MODULAR ELECTRIC VEHICLE PROGRAM -- (MEVP)

FINAL TECHNICAL REPORT

MARCH 1994

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DEPARTMENT OF ENERGY CONTRACT

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DE-AC07-90ID13019

PREPARED FOR: U.S. DEPARTMENT OF ENERGY
IDAHO OPERATIONS OFFICE

BY: FORD MOTOR COMPANY
TECHNICAL AFFAIRS STAFF
(PRIME CONTRACTOR)

&

GENERAL ELECTRIC COMPANY
DRIVE SYSTEMS
(MAJOR SUBCONTRACTOR)

&

SUNDSTRAND POWER SYSTEMS

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FINAL TECHNICAL REPORT
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ABBREVIATIONS AND ACRONYMS

A	ampere
ABB	Asea Brown-Boveri
ac	alternating current
A/C	air conditioning
ATF	automatic transmission fluid
BJT	bipolar/Darlington transistor
CCW	counter clockwise
CV	constant velocity (joints)
CW	clockwise
DABC	dual action bridge converter
dc	direct current
DDLM	Diagnostic/Data Logger Module
DOE	Department of Energy
DOT	Department of Transportation
EMI	electromagnetic interference
ETWC	Emissions Test Weight Class
ETX-I	Advanced Electric Vehicle Powertrain Program
ETX-II	Single-Shaft Electric Propulsion System Technology Development Program
EV	electric vehicle
EVDL	Electric Vehicle Development Laboratory
FET	field effect transistor
FMEA	failure mode and effect analysis
FMVSS	Federal Motor Vehicle Safety Standards
FORD	Ford Motor Company
FUDS	Federal Urban Drive Schedule
GE	General Electric Company
GEDS	GE-Drive Systems
GVW	gross vehicle weight

Hp	horsepower
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
I/O	input/output
IMC	inverter/motor controller
IPM	interior permanent magnet (motor)
MCT	MOS-controlled thyristors
MEVP	Modular Electric Vehicle Program
NHTSA	National Highway Traffic Safety Administration
NVH	noise, vibration, harshness
o.d.	outer diameter
PEC	Power Electronics Center
PI	proportional integral
ppm	parts per million
PRND	Park, Reverse, Neutral, Drive
PTC	positive temperature coefficient
PWM	pulse width modulation
ram	random access memory
rms	root mean square
RPO	regular production option
RTD	resistive temperature device
SAE	Society of Automotive Engineers
SCE	Southern California Electric (Company)
SCP	Standard Corporate Protocol
SERI	Solar Energy Research Institute
SLI	starting-lighting-ignition
SPAPS	SPA/Power Supply
SPS	Sundstrand Power Systems
SRM	switched reluctance motor

SSSW	six step square wave
TBD	to be determined
TENV	totally closed, non ventilated
ULEV	ultra-low emissions vehicle
V	volt
Vac	volt ac
Vdc	volt dc
VSC	Vehicle System Controller
WOT	wide open throttle

1.0 INTRODUCTION AND SUMMARY

The Modular Electric Vehicle Program (MEVP) was an EV propulsion system development program in which the technical effort was contracted by DOE to Ford Motor Company. The General Electric Company was a major subcontractor to Ford for the development of the electric subsystem. Sundstrand Power Systems was also a subcontractor to Ford, providing a modified gas turbine engine APU for emissions and performance testing as well as a preliminary design and producibility study for a Gas Turbine-APU for potential use in hybrid/electric vehicles. The four-year research and development effort was cost-shared between Ford, General Electric, Sundstrand Power Systems and DOE. The contract was awarded in response to Ford's unsolicited proposal. The program objective was to bring electric vehicle propulsion system technology closer to commercialization by developing subsystem components which can be produced from a common design and accommodate a wide range of vehicles; i.e., modularize the components. This concept would enable industry to introduce electric vehicles into the marketplace sooner than would be accomplished via traditional designs in that the economies of mass production could be realized across a spectrum of product offerings. This would eliminate the need to dedicate the design and capital investment to a limited volume product offering which would increase consumer cost and/or lengthen the time required to realize a return on the investment.

To the extent possible, components and technology developed in the First and Second Generation Single-Shaft Electric Propulsion System (ETX) Programs have been employed. It was envisioned that a family of components could be developed that would satisfy small passenger vehicles, compact vans and full-size vans. These components could be used in both front-wheel and rear-wheel drive applications. Three targets for component designs were chosen: a 50-Hp two-passenger commuter-type vehicle or micro-van, a 75-Hp small van (mini-van), and a 100-Hp full-size van.

The MEVP "propulsion system" is defined to include all components and subsystems (from the driver input to the vehicle wheels) that are required to store electric energy on board the vehicle and, using that energy, to provide motive power to the vehicle. Therefore, the major components comprising the MEVP propulsion system include:

1. Powertrain
 - Motor/Transaxle Assembly - An ac induction motor integrated with a single-speed transmission on the drive axle of the vehicle (single-shaft).
 - Dc to Ac Inverter and Inverter/Motor Controller
 - Vehicle System Controller
2. Battery Subsystem
 - Traction Battery
 - Battery Controller
 - On-board Battery Charger
3. Ancillary Vehicle Subsystems
 - Gas Turbine - APU

Sketches of the major components for MEVP are shown in Figure 1-1. This figure shows both the building blocks, such as the transmission, the motor, axle ends and separate electrical components, and the modules that could be assembled using these building blocks, such as sprung and unsprung transaxle assemblies and the electrical/electronic subassembly.

The MEVP performance goals are shown in Table 1-1.

Table 1-1. MEVP performance goals.

Acceleration to	50 mph in less than 18 seconds
	30 mph in less than 7 seconds
Top speed	70 mph
Ascend a 30% grade	
Automotive acceptable driveability	
Energy consumption less than 0.095 Wh/lbs-mi [330 Wh/mi for 3500 lb vehicle (from the battery on FUDS)]	
Range greater than 100 miles on Federal Urban Drive Schedule (FUDS)	

The project is divided into two phases. During FY91, Phase I - Preliminary System Studies, was completed. The results of these efforts were presented to DOE on April 3, 1991 and documented in the Phase I Technical Report. The main purpose of Phase I was to conduct system studies and trade-offs which would determine the technical direction for the remainder of the program. The major conclusion from Phase I is that a modular powertrain is a viable concept. Subsequent to the April 3, 1991 Phase I Project Review, approval was granted to proceed to Phase II. Phase II - Component Design, Build, Integration and Test, continued during FY92. Detailed designs of all components which make up the complete deliverable electric vehicle were completed during this phase. These component designs were implemented in hardware and tested, and the developed components were integrated into the test bed vehicle and tested. Due to funding constraints by DOE, only the 75-Hp test bed vehicle was built and delivered. In addition to the elimination of the 50 and 100-Hp design efforts, the efforts associated with the FMEA, dc-dc converter, vehicle build and traction battery technologies were eliminated. The Ancillary Subsystems' task was expanded to include a preliminary design and producibility study for a Gas Turbine-APU, and the end of the program became the first quarter 1994.

The contract involves the following nine specific tasks:

- Task
- 1.0 Preliminary System Studies
 - 2.0 Failure Mode and Effects Analysis (FMEA)
 - 3.0 Vehicle Control Subsystem Design, Build and Test
 - 4.0 Electric Subsystem Design, Build and Test
 - 5.0 Battery Subsystems Design, Development, Build and Test
 - 6.0 Transaxle Design, Build and Test
 - 7.0 Test Vehicles Design, Build and Test
 - 8.0 Ancillary Subsystems Design, Build and Test
 - 9.0 Program Management and Reporting

The above sketch shows the mechanical components (transmission, clutch packs, motors, and axle ends) required to assemble both the sprung and the unsprung transaxle assemblies shown.

The sketch on the left shows the electrical subassemblies (system controller, lube pump and transaxle controls, inverter and contactor) required to assemble the electrical subassembly for the vehicle.

Figure 1-1. Modular Components and Subassemblies.

During the first year of the program, Task 1.0 was completed and the remaining tasks were begun. Efforts in the first year were documented in Annual Report I. During the second year of the program, efforts continued on Tasks 2 through 9 as part of Phase II, and these efforts were documented in Annual Report II.

Phase I

The results of the Phase I activities provided a well-documented, quantitative definition of the electric vehicle subsystems that have determined the subsystem designs for the whole project. Specific objectives which were achieved for this phase were the evaluation of fundamental concepts, the factoring of multi-power capability into the component designs, determination of performance specifications for each of the target vehicles, and trade-off analyses which were used in formulating the designs of the components and subsystems. Preliminary specifications for all components and subsystems were completed during this phase.

Powertrain system issues addressed during Phase I included:

- Dc or ac system
- Single or multiple motor drive
- Single or two-speed transmission
- System voltage
- Maximum motor torque vs. motor speed
- Maximum inverter voltage and current
- Battery energy and power
- On-board vs. off-board charger
- Transaxle maximum torque and gear ratio

The major conclusion drawn from the system study is that the modular powertrain is a viable concept. Each of the major powertrain components, (i.e., motor, transmission, system controller, inverter, inverter/motor controller, battery, and battery controller) can be designed to have common features that enable them to be utilized in a range of powertrains, thereby providing the economy of volume production. Specific conclusions include:

- Ac system - Although at present there are only marginal cost differences between ac and dc powertrains, the ac system has efficiency benefits and significant cost reduction potential. It has been selected for the MEVP program.
- Single motor, single-speed (12.2:1 gear ratio) transaxle - A trade-off analysis including one motor versus multiple motor powertrains warranted the selection of a single motor configuration for MEVP. A single-speed transmission employing two planetary gear sets and a planetary differential offers distinct advantages for MEVP over a multiple-speed version.
- 336 V System voltage - A system voltage of 336 V has been found to offer significant advantages of increased efficiency and system cost reduction.

- Ac induction motor - The ac induction motor has been selected for the MEVP powertrain in preference to switched reluctance or interior permanent magnet types because of its greater technological maturity and lower production costs.
- Air cooling of inverter possible - Air cooling the inverter is possible as a result of more efficient inverter/power components, the use of a higher system voltage, and new packaging concepts.
- On-board charger - An on-board charger has been selected as the primary option based on market driven requirements.

Modularity achievements expected from MEVP, to accommodate multiple Hp ratings and multiple vehicles, include:

- Transaxle modularity can be accommodated by load sharing through adding additional pinions
- Inverter rating can change as a function of output devices (power semiconductor and filter capacitor)
- Motor designs are close enough to yield an "acceptable" compromise for 50 - 75 - 100-Hp powertrains
- Modularity of battery design is limited to cells and enclosures
- Additional component variations can be accommodated through software changes for:
 - System controller
 - Inverter/motor controller
 - Battery controller
- No changes are required for:
 - Charger
 - Dc-dc converter
 - Contactor (sized for largest application)

Phase II

The Phase II efforts in FY91 focussed on detailed designs of all components which make up the complete deliverable electric vehicles. These component designs were implemented in hardware and bench tested. The fully developed components will be integrated into test bed vehicles and tested as the program progresses.

The status of Phase II efforts at the end of FY91 was as follows:

- Initial efforts concentrated on 75-Hp design.
- Specifications issued for all major components.
- Overall vehicle system specification in process.
- Motor/transaxle assembly designed, and prototype hardware built.
- Inverter designed, and prototype hardware built.
- Brassboard inverter/motor controls built.
- Vehicle system controller designed, and prototype hardware built.
- 75-Hp prototype hardware being tested in prototype test bed vehicle.
- European Escort Van chosen as 75-Hp deliverable test bed vehicle.

- Battery controls development underway
 - Dc power subsystem configured
 - Battery control functions and algorithms in process
 - Sodium-sulfur battery cooling system specified
 - Specifications written for 50, 75, and 100-Hp powertrains
 - High voltage selected for all power levels

Additional traction battery efforts consisted of extensive interaction with battery suppliers to obtain design data for candidate technologies, and with the U.S. Advanced Battery Consortium (USABC) for guidance on battery technologies. Sodium-sulfur battery technology was provided for the 75-Hp test bed vehicle.

During FY92, funding constraints were imposed by DOE, and a revised Statement of Work was submitted to DOE. The resultant work scope allowed only the 75-Hp test bed vehicle to be built and delivered. In addition, several tasks were eliminated as noted earlier, the Ancillary Subsystems' task was expanded to include a preliminary design and producibility study for a Gas Turbine-APU, and the end of the program became the first quarter 1994. The Phase II efforts during FY92 focussed on detailed designs of all components which make up the complete deliverable 75-Hp electric vehicle. Second year efforts included completion of these 75-Hp component designs, and building and bench testing of the component hardware. Integration of the fully developed components into the 75-Hp test bed vehicle also began this year. An electrical schematic of the MEVP propulsion system is shown in Figure 1-2.

The status of Phase II efforts at the end of FY92 was as follows:

- Efforts concentrated on 75-Hp design.
- Specifications issued for all major components.
- Overall vehicle system specification complete.
- Motor/transaxle assembly designed, and hardware built.
- Inverter and inverter/motor controls designed, and hardware built.
- Vehicle system controller designed, and hardware built.
- SCP multiplex communication link established.
- 75-Hp hardware integrated in prototype test bed vehicle for testing.
- European Escort Van chosen as 75-Hp deliverable test bed vehicle.
- Battery controls development underway
 - Dc power subsystem configured
 - Battery control functions and algorithms developed, including charging
 - Sodium-sulfur battery cooling system specified
 - Specifications written for 50, 75, and 100-Hp powertrains
 - High voltage selected for all power levels

Phase II efforts continued during FY93, with completion of integration of the 75-Hp components into the test bed vehicle and testing of the vehicle.

MEVP

ELECTRIC VEHICLE

Figure 1-2. MEVP Electrical Schematic
1-7

The status of Phase II efforts at the end of FY93 was as follows:

- Efforts concentrated on 75-Hp design.
- Specifications issued for all major components.
- Overall vehicle system specification completed.
- Major propulsion system components designed, hardware built, integrated into test bed vehicle, and testing completed.
- European Escort Van chosen as 75-Hp deliverable test bed vehicle.
- Gas Turbine - APU
 - Sundstrand Power Systems
 - Existing engine modified to form APU.
 - Preliminary performance testing completed.
 - APU delivered to Ford for dynamometer testing.
 - Preliminary design and producibility study in process.

FY94 efforts included delivery of the test bed vehicle to DOE, writing the Final Technical Report and completing the program with the Final Program Review on March 15, 1994 in Washington, D.C. The goals established for the program were met.

2.0 VEHICLE CONTROL SUBSYSTEM DESIGN, BUILD AND TEST

2.1 Overview

Efforts in the Vehicle Control Subsystem task during Phase I concentrated on development of the preliminary specifications for the vehicle control subsystem. In addition, the system controller was designed. Efforts in this task during Phase II concentrated on the debug and fine-tuning of the control system during integration in the prototype test bed vehicle. Based on the integration efforts, major revisions to the Vehicle System Controller (VSC) specification were made. A Vehicle Electrical/Electronics System specification, encompassing the total vehicle propulsion system was completed. The VSC was designed and hardware was built. Development efforts also concentrated on the Diagnostic Data Logger Module (DDLDM), including hardware and software design and identification of a supplier for the module. In addition, communication between the Off-Board Diagnostic System and the DDLDM was tested and successfully demonstrated.

2.2 Phase I

Preliminary specifications for the vehicle control subsystem were developed during Phase I. In addition, the system controller was designed. The system controller proposed for the MEVP powertrain monitors and controls the functions of all powertrain components. Figure 2-1 shows the major functional blocks within the system controller and its interfaces with the rest of the powertrain. The microprocessor-based design of the system controller will provide the inherent flexibility and reliability of a software-based control strategy for accurate real time control of powertrain functions in various operating modes and the ability to accommodate variations in control required for application to a range of vehicles. As with internal combustion-powered vehicles, the vehicle requires its own "calibration" with operational parameters specifically established to match its requirements. The input signal conditioning blocks receive the signals from various appropriate sensors, such as pressure, temperature, speed, and pedal and switch positions, and convert them into analog or digital signals compatible with the input requirements of the processor. The power driver block converts the logic level output signals from the microprocessor into power signals required for actuators, such as solenoids, relays, or pumps. The input/output (I/O) circuits also provide any isolation and filtering required.

The vehicle controls portion (vehicle system controller (VSC)) of the system controller is fully digital and uses a microprocessor as its central element. It receives and interprets driver demands through conditioned signals from the accelerator and brake pedals and the shift lever. It performs the required real time computations to determine the required motor torque to be used by the inverter/ motor controls. In addition, the VSC regulates the operation of the auxiliary systems, such as cooling and regenerative braking; controls the shifting of the transmission, if required; and activates various pumps, fans, and relays, as required and provides powertrain information to the driver. The VSC has the ultimate responsibility for monitoring the operation of all powertrain components and for taking appropriate actions necessary for safe and smooth operation of the powertrain.

MEVP

Figure 2- 1. System Controller Block Diagram

The system controller integrates all of the vehicle and inverter/motor controls (IMC). It is self-contained and interconnected to other vehicle subsystems. (See Section 3.0 for a discussion of the IMC).

Details of the Phase I efforts are described in the Phase I Technical Report, which is included as Appendix A of this report.

2.3 Details of Phase II

Phase II efforts in this task, which concentrated on the 75-Hp design, included finalizing the control subsystem requirements for the total vehicle and the hierarchical distribution of the control functions (see Figures 2-2 and 2-3). The Vehicle System Controller (VSC) control architecture was designed and the state machine representation of the control strategy completed. A throttle/torque/motor speed analysis was performed, a torque schedule identified, and a preliminary brake control strategy successfully simulated. Software incorporating the torque, brake, and state control strategies into a real time architecture was also designed. The design of the VSC hardware was completed and prototype hardware fabricated. Debug and fine-tuning of the control system continued to take place during integration in the prototype test bed vehicle. Based on the integration efforts, major revisions to the VSC specification were made, and a revised VSC was designed and hardware built. Development efforts also concentrated on the Diagnostic Data Logger Module (DDLM), including hardware and software design and identification of a supplier for the module. In addition, communication between the Off-Board Diagnostic System and the DDLM was tested and successfully demonstrated. A Vehicle Electrical/Electronics System specification, encompassing the total vehicle propulsion system was also completed.

2.3.1 Specifications

Component specifications for each of the 75-Hp vehicle powertrain components were completed, as was a vehicle Electrical/Electronics System specification encompassing the total vehicle propulsion system. Efforts on this specification concentrated first on defining the operational requirements of the vehicle and their relationships. In following a classic "Systems Engineering" approach, the task of deriving the specification began by first defining the intended uses a 75-Hp small electric van might be experience. Seven primary uses were identified. These were:

1. General package delivery or pickup
2. General service calls
3. House to house package delivery or pickup
4. House to house service calls
5. Local commute
6. Intercity commute (Range Extender vehicles only)
7. Shopping trips

The list of uses was then used to derive the vehicle system modes which are a complete set of vehicle operating conditions which support those customer's intended uses. Seventeen system modes were identified. Illustrative examples include startup, creeping motion, acceleration, low speed cruise, high speed cruise, shutdown, standby, and unattended charge.

Control System Requirements

Vehicle Sequencing

Management of vehicle functions such that they occur at the appropriate time and in proper response to vehicle events.

Powertrain Control

Provide torque to the wheels under driver control.

Brake Control

Integrated management of regenerative and friction braking

Battery Control

Control battery temperature. Determine safe operating regions. Instrument and estimate battery parameters required for energy management.

Charging Control

Management of battery recharging functions.

Climate Control

Manage the interior temperature of the vehicle(including Preheat/Precool) in a manner which minimizes energy consumption, while preventing conflicts for available energy.

Auxilliary Subsystem Control

Control of subsystems and components which support vehicle operation (eg. lubrication, cooling, instrument cluster, power switching).

Figure 2-2

The next step was to define the complete set of system states that describe the status of the vehicle during a particular mode. Nineteen of these were identified, including operating with a range extender, charging, regenerative braking, and emergency power off.

The operational requirements necessary to satisfy the customer's intended uses were then established. A total of 32 of these were seen to be required. For example, the list included the following:

1. Carry payload
2. Climb hills
3. Initiate charge by driver
4. Determine if charge is sufficient for trip
5. Advise driver of service required
6. Heat vehicle interior
7. Restart vehicle with minimum delay
8. Startup and shutdown sequence

The last step was to establish the inter-relationship among the various operational requirements. These are illustrated in Figures 2-4 through 2-6. Figure 2-4 shows the normal operation of the vehicle by a typical driver. Figure 2-5 shows the sequence of events in an example of abnormal operation. Figure 2-6 shows the events involved in the service operation.

During this phase of the specification work much thought was given to defining a "Limited Operating Strategy" implementable during emergency situations. A proposed version had the following main stages:

- A warning light on the instrument cluster emphasizes the zero reading on the Distance to Empty gauge
- A limp home (a greatly reduced performance and function) capability is provided for an additional 5 to 10 miles, during which time climate control is shut off. Ultimately the vehicle shuts down totally.

Efforts spent on development of a vehicle propulsion system specification, involved completion of the definition of the functional subsystem interfaces, including their class and signal type. In addition, a description of the speed control algorithm functionality was completed, as was the instrument cluster specification. Additional messages were added to the Standard Corporate Protocol (SCP) message specification to improve the systems' fault management capability.

Using the information gathered through the propulsion system integration efforts, major revisions to the Vehicle System Controller (VSC) specification were made, with state machine prove-out through simulation.

2.3.2 Components

2.3.2.1 Vehicle System Controller

The vehicle system controller (VSC) was designed and developed using information and experience gained from the integration efforts mentioned in Section 6.0. Figure 2-7 is a photograph of the VSC.

NORMAL OPERATION

Figure 2-4

ABNORMAL OPERATION

Figure 2-5

SERVICE OPERATION

Figure 2-6

Figure 2-7 MEVP Vehicle
System Controller (VSC)

A new instrument cluster was designed. and a schematic of the cluster is shown in Figure 2-8. A summary of the cluster's indicators is shown in Figure 2-9.

Control Algorithms

Several new control requirements were investigated, and implemented. Algorithms were developed, including those for brake control, climate control, distance-to-empty, cooling fan control, lube pump control, speed control, and improved accelerator pedal (throttle) position. A new state map was developed, as were new torques schedules. The algorithm for accelerator pedal position sensing was developed to enhance accuracy and handle limited operating strategy for driver safety. The method of sensing the position of the accelerator in the vehicle is through the use of a variable potentiometer and an idle switch to determine the pedal's return to an idle state. A variety of failure modes for both the sensor (high, low in-range) and switch (open, short) are covered. Failure of one or the other results in the remaining "good" device being used to provide driving input. Failure of both devices results in the default use of creep torque.

A limited operating strategy (LOS) was developed, which operates at 10% battery state of charge (SOC). A less than 10% battery SOC, the systems will provide a maximum of 67% of the requested torque. If the SOC recovers to greater than 15% and the accelerator is released, LOS mode is terminated.

Climate Controller

Climate Controller Power Available is a function of battery state of charge (0 power available at 10% or less SOC and full power above that). The slope of the curve is close to a step function so that the driver can get as close as possible to the demand, up to the limited operating strategy point (10% SOC), at which time power will cut to zero. The Climate Controller has an override on it which will operate only if the driver demands defrosting.

Fault Management

The objective of the Fault Management system is that the vehicle must operate safely in the presence of faults. It must prevent the propagation of faults between system components, and it should minimize interference by system faults with the vehicle mission. Each system or subsystem is responsible for the detection and management of all faults in subordinate subsystems or components. The fault detection function occurs in real time for any fault that is known to compromise vehicle safety, other vehicle components, or that causes severe customer inconvenience. Subsystem operation is continuously monitored, and any anomaly is reported to the superior subsystem and classified into one of the following three states:

- Shutdown: The subsystem is no longer capable of operating within the fault management objectives.
- Warning: The subsystem has detected a defect that should be attended to by a repair technician.
- Advisories: The subsystem has detected a temporary condition that reduces or may reduce its performance.

Figure 2-8. MEVP Instrument Cluster

Summary of VCC110 Instrument Cluster Indicators

Indicator Name	Icon	Control System Function	Vehicle Function	Vehicle States	Comments
Vehicle Malfunction		Warning or Shutdown	Any permanent degradation of performance in a subsystem.	Keyon, Charging, and Cooldown	It is always on in conjunction with Service Soon or EPO.
Brake System Warning		Dual Pressure Switch, Pressure Sensor, or Brake Lamp Switch Failures or Parking Brake	Failure in hydraulics, pressure sensor, or brake switch OR parking brake on.	Keyon, Cooldown	
Power Limit		SOC LOS, APS LOS, or Overspeed	Low SOC in Traction Battery, Accelerator Fault, or Motor Overspeed	Keyon	Flashes for SOC LOS. Continuous for all others.
EPO		Shutdown from Critical Subsystem causing opening of the Main Contactor with Keyon OR a Shutdown of the Battery Subsystem or Charger while Charging	VSC, I/MC, or Battery Subsystem total failure. SCP total failure between VSC and I/MC or VSC and Battery Controller. Loss of Battery Charging Capability during a charge cycle.	Keyon, Charging, and Cooldown	Will force the Vehicle Malfunction Lamp On.
Service Soon		Subsystem Warning, or VSC Sensor Faults: PRND, APS, Lube Temp, Lube Pressure, Brake Pressure, Brake Switch, Speed Sensor, Key Switch	Any fault that does not disable the vehicle but reduces its performance permanently.	Keyon, Charging, Cool Down	Forces Vehicle Malfunction Lamp On.
Electrical Hazard		Battery Subsystem Electrical Hazard Warning	10 Milliamps or greater conduction to chassis detected from Traction Battery.	Keyon, Charging, Cool Down	Warnings of 10, 20, and 30 milliamps issued. Shutdown Initiated at 40 Milliamps forcing EPO and Vehicle Malfunction on.
Charging Warning		AC Detected and KeyOff or flash if (AC Detected or Charger Door) and KeyOn	Indicate that vehicle is connected to AC or charger door is open. Warn driver with flashing if start is attempted in this state.	Keyon, Charging, or Cool Down	
Motor Enabled		Main Contactor Engaged	Any time the vehicle is enabled to move when placed in Reverse or Drive	KeyOn	Slightly reduced intensity.

Figure 2-9

Fault management techniques were developed for all sensor and component failures, including the accelerator, brake, motor speed, flux, and temperature sensors, PRND selector, battery heater electronics and resistor, battery coolant pump and fluid, charger failures, high voltage isolation, and internal heater resistor shorts. If the VSC develops any problem within itself or detects problems in other subsystems for which an orderly shutdown is not required, an attempt is made to reset itself. If restoration is successful, a message is transmitted to the DDLM providing reason for the reset. Fault management was improved to provide run-time reset of faults in a critical subsystem.

Motor Speed Sensor

Two Hall Effect sensors communicate motor speed and direction information to both the Inverter/Motor Control (IMC) and VSC to enable closed-loop control of the motor as well as for determination of appropriate torque requests. Thermal expansion and excessive play in the mounting of these sensors were shown to cause intermittent or permanent loss of one or both motor speed sensors in the test bed vehicle. Also, it is possible for the sensor outputs to be lost to the VSC, but not the IMC. In the original vehicle design, tach sensor loss could cause severe driveline shudder, destruction of IGBTs in the inverter, and potential quits on road. GEDS implemented an initial solution that enabled the vehicle to drive with a single speed sensor with a low level of driveline shudder. This provided limp-home capability for single sensor loss. In addition, overcurrent protection was incorporated to protect the inverter's IGBTs. Fault detection and fault management code was implemented in the VSC to switch-over to an alternate non-speed-dependent torque schedule upon detection of a motor speed sensor failure. Fault detection can occur either in the IMC or VSC. Detection of a single sensor loss to the IMC causes an SCP warning message to be sent to the VSC which then switches torque schedules and illuminates the Service Soon light. Loss of both sensors to the IMC causes the vehicle to shutdown. Loss of one or both sensors to the VSC only is detected via comparisons of vehicle speed as computed by the VSC with the speed transmitted over the network by the IMC.

Fan Control to Support Battery Cooling

Since the Battery Controller does not have control over the cooling fan, close coordination with the VSC is required to provide cooling of the traction battery in all vehicle operating modes. A number of changes were implemented to support this function. For Standby Off-Plug operation, the VSC control scheme was modified to allow the Battery Controller to wake it up whenever traction battery cooling was required. Modifications were also made to the VSC to accept cooling requests from the Battery Controller in all VSC operating states. It is important that the battery be able to be cooled at all times. And modifications were made to the VSC to support the Battery Controller's low ambient (less than 5 degrees F) cooling control algorithm which requires intervals of cooling and waiting to effectively lower the battery temperature when the battery fluid is in a viscous state.

Undervoltage Strategy

A number of problems surfaced as a result of obtaining lower battery voltages than originally expected. This resulted in some changes to the low voltage operation of the system. The IMC begins cutting back on available torque when traction battery dips below 245 V. Power limit indications were originally presented to the driver whenever the battery voltage dipped below 245 V. Due to frequent occurrences, these warnings are no longer issued. An investigation was conducted to understand the impact of lowering the threshold substantially. The impact on the DC-DC Converter, PTC Heater, and A/C Inverter were of primary concern. In extreme cases, it is possible for the IMC to shutdown due to undervoltage (less than 160 V.) The voltage usually recovers very quickly as the load is removed, allowing the VSC to perform a rolling reset and resume normal driving without the driver being aware that a shutdown occurred. A global reset counter was implemented to limit the number of shutdown/restart cycles during a single drive cycle to prevent the main contactor from repeatedly opening and closing under load and to inform the driver that a problem exists.

2.3.2.2 Diagnostic/Data Logger Module

The on-board data logger module evolved into a diagnostic/data logger module (DDLm), thus acquiring not only basic data from the vehicle, but also providing diagnostic capability to support the vehicle. The DDLm is intended to be used for vehicle service to store fault codes to aid the technician servicing the vehicle; field evaluation to store data to be used by vehicle owners performing evaluations of vehicle drive cycles; and engineering validation to store data to be used by engineers integrating/testing vehicle components. Specifically, the primary function of the DDLm is to record selected messages from the SCP Network. The content is used for customer usage profiles, engineering parameters and diagnostics. A schematic picturing the diagnostics data flow is shown in Figure 2-10, and a photograph of the DDLm is shown in Figure 2-11.

A DOS-based DDLm that will support both SCP analysis and diagnostic analysis of the vehicle and can be built from commercially available components was identified, and a supplier chosen. Design of the SPA/Power Supply (SPAPS) Board, a component of the DDLm, was completed.

A diagnostic development plan was completed which integrates the activities of the off-board diagnostic system with the activities of the vehicle data acquisition system. Added capability was added to the DDLm to measure on-board power distribution. Data recorded by the DDLm is shown in Figure 2-12. The standard information provided to all customers includes:

- Miles driven and state of charge used per discharge cycle.
- Total energy used per discharge-charge cycle.
- Climate control energy used per discharge cycle.
- Miles driven during air conditioning and defrost use.
- Recharge time and corresponding SOC restored.
- Average and maximum speed per discharge cycle.
- Traction motor energy used per discharge cycle.

DIAGNOSTICS DATA FLOW

Figure 2-10

Figure 2-11 MEVP Diagnostic/
Data Logger Module (DDLDM)

Introduction

The Diagnostic Module/Data Logger records selected messages from the SCP Network. The content of the data to be recorded may be changed by the test technician with the Off-Board Diagnostic System. Current planned content is shown below.

History of SCP Network Traffic

Amount of data and triggering events are configurable using the off-board diagnostic system interface. Triggering events can include diagnostic messages or parametric data. Once triggered, selected bytes from selected messages are recorded to On-Board Memory, and optionally to a Removable Media Data Recording Device (if connected to the Diagnostic Module).

Strategic Data Recording

Historical Data Configurable Using the Off-Board Diagnostic System Interface. The configuration is to include the quantity of data and sampling rate. The data collected is shown below:

• Power Consumption	• Subsystem Status (eg. Pre-
• Traction Battery State of Charge	heat/Precool, Contactor)
• Traction Battery Measurements	• Climate Control Operation
• Charging System	• Climate Control Power
• Vehicle On/Off	• Range Extender Operation
• Vehicle Speed	• Range Extender Power
• Cooling Required	• Traction Motor Torque
	• Inverter Voltage

SCP Network Traffic Statistics

- Counts of messages, bits transmitted, acknowledgement errors, network operational timing, and other data which qualifies the performance of the network.

Vehicle System Diagnostics

- History of Diagnostic Fault Data Provided by Subsystem Controllers Connected to SCP Network
- Diagnostic Tests on Operational Data Expected from Subsystem Controllers (i.e., "Heartbeat" Message Checks, Operational Parameter Checks)

Figure 2-12. Data Recorded by the Diagnostic Module/Data Logger

An Off-Board Diagnostic System, which is a subset of the data acquisition system, was designed to be compatible with the auxiliary/portable data logging system being developed for the integration team. Screen display interfaces and the software to work with the screen displays were also developed. The "Lab Windows" software package is used to guide the user through the options and selections available.

2.3.2.3 Standard Corporate Protocol

Standard Corporate Protocol (SCP) communication control and watchdog control were adopted for all electronic modules. The VSC sends through the SCP network the diagnostic error codes to the Diagnostics Module for logging. This includes all the warnings and shutdowns with the reason, and any sensors and actuators that have failed. A list of fault codes were added to the SCP list, and were incorporated in the next specification revision. Development of software for the inverter control SCP board was supported, and SCP messages were defined. An optical isolation circuitry for this vehicular communication network (SCP) was designed, which allows information to flow between electrically-isolated subsystems.

2.3.2.4 Power Electronics Center

Design of the Power Electronics Center (PEC) was completed during FY92. A schematic of the PEC is shown in Figure 2-13. The PEC, shown in Figure 2-14, is divided into two halves, with a heat sink between each half. The two halves (upper and lower) are attached when assembled into the vehicle. The PEC Upper houses the traction inverter and the air conditioning (A/C) inverter, and the PEC Lower houses the dc-dc converter, battery charger and PTC heater switching. The charger cable reel is attached to the outside of the PEC Lower case. The PEC Upper and PEC Lower are shown in Figures 2-15 and 2-16 respectively.

The design of the PEC serves three main purposes. First, the high voltage wiring is contained in one area of the vehicle, thus simplifying the wiring and interconnect design and providing a safe environment. Much effort was required to adapt high voltage/current circuitry design to the automotive environment.

Second, the thermal management design of the PEC enables a smaller combined package of the high voltage modules. The PEC has one common channel of ram air flow with each module's heat sink in the path. In addition two parallel fans provide 200 cubic feet per minute air flow and are activated whenever the upper or the lower heat sink reaches a predetermined temperature. To lower their operating temperatures the traction IMC filter capacitors protrude into the air flow path. The overall heat flow components are smaller than what would be required if each module was packaged separately. An obvious example is the traction charger and the traction IMC can share thermal management because neither will be turned on at the same time.

Third, to protect occupant or service personal the modules in the PEC are designed to be factory serviced only. The PEC uses special bolts requiring non standard tools for opening. There is also a high voltage interlock system that opens the main contactor if a high voltage connection is opened.

VCC110 POWER ELECTRONICS CENTER (PEC) AND REEL ASSEMBLY

Figure 2-13

Figure 2-14 MEVP Power
Electronics Center (PEC)

Figure 2-15 MEVP PEC Upper

Figure 2-16 MEVP PEC Lower

Tests were conducted on the PEC Lower assembly gaskets to determine susceptibility to leaks. No leaks occurred. In addition, EMC testing verified that a conductive gasket would not be required between the two halves. See Section 3.0 for the inverter discussion.

2.3.3 Braking Strategy

A strategy for regenerative braking was derived that is compatible with anti-lock braking, and meetings were held with vehicle dynamics experts to discuss vehicle stability issues during regeneration. Meetings were also held with potential vendors to determine the optimum hardware and software system configuration necessary for the control system design for regenerative braking. Modeling efforts were conducted on motor, battery and vehicle steady state behaviors to determine maximum regenerative braking potential under various vehicle operating conditions. In addition, a method to calculate critical deceleration parameters pertaining to regenerative braking, establishing a model to study the effects of regenerative braking was formulated.

In order to provide adequate fault management for the brake system, software for the detection of a variety of brake master cylinder pressure sensor failure modes was implemented. Detection of sensor failures (out-of-range high, out-of-range low, erratic, in-range) results in disqualification of the sensor and termination of regenerative braking.

A method was also formulated which combines road surface coefficient estimation with a variable target wheel slip. This combination allows the maximum tractive force of the road to be determined under variable conditions.

The effects on vehicle range of using different proportions of regenerative and hydraulic braking were examined for various duty cycles. This information, included in Table 2-1, was factored into the regenerative braking control strategy development, and an improved method for calculating the road surface coefficient was proposed to help minimize the number of acceleration calculations that must be made. A traction control scheme and an anti-skid scheme to be used in conjunction with regenerative braking as energy saving strategies were derived. In order to obtain the best-in-class regenerative braking, the torque curve should follow a nonlinear pattern as a function of master cylinder pressure and motor speed. To avoid the complex implementation of nonlinear algorithms, the nonlinear curve was approximated.

Modeling was performed on the vehicle status portion of the regenerative braking strategy using the Matrix X simulation tool. Desired regenerative brake characteristics were provided by the vehicle engineering group, and were used to develop the strategy and software required in the vehicle system controller. In order to fully evaluate such strategies, a driveline dynamic model was developed.

