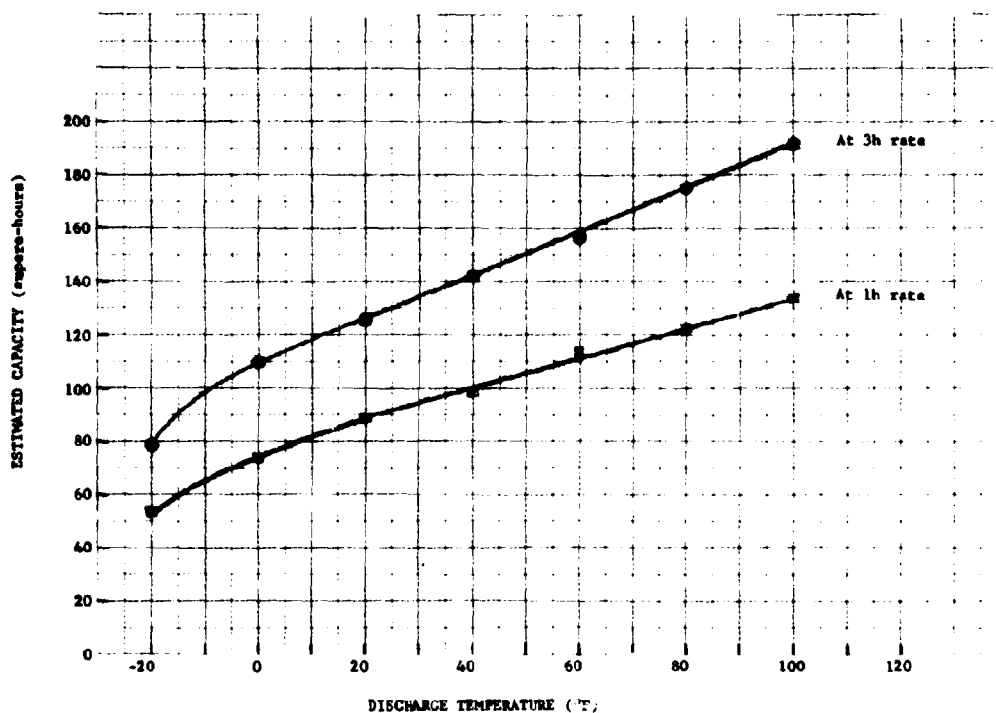


Figure 3.3.5-2. Effect of Temperature on Capacity of GE EV Battery - Design A

Globe-Union stated that exceeding this voltage limit could cause adverse effects on battery life. Based on experimental results with other batteries, General Electric has concluded that no serious degradation in battery performance is likely to result from occasional voltage excursions beyond this limit during regenerative braking.

Fuel Gauge

Figure 3.3.5-3 relates the open-circuit voltage (OCV) of a GC2-19 battery pack at 80 °F to the state of charge based on the 3 hour rate. The state of charge in Figure 3.3.5-3 is equivalent to the percentage of the 3 hour ampere-hour capacity that remains. It is estimated that for every degree below 80 °F, the battery pack OCV will be 0.01 V lower than it is at 80 °F for the same state of charge; and for every degree above 80 °F, it will be 0.01 V higher.

Figure 3.3.5-4 relates EV2-13 battery voltage that was observed during a constant-current discharge at the specified rate (at 80 °F) to state of charge values. The state of charge values were calculated by taking the ratio of the ampere-hour capacity remaining (at the specified rate and temperature) to the initial ampere-hour capacity (assuming 1.3 V/cell cutoff and no rest periods).

EV2-13 fuel gauge calibration curves were supplied for temperatures of 40, 80, and 105 °F. General Electric decided not to make temperature an input to the fuel gauge reading since the "during-driving" gauge is somewhat self-compensating with respect to temperature.

A complex fuel gauge calibration equation was developed. It will yield percent capacity (fuel) remaining when supplied with the simultaneous values of battery pack voltage and current at any time.

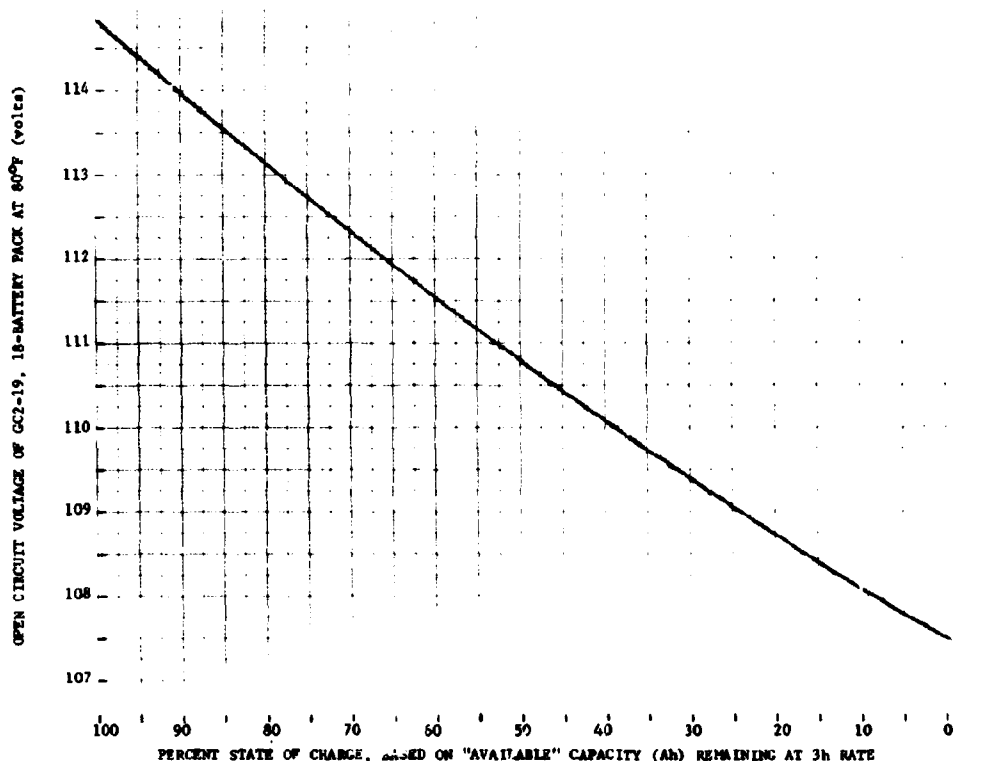


Figure 3.3.5-3. Battery Pack Open-Circuit Voltage vs State of Charge (80 °F)

Battery Mathematical Model

A measured Peukert curve for the EV2-13 is shown in Figure 3.3.5-5.

Hydrogen Gas Generation

Figure 3.3.5-6 shows the estimated cumulative amount of hydrogen generated during the charging of an 18-battery pack of standard Globe GC2-19 golf car batteries at 80 °F. The gas was collected on one cell by a water-displacement method during the charging of a battery, and this value was multiplied by 3 cells/battery and 18 batteries/pack. The data illustrate six separate experiments as described in the key. The solid lines on the graph are based on data and the dashed lines are based on calculations. The calculations assumed the worst possible case, where 100% of the current (1.5 A in these cases) is used for electrolysis of water.

The plotted curves, in conjunction with the estimated recharge times shown in the key in Figure 3.3.5-6, provided the values shown in Table 3.3.5-2, which is a convenient summary of the data. It is anticipated that the EV2-13 battery will generate lower hydrogen volumes than those shown in Figure 3.3.5-6 and Table 3.3.5-2 because the lead-alloy system which is employed should lower the gassing rate and the calculated values in the graph are based on the worst-case condition.

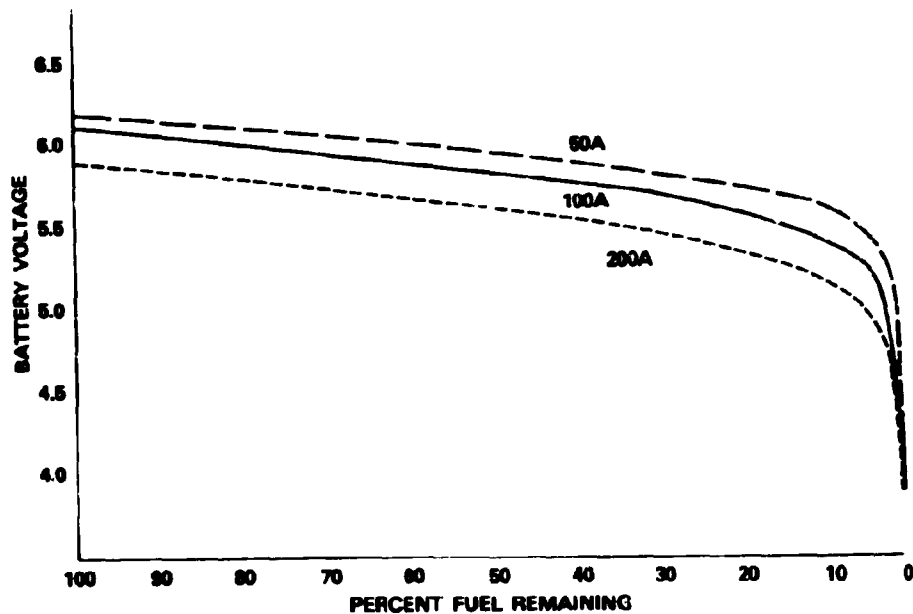


Figure 3.3.5-4. EV2-13 Battery Voltage During Constant-Current Discharges at 3 Rates at 80°F vs State of Charge

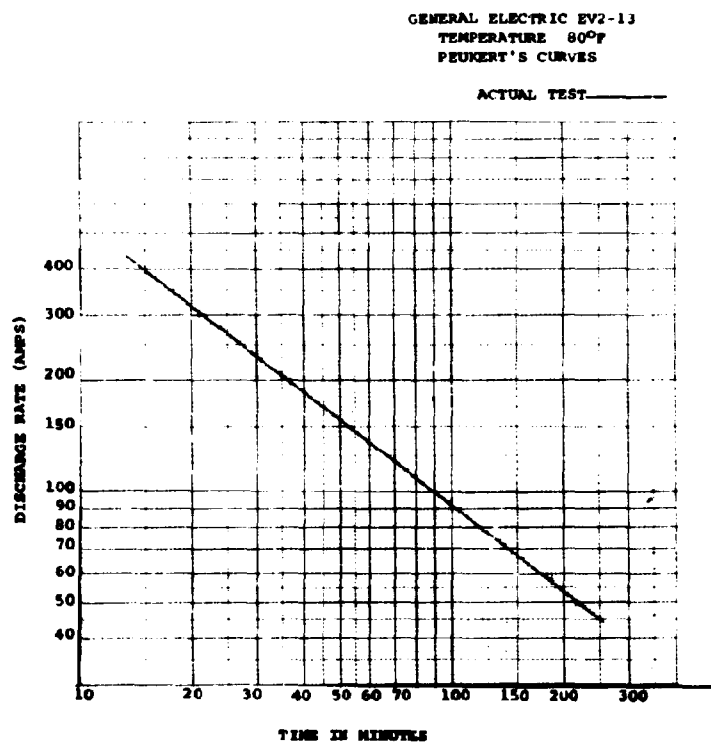
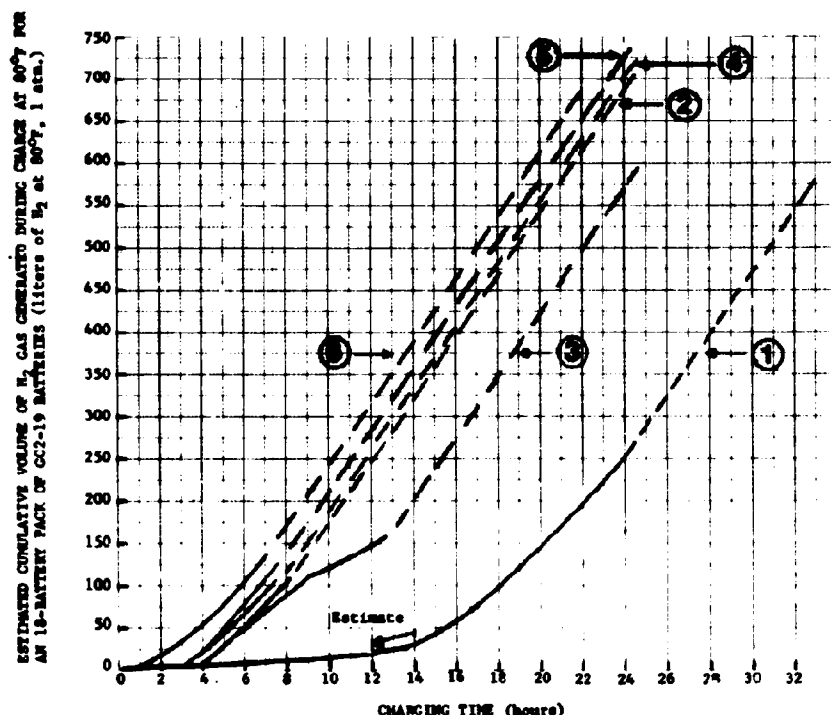


Figure 3.3.5-5. Peukert Curve for EV2-13 at 80°F (3 cell cutoff voltages)



NOTE: Solid lines = Actual Data
Dashed lines = Calculated. The calculation assumed the worst possible case where 100% of current is used for electrolysis of water.

KEY:	CURVE	PRIOR DISCHARGE	CHARGE SCHEME (A)	EST. CHARGE TIME REQ'D (h)	
				DAILY	EQUALIZATION
	#1	80%	8-4-2-1.5	19-21	31-33
	#2	80	24-12-6-3-1.5	10.5-11	22.5-23
	#3	80	24-12-6-3-1.5	10.5-11	22.5-23
	#4	80	24-12-6-3-1.5	10.5-11	22.5-23
	#5	77.2	24-12-6-3-1.5	10.5-11	22.5-23
	#6	40	24-12-6-3-1.5	6.3-10	20.5-22

Figure 3.3.5-6. Hydrogen Gas Generation During Charging

The volume of hydrogen generated during the charging at temperatures other than 80 °F will be different. It is expected that, in general, colder charging temperatures will result in larger volumes of hydrogen. Charging at very cold temperatures such as -15 °F is very inefficient and will generate much large volumes of hydrogen. For example, Figure 3.3.5-6 estimates that the daily charge of a 40% discharged (3 h rate) pack at 80 °F will generate less than 250 liters of hydrogen. A single charging test in which a 40% discharged battery was charged to the 85% state of charge at -15 °F leads to the estimate the 864-liters of hydrogen (80 °F, 1 atm) will be generated if the battery pack is similarly charged from the 60% state of charge to 85%.

Accessory Battery and Charger

Globe-Union UI-9AD52-81 electric vehicle battery, which weighs approximately 21 pounds and has a capacity of 22 ampere-hours at the 3 hour rate is used for the accessory battery. Based on anticipated accessory loads, a charging voltage of 2.35 V/cell at 80 °F with a temperature-correction factor of 0.002 V/°F/cell is recommended. The

recommended charging voltage is lowered 0.002 V/cell for every degree above 80 °F and raised 0.002 V/cell for every degree below 80 °F.

TABLE 3.3.5-2
RANGE OF ESTIMATED HYDROGEN GENERATION VOLUMES

Estimated Cumulative Volume of H ₂ Gas (at 80 °F, 1 atm) Generated During Charge at 80 °F for an 18-Battery Pack of 80% Discharged GC2-19 Batteries		
Charge mode	<u>Stepped-Current Charge Scheme</u>	
	24-12-6-3-1.5 A	8-4-2-1.5 A
Daily	125-225 liters (4-8 ft ³)	120-170 liters (4-6 ft ³)
Equalization	520-670 liters (18-24 ft ³)	510-585 liters (18-21 ft ³)

Maintenance Schedule

- **Watering** – A semiautomatic, single-fill-point watering system is provided with each battery pack. It is currently estimated that watering with distilled water should be performed once every two months. Charging should not be performed during or immediately after watering. The watering procedure should not be restarted after filling is complete.
- **Cleaning** – Cleaning of the battery package will be placed on a schedule similar to lubrication and general maintenance of the vehicle. Once every six months should be adequate if the pack is reasonably well isolated from road dirt. The pack will be removed from the vehicle and the battery connectors checked for corrosion or damage. Removal of dirt and other debris can be accomplished by washing with water.
- **Checking Specific Gravity of Electrolyte** – Specific gravity will be monitored at least once every six months by sensing the open-circuit voltage (OCV) of each battery. A temperature-dependent linear relationship exists between specific gravity and OCV. The OCV measurement should be made after equalization charging. Before the measurement is made, the batteries should be discharged a few seconds by driving twenty feet and allowed to recover for 10 minutes. An alternative procedure is to wait 18 hours after equalization charging ends.

Connectors, Connector Shields, and Cabling

Connectors used to electrically connect the batteries are "burned on" the battery terminal posts, because burned connections offer the lowest resistance and best reliability. The lead connectors are shown schematically in Figures 3.3.5-7 and 8.

Stranded Vulkaflex[®] cable is used for interbattery and battery-motor connections. It is a 1/0 cable with a conductor diameter of 0.374 inch, an overall diameter of

© Registered Trademark of the General Electric Company.

0.65 inch, a weight of 0.45 lb/ft, and a resistance of 0.128 ohm/1000 ft at 100°C. The special high-temperature cable has 133 copper strands, each of which is tin plated.

The estimated weight of the cabling system between batteries (which does not include cable to motor or controller) is 12.9 lb. This 12.9 lb can be broken down into 9.6 lb for the 36 lead connectors and 3.3 lb for the 7.3 feet of copper cable.

A connector shield is used to provide electrical protection for service personnel when the battery pack has been removed from the vehicle. Each lead connector is capped with a connector shield which snaps onto the cable. The connector shields were injection molded of polypropylene.