A study of the advantages and disadvantages of front wheel drive versus rear wheel drive vehicle configurations, with respect to regenerative braking, was performed. This study accounted for varying surface friction conditions varying vehicle weights, and varying centers of gravity (c.g.) with respect to height, as well as horizontal placement. The study was designed to show the trade-offs in the amount of potential energy recovery, as well as in vehicle stability issues. As the c.g. moves towards the rear of the vehicle, more braking can be performed on the rear. However, more braking can be performed on the front with the c.g. in the middle than can be performed on the rear with the

c.g. moved back. As the c.g. height is raised, less braking can be performed on the rear, and more braking can be performed on the front as the c.g. is moved towards the rear. As the vehicle weight is increased, front braking capability increases. Thus, in order to best meet the goals of maximizing regenerative energy recovery, while maintaining vehicle stability, a front wheel vehicle configuration is optimum.

2.3.4 Driveline Oscillations (Shudder)

Driveline oscillations were experienced in the prototype test bed vehicle, and investigations were made into the cause of these oscillations in all tasks. In this task, a study of the SCP update rates was made, with the results indicating that there is no relationship between SCP timing and the problem. Additional explanations of the oscillation problem and subsequent resolutions can be found in Sections 3.0 and 5.0. In particular, as indicated in Section 3.0, GE Drive Systems developed a proprietary closed loop control that eliminated the shudder.

2.3.5 RFI/EMC

A RFI/EMC analysis began during FY92 using the powertrain test bed vehicle, to explore grounding concerns and sources of RFI/EMC in the vehicle. Radiated EMI testing (under no load) using a "survey meter" was conducted to evaluate the benefit of braiding the 3-phase leads feeding the traction motor. This resulted in a reduction in the magnetic field generated around those leads. Full vehicle testing under load was conducted during FY93. See Section 3.0 for additional details on this effort.

Table 2-1. Regenerative braking effects on duty cycle

FUDS				
	0%	35%	65%	100%
Range (km)	145	156	166	177
Drive Energy (kWh/km)	0.206	0.198	0.197	0.197
Regen Energy (kWh/km)	0.000	-0.007	-0.019	-0.033

SAE J227-C				
	0%	35%	65%	100%
Range (km)	146	156	166	179
Drive Energy (kWh/km)	0.208	0.201	0.199	0.199
Regen Energy (kWh/km)	0.000	-0.008	-0.019	-0.033

SAE J227-D				
	0%	35%	65%	100%
Range (km)	151	161	169	180
Drive Energy (kWh/km)	0.198	0.193	0.193	0.193
Regen Energy (kWh/km)	0.000	-0.008	-0.019	-0.032

SCE Base				
	0%	35%	65%	100%
Range (km)	137	148	159	174
Drive Energy (kWh/km)	0.220	0.213	0.212	0.212
Regen Energy (kWh/km)	0.000	-0.012	-0.028	-0.047

SCE FS01				
	0%	35%	65%	100%
Range (km)	108	119	130	146
Drive Energy (kWh/km)	0.279	0.267	0.265	0.265
Regen Energy (kWh/km)	0.000	-0.018	-0.042	-0.070

SCE MR01				
	0%	35%	65%	100%
Range (km)	100	109	121	135
Drive Energy (kWh/km)	0.301	0.288	0.287	0.286
Regen Energy (kWh/km)	0.000	-0.019	-0.044	-0.075

Note: Range computed using a battery net efficiency of 86% and capacity of 29.9 kWh.

Cycle	Distance (miles)	Duration (hours)
SCE Base	41	1.9
SCE FS01	36	8.0
SCE MR01	32	7.2

3.0 ELECTRIC SUBSYSTEM DESIGN, BUILD AND TEST

3.1 Overview

The Electric Subsystem consists of the electric portion of the powertrain - the traction motor, the power electronics and control necessary to provide equivalent or better performance than a gasoline powered drivetrain. The critical issues defined early in the Program were cost, efficiency, performance, and driveability.

Phase I of the Program was dedicated to the examination of alternative drive concepts considering an array of motors and controllers, to arrive at the configuration which best met the criteria defined by the critical issues. The most promising configuration was an IGBT inverter employing field oriented controller techniques to power an asynchronous induction motor.

The powertrain employing this configuration was designed and built during Phase II of the Project with few major surprises. The design was thoroughly tested against the environmental specifications for temperature, shock, and vibration, as well as the RF electromagnetic specifications for emission and susceptibility commonly used in the automotive industry.

Some problems were encountered with drive smoothness during acceleration at two specific speed points, and the root of the problem was traced to driveline oscillations resulting from motor torque pulse excitation of driveline resonant frequencies. A digital compensator was developed to neutralize the effect taking advantage of the inherently wide bandwidth of the vector field oriented controller.

A comprehensive test program provided data which demonstrates that efficiency and performance goals were met, and in some instances, exceeded by the resulting powertrain.

3.2 Phase I

The following sections provide a summary of the Phase I efforts. Details of these efforts are described in the Phase I Technical Report, which is included as Appendix A of this report.

3.2.1 Motor

3.2.1.1 Motor Selection

In the ac-dc drive system tradeoff study, it was concluded that the traction drive would employ an ac motor. Three types of ac motors were considered for the traction drive. These included

- Interior permanent magnet synchronous motor
- Switched reluctance motor
- Induction motor.

Since the cost of the electronic unit for control is essentially the same for each of the candidate motors, it did not enter into the consideration. The induction motor was selected from a comparison of efficiency (particularly at light loads), manufacturability, low cost potential, and design maturity. Since the object of this program is to produce a commercial design, cost and efficiency are of paramount importance in the assessment of alternative designs.

3.2.1.1.1 Interior Permanent Magnet Motor

The interior permanent magnet synchronous machine was used in the ETX-II project and based upon the knowledge gained in that project, the following important points bear consideration when the interior permanent magnet is compared to the other candidates.

- It is a more expensive machine.
- The manufacture of interior permanent magnet motors presents formidable problems in the near term. The process is labor intensive, and no machinery has yet been developed to reduce the required amount of labor and the resulting manufacturing cost.
- This type of motor has several unresolved technical problems. In order to properly control the motor, the magnet strength, as well as the inductance of both the direct and quadrature axis, must be known with a fair degree of precision.

3.2.1.1.2 Switched Reluctance Motor

The switched reluctance motor has been used in traction applications and was considered as a candidate for the MEVP drive. The more salient points which eliminated the switched reluctance motor from consideration included

- The switched reluctance motor, like the interior permanent magnet, requires accurate position sensing.
- The switched reluctance motor requires a small air gap in order to obtain high output per unit volume.
- The switched reluctance motor exhibits a high level of torque pulsations.

3.2.1.1.3 Induction Motor

The induction motor was used successfully in the ETX-I program and calculations indicate that in the speed-torque region where most driving occurs, it will be more efficient than the interior permanent magnet (compared to efficiency data provided in the ETX-II Final Technical Report). A review of the ETX-II data shows that the interior permanent magnet is most efficient at the higher torque levels with the efficiency being reduced somewhat as the torque is reduced. On the other hand, in the ETX-I drive using an induction motor, the torque on the torque-speed envelope was somewhat less than that of the interior permanent magnet, but at lighter torque the induction motor showed a higher efficiency, primarily because of the copper losses associated with field weakening in the interior permanent magnet. Presently, the MEVP drives provide a greater power to weight ratio than either of the two previous programs and operate at higher motor speeds. The result of the increased power to weight ratio and higher speed is that most of the driving occurs at a lower per unit torque and at higher speeds where efficiency at weakened field is important. Under these conditions, the induction motor efficiency is somewhat better than that of the interior permanent magnet motor.

Thus, the induction motor was chosen from among the candidates because it is

- Equal or better in efficiency
- Simpler to manufacture
- Lower in cost
- Mature design.

3.2.1.2 Motor Design

3.2.1.2.1 Frame Size

The selection of motor size to support the design Hp is constrained by several parameters

- Maximum diameter is constrained by road clearance
- Maximum length is constrained by the maximum allowable angle at the constant velocity joints/half shafts
- Rotor length is limited by the required critical velocity.

The selected motor has a lamination outer diameter (o.d.) of 8.77 in. (80 frame) which is a standard. The selection of a standard was desirable for two reasons

- 1) Production costs will be lowest for large volume production if the motor has a standard. The ideal situation is one in which potential vendors already have production in the frame size selected for the traction motor.

- 2) Although only motor parts, - stator and rotor - are required for the transaxle, several motors (including shells, end shields, and bearings) must be provided for initial tests. This is most easily facilitated by selecting a standard frame size.

The 80 frame appears to be ideal for this application. The stack length of the motor is 7.5 in., which makes the stack length slightly less than the o.d. The manufacture of motors with stack lengths greater than the o.d. have been found to have difficulty in controlling the air gap. The stack length of 7.5 in. is the maximum allowable length from the standpoint of space limitations. It is also a desirable length from the standpoint of critical speeds of the rotor (the calculated critical speed is 24,000 rpm).

3.2.1.2.2 Operating voltage

The motor must be designed to provide the rated Hp over a large range, and the limiting parameter is the ability to produce this Hp at the maximum rated speed. This involves trading off operating voltage and the maximum allowable current; for example, if the operating voltage is halved and the maximum allowable current doubled, the number of turns is reduced by a factor of two, and twice as many conductors are paralleled to achieve the same performance envelope. Once a winding configuration is selected, the motor will produce this power at or above the specified voltage. This voltage is referred to as the rated voltage. The rated voltage selected was a battery voltage of 255 V corresponding to a 20% state of charge. This results in a line-line voltage of 194.9 V at the motor terminals.

3.2.1.2.3 Operating Speeds

The motor design selected was quite similar to the motor of ETX-I except for increased stack length. Again, a 2-pole motor was selected, and for the same reason that it was previously chosen. Also, the 2-pole design is more desirable in the inverter design since the operating frequency necessary to reach a given speed is 2:1 lower. A top speed of about 12000 rpm was selected because the strength of the aluminum in the rotor limited the critical velocity. For the selected shaft, and a 7.5-in. stack, the critical speed of the rotor is 24000 rpm. A top speed of 12000 rpm, then is 1/2 of the critical speed providing a reasonable safety margin.

3.2.1.2.4 Cooling Methods

The method of cooling the motor is similar to that of ETX-I and ETX-II. Automatic transmission fluid is caused to flow over the stator end turns and the rotor end rings. This warm fluid then passes through the gear train, and if necessary, is further cooled through a radiator before returning to the motor. Air cooling was considered. The major problem encountered in consideration of air cooling was an effective means for removing heat from the rotor during periods of high torque such as hill climbing. When climbing a 30% grade with the 100-Hp unit, the rotor dissipation is over 10 kilowatts. The design of the 100-Hp unit includes an oil spray of 5 gallons/minute to remove the motor heat and allow it to be removed from the system.

3.2.1.2.5 Optimum Motor Size

The concept conclusion that the identical motor can be used for all three of the drivelines, (50-75-100 Hp) would appear to concede either cost or performance for the sake of modularity. However, the three motor designs are considered to be a constrained optimum design, that is the three designs are the same because of imposed constraints. The single speed transmission design requires considerable stall torque from the motor, and the amount of available current is limited by the battery size and the inverter current rating. The cost of inverter capacity and the cost of battery weight are both large in comparison to the cost of motor weight. Thus the problem becomes one of maximizing the stall torque and operating efficiency of the motor subject to the constraints of specified maximum allowable stall current and space. In all three applications, the magnetic steel is driven close to its limits.

As mentioned earlier, the design was optimized at 75 Hp. The motor selection for this size was limited in maximum diameter by required road clearance and in length by the maximum angle allowed for the half shafts. This motor design is believed to be optimum for the 75-Hp drive.

The 50-Hp motor could be reduced in stack length by a small amount if greater stall current were made available or if stall torque requirements were reduced. However, efficiency would suffer somewhat. The 100-Hp motor would be larger, since it has very little power margin at high speeds.

An unconstrained optimum design would be somewhat larger in diameter. Since the MEVP motors must operate at higher speeds than the ETX-I design, a stiffer shaft is required to raise the critical velocity. The optimum design would also include larger magnetic paths for the stator flux. To meet the stall torque requirements, both stator and rotor magnetic paths are driven well into saturation. Larger flux paths, which could be obtained by increased stack length or increased diameter, could provide lower flux densities, lower core loss, and higher efficiencies.

3.2.1.3 Calculated Performance

As indicated previously, the motors for the 50, 75, and 100-Hp drives are the same; the inverter, the battery package, and motor cooling are different. This was brought about by the challenge of building drives with a single speed transmission while limiting motor current. Some of the salient points are given in Table 3-1 (based upon calculated data only). The stall torque values for the three drives indicated in the table exceed the values necessary to meet the minimum specified grade requirements. The low speed torque requirements needed to meet low speed driveability requirements (acceleration vs. velocity) resulted in significantly better gradeability than the specified minimum.

Table 3-1. Summary of salient performance features
(Based upon calculated data at 255-V battery).

	50-Hp drive	75-Hp drive	100-Hp drive
Max stall torque	107.6 lb-ft	144.9 lb-ft	179.4 lb-ft
Max stall current	255 amp	300 amp	370 amp
Max Hp @ 5000 rpm	52.8 Hp	80.1 Hp	128.2 Hp
Max current	135 amp	203 amp	342 amp
Max Hp @ 12000 rpm	53.7 Hp	75.2 Hp	97.4 Hp
Max current	135 amp	203 amp	338 amp

3.2.2 Inverter

3.2.2.1 Inverter Electrical Characteristics

3.2.2.1.1 Overview

The inverter bridge configuration chosen for the MEVP program is essentially the same as that employed in the ETX-I and ETX-II programs with IGBTs rather than Darlington transistors used as the main power switching device (see Figure 3-1). The six leg bridge configuration was chosen to make maximum use of the battery voltage. Each leg consists of an IGBT and an antiparallel diode, providing full, four-quadrant motor operation. A dc link capacitive filter is present to minimize the source inductance and provide an ac current bypass, removing the ripple components from the battery current. Devices for precharging and discharging the capacitor filter are included. Current sensors necessary for protection and regulation are connected in series with the motor leads.

The basic design for the 50, 75, and 100-Hp units is identical except for scaling of current sensitive devices.

3.2.2.1.2 Power Devices

Four types of power devices were considered for use as the main power switch in the inverter:

- Bipolar/Darlington transistors (BJTs)
- FETs
- MCTs
- IGBTs

All device types listed above provide technically acceptable alternatives for use in the MEVP inverter, with the exception of the MCT. The MCT is a new development and has not yet reached the level of maturity necessary to commit a production design to its use. To substitute one power device for a different one requires some but not extensive rework. Therefore, the choice was primarily driven by cost with consideration given to the projected costs in 1995.

TO COMPLY WITH

The most expensive alternative was the FET. The highest rated device at 600 V was 50 amperes. In order to provide the 300-ampere capability, six devices would need to be connected in parallel in each of the six switch positions, or 36 devices total. This presented both a reliability and a cost problem.

The BJTs and the IGBTs were comparable in current ratings. Quotes received from Toshiba for the two alternatives were

Device	1990	1991	1992	1993	1994	1995
Dual IGBT 300	\$132	\$119	\$107	\$97	\$87	\$79
Single BJT 300	\$54	\$52	\$49	\$47	\$45	\$43

Note that these costs do not include the drivers. Since the IGBT requires considerably less power to switch, hybrid gate drivers are available and offer excellent speed at a cost well below that needed to gate the BJT. Thus, with the driver included in the cost equation, the IGBT is the most cost effective choice at the present time, even without driver cost in 1995.

3.2.2.1.3 Capacitor Filter

The inverter has a high capacitance filter connected across the traction battery input terminals. This filter provides two functions. First it provides an alternate path for battery current to flow when a main switch is turned off, preventing a large rise in voltage caused by energy stored in the battery circuit inductance, and secondly, it provides a path for the ac components in the dc bus circuit preventing these from circulating in the battery. Generally, the controlling factor on the number of capacitors is the ripple current rating assigned to each capacitor can.

3.2.2.1.4 Current Sensors

The choice of an algorithm to control the induction motor will require a knowledge of the motor line current. ETX-I and ETX-II used hall effect current sensors in two of the three phase legs of the motor. Since the motor does not have a neutral connection, the third phase current can be reconstructed from a knowledge of the other two phases. Also in the ETX projects, the current sensor was used as a protective device to prevent over-current in the main switching devices. This results in the need for a relatively fast sensor to guarantee that the cells could be switched off before the current reached a destructive level.

The inverter design for the MEVP program will use voltage feedback from across the main switches (IGBT) to detect an over-current condition and switch the cell to the "off" state. The basic PWM control scheme will not use current band (hysteresis) switching, which requires sensor bandwidth at the chopping frequency speed, but rather will use a programmed PWM scheme. This then reduces the bandwidth requirement of the sensor to the motor frequency level.

The present implementation uses two hall effect current sensors in the motor leads. The third phase is reconstructed from the other two. Opportunities for reducing the sensor cost by capitalizing on the need for less bandwidth will be evaluated in Phase II.

3.2.2.1.5 Power Device Snubbers

The utilization of flat, parallel bus plates to connect the filter capacitors and power devices in addition to the compact packaging allows the elimination of power device snubbers by minimizing source inductance. This arrangement reduces losses, conserves space, and simplifies the design.

3.2.2.1.6 Changes With Power Rating

Most of the detailed work has been done with the 75-Hp rating since it is in the center of the design range. Changes in scaling up to 100 Hp and down to 50 Hp are presented in the following table:

	50 Hp	75 Hp	100 Hp
Power device rating	200	300	400
No. of capacitors	6	8	10
Current sensor	No change		
Controller	No change		

3.2.2.1.7 Results

Extensive tests have been conducted to characterize the IGBT device when physically mounted in a bridge package closely resembling the expected final arrangement. These include

- Gating requirements. Voltage levels, power supply current, and transient behavior
- Voltage transients occurring while turning off and turning on
- Switching losses including independent measurements of turn-on and turn-off losses.

The switching losses of the IGBT power devices measured with this arrangement are less than one-third of those expected on turn-off and one-sixth off the expected losses at turn-on. This improvement in switching losses was the result of unusually low apparent source inductance and very fast switching obtainable using the IGBT hybrid gating circuit. The characteristics that define a proper gate drive circuit and vendor hybrid circuits for driving IGBTs have been identified and other samples are being evaluated.

Strategies for IGBT protection utilizing the desaturation principle were investigated and integrated into the gate drive design. Using this technique, an IGBT in an overcurrent state can be detected in less than 10 microseconds and a recovery strategy initiated to avoid failing the device. The circuitry used to provide this protection utilizes cell voltages, avoiding the need to provide current sensors with unusually high bandwidths.

Design guidelines have been established for selecting the capacitors that make up the dc link filter. This includes relating the dc link ripple current harmonic content to the specifications of the candidate capacitors.

3.2.2.1.8 Inverter Testing

The inverter has been tested in a single phase configuration while switching at 2.5 kilohertz with an average load current of 300 amperes as a first step in understanding frequency limits and losses. A 10-Hp induction motor has also been successfully operated with the inverter using a slip control.

3.2.2.2 Inverter Packaging

3.2.2.2.1 General

Packaging of the MEVP inverter with control electronics offers some unique challenges since it involves much higher voltages and currents than are found in present day automobiles. The battery voltage, which may be as high as 385 V, introduces serviceability issues. Since the magnitude of current involved is much higher than in present automobile designs, there are essentially no automotive connectors available.

The inverter must be packaged in a protective housing that provides the following features:

- Enclose the live electrical parts to provide protection against shock hazards, including the charge stored on capacitors after the battery has been disconnected.
- Protect the electronics from the automotive environment, which includes pollutants, a wide range of ambient temperatures, vibration, humidity and condensation, wash-down, and salt spray.
- Remove heat generated by primary heat sources (IGBTs) and secondary heat sources (e.g., capacitors, coils) with a minimum component weight, volume, and cost.
- Minimize both conducted and radiated electromagnetic emissions to a level consistent with existing automotive and Federal Communications Commission (FCC) standards. Past projects provide no significant guidance in this area.
- Interface with external signal and power wiring where the interface means must provide long term reliability in the specified environment.
- Fit and compatibility with the available vehicle space with the accent on minimum size and weight. Needs to include understanding necessary to provide for a fit in different vehicles.
- Simple installation and removal including plans for accessibility for diagnostic reasons if required.
- Good manufacturability for low cost/function.
- Meet applicable standards and specifications. The list of applicable standards will need to be developed.

The packaging design challenge is to find an optimum solution that accomplishes these goals at a minimum cost. An iterative approach was required to trade off alternatives with conflicting goals. A number of solutions for the above functional mix have been analyzed and comparative data provided for consideration in the trade-off of overall system cost.

3.2.2.2.2 Design and Analysis, Liquid Cooled Inverters

Paper designs of different layouts were developed for a comparison of each approach. Principal variations included:

- Packaging alternatives with the main contactor within the package and separated were considered. Overall system design dictated that the contactor would be external.
- The exact number of filter capacitors has not yet been determined. The package design provides for minimum alterations when the quantity of filter capacitors changes.
- Several different arrangements for mounting of the capacitors were considered.

Comparative designs were also done that considered the packaging of accessory components, such as the charger/dc-dc converter, air conditioning inverter within the inverter package, and other combinations of individual and combinational packages. See Figures 3-2 and Table 3-2.

3.2.2.2.3 Build and Test - Liquid Cooled Inverter

Prototypes of the two most promising designs (liquid cooling) have been built.

- 1) The first version was built with onboard main contactors, IGBT technology, eight capacitors, internal cable termination box, and mounting details (see Figure 3-3).
- 2) The second version is a mockup of a more compact inverter with IGBT technology, four capacitors, no contactors, no internal cable termination area, with external inverter mounted power connectors (see Figure 3-4).

Package	Estimated Volume, Cu.Ft	Cont.Watt Loss
o Traction Inverter 4 Caps, Liquid Cooled 17W x 11D x 9H	1.0	1000
o Traction Inverter Air Cooled w/o Fans 18W x 13D x 9H	1.2	1000
o Charger/DC-DC Convert. Liquid Cooled 13W x 8D x 8H	.5	600
o Air Cond. Inverter Air Cooled 9W x 6D x 6H	.2	200
Combinations, 1 Box		
o Traction Inverter and o Air Cond. Inverter Liquid Cooled 17W x 11D x 9H Note 1	1.0	1200
o Traction Inverter and o Air Cond. Inverter Air Cooled 18W x 15D x 9H	1.4	1200
o Traction Inverter and o Air Cond. Inverter and o Charger/DC-DC Convert. Liquid Cooled 18W x 15D x 9H	1.4	1300 Driving 600 Charging
2 Boxes, Lig.Cooled		1000 Tract.Inv 200 A/C Inv 100 DC-DC
o Traction Inverter and o Air Cond.Inv. Box 1, 1.0 cu.ft o Charger/DC-DC Box 2, .5 cu.ft.	1.5	1300 Driving 600 Charging

Note 1- Packaging and thermal considerations allow for including the Air Conditioning Inverter within the Liquid Cooled Traction Inverter package (1.0 cu.ft.) Adding the A/C Inverter to the Air Cooled Traction Inverter package will increase package volume from 1.2 to 1.4 cu.ft. for the same flow conditions.

Figure 3-2. MEVP components. Typical package sizes and combinations.

Table 3-2. Inverter alternatives

	Alt.1	Alt.2	Alt.3
Box 1	Trac. Inv. A/C Inv. Charger/DC-DC	Trac. Inv. A/C Inv.	Trac. Inv.
Box 2	0	Charger/DC-DC	A/C Inv.
Box 3	0	0	Charger/DC-DC
Liq. Cool. Size Cu.Ft., est	1.4	1.5	1.7
Air Cool. Cu.Ft., est	2.1	2.1	2.1
Cost	Lowest ?	Middle	Highest
Maintain- ability	More Difficult	Middle	Easiest

Note: For Liquid Cooling, the ability to utilize both sides of the heat sink for mounting components brings package size economies not possible with a finned air cooled design. This is reflected, based on initial air cooled design effort, in the constant, larger volume, for the 3 different Air Cooled packaging alternatives shown above. Increasing flow rate should reduce air cooled package volume with the penalty of increased fan power consumption. Tradeoffs to be considered during Design Phase.

Figure 3-3. MEVP inverter, 75 hp, liquid cooled 1.5 cu.ft.,

Enclosure

Provides protection from 385VDC system volts, EMI containment, and weather/environment shield. Will be tested as dripproof-ventilated and TENV to determine best balance between thermal, environmental and cost needs. Thin gage steel construction.

Heat Sink Assembly

Includes extruded aluminum heat sink, 6 IGBTs, phase lead insulators, and sheetmetal support. Battery leads and phase leads will be brought out to in-line connectors to facilitate installation in the vehicle.

Capacitor and Bus Assembly

Design is evolving toward (4) 3" Dia.x 6" capacitors. Non-inductive sheet bus used to limit voltage overshoot.

Control Board

Board edge connectors will be positioned to accept external signal wires directly, without an intermediate harness with bulkhead connector. Flexible boot will provide environmental seal.

Size: 17W x 11D x 9H 1.0 Cu.Ft
Excluding cables, connectors.

Weight: 69 lbs.total, Traction function only, liquid cooled.

Air cooling and additional functions such as battery charger, DC-DC converter, and air conditioning inverter are being considered as part of the traction inverter package. If incorporated, inverter size and weight will increase.

Figure 3-4. MEVP Inverter, 75 hp, Liquid Cooled Design Features

3.2.2.2.4 Thermal Tests - Liquid Cooled

Initial thermal tests have begun with steady-state heat runs for simulated IGBT losses of 1000 and 1500 watts (the expected range of power dissipation with 75-Hp drive, 55 mph and 7% grade).

The inverter heat sink must provide the proper thermal mass to average the heat dissipation during short term overloads. This balancing of the thermal design for various duty cycle requires extensive testing to find the proper location of a temperature sensor, which can be relied on for use in an active over-temperature protection circuit, which operates effectively for any combination of transient loading. Since the transient thermal response is very dependent upon thermal masses and their locations, this testing will be deferred until the final packaging design has been selected.

Heat runs have also been conducted on size 1/0 and no. 4 cable to verify that the choice of battery and motor cable sizes are adequate to prevent overheating under extreme overload conditions.

3.2.2.2.5 Design and Analysis of Air Cooled Inverters

Air cooling the inverter represents a major variation from the liquid cooled packages. Variations may range from simply substituting fins for the liquid cooling plate to a complete redesign optimized for forced ventilation. Air cooling offers the potential of improved efficiency. With liquid cooling, a circulating pump must always be running to transfer heat from the cooling plate to the radiator. With air cooling and access to ram air, it may be possible to use the pressure generated by the ram effect to remove the heat from the heat sink during normal operation and only power the blower during short term high power situations such as climbing steep grades under high ambient air conditions. However, it should be kept in mind that air cooling the inverter does not eliminate liquid cooling from the system; circulation of ATF fluid is still necessary for cooling of the motor and transaxle.

A detailed analysis of air cooling the inverter has been completed and indicates that 200 cfm of air supplied at a pressure of 0.2 in. of water is adequate to meet the continuous rating in an ambient air of 50° C.

3.2.2.2.6 Build, Test - Air Cooled

The inverters used in the ETX-I and the ETX-II programs were liquid cooled. The cooling alternatives have been reviewed and the feasibility of air cooling proven by thermal analysis. The first build and test work was done with liquid cooling because of its proven performance in the previous programs. The design of the air cooled version requires closer coupling with the vehicle packaging effort since its location alternatives are limited to those where ram air can be supplied. The latest air cooled package concept (See Figure 3-5) appears to meet all of the objectives, and construction of a prototype for testing will be started in the very near future.

Figure 3-5. Current Air Cooling Package Concept

3.2.2.2.7 Modularity - Various Inverter Ratings

From a production and cost standpoint, it is desirable to have a maximum of common parts for the three inverter ratings, consistent with size, cost, and application (vehicle type) tradeoffs. As previously mentioned, the plan is to size most of the package parts around the midpoint of the range, 75 Hp, and downsize for the 50 Hp where justified by cost, and expand or enlarge the minimum number of parts and subassemblies to achieve the 100-Hp rating. For example, the design phase of the program may determine that the 50 and 75-Hp heat sinks and enclosures be identical and the corresponding 100-Hp parts larger.

3.2.2.2.8 Costs

All cost data has been based upon comparative cost to facilitate rapid evaluation of alternative design. Detailed costs are being determined for identified components as the design proceeds with absolute costs, assembly times, etc.

3.2.2.2.9 Manufacturability

Details of the design are being reviewed with in-house manufacturing experts to ensure producibility and outside sources of moldings, connectors, and heat sinks are being considered.

3.2.3 Inverter/Motor Controller

The inverter/motor controller effort for the MEVP induction motor was focused on the study and development of efficient drive system control techniques for a family of drives from 50 to 100 Hp. Based upon the experience gained in the development of the ETX-I drive, which was also an induction motor, the major areas targeted for further understanding and potential improvement included:

- Motor/controller simulator that accurately reflects system losses at low levels of torque
- Flux control strategies for optimizing efficiency at low levels of torque
- PWM algorithm alternatives for maximum efficiency and minimum capacitor filter current
- Motor control algorithms that provide independent control of flux to support the above mentioned functions and to reduce dependence upon tachometers
- Means for reducing current sensor cost and required accuracy
- Means for reducing the complexity of the control algorithms to minimize the computational resources required for operation.

3.2.3.1 Computer Simulation and Loss Modeling

Elimination of the multispeed transmission in the MEVP program and a significant increase in the ratio of motor power to vehicle weight means that the motor will be operating much of the time at higher speeds and lower per unit torque. Given the importance of efficiency (valued at over \$50 per point), considerable work was done to develop a simulation model that would make it possible to determine the efficiency of the motor, including harmonic losses, under varying conditions at high speed and light load. This simulator will serve as a model for the evaluation of alternative efficiency improvement strategies. Two features of this simulator are of particular interest:

- Since harmonic losses and stray load losses represent a significant proportion of the total losses under high speed, light load conditions, particular care was taken in the development of a model that accurately represents these losses under those circumstances
- The simulator software was partitioned to allow for the direct substitution of high level code implementing the control algorithms for evaluation and debugging; this code will then be used in the actual working prototype.

The computer simulation contains a model for the 3-phase 2-pole induction motor. During the development of the computer simulation, test cases were run to compare results from this motor model to the results obtained using the variable speed induction motor simulation employed in the development of the ETX-I controller and known to be correct for sine wave and six-step excitation. Good agreement between the two simulators indicated that the basic motor models were correct. Subsequent improvements in the model concentrated on improvements in modeling of the harmonic and stray load losses.

Final validation on the simulator model will be done when the first MEVP induction motor is available. This motor will be characterized using a variable voltage, variable frequency power source, and the data acquisition system used to characterize the ETX-I and ETX-II motors.

3.2.3.2 Current Regulator and Gating Control

An internal current control loop is required to convert the direct and quadrature axis current commands generated by the torque/flux controller into gating sequences for the inverter phase legs. The hysteresis switching PWM method used in the ETX-I and ETX-II programs provides a simple, reliable method for the regulation of current.

The synchronous current regulator translates the motor current references (expressed as the direct and quadrature components) into voltage commands for a PWM generation algorithm - effectively converting a voltage reference PWM into a current reference PWM control.

A major criterion used in the selection of a PWM strategy was the minimization of capacitor filter ripple currents. Vector ratio PWM eliminates the wrong voltage choices inherent in the hysteresis switching method discussed earlier by time modulating between the four states adjacent to the reference vector ratio.

The central concept of the vector ratio PWM algorithm is to minimize current harmonics by time modulating between the four states adjacent to the reference vector ratio - two active states corresponding to the boundaries of the sector that contains the reference space-vector and the two available zero states. The timing of the switching events is adjusted such that the mean or average vector ratio produced over one switching cycle corresponds to the reference vector.

Figure 3-6 illustrates the line-neutral voltage produced by the vector ratio PWM algorithm while Figure 3-7 illustrates the corresponding motor current and torque. The switching patterns are very regular and respect the pulse-polarity-rule, in that bipolar switching only occurs at the zero cross-over of the voltage fundamental. The harmonic spectrum associated with a vector ratio PWM is concentrated about the switching frequency. This spectrum can be spread by varying the timing of the basic switching rate to alter the audible noise produced by the drive.

3.2.3.3 Harmonic Reduction

The application of non-sinusoidal voltages to an induction motor results in harmonic currents having a frequency different from the desired frequency, and the resulting air gap fields reduce the overall efficiency of the drive. Two types of fields are created: backward fields and forward fields. Since torque is produced by current and the induction motor input impedance has an inductive component, it can be generally concluded that the higher the harmonic order, the smaller the resulting torque for the same harmonic voltage amplitude.

The amplitude of the harmonic currents in the motor can be reduced by increasing the inverter switching frequency; however, this will not necessarily improve system efficiency since the inverter losses increase with frequency; the optimum will occur where the sum of the inverter losses and motor harmonic losses are a minimum.

Four modulation strategies were compared, including SSSW, trapezoidal wave - 8 notch waveform, trapezoidal wave - 4 notch waveform, and vector ratio wave. Table 3-3 presents the motor efficiencies obtained by driving the motor model with the indicated modulation wave forms. These results indicate that about 1.5 points in motor efficiency may be obtained by selecting the best modulation scheme.

Table 3-3. Motor Efficiency with Various Modulation Patterns.

	Motor Volts	Motor Amps	M o t o r Efficiency
Six-step waveform	162.2	51.7	90.6
4-notch waveform	155.5	52	92.3
8-notch waveform	149.4	54.1	92.2
Vector ratio	150.4	52.7	91.9

Space Vector PWM: Asynchronous 10,000rpm 5#-ft

Figure 3-6

Space Vector PWM: Asynchronous 10,000rpm 5#-ft

Figure 3-7

3.2.3.4 Torque and Flux Control

A key element in motor efficiency improvement at light torque is the relationship between losses from magnetization (iron losses, copper losses due to magnetization current) and the losses caused by the torque producing component. It was shown in the ETX-I program that the efficiency of the motor can be improved significantly at light torques by reducing the motor flux level. Recognizing the need for flux control restricts the choices for motor control paradigms to those that allow for the independent specification of flux and torque (with slip as the variable) to obtain a desired operating point. Field oriented control offers this capability along with the advantages of a fast, stable, torque regulator.

In field oriented control, the flux producing stator current component, which is perpendicular to the torque producing component, is controlled independently to regulate the flux inside the induction motor. Two basic schemes exist to extract this information - direct field orientation and indirect field orientation.

Both of these control schemes has both advantages and disadvantages, for example

- The direct field orientation method requires a measurement of flux. This can be obtained through the use of Hall Effect devices, but they suffer from temperature dependence and cost disadvantages. Flux coils can be used within the motor, but these coils do not provide any output at zero frequency and therefore cannot be used at zero speed.
- The indirect field control scheme is highly dependent upon motor parameters and requires the use of a shaft speed sensor.

The control scheme proposed for the MEVP drives is a combination of direct and indirect control. The motor will be started in the indirect mode with a smooth transition to direct mode at a low speed. This combination, referred to as universal field oriented, maintains good flux control and produces excellent torque response. Once the transition to direct mode is completed, the tachometer input is no longer required.

3.2.3.5 Optimal Flux Programming

For a given induction motor, at each operating point of load and torque an optimum combination of applied voltage and frequency exists that will result in minimum power losses. Substantial increases in efficiency can be obtained by operating an induction motor at less than maximum magnetic flux levels at light load, particularly at high speeds. The detailed motor model built into the simulator was made to represent the losses as accurately as possible to provide a tool for the evaluation of various flux programming strategies.

This motor model was analytically solved to determine the flux level for minimum loss operation. The use of flux reduction provides significant improvements at light torque, and modest improvements may be obtainable over the previous (ETX-I) control scheme.

3.2.4 Dc-dc Converter

3.2.4.1 Overview

The dc-dc converter serves the same role as the alternator/voltage regulator function in the conventional internal combustion engine vehicle. The current requirements of the 12-V accessory system in a conventional vehicle may be as high as 60 amperes, and the energy available from a typical starting-lighting-ignition battery is capable of supplying this load for only an hour or two. Thus it is necessary to provide this power from the traction source (internal combustion engine in a conventional case, and the traction battery in an EV. The role of the dc-dc converter is to supply the required accessory current from the traction battery during periods of peak loads and charging current to the accessory battery when required.

The assumed rating required from the dc-dc converter is 60 amperes. The final required value may be somewhat above or below this rating, but the conclusions on circuit alternatives should not be significantly affected over the range from 40 to 80 amperes.

3.2.4.2 Functional Description

In previous EV applications, cost of the dc-dc converter has been a major problem. The electronic circuitry necessary for the conversion of power from the traction voltage to the accessory voltage is very similar to that required for power supplies used in electronic equipment.

Based upon the assumed power of 720 watts (60 amperes x 12 V), a high volume price would be \$360. When compared with the cost of a typical alternator and regulator which provides the equivalent function in a conventional automobile, the functional value does not agree well with the expected cost. Two major goals were identified to improve the functional value to expected cost:

- Since the output filter of a conventional power supply represents a significant cost item, investigate the possibility of using the accessory battery as the filter.
- Significant cost reductions in the converter circuitry are not too likely in the near future, underscoring the need to improve upon the functional value by incorporating other functions, such as battery charger.

3.2.4.3 Conversion Technology

High power dc-dc converters use either hard or soft switching technology. The classification of hard or soft refers to the presence or absence of voltage across the switches during turn-off. If voltage is present across the switch at turn-off (hard switching), the power dissipated in the switching element is greater, limiting the maximum operating frequency achievable without seriously degrading the efficiency. The use of soft switching technology allows the operation at a much higher frequency without the loss of efficiency associated with hard switching. The choice for a combination bridge was the dual active bridge converter (DABC). Other attractive features of the DABC include high power density, low KVA rating of the transformer, bidirectional power flow, buck-

boost capability, low component stress, constant frequency operation, and low sensitivity to system parasitics.