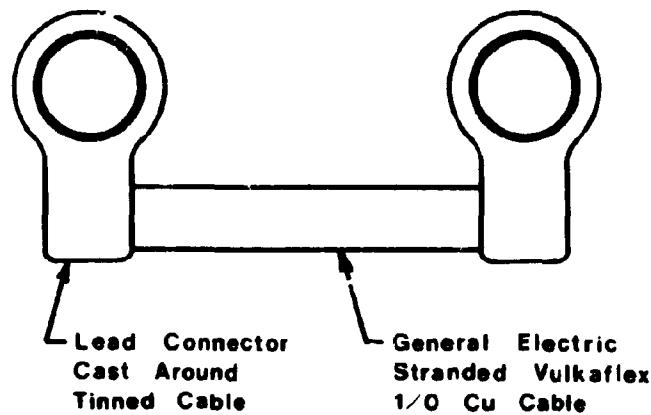


Figure 3.3.5-7. Connector and Cable Top View

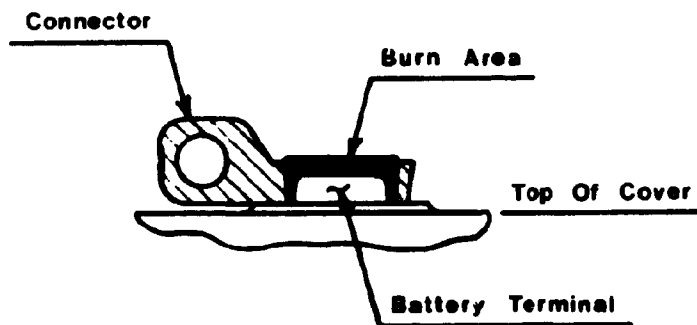


Figure 3.3.5-8. Section View of Connector on Battery Terminal

External (to the battery) Watering/Venting System

The external watering/venting system includes all of the watering/venting system apparatus except for the 18 watering/venting caps which fit on the eighteen EV2-13 batteries. Figure 3.3.1-1, discussed previously, shows the interbattery plumbing arrangement of the system. The 18 batteries are connected in series by plastic tubing.

Figure 3.3.5-9 is a schematic diagram of the watering/venting system. Safety vent ports which are flame-arresting devices provide for the safe venting of hydrogen from the battery pack to the atmosphere. Two safety vent ports are installed on each vehicle – one located near the front of the vehicle and one at the rear.

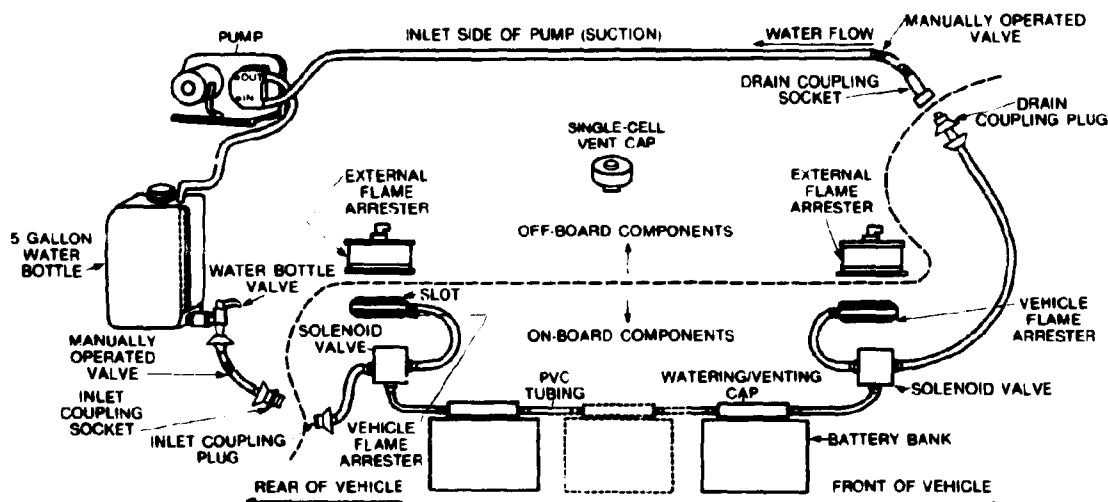


Figure 3.3.5-9. Venting/Watering System Schematic

Section 4

TEST AND EVALUATION

WBS 4.1 SYNOPSIS OF MASTER TEST PLAN

The Master Test Plan was issued in January 1978. The objective of the Master Test Plan is to describe and define the comprehensive testing program required for the successful development of the Electric Test Vehicle and to determine how well the vehicle performance conforms to DOE objectives. The test planning and integration activity provides overall planning, coordination and control of the comprehensive test program. The test plans provide the approval interface with DOE's technical contract manager at JPL. Testing verifies calculations and predictions and permits the characterization of components and subsystems required for verification of tradeoffs. The tests serve to evaluate the ETV before delivery to DOE. Testing and evaluation are performed on a continuing basis with appropriate changes and redirection as determined by engineering, and in turn approved by DOE.

Specific DOE design objectives for this program define a four-passenger car similar in concept to today's subcompact vehicle which is widely used for urban transportation and commuting service. The driving mission for this car is specified by means of the SAE J227a Schedule D driving cycle, which is representative of urban stop-and-go driving.

In addition to the ETV system test, there are three subsystems which were tested. These are:

- Vehicle Subsystem (WBS Element 3.1)
- Electrical Drive Subsystem (WBS Element 3.2)
- Battery Subsystem (WBS Element 3.3)

There is also a 30 mph mule car barrier test (WBS Element 4.3).

Integrated Vehicle Tests

The objective of the integrated vehicle tests is to determine the degree to which the DOE goals have been met. Before the integrated vehicle tests are begun, the vehicle is examined for completeness and condition. The vehicle is tested in its normal configuration with all normal appendages, such as mirrors, bumpers, and hub-caps.

The vehicle is tested at the rated gross vehicle weight. Tire pressures are set at the design pressure and, initially, new tires will be used. Lights, brakes, and safety equipment are checked for proper operation. Any instrumentation included in the vehicle is checked to see that it has been calibrated. The battery is fully charged for vehicle range, maximum speed, acceleration, and gradability tests. Weight of the vehicle with the driver, all test equipment, and ballast is recorded. The fifth wheel is included as part of the test equipment weight for those tests requiring the fifth wheel.

Ambient temperatures during ETV testing are those existing at the selected test site in conformance to the environmental conditions stated in SAE J227a. Checklists were developed for use prior, during, and post test. A detailed Electric Vehicle Test Plan was prepared and issued during the program.

Structural Safety Tests

The objective of the structural safety tests is to demonstrate compliance with current applicable industry-developed and federal mandated standards and to obtain extensive test data for analysis of vehicle impact performance.

Two structural tests were planned: a mule car 30 mph barrier test, and an ETV 30 mph barrier test. The ETV 30 mph barrier test was deleted from the program.

A mule car test vehicle was modified to accept the battery tunnel configuration and rear suspension attachments as well as the sheet metal modifications. Components simulating the electrical drive subsystem, transmission, air handling system, battery subsystem, accessory battery and tray, and other modified components were used to provide as much data as possible resulting from the 30 mph barrier test.

Vehicle Subsystem Tests

No subsystem tests have been conducted for the body structure. Chrysler ran a successful dynamometer durability test of the transmission.

Air handling tests were run to verify compliance with FMVSS 103, "Windshield Defrosting and Defogging Systems," and to ensure various performance levels to satisfy customer acceptance criteria.

Customer acceptance tests for heating and ventilation covered:

- Temperature control and response linearity tests
- Air flow and distribution tests
- Maximum performance warmup tests
- Stratification tests
- Jury evaluations

Defroster compliance tests have been performed in accordance with Compliance Procedure CP152 and established Chrysler Laboratory procedures and performance evaluation tests. The tests measure velocity profiles over the windshield.

Performance tests have been conducted on laboratory bucks and roadable bucks, in wind tunnels and cold rooms, and under actual road conditions, with suitable instrumentation to establish compliance with FMVSS 103 and other customer acceptance specifications.

Electrical Drive Subsystem Tests

The objective of the electrical drive subsystem tests is to provide an evaluation of the electrical drive subsystem prior to its installation in the vehicle. Tests

of the electrical drive subsystem are intended to measure energy flow rates, determine light load losses, measure efficiency of energy transfer, and verify design calculations.

Electrical signals obtained from the laboratory operation of the electrical drive subsystem are read and recorded. The drive motor and associated controls were set up in the laboratory. The drive motor was operated by power from the battery and controlled with respect to output torque and speed. The drive motor was also operated as a generator and returned energy to the battery.

The electrical drive subsystem tests verified the ability of the drive to perform the following:

- Accelerate from 0 to 30 mph in 9 seconds
- Accelerate from 0 to 45 mph in 28 seconds
- Accelerate from 25 to 55 mph in 18 seconds
- Sustain a speed of 50 mph on a 5 % grade
- Obtain minimum passing speed of 60 mph
- Obtain minimum cruising speed of 55 mph

Battery Subsystem Tests

The objective of the propulsion battery electrical test program is to provide a standard procedure to confirm the overall design specification and to ensure that the manufactured product performs as required. Globe-Union development facilities were used for the proposed work.

Tests were performed at 26.6 °C to determine the rated capacity of the battery at the 1-, 3-, and 6-hour rates. During the course of these tests, parameters measured and recorded included the following:

- Half-cell potentials vs $\text{Hg}/\text{Hg}_2\text{SO}_4$ reference electrode
- Electrolyte temperature
- Specific gravity
- Initial (minimum) volts vs current
- Connector drop (IR)

Life cycling tests were deleted from the Program. For peak power tests, the peak power capability of the battery was measured at 26.6 °C.

Support and Special Test Equipment

The objective in providing special test equipment is to permit measurement of significant performance parameters of the completed vehicle, which in turn permits evaluation of the vehicle design.

Electrical and mechanical quantities of interest are measured with a variety of devices such as shunts and load cells. To be useful to the engineer or technician

performing tests, the outputs of these devices are converted, using power sources available on the vehicle, into a format suitable for recording or display in engineering (SI) units.

The special test equipment connects to the vehicle in an easy manner so that all equipment can be removed.

Documentation

Reports presenting test results and conclusions have been prepared and submitted to DOE for the following tests:

- Integrated Vehicle Test
- Mule Car 30 Mph Barrier Test
- Electrical Drive Subsystem Test
- Battery Subsystem Test

WBS 4.2 SPECIAL TEST EQUIPMENT AND FACILITIES

This WBS category was created for the purpose of identifying, processing, and/or fabricating test instrumentation of a specialized nature needed during the electric test vehicle performance evaluation task (WBS 4.6). Figure 4.2-1 shows a schematic of the instrumentation configuration designed to measure the required drive subsystem quantities.

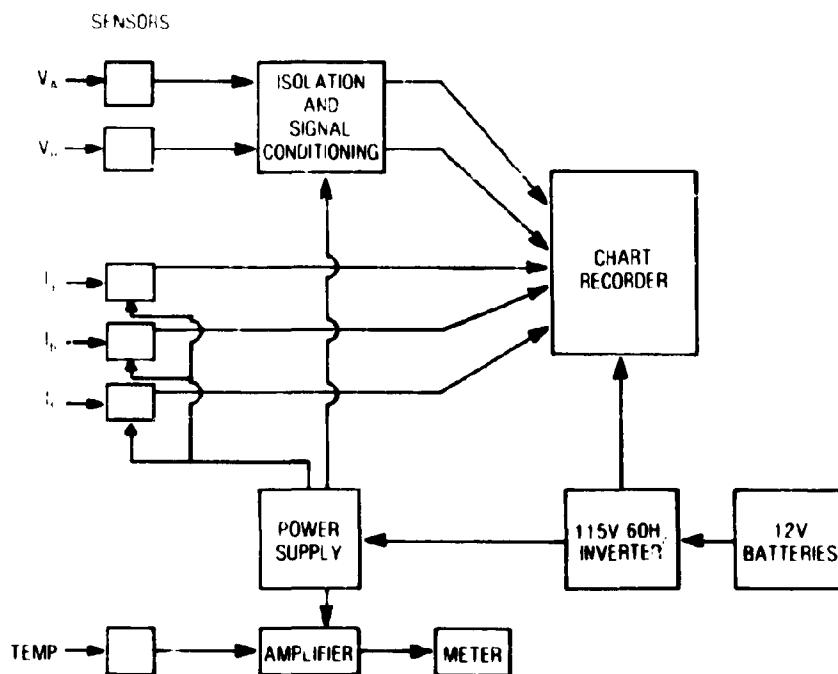


Figure 4.2-1. Instrumentation Schematic

Voltage Measurements

Armature and battery average voltage values, V_A and V_B respectively as shown in Figure 4.2-1, were to be measured using the combined sensor and signal conditioning circuitry shown in Figure 4.2-2. The important components in this circuit are the two optically coupled linear isolation amplifiers, A_A and A_B , which are implemented using Burr-Brown 3650 KG devices. The gain of the complete circuit is set by the trim potentiometers to be ± 0.05 . The local power supply "S," consists of a Burr-Brown quad isolated converter, Type 710. This circuit was constructed and satisfactorily tested.

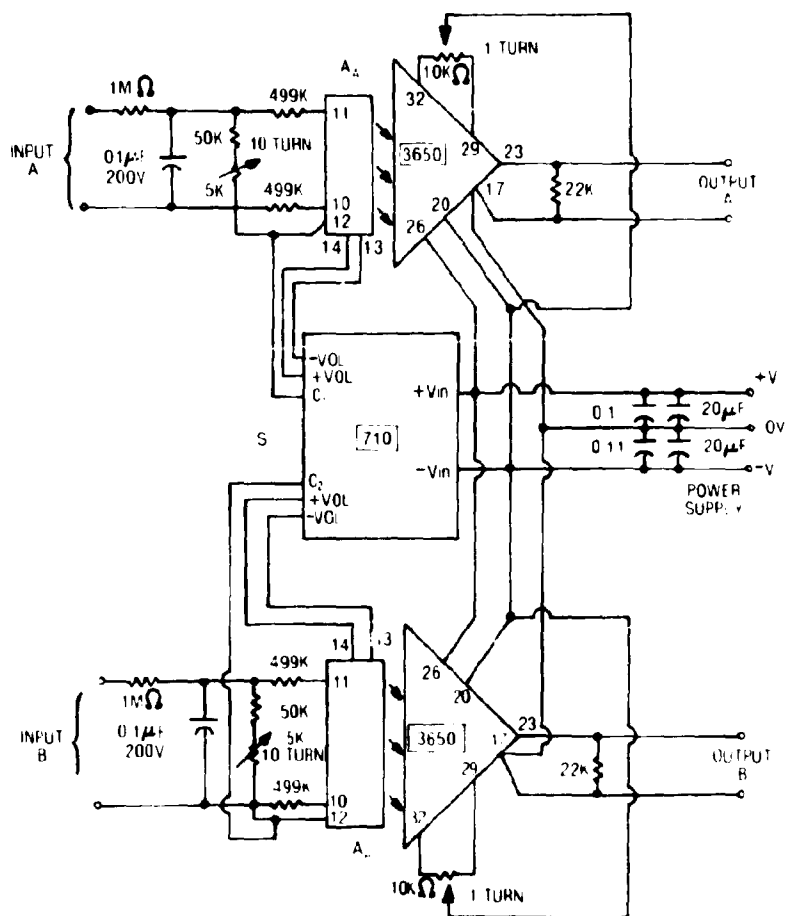


Figure 4.2-2. Sensor and Signal Conditioning Circuitry

Current Measurements

The three desired current values to be measured were battery, armature, and field currents, I_B , I_A , and I_f respectively. Since it was necessary to electrically isolate these measurements prior to recording, a magnetic type of pickup rather than a resistive shunt was used in each case. A ± 5 V sensor output corresponding to ± 500 A was chosen for use with armature and battery currents and a ± 5 V output for a ± 20 A value was chosen for field current measurements.

Because of time limitations on the testing program resulting from schedule delays in fabricating and debugging the vehicles, the special test equipment developed for this task was not used in the performance testing of the vehicles.

WBS 4.3 MULE CAR 30 MPH BARRIER TEST

The chassis mule vehicle was barrier-impact-tested at 30 mph to verify the front structure design concept and to obtain additional design guidelines for the final near-term vehicle. Body modifications made to the mule vehicle were as follows:

- Front floor pan assembly modified to accept new tunnel configuration
- Rear floor pan assembly modified to accept new tunnel configuration and rear suspension attachments
- Front impact structure installed at centerline of vehicle with a hexcel energy absorber for the battery mass
- Heat-treated 6009 series aluminum alloy fenders installed
- Heat-treated 6009 series aluminum alloy hood assembly installed
- Yoke panel assembly modified to accommodate spare tire retention system

The following components were installed on the mule vehicle to make it representative of the final car:

- Simulated electric motor with final NTEV mounts and impact plate
- Simulated transmission housing
- Simulated power conditioning unit (PCU) and supporting structure
- Simulated air handling system
- Modified front crossmember
- Front suspension complete with rack and pinion
- Finalized NTEV rear suspension
- Steering column assembly
- Carryover bumper system
- Battery tray and battery retaining rings
- 18 Globe-Union golf car batteries filled with noncorrosive liquid to simulate active batteries
- Modified front seats
- Accessory battery and tray
- Spare tire assembly with retention system
- Windshield glass
- Instrument panel assembly
- Tires and wheels
- Two-fiftieth percentile non-instrumented male dummies seated in front seats and restrained with unbelted

The mule car impact test was performed on May 10, 1978 in accordance with Mule Car 30-mph Barrier Test Plan, SRD-78-039, dated 3 March 1978.

Barrier Test Instrumentation

To analyze the performance relative to time of the vehicle components during impact, multi-channel data recorders and 14 cameras (13 high speed and one lower speed panning camera) were used to document the event. Cameras were located in the following positions:

- Three cameras in the pit for underbody analysis
- Three cameras on a boom adjacent to the driver's side for steering column penetration and dummy observation
- One camera for a 3/4 frontal view for hood analysis
- One camera on the catwalk directly above the pit for an overall plan view
- One ground level camera behind the vehicle for a rear view
- One camera each for left and right side views
- One camera on the barrier at C of vehicle
- One velocity analysis camera
- One panning camera for viewing the vehicle approach

In addition to the visual data collected, longitudinal and vertical deceleration of the body and other major components were monitored during impact. The raw deceleration data was plotted versus time and then integrated to give the time history of the velocity and displacement of the components.

Results

From the post barrier analysis of the mule car, all of the above federal compliance standards for frontal impact were met.

- The adjusted steering column displacement was 3.1 in. (78.4 mm) rearward for a vehicle speed of 30 mph (48.3 kph).
- Windshield adhesive retention was 100%.
- There was no intrusion into the lower zone.
- The first battery was destroyed and leaked all fluid.
- The second battery filler caps popped off.
- Battery terminals did not short against the battery tunnel. The attached photographs document the results.