3.2.4.4 Integrated Converter/Charger Circuit

A two way battery charger can be developed by taking maximum advantage of the features of each DABC. A candidate solution is shown in Figure 5-30. The main high voltage battery can be charged by the second full bridge converter, which also serves as a supply for the auxiliary battery during normal operation of the EV. The accessory battery is charged in parallel with the main traction battery, making the charging process more efficient.

Furthermore, only one transformer is used for both the charging and auxiliary supply functions. Because of the buck and boost capabilities of the DABC, it is possible to connect the input ac line rectifier to a small dc bus capacitor and produce near unity power factor waveforms at the ac input. This operation is possible because, internally, the DABC actually works as an electronically controlled current source. This feature can dramatically reduce the cost of the input line filters and reactive power compensators that are otherwise needed to operate the charger from a residential 115/220 V line in agreement with technical considerations (maximum current capability of ac line and protection) and international standards.

Further simplifications of the DABC are possible. A cost analysis is in progress and possible cost reductions resulting from these simplifications will be considered.

3.3 Details of Phase II

The Inverter/Motor Controls (I/MC) effort for the Modular Electric Vehicle Program (MEVP) has been focused on the study and development of a reliable, efficient drive control system suitable for high volume production. Consideration of alternative concepts and the selection of a preferred configuration were completed and discussed in Phase I.

The follow-on work of implementation of the concepts is a part of Phase II, with progress reported in this section of the report. Principal areas of effort in Phase II include

- Hardware development with continued improvements in size, weight and cost
- Control algorithms that minimize use of computational resources and hardware implementation costs
- PWM algorithms for maximum efficiency and minimum capacitor current
- Motor control algorithms which provide independent control of flux and torque
- Flux control strategies for optimizing efficiency of the induction motor/controller combination
- The use of the motor/controller simulator to predict losses and evolve control algorithms.

During the implementation phase, the simulator is being used to develop control algorithms. The algorithms are expressed in high level code and installed directly in the simulator to verify correctness of the basic algorithm.

Design and testing of the drive motor was completed. One motor was built and packaged as a stand alone unit (production motors are packaged within the transaxle) suitable for testing on a dynamometer.

3.3.1 Motor

3.3.1.1 Motor Design

The induction motor was chosen for use in the MEVP program not only because of its inherent ruggedness and low cost, but also because it

- Could be operated over a 4:1 constant horsepower region eliminating the need for a multiple speed transmission, and
- With proper controls, exhibits a high efficiency at the light loads encountered during constant speed driving.

The induction motor designed for use in the 50-100-Hp MEVP drives had a target of 140 lb-ft at 300 amperes of motor phase current. Since the transaxle housing provides the mounting means for the motor in the final drive, a special motor using conventional motor end bells was constructed to facilitate dynamometer testing of the design. As evidenced by the data presented in Figure 3-8, the projected and measured torque correlated very well. The maximum design stall torque of 142 lb-ft for the 75-Hp motor was achieved at the design maximum phase current of 300-amps rms. The efficiency of the motor was also very close to the design value. Figure 3-9 shows the excellent correlation between the projected and the measured motor efficiency for 60-Hz sinewave excitation. Motor stall torque performance was measured in the laboratory by locking the rotor and applying the proper phase current and frequency using inverter excitation from the preliminary drive.

3.3.1.2 Simulator

The computer simulator is being used extensively during the development of the Inverter/Motor Controller algorithms. Advanced control algorithms, written in high level "C" language, were first implemented/debugged/tested in the simulator and then ported to the TMS 320C30 digital signal processor in the Preliminary Drive control and tested in the laboratory with the inverter, motor, and transaxle. This technique has been especially useful in the development of strategies to smooth transitions between different control modes. Figure 3-10 shows an example simulator output during typical acceleration to 6,000 to 12,000 rpm.

3.3.2 Inverter/Motor Controller

A preliminary drive system for the inverter/motor controller (IMC) was built during the first year of this program consisting of an air cooled IGBT power bridge in one unit and a separate rack containing commercially available (VME) boards for the control electronics. One printed wiring board containing the IGBT gate drivers and signal conditioning was in the bridge unit and a total of nine boards were included in the control rack. This preliminary drive system is shown in Figure 3-11.

Figure 3-8. 75Hp Induction Motor Phase Current vs. Torque

Figure 3-9. 75 Hp Motor Efficiency vs. Torque for 60 Hz Sinewave Excitation

Figure 3-10. Simulator Output During Acceleration

Figure 3-11. Transaxle Test Using Preliminary Driver Controls and IGBT Inverter

The MEVP design combined the power bridge and control electronics into a single unit including two printed wiring boards. A photograph of the case for this unit, which also includes the air conditioning inverter, is shown in Figure 3-12. The unit is called the PEC upper, and is further described in Section 2.0.

3.3.2.1 Power Circuit

A simplified diagram of the power circuit is shown in Figure 3-13. The six-leg bridge configuration was chosen to make maximum use of the battery voltage. Each leg consists of an IGBT and an anti-parallel diode, providing full four quadrant operation. A dc-link capacitive filter minimizes the source inductance and provides an ac current bypass, removing the ripple components from the battery current. Devices for precharging the capacitor filter are included. Current sensors are included in two of the three phases of the motor. The current in the third phase is calculated from the two measured currents.

3.3.2.2 Control Architecture

A control block diagram is shown in Figure 3-14. This control includes:

- Field oriented control
- Speed sensors used for mechanical angle calculation
- Closed loop torque regulation
- Closed loop flux regulation
- Motor flux coils for flux feedback
- Flux and hysteresis programmed for optimum system efficiency

The control also includes the following protective features:

- Hardware detected overcurrent
- Software detected overcurrent
- Desaturation detection of the power IGBT's
- Heatsink temperature regulation
- Motor temperature regulation
- Overspeed
- Battery over/under voltage regulation
- Gate drive undervoltage detection

3.3.2.3 Control Implementation

This control is implemented on two printed wiring boards, EVDA and EVDB.

The functions on the EVDA printed wiring board are:

- Power supply
Input: Battery voltage, 150 - 400 Vdc
Outputs: 5 Vdc, +/- 15 Vdc, 11.7 Vdc
- Current feedback/control
- Flux coil signal conditioning
- Tach feedback conditioning
- IGBT gate drivers
- Over-temperature detection
- Heatsink
- Motor

Figure 3-12.MEVP PEC Upper
Case

REGULATOR BLOCK DIAGRAM

Figure 3-14. MEVP Inverter Control Block Diagram

The EVDB outer loop micro-controller includes the following functions and hardware:

- Functions
 - Communications outside the IMC
 - Executes the torque reference limit function
 - Command interface with DSP inner loop micro-controller
- Hardware Support
 - Intel processor
 - Memory
 - Analog to Digital converter
 - Digital input/output
 - Ford SCP
 - RS232

The EVDB inner loop micro-controller includes the following functions and hardware:

- Functions
 - Calculates speed based on tach input
 - Inputs current and flux feedbacks to calculate torque
 - Generates current references and hysteresis commands
 - Provides conditioned gating commands
- Hardware Support
 - Digital Signal Processor (DSP)
 - Memory
 - Analog to Digital converter
 - Tachometer interface
 - Digital input/output
 - Gating control

These two printed wiring boards were laid out using the GE in-house Computer Aided Design facility. Two iterations of the original design have been made to incorporate changes found necessary during bench, dynamometer and in-vehicle testing.

3.3.2.4 Driveline Oscillations (Shudder)

A large portion of the time during FY92 was spent testing the inverter/motor controller and correcting problems found during the tests. Testing of the inverter/motor controller was done on the bench, on the engineering dynamometer, in the vehicle on a chassis dynamometer and on the road. The driveline oscillations (shudder) problem was the most difficult to solve.

3.3.2.4.1 Shudder Causes

The long shaft between the differential and the wheel hub (including the half-shafts) along with the inertia of the motor rotor results in a single mass resonant loop with a natural frequency of 5.77 Hz. Clutches and other components associated with the automatic transmission in conventional transaxles provide a level of damping which tends to suppress driveline oscillations, but the absence of these components in the MEVP transaxles resulted in a very low damping coefficient and an objectionable shudder in the vehicle at specific speeds. It

is well known that dc offsets and dynamic variations in the motor airgap will lead to torque components which vary as a function of motor speed. When the motor speed was such that one of the components had a frequency coincident with the natural frequency of the driveline, fluctuations in motor speed at the resonant frequency led to shudder.

3.3.2.4.2 Motor Changes

In order to minimize the magnitude of the exciting torque variations, the motor airgap was increased from 0.020" to 0.030". The increase in airgap width reduced the percent change in gap resulting from tolerance buildup in the transaxle and from tolerances on eccentricity and concentricity in the motor rotor/stator. The dc offset was controlled by providing for an adjustment which could be done during factory test.

3.3.2.4.3 Control Modifications

A complete simulation of the powertrain and IMC was developed and disturbance torques of once per revolution and twice per revolution were introduced. The resulting oscillation in shaft torque closely resembled that observed in the vehicle. Using the simulation as a test bed, a compensator was developed to suppress the torque oscillations. The compensator design was then translated to fixed point code and installed in the test vehicle. The compensation effectively eliminated shudder in the vehicle. Dc offsets were deliberately introduced into the IMC of the test vehicle to evaluate the effectiveness of the compensation when the disturbance torques were considerably higher than the expected values. Good results were attained. The dc gain and time constants of the compensator were varied $\pm 2:1$ with no detectable change in the drive.

3.3.2.4.4 Simulation Results

A complete parametric evaluation was completed by varying (on the simulator) all of the significant parameters affecting the natural frequency and loop gains of the system by $\pm 10\%$. This study did not disclose any areas of particular sensitivity to parametric variations.

Figure 3-15 is a plot of the output shaft torque response to a 10 lb-ft step in reference with 5 degrees of CV joint backlash and once and twice per revolution disturbance torques of one lb-ft. The oscillation in motor speed is clearly shown.

Figure 3-16 is a plot of the same variables with the same set of parameters and the compensation network in place.

Figure 3-15. Output Shaft Torque Response Without Compensation Network

Figure 3-16. Output Shaft Torque Response with Compensation Network

3.3.2.5 EMC/RFI

3.3.2.5.1 Requirements

The following requirements were established by Ford:

RADIATED IMMUNITY						
BAND (MHz)	20 - 60	130 - 150	150 - 180	220 - 400	450 - 500	800 - 1000
REQ'T (V/m)	50	50	50	100	100	100
V E H I C L E POSITION	HOOD	HOOD	HOOD	HOOD	HOOD	HOOD
A N T E N N A ORIENTATION	VERT.	VERT.	VERT.	VERT.	VERT.	VERT.

RADIATED EMISSIONS				
BAND (MHz)	30 - 88	88 - 216	216 - 960	960 - 1000
REQ'T (microV/m)	100	150	200	500
REQ'T (dB MICROV/m)	40	43.5	46	54

Early testing of the inverter subsystem had found it to be susceptible to frequencies in the range of 300 to 500 MHZ and power levels below 50 V/M. This testing had also shown that the most sensitive antenna orientation was directly in front of the car.

The Ford Motor Electric Vehicle team secured the Romeo EMI test facility for the purpose of determining the level of susceptibility of the Ecstar electrical systems to Electromagnetic Interference over the radio frequency spectrum.

The conclusions from these tests were:

1. The inverter would, in general, only pass 20 V/M in the problem bands. This was true even if all control wiring is disconnected (except for Power connections).
2. There appeared to be at least 2 modes of failure. Near 380 MHZ, offset voltages in the analog circuitry caused high currents in the B phase. (Evidence to this effect was that the heat sink temperature climbed rapidly when the inverter was misbehaving.) Near 460 MHZ, it appeared that the EMI was acting directly on the gate drivers and causing misoperations.
3. The inverter would pass 50 V/M with no control wiring connected, inverter powered up but not controlling current into the motor. This implied that a noise level was established in the inverter by the motor current flowing and the PWM action. The EMI then added to this noise level to cause misoperations.

4. A likely port of entry for direct radiation was the power connector as it is near a quarter wavelength size for the 400 MHZ band.

Following the early EMI testing at Romeo, Ford and GE independently pursued EMI "hardening" approaches. Ford investigated ways of sealing the PEC from EMI. By testing with portable radios operating in the problem band, several improvements were found. These included -

1. Grounded screen across the front entry (cooling air path) of the heat sink.
2. Ground filter capacitors for each motor lead. Made by tuning a length of coax to be resonant at the problem frequency band.
3. After installing the cover of the PEC, copper tape was used at all seams as a further measure against EMI entry.

GE hired an EMI consultant to provide a mini version of the Romeo test facility for use in testing at GE Salem. The equipment included a log periodic antenna, a signal generator capable of producing the required frequency range, and a power amplifier. Using this equipment, GE was able to subject the inverter to approximately the same power levels as in Romeo. Furthermore, it was possible to observe the effect with an oscilloscope while operating in a condition which did not allow failure of the IGBTs. Effects were noted which closely paralleled those which had been observed in previous Romeo testing. These effects could explain the failure mechanism of the B phase IGBT. The following were noted:

1. Large per unit offsets in the current references. (Double in phase B).
2. Flux amplifier offsets.
3. Reduction in the value of hysteresis (leads to excessive switching speed).
4. Misoperation of the static switches controlling the current hysteresis.

By adding high frequency bypass capacitors and modifying several board traces, GE was able to significantly decrease the observed effects of the EMI.

These improvements along with improved shielding of the cables to the inverter and improved inverter grounding increased the immunity of the inverter subsystem. With these changes in place, the inverter passed the specified levels during later tests at Romeo.

Radiated emissions were within the specified limits.

3.3.3 Packaging

The IMC is packaged in a single unit called the PEC upper (see Section 2.0), and is shown in Figure 3-17. The IGBT power devices are mounted on an air-cooled heat sink which is normally cooled by ram air with a fan provided in the PEC lower (see Section 2.0) for cooling if sufficient ram air is not available. The air-conditioning inverter is mounted on the same heat sink as the traction inverter.

3.3.3.1 Vibration

The inverter was subjected to three vibrations tests. The first was on February 27, the second on July 30 and the last on August 20, 1992. These tests were conducted to verify the integrity of the design and to identify any problems.

The parameters for the first test were outlined in the original specifications shown in Figure 3-18. It was a three axis sinusoidal sweep from 5 to 50 to 5 Hz at a constant displacement of 1.27 mm (0.05 in).

The test showed several areas in the control electronics that required changes. These changes were incorporated in the design and a unit was built with these changes. A second test was performed to verify the design changes. At this time the specification was changed to increase the frequency and displacement. The frequency increased from 50 Hz to 500 Hz and the displacement increased from 1.27 mm to 1.6 mm. The G-forces were capped at 10 G from 54.8 Hz to 500 Hz.

The test was conducted at the new frequency and displacement. As expected, the significantly higher G-forces caused more items to fail. The design was changed again to correct these new problems and a third test was conducted at the same 10-G level. Only two problems were encountered and the design was again modified to correct these problems.

To verify the specification, Ford conducted a "Rough Road" test of a vehicle mounted with accelerometers. The data showed that the most severe level of G-forces that the vehicle would encounter would be 3.91 G. Based on the results of this test, the test specification was reduced to the final levels as shown in Figure 3-18.

The modifications required to pass the more severe test were left in the design.

3.3.4 Component Test Methodology

3.3.4.1 Test Goals

Define the transient and steady-state performance of the 75-Hp MEVP inverter design over the expected range of operating conditions. The data can then be used to determine the extent to which the goals of the MEVP program have been met as well as to provide application information for future electric vehicle opportunities.

Figure 3-17. MEVP Inverter/Motor Controller, Mounted in PEC Upper

Inverter Vibration Specifications

Figure 3-18.

3.3.4.2 Types of Tests

The following test categories will be used to define the inverter/motor operation.

Transient performance tests. These tests will be designed to characterize the ability of the drive to respond to step inputs of torque and flux over the operating range.

Envelope tests . These tests will determine the ability of the drive to operate on the envelope of the torque-speed curve.

Efficiency tests. Perform steady-state operational testing while measuring the input and output power to determine the drive efficiency.

Thermal heat runs. Operate the drive at the points designated as defining the rating to determine effectiveness of the thermal design

3.3.4.3 Test Parameters

The parameters listed below will be varied during the various tests to set the appropriate operating point and test condition.

1. Battery voltage
2. Motor speed
3. Motor torque
4. Motor oil temperature

3.3.4.4 Test Measurements

The parameters listed below will be measured

1. Battery voltage
2. Battery current
3. Motor line-to-neutral voltage
4. Motor line current
5. Motor speed
6. Shaft torque
7. Ambient temperature
8. Heatsink temperature
9. Motor temperature
10. Motor oil temperature

3.3.4.5 Test Equipment

The equipment listed below will be used.

1. Representative inverter with up-to-date hardware and software.
2. Lab 300-Hp dynamometer with upto date transaxle (including 30 mil airgap)
3. EMHP Model 400, 400 volt, 300 ampere power supply
4. Lab nominal 336 volt lead-acid battery.
5. Tektronics model 2510 Testlab data acquisition system with custom signal conditioner amplifiers.
6. LeCroy Model 9424 digital oscilloscope.
7. Fluke Model 87 multi-meter.

3.3.4.6 Test Procedures

3.3.4.6.1 Transient Tests

Operate the drive at the conditions specified. Use the monitor to step the specified variable (flux or torque). Record the response of the feedback parameter (flux or torque).

Motor Speed (RPM)	Torque (ft-lbs)	Battery (Volts)	Motor temp (deg C)
0	0	255	Ambient
	50	255	Ambient
	100	255	Ambient
	-50	255	Ambient
3,600	0	255	Ambient
	50	255	Ambient
	100	255	Ambient
	-50	255	Ambient
7,200	0	255	Ambient
	50	255	Ambient
	-20	255	Ambient
11,667	0	255	Ambient
	25	255	Ambient
	-10	255	Ambient
2000(REV)	0	255	Ambient
	50	255	Ambient
	100	255	Ambient
	-50	255	Ambient

3.3.4.6.2 Envelope Tests

These tests are designed to show that the motor is capable of maintaining its rated torque values over the entire speed operating range. The test conditions will be limited to the torque available at the particular battery voltage and motor speed while not exceeding the 75 Hp.

Motor Speed (RPM)	Torque (ft-lbs)	Battery (Volts)	Motor temp (deg C)
0	104	190	Ambient
	140	255	Ambient
	140	336	Ambient
3,600	104	190	Ambient
	140	255	Ambient
	140	336	Ambient
7,200	40	190	Ambient
	54	255	Ambient
	54	336	Ambient
11,667	25	190	Ambient
	34	255	Ambient
	34	336	Ambient

3.3.4.6.3 Efficiency Tests

The efficiency will be characterized at the operating points shown in the table. In order to calculate efficiency, the following power levels will be measured.

1. Battery power (from battery volts and amperes)
2. Motor power (by measuring motor line-to-neutral voltage and line current for the three phases.
3. Shaft horsepower (from shaft torque transducer and digital tachometer)

Motor Speed (RPM)	Torque (ft-lbs)	Battery (Volts)	Motor temp (deg C)
0	5	190	Ambient
		255	Ambient
		336	Ambient
0	25	190	Ambient
		255	Ambient
		336	Ambient
0	50	190	Ambient
		255	Ambient
		336	Ambient
0	100	190	Ambient
		255	Ambient
		336	Ambient
0	104	190	Ambient
	140	255	Ambient
		336	Ambient
0	-25	190	Ambient
		255	Ambient
		336	Ambient
3,600	5	190	Ambient
		255	Ambient
		336	Ambient
	25	190	Ambient
		255	Ambient
		336	Ambient
3,600	50	190	Ambient
		255	Ambient
		336	Ambient

Motor Speed (RPM)	Torque (ft-lbs)	Battery (Volts)	Motor temp (deg C)
3,600	100	190	Ambient
		255	Ambient
		336	Ambient
	104	190	Ambient
		255	Ambient
		336	Ambient
	-25	190	Ambient
		255	Ambient
		336	Ambient
7,200	5	190	Ambient
		255	Ambient
		336	Ambient
	25	190	Ambient
		255	Ambient
		336	Ambient
7,200	40	190	Ambient
	54	255	Ambient
		336	Ambient
	-25	190	Ambient
		255	Ambient
		336	Ambient
11,667	5	190	Ambient
		255	Ambient
		336	Ambient
	25	190	Ambient
	33	255	Ambient
		336	Ambient
	-10	190	Ambient
		255	Ambient
		336	Ambient

3.3.4.6.4 Thermal Heat Runs

The purpose of this section of testing is to verify the thermal design of all the inverter power components. Two operating points were designated as representative of the requirements.

- 35 Hp continuous at 3600 rpm
- 140 ft-lbs at stall with a duty cycle of 30 seconds on and 30 seconds off. The duty cycle will be repeated until all temperature parameters stabilize.

The following points will be monitored with thermocouples during the testing:

1. Heat sink
2. Exit air
3. Ambient air
4. Board box
5. Electrolytic capacitor core
6. Motor oil temperature

In addition, the motor stator winding temperature will be monitored using the imbedded temperature sensor.

3.3.4.7 GE Data Acquisition System/Data Analysis System

3.3.4.7.1 Introduction

Measuring the losses of a power converter or motor, in general, requires the measurement of the input power and the output power with the losses being the difference between the two. For high efficiency systems, the input and output power will be nearly the same; therefore, the accuracy of the power measurements must be much better than the desired accuracy of the efficiency. As an example, assume a system has a known efficiency of 98%. If the input/output power is measured to an accuracy of 1%, the measured losses will vary over a range from 1% to 3% which is a -50% to +50% error band. Increasing the measurement accuracy to .1% will reduce the error band to -5% to +5%.

3.3.4.7.2 Overview

Lumped losses were individually determined for the inverter and transaxle. The primary components of the transaxle are an induction motor and a 12.183:1 output gear. The gear losses were determined by independent testing. Motor losses were then assumed to be total measured transaxle losses minus predetermined gear losses. The following three quantities were measured to define the efficiencies.

Battery (or input power)
Motor input power.
Shaft power.

3.3.4.7.3 Tektronix Testlab

A Tektronix model 2510 Testlab mainframe with a 25AD3 A/D board was used to acquire the data needed to compute the desired efficiencies. Some of the relevant specifications for this system are

- 8 differential input channels
- 12 bit A/D with analog prescale feature to allow the full 12 bits of resolution for the selected analog input range.
- > 50KHZ bandwidth
- Up to 64,000 samples per channel
- Sample rates as high as 10 microseconds per sample
- The 8 available input channels are synchronously sampled
- Each input signal has independent offset and gain adjustments. This allows individual calibration of inputs to increase accuracy and, in addition, to scale inputs in engineering units.
- Calculated waveforms (from the 8 inputs) may be defined and stored in the Testlab. This allows power to be calculated and displayed by measuring current and voltage. Each calculation is done on a sample-by-sample basis.
- Additional quantities, which resolve to one number, may also be defined. For example, average power over the sample interval can be determined by taking the mean of the defined power waveform.
- All data may be stored on a hard disk or transferred to DOS computer for entry into other programs.

3.3.4.7.4 Testlab Program

The following quantities were measured by differential connections to the Tektronix Testlab:

Battery voltage
Battery current
Motor Phase A line current
Motor Phase B line current
Motor Phase C line current
Motor Phase A to neutral voltage
Motor Phase B to neutral voltage
Motor Phase C to neutral voltage

The following quantities were calculated from the measured quantities:

Battery power (Battery voltage * Battery current)
Average Battery power (mean (Battery power))
Motor power ($V_{a-n} * I_a + V_{b-n} * I_b + V_{c-n} * I_c$)
Average Motor power (mean (Motor power))

3.3.4.7.5 Shaft Power

The Tektronix Testlab was not used to measure shaft power. Shaft power was calculated by measuring the shaft torque and speed. This was converted to watts by the following equation.

Shaft power (in watts) = shaft torque (in lb-ft) X shaft RPM X 746) / 5252

Speed and torque were obtained from manual readings of the digital displays of the appropriate instruments.

3.3.4.7.6 Shaft Torque Measurement

A Himmelstein, model MCRT 6-02T, shaft torque transducer with corresponding model 6-201 torque readout was used to measure the shaft torque on the output shaft (wheel side). It was calibrated in the Himmelstein factory along with the readout to provide an accuracy specification of 1 lb-ft. This corresponds to an accuracy of $1/12.183$ lb-ft at the motor shaft. Since maximum motor torque is 140 lb-ft, this translates to a measurement accuracy of .06%. In making measurements, the 10 second filter (in the Himmelstein digital readout) was used to provide the long term average torque. Its maximum rating is 3000 lb-ft.

3.3.4.7.7 Shaft Speed Measurement

Speed was measured using a five digit frequency counter connected to a 60 tooth sensor on the wheel side of the transaxle shaft. Using a 60 tooth wheel results in a direct readout in RPM. Since resolution to .1 RPM was attainable, an accuracy at top speed of .01% was present.

3.3.4.7.8 Current Measurements

The battery and motor currents were measured using a LEM cat no LT 300-T. The device selected will measure 300 amperes rms or 600 amperes peak. It is a current mirror device and thus behaves in a similar fashion to a current transformer. Some of its relevant specifications are

- Turns ratio 1:2000
- Zero offset current at 25 deg C: max. $\pm .3\text{ma}$
- Thermal drift of offset current: typical $\pm .3\text{ma}$ (not relevant since ambient maintained at 25 deg C)
- Linearity: better than .1%
- Response time: better than 1 microsecond
- di/dt accurately followed: better than 50 A/microsecond
- Bandwidth: 0 to 150 KHZ (-1db)

Two selectable sets of burden resistors were used - one set when the expected currents were low (less than 60 amperes) and another when the currents were higher (up to 300 amperes). High stability .1% resistors with temperature specifications of 10 PPM were used for the burden resistors. The value of the burden resistor was chosen as large as possible to make full use of the +15 volt sensor supply without saturation at the high end of the current measurement range. The burden resistors were also located near the data acquisition system rather than at the LEM to get the best signal-to-noise ratio.

Temperature dependent variations in accuracy were eliminated by maintaining the ambient temperature of all equipment at 25 ± 3 deg C.

While the basic accuracies of the LEM current sensors are very good, it was further improved by calibrating the measured quantities against high accuracy shunts. This was done as follows:

- A high accuracy shunt rated 100mv at 200 amperes was obtained. It was specified as having a .1% accuracy.
- The resistance of the shunt was calibrated to an accuracy of .05% using a wheatstone bridge.
- A 200 ampere current was then passed through the shunt and the LEM under calibration. The readings were compared.
- The offset and gain parameters of the Tektronix Testlab were adjusted until the 0 current and 200 ampere current measurements were identical. A high precision digital voltmeter was used to read the shunt output.
- The procedure was repeated for the low current burden resistor so that two separate gain and offset numbers available.

This procedure ensured an accuracy of .05% of 600 amperes in the high current position and an accuracy of .05% of 60 amperes in the low current position.

3.3.4.7.9 Voltage Measurements

The basic method of voltage measurement was to build high resistance attenuator strings to each of the voltage nodes and derive the appropriate voltages using high accuracy differential op amps. The nodes measured were

1. Battery + to ground
2. Battery - to ground
3. Motor phase A to ground
4. Motor phase B to ground
5. Motor phase C to ground
6. Motor neutral to ground

These were used to derive

1. Battery + to -
2. Motor A to neutral
3. Motor B to neutral
4. Motor C to neutral

Resistors with .1% tolerance and 10 PPM temperature coefficient were used for all attenuator strings and op amp components. Enough filtering was added to avoid op amp slew rate problems but allow representation of motor voltage harmonics.

Calibration of each input was made using the following procedure.

1. A DC voltage was applied to each of the signals. Its value was determined by a .01% digital voltmeter.
2. A test run was then initiated on the Tektronix Testlab and the average value of the input signal obtained.
3. The Tektronix Testlab gain and offset parameters for the particular signal under calibration were adjusted until the readings were in agreement.

Most tests were done by sampling 20,000 samples of each signal at a sample rate of 10 micro-seconds. This ensured that several fundamental cycles were included for averaging in each test. For lower speeds, the number of samples was increased to 40,000.

3.3.5 Summary of Test Results

3.3.5.1 Introduction

A series of tests designed to define the transient and steady-state performance of the 75 horsepower MEVP inverter were performed. With the exception of the electromagnetic interference section, all testing was done at the General Electric laboratory. For purposes of drive development and the associated testing, a standard transaxle was modified to allow the total torque to be transmitted from the right side. This allowed the transaxle to be direct coupled to the dynamometer with the additional benefit of avoiding belts and/or pulleys with their associated losses.

The tests were divided according to the following categories.

1. Transient performance
2. Envelope operation
3. Efficiency
4. Thermal ratings
5. EMI

Test Equipment

1. Representative 75-Hp inverter with up-to-date hardware and software.
2. Hp dynamometer/transaxle
3. EMHP model 400, 400 volt, 200 ampere power supply
4. Adjustable battery rack (lead-acid).
5. Tektronix model 2510 Testlab data acquisition system
6. LeCroy Model 9424 digital oscilloscope

The test system showing critical system parameters for measurement are depicted below.

SYSTEM MEASUREMENTS

3.3.5.2 Transient Performance

Description of Tests

The MEVP 75-Hp inverter is configured as a torque regulator. That is, the purpose of the inverter is to produce a torque commanded by the vehicle control computer on the vehicle axle. This series of tests determines the inherent ability of the drive to respond to the torque command. The torque feedback response to a unit step torque reference is used to measure the speed of response and the margin of stability.

Several parameters were varied to determine their effect (if any) on the torque transient response. These were:

1. Motor speed
2. Average torque level

The battery voltage was maintained at 255 VDC as this represented the nominal DC link voltage.

Motor torque can not be directly measured as a torque sensor would be required in the transaxle (between the output gear and motor). However, motor electrical torque is calculated in the control by measuring stator current and flux. The equation for this calculation is

$$\vec{T_E} = \vec{I_D} \cdot \vec{F_D} - \vec{I_Q} \cdot \vec{F_Q}$$

The size of the torque step must be kept to a small value to avoid non-linear effects caused by operating in regulating loop clamps. In most cases, the step size used was 5 lb-ft.

Regulator response is commonly referred to in units of radians/second which is derived from bode plot terminology. The bode diagram "crossover" point may be inferred from the unit step response by using one of the following two rules of thumb:

1. Critically damped - $W_c = 1 / (\text{time to } 63\% \text{ of the final value})$
2. Overshoot $W_c = 3 / (\text{time to peak})$

The third possibility of an over damped response is rarely encountered in actual systems.

For determining the system response, Electrical torque and torque reference were captured using the "circular list" feature of the drive monitor. The data is then transferred to a host computer file using a terminal emulator via the RS232 interface. An example of the results obtained is shown below.

Conclusions

A transient response of 50 radians/sec over the entire operating range (torque and speed) was considered a goal. Actual responses varying from a minimum of 30 radians/sec to a maximum of 100 radians/sec were measured. A 50 radian/sec average was obtained.

3.3.5.3 Envelope Operation

Description of Test.

This series of tests measured the ability of the inverter/motor combination to develop rated torque over the speed and battery voltage operating range. Tests were conducted at speed points of

1. 0 rpm (0 MPH)
2. 3600 rpm (21 MPH)
3. 7200 rpm (43 MPH)
4. 11,667 rpm (70 MPH)

At each point a separate test was conducted at battery voltages of 190, 255, and 336 Vdc. The maximum torque expected was limited at speeds above 3600 rpm by the 75-Hp peak motor power limit. Another limiting factor was the DC motor voltage. Above motor base speed, rated flux can only be obtained on the motor with link voltages above 245 Vdc. This causes the available torque to be reduced linearly with link voltage below this point.

It should also be noted that the capability of the battery to provide the required power may limit the envelope power developed. This effect has not been included in these results. The shaft power was measured on the output shaft of the transaxle, and therefore, includes the transaxle gear losses. Motor power is somewhat higher than measured.

Typical Waveforms

Tektronix 2500 TestLab
19-Feb-1994 13:18:45
CATSTHLEXP

Phase A Waveforms
7000RPM, 40 LB-ft 190VDC

TYPICAL WAVEFORMS NEAR SQUARE WAVE MODE

The waveforms depicted above are indicative of operating near square wave. This condition occurs as the battery voltage decreases below 245 volts and the torque requirement commands rated flux on the motor.

The Tektronix 2510 data acquisition system was used to measure power into the inverter and power into the motor. Shaft power was calculated from shaft speed and torque.

The envelope test results are shown in the graph below.

Conclusions.

The drive was easily able to develop the required torque under most operating conditions. Some loss of torque was noticed near zero speed where the torque regulator is not closed. There was also a drop in expected torque when the battery voltage was near minimum (190 V) and the speed above 3600 RPM (base speed). This is because PWM operation is near pure square wave and the gain of the torque regulator is reduced.

3.3.5.4 Efficiency Tests

Description of Tests.

Efficiency of the components of the drive system is very important in a battery powered application. The tests identified here are aimed at determining the efficiency of the following items.

1. Inverter alone
2. Motor alone
3. Total transaxle.

The efficiency of the transaxle gearing was not included here. Ford Motor Co. supplied efficiency information for speeds below 6000 RPM.

To determine the efficiency, the following parameters were measured.

1. DC link power
2. Motor input power
3. Transaxle power.

The efficiency of each component was determined by the following equations.

$$INVERTER\ EFFICIENCY = \frac{MOTOR_INPUT_POWER}{DC_LINK_POWER} \cdot 100\%$$

$$TRANSAXLE\ EFFICIENCY = \frac{MOTOR_INPUT_POWER}{SHAFT_POWER} \cdot 100\%$$

$$MOTOR\ EFFICIENCY = \frac{MOTOR_INPUT_POWER}{SHAFT_POWER - GEAR_LOSSES} \cdot 100\%$$

The Tektronix Model 2510 data acquisition system was used to measure the motor and inverter power. Shaft power was calculated from shaft torque and speed.

The following parameters were varied to determine each point to measure efficiency

SPEED(RPM)	TORQUE	DC LINKVOLTS
0	5	190
3,600	25	255
7,200	110 (or max avail)	336
11,667	-10	

Efficiency measurements points were defined at each speed point for each torque level and each voltage level at each torque level.

Extended Efficiency Tests

For purposes of modeling the battery current, it was requested that a larger number of tests be run. The data obtained was used in Ford's vehicle control computer for managing the battery system. Points where efficiency was measured were defined by the following two series which define the speed and torque settings.

500, 1000, 2000, , 13000 RPM

At each speed, torque values of

2, 4, 6, 8, 10, 20, 30 , 140 LB-FT (maximum limited by rating)

The torque values are defined at the output shaft of the transaxle. Refer to Appendix B for the matrix of the speed-torque points tested. The following results were obtained.

Conclusions

One objective of the control strategy was to optimize the efficiency in the range of 5 to 30 lb-ft. This is the area where most practical operation occurs including both highway driving and the FUDS cycle. It can be seen from the efficiency graphs that both the inverter and transaxle peak up in this area. Above base speed, the inverter is always above 96% efficient with an average over 97%. Peak efficiencies are above 98%.

The transaxle is above 75% efficiency over the range of 5 to 30 lb-ft at all speeds above base speed (3600 RPM). Average efficiency is above 85% with peak efficiency of 91%.

INVERTER EFFICIENCY 255 VOLT BATTERY

FILE INV.SPW
RWB (10/14/93)

TRANSAXLE EFFICIENCY 255 VOLT BATTERY

FILE TRANS.SPW
RWB (10/15/93)

3.3.5.5 Inverter/Transaxle Thermal Tests

Description of test.

The inverter was configured for the hardware presently being shipped with the final design. The major components being:

1. Toshiba IGBTs MG300J2YS45, 300 ampere, 600 volt.
2. Philips electrolytic capacitors (3186GH5025400KHA2) 5000MFD, 400 volts
3. Ford supplied muffin fans identical with those in the vehicle. (Air flow 300CFM, .5")
4. A radiator for cooling the motor oil was used since no ram air from vehicle motion was available.

The inverter was fitted with thermocouples. A Ford cover was installed with tape used to seal around openings needed for wiring/thermocouples. The transaxle contained a representative AO Smith motor.

For all tests, the following special hardware was used.

1. Capacitor with a thermocouple in its core and another attached to the outside of the can.
2. IGBT with a hole drilled in its base for attaching a thermocouple
3. Motor oil temperature was measured by inserting a thermocouple through a small hole in the filler cap.

35-Hp Continuous Heat Run.

The following parameters define this test:

1. 35-Hp continuously
2. 3600 rpm (at motor)
3. 255 volts battery voltage

3600 rpm was chosen because this is the motor corner point for a 75-Hp rating with 110 lb-ft of torque. Since the motor flux continues to rise until 5000 RPM, the maximum motor current required for 35 Hp occurs at 3600 RPM.

The Tektronix 2510 Testlab was used to measure the inverter losses which allowed the IGBT junction-to-case temperature to be calculated.

$$\Delta T_j = 14 \text{ deg } C$$

Results

1. Capacitor - Maximum core rise was 7 deg C, well within expected values
2. IGBT - Maximum junction rise was 59 deg C, well within expected values
3. Electronics - The maximum rise approached 35 deg C but did not exceed it.
4. Motor - The maximum rise was well within expected values
5. The motor oil temperature tracked the end-turn temperature closely indicating good heat transfer.