A detailed Mule Car 30 mph Barrier Test Report SRD-78-089 dated 16 June 1978 was issued.

WBS 4.4 ELECTRICAL DRIVE SUBSYSTEM TESTS

Tests Performed

Prior to testing the complete electrical drive subsystem, separate performance testing of the Power Conditioning Unit (PCU) and microcomputer was conducted.

Microcomputer Tests

After the hardware of the microcomputer was designed and fabricated, it was tested thoroughly in the laboratory to check its reliability and accuracy of operation. The four microcomputer cards, i.e., CPU card, I/O card, interface card, and dc-dc converter card, were placed in the sockets of the shielding box and were subjected to a power supply drain test. The power drain indicates the loading on the Logic Power Supply (LPS) and also determines the degree of temperature rise in the box. The LPS was initially designed for $\pm 10\%$ regulation, which was satisfactory for Intel mil spec chips. The precision power supply requirement for the DAC 8253 and 8259 data acquisition system chips was met by the dc-dc converter. Table 4.4-1 shows power supply drain data for the microcomputer. The loading due to the microcomputer was practically constant and, therefore, the 48 V LPS was adjusted until all the voltages were in the required tolerance limit. The no load-to-load regulation of the ± 5 V power supply was large, but this is perfectly acceptable to the microcomputer. The total power dissipation was 22.8 W with the converter and 18.3 W without the converter. Since the LPS output voltages are satisfactory for the microcomputer, the converter card was subsequently removed.

TABLE 4.4-1
LOGIC POWER SUPPLY OUTPUT

O.C. Voltage	Voltage with Load	Permitted Deviation	Drain with Microcomputer (Amperes)
+ 6.37	+ 4.93	+ 5 $\pm$ 0.25	1.70
- 6.968	- 5.00	- 5 $\pm$ 0.5	0.12
+12.07	+11.81	+12 $\pm$ 0.61	0.27
+15.53	+15.33	+15 $\pm$ 0.5	0.16
-15.56	-15.34	-15 $\pm$ 0.5	0.24

Total watts = 18.3 W

Next, the temperature rise within the closed box as a function of temperature was measured with a thermistor probe inserted inside the box. The temperature profiles with and without the converter are shown in Figure 4.4-1. The temperature rise is 19.5°C with the converter and 14.2°C without the converter. With additional cooling from the top of the microcomputer box, the maximum temperature within the box will not exceed 70°C in either condition under the maximum field ambient condition of 125°F (51.7°C).

A separately built logic simulation box, test box, and debug panel with EV MONITOR diagnostic software were used to check reliable operation of the hardware. The logic simulation box can command logic input by a miniature toggle switch and can display

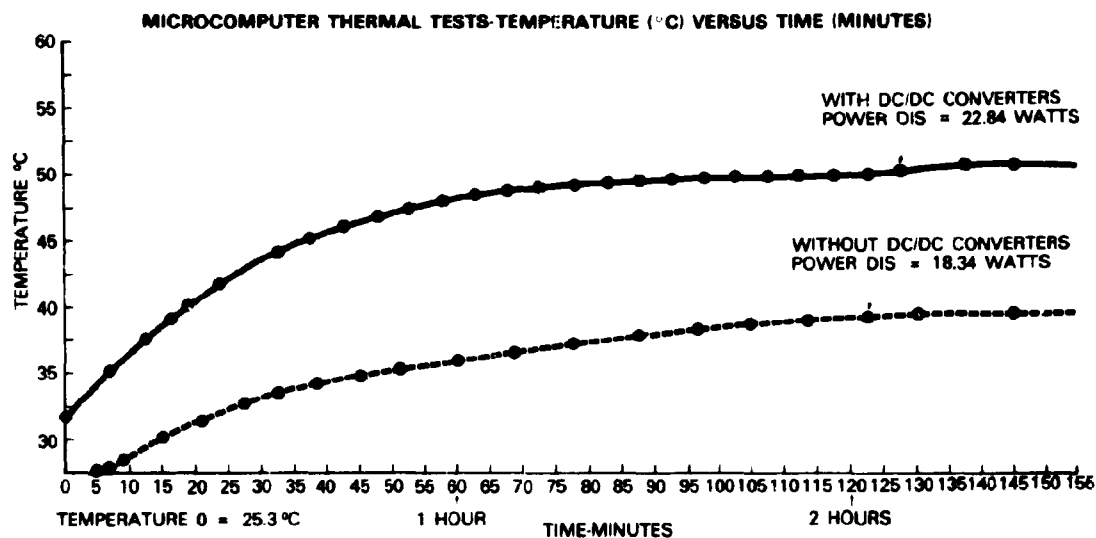


Figure 4.4-1. Thermal Transient Response Within the Microcomputer Box

the logic output by light-emitting diodes (LEDs). The test box can simulate the logic and analog I/O and communicate to the microcomputer through interface electronics. The debug panel can read or write any memory location and is a very powerful tool for on-line or off-line debugging of the system. Simple read/write routines were exercised for the memory and I/O ports to ensure reliable operation. Operation was further checked with interrupt channels, a 4 ms timer, AD/DA channels, an SSO driver, continuous memory, etc., to ensure full integrity of the hardware operation. In addition, all the AD/DA channels with interface electronics were precisely calibrated for accuracy of the signals.

Propulsion/Sequencing Control

Once the reliability of the microcomputer hardware was verified, it was interfaced with the MDS system through the incircuit emulator. Software functional routines were statistically checked. The drive subsystem was operated separately by manual control, and calibration of input signals and noise and harmonic effects were checked in detail.

PCU Tests

Before the complete drive subsystem was tested, the PCU was tested separately using the dc motor and flywheel as a load and the PCU exerciser as the means of manual control. The PCU exerciser allows the drive subsystem to be operated without the use of the microcomputer. The first circuit of the PCU to be tested was the logic power supply. The three printed circuit boards, which were previously bench-tested, were inserted into the PCU, and the PCU was energized using a laboratory power supply. When oscilloscope tests indicated satisfactory operation, attention was directed to the field chopper charger circuit which was tested using the actual motor field as a load. Satisfactory operation was achieved up to a field current value of 10.6 A.

Armature chopper tests were conducted initially with a resistive load and subsequently with the motor armature itself. The most important electrical test involved extensive checking of the motor/generator base drive crossover inhibit logic. This was derived to avoid transmission of base drive signals to the motoring and generating modules simultaneously. Internal armature chopper current limits were also readjusted at this time.

The final circuit that was tested was the accessory charger. This was tested using an adjustable-voltage current-limited power supply to replace the propulsion battery. When satisfactory operation was obtained, final testing was done using the propulsion battery itself.

Electrical Drive Subsystem Tests

The elements of the electrical drive subsystem which were assembled for testing were:

- DC Drive Motor
- Power Conditioning Unit
- Microcomputer and Controls
- Signal Level Harnesses
- Propulsion Battery Pack

These units were interconnected and tested using the dynamometer described in WBS 3.2.8. Figure 4.4-2 shows the test configuration.

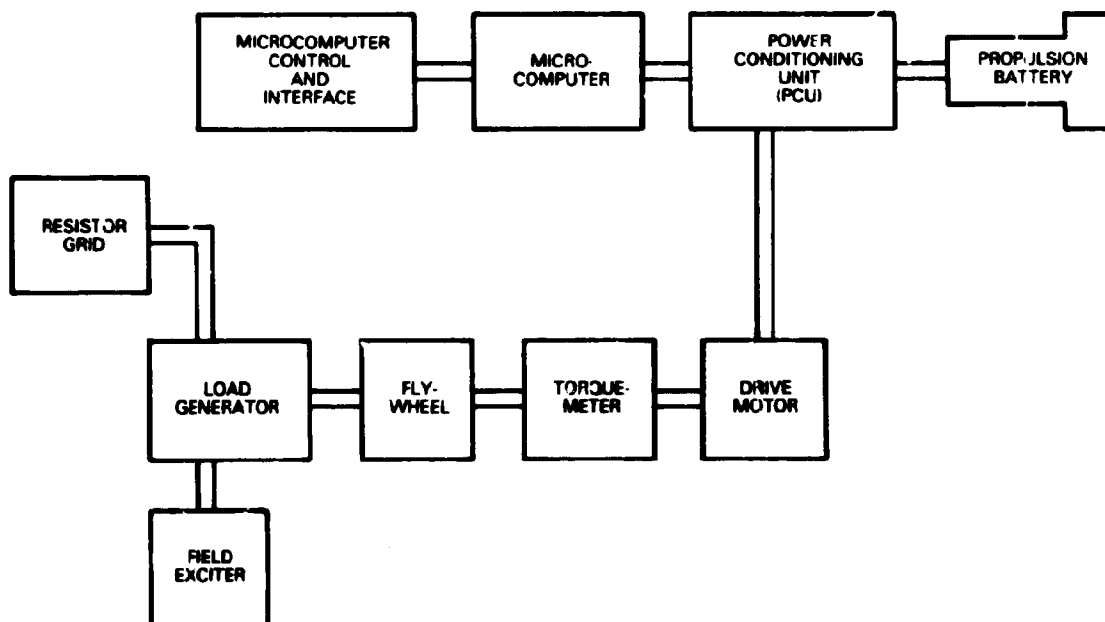


Figure 4.4-2. Electrical Drive Subsystem Test Configuration

The drive was tested in an independent, General Electric-funded electric vehicle propulsion system test facility. This facility includes a propulsion battery, drive motor, load motor, mechanical flywheel and control, and metering equipment. The drive motor, the load motor, and the mechanical flywheel are mounted on a steel railbed, which is bolted to the floor. This ensures ease in handling of the larger components, isolation of those sensitive to mechanical vibrations, and the stability necessary for high-speed testing.

Measurements taken of drive performance were monitored by the voltage and current sensors inside the PCU and the results recorded on a Brush 8-channel chart recorder.

WBS 4.6 INTEGRATED VEHICLE PERFORMANCE TESTS

Objective

The objective is to test and evaluate the performance of the Integrated Test Vehicle, to determine the degree to which the Department of Energy (DOE) performance goals have been met, and to compare the performance results with the theoretical performance predictions. The tests conducted concern the performance of the total vehicle system rather than its individual subsystems and components.

Scope

The specific tests conducted and covered by this document are:

- Range on prescribed driving cycle (SAE J227a Schedule D)
- Range at constant speed: 35 mph and 45 mph
- Maximum speed on level road
- Acceleration on level road: 0 to 30 mph
25 to 55 mph
- Gradability: Sustained speed on 5% grade and maximum grade-climbing ability

Tests

Range on SAE J227a Schedule D Driving Cycle

The purpose of this test is to determine the maximum range traveled and the energy consumed by the vehicle when operated on a level surface in a repeatable driving cycle.

The SAE J227a Schedule D driving cycle requires acceleration to 45 mph, cruising speed of 45 mph, coast, braking, and idle. The cycle is intended for use in testing a vehicle designed for a variable route in stop-and-go driving typical of suburban areas.

A NASA Lewis Research Center cycle timer simulating this driving cycle was used. A Programmable Read Only Memory (PROM) card with the test profile generates a dc analog signal which drives the speedometer displayed on one scale of a dual meter whose second scale displays the vehicle actual speed. The vehicle operator controls vehicle speed to match the desired speed. The cycle programmer forewarns the operator of a change with a buzzer that sounds one second prior to each speed transition, such as, acceleration-to-constant speed or constant-speed-to-coast and a longer duration signal after the idle period to emphasize the start of a new cycle.

The vehicle is operated repeatedly starting with a fully charged battery and without interruption over the driving cycle on a level road (Oval Test Track*) until it reaches the end of its range. The end of the driving range is defined as the end of the driving cycle immediately preceding the cycle in which the vehicle ceases to meet the requirements of the driving cycle or reaches some other vehicle performance limitation specified by the vehicle manufacturer.

*Performance testing was conducted at Chrysler Proving Ground, Chelsea, Michigan. See the map on page 6 for the location of specific test facilities.

Range at Constant Speed

The purpose of this test is to determine the maximum distance traveled and the energy consumed by the vehicle when operating at various constant speeds starting with a fully charged battery.

The vehicle is operated in a normal manner and is accelerated under its own power to the pre-selected test speed. The range test is continued without interruption at the pre-selected speed maintained to within + 5% until the vehicle reaches its end-of-range. The end-of-range is reached when the vehicle speed falls below 95% of the initially programmed steady speed or when such other vehicle performance limitation is reached as may be specified by the vehicle manufacturer.

Maximum Speed on Level Road

The purpose of this test is to determine the maximum speed which the vehicle can attain on a level road.

The vehicle is accelerated until it reaches a maximum speed, starting with a fully charged battery.

The test is conducted on the Vehicle Dynamics Facility; three runs are taken in each direction.

Acceleration on Level Road

The purpose of this test is to determine the maximum acceleration that the vehicle can achieve on a level road as a measure of ability to move in traffic.

Acceleration from 0 to 30 mph and 25 to 55 mph

The vehicle is started from rest and subjected to maximum acceleration until a speed of 60 mph or peak speed is attained.

A total of 16 runs were taken on the north-south straightaway - 8 runs in each direction. Typical plots of speed versus time are shown on page 18.

Gradability

Sustained Speed on 5% Grade

The purpose of this test is to determine the maximum vehicle speed which the vehicle can maintain on a 5% grade starting with a fully charged battery.

The 5% grade is simulated by towing an absorption vehicle on the "Ride Road." The ITV is operated on the "Ride Road" with the absorption vehicle in tow until a speed of 50 mph is attained. The load due to the absorption vehicle (180.52 lbs) is adjusted to simulate a 5% grade. The maximum speed which the ITV is capable of maintaining for 1 mi. for the simulated 5% grade is recorded.

Grade Climbing Ability

The purpose of this test is to determine the maximum grade on which the test vehicle can just move forward.

The tractive force, defined as the maximum force which can be maintained by the vehicle propulsion system for a period of 20 s while moving the vehicle at 2 mph, is measured on a horizontal surface.

The percent gradability limit is determined by using the following relationship:

Where: Percent Gradability Limit = $100 \tan (\sin P/W)$
P = measured traction force
W = gross vehicle weight, lb

Instrumentation

For Performance Testing*

- 2-Channel Brush Recorder
Model 222 Recorder, Model No. 15-6325-00
Serial No. 341
Manufacturer: Gould, Inc., Instrument Systems Division., Cleveland, Ohio
- HP 9815 Calculator
Model: HP 9815A
Serial No. 23046
Manufacturer: Hewlett Packard
- Power Inverter
Model 12DSW10
Serial No. 1244
Manufacturer: CDE Powercon
Fuquay Varina, NC
- Fifth Wheel Assembly
 - a. Traction test fifth wheel
Wheel No. 12
Serial No. 24071
Manufacturer: Labeco
Moorseville, Indiana
 - b. Tachometer Generator
Model 750
Manufacturer: Labeco
Moorseville, Indiana
- NASA-Lewis Cycle Timer
Model: NASA C-77-1722
Serial No. N4
Manufacturer: NASA-Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio

*Two heavy-duty 12-V dc batteries other than the vehicle propulsion batteries are used to power the instrumentation during the performance testing.

For Charging Propulsion Batteries

- Sorenson Power Supply
Model No. DCR 150-18B
Serial No. 0264
Manufacturer: Ratheon Company, Manchester, NH
- Watt-Hour Meter
Model No. WH-926
Serial No. 353
Manufacturer: Ohio Semitronics, Inc.
1205 Chesapeake Avenue
Columbus, Ohio
- Off-Board Charging & Measurement Adapter Unit
Model No. N.A.
Serial No. N.A.
Manufacturer: General Electric Company
Schenectady, New York

Test Facilities

The extensive test and development programs at the Chelsea Proving Ground (See Figure 4.6-1) require the availability of various test facilities. Paved and unpaved roads, straightaways, curves of different radii, smooth and bumpy roads, and special-purpose facilities are designed and maintained by the Proving Ground personnel for constant use by test engineers. The following sections describe the facilities that have been specifically used in conducting the performance tests of the integrated test vehicle.

Oval Test Track

The oval test track is used for high-speed durability, simulated city traffic, endurance cycling of engines, transmissions and rear axles, fuel economy measurements, brake performance, temperature measurements, and draw bar pull tests.

The track is a six-lane, concrete road of 4.71 miles long. The width varies from 60 ft in two 3757-ft straightaways to 64 ft in the 1800-ft radius curves. The curves are designed to accommodate vehicle speed from 30 to 140 mph without side thrust.

Straightaways

Two straightaways are used for stopping distance, acceleration, engine driveability, directional stability, and force required tests.

The two concrete straightaways are located at right angles to each other to permit selection of the road to nullify the effects of wind. Both are straight, level, two-lane roads, 12 ft in width. The east-west road is 1.58 miles long; the north-south road is 2.23 miles long.

Ride and Development Road

This road is used to evaluate vehicles for ride, steering, body shake, noise, and vibration.

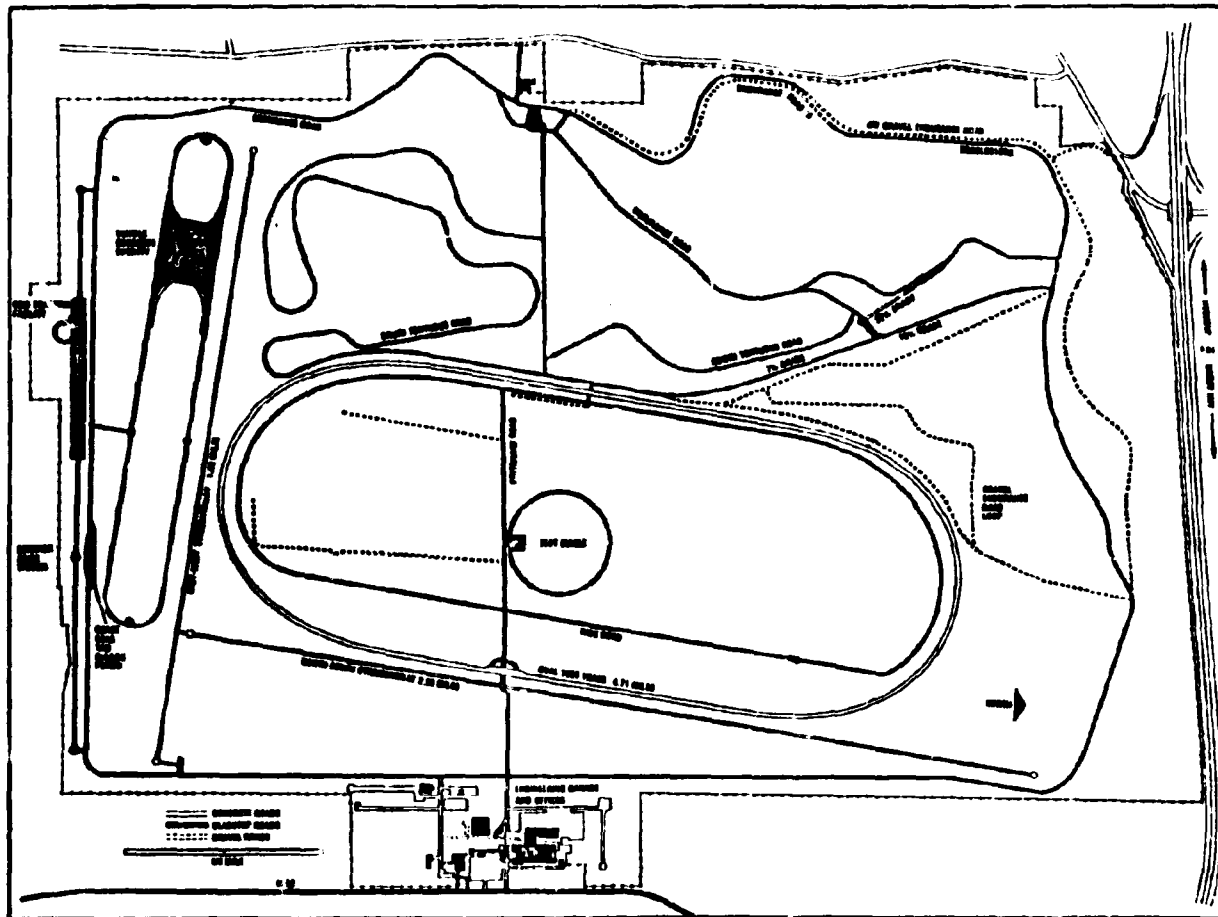


Figure 4.6-1. ETV-1 Performance Test Location - Chrysler Corporation, Chelsea Proving Grounds

The road is 4-1/3 miles long, two and three lanes wide. One lane is a smooth sheet-asphalt surface for vehicle-induced noises and vibrations. The second lane incorporates various waveforms and rough surfaces. A shorter third lane is surfaced with crushed stone to initiate road noise.

Dynamic Handling Facility

The dynamic handling facility is used for evaluating the steering, suspension, and braking characteristics of a vehicle during severe maneuvers at varying speeds up to 100 mph.

The basic feature is a 640 sq ft asphalt pad with a 75 skid number surface, enclosed by a one-lane oval road. The oval road permits the test vehicle to approach the pad from either the right or left side, perform a particular maneuver, recover, and decay speed on the loop at the far end of the pad. The oval road is 2.7 miles long, 16 ft wide, and the curves are designed for 40 mph speed.

Highlights of ETV-1 Performance Results

Table 4.6-1 gives the main ETV-1 Performance Results.

Table 4.6-1
ETV-1 PERFORMANCE TEST RESULTS

	Predicted Performance (300-lb Payload)	DOJ Goal	Actual Performance (300-lb Payload)
• Range at constant speed			
35 mph	122.2 mi	N/A	124.1 mi
45 mph	101.7 mi	N/A	91.9 mi
• Range on prescribed driving cycle (SAE J227a Schedule D)	74.6 mi*	75	74.2 mi
• Acceleration on level road			
0 to 30 mph	8.2 ⁺ s	9	8.77 s (min.) 9.04 s (max.)
25 to 55 mph	16.2 ⁺ s	18	20.17 s (min.) 23.19 s (max.)
• Maximum speed on level road		60	70.75 mph (max.) 65.90 mph (min.)
• Gradability			
Sustained speed on 5% grade	56.2 mph ⁺	50	47 mph
Grade climbing ability	18.75 % ⁺	N/A	18.3%
• Maximum electric recharge energy (J227 A Schedule D)	0.36 kWh/mi	0.5 kWh/mi	0.43 kWh/mi

*See Figure 4.6-2 for constant power acceleration segment of J227 A Schedule D test program used in the NASA Low-Speed Tunnel.

⁺Fully-charged battery.

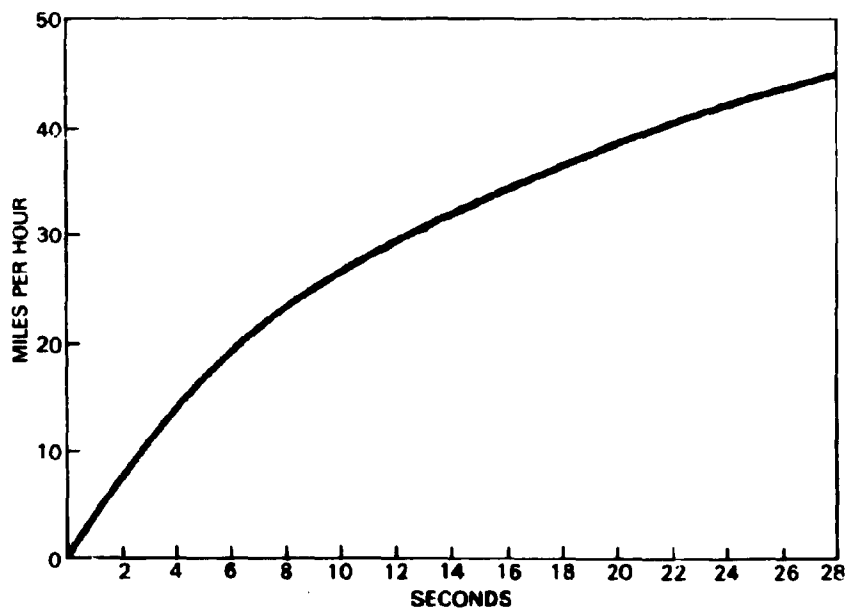


Figure 4.6-2. J227 A Schedule D Acceleration Segment

Test Data and Results

EV-1 PERFORMANCE TEST SHEET

TEST DESCRIPTION ACCELERATION TEST: ① 0-30 MPH
② 25-55 MPH
 TEST LOCATION NS-STRAIGHTWAY, CHRYSLER CORP.
CHRYSLER PROving GROUNDS

TEST NO. 1 DATE 5/28/79
 VEHICLE NO. LS 22 E 9N TEV 001

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	678	687
Prop. Battery Open Circuit Voltage (Volts)	109.51	108.04
Battery Gauge Reading	0.5 FULL	0.20 FULL
Access. Battery Specific Gravity	1.3	1.285
Tire Pressures (PSI)	LF 29 RF 29	LF RF
	LR 41 RR 41	LR RR

POST-TEST CONDITION

	Before Test	After Test
Inst. Battery Specific Gravity	1.24	1.22
Fifth Wheel Tire Pressure (PSI)	25 PSI	25 PSI
Strip Chart Calib. Velocity (MM)	—	—
Distance (FT)	—	—

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	896	893	1789
Rear	922	933	1855
Total	1818	1826	3644

(FIFTH WHEEL UP)

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	67°F	67.5°F
Humidity (Percent)	97%	96%
Wind Velocity and Direction ()	1-5 MPH (140°)	1-6 MPH (150°)
Precipitation ()	0	0
Bar. PRESS.	28.91" →	28.91" →

TIME OF TEST

DRIVER T. BAILEY

START 10:10 AM FINISH 10:40 AM

CONDUCTOR

COMMENTS Batteries have not fully charged. Spare Tire & Jack were
removed to get to above Test Weight

RESULTS	TEST RUN NO.	DIRECTION	0-30 MPH	25-55 MPH
	1	N	10.22 Sec	28.38 Sec
	2	S	10.52 "	28.43 "
	3	N	10.87 "	36.37 "
	4	S	11.43 "	—

TEST DESCRIPTION ACCELERATION TEST: ① 0-30 MPH
② 25-55 MPH

TEST NO. 1 DATE 8/28/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.023		10	5.985	
2	6.017		11	6.005	
3	6.026		12	5.979	
4	6.000		13	5.997	
5	6.027		14	5.996	
6	6.016		15	5.966	
7	6.036		16	5.996	
8	6.006		17	5.999	
9	6.015		18	5.997	

Description	Before Test	After Test
Open Circuit Voltage (V)	109.51	108.04
Energy to Recharge Batteries (WH)	—	33,414 (25,060)*

Test Engineers:

Chrysler Corporation, H.P.

R.R. VENKATAPPERUMAL

Chrysler Corporation, P.G.

C.G. TRIANTAFYLLOS

General Electric

R.J. TWARDZIK

Jet Propulsion Laboratory

J. TOCZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

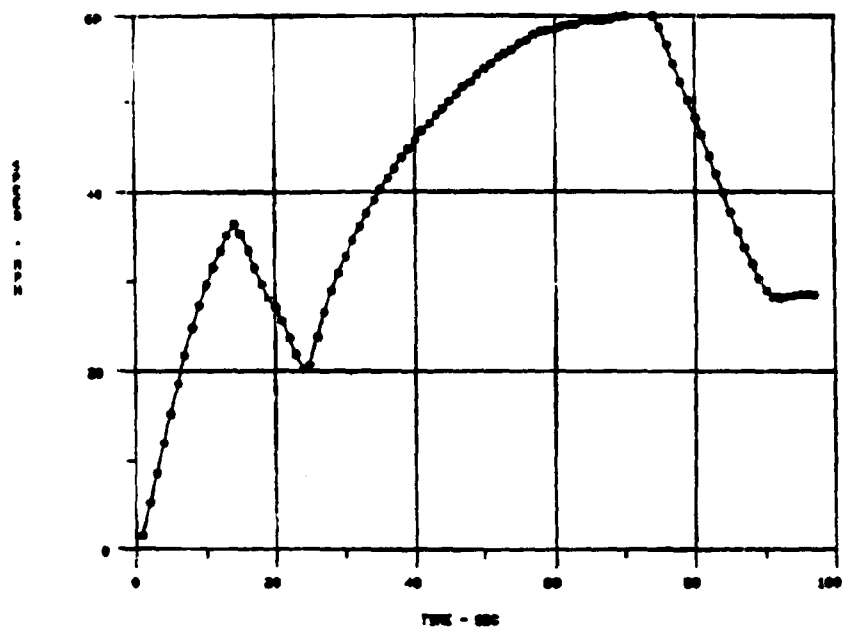
TEST DESCRIPTION ACCELERATION TESTS: ① 0-30 MPH & ② 25-55 MPH

TEST NO. 1

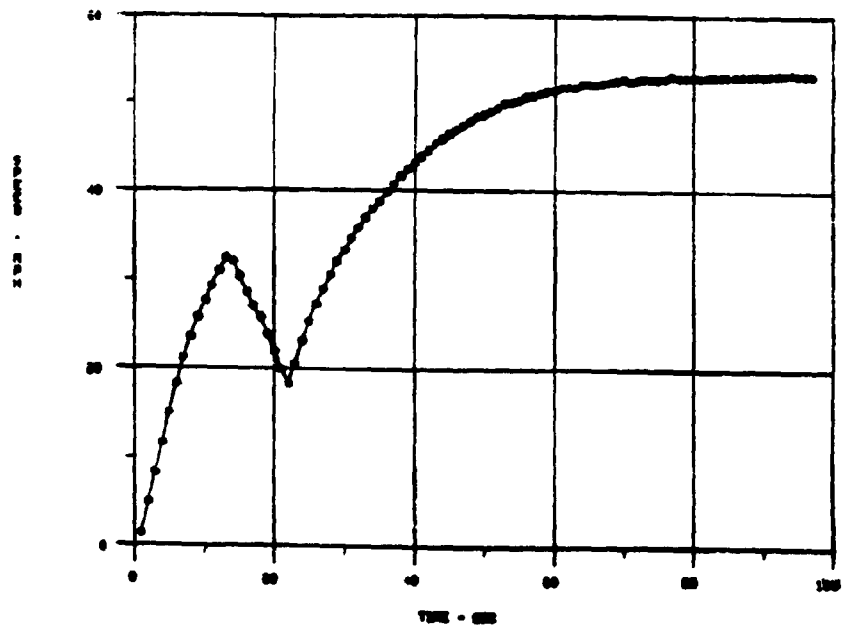
DATE 8/28/79

RESULTS:

ACCELERATION TEST - RUN 1



ACCELERATION TEST - RUN 4



TEST DESCRIPTION ACCELERATION TESTS ① 0-30 MPH & ② 25-55 MPH

TEST NO. 1

DATE 8/28/79

RESULTS:

RUN NO	DIRECTION	TIME (SEC)	
		0-30 MPH	25-55 MPH
1	NORTH	10.22 SEC	25.38
2	SOUTH	10.52	28.43
3	NORTH	10.87	36.37
4	SOUTH	11.43	—

RTV-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION RANGE AT CONSTANT SPEED 45MPH TEST NO. 2 DATE 8/29/79
 TEST LOCATION OVAL TEST TRACK, CHRYSLER CORP VEHICLE NO. LS22E9 NTEV001
CHELSEA PROVING GROUNDS

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>687</u>	<u>777</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>117.62</u>	<u>107.49</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Acid. Battery Specific Gravity	<u>1.27</u>	<u>1.30</u>
Tire Pressure (PSI)	<u>LR 29 RR 29</u>	<u>LR RR</u>
	<u>LR 41 RR 41</u>	<u>LR RR</u>

DISCHARGE DATA

	Bat ①	②	D	②
Inst. Battery Specific Gravity	<u>1.23</u>	<u>1.25</u>	<u>1.22</u>	<u>1.24</u>
Fifth Wheel Tire Pressure (PSI)	<u>25 PSI</u>		<u>25 PSI</u>	
Strip Chart Calib. Velocity (MM)	<u>1</u>	<u>1mm/SEC</u>	<u>200mV/div</u>	
Distance (FT)	<u>—</u>	<u>—</u>	<u>—</u>	

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>862</u>	<u>841</u>	<u>1706</u>
Rear	<u>952</u>	<u>964</u>	<u>1946</u>
Total	<u>1845</u>	<u>1805</u>	<u>3650</u>

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>68.5°F</u>	<u>70.0°F</u>
Humidity (Percent)	<u>92%</u>	<u>85%</u>
Wind Velocity and Direction ()	<u>8-16MPH (200°)</u>	<u>7-12MPH (200°)</u>
Precipitation ()	<u>0</u>	<u>0</u>

TIME OF TEST

DRIVER <u>T. BAILEY</u>	START <u>10.27</u>	FINISH <u>2.08 PM</u>
	CHARGE	

COMMENTS

CAR STOPPED AT 11:30AM - MAIN CONTROLLER OPENED
TEST RESTARTED AT 1:00 PM - MAIN CONTROLLER OPENED
AGAIN AT 2:08 PM - TEST TERMINATED

RESULTS

90.3 MILES - RANGE

EST DESCRIPTION RANGE AT CONSTANT SPEED 45 MPH

TEST NO. 2

DATE 8/29/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.546	5.979	10	6.505	5.988
2	6.551	5.982	11	6.515	5.972
3	6.526	5.988	12	6.496	5.953
4	6.521	5.966	13	6.486	5.966
5	6.509	5.974	14	6.505	5.966
6	6.545	5.988	15	6.449	5.935
7	6.490	5.972	16	6.496	5.968
8	6.525	5.975	17	6.498	5.974
9	6.508	5.981	18	6.487	5.969

Description	Before Test	After Test
Open Circuit Voltage (V)	117.62	107.49
Energy to Recharge Batteries (WH)	33,414	25,640

(19,230) *

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

C. G. TRIANTAFYLLOS

General Electric

R. J. TWARDZIK

Jet Propulsion Laboratory

J. TOBZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

EV-1 PERFORMA TEST CHECKLIST

TEST DESCRIPTION ACCELERATION TESTS: 0-30MPH 25-55MPH TEST NO. 3 DATE 9/4/79
 TEST LOCATION NS - STRAIGHTWAY, CHRYSLER CORP VEHICLE NO. LS22E9 NTEV 001
CHELSEA PROVING GROUNDS

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>786</u>	<u>804</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>115.56</u>	<u>112.8</u>
Battery Gauge Reading	<u>FULL</u>	<u>7/8 FULL</u>
Acid. Battery Specific Gravity	<u>1.27</u>	<u>1.295</u>
Tire Pressures (PSI)	<u>L2 29 R2 29</u>	<u>L2 31 R2 31</u>
	<u>L1 41 R1 41</u>	<u>L1 42.5 R1 42.5</u>

DISSEMINATION

	Bot ①	②	①	②
Int. Battery Specific Gravity	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>
Fifth Wheel Tire Pressure (PSI)	<u>18.5 PSI</u>		<u>18.5 PSI</u>	
Strip Chart Calib. Velocity (MPH)	<u>NU</u>			
Distance (FT)	<u>NU</u>			

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>870</u>	<u>832</u>	<u>1702</u>
Rear	<u>979</u>	<u>958</u>	<u>1937</u>
Total	<u>1849</u>	<u>1790</u>	<u>3639</u>

(FIFTH WHEEL LP)

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>72°F</u>	<u>74.5°F</u>
Humidity (Percent)	<u>65%</u>	<u>61%</u>
Wind Velocity and Direction ()	<u>2-8 MPH 140°</u>	<u>4-11 MPH (110°)</u>
Precipitation ()	<u>0</u>	<u>0</u>

TIME OF TEST

DRIVER T. BAILEY START 1:16 PM FINISH 2:16 PM

COMMENTS

RESULTS P TOTAL OR 16 RUNS WERE TAKEN: 8 RUNS TOWARDS NORTH DIRECTION
AND 8 RUNS TOWARDS SOUTH DIRECTION:
ACC. TIME: 0-30MPH 8.77 SEC (MIN) ; 9.04 SEC (MAX)
25-55MPH 20.17 SEC (MIN) ; 23.19 SEC (MAX)

TEST DESCRIPTION ACCELERATION TESTS : 0-30 MPH & 25-55 MPH.