35 HP Continuous Heat Run

Motor Temperature Delta

Electronics Temp Deltas

100 FT-LB Stall Test

The following parameters define Test 2.

1. 140 ft-lbs torque for a duty cycle of 30 seconds on and 30 seconds off repeated continuously.
2. Stall (0 RPM).
3. 255 Vdc battery voltage

This point was chosen, in part, because it represents a worst case from the standpoint of capacitor ripple current.

The Tektronics 2510 Testlab was used to measure the inverter losses which allowed the IGBT junction to case temperature to be calculated.

$$\Delta T_j = 23 \text{ deg } C$$

Results.

The IGBT junction temperature would not support the current required for 140 lb-ft with this duty cycle. The torque requirement was reduced to 100 lb-ft to allow the test to be completed.

1. Capacitor - The maximum core rise was well within expected values
2. IGBT- The IGBT rise was more than originally calculated. Operation in the application is not affected.
3. Electronics - The maximum rise was well within safe limits
4. Motor temperatures - The motor temperatures were within limits. The divergence of winding temperature from oil temperature indicates diminished cooling capability at zero speed.

100 FT-LB Stall Test

IGBT Temp Deltas

Electronics Temp Deltas

The following chart shows typical line current and line-to-neutral motor voltage. The data was acquired during the 35-Hp continuous heat run (3600 RPM, 255 Vdc).

3.3.5.6 Motor Characterization Test Results

The original MEVP induction motor was fabricated and mounted in conventional motor end-bells to facilitate dynamometer testing, and was used during phase I of the program for control algorithm development. A second MEVP motor (1A) was fabricated, based on the original induction motor design with very slight modifications. This motor was also fabricated in end bells to facilitate dynamometer testing. Figure 3-19 shows the resulting no-load tests of this motor (1A) for 60-Hz sinewave excitation. Test results showed somewhat increased saturation, compared to the original motor that was used during algorithm development. Based on preliminary motor evaluation tests, both with 60-Hz sinewave excitation and inverter excitation, motor (1A) design was unacceptable for two reasons. First, motor 1A efficiency was several percentage points lower than the original motor efficiency data shown in the MEVP Annual Report I. Also, this motor was unacceptable because the maximum torque goal of 143 lb-ft could not be met with the 300-A rms inverter current limit.

A new rotor was designed for the MEVP induction motor. This motor was also fabricated in end-bells to facilitate dynamometer testing. No-load test results for this motor with 60 Hz excitation are shown in Figure 3-20. No-load test results for the motor 1A, shown in Figure 3-19, and the final MEVP motor no-load test results, shown in Figure 3-20, are quite similar. Motor efficiency tests were conducted using the GE adjustable frequency, adjustable voltage 3-phase sinewave generator. Motor output power was measured using an enhanced resolution Himmelstein torque transducer. Motor input electric power was measured using a commercially available 3-phase digital power meter and also the computer controlled data acquisition/analysis system that was used extensively during the ETX-I and ETX-II programs. Efficiency measurements were conducted for motor

torque levels of 10, 20, and 30 lb-ft, at motor speeds of 3,600, 5,000, 7,000 and 9,000 rpm, respectively, plus a point at 50 lb-ft and 3,600 rpm. Applied sinewave voltage was adjusted appropriately to achieve near optimal flux levels at each motor operating point. Figure 3-21 shows results of motor efficiency versus motor speed for a range of motor torques. These test results show that the redesigned motor has an outstanding efficiency of over 95% for 10-lb-ft torque levels over a wide speed range from 3,600 through 9,000 rpm, corresponding to constant speed cruise operation of the MEVP vehicle on a level highway.

Motor tests to verify maximum torque performance were run with the output shaft of the Himmelstein torque transducer locked in a stationary position. Inverter excitation was applied to the MEVP motor through open loop software that controlled the pulse-width-modulated (PWM) inverter current amplitude and slip frequency. Figure 3-22 shows the resulting motor phase current and slip frequency versus motor torque for these locked rotor tests. Maximum torque of 145 lb-ft was achieved at 302-A rms current.

Table 3-1 shows the MEVP motor design goals and corresponding GE test results for maximum torque (locked rotor) and maximum power at 9,000 rpm both with inverter excitation, using the MEVP inverter that was designed for a maximum of 300-A rms phase current. Both MEVP motor design goals of maximum torque of 143 lb-ft and maximum power of 75 Hp were exceeded with this motor. Projections of the rms phase current to achieve these goals were also met, as shown in Table 3-1.

PARAMETER	PROGRAM GOALS	TEST RESULTS
Max Stall Torque (lb-ft)	143	145
Max Stall Current (A rms)	300	302
Max Power (Hp) @255 V dc link	75	77.3 @ 9000 rpm
Max Current (A) @ Max Power	203	205 @ 9000 rpm

Table 3-1. MEVP 75-Hp Drive System Performance Summary

MEVP Motor (1A) in End-Bells 60 Hz Sinewave No-Load Test

Figure 3-19.

MEVP Motor in End-Bells 60 Hz Sinewave No-Load Test

Figure 3-20.

MEVP Motor Efficiency vs Speed and Torque (Near Optimal Sinewave Excitation)

Figure 3-21

MEVP Induction Motor Locked Rotor Test (Inverter Excitation)

Figure 3-22

3.3.6 Facilities

Engineering dynamometer facilities were installed at GE Drive Systems, using its own funds, for engineering development. Figure 3-23 is a photograph of the engineering facility and Figure 3-24 shows the chassis dynamometer used for vehicle testing.

A pilot production facility was also established at GE Drive Systems, again using its own funds. A team consisting of manufacturing engineering, design engineering and hourly assembly personnel was formed to identify improvements to the design, tools and instructions to minimize the assembly time and improve quality. This team spent considerable time jointly assembling units and then documenting improvements in the design and tools. A 4:1 assembly time improvement resulted from this effort. Figure 3-25 is a photograph of the prototype assembly area.

GE Drive Systems, with its own funds, installed a prototype assembly and test facility for low volume production of inverter/motor controllers. Over 180 units were built and tested at this facility.

A test facility was installed for bench and dynamometer testing of assembled units. This facility includes a transaxle for testing the control with an actual motor. Figures 3-26 and 3-27 are photographs of the test facility.

The production inverter/motor controllers receive the following tests:

- Bare (no components) printed wiring board test
- Assembled printed wiring boards receive an "in-circuit" test of all components
- Functional tests of the printed wiring boards
- Wire check of the assembled inverter/motor controller
- Bench test of the inverter/motor controller
- Dynamometer test of the inverter/motor controller
- "Run-in"

A chassis dynamometer has been installed at GE Drive Systems, also with its own funds, for inverter/motor controller testing in a vehicle. A prototype test bed vehicle was provided by Ford to GE Drive Systems for dynamometer and road testing. The availability of this vehicle at GE significantly improved their ability to solve problems in a short period of time.

Figure 3-23. GE Drive Systems'
Engineering Facility

Figure 3-24. Chassis Dynamometer
at GE Drive Systems

Figure 3-25. MEVP PDC Upper
Assembly Area at GE Drive Systems

Figure 3-26. MEVP Test Facility
at GE Drive Systems - IMC Bench

Figure 3-27. MEVP Test Facility
at GE Drive Systems - Transaxle
Dynamometer

4.0 BATTERY SUBSYSTEMS DESIGN, DEVELOPMENT, BUILD AND TEST

4.1 Overview

Efforts in the Battery Subsystem task included discussions with sodium-sulfur battery suppliers in anticipation of delivery of prototype units for testing in the prototype test bed vehicle. A prototype ABB sodium-sulfur battery was received and was used for preliminary battery controller work and testing in this vehicle. The designs of the battery controller, traction battery charger and auxiliary battery charger (dc-dc converter) modules were completed. The battery controller software for sodium-sulfur batteries was tested using this vehicle connected via an umbilical cord to the sodium-sulfur battery. Efforts were also spent on updating the battery controller specification, using data accumulated through this testing, and subsequent discussions between the vehicle system controller engineers and the battery controller engineers.

4.2 Phase I

During Phase I, an assessment process was established, in order to identify the battery technologies that are potentially viable in the MEVP program. An extensive review of the literature on previous assessments and comparative evaluations of battery technologies for MEVP application was undertaken to identify candidate battery systems. Emphasis was placed on identifying the suitability of high energy density batteries for this program based on range, vehicle performance, and defined missions.

A combination of on-site visits, telephone discussions, and visits to Ford in Dearborn was used by several battery manufacturers to identify potential battery subsystems. In addition to energy and power density, issues relating to reliability, technological maturity, efficiency, stand losses, costs, packageability, and prior demonstration of a vehicle-size battery were considered.

A number of potential EV batteries were judged to be viable candidates for MEVP applications. Within the MEVP program, depending on funding, it was expected that as many as three candidate systems would be selected, with the national laboratories perhaps conducting parallel programs on other battery systems. During Phase I of this program, emphasis was placed on the sodium-sulfur battery technology.

In consideration of the power requirements of the propulsion system and the constraints imposed by the inverter, preliminary specifications for the sodium-sulfur traction battery were generated. The battery energy capacity for each vehicle type was determined on the basis of vehicle range, payload capacity, and power requirements.

Battery envelope limits were estimated for several candidate vehicles at the three powertrain ratings. Generally, as the vehicle size increases, there is more room and more flexibility in packaging the traction battery. This is influenced by the fact that the smallest vehicles are passenger cars, while the larger vehicles are vans. A packaging concept for the sodium-sulfur system was proposed. The 50, 75, and 100-Hp batteries would be contained in one or two thermal enclosures of two basic sizes.

Two suppliers of sodium-sulfur batteries were contacted and subsequently provided design data to support definition of candidate battery configurations. These data were limited to the 75-Hp vehicle design, and extrapolations to 50 and 100-Hp designs were made by Ford.

Several sodium-sulfur battery configurations were developed for evaluation of their performance in the candidate vehicles. Each powertrain rating and candidate vehicle was provided with at least one configuration.

Details of the Phase I efforts are described in the Phase I Technical Report, which is included as Appendix A of this report.

4.3 Details of Phase II

During Phase II, battery technology activities included interfacing with the two sodium-sulfur suppliers to define battery control algorithms and physical interfaces. Control algorithms were specified for development of battery controller hardware and software by Ford. Physical interfaces include structural support requirements and location of interconnections. Also, a battery cooling system for the Asea Brown-Boveri (ABB) battery was developed. This system uses a pumped-liquid coolant loop with a cooling plate assembly built into the battery core. A prototype ABB sodium-sulfur battery was used for preliminary battery controller work and testing in the prototype test bed vehicle. The battery controller software for sodium-sulfur batteries was tested initially using this vehicle connected via an umbilical cord to the sodium-sulfur battery. The battery controller specification was completed, using data accumulated through this testing, and subsequent discussions between the vehicle system controller engineers and the battery controller engineers.

The designs of the battery controller and the auxiliary battery charger (dc-dc converter) modules were completed. The traction battery charger was designed to accept either a 110 Vac or 220 Vac input, and is capable of acting as a loosely regulated dc supply at approximately 380 volts, in order to support pre-heat, pre-cool, and unattended storage. Functional specifications for each of these three modules were written.

The method of monitoring sodium-sulfur battery state-of-health was reviewed with ABB, the discharge and recharge sequences were selected, and the fault detection/management routines were defined in accordance with the proposed vehicle's Limited Operating Strategy.

4.3.1 Battery

Battery technology activities included interfacing with the two sodium-sulfur suppliers to define battery control algorithms and physical interfaces. Control algorithms were specified for development of battery controller hardware and software by Ford. Physical interfaces include structural support requirements and location of interconnections. A prototype ABB sodium-sulfur battery was used for preliminary battery controller work and testing in this vehicle.

Also, development of a battery cooling system for the Asea Brown-Boveri (ABB) battery was completed. The system uses a pumped-liquid coolant loop with a cooling plate assembly built into the battery core. A cooling system pump was selected for initial development testing and for vehicle packaging studies. Flammability tests for the cooling system fluid were completed, with the results indicating performance comparable to transmission fluid.

4.3.2 Battery Controller

The battery controller acts as the interface between the vehicle system controller and the battery and battery charging subsystems. In the 75-Hp test bed vehicle, the target battery technology is sodium-sulfur, although a lead-acid battery technology was supported for vehicle development purposes only.

The battery controller has the following main functions:

- Maintain an optimum operating temperature for the battery, taking action to raise or lower the temperature as required when preset limits are exceeded.
- Monitor the state of charge remaining in the traction battery, report this information to the other vehicle subsystems, and request limited operation when the state of charge requires this.
- Provide an automatic method of recharging the battery, which guarantees that a full charge is achieved without risking damage to the battery.
- Keep the auxiliary battery at or near a full state of charge.
- Detect and report any malfunctions or impending failures to the other vehicle subsystems, and either take or request appropriate action to correct or limit the problems.

Specific battery controller functions include:

Thermal Management

Temperature Monitoring/Sensor Failure Detection
Heater On/Off Commands / Heater Failure Detection
Cooling System On/Off Command / Failure Detection
Emergency Condition Detection / Powerdown Sequence
Cell Pack and/or External Case Over-temperature

Electrical Management

Voltage and Current Monitoring
State-of-Charge (SOC) Determination
State-of-Health (Failed Cell) Determination
Discharge and Regenerative Current Limits Output
Recharge Sequence Management
Battery Current Leakage Monitoring

Diagnostic Support

Storage and Playback Off-Line
Real-Time output to On-Board Display

The controller is packaged in two assemblies -- a logic module and an input/output (I/O) module. See Figures 4-1 and 4-2 for photographs of the two modules. The intelligent part of the controller (logic module) holds the microprocessor, memory, digital input/output (I/O), and the multiplex network interface. The logic module interfaces with the on-board charger and dc-dc converter, and processes the control algorithms for thermal management, electrical management, leakage current detection, and recording of diagnostic data for the traction battery. The I/O signal conditioning box holds the input signal conditioning circuitry, the A/D conversion device(s), and the output driver circuits and is located near the batteries. This is done to minimize the length of signal runs between the battery and the signal input sensors. The I/O module interfaces with all high-voltage sense leads, RTD probes, current shunts, and output control relays. It provides sensor signal conditioning, isolation, digital conversion, and transmission to the logic module over a dedicated serial link.

The two assemblies communicate over a set of digital, optically isolated signal wires. This interface allows for modulation of the I/O signal conditioning box as new battery technologies require, with only minimal modifications to the structure of the intelligent controller package.

The controller also interfaces with the traction battery charger. This interface supports an interlock function that will prevent the vehicle from operating while connected to ac power and will vary the amount of current supplied to the battery depending on conditions within the battery.

The auxiliary battery charger (dc-dc converter) requires no control from the battery controller. Connections to it are limited to a pair of fault condition indicators for diagnostic and failure prediction purposes.

The battery controller is designed to support both candidate sodium-sulfur batteries, as well as a generic lead-acid battery, without requiring hardware modification, and with minimal software revision. In particular, the instrumentation connectors were configured to support up to 32 battery internal voltages and 10 resistance temperature detector (RTD) probes. Pin assignments were made to allow exchange of one battery type for another without modification of the wiring harness.

Algorithms were developed for one of the two sodium-sulfur batteries, and the revisions needed to support lead-acid batteries were identified. These algorithms are developmental in nature, reflecting a conservative approach to managing the battery. Simplification of instrumentation and associated algorithms is desirable for production vehicles. Therefore, a plan to verify the adequacy of a simplified approach was implemented. Software for the controller was developed to simulate a reduced number of sensed internal voltages and

Figure 4-1. MEVP Battery
Controller Logic Module

Figure 4-2. MEVP Battery
I/O Module

temperatures. This software was executed in parallel with the baseline algorithms to assess its ability to manage the battery functions without adversely affecting battery reliability. The algorithms developed cover the state-of-charge, electrical management, and the battery cooling systems.

Software integration of the battery controller logic and I/O modules was conducted on the bench. Initial efforts concentrated on the lead-acid battery software code development, without traction battery charger control, but with high current regeneration capability. The prototype battery controller was integrated into the prototype test bed vehicle and tested. Testing included checking out the current and temperature inputs and the leakage detector circuitry. The on-board power supply was tested, as were the input voltage scaling resistor and input amplifier circuit. This design level supports the basic messaging strategy and reports basic operating data such as voltage and current. A breadboard wiring harness was used to check out the battery controller, I/O module, battery charger, and dc-dc converter. Subsequent efforts included testing the first battery controller software for sodium-sulfur batteries on the bench, and on a sodium-sulfur integration/test breadboard. The software was then tested using a prototype test bed vehicle connected via an umbilical cord to a sodium-sulfur battery.

4.3.3 Battery Charger

The traction battery charger, located in the power electronics center (PEC) lower and shown in Figure 2-10, must efficiently supply the battery with energy derived from an external ac service. The system supports both 220-Vac, 30-amp service as the main charging source, and 110-V, 15-amp service for emergency charging, and is also capable of acting as a loosely regulated dc supply at approximately 380 volts, in order to support pre-heat, pre-cool, and unattended storage.

The charger design provides greater than 90% conversion efficiency, and provides a power correction factor of 0.98 or greater. For purposes of safety interlocks, the charger will detect the application of ac power at the input and indicate this to the controller. The level of output current is regulated by the battery controller, which contains all of the intelligence required for charging.

This charger is designed for use either on board the vehicle or external to it. The interface between the charger and controller is the same regardless of charger location.

The charger subsystem for lead-acid batteries functions on the bench, and can identify either 120-Vac opportunity charging, or 240-Vac base charging without user intervention. Further enhancements allow U.K. and European opportunity and base charging.

A new charger PC board layout was processed to correct minor stability problems realized from bench testing. Switch boxes for manual control of the traction battery charger were fabricated, and were used during the initial integration and testing phase.

5.0 TRANSAXLE SUBSYSTEM DESIGN, BUILD AND TEST

5.1 Overview

The main design objectives for the design of the motor/transaxle assembly, as stated during Phase I, were that it would be as simple and efficient as possible yet provide modular features at the different powertrain levels (i.e., 50, 75, or 100-Hp). The general transmission design was governed by the systems study conclusion that a single-speed transaxle would be adequate in meeting the required performance objectives. In addition, a gear ratio of 12.18:1 was selected, along with other design parameters noted in the following sections.

Efforts during Phase II in this task concentrated on speed sensor and electrical connector development, and lubrication and cooling issues, including build of a special rig to determine how the oil for lubrication and cooling is distributed among the gears, bearings and motor. Extensive transaxle development testing began during FY92, and the transaxle design was completed and hardware built. The transaxle subsystem was subjected to all the testing normally conducted for any Ford Motor Company regular production transmission, and passed all such tests.

5.2 Phase I

The main design objectives for the design of the motor/transaxle assembly were that it would be as simple and efficient as possible yet provide modular features at the different powertrain levels (i.e., 50, 75, or 100 Hp). The general transmission design was governed by the systems study conclusion that a single-speed transaxle would be adequate in meeting the required performance objectives.

As vehicle performance is directly linked to transmission gearing, one of the first design aspects to be considered was the determination of a gear ratio that would meet the above objectives. As a consequence, WOT computer simulations were run with a range of gear ratios (9:1 through 13:1) using the compact van as the subject vehicle, and a gear ratio of 12.18:1 was selected.

Having selected the gear ratio, the transmission design study then progressed to consider the other main features of its operation. The preferred design for MEVP is based on a double stage planetary geartrain with a planetary type differential, in which power is transmitted from the motor to the wheels through the following stages (refer to Figure 5-1):

- Electrical power is supplied to the motor stator from the upper right hand side of the transaxle case, which induces the rotating magnetic fields in the rotor, causing it to turn.
- The input shaft is pressed by a heat shrink into the motor rotor, where power begins to be converted from electrical to mechanical.

Figure 5-1. Preferred Design for MEVP

- The transmission input shaft has the sun gear cut into its end, forming the input for the first reduction planetary system.
- The ring gear in the first planetary is held stationary and the carrier becomes the output. This output is coupled directly into the second planetary as the second sun gear.
- The ring gear on the second planetary set is also held stationary and the output for this set also its carrier.
- Since the carrier from the second planetary is integral with the ring gear of the differential, the traction power is output here from the transmission to the wheels.
- The differential is designed so that the ratio from the ring gear to the sun gear is 2:1. Therefore, if there are equal loads on the wheels there will be no rotation of the pinions, giving equal output to each side. Hence, one side is output through the sun gear and the other is output through the carrier.

As the transmission design outline progressed, several ways of achieving modularity in the MEVP transaxle were considered. At the same time, an assessment was made of the deviations that had to be made from the optimal design in order to achieve modularity.

In order to carry out computer simulations of vehicle performance and energy consumption, efficiency maps are needed for each drivetrain component, including the transmission. The estimates of efficiency that were finally used for the MEVP transmission were derived by comparing the design improvements that were made, their appropriate weighing factor, and actual test data taken from the previous ETX-II transaxle design. The decision to generate the efficiency estimate from actual data was based on the belief that better accuracy would be obtained by this comparative method rather than estimating losses for every component separately.

Five planetary gear sets (i.e., one primary, three secondary, and one differential) were considered for MEVP. Preliminary design studies concluded that the prime gear ratio will be 12.18 with 12.74 and 11.69 being the secondary back-up options. These sets are fully manufacturable with current production practice and are also expected to fully meet noise requirements along with all durability requirements. As the transaxle forms a major part of total powertrain weight, every attempt was made in the design studies to minimize component weight.

A number of alternatives were considered for a single pump assembly that would be lubricating the geartrain and cooling the motor. Since the major design goals were efficiency and reliability, the preference was to have an electrical driven pump integrated into the transmission that would give maximum efficiency and variability of control.

Details of the Phase I efforts are described in the Phase I Technical Report, which is included as Appendix A of this report.

5.3 Details of Phase II

Design and fabrication efforts concentrated on the 75-Hp MEVP design. Solid model geometry techniques were used for the finite element analysis of the transmission case and cover, and fabrication methods were investigated for the castings of these parts. The gears were designed, and fabrication was completed. Design parameters were set for an oil pressure sensor, and candidate controllers and motors for the lube and cooling pump/motor assembly were investigated.

Assembly methods for the motor/transaxle assembly were investigated, and a functional test plan was designed for the assembly. Initial effort included assembly of a prototype rotor/input shaft to check the feasibility of different assembly techniques. GE tested the transmission fluid for compatibility with the motor, and the results were favorable.

The first motor/transaxle assembly was installed on a vehicle frame rickshaw, and was tested at GE-CRD using a sine wave generator with the prototype inverter and inverter/motor controls. A dc variable-speed motor for the motor/transaxle assembly lube system was pursued for development purposes.

Various speed sensors for the motor/transaxle assembly were investigated, with one specific sensor chosen to be installed in the assembly in order to continue development and testing at GE-CRD. In addition, the assembly was torn down for examination of the internal parts after the initial testing at GE-CRD, and all mechanical parts were found to be in excellent condition. Flux measurements were made at GE-CRD in the area of the speed sensor, as an aid in the investigation into alternative speed sensors for the motor/transaxle assembly, and a matrix was developed to identify the alternatives.

Efforts during FY92 in the Transaxle task concentrated on speed sensor and electrical connector development, and lubrication and cooling issues, including build of a special rig to determine how the oil for lubrication and cooling is distributed among the gears, bearings and motor. Extensive transaxle development testing, the same as used for Ford Motor Company regular production transmissions, began during FY92, and the transaxle design was completed and hardware built.

5.3.1 Design

Based on testing, appropriate design changes were incorporated as required. Several design upgrades were considered for the motor/transaxle assembly, including electrical connectors replacing the feed throughways for assembly, updating the park mechanism, and updating the locating rings on the motor assembly. In addition, needle bearings were added to the pinion gears in the differential. In order to minimize weight, magnesium was chosen as the material for the case, cover and center support. Figure 5-2 depicts the efforts associated with the magnesium corrosion issues. A photograph of the 75-Hp motor/transaxle assembly cutaway is shown in Figure 5-3.

21 iterations later, the roots causes were found

- 1.) Industry magnesium corrosion standard B117 is not representative of vehicle needs.
- 2.) Magnesium sand casting suppliers are typically low volume suppliers so they are not tied closely with automotive needs.
- 3.) Corrosion was caused by a galvanic cell on the surface between the magnesium and foreign materials (eg, iron, copper).
- 4.) Nitric Acid pickling was not strong enough to remove all foreign materials on the surface.
- 5.) Little to no process controls were in place by the suppliers.

Figure 5-2

Figure 5-3 MEVP 75Hp Motor/
Transaxle Assembly Cutaway

An out-of-balance specification was written for the rotor assembly, and manufacturing issues were resolved, including cooling/lubrication tubes within the assembly and sealing of the case.

5.3.2 Speed Sensor

Speed sensor development was completed, with evaluation of up to 25 different sensors. The study included investigating the effects of different motor speed sensors on the induction motor performance. The outcome of this study showed the minimum resolution needed for operation of the vehicle under maximum load, and showed the trade-offs between several speed sensors. Three (3) were selected for further tests, to evaluate performance in hot/cold environments and vibration. Tests that were conducted helped establish high temperature failure points and shock and vibration limits.

5.3.3 Lube Pump / Cooling

Several lube pump motor alternatives were investigated and cooling tests of the motor/transaxle assembly were conducted in a wind tunnel with the assembly installed in the prototype test bed vehicle. The preliminary analysis of the data indicated that the 75-Hp assembly does not require a heat exchanger. For the 100-Hp assembly however, an external oil cooler is believed to be necessary.

A high voltage ac motor for lube/cooling was pursued with GE, with favorable results. The lube pump design was upgraded with improved efficiency characteristics, and a new fluid was identified. In order to reduce the energy draw from the lube motor, a PWM module was implemented to provide control via a 5-Vdc signal from the vehicle system controller. Changes were also incorporated in the lubrication system to prevent starvation of the pump during high G turns.

Testing using the "oil pig" to determine how lube and cooling flow is distributed among the gears showed that 75% of the flow is used for cooling, with the remaining 25% for lubrication.

5.3.4 Driveline Oscillations (Shudder)

Investigation were made into mechanical interactions within the transaxle assembly that may be contributing to the driveline oscillations mentioned in Section 2.0. Specific testing was conducted using instrumented half-shafts and other special instrumentation on related vehicle components.

5.3.5 Test Results

A motor/transaxle test stand was built during FY92, and an efficiency test matrix was developed. Efficiency and durability tests were run for the motor/transaxle assembly using a test transaxle and this test stand. Figure 5-4 shows the results of the efficiency testing. Gear durability tests were also completed, with good results. High speed, wide-open throttle, torque cycling, simulated towing and dynamometer-simulated durability tests were also run.

The motor/transaxle assembly was subjected to all the testing normally conducted for any Ford Motor Company regular production transmission, and passed all such tests. A listing of the major tests conducted on the assembly is included in Figure 5-5.

EFFICIENCY OF MEVP TRANSAXLE GEARTRAIN

		TORQUE														
		5	10	20	30	40	50	60	70	80	90	100	110	120	130	140
RPM	100	85.9	90.5	92.4	92.4	95.3	92.9	93.1	93.1	93.1	93.5	93.3	93.2	93.5	93.5	92.8
	500	89.4	92.0	93.5	93.9	94.2	93.4	93.4	93.4	93.5	93.4	93.7	92.9	93.5	93.6	92.9
	1,000	88.4	91.9	93.4	93.8	94.4	94.2	94.3	94.4	94.3	94.2	94.1	94.0	94.4	94.4	94.3
	2,000	88.6	92.2	93.5	94.1	94.7	94.7	94.7	94.5	94.3	94.2	94.1	94.0	94.1	94.3	94.4
	3,000	88.4	92.4	94.3	94.4	94.6	93.9	94.5	94.5	94.4	94.2	94.3				
	4,000	88.0	92.3	94.2	94.6	94.8	94.7	94.6	94.7	94.7	94.7	94.5				
	5,000	86.7	91.4	93.8	94.4	94.5	94.4	94.3	94.4	94.3	94.2					
	6,000	87.6	91.9	94.0	94.8	94.9	95.0	94.9	94.8	94.6						
	7,000	DATA UNOBTAINABLE DUE TO 6,000 RPM DYNAMOMETER LIMITATIONS														
	8,000															
9,000																
10,000																
11,000																
12,000																
13,000																

Figure 5-4

COMPONENTS:

- All materials compatibility
- Corrosion issues related to magnesium
- Lube pump & motor durability testing
- Fastener studies (i.e. torque to failure)
- Output shaft torsion tests
- Gasket thermal torque testing
- Gasket vibration cycling
- Planetary housing fatigue
- Parking pawl tests
- Rotor/Shaft torque breakaway
- Rotor/shaft torque cycling
- Wave spring breakaway
- Wave spring fatigue
- Secondary carrier/differential fatigue
- Primary/secondary sun gear fatigue
- Differential carrier/output shaft fatigue
- Vent removal tests (i.e. sealing up the box)
- NVH work on gearing
- Gear shaft push out forces

DYNAMOMETER:

- Efficiency
- High temperature wind tunnel
- High speed testing
- Wide open throttle
- Burst test
- Torque cycling
- Simulated towing
- Water/motor compatibility testing
- Simulated durability testing
 - Collecting/processing the data

MATERIALS, PARKING, SENSORS:

- Miscellaneous tests

VEHICLE:

- 75 mph constant highway
- FUDS

Figure 5-5. EV Transaxle Testing Summary

6.0 TEST BED VEHICLES DESIGN, BUILD AND TEST

6.1 Overview

The Test Bed Vehicles Design, Build and Test task encompasses the integration of the electric vehicle components into the test bed vehicle and testing the vehicle.

6.2 Details of Phase II

6.2.1 Integration Plan

An integration plan was written at the beginning of FY92 outlining a step-by-step procedure for integrating all the electrical/electronic (E/E) system and powertrain components in the vehicle and bringing them up together. The system integration consists of the assembly/installation of these components in the test bed vehicle, and verification that these components provide their specified functions and interfaces within the vehicle context. The basic steps involved in the integration of the components in the vehicle, after checkout of the wiring harness on a breadboard with the major components, include the following:

- Integrate the wiring (high voltage and low voltage), contactors, and instrument cluster
- Integrate the traction battery and traction battery electronics, including the controller, I/O module, charger and dc-dc converter (auxiliary battery charger)
- Integrate the vehicle system controller and diagnostic data logger module, and verify sensor and instrument cluster operation, fault management and subsystem interaction
- Integrate the inverter and inverter/motor controls
- Integrate the climate control system modules
- Integrate the motor/transaxle assembly
- Establish the SCP communication link and verify subsystem communication and interaction
- Verify diagnostic operation with fault injections into the system
- Characterize and minimize EMC/RFI emissions and susceptibility
- Final checkout of the complete system

Ford organized a team of engineers and technicians (integration/development team) to assist in the development of the electric vehicle components and to accomplish the integration of these components in the test bed vehicle. A special laboratory (Electric Vehicle Development Laboratory (EVDL)) was established, using Ford's own funds, to provide a dedicated facility with equipment necessary to conduct the integration and development and integration efforts of the program. The facility includes two chassis dynamometers, two vehicle hoists, a fully-equipped electronics laboratory, several charging stations, and storage area.

As indicated above, a wiring harness breadboard was used to check out the functionality of the major components, prior to integration in the test bed vehicle. The breadboard for wiring harness #1 was used to check out the vehicle system controller, main contactor box and throttle position sensor. Wiring harness #2 was used to perform the complete check-out of the total system with all the components. All the E/E system and powertrain components were then installed in two 75-Hp prototype test bed vehicles, and integration began.

Efforts first concentrated on debug and fine-tuning of the control system, with particular emphasis spent on debug of the vehicle system controller and the inverter/motor controller, followed by the remainder of the control system components. The SCP multiplex link, establishing communications between the inverter/motor controller and the vehicle system controller is operational.

Meetings were held with GE Drive Systems personnel throughout the year to provide assistance in the debug, and to discuss system issues, including the main contactor, inverter and inverter/motor controls.

A vehicle schematic with the actual component locations is shown in Figure 6-1, a concept illustration of the 75-Hp test bed vehicle is shown in Figure 6-2, and a photograph of the deliverable 75-Hp Ecostar test bed vehicle is shown in Figure 6-3.

6.2.2 Test Results

The test bed vehicle was tested in order to prove it met the performance goals set out at the beginning of the program. A PC-based data acquisition system, a schematic of which is shown in Figure 6-4, was used to acquire the test results. The results of this testing are shown in Tables 6-1 and 6-2. Table 6-1 compares the target, simulated and measured performance. Table 6-2 compares the actual results to the program goals. All performance goals for the program were met.

VCC-110 MASTER PACKAGE

Figure 6-1

ECOSTAR

Figure 6-2. MEVP 75Hp Concept Vehicle

Figure 6-3. MEVP 75hp Test
Bed Vehicle

PC - DATA ACQUISITION SYSTEM

Figure 6-4

Table 6-1
Target, Simulated, and Measured Performance

	Target	Simulated	Actual
Range	100 miles	121 miles (1)	116 - 121 miles (1)
Energy Consumption	< 0.330 kWh/mi	0.331 kWh/mi	0.275 - 0.288 kWh/mi
Top Speed	70 mph	75 mph	70 mph
Acceleration Time (0 - 50 mph)	< 14 s	10.8 s (2)	12.5 s (3)

Notes:

- (1) Discharged to 10% SOC (Empty)
- (2) Assumed 66kW from battery for 75Hp
- (3) Actual battery output power limited to 56kW

Table 6-2. MEVP Performance Goals and Actual Test Results.

GOALS

ACTUAL

Acceleration to	50 mph in less than 18 seconds	12.5s
	30 mph in less than 7 seconds	4.8s
Top speed	70 mph	70 mph
Ascend a 30% grade		Yes
Automotive acceptable driveability		Yes
Energy consumption less than 0.095 Wh/lbs-mi [330 Wh/mi for 3500 lb vehicle (from the battery on FUDS)]		0.082 Wh/lbs-mi measured [286 Wh/mi for 3500 lb vehicle]
Range greater than 100 miles on Federal Urban Drive Schedule (FUDS) to 0% Battery State of Charge		130 miles measured for 3500# ETWC*

* ETWC = Equivalent Test Weight Class

7.0 ANCILLARY SUBSYSTEMS DESIGN, BUILD AND TEST

7.1 Overview

The Ancillary Subsystems Design, Build and Test task of the Modular Electric Vehicle Program (MEVP) was modified in January, 1993 to include a subcontract to Sundstrand Power Systems (SPS) for the purpose of providing a modified gas turbine engine APU for emissions and performance testing as well as performing a preliminary design study of an advanced turboalternator auxiliary power unit (APU) for potential use in a hybrid electric vehicle.

The first portion of this subcontract included demonstration testing of an existing SPS Gemini series APU at SPS with some follow-up testing to be performed at Ford. Testing at SPS was completed in late May, 1993 and the APU was shipped to Ford in early June, 1993. Test work performed by SPS has been reported in a series of test reports covering both the APU performance as well as noise testing.

After receipt by Ford, the APU was outfitted with inlet and exhaust duct work fabricated at Ford based on design information supplied by SPS and subsequently mounted on a portable test cart that could be moved from one location to another with minimum disassembly. Test cart assembly was completed in early August, 1993, and a number of engine start/stop runs were made to check-out the installation. No data was recorded during these exercises.

During the week of August 9, 1993, a representative from SPS was on hand at Ford to assist in the final test and check-out of the APU prior to beginning of tests at Ford. On August 12, an operating demonstration of the APU was provided for visiting House and Senate staff members and DOE representatives. The demonstration consisted of a non-instrumented run using a manually-controlled load bank. A similar demonstration was provided representatives of DOE and EG&G Idaho during the monthly MEVP Technical Review meeting on September 9, 1993.

7.2 Details of Phase II

7.2.1 Ford Testing

7.2.1.1 Test Procedure

The original test plan for the Gemini APU (Appendix D) was devised to complement and extend the work completed at SPS by utilizing a programmable electronic load bank which would be able to provide second-by-second load commands to the APU. Using this hardware any vehicle operating strategy could, in principle, be duplicated. Fuel consumption, emissions characteristics and APU operation could all be assessed without actually having to install the unit in a vehicle or do any on-road testing.

Figure 7-1 is a schematic representation of the test set-up at the beginning of instrumented testing. The air-cooled, brushless, alternating current (ac) generator is driven by the gas turbine through a speed reduction gear system. The alternator provides 20 KVA, voltage regulated three phase power at 120 volts, 400 Hz at a nearly constant engine speed of 96000 rpm. Alternator output is rectified to dc through a bridge rectifier. Output dc current is connected to an electronic load bank where the power is monitored and recorded.

The electronic load bank used for these tests is an Automation Technology Model LC-30-400/25. This particular model was configured with a constant potential option which could be controlled by an external signal voltage. Zero to ten volts input to the controller of the load bank corresponds to zero to four hundred volts on the constant potential output.

This load bank was the only load bank available for use at the time of the test that could dissipate the power produced by the APU, having the capability to dissipate 30 KVA. If the voltage regulated output of the alternator was connected directly to the load bank, the two systems, the voltage regulator on the alternator and the constant potential option on the load bank, would be fighting for constant voltage control. To solve this problem the circuit shown in Figure 7-2 was used.

The rectified output was first connected to a high wattage low resistance load, then as part of a series circuit, the electronic load bank was connected as a voltage controlled voltage source bucking the voltage of the rectified output of the alternator. With this configuration the current through the series circuit, as well as the power produced by the alternator, could be controlled by varying the constant voltage output of the electronic load. Since the constant potential could be controlled by an external source, a load cycle could be programmed into this system by connecting a computer to a digital to analog converter which in turn is connected to the control input of the load bank. One of the objectives of the Ford test program was to program the Federal Urban Driving Simulation (FUDS cycle) into the computer to load the APU.