TEST NO. 3 DATE 9/4/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.434	6.280	10	6.402	6.250
2	6.432	6.279	11	6.428	6.272
3	6.439	6.285	12	6.403	6.250
4	6.419	6.265	13	6.411	6.260
5	6.421	6.269	14	6.406	6.256
6	6.434	6.281	15	6.380	6.228
7	6.416	6.265	16	6.410	6.259
8	6.422	6.269	17	6.414	6.264
9	6.429	6.276	18	6.415	6.262

Description	Before Test	After Test
Open Circuit Voltage (V)	115.56	112.5
Energy to Recharge Batteries (WH)	25,640	11,520

(8640)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

C. S. TRIANTAFYLLOS

General Electric

R. J. TWARDZIK.

Jet Propulsion Laboratory

J. TOCZYLOWSKI

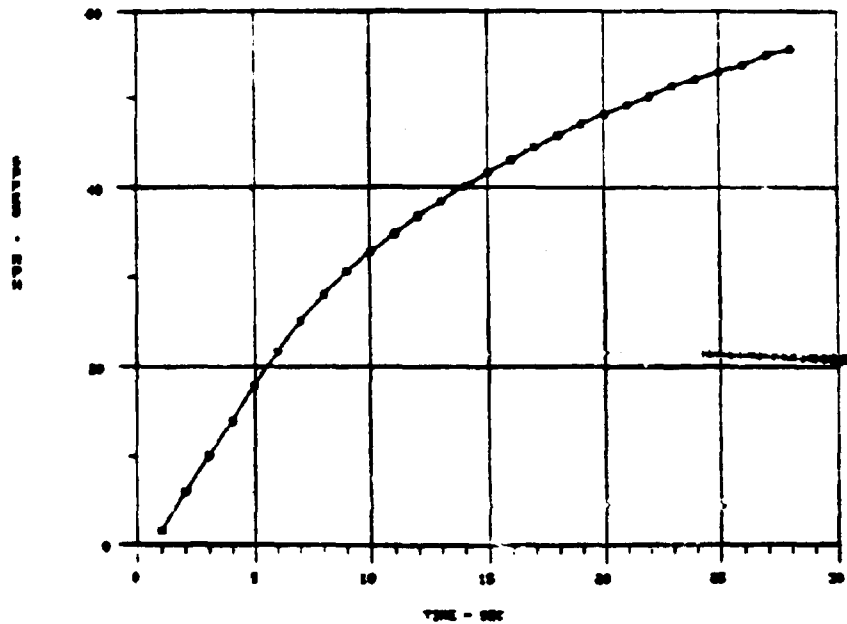
*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

TEST DESCRIPTION ACCELERATION TESTS: 0-30 MPH
35-55 MPH.

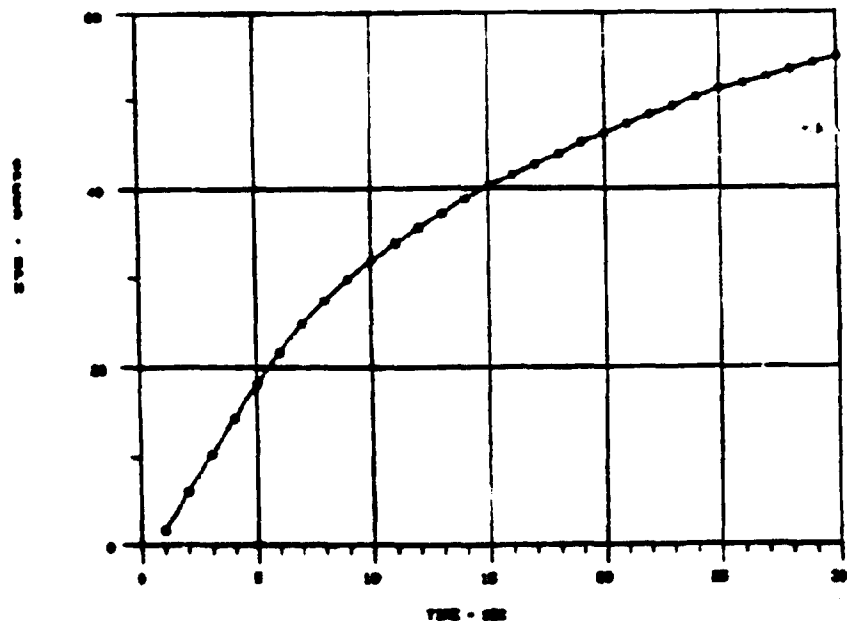
TEST NO. 3 DATE 9/4/79

RESULTS:

ACCELERATION TEST - RUN 6



ACCELERATION TEST - RUN 15



TEST DESCRIPTION ACCELERATION TESTS 0-30 MPH & 25-55 MPH

TEST NO. 3

DATE 9/4/79

RESULTS:

RUN NO.	DIRECTION	TIME /SEC	
		0-30 MPH	25-55 MPH
1	NORTH	9.00	20.58
2	NORTH	8.80	20.60
3	SOUTH	8.97	21.03
4	SOUTH	8.77	20.52
5	NORTH	8.84	20.66
6	NORTH	8.77	20.17
7	SOUTH	8.89	21.48
8	SOUTH	8.78	21.57
9	NORTH	8.87	21.31
10	NORTH	8.79	20.97
11	SOUTH	8.90	21.95
12	SOUTH	8.83	21.68
13	NORTH	9.00	22.37
14	NORTH	8.87	22.30
15	SOUTH	9.04	23.19
16	SOUTH	8.95	22.40

EV-1 PERSONAL TEST CHECKLIST

TEST DESCRIPTION RANGE AT CONSTANT SPEED 45MPH TEST NO. 4 DATE 9/8/79
 TEST LOCATION OVAL TEST TRACK, CHRYSLER CORP. VEHICLE NO. LS 22 E 9 NTEV001
CHELSEA PROVING GROUNDS.

VEHICLE CONDITIONS

	Before Test	After Test
Odometer Reading (Miles)	<u>804</u>	<u>886</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>121.58</u>	<u>107.69</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Approx. Battery Specific Gravity	<u>1.248</u>	<u>1.305</u>
Tire Pressures (PSI)	<u>LF 27 RF 27</u> <u>LR 41 RR 41</u>	<u>LF RF</u> <u>LR RR</u>

INSTRUMENTATION

	BAT. ①	②	①	②
Inst. Battery Specific Gravity	<u>1.262</u>	<u>1.265</u>	<u>1.240</u>	<u>1.245</u>
Flitch Wheel Tire Pressure (PSI)	<u>25 PSI</u>		<u>25 PSI</u>	
Strip Chart Calib. Velocity (MPH)	Ch. No. <u>1</u>	Horiz. Scale <u>1mm/sec</u>	Vert. Scale <u>25CMV/div</u>	
	Distance (FT)	<u>NU</u>		

WEIGHT CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>869</u>	<u>834</u>	<u>1703</u>
Rear	<u>975</u>	<u>957</u>	<u>1932</u>
Total	<u>1844</u>	<u>1791</u>	<u>3635</u>

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>57.5°F</u>	<u>58°F</u>
Humidity (Percent)	<u>48%</u>	<u>50%</u>
Wind Velocity and Direction ()	<u>AVG 10 MPH (300° - 60°)</u> <u>4-18 MPH</u>	<u>AVG 7 MPH (360° - 90°)</u> <u>2-10 MPH</u>
Precipitation ()	<u>39.154</u>	<u>39.204</u>

TIME OF TEST

DRIVER R. WIRTZ START 12:02 PM FINISH 1:51 PM
 COMMENTS —

COMMENTS MOTOR SPEED LIGHT FLASHED AT 23.2 & 77.9 MILES OF RANGE
TEST.

RESULTS Range = 83.045 miles.

TEST DESCRIPTION RANGE AT CONSTANT SPEED 45 MPH.

TEST NO. 4 DATE 9/8/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.771	5.990	10	6.732	5.967
2	6.759	5.995	11	6.747	5.982
3	6.767	5.999	12	6.725	5.964
4	6.746	5.977	13	6.741	5.976
5	6.746	5.986	14	6.735	5.977
6	6.756	5.988	15	6.721	5.961
7	6.748	5.981	16	6.753	5.979
8	6.750	5.985	17	6.752	5.984
9	6.759	5.991	18	6.744	5.976

Description	Before Test	After Test
Open Circuit Voltage (V)	121.58	107.69
Energy to Recharge Batteries (WH)	11,520	34,000

(25,550) *

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

M. J. ANDRES

General Electric

Jet Propulsion Laboratory

J. TOCZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

EV-1 PERFORMANCE TEST SHEET

TEST DESCRIPTION RANGE AT CONSTANT SPEED ^{35 MPH} TEST NO. 5 DATE 9/9/79
 TEST LOCATION OVAL TEST TRAK, CHRYSLER CORP. NO. LS22E9 NTEV 001
CHELSEA PROVING GROUNDS.

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>892</u>	<u>1016</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>120.0V</u>	<u>105.33</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Acid. Battery Specific Gravity	<u>1.30</u>	<u>1.30</u>
Tire Pressures (PSI)	<u>LF 29 RR 29</u> <u>LF 41 RR 41</u>	<u>LF 30 RR 30</u> <u>LF 42.5 RR 42.0</u>

DATA ACQUISITION

	①	②	①	②
Inst. Battery Specific Gravity	<u>1.27</u>	<u>1.265</u>	<u>1.23</u>	<u>1.24</u>
Fifth Wheel Tire Pressure (PSI)	<u>25 PSI</u>	<u>25 PSI</u>		
Strip Chart Calib. Velocity (MM)	<u>1</u>	<u>2mm/sec</u>	<u>200 mV/div</u>	
Distance (FT)	<u>NU</u>	<u>—</u>	<u>—</u>	

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>878</u>	<u>846</u>	<u>1724</u>
Rear	<u>960</u>	<u>938</u>	<u>1898</u>
Total	<u>1838</u>	<u>1784</u>	<u>3622</u>

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>63°F</u>	<u>68°F</u>
Humidity (Percent)	<u>50%</u>	<u>42.0%</u>
Wind Velocity and Direction ()	<u>8-14 MPH (190°)</u>	<u>9-15 MPH (210°)</u>
Precipitation ()	<u>0</u>	<u>0</u>
BAR. PRESS	<u>29.2" Hg</u>	<u>29.1" Hg</u>

TIME OF TEST

DRIVER R. WIRTZ START 11:38 AM FINISH 3:14 PM

COMMENTS CAR STOPPED AT 24 MILES DUE TO LOSS OF POWER.
RESTARTED AFTER A FEW SECONDS AND COMPLETED THE
TEST.

RESULTS RANGE: 123.11 MILES.
BATTERY CURRENT AT 35MPH: 60 AMPS when the car was moving
to north track. 65-70 amps when it was moving towards south.

TEST DESCRIPTION RANGE AT CONSTANT SPEED 35MPH.

TEST NO. 5 DATE 9/9/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.724	5.853	10	6.642	5.834
2	6.707	5.855	11	6.646	5.848
3	6.692	5.871	12	6.619	5.827
4	6.680	5.843	13	6.635	5.847
5	6.669	5.858	14	6.644	5.846
6	6.690	5.874	15	6.595	5.800
7	6.655	5.854	16	6.643	5.849
8	6.674	5.858	17	6.642	5.844
9	6.663	5.864	18	6.617	5.847

Description	Before Test	After Test
Open Circuit Voltage (V)	120.00	105.33
Energy to Recharge Batteries (WH)	34,000	22,440

(16,830) *

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

C. G. TRIANTAFYLLOS

General Electric

Jet Propulsion Laboratory

J. TOCZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

EV-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION MAXIMUM LEVEL SPEED TEST TEST NO. 6 DATE 9/11/79
 TEST LOCATION VEHICLE DYNAMIC FACILITY, VEHICLE NO. LS 2289N TEV 001
CHEYSER CORP. CHELSEA PROVING GROUNDS.

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>1016</u>	<u>1032</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>118.67</u>	<u>114.33</u>
Battery Gauge Reading	<u>FULL</u>	<u>90% FULL</u>
Access. Battery Specific Gravity	<u>1.3</u>	<u>1.3</u>
Tire Pressures (PSI)	LF <u>29</u> RF <u>29</u> LR <u>41</u> RR <u>41</u>	LF <u>30.5</u> RF <u>30.5</u> LR <u>42.5</u> RR <u>42.5</u>

INSTRUMENTATION

	①	②	③	④
Inst. Battery Specific Gravity	<u>1.27</u>	<u>1.27</u>	<u>1.252</u>	<u>1.252</u>
Fifth Wheel Tire Pressure (PSI)	<u>25 PSI</u>		<u>25 PSI</u>	
Strip Chart Calib. Velocity (MPH)	<u>NU</u>	<u>—</u>	<u>—</u>	<u>—</u>
Distance (FT)	<u>NU</u>	<u>—</u>	<u>—</u>	<u>—</u>

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>861</u>	<u>828</u>	<u>1689</u>
Rear	<u>969</u>	<u>955</u>	<u>1924</u>
Total	<u>1830</u>	<u>1783</u>	<u>3613</u>

(FIFTH WHEEL UP)

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>67.5°F</u>	<u>67.5°F</u>
Humidity (Percent)	<u>69%</u>	<u>69%</u>
Wind Velocity and Direction ()	<u>8-12 MPH (140°)</u>	<u>8-12 MPH (140°)</u>
Precipitation ()	<u>0</u>	<u>0</u>
Bar. Press.	<u>29.15" Hg</u>	<u>29.15" Hg</u>

TIME OF TEST

DRIVER T. BAILEY START 2:55 PM FINISH 3:14 PM
 OBSERVER —

COMMENTS MOTOR SPEED LIGHT FLASHED EVEN WHEN THE CAR WAS NOT MOVING.

RESULTS A TOTAL OF 6 RUNS WERE TAKEN. 3 RUNS TOWARDS WEST & 3 RUNS TOWARDS EAST:

	WEST DIR	EAST DIR	AVG. SPEED
①	<u>71.46</u>	① <u>70.04</u>	<u>70.75 MPH</u>
②	<u>67.72</u>	② <u>66.93</u>	<u>67.33 MPH</u>
③	<u>66.03</u>	③ <u>65.75</u>	<u>65.89 MPH</u>

TEST DESCRIPTION MAXIMUM LEVEL SPEED TEST
 TEST NO. 6 DATE 9/11/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.629	6.365	10	6.566	6.333
2	6.613	6.364	11	6.576	6.357
3	6.609	6.369	12	6.550	6.334
4	6.589	6.351	13	6.566	6.343
5	6.585	6.353	14	6.566	6.338
6	6.603	6.366	15	6.518	6.310
7	6.578	6.347	16	6.571	6.342
8	6.592	6.353	17	6.571	6.346
9	6.590	6.360	18	6.557	6.346

Description	Before Test	After Test
Open Circuit Voltage (V)	119.47	114.33
Energy to Recharge Batteries (WH)	22,440	3,338

(2504)*

Test Engineers:

Chrysler Corporation, H.P.

R.R. VENKATAPERUMAL

Chrysler Corporation, P.G.

T.J. FOHEY & C.G. TRIANTAFYLLOS

General Electric

—

Jet Propulsion Laboratory

J. TOCZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

ETV-1 PERFORMANCE TEST REPORT

TEST DESCRIPTION MAX. SUSTAINED SPEED ON 5% GRADE TEST NO. 7 DATE 9/12/59
 TEST LOCATION PLATE CLAY, TEXAS, 12.000' GRP VEHICLE NO. 28229 NTC 1001
CHASSIS RUNNING SOUNDS

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	1032	1042
Prop. Battery Open Circuit Voltage (Volts)	120.65	114.05
Battery Gauge Reading	FULL	95% FULL
Access. Battery Specific Gravity	1.32	1.32
Tire Pressures (PSI)	LF 39 RF 29	LF RF
	LR 41 RR 41	LR RR

DATA INDICATION

	Ch. No.	Horiz. Scale	Vert. Scale
Inst. Battery Specific Gravity	—	—	—
Fifth Wheel Tire Pressure (PSI)	—	—	—
Strip Chart Calib. Velocity (MPH)	—	—	—
Distance (FT)	—	—	—

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	872	836	1708
Rear	942	926	1868
Total	1814	1760	3574

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	81°F	81°F
Humidity (Percent)	50%	50%
Wind Velocity and Direction ()	6-12 mph (150°)	6-12 mph (150°)
Precipitation ()	0	0
Bar. Press	29.0" Hg	29.0" Hg

TIME OF TEST

DRIVER M. NATHAN

START

FINISH

OBSERVER

COMMENTS

5% GRADE. $\theta = \tan^{-1}(0.05) = 2.86^\circ$

Drawbar pull = $3615 \times \sin 2.86 = 150.52 \text{ lbs.}$
Set at }

RESULTS

Maximum Sustained Speed on 5% Grade: 47 MPH

(I DESCRIPTION MAX SUSTAINED SPEED ON 5% GRADE

TEST NO. 7 DATE 9/12/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.754	6.346	10	6.688	6.318
2	6.737	6.347	11	6.697	6.341
3	6.737	6.351	12	6.669	6.319
4	6.712	6.334	13	6.692	6.327
5	6.710	6.336	14	6.687	6.322
6	6.719	6.350	15	6.647	6.294
7	6.698	6.330	16	6.701	6.325
8	6.703	6.337	17	6.702	6.330
9	6.709	6.344	18	6.679	6.331

Description	Before Test	After Test
Open Circuit Voltage (V)	120.65	114.05
Energy to Recharge Batteries (WH)	3,338	3,540

(2655)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

T. J. FOHEY & C. G. TRIANTAFYLLOS

General Electric

Jet Propulsion Laboratory

J. TDCZYLOWSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

EV-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION MAXIMUM GRADABILITY TEST TEST NO. 8 DATE 9/13/79
 TEST LOCATION QUAL TEST TRACK, CHRYSLER CORP. VEHICLE NO. L322E9 NTEVOC1
CHELSEA PROVING GROUNDS.