A software program to control the second-by-second load to the APU was written and installed on a 386 PC. Appendix E contains a brief description of the software program, including calibration and governing equations. To test the concept of the circuit, a high voltage laboratory power supply was used in place of the alternator to calibrate the system as well as to insure that the computer program was operating properly.

Alternator output was wired into the circuit shown in Figure 7-2. The voltages across the rectifier and load bank should have been constant during operation at any fixed power demand on the APU. However, the voltage across the rectifier varied from 213 to 268 volts depending on the load conditions. Figure 7-3 shows alternator voltage as a function of current across the rectifier.

Figure 7-1. Gemini APU Test Setup

Figure 7-2. Gemini APU Test Circuit

Figure 7-3. Gemini APU Alternator Voltage Output

Personnel from Sundstrand Electric Power in Lima, Ohio, were contacted to evaluate the voltage change in the alternator. SPS originally tested the alternator with an ac load. During SPS testing it was observed that each leg of the 3 phase output did not vary by more than 0.5 volts over the maximum load range. However, the circuit used at Ford rectified the ac voltage with a diode bridge. According to SPS the rectifier distorted the peak sensing signal going to the voltage regulator circuitry of the alternator voltage regulator circuit. Modifications of input filters were made to the voltage regulator circuit by SPS personnel, however, this did not solve the problem. In addition, SPS believed that the rectifier and load bank distorted the signal needed by the voltage regulator circuit. Major modifications would have to be made to the circuit module on the alternator to hold a constant voltage under these circumstances.

A plan was devised to overcome the inconsistent voltage problem with the alternator. The output power, the voltage across the alternator and the current through the series circuit, was mapped at steady-state currents. A plot of output power vs. current is shown in Figure 7-4. By knowing the current flowing through the series circuit the operator running load tests may infer the power output of the alternator by monitoring the current on an ammeter located on the load bank.

Load tests were run by an operator dialing a potentiometer on the load bank and monitoring the current with an ammeter located on the load bank. However, with this procedure it was not possible to use the programmable feature of the load bank and as a consequence those test items associated with time-varying load could not be accomplished.

7.2.1.2 Results

After a number of moves necessitated by facilities issues, the APU test cart was readied for final evaluation testing on December 4, 1993.

Initial APU Evaluation

The APU was operated from zero load to 20 kW_e in 5 kW_e increments using manual control of the output load bank. Stable engine operation at each steady-state load point was achieved quickly. The following Table 7-1 compares average measured emissions and calculated air/fuel ratio to similar steady-state load points obtained from SPS. Ford results are given first, followed by SPS measurements.

In general, air/fuel ratio was in good agreement except at very light load, NO_x agreement was good, and both the Ford measured HC and CO were somewhat low compared to SPS results. The fact that the measured air/fuel ratio at 5 kW_e is leaner than at 0 kW_e output suggests that some error in either the applied load, the measurement, or engine response to the applied load occurred. Emissions results are based on a 10 second sample.

Figure 7-4. Gemini APU Alternator Power Output

Table 7-1. Steady-State Output Summary

Load (kW _E)	Air/Fuel ratio		NO _x ppm		HC ppm		CO ppm	
0	94	107	58	16	7	18	216	171
5	102	90	18	25	5	10	170	160
10	86	77	28	35	3	9	178	251
15	60	63	43	39	2	8	278	345
20	52	53	46	42	2	7	278	310

From the preceding results, it would appear that at 0 and 5 kW_E output actual fuel flow differences could help explain the fluctuations in air/fuel ratio and emissions. Unfortunately, the fuel flow information recorded by Ford is suspect due to flow meter calibration errors. However, for the purpose of qualitative APU evaluation, the results are considered acceptable.

Operating the APU as a Range Extender :

The following Table 7-2 summarizes APU operation at load points corresponding to points representative of hybrid Ecostar vehicle operation over the FUDS driving cycle with 2 minute update cycles for the APU :

Table 7-2. FUDS Cycle Operating Points

Point #	kW _E	Air/Fuel ratio	NO _x ppm	HC ppm	CO ppm
1	7.00	82	31	2	206
2	5.41	87	28	2	175
3	10.8	70	40	1	278
4	7.03	82	32	1	194
5	6.31	84	30	1	183
6	4.00	92	25	5	155
7	5.62	85	30	3	184
8	4.34	91	26	3	153
9	4.57	90	27	3	156
10	4.00	91	26	3	152

Because the programmable load bank feature was not available, load changes were made manually using a potentiometer input on the load bank front panel. These changes were made quickly, on the order of 3-5 seconds. APU output followed the load changes smoothly, as evidenced by continuous strip-chart recordings made of exhaust emissions.

All of these points are considered fairly light loads compared to the maximum output capability of the Gemini APU. Air/Fuel ratio and NO_x emissions compare favorably to the SPS measured values from Table 7-1. There are some small differences in HC levels for similar operating points, but levels are quite low to begin with.

Transient Operation

The original plan was to operate the APU between two output power levels using the programmable load bank, varying the time required to make the transition between the lower level and the higher level, and then back again. This would be repeated for a number of output power combinations. This testing was performed in an abbreviated manner using manual control of the load bank and is summarized in Table 7-3. As before, load changes were made in from 3-5 seconds, with some minor adjustment to final value as the APU reached steady-state.

As shown in Table 7-3, APU load was initially set to the 'start' value, was changed to the 'mid' value, and then returned to the 'end' value. Data was recorded once APU parameters reached steady-state.

Additional transient testing was planned, but difficulties with the APU over-temperature monitoring thermocouple caused the APU to shut down unexpectedly on a number of occasions during this test sequence. As a consequence, allotted test cell time was exhausted and further testing of the unit was not possible.

Generally, the results in Table 7-3 agree quite well with the steady state results summarized in Table 7-1. Table 7-3 air/fuel ratios at 10 kW_E and below match SPS results in Table 7-1 better than the Ford values.

It is believed that the important conclusion from this test sequence is that the APU behaves quite well during transients. There were no severe emissions or air/fuel ratio excursions while the load was adjusted between starting and ending values which indicates that data obtained at steady-state conditions can be used with confidence to predict the behavior of the APU in transient operation.

Sharp off-loading of the APU was performed in detail by SPS (refer to SPS report ERR-2145 in Appendix C). No severe excursions were observed during those tests.

Simulation Results

Using Gemini test data and the preliminary 24 kW_E design projections supplied by SPS, Ford conducted a number of vehicle simulation calculations comparing the two turboalternators operating under a similar control strategy in a range-extended hybrid vehicle. Results are given in Table 7-4.

Table 7-3. Evaluation of Transient Operation

Load (kW _E)			Air/Fuel ratio	NO _x ppm	HC ppm	CO ppm
Start	Mid	End				
1	5	1	99	20	2	150
			87	28	1	168
				20	1	151
1	10	1	72	20	1	151
				37	1	286
				20	1	152
1	15	1	59	20	1	152
				42	1	387
				20	1	152
1	20	1	50	20	1	152
				45	1	362
				97	2	149
5	10	5	86	28	1	172
				72	1	290
				28	1	173
5	15	5	58	28	1	173
				43	1	389
				28	1	160
5	20	5	50	28	1	160
				47	1	359
				86	1	170

Table 7-4. Range, Fuel Consumption, and Emissions Comparison

		Ford IC Engine	Gemini APU	Preliminary Design
City	Range (mi)	337	104	261
	MPG	28.5	6.5	21.4
	NO _x (gm/mi)	16.5	1.7	0.16
	HC (gm/mi)	1.6	0.12	0.02
Highway	Range (mi)	417	139	332
	MPG	35.7	9.4	27.6
	NO _x (gm/mi)	13.6	1.2	0.15
	HC (gm/mi)	1.2	0.07	0.01

As shown in the table, driving range and fuel efficiency of the preliminary design turboalternator is substantially better than the Gemini unit but still somewhat inferior to a small IC engine. Estimated NO_x and HC emissions of the preliminary design meet ULEV standards while actual Gemini emissions do not. Both turboalternators are at least a factor of 10 better than the feedgas emissions of the conventional IC engine for both emissions species.

This comparison was done for only one vehicle/APU operating strategy. Other strategies may show different absolute results, but we suspect that relative results will be similar.

7.2.1.3 Lessons Learned/Results

Ford considers this qualitative evaluation of the Sundstrand Gemini APU was quite useful for a number of reasons :

- Turboalternators have been proposed as candidate power units for potential hybrid electric vehicles, and they play a major role in the current DOE Hybrid Propulsion systems contract. Testing of the Gemini APU provided Ford with an early opportunity to gain valuable experience in testing a turboalternator. Ford testing confirmed SPS results to the extent possible.
- Inability to load the APU in the manner we had planned and to record second-by-second emissions has defined more clearly facilities and test procedure requirements for subsequent APU evaluations.
- Based on the Gemini example, fuel flow rates for a simple cycle (non-recuperated) APU are high enough to eliminate this type of machine for user in a series hybrid electric vehicle where the power source is required to operate a significant amount of time. For reasons of cost and simplicity, however, such a machine may be appropriate in a range-extended hybrid application where fuel efficiency is not of primary importance.
- Results of preliminary fuel efficiency and range calculations performed using data from the Gemini engine testing at SPS and the projected performance of the preliminary design 24 kW_E made by SPS indicate that continued progress must be made to improve the part load performance of a turboalternator to be competitive on a fuel efficiency basis with a conventional IC engine.
- Based on the projected emissions for the preliminary design turboalternator, it appears that a well-designed conventional combustor has a reasonable chance of meeting ULEV emissions standards. Demonstrating this capability in hardware would be a logical next step.

7.2.2 Sundstrand Efforts

The Sundstrand Power Systems' efforts on this program are described in the Sundstrand Final Technical Report, which is included as Appendix C of this report.

8.0 PROGRAM MANAGEMENT AND REPORTING

The Modular Electric Vehicle Program (MEVP) was an EV propulsion system development program in which the technical effort was contracted by DOE to Ford Motor Company. The General Electric Company was a major subcontractor to Ford for the development of the electric subsystem. Sundstrand Power Systems was also a subcontractor to Ford, providing a modified gas turbine engine APU for emissions and performance testing as well as a preliminary design and producibility study for a Gas Turbine-APU for potential use in hybrid/electric vehicles. The program objective is to bring electric vehicle propulsion system technology closer to commercialization by developing subsystem components which can be produced from a common design and accommodate a wide range of vehicles; i.e., modularize the components.

The Modular Electric Vehicle Program (MEVP) began September 18, 1990 and the Kick-off Meeting was held October 24, 1990 at Ford in Dearborn, with representatives of DOE and EG&G Idaho, Inc. Monthly Technical Review (MTR) meetings were held with DOE and EG&G Idaho, Inc. throughout the program. MTR meetings at Ford in Dearborn were held on December 6, 1990, January 24, 1991, June 26, 1991, October 31, 1991, December 6, 1991, February 28, 1992, May 13, 1992, July 9, 1992, September 17, 1992, March 4, 1993, September 9, 1993 and October 20, 1993. MTR meetings at GE-Drive Systems were held on April 6, 1992 and December 16, 1992. The status of program efforts was presented in detail by the responsible engineers at these meetings. In addition, the Kick-off meeting for Sundstrand Power Systems was held at Sundstrand on February 11, 1993. Ride and drive demonstrations of a prototype test bed vehicle were provided the DOE and EG&G Idaho, Inc. representatives at the October 31, 1991 and April 6, 1992 meetings.

The Phase I Technical Report Approval Draft was submitted to DOE on March 19, 1991 and the Phase I Project Review was held April 3, 1991 at Ford in Dearborn. Approval was provided by DOE on April 10, 1991 to proceed to Phase II of the program for three months, pending submission of preliminary life cycle cost information for the three electric vehicle types. This information was subsequently provided to DOE, and Phase II efforts continued.

Presentations on MEVP were made at the DOE Automotive Technology Development Contractors' Coordination Meetings on October 29, 1991 for FY91, on November 5, 1992 for FY92, and on October 21, 1993 for FY93 in Dearborn. An abstract and preprints of the presentation material for each meeting were submitted to DOE for incorporation into the handbook which was available to attendees at the conference. A paper for each meeting incorporating the presentation material was subsequently submitted to DOE.

Suggestions for the 15th Annual Report to Congress - FY 1991, were submitted to EG&G Idaho, Inc. in October 1991, and an updated Cost Plan dated December 7, 1991 for the program was submitted to DOE on December 10, 1991. Suggestions for the 16th Annual Report to Congress - FY 1992, were submitted to EG&G Idaho, Inc. in October 1992, and suggestions for the 17th Annual Report to Congress - FY 1993, were submitted in October 1993.

The Phase I Technical Report was submitted to DOE on May 29, 1992 and the Annual Report I was submitted in June 1992. The Annual Report II was submitted to DOE in June 1993.

As mentioned in Section 1.0, due to funding constraints by DOE, only the 75-Hp test bed vehicle was built and delivered, with completion of the program in the first quarter 1994. Detailed designs of all components which make up the complete deliverable electric vehicle were completed during this phase. These component designs were implemented in hardware and tested, and the developed components were integrated into the test bed vehicle and tested. The MEVP test bed vehicle was delivered to DOE at the Idaho National Engineering Laboratory (INEL) on January 26, 1994. A media event was held to commemorate this delivery and Ford representatives participated in the event. The modular concept was proven to be viable, and the performance goals established for the program were met.

MODULAR ELECTRIC VEHICLE PROGRAM -- (MEVP)

PHASE I TECHNICAL REPORT

MARCH 1991

DEPARTMENT OF ENERGY CONTRACT

DE-AC07-90ID13019

**PREPARED FOR: U.S. DEPARTMENT OF ENERGY
IDAHO OPERATIONS OFFICE**

**BY: FORD MOTOR COMPANY
TECHNICAL AFFAIRS STAFF
(PRIME CONTRACTOR)**

&

**GENERAL ELECTRIC COMPANY
DRIVE SYSTEMS
(MAJOR SUBCONTRACTOR)**

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ABBREVIATIONS AND ACRONYMS

A	ampere
ac	alternating current
A/C	air conditioning
ATF	automatic transmission fluid
BJT	bipolar/Darlington transistor
CV	constant velocity (joints)
DABC	dual action bridge converter
dc	direct current
DOE	Department of Energy
DOT	Department of Transportation
EMI	electromagnetic interference
ETX-I	Advanced Electric Vehicle Powertrain Program
ETX-II	Single-Shaft Electric Propulsion System Technology Development Program
EV	electric vehicle
FET	field effect transistor
FMEA	failure mode and effect analysis
FMVSS	Federal Motor Vehicle Safety Standards
FORD	Ford Motor Company
FUDS	Federal Urban Drive Schedule
GE	General Electric Company
GVW	gross vehicle weight
hp	horsepower
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
I/O	input/output
IPM	interior permanent magnet (motor)
MCT	MOS controlled thyristors

MEVP	Modular Electric Vehicle Program
NHTSA	National Highway Traffic Safety Administration
NVH	noise, vibration, harshness
o.d.	outer diameter
PI	proportional integral
PWM	pulse width modulation
ram	random access memory
rms	root mean square
RPO	regular production option
SAE	Society of Automotive Engineers
SCP	Standard Corporate Protocol
SERI	Solar Energy Research Institute
SRM	switched reluctance motor
SSSW	six step square wave
TBD	to be determined
TENV	totally closed, non ventilated
V	volt
Vac	volt ac
vdc	volt dc
WOT	wide open throttle

1.0 INTRODUCTION

The objective of the Modular Electric Vehicle Program (MEVP) is to advance electric vehicle (EV) technology towards commercialization by modularizing the components and by making as many modules as possible suitable for use in a range of vehicle sizes. This approach of making components suitable for a wide range of vehicles would allow manufacturers to achieve economies of scale sooner, thus improving the chances for this approach to serve as a foundation technology for commercial product development. Additionally, a major goal is the physical integration of components to allow more cost effective series production on automotive assembly lines. In this program, the propulsion system includes all components and subsystems (from the driver input to the vehicle wheels) that are required to store electric energy on-board the vehicle and, using that energy, to provide motive power to the vehicle. Therefore, the propulsion system includes the battery subsystem, the control subsystem, the dc-to-ac inverter, the ac motor, and the transmission. The single-shaft is a configuration in which the electric motor and the transmission operate on a common axis with the drive wheels.

The purpose of Phase I (Preliminary Systems Studies) of the program was to provide a well documented, quantitative definition of the EV subsystems that shall determine the subsystem designs for the whole project.

Specific objectives for this phase were to evaluate fundamental concepts, factor multi-power capability into the ETX designs, determine performance specifications for each of the target vehicles, and conduct trade-off studies for subsequent designs for the components and subsystems. In addition, specifications for all components and subsystems were to be completed during this phase. This report documents the effort undertaken during Phase I.

Approach

The approach used in pursuing Phase I objectives involved

- 1) The derivation and evaluation of preliminary modularized EV component designs based on the powertrain development methodology and technology developed by Ford Motor Company (Ford) and the General Electric Company (GE) under Department of Energy (DOE) Contract DE-AC08-82NV10308, "Advanced Electric Vehicle Powertrain Program (ETX-I)", and DE-AC07-85NV10418, Single-Shaft Electric Propulsion System Technology Development Program (ETX-II)
- 2) The assessment of suitable advanced battery subsystems
- 3) A study of the packaging issues and performance requirements that arise from their integration to form propulsion systems in a range of suitable host vehicles.

Sketches of the major components for MEVP are shown in Figure 1-1. This figure shows both the building blocks, such as the transmission, the motor, axle ends and separate electrical components, and the modules that could be assembled

The above sketch shows the mechanical components (transmission, clutch packs, motors, and axle ends) required to assemble both the sprung and the unsprung transaxle assemblies shown.

The sketch on the left shows the electrical subassemblies (system controller, lube pump and transaxle controls, inverter and contactor) required to assemble the electrical subassembly for the vehicle.

Figure 1-1. Modular Components and Subassemblies.

using these building blocks, such as sprung and unsprung transaxle assemblies and the electrical/electronic subassembly.

The propulsion system will consist of

- Powertrain Components

Motor/Transaxle - An ac induction motor or interior permanent magnet motor and a single-speed or two-speed automatic transaxle integrated on the same axis as the drive wheels and with a common oil system for lubrication, cooling, and control.

Inverter - A current controlled, pulse-width-modulated dc to ac inverter, accompanying cooling system, and the inverter/motor control subsystem to generate the required control signals.

System Controller - A microcomputer-based subsystem that interfaces with the battery subsystem, the motor/transaxle assembly, the inverter, and vehicle driver commands (accelerate, coast and brake) and other subsystems for complete propulsion system control and vehicle information display. The various subsystems will communicate/transfer data over a general purpose multiplex network known as SCP (Standard Corporate Protocol), which operates to the SAE J1815 standard and is planned for use in other production vehicles.

Dc-dc converter - To provide the power for auxiliary components and contactors or other devices that operate on the standard vehicle 12 V bus.

- Battery Subsystem Components

Traction battery - An energy storage subsystem that will be developed as a cooperative effort by the powertrain developer and the battery manufacturer, which carefully balances cost and performance to provide the most cost effective energy storage subsystem for a range of vehicles. (As noted in the work plan, several technologies will be developed if resources are available.)

Battery Subsystem Controller - A microcomputer-based subsystem that is responsible for monitoring the battery state-of-charge, controlling the charging process, thermal control (heating or cooling, if required), and transmitting any required information for powertrain control or driver display (such as power cutback, temperature warnings, and state-of-charge) to the system controller.

Charger - A unit that is suitable for a wide range of traction batteries. This may be on-board or off-board and integrated with other components or not, as determined in the initial study phase.

While the ETX powertrains represent measurable progress in ac powertrain technology, substantial advancement of this technology is required before it can be transitioned from research to a product engineering stage. A successful modularization of the ETX propulsion system components would permit this transition to occur should market factors, environmental factors, and business conditions suggest such a commercial effort is justified.

The first phase of the program has built on the technology developed in the ETX programs and has included a battery subsystem as an integral element of the program. This combination has been assessed with the objective of realizing the most reliable, lowest cost system capable of achieving the desired goals. Listed in Table 1-1 are the performance goals for Phase I of the program. At the end of this preliminary system design phase, the MEVP goals will be confirmed and suitable test vehicles selected.

Table 1-1. MEVP performance goals.

Acceleration to	50 mph in less than 18 seconds
	30 mph in less than 7 seconds
Top speed	70 mph
Ascend a 30% grade	
Automotive acceptable driveability	
Energy consumption less than 0.095 Wh/lbs-mi [330 Wh/mi for 3500 lb vehicle (from the battery on FUDS)]	
Range greater than 100 miles on Federal Urban Drive Schedule (FUDS)	

The modular EV system will be made up of expandable components that will allow subassemblies to serve various-size vehicles and be installed on conventional automotive assembly lines. It was envisioned that a family of components could be developed that would satisfy small passenger vehicles, compact vans, and full-size vans. These could involve both front-wheel and rear-wheel drive applications. The motor ratings have been chosen to be 50, 75, and 100 horsepower (hp) respectively.

2.0 DEFINITION OF VEHICLES, SUBSYSTEMS AND RELATED TASKS

2.1 Powertrain Parameters and Performance Requirements

The decision to select a powertrain range of 50 hp to 100 hp was based on both favorable experience with the ETX program and the need to extend the upper end to serve the needs of a traffic compatible full-size van. In order to commence system studies it was essential to identify suitable host vehicles for the three MEVP drivetrains so that appropriate vehicle parameters could be used in computer simulations and trade-off studies. Table 2-1 lists the basic parameters of the vehicles selected

Table 2-1. Basic MEVP vehicle parameters.

	MEVP-1	MEVP-2	MEVP-3
Vehicle Type	2 Passenger Commuter	Compact Van	Full Size Van
Payload	300-400 lbs.	500-700 lbs.	1,000 lbs.
Cd	0.39	0.34	0.48
AF	18.5 ft ²	23.6 ft ²	37.7 ft ²
G.V.W.	2,750 lbs.	4,070 lbs.	6,500 lbs.
Power: Weight Ratio	55 lbs/Hp	54 lbs/Hp	65 lbs/Hp

The assessments that were to be undertaken in the preliminary system study required that performance requirements be defined for each of the vehicle types listed above. However, during the early stages of the studies, it became apparent that it would be possible to redefine the performance objectives in line with improved figures and expectations that were emerging. Based on these early indications and previous ETX powertrain performance achievements, new goals were set for Phase I. These are listed in Table 2-2. Although all three vehicles were considered in the system study, efforts were initially focused on the mid-range 75 hp powertrain and to use the results of these efforts as the base for the program. The vehicle was not determined at the beginning of the Phase I efforts. However, the 50 and 100-hp powertrain could be installed as replacement powertrains in the ETX-I (Mercury LN7) and the ETX-II (Aerostar), respectively, to form the MEVP contract deliverables and early performance simulations of the 50 and 100-hp powertrains were based on the two latter host vehicles. More recent model vehicles will be studied as well to assess their suitability as host vehicles.

Table 2-2. MEVP goals for Phase I.

	MEVP-1	MEVP-2	MEVP-3
Powertrain	50 Hp	75 Hp	100 Hp
Range	100 miles	100 miles	100 miles
Energy Consumption	<0.30 kWh/mi	<0.35 kWh/mi	<0.55 kWh/mi
Top Speed	70 mph	70 mph	70 mph
Acceleration Time (to 50 mph)	<14 secs	<14 secs	<16 secs
Gradeability (min. stall torque)	30% (950 ft-lbs)	30% (1250 ft-lbs)	30% (1660 ft-lbs)
Driveability	Automotive Industry Acceptable Standard		

The assessment of powertrain performance in their respective vehicles was to be based on the use of wide-open-throttle (WOT) acceleration simulations and the standard EV duty cycles such as the FUDS, Highway, and SAE J227a/C&D for range estimation. Constant speed grade tests were also simulated for both energy consumption measurement and powertrain power loss predictions for cooling system sizing. The latter duty cycles are shown in Table 2-3.

Table 2-3. Standard EV duty cycles.

	Speed (mph)	Grade (%)
Inter-state highway	55	6
Freeway I	55	0
Freeway II	65	0
Davis dam 1	30	7
Davis dam 2	45	5
Sustained power for cooling system sizing	55	7

2.2 Vehicle Stability, Ride, and Handling Quality

One of the key factors in achieving good ride and handling in a vehicle is the ratio of sprung to unsprung masses, which should be maximized for better ride and handling. During rigorous driving a vehicle's wheels can traverse vertically at up to 20 G, while the sprung body experiences only about 3 to 4 G. The earlier ETX programs successfully demonstrated both sprung front wheel and unsprung rear wheel drive configurations.

If sprung rear wheel drive were to be considered for a vehicle then it is likely that a new suspension would be necessary, raising such issues as body structure mounting, spring and shock absorber location, new CV joint and

suspension arm designs, and overall durability of the suspension system. Clearly, these issues are all vehicle specific, but their influence on powertrain configuration would have to be considered. Similarly, in pursuing the modular concept, it is possible that for any rigid rear axle assembly, the CV joints of the sprung transaxle could be removed and replaced by rigidly-housed half-shafts.

Ride and handling quality is also affected by front-to-rear weight distribution and in particular the battery weight and location. A rear-biased battery location in a front wheel drive vehicle can lead to an excessively light front end, which can affect the gradeability and steering efforts.

The mounting system used to support the transaxle assembly can dramatically affect the level of powertrain-induced vibration, along with the need to ensure the well-controlled application of starting torque during pull-away. The use of internal combustion engine (ICE) mounts in EV conversions often are not appropriate as these are designed to give optimal isolation during the engine idling condition, which is not applicable in an EV.

2.3 Electric Vehicle Underhood Ambient Temperature

The standard vehicle low temperature at which all vehicle components are designed to function as specified is -40°C . The upper vehicle ambient temperature is $+70^{\circ}\text{C}$. In general, in ICE vehicles, all underhood electronic components are designed to operate up to 100°C without damage. This elevated temperature is due to worst case sun loading during non-moving engine idling. The EV underhood ambient temperature should be much less due to two major factors. First, the overall powertrain efficiency is much greater (80% compared to 25%); therefore overall power dissipated as heat is much less. Second, the electric motor is off - not generating any heat at all when the vehicle is stationary and idling. Therefore, the underhood ambient should be less severe than with an ICE vehicle.

Because of the anticipated lower underhood ambient temperatures, air cooling the transaxle and inverter assembly will be considered. Extensive testing is planned to validate this design possibility and confirm temperature calculations.

2.4 Vibration

The EV components will be designed to meet Ford's vibration specifications. The electric powertrain should experience less vibration than the ICE vehicle. In general, it is anticipated that these vehicles will provide a ride as smooth as any production vehicle in their class.

2.5 Battery Safety Needs and Concerns

Safety concerns for EV traction batteries include the reactivity of the battery compounds and high operating temperatures. The primary failure modes of the sodium-sulfur battery are cell rupture due to failure of the beta electrolyte, seal failure, and failure of the cell container. A safety barrier within the ceramic, which limits the amount of sodium available for reaction with sulfur, should the ceramic fail, is incorporated into all cells presently being manufactured. Cell failure can also be caused by collision or by system operating failure such as internal or external shorts, over-temperature, and high charging voltages.

All of these concerns are being addressed by the battery manufacturers through their own safety tests. These tests, at the cell and battery level, include deliberate fracture of the ceramic electrolyte at operating temperature, both internally (high over-voltage, elevated temperatures) and externally by cell deformation. Battery tests on full-size EV battery units have been performed and are continuing at each battery manufacturer. Battery tests include deformation of the battery container, exposure to flooding, short circuits, shock, crash, and vibration. These test are continuing as the battery manufacturers strive to produce a safe and reliable product.

The National Highway Traffic Safety Administration (NHTSA), under the U.S. Department of Transportation (DOT), is concerned with all matters related to the National Traffic and Motor Vehicle Safety Act. This includes ensuring that all vehicles meet the Federal Motor Vehicle Safety Standards (FMVSS). In 1978 the NHTSA completed a study, "Applicability of FMVSS to Electric and Hybrid Vehicles." The applicability of the FMVSS to EVs and safety standards not addressed by existing standards are described in this study.

A DOE-sponsored meeting (Sodium/Beta Battery Planning Meeting, May 1-2, 1990, Fairfax, VA) on vehicle safety of the sodium-sulfur battery concluded that existing FMVSS are adequate for EV commercialization.

2.6 On-board vs. off-board Charging

2.6.1 Charger

The design, construction, and test of a charger suitable for on-board use, which may or may not be integral with the motor inverter, will have to address numerous technical and operational issues. A preliminary design study has been carried out that considered the factors outlined below, enabling a comparative assessment of the on-board options to be made. This, in turn, will enable a more detailed design specification to be derived.

2.6.2 On-board vs. Off-board Charger

2.6.2.1 Power Quality

The supply of ac line power to the vehicle for an on-board charger must not result in the generation and feedback of harmonic waveforms onto the supply grid and risk violating any future utility power quality regulations.

2.6.2.2 Electrical Issues

The use of ac line power on the vehicle will necessitate compliance with additional electrical safety and electromagnetic interference (EMI) codes. Ground fault interrupters and/or ac line isolation might prove essential.

2.6.2.3 Packaging

In-vehicle location of the charger (without payload space obtrusion) could compromise other subsystem components in terms of heat dissipation, EMI, space, and weight constraints.

2.6.3 On-board Charger Integrated with Inverter

2.6.3.1 Propulsion System Electronics

The possibility of incorporating the traction battery charger within the power inverter used to power the traction battery sharing components to reduce costs was examined. Of principle importance here is the use of the main switching devices, Insulated Gate Bipolar Transistors (IGBTs), to provide a high frequency inverter and minimizing the weight by using motor stray inductance. An investigation into the possibility of using the motor winding revealed that the rotor, which is fairly tightly coupled to the stator, acts as a shorted winding, leading to additional power loss and lower efficiency. A method was found to use the IGBT at a high frequency (20 kHz) and a small (2-lb) reactor to charge the battery from a 115-V, 60-Hz line, but the converter was an "up-converter" and could not be used with a 230-V line. Likewise, a relatively simple "down-converter" could be configured, but would be unusable with a 115-V source. No configuration was found that would provide a converter capable of both up and down conversion and still effectively use the inverter power components.

2.6.3.2 Reliability

Failure of the charger, particularly in components common to both the inverter and charger, could result in damage to the propulsion system. Similarly, the inverter could also be susceptible to damage from poor input line quality (i.e., imported ac line voltage spikes) with consequential loss of propulsion power.

2.6.3.3 Power Quality

The input current of a high frequency boost charger could be profiled to give a sinusoidal, synchronized waveform with resulting high energy efficiency, unity power factor operation. This would ensure that the charger would present a clean harmonic-free load to the ac line that would comply with any present or projected utility power quality regulations.

2.6.3.4 System Complexity

Although system components can be used in a dual function mode in both the inverter and integrated charger, the resulting added complexity arising from interlocks, isolation, screening, etc., could more than offset any silicon cost savings as well as compromise system reliability.

2.6.3.5 Dc-dc Converter/Charger Integration

A much greater degree of commonality exists between the power circuit components of the dc-dc converter and the charger. See Section 5.7.

2.6.4 Dedicated On-board Charger

2.6.4.1 Operating Frequency

The design freedom that comes from not integrating the charger with the inverter enables low loss, high frequency switching devices to be used in a

resonant mode boost charger. Such a design would give the best prospects of minimizing charger size and weight and also maximizing operational efficiency.

2.6.4.2 Reliability

Unlike the integrated version, failure of the dedicated charger would not result in damage to the inverter or motor.

2.6.4.3 Operational Flexibility

In addition to the benefit of improved versatility that comes from an on-board 220 V supply charger, there is a growing prospect that a compact, high frequency charger could be integrated into the battery tray such that the battery could also be charged when out of the vehicle. Additionally, any battery type (e.g., lead-acid and sodium-sulfur) could be interchanged between vehicles without any reprogramming of charging schedules.

The achievement of satisfactory, energy efficient charging that maximizes battery life will not only depend on the battery controller implementing the appropriate charging schedule but also on the ability of the charger's power supply (i.e., power converter) to provide a suitable range of regulated charging current (e.g., 0.5 to 50 A). For comparison, it is worth noting that classical taper chargers have limited current range (e.g., 4:1 starting to finishing rates) with virtually no low current control.

In addition to considering the above issues, the preliminary design study will have to address a baseline specification that will define operating voltage and current limits suitable for all battery types. A nominal specification for these might be

Nominal voltage: 336 V
Maximum voltage: 385 V
Maximum current: 20 A
Minimum float current: 0.5 A
Nominal input voltage: 230 V, 30 A, 1 phase
(115 V, 1 phase input available for emergency).

Of equal importance will be the need to address the numerous battery charger standards that exist. Each of the standards and regulations itemized below will be assessed for their applicability to the charger design being pursued.

UL Standard 1564, Industrial Battery Chargers

UL Standard 1236, Residential & Commercial Chargers

FCC 47 CFC Part 15 General Docket No. 87-389, Emissions from Digital Switching Equipment

IEEE Standard 519-1981, IEEE Guide for Harmonic Control @ Reactive Compensation of Static Power Converters.

The following standards and recommended practices will be employed to measure electromagnetic radiation levels from the charger and associated vehicular components:

SAE J551	Oct 85 - Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles & Devices (30-100 MHz)
SAE J1816	Oct 87 - Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles & Devices Narrowband, 10 kHz to 1000 MHz
SAE J1113	Aug 87 - Electromagnetic Susceptibility Measurement Procedures for Vehicle Components.

The testing of the charger will essentially comprise two stages. In the first stage, the quality of the output power and its stability with time and power level, ac line input waveform, and power factor will be measured both on the bench and as part of a vehicle system using initially a lead-acid traction battery. In the second stage, charging tests will be undertaken using the other advanced batteries selected for the MEVP, both in the laboratory and on-road.

2.7 Driveability

A major consideration in the early stages of Phase I was the achievement of "automotive industry acceptable driveability," which is both subjective and relative. A good driver feel is partly determined by how the powertrain responds to the driver's demand in terms of response time and predictability and the smoothness of response. The driver can be viewed as one of the input elements in a closed loop system that constitutes the powertrain, the response of which must match human reaction times. As electric motors are capable of rapid changes in torque, it is essential to have means of controlling and changing the torque response of the motor. The achievement of a smooth power flow is important, particularly during any gear changing or when the ac motor switches from pulse width modulation (PWM) to six step square wave (SSWW) mode of operation. The relative merits of one-speed and multiple-speed transmissions, one motor or multiple motors, and sprung or unsprung transaxle configurations were factored in during early trade-off studies that included driveability issues. Other major considerations included

- WOT response
- Part throttle response
- Brake response, inclusive of regenerative braking
- Shift response, if multiple speed transmission used.

The quantitative representation of the "performance feel" of a vehicle has traditionally been based on acceleration vs velocity curves for the vehicle/powertrain under consideration. Performance feel estimates were derived for the MEVP powertrains using WOT computer simulations. Automotive industry datum acceleration/velocity curves were used in comparative assessments.

2.8 ETX Technology - MEVP Component Concept-Implications

The objective of MEVP is to advance EV technology toward commercialization by modularizing the components and making as many modules as possible suitable for use in a range of vehicle sizes. In order to attain this objective, the components and technology developed in ETX-I and ETX-II will serve as a foundation for the MEVP.

In general, the modular propulsion system concept being proposed is aimed at moving the technology toward commercialization through improving the size, weight, efficiency, reliability, and cost effectiveness of the powertrain components developed in the ETX program and by developing and integrating advanced battery technologies compatible with the powertrain to form a complete propulsion system. The major technological advancements of the modular propulsion concept will be a function of the range of applicability of the components.

The integration and simplification of system controls is an important element of moving ac propulsion system technology forward. While it may not be beneficial to integrate all vehicle, powertrain, battery, and other subsystem controls into one central vehicle controller (as evidenced by present automotive designs), ETX program experience has clearly indicated a greater level of integration and simplification is necessary. A major effort in the program will be to evaluate the level of integration and simplification of controls and signal conditioning and to develop a single system controller with internal signal conditioning. The system controller will be developed to interface with one or more battery subsystem controllers for exchange of vehicle and battery control information.

One of the successes of the ETX program was the power electronics, motor, and semiconductor technology and experience and expertise contributed by GE as a subcontractor to Ford. In MEVP, Ford again is working with GE to accomplish the objectives of the program.

ETX-I, as a first generation ac powertrain technology effort, featured a compact size, low weight, efficient, and potentially low cost integrated motor/transaxle concept and an advanced power transistorized dc to ac inverter. The ETX concept features an ac motor integrated with a two-speed automatic transmission and concentrically mounted on the drive axle of the vehicle. In comparison to other known powertrain concepts at the time of its proposal, ETX-I represented a substantial step forward in this technology.

ETX-II, a second generation ac powertrain, took concepts developed in ETX-I and moved them a step closer to commercialization as well as exploring some new technology in the motor and controls. Unique developments for the ETX-II Program included the transaxle, a two-speed automatic transmission and three-phase interior permanent magnet ac motor on a common axis integrated with the rear axle of the test bed van; two sets of three ZJ704 250-A, 360-V Darlington transistors mounted with their associated fly-back diode in a full phase leg module; a compact water cooled inverter to operate up to 500 A from a 200-V battery pack; a system controller that included digital inverter/motor controls, which generate the necessary motor drive signals, and microprocessor-based vehicle controls that interface with the driver; and all of the vehicle subsystems to control motor torque, regenerative braking, transmission shifting, and other necessary functions. In addition, a plug-compatible MOS-controlled

thyristor (MCT)-based inverter was added to the scope of the program to test the MCT technology in the ETX-II system.