VEHICLE CONDITION

	<u>Before Test</u>	<u>After Test</u>
Odometer Reading (Miles)	<u>1042</u>	<u>1043</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>120.42</u>	<u>-</u>
Battery Gauge Reading	<u>FULL</u>	<u>FULL</u>
Access. Battery Specific Gravity	<u>1.31</u>	<u>-</u>
Tire Pressures (PSI)	LF <u> </u> RF <u> </u> LR <u> </u> RR <u> </u>	LF <u> </u> RF <u> </u> LR <u> </u> RR <u> </u>

INSTRUMENTATION

Instr. Battery Specific Gravity	<u>-</u>	<u>-</u>
Fifth Wheel Tire Pressure (PSI)	<u>-</u>	<u>-</u>
	<u>Ch. No.</u>	<u>Horiz. Scale</u>
Strip Chart Calib. Velocity (MPH)	<u>-</u>	<u>-</u>
Distance (FT)	<u>-</u>	<u>-</u>

TEST CONDITIONS

	<u>Left</u>	<u>Right</u>	<u>Total</u>
Vehicle's Test Weight (Lbs.)			
Front	<u>885</u>	<u>853</u>	<u>1738</u>
Rear	<u>950</u>	<u>935</u>	<u>1885</u>
Total	<u>1835</u>	<u>1788</u>	<u>3623</u>

WEATHER CONDITIONS

	<u>Before Test</u>	<u>After Test</u>
Temperature (F.)	<u>71°F</u>	<u>71°F</u>
Humidity (Percent)	<u>80%</u>	<u>80%</u>
Wind Velocity and Direction ()	<u>5MPH (180°)</u>	<u>5MPH (180°)</u>
Precipitation ()	<u>0</u>	<u>0</u>
Bar. Press		
	<u>29.94</u>	<u>29.94</u>

TIME OF TEST

DRIVER M. NATSON START FINISH

COMMENTS

THIS TEST WAS REPEATED 2 TIMES.

CAR LOST POWER AT THE END OF 2ND RUN. COULD NOT
START THE CAR AGAIN. TOWED TO DISPLAY ROOM AND
SENT BACK TO H.P. FOR REPAIR.

RESULTS

Maximum Drawbar Pull measured: 650 lbf

PERCENT GRADE = $\frac{100 \text{ TAD} (500 - 1.650)}{3615} = 18.3\%$

1ST DESCRIPTION MAXIMUM GRADABILITY TEST

TEST NO.

8

DATE _____

9/13/79

<u>Battery No.</u>	<u>Battery Voltage (V)</u>	<u>Battery Voltage (V)</u>	<u>Battery No.</u>	<u>Battery Voltage (V)</u>	<u>Battery Voltage (V)</u>
	Before Test	After Test		Before Test	After Test
1	6.792		10	6.695	
2	6.772		11	6.712	
3	6.767		12	6.686	
4	6.743		13	6.707	
5	6.737		14	6.703	
6	6.747		15	6.658	
7	6.720		16	6.714	
8	6.726		17	6.715	
9	6.726		18	6.688	

Description	Before Test	After Test
Open Circuit Voltage (V)	120.92	
Energy to Recharge Batteries (WH)	3,540	CHARGED AT H.F. ON 5/20/79 NIGHT " " A.G. 5/21/79 " (4,776 WH FROM P.G. CHARGING) (3582)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKAT APEDUMAL

Chrysler Corporation, P.G.

T. J. FONEY & C. G. TRIANTAFYLLOS

General Electric

Jet Propulsion Laboratory

J. TOCZYŃSKI

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

HY-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION J227a Schedule D. Test TEST NO. 9 DATE 9/22/79
 TEST LOCATION OVAL TEST TRACK, CHRYSLER CORP. VEHICLE NO. LS22E9NTEV001
CHELSEA PROVING GROUNDS.

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>1050</u>	<u>1101</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>121.21</u>	<u>109.11</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Access. Battery Specific Gravity	<u>1.27</u>	<u>1.240 - 1.270</u>
Tire Pressures (PSI)	<u>LF 29 RF 29</u>	<u>LF RF</u>
	<u>LR 41 RR 41</u>	<u>LR RR</u>

INSTRUMENTATION

	But ①	②	①	②
Inst. Battery Specific Gravity	<u>1.27</u>	<u>1.27</u>	<u>1.235</u>	<u>1.240</u>
Fifth Wheel Tire Pressure (PSI)	<u>25 PSI</u>	<u>25 PSI</u>		
	Obs. No.	Horiz. Scale	Vert. Scale	
Strip Chart Calib. Velocity (MPH)	<u>1</u>	<u>1 mm/sec</u>	<u>200 mv/div</u>	
Distance (FT)	<u>NU</u>	<u>—</u>	<u>—</u>	

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>904</u>	<u>869</u>	<u>1753</u>
Rear	<u>975</u>	<u>955</u>	<u>1930</u>
Total	<u>1879</u>	<u>1804</u>	<u>3683</u>

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>50°F</u>	<u>57°F</u>
Humidity (Percent)	<u>74%</u>	<u>56%</u>
Wind Velocity and Direction ()	<u>10-14 MPH (360°)</u>	<u>12-16 MPH (360°)</u>
Precipitation ()	<u>0</u>	<u>0</u>
Bar. Press	<u>29.5" Hg</u>	<u>29.5"</u>

TIME OF TEST

DRIVER M. COPPERNOLL START 9:40 AM FINISH 12:05 AM
 OBSERVER —

COMMENTS CAR LOST POWER AFTER THE 4TH CYCLE. RESTARTED
& FINISHED THE TEST.

RESULTS RANGE: 50.03 MILES. TOTAL CYCLES: 49

TEST DESCRIPTION J 227a Schedule D Test

TEST NO. 9

DATE 9/22/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.765	6.073	10	6.714	6.047
2	6.753	6.081	11	6.737	6.076
3	6.755	6.081	12	6.714	6.044
4	6.735	6.059	13	6.731	6.052
5	6.734	6.066	14	6.726	6.056
6	6.745	6.050	15	6.692	6.018
7	6.726	6.059	16	6.735	6.054
8	6.733	6.067	17	6.736	6.062
9	6.739	6.071	18	x	x

Description	Before Test	After Test
Open Circuit Voltage (V)	121.21	109.11
Energy to Recharge Batteries (WH)	CHARGED AT H.P. ON 9/20/79 NIGHT CHARGED AT P.G. ON 9/21/79 NIGHT (4,776 WH FROM P.G. CHARGING)	28,956 (21,717)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

T. J. FOLEY.

General Electric

Jet Propulsion Laboratory

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

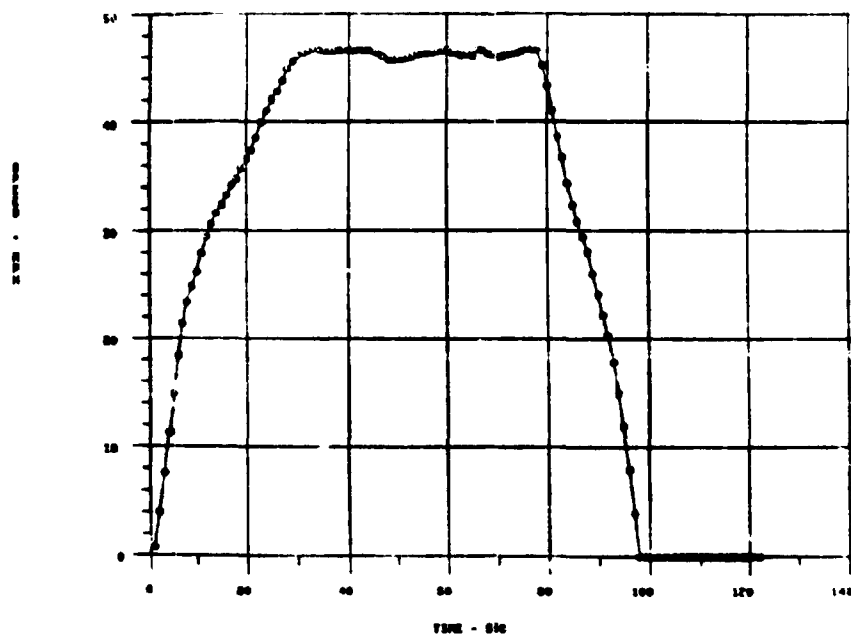
TEST DESCRIPTION J 227.3 Schedule 'D' Test

TEST NO. 9

DATE 9/22/79

RESULTS:

J227.3 SCHEDULE D DRIVING CYCLE ME - 1

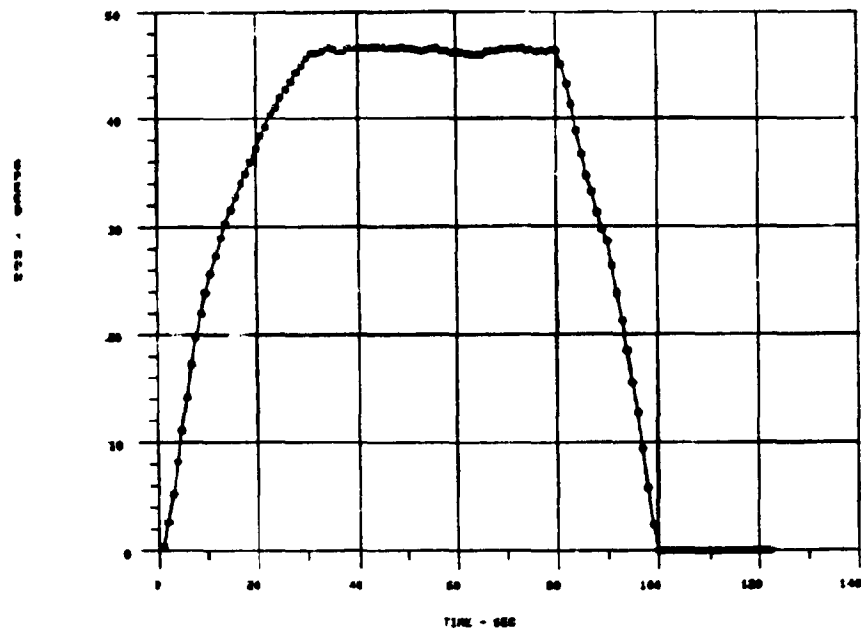


TEST DESCRIPTION J 227.3 Schedule 'D' Test

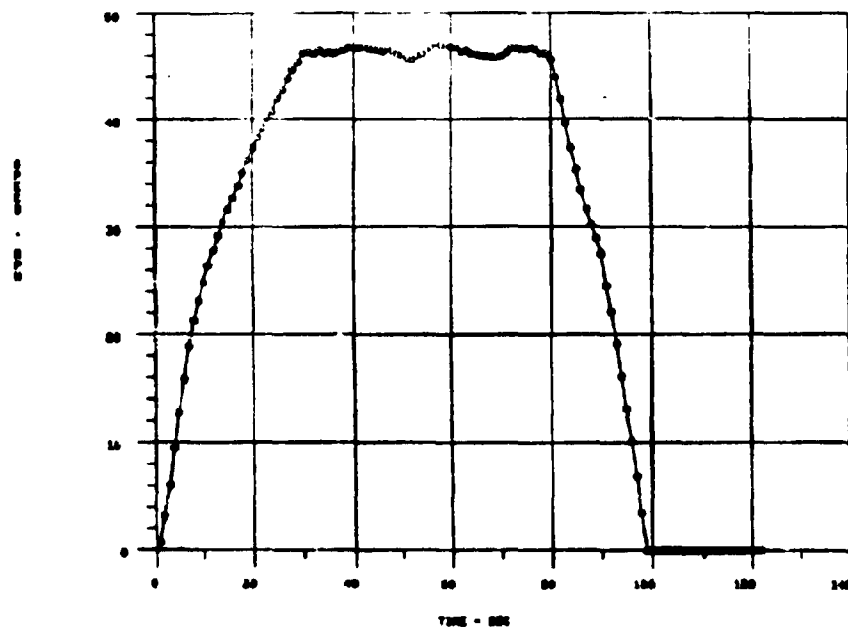
TEST NO. 9 DATE 9/22/79

RESULTS:

J227.3 SCHEDULE D DRIVING CYCLE NO 11



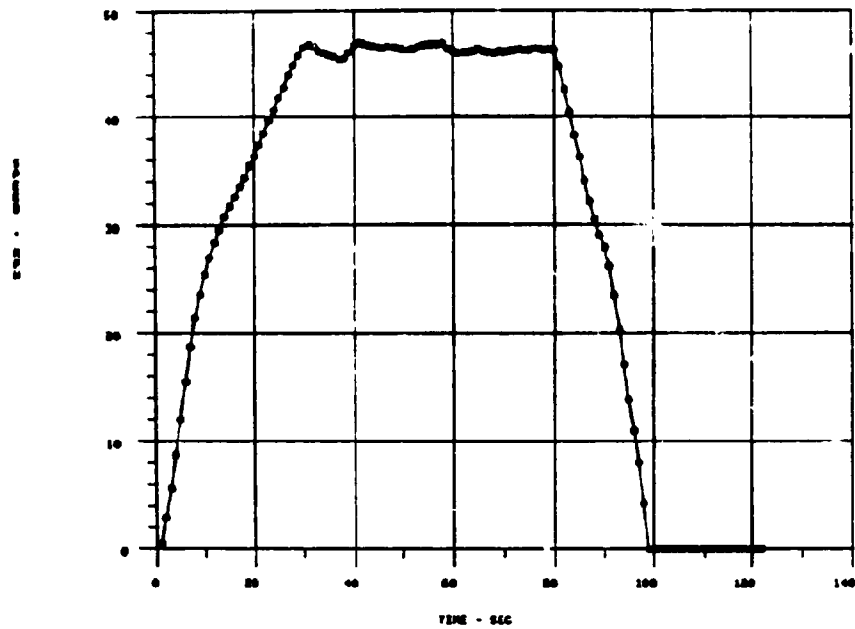
J227.3 SCHEDULE D DRIVING CYCLE NO - 81



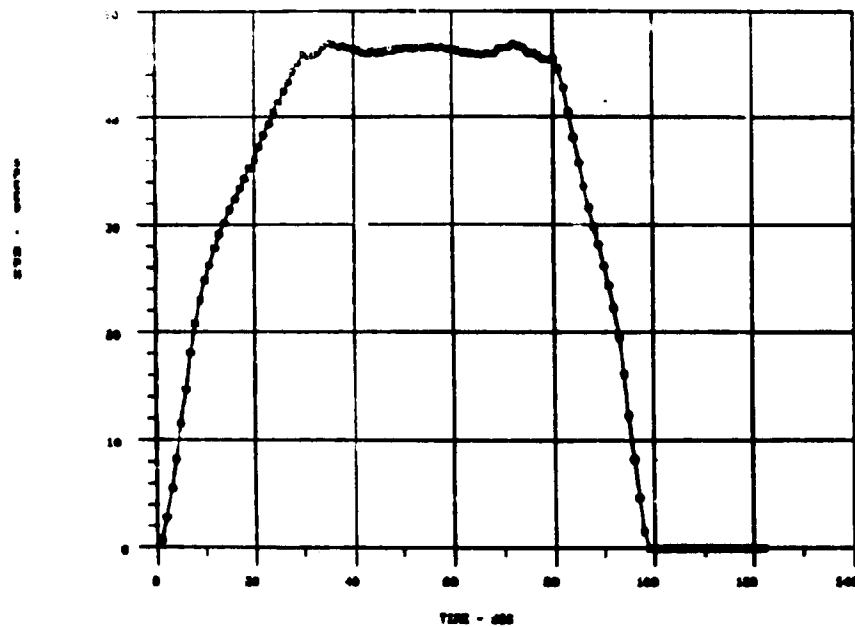
TEST DESCRIPTION J2272 Schedule 'N' Test
TEST NO. 9 DATE 9/22/79

RESULTS:

J227A SCHEDULE B DRIVING CYCLE NO - 31



J227A SCHEDULE B DRIVING CYCLE NO - 40



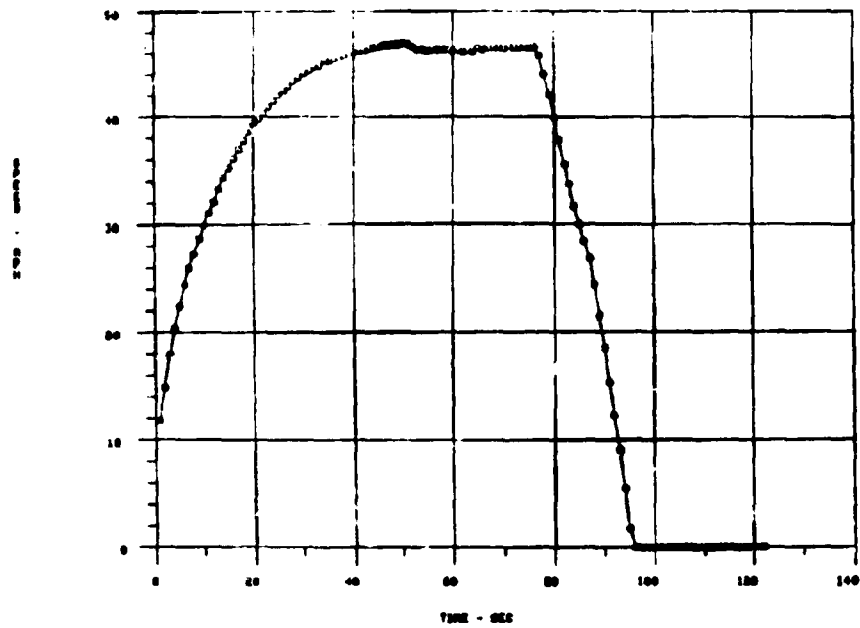
TEST DESCRIPTION J 2272 Schedule 'D' Test

TEST NO. 9

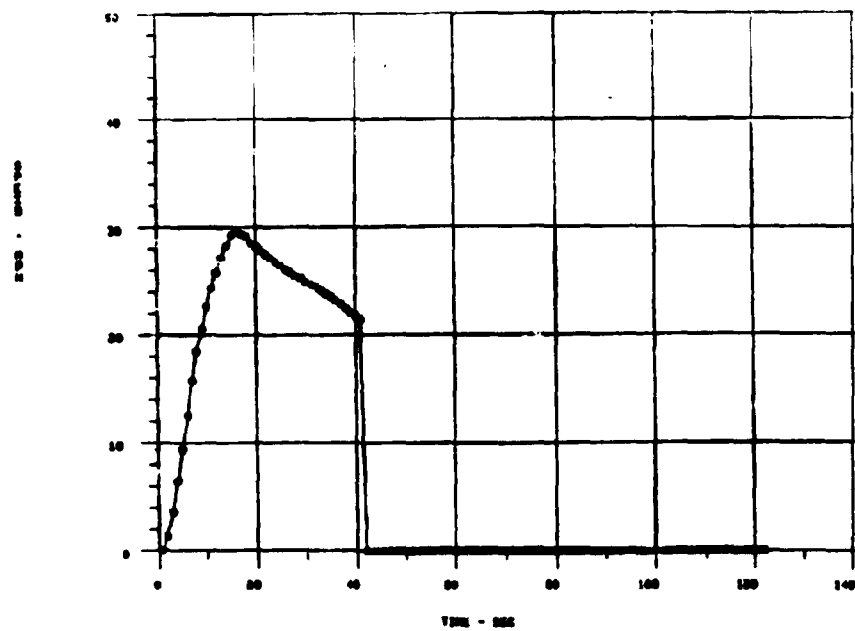
DATE 9/22/79

RESULTS:

J227A SCHEDULE B DRIVING CYCLE NO - 40



J227A SCHEDULE B DRIVING CYCLE NO - 50



EV-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION RANGE AT CONSTANT SPEED 45MPH TEST NO. 10 DATE 4/29/79

TEST LOCATION QUAL TEST TRACK, CHRYSLER CORP. VEHICLE NO. LS22E9NTEV001
CHELSEA PROVING GROUNDS.