While the ETX powertrains are believed to represent measurable progress in ac powertrain technology, substantial advancement of this technology is still required before it can be transitioned from research to an advanced or product engineering stage. A successful modularization of the ETX propulsion system could permit this transition to occur should market factors and business conditions suggest such an industrial effort is justified.

2.9 Auxiliary Subsystem Issues

As EV development progressed through the 1980s, it became increasingly evident that in addition to developing powertrains capable of true traffic compatible driveability, it was also necessary to provide air conditioning and power assisted brakes and steering. Although supplying power to run either pumps or actuators for braking and steering is not too energy-demanding, the provision of an emission-free electric heater and air conditioning does place significant electrical burden on the battery such that range can be notably reduced. Nonetheless, it is acknowledged that a marketable vehicle will have to offer those regular production options (RPOs) and therefore the system impacts of their inclusion must be assessed. The major issues that have to be addressed include

- Air Conditioning (A/C) -
an estimated 3.5 kW is needed for an electrically driven scroll, semi-hermetic A/C compressor using R134a refrigerant
- Heating -
a polymeric positive temperature coefficient (PTC) heating system requires 4-5 kW power (a hydrocarbon fuel-fired heater system can be used in vehicles without A/C where emission free operation is not imperative)
- Braking -
electrically-powered vacuum-assisted brakes can supplement regenerative braking if required and can be regulated so as to maximize regenerative energy returned to the battery.

In addition to pursuing the highest efficiency system components for vehicle climate control, other novel approaches have also been considered for minimizing the overall energy loading on the vehicle. These include

- A solar-cell powered ventilation system for purging hot air from the vehicle interior
- Variable speed A/C and heater control using electronically-commutated motors
- Timers to pre-activate the heater or A/C operation using ac line power when connected to charger (eliminate transient cooldown/heatup power demands)
- Partial recirculation in A/C mode (and possibly in vent mode) to reduce PTC, A/C and blower motor power levels

- Cooling fans to be PWM-controlled and will operate at reduced power levels dependent upon vehicle speed and head pressure
- The PTC heater and the A/C compressor will operate at reduced power levels depending upon temperature lever position and ambient condition (when the blower is 'on') in all modes. Equally, heater and A/C power levels will also be reduced during heavy vehicle performance demands so as to maximize battery power for tractive use.

The desire to offer power-assisted steering in EVs has spurred the development of systems employing electrically-powered actuators. These fall into the two categories of electro-hydraulic and full electric systems. Electrically driven conventional hydraulic steering systems have been developed by several suppliers, but noise and susceptibility to leaks have more than offset their relative ease of packaging compared to the full electric types. Hence their widescale application has been restricted. For the full electric system, accommodating the relatively bulky, electric actuator on either the steering rack or input shaft can necessitate a repositioning of the rack, which can upset the optimum steering geometry, possibly resulting in NVH issues. At present, steering equipment suppliers do not appear to have a fully proven, full electric system capable of meeting automotive industry safety and product liability requirements. This shortcoming will force additional research in order to provide a fully marketable EV product for the mid-1990s.

3.0 SYSTEM TRADE-OFFS, MODELLING AND REQUIREMENTS DEFINITION

3.1 Comparison of ac and dc Drives for Automotive Applications

Although the Ford ETX program successfully demonstrated the advantages of ac powertrains during the late 1980s, it was decided that before any in-depth trade-off studies could be undertaken in the MEVP system study it was necessary to review the factors that had led to favoring ac drives over the longer standing dc versions.

3.1.1 Background

Most variable speed drive applications in the past have been implemented using dc motors. These drives used well established motor designs and a simple controller. Although the advantages of ac drives were known, the principle reason they were not widely used is the high cost of the controller. Recent advances in microprocessor-based controllers, field oriented control, and power devices now allow the application of cost effective ac drives for some applications. For most applications where the power source is a 60 Hz power line, ac drives are still more expensive than equivalent dc drives, since these ac drives require converting the power twice, once to convert the ac line to dc and again to convert the dc to a variable frequency ac. Automotive applications do not require converting the power twice since the power source is a dc battery. Some of the advantages of ac drives, such as higher efficiency, smaller size, and lower weight, are especially important in automotive applications. The advances in electronics make the cost of an ac drive now roughly the same as a dc drive for automotive applications, and other advantages make an ac drive the best choice for a drive being developed for high volume production in several years.

3.1.2 Comparison

The following is a comparison of a dc and an ac implementation of a 75-hp automotive drive. For the cost comparison, a \$50 advantage was assumed for each percentage point of efficiency improvement and one dollar per pound. These numbers come from assuming a one percent improvement in efficiency could reduce the cost of a \$5,000 battery by one percent (or improve the range by one percent) and a reduction of one lb out of a 5,000-lb vehicle could reduce the battery cost of one dollar. The cost estimates used are for a product being designed now for high volume production in three to five years.

3.1.2.1 Motor Comparison

Table 3-1 shows the comparison of the ac and dc motors. The ac motor has a significant size and weight advantage mainly due to the fact that it can be run at higher speeds than a dc motor. The commutator on a dc motor limits its upper speed to about 6,000 rpm or possibly as high as 8,000 rpm. The ac motor can easily be run at twice this speed or even higher. Since the size of the motor is proportional to the torque produced, a motor running at double speed and half the torque will be roughly half the size of a slower motor. The absence of a commutator on the ac motor also reduces the size, weight, maintenance, and cost. The higher volume of ac motors also contributes to a significant cost advantage. GE produces over ten ac motors for every one dc motor produced.

Table 3-1. Ac vs. dc motor comparison.

Power (hp)	<u>ac</u> 75	<u>dc</u> 75	<u>ac System Cost</u>
Max rpm	13,000 rpm	8,000 rpm	
Efficiency			
70 mph (26 hp)	93.7%	86%	-385
35 mph (5.9 hp)	87%	80%	-350
Weight	110 lb	180 lb	-\$70
Cost	\$300	\$750	-\$450
Cooling	Direct spray on rotor and stator	Water cooled jacket	
Size	8.75 inch dia. 7.75 inch long	9 inch dia. 17 inch long	
Reliability	Higher	Lower	
Total			-\$870 to -\$905

Another advantage of an ac motor over a dc motor is improved efficiency. Overall motor efficiency is affected by several factors, such as copper losses, iron losses, windage, and bearings. The differences in losses will vary depending on the type of ac and dc motors being compared. For purposes of this comparison, ac induction motors are compared directly with separately excited dc motors.

If the rotating member of a machine must include wire coils for conduction of currents to produce torque, there are limitations imposed upon the amount of copper that can be fitted into the available slot space, such as insulation and support necessary to hold them in place at high speed, etc. The efficiency of wound-rotor induction motors typically range above 90%. By comparison, the efficiency of squirrel-cage induction motors is typically higher, where the difference in efficiency is primarily the difference in rotor losses. The required armature winding on a dc motor results in the same limitations discussed for wound-rotor induction motors. There are other second order effects, such as brush drop, and increased windage which tend to further reduce the dc motor efficiency in comparison to ac.

A comparison of the efficiency of the two motors was made, assuming a 1.5:1 ratio of speeds. The vehicle speeds and hp required for the two motor speed will depend on the vehicle weight and gear ratios. If the speed is 70 mph, the hp required is 26 hp on a 0% grade. For 35 mph, 5.9 hp is required on a 0% grade. The efficiencies for the ac motor are what can be expected with a PWM type controller, which are less than the efficiency with a pure sine wave. Control algorithms are being developed to improve the efficiency toward the pure sine wave efficiency. The dc efficiencies assume a steady dc voltage and will actually be slightly less when supplied from a chopping dc controller.

The cooling of an ac motor is much simpler than for a dc motor. Since there is no commutator, cooling oil can be sprayed directly on the rotor and stator. The dc motor either requires a liquid cooled jacket or forced air cooling, which also increases weight, cost, and reduced efficiency.

The simplicity of the ac motor with no commutator or brushes results in higher reliability.

The cost of an ac motor is \$450 less than a dc motor. When the system cost advantages of the improved efficiency and the lower weight are included, this cost advantage is approximately \$800. If only the motor is considered, there is a clear advantage for the ac drive.

3.1.2.2 Controller Comparison

The controller comparison shown in Table 3-2 is based on a GE dc drive controller manufactured in high volume for fork lift truck applications and the ac controller being developed on the MEVP program. There are simpler field weakening dc controllers but these have a limited speed range and limited regeneration capability and cannot be started from zero speed under load. This type of controller was not considered in this comparison.

Table 3-2. Ac vs. dc controller comparison.

Efficiency	<u>ac</u> 95%	<u>dc</u> 97%	<u>ac system cost</u> +\$100
Weight	90 lb	60 lb	+\$30
Size	1.0 cu ft	0.6 cu ft	
Cost	\$2,200	\$1,500	+\$700
Reliability	Lower	Higher	
Total			+\$850

A dc controller is less efficient than an ac controller since there are always two power switches in series carrying the current in an ac controller and only one in a dc controller. This efficiency difference will decrease in the future as power devices are improved. MOS-controlled thyristors (MCTs) and improved IGBTs currently under development will result in higher efficiency ac controllers, but they can also be used in dc controllers to improve their efficiency. The ac controller efficiency will approach the efficiency of a dc controller but will never be quite as high.

The size and weight of a dc controller will probably always be less due to the fewer power devices and reduced complexity. This difference will also decrease with the development of better power devices.

The normal failure mode for power devices in either a dc or an ac drive is a shorted device. A shorted device in a dc drive can result in full voltage being applied to the motor and an unintended acceleration if additional circuitry

is not included to protect against this failure. Since there are two devices in series with the motor windings in an ac inverter, the probability of a shorted power circuit is less and the consequence of full dc voltage on a single phase is a loss of motor torque and therefore a safer failure mode.

The cost of an ac controller is \$700 higher, mainly due to the cost of the power devices. This cost difference will also decrease with time but will probably never favor an ac controller.

3.1.2.3 System Comparison

Table 3-3 shows a summary of system advantages of ac and dc drives for automotive application.

Table 3-3. System advantages.

<u>Ac system advantages</u>	<u>Dc system advantages</u>
<ul style="list-style-type: none"> - Higher Efficiency - More reliable (no brushes) - Smaller motor - Lighter weight - Lower cost motor - Motor easier to cool - Long term cost advantages 	<ul style="list-style-type: none"> - Less complex control - Smaller control - More mature technology
Current systems cost projections are about equal	

Although there are no firm numbers now, the system reliability of the ac system is expected to be higher. The reduced reliability of the controller is more than offset by the higher motor reliability.

The cost comparison considering only the motor and controller favors a dc drive by \$250 today. This cost difference will decrease in the future as the cost of electronics decreases. Both motor costs will increase since these are mature technologies and the cost of copper and iron are likely to increase.

When system cost advantages of weight and efficiency are included, there is a slight cost advantage for an ac drive today. When the additional advantages of reliability, motor size, and cooling are considered, there is a clear advantage to an ac drive.

3.2 Single or Multiple Motor Powertrain Configurations

Traditionally, EV powertrains have been based on a single motor transmission driveline, but as motor designs and motor control technology improved, alternative configurations appeared in which two or even four motors (one adjacent to or integrated into each wheel) were used. While these multiple motor arrangements often provided packaging advantages through distributing several small motors instead of a single larger motor (that is, if one were available that could provide the total stall torque requirement), trade-offs had to be made in terms of cost and control complexity. Therefore, it was considered essential to carry out a trade-off study during Phase I that could quantify the relative merits of one motor versus multiple motor powertrains. The study, which is summarized in Figure 3-1, was undertaken (for a 75-hp powertrain) to

• 1 VS 2 MOTORS

	<u>1 Motor</u>	<u>2 Motors</u>	
		<u>Inboard</u>	<u>Outboard</u>
Motor Cost	Less	+135	+135
Inverter Cost	Less	+354	+354
Transaxle Cost	Less	+ 40 %	+ 40 %
Differential		-\$80	-\$80
Joints, Shafts			-\$120
Size	Smaller	Larger	Larger
Weight	Less		
Motor		+40 lb (+ \$40)	+40 lb (+ \$40)
Transaxle		+56 lb (+ \$56)	+56 lb (+ \$56)
Reliability	Higher	Lower	Lower
Redundancy	No	Yes	Yes
Failure Modes	Better	Worse	Worse
Efficiency		+1% (-\$50)	+3% (-\$150)
Development Time	Less	More	More

CONCLUSION - ONE MOTOR

Figure 3-1. System Configuration

compare both single motor and two motor designs, with the latter being configured with both inboard and outboard motor locations.

From Figure 3-1, it can be seen that approximately \$500 additional cost was incurred with the two motors option because of additional total motor materials and machining costs, higher inverter costs (two separate driver and control circuits needed), and increased transmission costs (two half-rated torque transmissions costlier than one full torque transmission). A further \$100 added system cost arises from the extra weight of the two motors and transaxles (based on one dollar additional battery cost per pound of extra vehicle weight).

Some cost savings were identified for the two motor alternatives from the elimination of transmission differentials and half-shafts (approximately \$80 and \$200 for inboard and outboard motors respectively). Similarly, small efficiency gains with two motors resulted from lower ripple losses and, for the outboard configuration, from the elimination of constant velocity joints. For each one percent gain in efficiency a \$50 saving in battery cost was factored.

Overall, it was concluded that the additional costs, increased weight, and longer development times associated with the multiple motor configuration favored the adoption of a single motor arrangement for the modular powertrain development program.

3.3 One-speed vs. Two-speed Transmission

Powertrains developed during the ETX programs employed two-speed transmissions primarily because of the advantage of achieving the stall torque through gearing a smaller motor with its lower peak inverter current rating (determined by the maximum power transistor rating available at that time) rather than using a single speed, larger motor with its correspondingly greater current demand. The second gear provided the top speed capability of the vehicle.

The last five years have seen significant improvement in both power device ratings and cost reduction, such that it was viewed important to revisit the issues that surround the one-speed versus multiple-speed transmission decision. The outcome of the study made on this subject is summarized in Figure 3-2.

On the basis of achieving similar vehicle performance from the both one speed and two-speed options, it can be seen that the major factors were the additional device cost of the two speed motor inverter and the offsetting gains in efficiency that the single speed offered. As in the one motor versus two motor study (Section 3.2), each efficiency point saved was viewed as a \$50 battery cost reduction. The extra control complexity, added weight, and longer development times associated with the two-speed transmission further reinforced the preference for the single speed alternative. (See Appendix A for a description of the relative complexities of the transmission design).

In order to assess any energy consumption differences that might result between one and two-speed transmissions, ETX-I computer simulations were run with both alternatives; only negligible differences were found. As a consequence, it was decided to pursue a single speed transmission design in the subsequent system study.

- 1 VS 2 SPEED

	<u>1 Speed</u>	<u>2 Speed</u>
Transaxle Cost	Less -\$150	More
Control Complexity	Less -\$100	More
Transaxle Efficiency	Higher 4-6% (-\$250)	Lower
Inverter Cost	Higher +\$390	Lower
System Control Cost	Less -\$100	More
Weight	Lower	Higher
Reliability	Higher	Lower
Failure Modes	Equal	Equal
Development Time	Less	More

CONCLUSION - ONE SPEED

- BATTERY VOLTAGE

Maximum - 385 V
Minimum - 237 V

Figure 3-2. System Configuration

3.4 System Cost vs. System Voltage

Having decided that the modular powertrain design should be based on a single speed, single motor transaxle, the next system design factor to be considered was nominal system voltage and its impact on system costs. The power devices chosen were IGBTs projected at 1995 costs. A normalized comparison of power device cost for IGBTs, field effect transistors (FETs), and bipolar transistors projected over the next five years is shown in Figure 3-3. MCT devices were not included in this cost comparison for the reasons outlined in Section 5.5.1.2.

The effect that system voltage has on electric subsystem costs is shown, in normalized form, in Figure 3-4. It can be clearly seen that total system costs are driven by the IGBT devices with a minimum total system cost range occurring between 280 and 340 V. From a system efficiency standpoint, the higher voltages in this minimum cost range would result in lower I^2R losses. However, the maximum system design voltage is limited in this voltage range by the capacitors.

A maximum capacitor voltage criterion used for circuit design is not to exceed 85% of the capacitor's maximum rated voltage. At these system voltages 450-V capacitors would be used, which when applying the 85% limit results in a maximum system voltage of 385 V. This maximum system voltage would be encountered during regenerative braking of the vehicle. As this corresponds to a maximum battery charge voltage, the equivalent open circuit voltage would be 340 V. In considering this as a system voltage, it was considered prudent to select a voltage that is divisible by 12 in order to provide the option of using 12 V battery modules. As a consequence, a system voltage of 336 V was selected, which would form the basis for subsequent system component designs.

Preliminary motor design studies were focussed on the 75 hp, which at the 336-V nominal voltage necessitated 300-ampere IGBT devices in the inverter to handle the corresponding motor currents. Early discussions concluded it was possible to design a motor with a 4:1 constant hp speed range and meet the minimum stall torque requirements for a 4000-lb vehicle on a 30% grade .

In order to further refine the design it was essential to have both a vehicle performance target and the basic vehicle parameters for the 75-hp host vehicle. Figure 3-5 summarizes the preliminary system specification used for computer simulations carried out in support of the motor design.

POWER DEVICE COST INCLUDES DRIVER

Figure 3-3. Power Device Cost (includes driver)

Figure 3-4. Normalized Cost vs. Voltage

Nominal battery voltage: 336 V
Maximum voltage: 385 V
Minimum operating voltage: 200 V
Minimum voltage for rated power: 255 V
Combined motor & inverter efficiency: 0.855
Inertia test weight: 3500 lbs
GVW 4070 lbs
Tire rolling radius: 0.97 ft
Rolling Resistance: 0.011 lbs/lb
Cd: 0.34
Af: 23.57 sq ft
WOT gear efficiency: 0.91
Battery voltage is defined as that present at the inverter terminals.
Maximum inverter power rating is defined at nominal battery voltage under load.

Figure 3-5. Preliminary 75 hp system/component values for simulation studies

Figure 3-6 shows the performance profile of a 1.9-liter ICE vehicle (test weight 2750 lb), considered to be a representative performance target and an appropriate datum for simulation. After numerous iterations on motor design and the assessment of a range of transmission gear ratios of 13:1 and below, a good match with the performance target was achieved, details of which can be found in the transmission section of this report.

3.5 Vehicle Simulation

As mentioned in the previous section, performance estimates (WOT acceleration) needed during the preliminary phase of the system study were carried out by computer simulation. This capability was further developed so as to provide a measure of energy consumption and power loss for the vehicle/powertrain combinations under consideration. Early estimations of vehicle range and cooling system loads were confined to the 75-hp powertrain installed in the compact van (Table 3-4) as defined in the preliminary specification.

1.9L I.C. Engine Vehicle (2750 lbs: Test Weight)

Figure 3-6. WOT - Acceleration vs. Velocity

Table 3-4. MEVP Simulation Summary.

I. Sodium-Sulfur

	0-30 MPH (s)	0-50 MPH (s)	0-60 MPH (s)	RANGE (Mi.)
A) 3 B15 Modules (56 Hp & 30 kWh)	7.7	18.0	28.2	86
B) 4 B15 Modules (75 Hp & 40 kWh)	6.1	14.0	21.0	108

Notes:

1. MEVP-2 EV Baseline Weight: 2,150 lbs.
2. Inertia Test Weight: 3,500 lbs. (Vehicle GVW 4,070 lbs)
3. Payload: 300 lbs. in all cases.
4. Drivetrain Efficiency based on ETX measurements.
5. All ranges are for FUDS duty cycle.

POWER LOSSES

	30 MPH 7% Grade	45 MPH 5% Grade	55 MPH 6% Grade	FUDS
Transmission -	1.6 kW	2.5 kW	3.3 kW	1.1 kW
Motor -	1.1 kW	1.5 kW	3.5 kW	0.7 kW
Inverter -	0.6 kW	0.7 kW	1.0 kW	1.0 kW

Notes:

1. Speed/Grade simulations computed with vehicle test weights at GVW (4,070 lbs.)
2. FUDS simulated with vehicle test weight at 3,500 lbs.

As can be seen, not only have the two batteries given the expected difference in range, the acceleration times have been significantly influenced by the different power output. Although the 40-kWh battery is capable of outputting 75 hp (56 kW), losses in the motor and inverter of approximately 15% limit the powertrain to well below its rated 75 hp (i.e., in effect 66-kW battery needed to ensure 75-hp output from motor). Nonetheless, an acceleration time of 14 seconds to 50 mph and a range in excess of 100 miles is achieved. Simulations carried out later in Phase I with higher power density versions of sodium-sulfur battery show markedly improved acceleration times.

The power loss estimates indicate a total system loss of approximately 3 kW during FUDS operation, increasing by a factor of three when driving at 55 mph on a 6% grade (inter-city cycle) is simulated. The transmission, inverter, and motor efficiency maps used in the above simulations are given in Tables 3-5 to 3-7 respective.

Later, as powertrain modular concepts at the 50 and 100-hp rating were explored, a fuller range of vehicle/powertrain combinations were simulated, using a battery mass fraction of approximately 25% GVW and assuming powertrain-rated power demand could be sustained by the battery (Table 3-8).

In all three powertrain/vehicle combinations the target acceleration times were achieved or improved. Power loss estimates varied between 3.4 and 4.9 kW at constant 55 mph at zero grade, increasing to 6 and 14.2 kW on a 6% grade for the MEVP-1 and MEVP-3 vehicles, respectively.

The effect of operating temperature on motor efficiency was also determined and mapped at 25, 50, 75, and 100°C (see Appendix B for details). Generally, it was found there was very little change (approximately 1 Wh/mi) in energy depletion rate for each 25°C fall in motor/inverter temperature; the minimum occurring at 75°C.

3.6 • Performance vs. Cost

Cost is a key factor in the selection of a powertrain for any vehicle, but when several powertrains are available, their performance trade-offs are rarely established. Normally, vehicle performance is defined first, then the cost of the powertrain that can provide that performance is determined; only rarely are other performance/powertrain cost options considered. One fundamental objective of the modular powertrain program was to determine this relationship. As a consequence, it was first essential to establish the powertrain power rating/cost relationship and its sensitivity to volume as a basic input to the performance study. A summary of these relationships is given in Table 3-9.

For this cost study, three levels of product volume (10,000, 20,000, and 50,000 units) were selected as being appropriate for mid-1990s timescales. Inverter costs are based on the use of IGBT power devices rated at 200, 300, and 400 amperes for the 50, 75, and 100-hp drives, respectively. The total electric subsystem cost figures were normalized relative to the 75-hp drive at a volume of 50,000.

Table 3-5. Transmission Efficiency Map.

		Torque (ft.lb):																			
LU Table:		0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	
Trans. Losses (kW)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Vs Operating Point		1000	0.052	0.304	0.313	0.334	0.356	0.379	0.404	0.431	0.460	0.490	0.522	0.557	0.594	0.633	0.674	0.719	0.766	0.817	0.871
Motor rpm	2000	0.105	0.512	0.545	0.503	0.625	0.669	0.716	0.767	0.821	0.880	0.942	1.009	1.080	1.157	1.239	1.326	1.420	1.521	1.629	
	3000	0.162	0.780	0.806	0.867	0.933	1.004	1.081	1.163	1.251	1.347	1.449	1.559								
	4000	0.212	1.098	1.132	1.214	1.302	1.397	1.498	1.607	1.724	1.849	1.983	2.127								
	5000	0.272	1.427	1.478	1.590	1.709	1.838	1.976	2.125	2.285	2.457										
	6000	0.318	1.730	1.814	1.961	2.120	2.291	2.477	2.677	2.894											
	7000	0.370	1.939	2.082	2.277	2.490	2.723	2.978	3.257												
	8000	0.399	2.103	2.305	2.559	2.840	3.153	3.501													
	9000	0.449	2.302	2.544	2.848	3.188	3.569														
	10000	0.498	2.530	2.812	3.173	3.581	4.042														
	11000	0.517	2.798	3.097	3.464																
	12000	0.564	3.052	3.400	3.823																
	13000	0.611	3.325	3.649																	

Table 3-6. Inverter Efficiency Map.

		Torque (ft.lb):														
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140
Inverter Losses (kW)	0	0.438	0.440	0.560	0.660	0.760	0.890	1.030	1.180	1.350	1.530	1.730	1.930	2.150	2.380	2.630
Vs Operating Point	1000	0.615	0.540	0.750	0.970	1.140	1.330	1.540	1.760	1.990	2.240	2.490	2.760	3.040	3.330	3.630
75 Deg	2000	0.717	0.610	0.870	1.130	1.320	1.540	1.770	2.010	2.270	2.540	2.810	3.100	3.390	3.700	4.010
	3000	0.749	0.660	0.930	1.110	1.300	1.500	1.720	1.950	2.180	2.430	2.680	2.940	3.200	3.470	3.750
	4000	0.656	0.680	0.920	0.930	1.070	1.220	1.390	1.560	1.730	1.910					
	5000	0.433	0.495	0.565	0.640	0.740	0.850	0.970	1.100	1.250						
	6000	0.392	0.464	0.540	0.650	0.780	0.920	1.080	1.250							
Motor rpm	7000	0.374	0.459	0.560	0.700	0.860	1.040									
	8000	0.364	0.450	0.600	0.770	0.980	1.180									
	9000	0.354	0.460	0.640	0.850	1.080										
	10000	0.361	0.480	0.690	0.940	1.220										
	11000	0.354	0.500	0.750	1.030											
	12000	0.367	0.530	0.840	1.160											
	13000	0.348	0.550	0.870												

Table 3-7. Motor Efficiency Map.

		Torque (ft.lb):														
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140
Motor Losses (kW)	0	0.075	0.13	0.32	0.47	0.72	1.05	1.46	1.94	2.49	3.12	3.82	4.59	5.44	6.37	7.37
Vs Operating Point	1000	0.083	0.150	0.360	0.560	0.830	1.180	1.600	2.100	2.680	3.330	4.070	4.880	5.770	6.740	7.800
	2000	0.090	0.170	0.420	0.690	0.980	1.340	1.790	2.320	2.930	3.620	4.390	5.250	6.190	7.210	8.320
75 Deg.	3000	0.109	0.210	0.490	0.860	1.160	1.550	2.020	2.580	3.230	3.960	4.780	5.690	6.690	7.770	8.950
	4000	0.126	0.250	0.570	1.050	1.380	1.790	2.290	2.880	3.570	4.350					
	5000	0.161	0.300	0.650	1.120	1.510	2.020	2.670	3.460	4.410						
Motor rpm	6000	0.193	0.340	0.720	1.160	1.770	2.590	3.650	4.970							
	7000	0.216	0.400	0.820	1.440	2.370	3.640									
	8000	0.232	0.460	0.980	1.880	3.390	5.180									
	9000	0.231	0.500	1.210	2.480	4.470										
	10000	0.236	0.560	1.510	3.370	6.210										
	11000	0.251	0.630	1.890	4.350											
	12000	0.280	0.730	2.640	5.840											
	13000	0.239	0.850	3.020												

Table 3-8
MEVP ACCELERATION PERFORMANCE

	MEVP-1 50 Hp	MEVP-2 75 Hp	MEVP-3 100 Hp
0-30 MPH	4.5	4.2	5.7
0-50 MPH	12.0	10.8	12.8
0-60 MPH	18.4	16.5	19.0
Performance Simulation Wt. (lbs)	2,900	3,600	5,800

POWER LOSSES

	MEVP-1 50 Hp	MEVP-2 75 Hp	MEVP-3 100 Hp
55 MPH 6%	5.97 kW	7.89 kW	14.15 kW
45 MPH 5%	4.45 kW	4.72 kW	8.17 kW
30 MPH 7%	3.62 kW	3.42 kW	5.34 kW
55 MPH 0%	3.36 kW	3.63 kW	4.86 kW
65 MPH 0%	4.53 kW	4.38 kW	7.37 kW

Table 3-9

**Normalized Electric Subsystem Cost vs Volume (1995 Projections)
(One Speed Transmission)**

	<u>One Motor</u>			<u>Two Motors</u> (One Inverter Enclosure)		
	<u>50HP</u>	<u>75HP</u>	<u>100HP</u>	<u>50HP</u>	<u>75HP</u>	<u>100HP</u>
<u>10,000</u>						
Motor	0.87	1.05	1.08	1.30	1.52	1.75
Control	1.54	1.54	1.54	2.50	2.50	2.50
Inverter	1.04	1.28	1.52	1.17	1.38	1.56
TOTAL	1.11	1.30	1.47	1.42	1.59	1.74
<u>20,000</u>						
Motor	0.87	1.05	1.08	1.30	1.52	1.75
Control	1.19	1.19	1.19	1.88	1.88	1.88
Inverter	0.90	1.13	1.35	1.01	1.20	1.37
TOTAL	0.95	1.13	1.29	1.20	1.36	1.50
<u>50,000</u>						
Motor	0.83	1.00	1.03	1.24	1.45	1.65
Control	1.00	1.00	1.00	1.56	1.56	1.56
Inverter	0.80	1.00	1.20	0.92	1.07	1.21
TOTAL	0.84	1.00	1.14	1.06	1.20	1.33

In terms of performance estimates, computer simulations were carried out in two stages, using the latest modular powertrain component designs in both instances. The first series were run with all three powertrains in three vehicles, namely the compact van, ETX-I, and ETX-II respectively, as these three vehicles form the deliverables currently planned for the contract. The results are presented in Table 3-10.

In all instances other than the 50 hp/ETX-II combination acceptable acceleration and gradeability characteristics were obtained.

A second series of simulations were run using the three powertrains, again in the compact van, but with a subcompact commuter car and a full size van as the lower and upper size vehicles. Furthermore, an additional 500 W for drive ancillary loads (lubrication, circulation pumps, and cooling fans) was included in the energy consumption simulation. These results are given in Table 3-11.

These results show the expected diverse performance figures arising from a 2:1 GVW range and 3:1 powertrain rating spread. However, if the extreme figures are disregarded it can be seen that the 50 to 100-hp powertrains offer a good, acceptable range of performance and energy consumption.

In order to make a more viable comparison of performance vs powertrain rating, the tabulated data above is presented in acceleration/velocity curve form (Figures 3-7 to 3-9). As a general guideline for interpretation, a good performance feel will be experienced by the driver if acceleration during the pull-away to 20-mph phase can approach 15 ft/sec^2 . Although this is readily achieved with the commuter car and microvan, the full-size van, with its high GVW, falls short of this. Its performance may be adequate for a vehicle of this size, however, since it exceeds that of comparable existing commercial EVs.

Table 3-10. Performance Data.

ETX I @ 3100 lbs.

	Acceleration			Ramp Power			Level Power	
	Acc 0-15	Acc 0-30	Acc 0-55	Max Gr. Grad	Gr. Spd 30%	Gr. Spd 7%	HP rqd 60 mph	HP dev 60 mph
50 Hp	1.8	4.5	14.2	0.438	20	57	16.4	49.2
75 Hp	1.3	3.2	9.5	0.642	29	70+	16.4	68.6
100 Hp	1.0	2.4	6.8	0.915	40	70+	16.4	104.0

MEVP-2 @ 3500 lbs.

	Acceleration			Ramp Power			Level Power	
	Acc 0-15	Acc 0-30	Acc 0-55	Max Gr. Grad	Gr. Spd 30%	Gr. Spd 7%	HP rqd 60 mph	HP dev 60 mph
50 Hp	2.0	6.7	16.4	0.366	18	55	18.0	50.6
75 Hp	1.5	3.7	10.9	0.523	25	65	18.0	70.0
100 Hp	1.2	2.7	7.7	0.712	36	70+	18.0	101.0

ETX II @ 5100 lbs.

	Acceleration			Ramp Power			Level Power	
	Acc 0-15	Acc 0-30	Acc 0-55	Max Gr. Grad	Gr. Spd 30%	Gr. Spd 7%	HP rqd 60 mph	HP dev 60 mph
50 Hp	3.3	8.0	24.0	0.218	(-)	42	26.2	50.9
75 Hp	2.4	5.7	16.0	0.302	0	53	26.2	70.1
100 Hp	1.9	4.3	11.8	0.389	20	65	26.2	104.0

Table 3-11

ACCELERATION PERFORMANCE AND RANGE

	MEVP-1	MEVP-2	MEVP-3
100 Hp			
	(Time in Seconds)		
0 - 30 mp	2.5	3.2	5.7
0 - 50 mp	6.1	7.4	12.8
0 - 60 mp	9.1	11.0	19.0
75 Hp			
	(Time in Seconds)		
0 - 30 mp	3.3	4.2	7.3
0 - 50 mp	8.8	10.8	19.1
0 - 60 mp	13.4	16.5	31.2
50 Hp			
	(Time in Seconds)		
0 - 30 mp	4.5	5.8	10.2
0 - 50 mp	12.0	15.4	29.4
0 - 60 mp	18.4	23.5	55.7
Performance			
Simulation Wt. (lbs.)	2900	3600	5800
Energy Consumption			
(kWh/Mi) on FUDS*	0.289	0.331	0.515
Range on FUDS*	73	121	97
(Miles)			
Range			
Simulation Wt. (lbs.)	2750	3500	5580

* Includes 500 Watts drivetrain ancilliary loads (i.e. pumps, fans, etc.)

Figure 3-7. MEVP-2 Performance

Figure 3-8. MEVP-1 Performance

Figure 3-9. MEVP-3 Performance

4.0 VEHICLE REQUIREMENTS

4.1 Powertrain Layout

The degree of design freedom available to pursue various powertrain configurations in a vehicle will depend on whether an existing vehicle is to be converted to electric drive or the vehicle is custom designed from the wheels up. However, there are generic aspects of the modular powertrain concept that warrant preliminary layout studies of the three vehicle types. The outcome of the design feasibility studies are shown in Figures 4-1 through 4-3.

All components shown are based on either the latest design estimates or existing prototypes. One dominant modular feature worth noting is the modular battery enclosures. It is proposed that each vehicle battery requirement can be met by two basic module sizes, one full and one half-size modules, both being used in the 75-hp vehicle. The 50 and 100-hp vehicles would need one and two full modules, respectively (albeit with different internal configurations). The packaging constraints encountered for each major component through implementing these component layouts are described in Section 5.0.

PRELIMINARY 50 Hp MEVP VEHICLE PACKAGE

Figure 4-1

PRELIMINARY 75 Hp MEVP VEHICLE PACKAGE

Figure 4-2

PRELIMINARY 100 Hp MEVP VEHICLE PACKAGE

Figure 4-3

5.0 POWERTRAIN REQUIREMENTS

5.1 Preliminary Powertrain Packaging

Throughout the course of the vehicle layout study, potential problems from interaction between the vehicle structure and the powertrain were considered. These potential issues include:

5.1.1 50-hp Vehicle

- A clearance issue appears possible between the transaxle case and the steering rack.
- The provision of adequate underhood air flow could be an issue, especially for air cooled inverter designs.
- Less than desirable transaxle to wheel distance could result in too steep half-shaft angles, possibly generating NVH issues.
- Auxiliary 12 V battery could be a location issue.

5.1.2 75-hp Vehicle

- The rear battery (aft of rear axle) could be both a damageability issue and a ground clearance deviation.
- Unfavorable weight distribution from rear battery location.
- Front suspension cross-member modifications might be required if an electric steering rack is to be used instead of the manual gear.
- Auxiliary 12-V battery could be a location issue.

5.1.3 100-hp Vehicle

- A modified floor pan might be necessary, depending on the contour of the original floor (if applicable).
- Rear located inverter/charger (aft of rear axle) might cause rear damageability issues.
- Rear suspension modifications might be needed depending on whether rear axle is live or sprung.

5.2 Transaxle

5.2.1 Design Objectives

The main design objectives for the design of the motor/transaxle assembly were that it would be as simple and efficient as possible yet provide modular features at the different powertrain levels (i.e., 50, 75, or 100 hp).

The general transmission design was governed by the systems study conclusion that a single speed transaxle would be adequate in meeting the required performance objectives.

Hence, the transmission design goals and vehicle performance requirements were considered to be

- Design targets
 - Maximum efficiency
 - Low weight (including alternative materials)
 - Minimal fluid leakage points
 - Modular design compatibility with other powertrain component requirements
 - Ease of manufacturing
 - Ease of assembly
- Preliminary vehicle performance requirements
 - 75 mph design limit maximum speed
 - 30% gradeability
 - Good driver "performance feel"
 - Minimal NVH
 - Meet vehicle packageability requirements

As vehicle performance is directly linked to transmission gearing, one of the first design aspects to be considered was the determination of a gear ratio that would meet the above objectives. As a consequence, WOT computer simulations were run with a range of gear ratios (9:1 through 13:1) using the compact van as the subject vehicle. Figures 5-1 to 5-3 summarize the findings of the study.

Figure 5-1 shows the relationship between motor speed and the expected top speeds of the vehicle at the different gear ratios with a single speed transmission. It can be seen that in order to achieve a limiting vehicle design speed of 75 mph at a maximum motor speed limit of 13,500 rpm, a gear ratio of approximately 12:1 reduction appears appropriate.

Figure 5-2 shows the performance of the compact van at different gear ratios. As stated earlier, a vehicle's "performance feel" is best defined in terms of its acceleration vs. velocity relationship. The bold line indicates the performance of a 1.9-liter ICE vehicle that is viewed as having a market acceptable performance. The five gear ratios plotted show the different peak accelerations achieved by their respective initial wheel torques and their subsequent convergence in the constant 75-hp region.

Table 5-1 compares the corresponding acceleration times for 0-10 mph through 0-70 mph and the "passing time" from 40-60 mph at the different gear ratios. Again, these times are based on compact van parameters and a 75 hp motor design capable of 143-ft-lb torque.

5.2.2 Transaxle Operation

Having selected a gear ratio of 12.2:1 the transmission design study then progressed to consider the other main features of its operation, which is summarized below. The preferred design for MEVP is based on a double stage planetary geartrain with a planetary type differential, in which power is transmitted from the motor to the wheels through the following stages (refer to Figure 5-3):

- Electrical power is supplied to the motor stator from the upper right hand side of the transaxle case, which induces the rotating magnetic fields in the rotor, causing it to turn.
- The input shaft is pressed by a heat shrink into the motor rotor, where power begins to be converted from electrical to mechanical.
- The transmission input shaft has the sun gear cut into its end, forming the input for the first reduction planetary system.
- The ring gear in the first planetary is held stationary and the carrier becomes the output. This output is coupled directly into the second planetary as the second sun gear.
- The ring gear on the second planetary set is also held stationary and the output for this set also its carrier.
- Since the carrier from the second planetary is integral with the ring gear of the differential, the traction power is output here from the transmission to the wheels.

Figure 5-1. RPM of the Motor vs. Speed of the Vehicle

Figure 5-2. Performance of Compact Van at Different Gear Ratios

Table 5-1. Accelerating and passing times at different gear ratios.

MOTOR DESIGN # 10

MAXIMUM STALL TORQUE OF 143 FT. LBS.

79 HP

TIME	GEAR RATIO				
	9	10	11	12	13
TIME TO 10MPH:	1.41	1.27	1.15	1.05	0.97
TIME TO 20MPH:	2.85	2.55	2.32	2.12	2.02
TIME TO 30MPH:	4.51	4.13	3.92	3.81	3.73
TIME TO 40MPH:	6.85	6.52	6.25	6.27	6.14
TIME TO 50MPH:	10.11	9.74	9.56	9.58	9.44
TIME TO 60MPH:	14.56	14.22	14.11	14.03	14.11
TIME TO 70MPH:	20.60	20.43	20.31	20.45	20.76
TIME FROM 40-60	8.23	8.26	8.36	8.31	8.56

Figure 5-3. Preferred Design for MEVP

- The differential is designed so that the ratio from the ring gear to the sun gear is 2:1. Therefore, if there are equal loads on the wheels there will be no rotation of the pinions, giving equal output to each side. Hence, one side is output through the sun gear and the other is output through the carrier.

5.2.3 Modularity Design Options

As the transmission design outline progressed, several ways of achieving modularity in the MEVP transaxle were considered. At the same time, an assessment was made of the deviations that had to be made from the optimal design in order to achieve modularity.

Scenario 1. Maximum Modularity

Assumptions used

- The motor would stay at 7.5-in. stack length for all three hp requirements
- The objective would be to minimize the number of different components required
- Production volumes will be low (under 10,000/yr)
- Stall torque would increase or decrease proportionately with the base 75-hp requirement.

Unique components required

50-hp transaxle

- Minimal (See note under 100 hp design.)

75-hp transaxle - base unit

- None

100-hp transaxle

- Differential. Concerns over the durability of a common design would probably necessitate a unique carrier for each powertrain, having three, four and six pinions for 50, 75, and 100 hp, respectively. In this manner, the pinions are of identical design with the majority of the machining of the carrier remaining unchanged.

Scenario 2. Optimum Design for each hp Rating

Assumptions used

- The motor would minimize its stack length (to minimize weight) for the 50-hp system (approx. 5.0 in.), and retain the 7.5-in. stack length for the 75 & 100-hp requirements
- The objective will be to optimize the designs by minimizing the weight and sizes of the three different powertrains
- Production volumes will be medium to high (over 10,000/yr)
- Stall torque of the 50 & 100-hp powertrains would increase or decrease proportionately with the base 75 hp requirement.

Unique components required

50-hp transaxle

- Case - passenger side half will be unique (i.e., shorter)
- Input shaft - shorter design
- Output shaft - shorter design
- Cooling tubes - shorter design.

75-hp transaxle - base unit

- None

100-hp transaxle

- Input, output shaft, gears and carriers: There would be no expected increase in size, as the 75-hp transmission has sufficient torque capacity to accommodate the increase in torque at a 100-hp system
- Differential: Concerns over the durability of a common design would probably necessitate a unique carrier for each powertrain, having three, four, and six pinions for 50, 75, and 100 hp respectively. In this manner, the pinions are of identical design with the majority of the machining of the carrier remaining unchanged.

5.2.4 Transmission Efficiency

In order to carry out computer simulations of vehicle performance and energy consumption, efficiency maps are needed for each drivetrain component, including the transmission. The estimates of efficiency that were finally used for the MEVP transmission were derived by comparing the design improvements that were made, their appropriate weighing factor, and actual test data taken from the

previous ETX-II transaxle design. The decision to generate the efficiency estimate from actual data was based on the belief that better accuracy would be obtained by this comparative method rather than estimating losses for every component separately.

The relationships used in the efficiency estimation process are shown in tabular form in Figure 5-4 which shows four segments of the transaxle and their estimated weighting factor

- Losses due to the geartrain are estimated at an equal efficiency to the ETX-II gears
- Losses associated with the bearings are estimated at 90% due to using all needle bearings and only one roller bearing
- Losses associated with the pump are estimated at 70% due to the pump being only a low pressure lubrication/cooling pump with no high pressure control side
- Losses associated with the oil churning are estimated at 50% due to the elimination of the clutches, one way clutch, and the use of a low viscosity oil.

Once these factors were established, an efficiency map (see Table 5-2) could be created to meet the computer simulation requirements.

A general indication of planetary gear sets and how their efficiency is related to the ratio of the ring and sun gears (R/S) is given in Figure 5-5. Note that as the ratio of R/S increases the efficiency decreases. This relationship, along with packaging considerations, lead to the current design of two smaller planetaries in series over other types of configurations.

5.2.5 Gear Design Considerations

Five planetary gear sets (i.e., one primary, three secondary, and one differential) have been considered for MEVP. Secondary sets B & C (refer to Table 5-3) provide some latitude in the final gear ratio. Preliminary design studies concluded that the prime gear ratio will be 12.18 with 12.74 and 11.69 being the secondary back-up options. These sets are fully manufacturable with current production practice and are also expected to fully meet noise requirements along with all durability requirements. Some design guidelines were compromised, however, including

- Helical contact ratio was reduced to obtain minimum package width, decreased and semi-balanced thrust, and increased efficiency. This compromise might create higher gear noise.

	MEVP	ETX - II
Gear Train	100	100%
Bearings	90	
Pump •	70	
Oil Churning **	50	

Efficiency Improvement F
of MEVP vs. ETX-II:

$$K = 1.29$$

$$K = \frac{(4 \times 100)}{(100 + 90 + 70 + 50)} = 1.29$$

- Reflects low viscosity oil and deletion of high pressure pump.
- ** Reflects low viscosity oil and deletion of clutches and OWC.

$$\text{Eff (mevp)} = 100 - \frac{(100 - \text{Eff (etx-II)})}{K}$$

Figure 5-4. Comparison Chart of the Transaxle Losses

Table 5-2. Transmission Efficiency (%).

SPEED (rpm)	TORQUE (FT-LBS)							
	5	10	20	30	40	50	60	70
0	67.5	72.0	85.9	89.7	91.6	92.7	93.4	93.9
500	74.7	78.3	89.1	92.0	93.5	94.3	94.9	95.3
1000	74.9	78.5	89.2	92.1	93.6	94.3	94.9	95.3
2000	78.3	81.9	90.8	93.1	94.3	95.0	95.3	95.7
3000	77.9	81.6	90.6	93.1	94.3	95.0	95.4	95.7
4000	76.9	80.6	90.1	92.8	94.0	94.7	95.3	95.6
5000	76.1	79.8	89.7	92.4	93.7	94.5	95.0	95.3
6000	76.0	79.6	89.5	92.2	93.4	94.2	94.7	95.0
7000	76.8	80.4	89.6	92.1	93.3	94.0	94.5	
8000	78.0	81.4	89.8	92.2	93.2	93.9		
9000	78.5	81.9	90.0	92.2	93.2			
10000	78.7	82.1	90.1	92.1	93.1			
11000	78.8	82.0	90.1	92.1				
12000	78.8	82.0	90.0	92.0				
13000	78.7	81.9	89.9

Figure 5-5. Efficiency-Planetary Gear Sets

Table 5-3. Electric Car Transmission Gear Design Summary.

Design Assumptions: Motor torque = 150 ft-lbs.
 Gear test requirements: 9.25 hours on dyno test dts. - 4 - A at 450 RPM out of
 Differential set: same as above test with 10 RPM speed difference (like AXOD).

Transmission Ratios: 12.74, 12.18, 11.69 Overall using secondary sets A, B, C respectively.
 50% - 50% torque split in differential set.

Gear Set	Primary	Secondary Set A	Secondary Set B	Secondary Set C	Differential
Tooth Nos. (Sun-Pinion-Ri	38-40-118	58-32-122	62-30-122	66-28-122	40-16-16-80
Number of Pinions	4	4	4	4	4
Module (D.P. In.)	.97 (26.18)	1.25 (20.32)	1.25 (20.32)	1.25 (20.32)	1.75 (14.51)
Pressure Angle	15.297	19.172	19.172	19.172	24.114
Helix Angle	25	15	15	15	Spur
Phasing *	Counterphased	Counterphased	Counterphased	Counterphased	Phased
Hunting *	Semi-Hunting	Semi-Hunting	Semi-Hunting	Semi-Hunting	Non-Hunting
Face Width	13	18.5	18.5	18.5	18

Center Distance @	42	58.488	58.782	61.08	.25, 28.25, 56.
S-P (Stat., Arith.)	0.125, 0.25	0.125, 0.25	0.125, 0.25	0.125, 0.25	0.125, 0.25
R-P (Stat., Arith.)	0.125, 0.25	0.125, 0.25	0.125, 0.25	0.125, 0.25	0.125, 0.25

Contact Ratios					
S-P Inv.	2.039	2.023	2.018	2.005	1.412, 1.416
S-P Helical %	1.456	1.055	1.055	1.055	0, 0
S-P Total	3.495	3.077	3.073	3.06	1.412, 1.416
R-P Inv.	1.974	1.988	1.975	1.965	1.388
R-P Helical %	1.456	1.055	1.055	1.055	0
R-P Total	3.43	3.043	3.03	3.02	1.388

Torque Capacity \$	145.94	167.97	180.375	190.35	156.842
--------------------	--------	--------	---------	--------	---------

Notes %, \$ Helical contact ratios & torque compromised to obtain reduced thrust and increased efficiency
 * Phasing, hunting, compromised to obtain 3, 4, 5 pinion capability in diff. set.
 @ Assumed, Stackup not available

Shading Indicates Compromised Parameters

- Torque capacity was reduced in the primary set and will compromise the design to a very small degree. It is expected that durability will not be measurably affected
- Hunting and phasing (design processes used by transmission engineers for noise control) were compromised by having complete hunting and phasing of the differential gear set. This was done to obtain an evenly spaced 3, 4, or 5 pinion assembly option and would permit torque capacity flexibility of the gear set without changing the gear design. Noise is considered to be of little concern since gear mesh frequencies will be very low under normal driving conditions.

5.2.6 Transaxle Weight

As the transaxle forms a major part of total powertrain weight, every attempt was made in the design studies to minimize component weight. Table 5-4 is a weight analysis of the MEVP transaxle. Each component was broken down into its basic materials and the total weight determined. All weights are approximate due to the availability of a completed assembly. The estimated weight of the transaxle assembly was 223 lb, consisting of 342 parts.

5.2.7 Transaxle Lubrication & Cooling

Since in preliminary designs a single pump assembly would be lubricating the geartrain and cooling the motor (see Figure 5-6), there were a number of alternatives that were considered for this system. The two primary options that were studied are

- Use a mechanically driven pump with a drivegear incorporated somewhere in the geartrain.

Advantages

- No leaks points
- Reliable
- Simple
- No electrical complexity

Disadvantages

- Flow varies according to speed
- Cannot regulate cooling of the motor
- Potentially high churning losses
- No ability to control flow rates.

- Use an electrically driven pump. This system could be accomplished by two different approaches.

- Make the pump & motor assembly remote from the transmission.

Advantages

- Simplifies case design
- Easy to package
- Could drive other fluids

Disadvantages

- More leak points
- Requires separate packaging
- Requires close packaging to avoid cavitation
- Decreases efficiency because the pump has to pump additional cold oil.

Table 5-4. MEVP Estimated Transaxle Material Weight Summary.

MATERIAL	Part Number	Part Name	Unit Wt. (lbs.)	Quantity Required	Total Weight
SUBTOTAL - MAGNESIUM	-----	-----	-----	3	18.60
SUBTOTAL - BRONZE	-----	-----	-----	21	0.36
SUBTOTAL - COMPOSITE	-----	-----	-----	1	0.10
SUBTOTAL - OIL	-----	-----	-----	10	10.00
SUBTOTAL - PAPER	-----	-----	-----	2	0.01
SUBTOTAL - POWDERED METAL	-----	-----	-----	1	0.10
SUBTOTAL - RUBBER	-----	-----	-----	15	0.40
SUBTOTAL - STEEL	-----	-----	-----	285	165.18
SUBTOTAL - TEFLON	-----	-----	-----	2	0.01
 TOTAL - ALL MATERIALS	=====	=====	=====	340	194.76
 OTHER DRIVELINE COMPONENTS					
CV JOINTS					
Left Halfshaft & CV Joint Assy.	-----	-----	-----	1	13.40
Right Halfshaft & CV Joint Assy	-----	-----	-----	1	14.50
 TOTAL - OTHER	=====	=====	=====	2	27.90
 TOTAL	=====	=====	=====	342	223

TRANSAXLE AND MOTOR ASSEMBLY LUBE AND COOLING SYSTEM

5-17

Figure 5-6. Transaxle and Motor Assembly Lube and Cooling System

- Install the electrically driven pump as an integral part the transmission.

Advantages

- Minimizes leak points
- Pump always gets packaged correctly
- Minimizes efficiency losses
- Allows option of variable control.

Disadvantages

- Complicates case design
- Requires electrical control

Since the major design goals were efficiency and reliability, the preference was to have an electrical driven pump integrated into the transmission that would give maximum efficiency and variability of control.

5.3 Motor

5.3.1 Motor Selection

In the ac-dc drive system tradeoff study (see Section 3.1), it was concluded that the traction drive would employ an ac motor. Three types of ac motors were considered for the traction drive. These included

- Interior permanent magnet synchronous motor
- Switched reluctance motor
- Induction motor.

Since the cost of the electronic unit for control is essentially the same for each of the candidate motors, it did not enter into the consideration. The induction motor was selected from a comparison of efficiency (particularly at light loads), manufacturability, low cost potential, and design maturity. Since the object of this program is to produce a commercial design, cost and efficiency are of paramount importance in the assessment of alternative designs.

5.3.1.1 Interior Permanent Magnet Motor

The interior permanent magnet synchronous machine was used in the ETX-II project and based upon the knowledge gained in that project, the following important points bear consideration when the interior permanent magnet is compared to the other candidates.

- It is a more expensive machine because of the cost of high energy magnets and the need to use an accurate absolute position sensor, such as the resolver used in the ETX-II project.
- The manufacture of interior permanent magnet motors presents formidable problems in the near term. The motors for the ETX-II project were built by attaching small rectangular pieces of energized magnets to a rotor core with epoxy, attaching the pole shoes with epoxy, and finally wrapping the rotor with a Kevlar wrap. The process is labor intensive, and no machinery has yet been developed to reduce the required amount of labor and the resulting manufacturing cost.

- This type of motor has several unresolved technical problems. In order to properly control the motor, the magnet strength, as well as the inductance of both the direct and quadrature axis, must be known with a fair degree of precision. Experience with the ETX-II project indicated that residual induction could be expected to vary $\pm 10\%$ from the nominal and the magnet strength was greatly affected by temperature. Since the magnet temperature could not be directly measured and the residual was variable, no compensation scheme was developed. As a further complication, there was a significant variation in the inductance of the direct and quadrature axes from motor to motor which forces one to tailor the control to a specific motor.

5.3.1.2 Switched Reluctance Motor

The switched reluctance motor has been used in traction applications and was considered as a candidate for the MEVP drive. The more salient points which eliminated the switched reluctance motor from consideration included

- The switched reluctance motor, like the interior permanent magnet, requires accurate position sensing. Activity is now underway to sense position in a relatively inexpensive manner, but unless these proposed methods can be shown to work properly, an expensive encoder would be required
- The switched reluctance motor requires a small air gap in order to obtain high output per unit volume. In the past, switched reluctance motor traction motors have been built with air gaps as small as 0.007 in. An air gap of 0.020 in. is the smallest that can be accomplished with a high yield in present manufacturing facilities. This is a distinct disadvantage compared with the induction motor
- The switched reluctance motor exhibits a high level of torque pulsations. Methods for using electronic circuitry to reduce or eliminate these pulsation have been proposed but as of yet are unproven.

5.3.1.3 Induction Motor

The induction motor was used successfully in the ETX-I program and calculations indicate that in the speed-torque region where most driving occurs, it will be more efficient than the interior permanent magnet (compared to efficiency data provided in the ETX-II Final Technical Report). A review of the ETX-II data shows that the interior permanent magnet is most efficient at the higher torque levels with the efficiency being reduced somewhat as the torque is reduced. On the other hand, in the ETX-I drive using an induction motor, the torque on the torque-speed envelope was somewhat less than that of the interior permanent magnet, but at lighter torque the induction motor showed a higher efficiency, primarily because of the copper losses associated with field weakening in the interior permanent magnet. Presently, the MEVP drives provide a greater power to weight ratio than either of the two previous programs and operate at higher motor speeds. The result of the increased power to weight ratio and higher speed is that most of the driving occurs at a lower per unit torque and at higher speeds where efficiency at weakened field is important. Under these conditions, the induction motor efficiency is somewhat better than that of the interior permanent magnet motor.

Thus, the induction motor was chosen from among the candidates because it is

- Equal or better in efficiency
- Simpler to manufacture
- Lower in cost
- Mature design.

5.3.2 Motor Design

5.3.2.1 Frame Size

The selection of motor size to support the design hp is constrained by several parameters

- Maximum diameter is constrained by road clearance
- Maximum length is constrained by the maximum allowable angle at the constant velocity joints/half shafts
- Rotor length is limited by the required critical velocity.

The selected motor has a lamination outer diameter (o.d.) of 8.77 in. which is a standard. The selection of a standard was desirable for two reasons

- 1) Production costs will be lowest for large volume production if the motor has a standard. The ideal situation is one in which potential vendors already have production in the frame size selected for the traction motor.
- 2) Although only motor parts, - stator and rotor - are required for the transaxle, several motors (including shells, end shields, and bearings) must be provided for initial tests. This is most easily facilitated by selecting a standard frame size.

In the ETX-I project, the 60 frame size (7.45-in. o.d.) was determined to be too small for the 50-hp motor and thus, a 80 frame (8.77 in.) motor was selected. In the ETX-II project, a diameter larger than the 80 frame was briefly considered, but the next larger frame size did not allow sufficient clearance between the motor and the road.

The 80 frame appears to be ideal for this application. The stack length of the motor is 7.5 in., which makes the stack length slightly less than the o.d. The manufacture of motors with stack lengths greater than the o.d. have been found to have difficulty in controlling the air gap.

As indicated previously, the stack length is 7.5 in. This is the maximum allowable length from the standpoint of space limitations. It is also a desirable length from the standpoint of critical speeds of the rotor (the calculated critical speed is 24,000 rpm).

5.3.2.2 Operating Voltage

The motor must be designed to provide the rated hp over a large range, and the limiting parameter is the ability to produce this hp at the maximum rated speed. This involves trading off operating voltage and the maximum allowable current; for example, if the operating voltage is halved and the maximum allowable current doubled, the number of turns is reduced by a factor of two, and twice as many conductors are paralleled to achieve the same performance envelope. Once a winding configuration is selected, the motor will produce this power at or above the specified voltage. This voltage is referred to as the rated voltage. The rated voltage selected was a battery voltage of 255 V corresponding to a 20% state of charge. This results in a line-line voltage of 194.9 V at the motor terminals.

The line-line voltage for ETX-I was 115.4 V. Many advantages result from having an increased line voltage - from the motor and the inverter standpoint. Only the motor considerations will be discussed here. Ordinarily, motors rated in the 50-100 hp range are operated at voltages of 460 V. Two reasons for this are

- Limit the magnitude of the current
- Make the motor easier to manufacture.

The 100 hp motor of this project is expected to draw in excess of 340 amperes. If the line-line voltage were 115.4 V rather than 194.9 V, this current would be 578 amperes. As the current magnitudes increase, the problems and cost associated with the increasing conductor size create additional concerns.

As the motor operating voltage is reduced, the number of turns in the motor winding is reduced, and the cross sectional area of each turn is increased. The cross sectional area per turn is so large that it is impractical to consider making each turn of one strand. In ETX-I, ten strands of wire were simultaneously placed in each slot for each turn required. If the voltage had remained at 115.4 V, 17 "strands in hand" would have been required for this project. This large number of parallel strands represents a significant problem in making a neutral connection. For 17 strands in parallel, 2 poles in parallel, and 3 phases, 102 conductors must be connected together to form a neutral. This is a formidable manufacturing challenge.

5.3.2.3 Operating Speeds

The motor design selected was quite similar to the motor of ETX-I except for increased stack length. Again, a 2-pole motor was selected, and for the same reason that it was previously chosen. In the ETX-I Program, it was shown that the 2-pole motor and a comparable 4-pole motor have about the same leakage inductance, but the 4-pole motor must run at twice the frequency of the 2-pole motor. Thus, at any speed, the 4-pole motor has twice the leakage reactance and therefore lower power factor. At high speeds, the low power factor of the 4-pole machine severely limits its output making it unacceptable for this application.

Also, the 2-pole design is more desirable in the inverter design since the operating frequency necessary to reach a given speed is 2:1 lower. Since switching losses, which are proportional to the operating frequency, represent a significant part of the inverter losses when operating at high speed at lighter

torques, overall drive efficiency favors the 2-pole design over the 4-pole motor, which operates at twice the frequency.

A 7.5-in. stack length and a top speed of about 12000 rpm were selected. The 7.5-in. stack was the maximum stack length that space limitations allowed. A top speed of about 12000 rpm was selected because of the strength of the aluminum in the rotor limited the critical velocity. For the selected shaft, and a 7.5-in. stack, the critical speed of the rotor is 24000 rpm. A top speed of 12000 rpm, then is 1/2 of the critical speed providing a reasonable safety margin.

A top speed of 12000 rpm, rather than the 9000 rpm of ETX-I, allows a higher gear ratio and increased torque at low speeds. The longer stack length (7.5 in. vs. 4.9 in. for ETX-I and 7.0 in. for ETX-II) allows the motor to provide the low speed torque necessary for a single speed transmission. The stall torque requirements for the 50, 75, and 100-hp applications with a single speed transmission is the parameter that controls the motor size. It was found that by providing more current to the motor at low speeds and increasing the oil flow for cooling, it would be possible to use the identical motor for all three drives (50, 75, & 100 hp) without making major sacrifices in cost or performance, as is in keeping with the objectives of MEVP.

The rotor and stator laminations are only slightly modified from those of ETX-I. A stator lamination with slightly more slot area is planned for mass production of compressor motors. This lamination was selected so that future motor cost for both limited and high volume traction motor production will be a minimum. The laminations will be 3.00 watts/lb, 0.019-in. thick silicon steel. With this lamination, the efficiency for sine wave excitation will exceed 95% in the region where the motor will be operating most of the time over the FUDS cycle.

5.3.2.4 Cooling Methods

The method of cooling the motor is similar to that of ETX-I and ETX-II. Automatic transmission fluid is caused to flow over the stator end turns and the rotor end rings. This warm fluid then passes through the gear train, and if necessary, is further cooled through a radiator before returning to the motor. Air cooling was considered. The major problem encountered in consideration of air cooling was an effective means for removing heat from the rotor during periods of high torque such as hill climbing. When climbing a 30% grade with the 100-hp unit, the rotor dissipation is over 10 kilowatts. The design of the 100-hp unit includes an oil spray of 5 gallons/minute to remove the motor heat and allow it to be removed from the system.

5.3.2.5 Optimum Motor Size

The concept conclusion that the identical motor can be used for all three of the drivelines, (50-75-100 hp) would appear to concede either cost or performance for the sake of modularity. However, the three motor designs are considered to be a constrained optimum design, that is the three designs are the same because of imposed constraints. The single speed transmission design requires considerable stall torque from the motor, and the amount of available current is limited by the battery size and the inverter current rating. The cost of inverter capacity and the cost of battery weight are both large in comparison to the cost of motor weight. Thus the problem becomes one of maximizing the

stall torque and operating efficiency of the motor subject to the constraints of specified maximum allowable stall current and space. In all three applications, the magnetic steel is driven close to its limits.

As mentioned earlier, the design was optimized at 75 hp. The motor selection for this size was limited in maximum diameter by required road clearance and in length by the maximum angle allowed for the half shafts. This motor design is believed to be optimum for the 75-hp drive. If the concept of modularity had been abandoned, how would the 50 and 100-hp motor designs have differed?

The 50-hp motor could be reduced in stack length by a small amount if greater stall current were made available or if stall torque requirements were reduced. However, efficiency would suffer somewhat. The 100-hp motor would be larger, since it has very little power margin at high speeds.

An unconstrained optimum design would be somewhat larger in diameter. Since the MEVP motors must operate at higher speeds than the ETX-I design, a stiffer shaft is required to raise the critical velocity. Since the diameter of the hollow portion of the shaft needed to accommodate the axle is the same as the ETX-I design and the o.d. is constrained to be the same diameter as ETX-I, the rotor magnetic path area was reduced somewhat. The optimum design would also include larger magnetic paths for the stator flux. To meet the stall torque requirements, both stator and rotor magnetic paths are driven well into saturation. Larger flux paths, which could be obtained by increased stack length or increased diameter, could provide lower flux densities, lower core loss, and higher efficiencies.

5.3.3. Calculated Performance

As indicated previously, the motor for the 50, 75, and 100-hp drives are the same; the inverter, the battery package, and motor cooling are different. This was brought about by the challenge of building drives with a single speed transmission while limiting motor current. Some of the salient points are given in Table 5-5 (based upon calculated data only). The stall torques values for the three drives indicated in the figure exceed the values necessary to meet the minimum specified grade requirements. The low speed torque requirements needed to meet low speed driveability requirements (acceleration vs. velocity) resulted in significantly better gradeability than the specified minimum.

Table 5-5. Summary of salient performance features
(Based upon calculated data at 255-V battery).

	50-hp drive	75-hp drive	100-hp drive
Max stall torque	107.6 lb-ft	144.9 lb-ft	179.4 lb-ft
Max stall current	255 amp	300 amp	370 amp
Max hp @ 5000 rpm	52.8 hp	80.1 hp	128.2 hp
Max current	135 amp	203 amp	342 amp
Max hp @ 12000 rpm	53.7 hp	75.2 hp	97.4 hp
Max current	135 amp	203 amp	338 amp

5.4 System Controller

The system controller proposed for the MEVP powertrains will monitor and control the functions of all powertrain components. Figure 5-7 shows the major functional blocks within the system controller and its interfaces with the rest of the powertrain. The microprocessor-based design of the system controller will provide the inherent flexibility and reliability of a software based control strategy for accurate real time control of powertrain functions in various operating modes and the ability to accommodate variations in control required for application to a range of vehicles. As with internal combustion powered vehicles, each unique vehicle will require its own "calibration" with operational parameters specifically established to match its requirements, but the hardware design will be common to all vehicles. The input signal conditioning blocks will receive the signals from various appropriate sensors, such as pressure, temperature, speed, and pedal and switch positions, and convert them into analog or digital signals compatible with the input requirements of the processor. The power driver block will convert the logic level output signals from the microprocessor into power signals required for actuators, such as solenoids, relays, or pumps. The input/output (I/O) circuits will also provide any isolation and filtering required.

The vehicle controls portion of the system controller will also be fully digital and use a microprocessor as its central element. It will receive and interpret driver demands through conditioned signals from the accelerator and brake pedals and the shift lever. It will perform the required real time computations to determine the required motor torque to be used by the inverter/motor controls. In addition, the vehicle controls will regulate the operation of the auxiliary systems, such as cooling and regenerative braking; control the shifting of the transmission, if required; and activate various pumps, fans, and relays, as required and provide powertrain information to the driver. These controls will have the ultimate responsibility for monitoring the operation of all powertrain components and for taking appropriate actions necessary for safe and smooth operation of the powertrain.

Figure 5-7. System Controller Block Diagram

The system controller will integrate all of the vehicle and inverter/motor controls. It will be self-contained and interconnected to other vehicle subsystems.

Type:	Microprocessor-based
Microprocessor:	To be determined (TBD)
Size and configuration:	TBD
Weight:	TBD
Cooling:	Self-cooled
Environmental characteristics:	Automotive compatibility
Inverter/motor controls:	
Type	Digital
Controls	TBD
Inputs	TBD
Outputs	Inverter base drive signals, serial/parallel data
Vehicle controls:	
Type	Digital/analog
Controls	Torque command, transmission shift, Regenerative braking, driver display
Inputs	Driver commands and vehicle subsystem data through switches, potentiometers, transducers
Outputs	Solenoids, relays, lights and serial/ parallel data links

5.5 Inverter

5.5.1 Inverter Electrical Characteristics

5.5.1.1 Overview

The inverter bridge configuration chosen for the MEVP program is essentially the same as that employed in the ETX-I and ETX-II programs with IGBTs rather than Darlington transistors used as the main power switching device (see Figure 5-8). The six leg bridge configuration was chosen to make maximum use of the battery voltage. Each leg consists of an IGBT and an antiparallel diode, providing full, four-quadrant motor operation. A dc link capacitive filter is present to minimize the source inductance and provide an ac current bypass, removing the ripple components from the battery current. Devices for precharging and discharging the capacitor filter are included. Current sensors necessary for protection and regulation are connected in series with the motor leads.

The basic design for the 50, 75, and 100-hp units is identical except for scaling of current sensitive devices.

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5.5.1.2 Power Devices

Four types of power devices were considered for use as the main power switch in the inverter:

- Bipolar/Darlington transistors (BJTs)
- FETs
- MCTs
- IGBTs

All device types listed above provide technically acceptable alternatives for use in the MEVP inverter, with the exception of the MCT. The MCT is a new development and has not yet reached the level of maturity necessary to commit a production design to its use. To substitute one power device for a different one requires some but not extensive rework. Therefore, the choice was primarily driven by cost with consideration given to the projected costs in 1995.

The most expensive alternative was the FET. The highest rated device at 600 V was 50 amperes. In order to provide the 300-ampere capability, six devices would need to be connected in parallel in each of the six switch positions, or 36 devices total. This presented both a reliability and a cost problem.

The BJTs and the IGBTs were comparable in current ratings. Quotes received from Toshiba for the two alternatives were

Device	1990	1991	1992	1993	1994	1995
Dual IGBT 300	132.00	119.00	107.00	97.00	87.00	79.00
Single BJT 300	54.00	52.00	49.00	47.00	45.00	43.00

Note that these costs do not include the drivers. Since the IGBT requires considerably less power to switch, hybrid gate drivers are available and offer excellent speed at a cost well below that needed to gate the BJT. Thus, with the driver included in the cost equation, the IGBT is the most cost effective choice at the present time, even without driver cost in 1995.

To date, inverter testing has utilized the Toshiba MG300J2YS11 as the power device. Two IGBTs with anti-parallel diodes are included in each unit; therefore, three power devices make up the full bridge circuit. Each device is rated to switch 600 amperes at 600 V for a short period of time, and 300 amperes on a continuous basis.

5.5.1.3 Capacitor Filter

The inverter has a high capacitance filter connected across the traction battery input terminals. This filter provides two functions. First it provides an alternate path for battery current to flow when a main switch is turned off, preventing a large rise in voltage caused by energy stored in the battery circuit inductance, and secondly, it provides a path for the ac components in the dc bus

circuit preventing these from circulating in the battery. Generally, the controlling factor on the number of capacitors is the ripple current rating assigned to each capacitor can. If one rates this conservatively, the number of cans would reflect the maximum current expected. However, the capacitors are known to accept higher current levels for a short period of time, the limiting factor being the hot spot temperature. Providing more capacitors than is required increases both the volume and the cost of the inverter. The optimum number of capacitors will be determined by thermal tests after the prototype has been built and the final PWM algorithms are in place. The present capacitor bank consists of quantity 8, 4700 microfarad, 450-Vdc capacitor cans in parallel. The number of cans is expected to drop to four when the final control algorithm is defined. The number of capacitors required for the 50 and 100-hp drives will also be reduced when the final algorithm is in place.

5.5.1.3 Current Sensors

The choice of an algorithm to control the induction motor will require a knowledge of the motor line current. ETX-I and ETX-II used hall effect current sensors in two of the three phase legs of the motor. Since the motor does not have a neutral connection, the third phase current can be reconstructed from a knowledge of the other two phases. Also in the ETX projects, the current sensor was used as a protective device to prevent over-current in the main switching devices. This results in the need for a relatively fast sensor to guarantee that the cells could be switched off before the current reached a destructive level.

The inverter design for the MEVP program will use voltage feedback from across the main switches (IGBT) to detect an over-current condition and switch the cell to the "off" state. The basic PWM control scheme will not use current band (hysteresis) switching, which requires sensor bandwidth at the chopping frequency speed, but rather will use a programmed PWM scheme. This then reduces the bandwidth requirement of the sensor to the motor frequency level.

The present implementation uses two hall effect current sensors in the motor leads. The third phase is reconstructed from the other two. Opportunities for reducing the sensor cost by capitalizing on the need for less bandwidth will be evaluated in Phase II.

5.5.1.4 Power Device Snubbers

The utilization of flat, parallel bus plates to connect the filter capacitors and power devices in addition to the compact packaging allows the elimination of power device snubbers by minimizing source inductance. This arrangement reduces losses, conserves space, and simplifies the design. The maximum voltage overshoot observed across the IGBT on power device turn-off is 75 V without a snubber. This overshoot is somewhat less than is usually achieved with snubbers in common circuit designs.

5.5.1.6 Changes With Power Rating

Most of the detailed work has been done with the 75-hp rating since it is in the center of the design range. Changes in scaling up to 100 hp and down to 50 hp are presented in the following table:

	50 hp	75 hp	100 hp
Power device rating	200	300	400
No. of capacitors	6	8	10
Current sensor	No change		
Controller	No change		

5.5.1.7 Results

Extensive tests have been conducted to characterize the IGBT device when physically mounted in a bridge package closely resembling the expected final arrangement. These include

- Gating requirements. Voltage levels, power supply current, and transient behavior
- Voltage transients occurring while turning off and turning on
- Switching losses including independent measurements of turn-on and turn-off losses.

The measured switching losses of the IGBT power devices at the specified operating conditions are shown below.

Condition	Ref. volts	Rev. current	Energy
Switch on	150	230	3.1 mJ
Switch off	150	300	18.5 mJ

The switching losses achieved with this arrangement are less than one-third of those expected on turn-off and one-sixth off the expected losses at turn-on. This improvement in switching losses was the result of unusually low apparent source inductance and very fast switching obtainable using the IGBT hybrid gating circuit. The characteristics that define a proper gate drive circuit and vendor hybrid circuits for driving IGBTs have been identified and other samples are being evaluated.

Strategies for IGBT protection utilizing the de-saturation principle were investigated and integrated into the gate drive design. Using this technique, an IGBT in an over-current state can be detected in less than 10 microseconds and a recovery strategy initiated to avoid failing the device. The circuitry used to provide this protection utilizes cell voltages avoiding the need to provide current sensors with unusually high bandwidths.

Design guidelines have been established for selecting the capacitors that make up the dc link filter. This includes relating the dc link ripple current harmonic content to the specifications of the candidate capacitors. Since the capacitors provide only a continuous current rating but are known to withstand

considerably higher current for short periods, capacitors with thermal sensors imbedded in the rolls are being acquired to track capacitor temperature during transient loading, such as grade climbing. After additional laboratory testing, a decision will be made as to the required number of capacitors.

5.5.1.8 Inverter Testing

The inverter has been tested in a single phase configuration while switching at 2.5 kilohertz with an average load current of 300 amperes as a first step in understanding frequency limits and losses. A 10-hp induction motor has also been successfully operated with the inverter using a slip control.

5.5.2 Inverter Packaging

5.5.2.1 General

Packaging of the MEVP inverter with control electronics offers some unique challenges since it involves much higher voltages and currents than is found in present day automobiles. The battery voltage, which may be as high as 385 V, introduces serviceability issues. Since the magnitude of current involved is much higher than in present automobile designs, there are essentially no automotive connectors available.

The inverter must be packaged in a protective housing that provides the following features:

- Enclose the live electrical parts to provide protection against shock hazards, including the charge stored on capacitors after the battery has been disconnected.
- Protect the electronics from the automotive environment, which includes pollutants, a wide range of ambient temperatures, vibration, humidity and condensation, wash-down, and salt spray.
- Remove heat generated by primary heat sources (IGBTs) and secondary heat sources (e.g., capacitors, coils) with a minimum component weight, volume, and cost.
- Minimize both conducted and radiated electromagnetic emissions to a level consistent with existing automotive and Federal Communications Commission (FCC) standards. Past projects provide no significant guidance in this area.
- Interface with external signal and power wiring where the interface means must provide long term reliability in the specified environment.
- Fit and compatibility with the available vehicle space with the accent on minimum size and weight. Needs to include understanding necessary to provide for a fit in different vehicles.
- Simple installation and removal including plans for accessibility for diagnostic reasons if required.