VEHICLE CONDITION

	<u>Before Test</u>	<u>After Test</u>
Odometer Reading (Miles)	<u>1150</u>	<u>1272</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>121.24</u>	<u>108.49</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Avg. Battery Specific Gravity	<u>1.28</u>	<u>1.30</u>
Tire Pressure (PSI)	<u>LF 29 RF 29</u> <u>LR 41 RR 41</u>	<u>LF 31 RF 31</u> <u>LR 44 RR 44</u>

DISCHARGE DATA

	<u>①</u>	<u>②</u>	<u>①</u>	<u>②</u>
Inst. Battery Specific Gravity	<u>1.26</u>	<u>1.26</u>	<u>1.24</u>	<u>1.24</u>
Fifth Wheel Tire Pressure (PSI)	<u>23 PSI</u>		<u>23 PSI</u>	

	<u>Ch. No.</u>	<u>Horiz. Scale</u>	<u>Vert. Scale</u>
Strip Chart Calib. Velocity (MPH)	<u>-</u>	<u>-</u>	<u>-</u>
Distance (FT)	<u>-</u>	<u>-</u>	<u>-</u>

TEST CONDITIONS

	<u>Left</u>	<u>Right</u>	<u>Total</u>
Vehicle Test Weight (Lbs.)			
Front	<u>873</u>	<u>847</u>	<u>1720</u>
Rear	<u>946</u>	<u>913</u>	<u>1859</u>
Total	<u>1819</u>	<u>1760</u>	<u>3579</u>

WEATHER CONDITIONS

	<u>Before Test</u>	<u>After Test</u>
Temperature (F.)	<u>62°F</u>	<u>77°F</u>
Humidity (Percent)	<u>76%</u>	<u>40%</u>
Wind Velocity and Direction ()	<u>4-6 MPH</u>	<u>5 MPH</u>
Precipitation ()	<u>0</u>	<u>0</u>

TIME OF TEST

START 10:15 AM FINISH 12:15 PM
 DRIVER T. BAILEY OBSERVER _____

COMMENTS

TEST WAS TERMINATED WHEN THE DRIVER COULD NOT
MAINTAIN THE TEST SPEED OF 42.5 MPH.

RESULTS

RANGE: 91.87 MILES

TEST DESCRIPTION RANGE AT CONSTANT SPEED 45 MPH
 TEST NO. 10 DATE 9/29/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1		6.034	10		6.020
2		6.026	11		6.019
3		6.036	12		6.005
4		6.020	13		6.013
5		6.026	14		6.018
6		6.043	15		5.979
7		6.020	16		6.019
8		6.030	17		6.025
9		6.032	18		6.018

Description	Before Test	After Test
Open Circuit Voltage (V)	121.24	108.49
Energy to Recharge Batteries (Wh)	28,956	33,798

(25,349)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

C. G. TRIANTAFYLLOS

General Electric

R. J. TWARDZIK

Jet Propulsion Laboratory

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

EV-1 PERFORMANCE TEST CHECKLIST

TEST DESCRIPTION J2272 Scheduled Test TEST NO. 11 DATE 9/30/79
 TEST LOCATION OVAL TEST TRACK, CHRYSLER CORP VEHICLE NO. LS22E9NTEV001
CHELSEA PROVING GROUNDS

VEHICLE CONDITION

	Before Test	After Test
Odometer Reading (Miles)	<u>1272</u>	<u>1347</u>
Prop. Battery Open Circuit Voltage (Volts)	<u>119.61</u>	<u>107.99</u>
Battery Gauge Reading	<u>FULL</u>	<u>0</u>
Access. Battery Specific Gravity	<u>1.290</u>	<u>1.120</u>
Tire Pressures (PSI)	LF <u>29</u> RR <u>29</u>	LF <u>27</u> RR <u>27</u>
	LR <u>41</u> RR <u>41</u>	LR <u>41</u> RR <u>41</u>

DISCHARGE PROCEDURE

	①	②	①	②
Inst. Battery Specific Gravity	<u>1.27</u>	<u>1.27</u>	<u>1.24</u>	<u>1.24</u>
Fifth Wheel Tire Pressure (PSI)	<u>23 PSI</u>		<u>23 PSI</u>	
Strip Chart Calib. Velocity (MPH)	<u>—</u>	<u>—</u>	<u>—</u>	<u>—</u>
Distance (FT)	<u>—</u>	<u>—</u>	<u>—</u>	<u>—</u>

TEST CONDITIONS

	Left	Right	Total
Vehicle Test Weight (Lbs.)			
Front	<u>879</u>	<u>850</u>	<u>1729</u>
Rear	<u>948</u>	<u>942</u>	<u>1890</u>
Total	<u>1827</u>	<u>1792</u>	<u>3619</u>

WEATHER CONDITIONS

	Before Test	After Test
Temperature (F.)	<u>65°F</u>	<u>73°F</u>
Humidity (Percent)	<u>73%</u>	<u>57%</u>
Wind Velocity and Direction ()	<u>8-10MPH (270° W)</u>	<u>5-9MPH (270° W)</u>
Precipitation ()	<u>0</u>	<u>0</u>
Bar. Press	<u>28.93 ↑</u>	<u>28.93 →</u>

TIME OF TEST

DRIVER T. BAILEY START 10:10 AM FINISH 12:53 PM

COMMENTS

RANGE: 74.16 MILES TOTAL NO. OF CYCLES: 74

TEST DESCRIPTION J227a Schedule D Test
 TEST NO. 11 DATE 9/30/79

Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test	Battery No.	Battery Voltage (V) Before Test	Battery Voltage (V) After Test
1	6.736	6.005	10	6.626	5.984
2	6.716	6.015	11	6.623	6.001
3	6.685	6.016	12	6.597	5.983
4	6.682	5.994	13	6.605	5.993
5	6.659	6.004	14	6.619	5.945
6	6.681	6.019	15	6.563	5.956
7	6.634	5.997	16	6.629	5.995
8	6.661	6.005	17	6.629	6.003
9	6.642	6.009	18	6.599	5.998

Description	Before Test	After Test
Open Circuit Voltage (V)	119.61	107.99
Energy to Recharge Batteries (WH)	33,798	42,526

(31,895)*

Test Engineers:

Chrysler Corporation, H.P.

R. R. VENKATAPERUMAL

Chrysler Corporation, P.G.

C. G. TRIANTAFYLLOS

General Electric

R. J. TWARDZIK

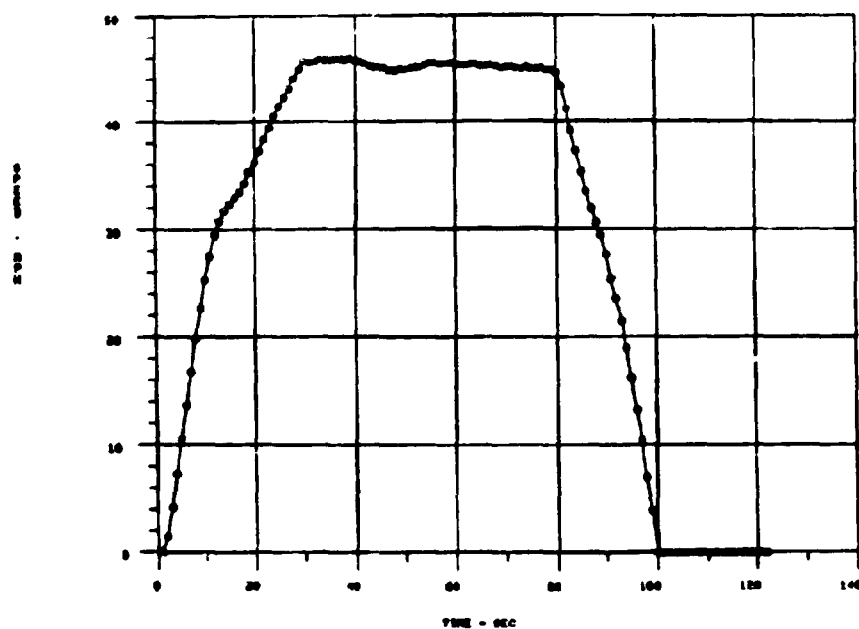
Jet Propulsion Laboratory

*The watt-hours to recharge the battery pack after each test are as measured by the Ohio Semitronics, Inc. watt-meter X 0.75 (the Sorenson Power Supply efficiency at rated current).

TEST DESCRIPTION J 2273 Schedule 'D' TEST
TEST NO. 11 DATE 7/31/79

RESULTS:

J2273 SCHEDULE D DRIVING CYCLE NO. 1



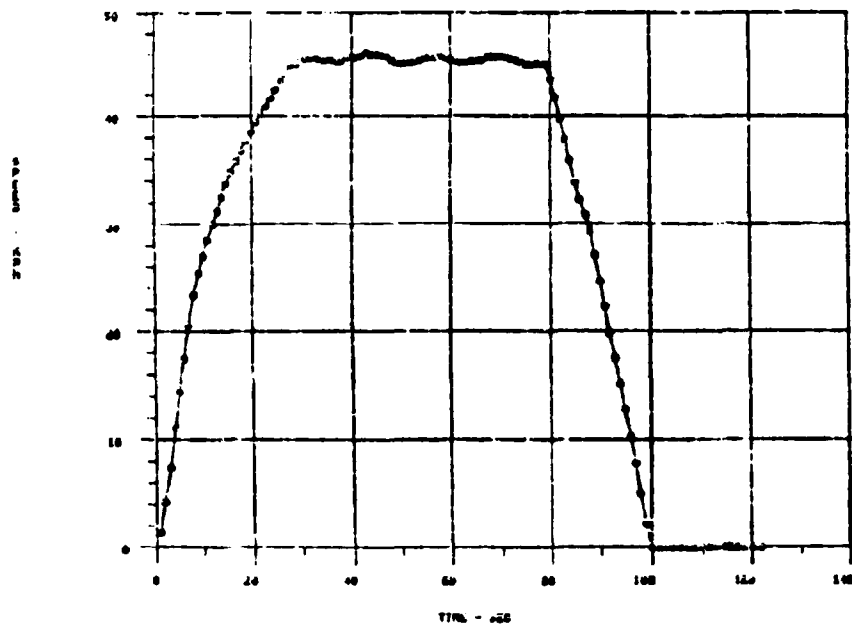
TEST DESCRIPTION J 227a Schedule 'D' Test

TEST NO. 11

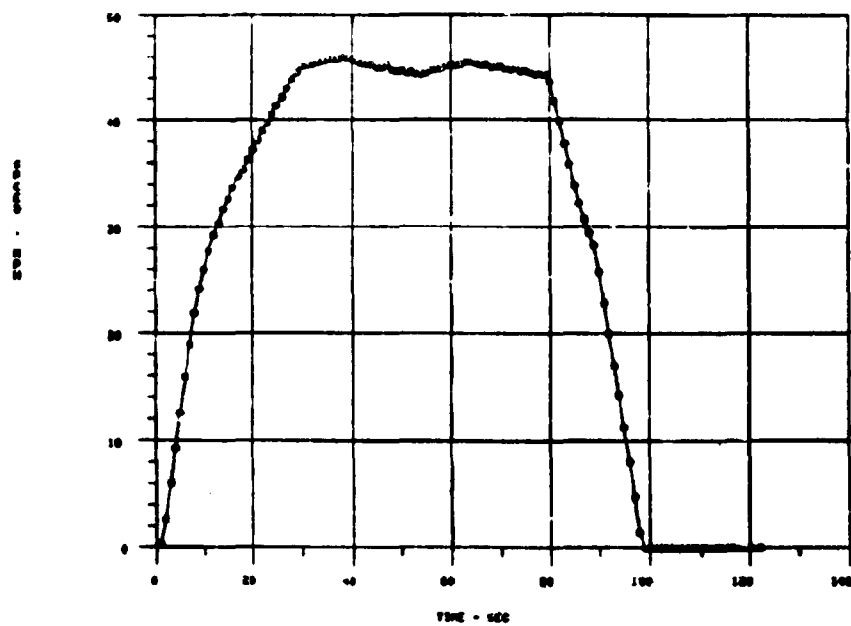
DATE 9/20/79

RESULTS:

J227a SCHEDULE D DRIVING CYCLE NO. 11



J227a SCHEDULE D DRIVING CYCLE NO. 21

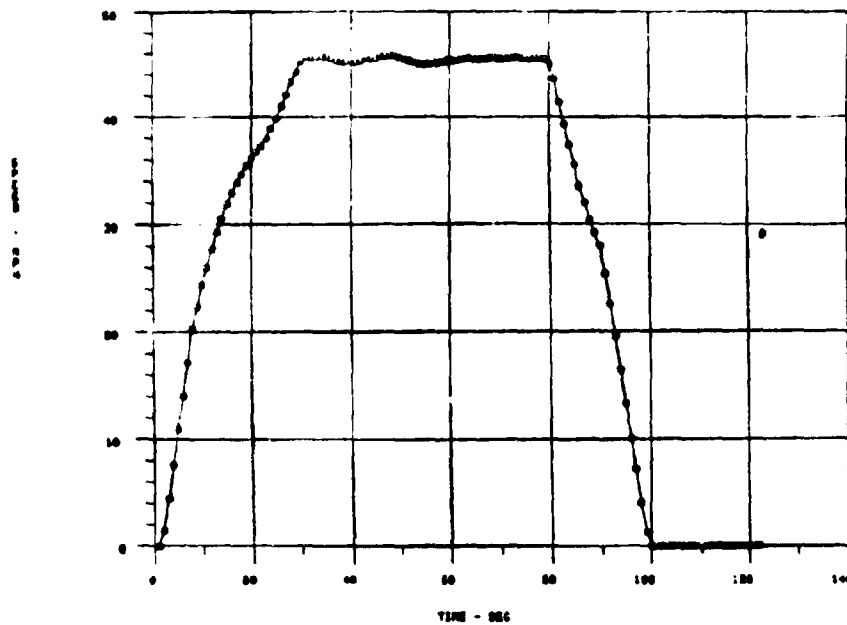


TEST DESCRIPTION J 227a Schedule D Test

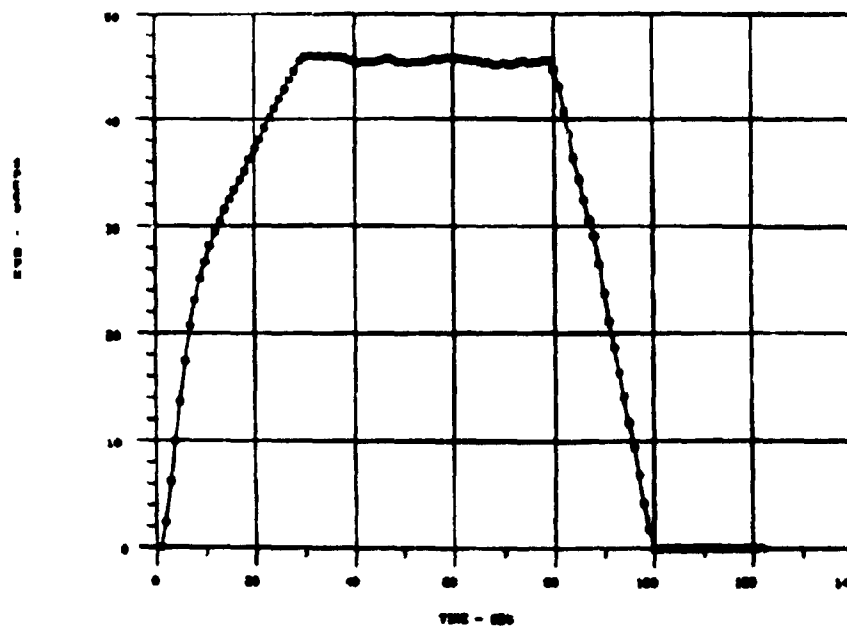
TEST NO. 11 DATE 01/30/79

RESULTS:

J227a SCHEDULE C DRIVING CYCLE NO. 31



J227a SCHEDULE D DRIVING CYCLE NO. 40

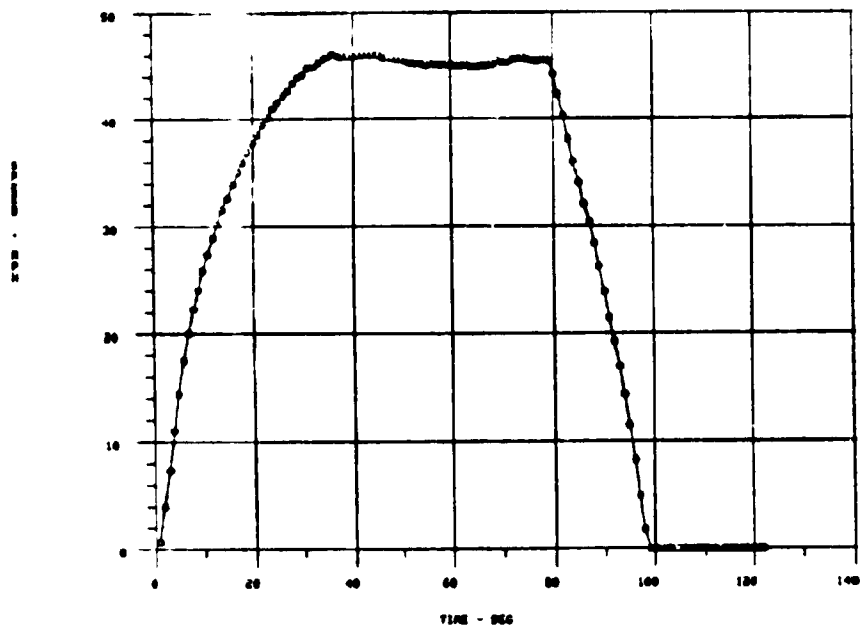


TEST DESCRIPTION J2272 Schedule 'D' Test

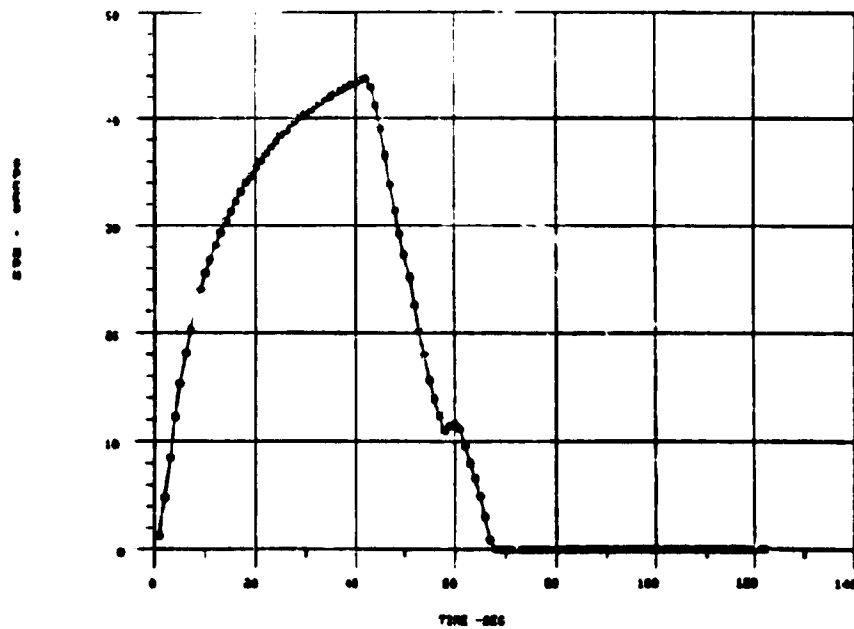
TEST NO. 11 DATE 9/30/79

RESULTS:

J2272 SCHEDULE D DRIVING CYCLE NO. 74



J2272 SCHEDULE D DRIVING CYCLE NO. 75



Summary of ETV-1 Performance Test Results

Table 4.6-2 summarizes the ETV-1 Performance Test Results.

Table 4.6-2
ETV-1 PERFORMANCE TEST RESULTS

No.	Date	Test Description	Predicted Performance (Range 1, 45 mph)	Actual Performance (Range 1, 45 mph)	Remarks
1	8-11-79	Range: Constant Speed 45 mph	8.7 mi* 16.3 mi*	10.72 mi range 13.43 mi range 7.4 mi range 16.37 mi range	Propulsion batteries were not fully charged.
		Watt-hours to recharge - 92,300 (0.14 kWh/mi)			
2	8-11-79	Range: Constant Speed 45 mph	8.7 mi* 16.3 mi*	8.72 mi range 9.04 mi range 6.17 mi range 5.29 mi range	Vehicle lost 16 miles while driving towards the south and 8 miles towards the north.
3	8-11-79	Range: Constant Speed 45 mph	10.17 mi	8.30 mi	Motor speed 1000 rpm immediately during the test.
		Watt-hours to recharge - 74,900 (0.14 kWh/mi)			
4	8-11-79	Range: Constant Speed 45 mph	13.57 mi	11.24 mi	Power was lost once this test began. The reason for this was P.C.U.
		Watt-hours to recharge - 16,800 (0.14 kWh/mi)			
5	8-11-79	Maximum Level Speed	Direction: West East 61.48 70.04 67.73 66.81 66.03 63.75	Average Speed 70.75 mph 67.43 mph 65.89 mph	Braking indicator lamp light was noted even when the car was not moving.
6	8-12-79	Maximum Sustained Speed on 5% Grade	56.2 mph*	47 mph	
7	8-13-79	Maximum Grade	18.75 %	18.1%	Two runs were taken. could not start the car at the end of second run. Shipped the car to Highland Park for repair.
8	8-12-79	J227a Schedule B Driving Cycle	74.8 mi	50.03 mi	Car lost power after the fourth cycle. Restarted and finished the test.
		Watt-hours to recharge - 21,717 (0.43 kWh/mi)			
9	8-29-79	Range: Constant Speed 45 mph	101.7 mi	91.87 mi	
		Watt-hours to recharge - 25,349 (0.28 kWh/mi)			
10	8-30-79	J227a Schedule B Driving Cycle	74.6 mi	74.18 mi	
		Watt-hours to recharge - 31,895 (0.43 kWh/mi)			

*Predicted performance with a fully charged battery

Reproduced from
best available copy

Battery Gauge Calibration/Range Test

A constant 45 mph range test was performed on June 14, 1979. The objectives of this test were twofold:

1. To provide a preliminary indication of range performance at a constant 45 mph
2. To provide a preliminary calibration of the vehicle battery gauge

The test was performed on the Vehicle Dynamics Handling Facility oval. The driving conditions were less than ideal at the vehicle speed chosen resulting in large variations in armature current on turns. The measured vehicle range achieved was ≈ 93 miles at which time the test was terminated because of a drive system failure. The battery gauge calibration was performed using data provided by the driver who noted the time of a visual observation of the battery gauge pointer. Figure 4.6-3 is the resultant battery gauge performance.

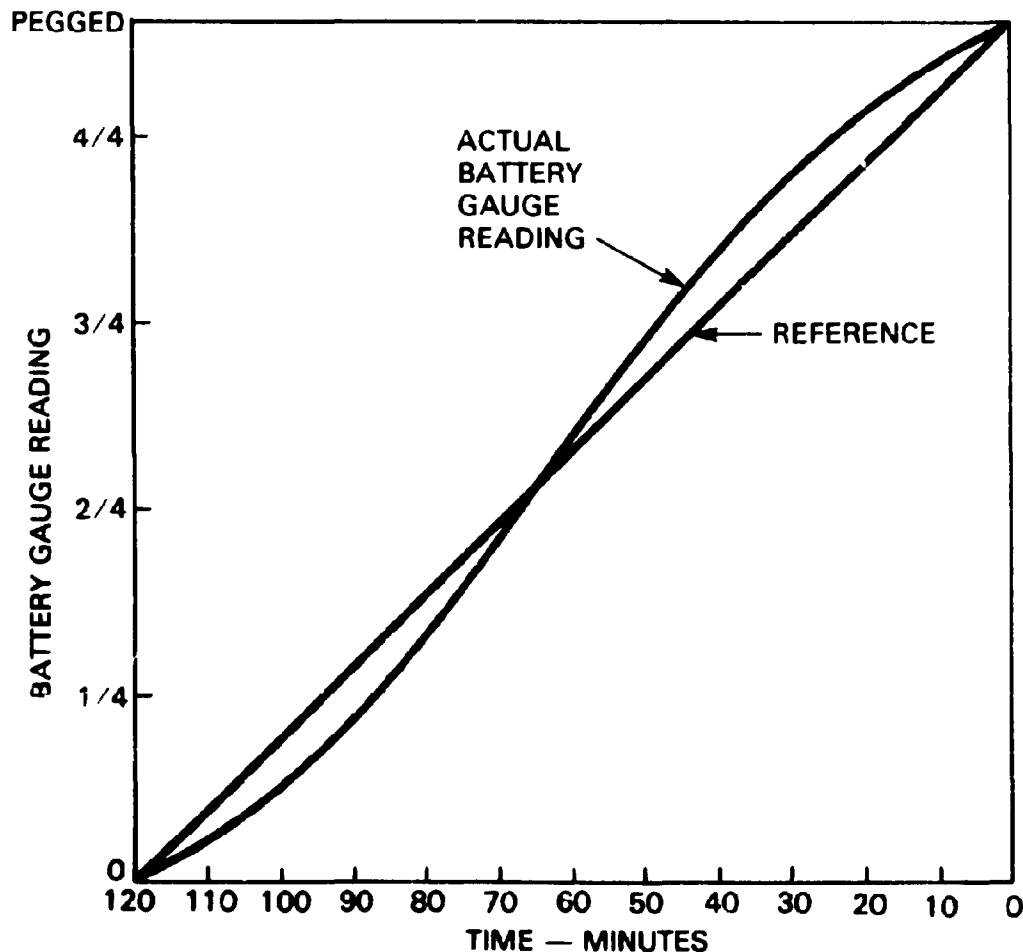


Figure 4.6-3. ETV-1 Battery Gauge Performance Based on the Time During the Constant 45 mph Range Test on June 14, 1979

Test Results Discussion

(Reference Summary of Performance Test Results Section 8.0)

Test 1 - Acceleration

0 to 30 mph

The actual measured performance of 10.22/s does not meet the DOE goal of nine seconds because:

1. The propulsion batteries were not fully charged (the fuel gauge indicated a 50% state of charge; the open circuit voltage indicated 30% state of charge).
2. The armature current limit in the power conditioning unit (PCU) was not set to 400 A.

25 to 55 mph

The actual measured performance of 25.38 did not meet the DOE goal of 18 s or less because:

1. The propulsion batteries were not fully charged (the fuel gauge indicated a 50% state of charge; the open circuit voltage indicated ~30% state of charge).
2. The armature current software limit was not set to 400 A.
3. The minimum field current limit was set at 2.0 A, which has the effect of limiting armature current to a value less than 400 A and thus reduces the maximum torque available from the drive motor.

Test 2 - Constant 45 mph

Test was terminated at a range of 90.3 miles due to a failure. A failure in the electrical drive subsystem occurred due to an apparent intermittent interlock switch in the rear battery compartment access door. This may have caused a transient which caused a transistor failure in the logic power supply.

Test 3 - Acceleration

0 to 30 mph

The actual measured performance of 8.77 s met the DOE goal of 9 s.

25 to 55 mph

The actual measured performance of 20.17 s did not meet the DOE goal of 18 s or less because:

1. The minimum field current was set at 2.0 A. Resetting the minimum field current to 1.5 A (completed on Car #2) will improve the acceleration performance.

Test 4 - Constant 45 mph

The measured result of this range test (83 miles) does not compare favorably to the results of Test 2 (a similar test) which was terminated because of a failure in the drive system. An explanation of the longer range achieved in this test is not available except to speculate that the batteries may not have been fully charged even though the measured open circuit pack voltage indicates a full charge (open circuit voltage is not a fool-proof measure of state-of-charge). Note that the predicted range performance was 101.7 miles.

Test 5 - Constant 35 mph

The results of the 35 mph constant speed test agree very closely with the predicted range performance.

Test 6 - Maximum Level Speed

The measured maximum average speeds of 65.89 to 70.75 mph exceed the DOE goal of 60 mph. Note that the maximum average speed decreased as the battery pack discharged.

Test 7 - Maximum Sustained Speed on 5% Grade

The actual measured performance of the vehicle did not meet the DOE goal of 50 mph on a 5% grade. As with the 25 to 55 mph acceleration tests, the performance on this test should be improved by decreasing the minimum field current limit from 2.0 to 1.5 A.

Test 8 - Maximum Gradability Test

The actual measured maximum gradability of 19.3% agrees closely with the predicted maximum gradability of 18.75%.

Test 9 - J227A Schedule D

The J227a Schedule D test was terminated during the 0 to 45 mph acceleration segment of the cycle (see J227A Schedule D Driving Cycle No. 50). An analysis of the fifth cycle plot of velocity versus time indicates that the acceleration rate had decreased from the prior cycle indicating a drop in vehicle acceleration performance. Apparently the vehicle was not able to increase its velocity beyond 30 mph and caused a resulting loss of power. The resultant measured range of 50.03 miles was significantly lower than the predicted 74.6. The reason for the low range is not obvious since the open circuit pack voltage of 121.21 V indicated that the pack was fully charged. However, note that only 21,717 Wh of energy was required to equalize the pack (as compared to 31,895 Wh required after Test 11). This lower recharge energy tends to indicate that the battery pack may not have been fully discharged at end of range, thus implying possible drive system problems. Note that the vehicle lost power after the fourth cycle but was able to continue after restart. A comparison of calculated recharge energy per mile of 0.43 kWh in this test versus a recharge energy per mile of 0.43 kWh in Test 11 tends to substantiate the assumption that the pack was probably not fully discharged when the test was terminated.

Test 10 - Constant 45 mph

The resultant measured performance of 91.87 miles at a constant 45 mph is $\approx$ 10% lower than the predicted range of 101.7 miles. The reason for the lower measured performance is not obvious.

Test 11 - J227A Schedule D

The actual measured performance of 74.16 miles on the J227a Schedule D cycle agrees very closely with the predicted range of 74.6 miles and, in essence, meets the DOE goal of 75 miles.

Section 5

MANUFACTURING STUDY

WBS 5.0 MANUFACTURING STUDY

A Consumer Cost Analysis was performed to determine and provide to DOE an estimate of the 1975 selling price for a production electric vehicle similar to the ETV-1. The cost analysis resulted in a differential cost estimate between a base vehicle comparable to the gasoline-powered Horizon TC-3 and the production electric vehicle. The study reflects the effect of incremental variable and investment costs associated with electric versus internal combustion propulsion systems.

The consumer cost analysis identified incremental costs broken down into the following two categories:

1. Items directly related to the electrical drive system.
2. Items specifically intended for reduction of aerodynamic drag and rolling resistance.

The final consumer cost data is given in 1975 dollars and is based on an annual production rate of 300,000 units per year. This production rate was used in order to provide a fair cost comparison between the electric vehicle and a conventional car since the conventional car is produced in this quantity. An annual volume of 100,000 units per year had originally been specified by DOE, but it was discovered that this volume is too low for efficient production in today's domestic automobile industry.

Table 5-1 delineates the incremental consumer cost (retail) for the electric vehicle and the consumer cost for the base vehicle - comparable to the gasoline powered Horizon TC-3 in 1980 dollars.

TABLE 5-1
1975 ELECTRIC VEHICLE COSTS

1980	Dollars
Incremental Consumer Cost (Retail) for pre Electric Vehicle	\$3220
Consumer Cost for Base Vehicle - Comparable to Gasoline-Powered Horizon TC-3	5300
TOTAL 1980 Consumer Cost	<u>8520</u>
1975	
Adjusted* 1975 Consumer Cost	<u>6430</u>

*Adjustment for 1975 dollars is based on the Consumer Price Index for new cars (January 1980 versus average for 1975).

The final consumer cost of \$8520 is adjusted from 1980 dollars to the selling price in 1975 dollars. This results in a 1975 dollars consumer cost of \$6430.

Table 5-2 summarizes the Incremental Consumer Costs and the Incremental Investment for each of the categories.

TABLE 5-2
CONSUMER COST AND INVESTMENT SUMMARY BY CATEGORY

	<u>Incremental Consumer Cost</u> (Dollars)	<u>Incremental Investment</u> (Dollars in Thousands)
1. Electric Propulsion & Associated Body and Chassis Revisions versus Conventional Gasoline Powered L-24 Type Vehicle	+2,872.00	+33,575.00
2. Items specifically intended for Reduction of Aerodynamic Drag and Rolling Resistance	+348.00	+425.00
	<u>+3,220.00</u>	<u>+34,000.00</u>
Assembly Plant Tooling		+5,500.00
Preproduction & Launch Expense		+8,800.00
Engineering Expense		<u>+28,000.00</u>
TOTAL Investment		<u>+76,300.00</u>

In performing the analysis prices of major items, such as the electrical drive system which includes the electronics, electric drive motor, and propulsion batteries, were obtained from sources within General Electric supplying functionally similar electronic equipment adjusted for the 300,000-unit production rate and from the Globe-Union for the propulsion batteries.* In some cases, e.g., the electric motor, the prices were compared for validity to estimates provided by other sources.⁽¹⁾ In certain other cases, such as the accelerator potentiometer, drive mode selector switch, quick disconnect system, certain brake system components, and the gasoline heater system, prices were only available based on low-volume prototype components. In these cases a lowered price was projected based on high annual volumes and additional investment cost.

Table 5-3 provides a more detailed breakdown in the area of chassis and electrical.

*Based on a price of lead of \$0.50/lb

1. Characterization Study of an Electric Motor - Transmission System for Electric Vehicles - prepared for DOE by Mechanical Technology, Inc., Report COO/2835-2-Sep 1977.

**TABLE 5-3
COST BY CATEGORY**

	<u>Incremental Consumer Cost</u> (Dollars)	<u>Incremental Investment</u> (Dollars in Thousands)	<u>Notes</u>
1. <u>Electric Propulsion & Associated Revisions</u>			
<u>Underbody Assembly</u> (Battery tunnel assembly, impact barrier, liftgate opening - lower construction)	+134.50	+4,675.00	
<u>Instrument Panel</u>	+112.50	+2,575.00	
<u>Interior Trim</u>	+19.00	+400.00	
<u>Chassis & Electrical</u>			
Electric Motor	-422.00	-4,300.00	Replaces engine and related components
Propulsion Batteries	+1,470.00	+6,600.00	Includes battery carrier
Electronics	+1,245.00	In price	
Hydrogen Vent System	+20.00	+250.00	
Accelerator Pedal	+27.00	+650.00	
Rear Suspension	+16.00	+500.00	
Transmission	-128.50	+14,800.00	Replaces 4-speed manual transmission
Brakes	+87.50	+6,000.00	
Heater/Defroster	+193.00	+1,600.00	
Electrical Wiring	+80.00	-225.00	
Miscellaneous	+18.00	+50.00	
TOTAL	+2,872.00	+33,575.00	
2. <u>Aerodynamics & Rolling Resistance</u>			
(Aerodynamic shield, windshield, liftgate assembly, door glass, quarter window, front and rear fascia, concealed headlamps, tires)	+348.00	+425.00	