- Good manufacturability for low cost/function.
- Meet applicable standards and specifications. The list of applicable standards will need to be developed.

The packaging design challenge is to find an optimum solution that accomplishes these goals at a minimum cost. An iterative approach was required to trade-off alternatives with conflicting goals. A number of solutions for the above functional mix have been analyzed and comparative data provided for consideration in the trade-off of overall system cost.

5.5.2.2 Design and Analysis, Liquid Cooled Inverters

Paper designs of different layouts were developed for a comparison of each approach. Principle variations included:

- Packaging alternatives with the main contactor within the package and separated were considered. Overall system design dictated that the contactor would be external.
- The exact number of filter capacitors has not yet been determined. The package design provides for minimum alterations when the quantity of filter capacitors change.
- Several different arrangements for mounting of the capacitors was considered.
- Installation and removal of the unit involves user access to the traction battery power cable terminations, which can lead to both hazard and reliability problems. Several arrangements have been studied.
- Different methods for mechanically mounting the inverter within the vehicle were explored. The goal is to provide for a 5-minute installation or removal of the unit.
- The unit was arranged into three major sub-assemblies and alternatives arrangements of the sub-assemblies within the package were evaluated. The major sub-assemblies are
 - Heat sink/IGBT
 - Capacitor/bus
 - Control board
- Various enclosure fabrication styles, including welded, and riveted/screwed
 - High performance or low performance heat sinks.

Comparative designs were also done that considered the packaging of accessory components, such as the charger/dc-dc converter, air conditioning inverter within the inverter package, and other combinations of individual and combinational packages. See Figures 5-9 and Table 5-6.

Package	Estimated Volume, Cu.Ft	Cont.Watt Loss
o Traction Inverter 4 Caps, Liquid Cooled 17W x 11D x 9H	1.0	1000
o Traction Inverter Air Cooled w/o Fans 18W x 13D x 9H	1.2	1000
o Charger/DC-DC Convert. Liquid Cooled 13W x 8D x 8H	.5	600
o Air Cond. Inverter Air Cooled 9W x 6D x 6H	.2	200
Combinations, 1 Box		
o Traction Inverter and o Air Cond. Inverter Liquid Cooled 17W x 11D x 9H Note 1	1.0	1200
o Traction Inverter and o Air Cond. Inverter Air Cooled 18W x 15D x 9H	1.4	1200
o Traction Inverter and o Air Cond. Inverter and o Charger/DC-DC Convert. Liquid Cooled 18W x 15D x 9H	1.4	1300 Driving 600 Charging
2 Boxes, Lig.Cooled		1000 Tract.Inv 200 A/C Inv 100 DC-DC
o Traction Inverter and o Air Cond.Inv. Box 1, 1.0 cu.ft o Charger/DC-DC Box 2, .5 cu.ft.	1.5	1300 Driving 600 Charging

Note 1- Packaging and thermal considerations allow for including the Air Conditioning Inverter within the Liquid Cooled Traction Inverter package (1.0 cu.ft.) Adding the A/C Inverter to the Air Cooled Traction Inverter package will increase package volume from 1.2 to 1.4 cu.ft. for the same flow conditions.

Figure 5-9. MEVP components. Typical package sizes and combinations.

Table 5-6. Inverter alternatives

	Alt.1	Alt.2	Alt.3
Box 1	Trac. Inv. A/C Inv. Charger/DC-DC	Trac. Inv. A/C Inv.	Trac. Inv.
Box 2	0	Charger/DC-DC	A/C Inv.
Box 3	0	0	Charger/DC-DC
Liq. Cool. Size Cu.Ft.,est	1.4	1.5	1.7
Air Cool. Cu.Ft.,est	2.1	2.1	2.1
Cost	Lowest ?	Middle	Highest
Maintain- ability	More Difficult	Middle	Easiest

Note: For Liquid Cooling, the ability to utilize both sides of the heat sink for mounting components brings package size economies not possible with a finned air cooled design. This is reflected, based on initial air cooled design effort, in the constant, larger volume, for the 3 different Air Cooled packaging alternatives shown above. Increasing flow rate should reduce air cooled package volume with the penalty of increased fan power consumption. Tradeoffs to be considered during Design Phase.

5.5.2.3 Build and Test - Liquid Cooled Inverter

Prototypes of the two most promising designs (liquid cooling) have been built.

- 1) The first version was built with onboard main contactors, IGBT technology, eight capacitors, internal cable termination box, and mounting details. The dimensions are 20 W x 14 D x 9 H, 1.5 cubic ft sheetmetal welded enclosure and a total weight of 90 lb. Two units were built, one for electrical and one for thermal tests. See Figure 5-10 and 5-11.
- 2) The second version is a mockup of a more compact inverter with IGBT technology, four capacitors, no contactors, no internal cable termination area, with external inverter mounted power connectors. It includes a non-welded thinner gage steel enclosure. The dimensions are 17 W x 11 D x 9 H, 1.0 cubic ft. The calculated weight is 69 lb including 7 lb of power cable, connectors, and fittings. See Figures 5-12, 5-13 and, 5-14.

5.5.2.4 Thermal Tests - Liquid Cooled

Initial thermal tests have begun and results of steady-state heat runs for simulated IGBT losses of 1000 and 1500 watts (the expected range of power dissipation with 75-hp drive, 55 mph and 7% grade) are shown in Table 5-7 and Figure 5-15. Present testing uses cartridge heaters buried in aluminum blocks to simulate IGBT losses for heat sink evaluation, which is acceptable for steady state results. Enclosure temperature rise will be measured as a function of enclosure ventilation styles including totally enclosed, non ventilated (TENV). Later this data will be correlated with data for actual IGBT steady state thermal tests.

The inverter heat sink must provide the proper thermal mass to average the heat dissipation during short term overloads. This balancing of the thermal design for various duty cycle requires extensive testing to find the proper location of a temperature sensor, which can be relied on for use in an active over-temperature protection circuit, which operates effectively for any combination of transient loading. Since the transient thermal response is very dependent upon thermal masses and their locations, this testing will be deferred until the final packaging design has been selected.

Heat runs have also been conducted on size 1/0 and no. 4 cable to verify that the choice of battery and motor cable sizes are adequate to prevent overheating under extreme overload conditions. The results of these tests are tabulated in Figure 5-16. The resistive power loss in a 2 ft length of no. 4 cable is 10 watts for a continuous phase current of 123 amperes, the calculated motor phase current with 75-hp drive in a 3500-lb vehicle at 55 mph up a 7% grade. Peak rms currents for this drive reach 300 amperes (inverter current limit) transiently, but the average over an extended period of time will be under 150 amperes.

GEDS/GBQ

MEVP INVERTER

50-75, 100HP

LIQUID COOLED, IGBT

PM 20W x 14D x 9.4H

1.5 CUFT.

Figure 5-10. MEVP inverter, 75hp, liquid cooled 1.5 cu.ft.,
8 capacitors internal cable connection space - first version

Figure 5-11. MEVP inverter, 75hp, liquid cooled 1.5 cu. ft.,
8 capacitors internal cable connection space - first version

Figure 5-12. MEVP inverter, 75hp, liquid cooled 17W x 11D x 9H,
1.0 cu. ft. 4 capacitors external line and load connectors - second version

Enclosure

Provides protection from 385VDC system volts, EMI containment, and weather/environment shield. Will be tested as dripproof-ventilated and TENV to determine best balance between thermal, environmental and cost needs. Thin gage steel construction.

Heat Sink Assembly

Includes extruded aluminum heat sink, 6 IGBTs, phase lead insulators, and sheetmetal support. Battery leads and phase leads will be brought out to in-line connectors to facilitate installation in the vehicle.

Capacitor and Bus Assembly

Design is evolving toward (4) 3" Dia.x 6" capacitors. Non-inductive sheet bus used to limit voltage overshoot.

Control Board

Board edge connectors will be positioned to accept external signal wires directly, without an intermediate harness with bulkhead connector. Flexible boot will provide environmental seal.

Size: 17W x 11D x 9H 1.0 Cu.Ft
Excluding cables, connectors.

Weight: 69 lbs.total, Traction function only, liquid cooled.

Air cooling and additional functions such as battery charger, DC-DC converter, and air conditioning inverter are being considered as part of the traction inverter package. If incorporated, inverter size and weight will increase.

Figure 5-13. MEVP Inverter, 75 hp, Liquid Cooled Design Features

Inverter Weight, 75HP Liquid Cooled, 4 Capacitors

Enclosure	18.4	
Heatsink Asm.	17.0	
Capacitor/Bus Asm.	18.0	
Wire, CTs, Resistors	4.0	
Board Asm.	<u>4.6</u>	
	62.0	Pounds
Batt.Conn.1/0 Cable	4.0	
Motor Conn.#4 Cable	<u>3.0</u>	
	69.0	Pounds Total

Figure 5-14. Enclosure, Component Parts

Table 5-7. Temperature Rise Above Ambient Air

Loss, Watts	IGBT Case	Heat Sink	Coolant In	Coolant Out
1000	29	20.5	--	--
1500	45	32	21	24.2

Notes: Steady state 30 minute heat run. IGBT losses simulated by aluminum blocks with cartridge heaters. Wakefield 180-20, 5" x 13" x .7" heat sink, 1.7gpm 100% water coolant, Wakefield 908SP water-air heat exchanger, $R_{\theta} = 13$ degree C /Kw for 1.7 gpm. Applies to Figure 6 and Table 3.

Coolant rise with production heat exchanger to be 10 degrees C. Calculated rise from case to junction, 20 degrees C for 1500 W losses.

Figure 5-15

Figure 5-16. Cable Temperature Rise vs. Time

5.5.2.5 Design and Analysis of Air Cooled Inverters

Air cooling the inverter represents a major variation from the liquid cooled packages. Variations may range from simply substituting fins for the liquid cooling plate to a complete redesign optimized for forced ventilation. Air cooling offers the potential of improved efficiency. With liquid cooling, a circulating pump must always be running to transfer heat from the cooling plate to the radiator. With air cooling and access to ram air, it may be possible to use the pressure generated by the ram effect to remove the heat from the heat sink during normal operation and only power the blower during short term high power situations such as climbing steep grades under high ambient air conditions. However, it should be kept in mind that air cooling the inverter does not eliminate liquid cooling from the system; circulation of ATF fluid is still necessary for cooling of the motor and transaxle.

A detailed analytical analysis of air cooling the inverter has been completed and indicates that 200 cfm of air supplied at a pressure of 0.2 in. of water is adequate to meet the continuous rating in an ambient air of 50° C. Thermal performance and pressure drop data are presented graphically in Figures 5-17 and 5-18.

5.5.2.6 Build, Test - Air Cooled

The inverters used in the ETX-I and the ETX-II programs were liquid cooled. The cooling alternatives have been reviewed and the feasibility of air cooling proven by thermal analysis. The first build and test work was done with liquid cooling because of its proven performance in the previous programs. The design of the air cooled version requires closer coupling with the vehicle packaging effort since its location alternatives are limited to those where ram air can be supplied. The latest air cooled package concept (See Figures 5-19 and 5-20) appears to meet all of the objectives, and construction of a prototype for testing will be started in the very near future.

5.5.2.7 Modularity - Various Inverter Ratings

From a production and cost standpoint, it is desirable to have a maximum of common parts for the three inverter ratings, consistent with size, cost, and application (vehicle type) tradeoffs. As previously mentioned, the plan is to size most of the package parts around the midpoint of the range, 75 hp, and downsize for the 50 hp where justified by cost, and expand or enlarge the minimum number of parts and subassemblies to achieve the 100-hp rating. For example, the design phase of the program may determine that the 50 and 75-hp heat sinks and enclosures be identical and the corresponding 100-hp parts larger.

5.5.2.8 Costs

All cost data has been based upon comparative cost to facilitate rapid evaluation of alternative design. Detailed costs are being determined for identified components as the design proceeds with absolute costs, assembly times, etc; be determined once a design configuration is chosen.

5.5.2.9 Manufacturability

Details of the design are being reviewed with in-house manufacturing experts to ensure produceability and outside sources of moldings, connectors, and heat sinks are being considered.

—□— 75 deg —x— 85 deg —▽— 95 deg

Each curve defines losses at the specified
Junction temperature rise above ambient

Figure 5-17. Air cooled inverter, 75hp junction rise as a
function of losses and air flow

50 deg C air
 Heatsink similar to 305A6668
 2.64 x 11.7 x 8.0, 31 fins

Figure 5-18. Air Cooled Inverter (second chart)

Figure 5-19. Current Air Cooling Package Concept

Figure 5-20. Current Air Cooling Package Concept (second picture)

5.6 Inverter/Motor Controller

The inverter/motor controller effort for the MEVP induction motor was focused on the study and development of efficient drive system control techniques for a family of drives from 50 to 100 hp. Based upon the experience gained in the development of the ETX-I drive, which was also an induction motor, the major areas targeted for further understanding and potential improvement included:

- Motor/controller simulator that accurately reflects system losses at low levels of torque
- Flux control strategies for optimizing efficiency at low levels of torque
- PWM algorithm alternatives for maximum efficiency and minimum capacitor filter current
- Motor control algorithms that provide independent control of flux to support the above mentioned functions and to reduce dependence upon tachometers
- Means for reducing current sensor cost and required accuracy
- Means for reducing the complexity of the control algorithms to minimize the computational resources required for operation.

5.6.1 Computer Simulation and Loss Modeling

Considerable work was done in the ETX-I program on improving motor efficiency at high speed and light torque by reducing the motor flux when the torque was low. As a result, the ETX-I motor efficiency remained relatively high in this region. In addition, during the ETX-I program, an algorithm for optimum sine wave efficiency of the motor was developed, but empirical means were used to adjust for motor harmonic losses.

Elimination of the multispeed transmission in the MEVP program and a significant increase in the ratio of motor power to vehicle weight means that the motor will be operating much of the time at higher speeds and lower per unit torque. Given the importance of efficiency (valued at over \$50 per point), considerable work was done to develop a simulation model that would make it possible to determine the efficiency of the motor, including harmonic losses, under varying conditions at high speed and light load. This simulator will serve as a model for the evaluation of alternative efficiency improvement strategies. Two features of this simulator are of particular interest

- Since harmonic losses and stray load losses represent a significant proportion of the total losses under high speed, light load conditions, particular care was taken in the development of a model that accurately represents these losses under those circumstances
- The simulator software was partitioned to allow for the direct substitution of high level code implementing the control algorithms for evaluation and debugging; this code will then be used in the actual working prototype.

The computer simulation contains a model for the 3-phase 2-pole induction motor. During the development of the computer simulation, test cases were run to compare results from this motor model to the results obtained using the variable speed induction motor simulation employed in the development of the ETX-I controller and known to be correct for sine wave and six-step excitation. Good agreement between the two simulators indicated that the basic motor models were correct. Subsequent improvements in the model concentrated on improvements in modeling of the harmonic and stray load losses.

Final validation on the simulator model will be done when the first MEVP induction motor is available. This motor will be characterized using a variable voltage, variable frequency power source, and the data acquisition system used to characterize the ETX-I and ETX-II motors.

5.6.2 Current Regulator and Gating Control

An internal current control loop is required to convert the direct and quadrature axis current commands generated by the torque/flux controller into gating sequences for the inverter phase legs. The hysteresis switching PWM method used in the ETX-I and ETX-II programs provides a simple, reliable method for the regulation of current. However, as illustrated by the oscillograms in the ETX-I and ETX-II final reports, this method results in voltage being applied to the motor, which is of an opposite polarity from the desired voltage, referred to as pulse-polarity-rule violations. These wrong polarity choices lead to increased filter capacitor current increasing both the volume and cost of the inverter. The selection of a PWM switching strategy considered algorithms that would eliminate this problem. Other criteria considered in the choice included:

- Easy microprocessor implementation with a maximum switching frequency of 5 kHz
- Deterministic switch timings
- Minimize harmonic voltage distortion applied to the motor
- Accurate tracking of reference current commands
- Smooth transitioning between linear modulation, overmodulation, and six-step (square wave) operation
- Minimize the sum of inverter switching losses and motor harmonic losses.

5.6.2.1 Synchronous Current Regulator

The synchronous current regulator translates the motor current references (expressed as the direct and quadrature components) into voltage commands for a PWM generation algorithm - effectively converting a voltage reference PWM into a current reference PWM control. Figure 5-21 is a block diagram of this current controller in a synchronously rotating dq reference frame.

Motor current feedbacks are first translated into an orthogonal stationary reference frame and then rotated by the angle $[T(\theta)]$ into a synchronous reference frame. The reference angle (θ) for this rotation is supplied by the flux/torque controller. Current errors are then determined in the synchronous (dq) reference frame by comparing current feedback quantities to the current reference quantities produced by the torque/flux controller. In steady-state operation, the motor drive, reference, feedback, and error quantities in the synchronous dq reference frame are dc quantities. The error quantities are then processed by a PI control algorithm, the integral action of which ensures zero error in the steady state. The combination of integral controller action with error quantities computed in a synchronous reference frame will result in the regulated motor currents tracking the steady-state sinusoidal reference currents with neither magnitude nor phase error - an attribute important to the performance of the outer torque/flux controller.

5.6.2.2 Vector Ratio PWM

A major criteria used in the selection of a PWM strategy was the minimization of capacitor filter ripple currents. Vector ratio PWM eliminates the wrong voltage choices inherent in the hysteresis switching method discussed earlier by time modulating between the four states adjacent to the reference vector ratio. The algorithm divides the complex plane into six sectors. Sector boundaries are defined by the six active states that can be produced by the inverter, labeled V1-V6 in Figure 5-22. Each state corresponds to a gating arrangement of the inverter switches as indicated (e.g., V1(100) corresponds to a phase A switched high, phase B switched low, and phase C switched low). The six active states can produce six vector ratios equally spaced 60 degrees apart on the complex plane, the magnitude of each vector ratio being proportional to the available dc bus voltage. The inverter is also capable of producing two freewheeling or zero states V0(000) and V7(111) corresponding to all inverter phase legs switched high or low respectively - these two states apply zero line-line voltage to the motor and are represented in the complex plane as a point at the origin. This point is available when it is preferable to switch no voltage rather than a wrong voltage since the wrong voltage choices leads to increased capacitor filter current. Hysteresis switching does not provide this zero voltage state.

The central concept of the vector ratio PWM algorithm is to minimize current harmonics by time modulating between the four states adjacent to the reference vector ratio - two active states corresponding to the boundaries of the sector that contains the reference space-vector and the two available zero states. The timing of the switching events is adjusted such that the mean or average vector ratio produced over one switching cycle corresponds to the reference vector.

Figure 5-21. Synchronous Current Regulator

Figure 5-22. PWM Generation

Figure 5-23 illustrates the modulation process for a reference vector in the first sector. The switching sequence proceeds from V0-V1-V2-V7-V1-V0, where each state change corresponds to a change in status of one phase leg. The switching pattern is arranged so that each inverter switch turns on & off once only - by implication the inverter switching frequency is strictly determined by the generation rate of this PWM pattern.

Figure 5-24 illustrates the line-neutral voltage produced by the vector ratio PWM algorithm while Figure 5-25 illustrates the corresponding motor current and torque. The switching patterns are very regular and respect the pulse-polarity-rule, in that bipolar switching only occurs at the zero cross-over of the voltage fundamental. The harmonic spectrum associated with a vector ratio PWM is concentrated about the switching frequency. This spectrum can be spread by varying the timing of the basic switching rate to alter the audible noise produced by the drive.

Figure 5-26 compares the filter capacitor ripple currents using vector ratio PWM control in the simulator to that using hysteresis switching. As shown in Figure 5-26, a considerable reduction in the ripple currents is achieved through the use of vector ratio PWM.

5.6.3 Harmonic Reduction

The application of non-sinusoidal voltages to an induction motor results in harmonic currents having a frequency different from the desired frequency, and the resulting air gap fields reduce the overall efficiency of the drive. Two types of fields are created: backward fields, which generate torques in a direction opposite to the desired direction, and forward fields, which develop torque in the correct direction but inefficiently because of large slip values. Since torque is produced by current and the induction motor input impedance has an inductive component, it can be generally concluded that the higher the harmonic order, the smaller the resulting torque for the same harmonic voltage amplitude.

The amplitude of the harmonic currents in the motor can be reduced by increasing the inverter switching frequency; however, this will not necessarily improve system efficiency since the inverter losses increase with frequency; the optimum will occur where the sum of the inverter losses and motor harmonic losses are a minimum. A series of simulations was run with a variety of modulation patterns to examine this issue. The motor operating point was chosen at a speed of 9700 rpm and a load torque of 7.9 lb-ft corresponding to the vehicle running at 55 mph on level terrain.

Four modulation strategies were compared:

- SSSW - commonly used in inverter control and produces significant 5th and 7th harmonic components and all higher order odd harmonics not divisible by three

Figure 5-23. Modulation process for a reference vector in the first sector.

Space Vector PWM: Asynchronous 10,000rpm 5#-ft

Figure 5-24

Space Vector PWM: Asynchronous 10,000rpm 5#-ft

75 HP MEVP DC Link Capacitor Ripple Current vs Motor Speed
(Max Torque Envelope, 255 V Battery @ 65.4 kW Pwr Limit)

GE-CRD, RDK-910208

Motor Speed (rpm)
Figure 5-26

- Trapezoidal wave - 8 notch waveform with the notch location chosen to eliminate completely the 5th and 7th harmonic components, reduces the 11th and 13th, and increases harmonics of order 19 and above
- Trapezoidal wave - 4 notch waveform generated by eliminating half the notches in the 8 notch waveform. Does not completely eliminate the 5th and 7th harmonics, but when compared to the six-step, these components along with the 11th and 13th harmonics are substantially reduced in amplitude. Like the 8 notch, this wave also increases harmonics of order 19 and above
- Vector ratio wave - generated by allowing natural overmodulation of the asynchronous vector ratio algorithm. This waveform generates a small 2nd harmonic component (due to waveform asymmetry) but also substantially reduces the 5th and 7th harmonic components.

Table 5-8 presents the motor efficiencies obtained by driving the motor model with the indicated modulation wave forms. These results indicate that about 1.5 points in motor efficiency may be obtained by selecting the best modulation scheme. This judgement is somewhat premature for two reasons. First, the simulation model needs to be verified for accuracy at these light torques, and this will be accomplished as soon as the first MEVP motor is available. Secondly, the inverter switching losses enter into the system efficiency (switching losses will increase with the number of notches per cycle). An accurate representation for inverter switching losses will be added to the simulator in the very near future. Once these two improvements have been made, the simulator will provide an accurate tool for assessment of alternatives.

Table 5-8. Motor Efficiency with Various Modulation Patterns.

	Motor Volts	Motor Amps	Motor Eff.
Six-step waveform	162.2	51.7	90.6
4-notch waveform	155.5	52.0	92.3
8-notch waveform	149.4	54.1	92.2
Vector ratio	150.4	52.7	91.9

5.6.4 Torque and Flux Control

A key element in motor efficiency improvement at light torque is the relationship between losses from magnetization (iron losses, copper losses due to magnetization current) and the losses caused by the torque producing component. It was shown in the ETX-I program that the efficiency of the motor can be improved significantly at light torques by reducing the motor flux level. Recognizing the need for flux control restricts the choices for motor control paradigms to those that allow for the independent specification of flux and torque (with slip as the variable) to obtain a desired operating point. Field oriented control offers this capability along with the advantages of a fast, stable, torque regulator.

In field oriented control, the flux producing stator-current component, which is perpendicular to the torque producing component, is controlled independently to regulate the flux inside the induction motor. Hence, independent torque and flux control is obtained for the induction machine whenever the position of the flux vector is known. Two basic schemes exist to extract this information.

- The first method is the so-called direct field orientation. In direct field orientation, the position of the flux is directly sensed through the use of search coils, tapped stator windings, or Hall sensors
- The indirect field orientation method uses a motor model to compute the flux position from rotor position and stator currents. Figure 5-27 illustrates the motor torque response at low speeds with indirect field oriented control.

Each of these two control schemes has both advantages and disadvantages, for example

- The direct field orientation method requires a measurement of flux. This can be obtained through the use of Hall Effect devices, but they suffer from temperature dependence and cost disadvantages. Flux coils can be used within the motor, but these coils do not provide any output at zero frequency and therefore cannot be used at zero speed.
- The indirect field control scheme is highly dependent upon motor parameters and requires the use of a shaft speed sensor.

The control scheme proposed for the MEVP drives is a combination of direct and indirect control. The motor will be started in the indirect mode with a smooth transition to direct mode at a low speed. This combination, referred to as universal field oriented, maintains good flux control and produces excellent torque response. Once the transition to direct mode is completed, the tachometer input is no longer required.

5.6.5 Optimal Flux Programming

For a given induction motor, at each operating point of load and torque an optimum combination of applied voltage and frequency exists that will result in minimum power losses. Substantial increases in efficiency can be obtained by operating an induction motor at less than maximum magnetic flux levels at light load, particularly at high speeds. The detailed motor model built into the simulator was made to represent the losses as accurately as possible to provide a tool for the evaluation of various flux programming strategies.

Figure 5-27. Universal Field Oriented Control

This motor model was analytically solved to determine the flux level for minimum loss operation. Figure 5-28 presents the optimal flux reference as a function of speed and torque.

The motor efficiency as a function of motor torque (at 3000 rpm) was plotted from the simulator. Three curves are provided in Figure 5-29 to compare the results of the three curves

- 1) The efficiency of the motor model with one algorithm for the reduction of flux with decreasing torque (other strategies will be investigated)
- 2) The efficiency using the ETX-I algorithm variable speed induction
- 3) The efficiency that would result if full flux were maintained with light torque.

As can be seen, the use of flux reduction provides significant improvements at light torque, and modest improvements may be obtainable over the previous (ETX-I) control scheme. These curves provide a relative comparison between alternatives but should not be used to estimate the true value of efficiency obtainable. As mentioned earlier, the model is yet to be validated at low torque, and more work remains to be completed in determining the optimal flux schedule as a function of torque.

5.7 Dc-dc Converter

5.7.1 Overview

The dc-dc converter serves the same role as the alternator/voltage regulator function in the conventional internal combustion engine vehicle. The current requirements of the 12-V accessory system in a conventional vehicle may be as high as 60 amperes, and the energy available from a typical starting-lighting-ignition is capable of supplying this load for an hour or two. Thus it is necessary to provide this power from the traction source (internal combustion engine in a conventional case, and the traction battery in an EV. The role of the dc-dc converter is to supply the required accessory current from the traction battery during periods of peak loads and charging current to the accessory battery when required.

The assumed rating required from the dc-dc converter is 60 amperes. The final required value may be somewhat above or below this rating, but the conclusions on circuit alternatives should not be significantly affected over the range from 40 to 80 amperes.

Figure 5-28. Optimal flux vs. torque with speed as a parameter.

Figure 5-29. 75 hp MEVP projected motor efficiency vs. motor torque
(3,000 rpm, 255 V battery)

5.7.2 Functional Description

In previous EV applications, cost of the dc-dc converter has been a major problem. The electronic circuitry necessary for the conversion of power from the traction voltage to the accessory voltage is very similar to that required for power supplies used in electronic equipment. A general rule of thumb for cost of power supplies is

Custom supplies	- \$1.25/watt
Semi-custom	- \$1.00/watt
Standard	- \$0.75/watt
High volume	- \$0.50/watt

Based upon the assumed power of 720 watts (60 amperes x 12 V), a high volume price would be \$360. When compared with the cost of a typical alternator and regulator which provides the equivalent function in a conventional automobile, the functional value does not agree well with the expected cost. Two major goals were identified to improve the functional value to expected cost:

- Since the output filter of a conventional power supply represents a significant cost item, investigate the possibility of using the accessory battery as the filter.
- Significant cost reductions in the converter circuitry are not too likely in the near future, underscoring the need to improve upon the functional value by incorporating other functions, such as battery charger.

5.7.3 Conversion Technology

High power dc/converters use either hard or soft switching technology. The classification of hard or soft refers to the presence or absence of voltage across the switches during turn-off. If voltage is present across the switch at turn-off (hard switching), the power dissipated in the switching element is greater, limiting the maximum operating frequency achievable without seriously degrading the efficiency. The use of soft switching technology allows the operation at a much higher frequency without the loss of efficiency associated with hard switching. The choice for a combination bridge was the dual active bridge converter (DABC). Other attractive features of the DABC include high power density, low KVA rating of the transformer, bidirectional power flow, buck-boost capability, low component stress, constant frequency operation, and low sensitivity to system parasitics.

5.7.4 Integrated Converter/Charger Circuit

A two way battery charger can be developed by taking maximum advantage of the features of each DABC. A candidate solution is shown in Figure 5-30. The main high voltage battery can be charged by the second full bridge converter, which also serves as a supply for the auxiliary battery during normal operation of the EV. The accessory battery is charged in parallel with the main traction battery, making the charging process more efficient.

Two Way Dual Bridge Charger

Figure 5-30

Furthermore, only one transformer is used for both the charging and auxiliary supply functions. Because of the buck and boost capabilities of the DABC, it is possible to connect the input ac line rectifier to a small dc bus capacitor and produce near unity power factor waveforms at the ac input. This operation is possible because, internally, the DABC actually works as an electronically controlled current source. This feature can dramatically reduce the cost of the input line filters and reactive power compensators that are otherwise needed to operate the charger from a residential 115/220 V line in agreement with technical considerations (maximum current capability of ac line and protection) and international standards.

Further simplifications of the DABC are possible. A cost analysis is in progress and possible cost reductions resulting from these simplifications will be considered.

5.8 Safety and Reliability

Both safety and reliability will be addressed as part of the MEVP design process. The majority of the effect that the standards shown below will have, will be at the component design level. The phase I design effort has primarily been concerned with operational assumptions and the resulting functional requirements. Therefore the following standards will come into play when the component specifications are finalized. This should occur by the end of March.

- UL Standard 1564, "Industrial Battery Chargers"
- UL Standard 1236, "Residential & Commercial Chargers"
- FCC 47 CFC Part 15 General Docket No. 87-389, "Emissions from Digital Switching Equipment"
- IEEE Standard 519-1981, "IEEE Guide of Harmonic Control @ Reactive Compensation of Static Power Converters."

To date, and in anticipation of complying with the following standards, tests have been performed on the ETX-II test bed vehicle. These tests included Federal Communications Commission Part 15 (radiated emissions). (It should be noted that the FCC limits are higher than what is required to achieve acceptable vehicle radio reception performance). An EMC/RFI task force has been organized within Ford to provide guidance on the component design to ensure high quality. Further tests on the platform vehicle will be run with an internal combustion engine and with the electric power train to better assess the differences between the EV and ICE on the same platform. This information will be used to help guide the development of shielding and filtering for the MEVP powertrain. These tests will be conducted by June 1991.

Few safety and reliability standards pertain specifically to EVs (such as National Electric Code 511-9, "Electric Vehicle Charging"), although many are needed. To aid in establishing required standards, a member of the EV staff has been appointed chairperson of the SAE (Society of Automotive Engineers) Electric Vehicle Standards Committee. This committee will include members from the automobile industry, utility companies, and potential component suppliers. (GM and Chrysler representatives have been appointed). In addition, consultants who are familiar with Underwriters Laboratories, Inc., have been contacted to provide guidance on the component designs.

System level reliability will be ensured primarily by following through on the failure mode and effects analysis (FMEA). Based on cumulative failure rates, certain component reliability tolerance requirements may be improved, or appropriate changes will be made in the system to ensure that the system function will meet targeted mean time between failure requirements.

Ford has a set of test procedures designed to ensure component reliability in the field. All components will be required to meet applicable portions of these standards. Components will be subjected to temperature, vibration, and humidity stresses to minimize field failures. The results of these tests will be analyzed and appropriate changes identified for future designs.

6.0 BATTERY SUBSYSTEM

6.1 Technology Studies

6.1.1 Assessment

In order to identify the technologies that are potentially viable in the MEVP program an assessment process was established. An extensive review of the literature on previous assessments and comparative evaluations of battery technologies for MEVP application was undertaken to identify candidate battery systems. A significant study assessing battery technology for EVs by the Electric and Hybrid Propulsion Division of the Office of Transportation Systems (DOE Contract C87-101249)) was used extensively to complement our evaluation. Battery types and manufacturers included in the survey will have already demonstrated a level of technical maturity at least equal to those in the ETX program. Emphasis was placed on identifying the suitability of high energy density batteries for this program based on range, vehicle performance, and defined missions.

A combination of onsite visits, telephone discussions, and visits to Ford in Dearborn was used by several battery manufacturers to identify potential battery subsystems. In addition to energy and power density, issues relating to reliability, technological maturity, efficiency, stand losses, costs, package-ability, and prior demonstration of a vehicle-size battery were considered.

A number of potential EV batteries were judged to be viable candidates for MEVP applications. Within the MEVP program, depending on funding, it was expected that as many as three candidate systems would be selected, with the national laboratories perhaps conducting parallel programs on other battery systems. During Phase I of this program, emphasis was placed on the sodium-sulfur battery technology.

In consideration of the power requirements of the propulsion system and the constraints imposed by the inverter, preliminary specifications for the sodium-sulfur traction battery have been generated, as shown in Figure 6-1.

The maximum system voltage is specified at 385 V; the nominal battery voltage at 100% SOC will be typically 330 - 345-V open circuit. The lower limit of 250 V, while delivering the required power for each hp rating (50, 75, 100 hp), is imposed by the motor design. It is the lowest voltage, based on motor design computations, that will develop rated the power demands for each horsepower rating without exceeding the power module current limits. However, the motor design can operate to a minimum of 200 V at a reduced, battery-limited power rating. A sustained power requirement, a standard requirement for Ford passenger cars and light trucks, is included in the battery specifications for each vehicle size. These values were derived from the requirement for the vehicle to ascend a 7% grade at 30 mph.

System voltage:

Maximum: 385 Vdc (@ top of battery charge cycle)
OCV @ 100% SOC will be below this value,
typically 330-345 volts

Battery must
operate between
these limits

Minimum: 200 Vdc (2/3 Vdc under peak load @40% SOC)

Power:

Peak: (45) 65 (90) kW at 250 Vdc min. to 60% depth of discharge
(50) 75 (100) hp

Sustained: (TBD) 35 (TBD) kW (based on gradeability requirements)
(TBD) 47 (TBD) hp

Energy capacity: (30) 40 (60) kWh, measured during operation of a vehicle
over the FUDS

Weight: (350) 450 (700) kg (maximum including controller and
auxiliaries)
(770) 990 (1540) lb

Charging system: On-board vehicle input 220 V, 30 Amp 60 hz

Exterior size: Plans are to package and install the battery within the
specified volumes

Preliminary.battery envelope:

50-hp vehicle

1. ETX-I TBD

75-hp vehicle

1. 33.5 (l) x 38.0 (w) x 12.6 (h) inch (mid-vehicle)
(850 x 965 x 320 mm)
2. 12.6 (l) x 38.0 (w) x 12.6 (h) inch (rear)
(320 x 965 x 320 mm)

100-hp vehicle Aerostar

1. 75.0 (l) x 30.0 (w) x 10.8 (h) inch
(1900 x 760 x 275 mm)

Vibration: see attachment

Electronic/environmental/electromagnetic: Compatible with automotive
industry practices

Control system: Compatible with automotive industry practices

Figure 6-1. Preliminary sodium-sulfur battery specifications

The battery energy capacity for each vehicle type was determined on the basis of vehicle range, payload capacity, and power requirements. The performance values are given for 50, 75, and 100-hp subsystems.

Preliminary lead-acid battery specifications for the 75-hp vehicle are shown in Table 6-1. These requirements assume the use of such batteries as backup for support of hardware evaluations.

6.2 Design Criteria and Preliminary Packaging

6.2.1 Vehicle Packaging Constraints

Battery envelope limits were estimated for several candidate vehicles at the three powertrain ratings. These are presented in Figure 6-2. Generally, as the vehicle size increases, there is more room and more flexibility in packaging the traction battery. This is influenced by the fact that the smallest vehicles are passenger cars, while the larger vehicles are vans.

Table 6-1. Battery Envelope Limits.

Vehicle powertrain rating (hp)	50	75	100
Available envelope dimensions			
Length	33.5 inch (850 mm)	33.5 & 12.6 inch (850 mm) (320 mm)	33.5 inch (x2) (850 mm)
Width	38.0 inch (965 mm)	38.0 inch (965 mm)	38.0 inch (965 mm)
Height	12.6 inch (320 mm)	12.6 inch (320 mm)	12.6 inch (320 mm)

6.2.2 Battery Packaging Concepts

The performance goals and packaging constraints discussed above suggest a packaging concept for the sodium-sulfur system. The 50, 75, and 100-hp batteries would be contained in one or two thermal enclosures of two basic sizes: a full-size enclosure containing the 50-hp configuration, and a half-size enclosure containing a 25-hp incremental configuration. The 75-hp battery would consist of one of each of these two enclosures, while the 100-hp battery would consist of two 50-hp enclosures. The electrical circuit would be to connect the two enclosures in series. If they were to be connected in parallel, the battery thermal management would have to provide very precise matching of the two enclosures' internal temperatures to achieve acceptable load-sharing between the two battery modules. This is due to the intrinsic nature of sodium-sulfur cells' internal resistance, which decreases strongly with increased temperature, leading to a thermal instability for parallel circuit elements.

System voltage:

Maximum : 385 Vdc (@ top of charge cycle)
Nominal : 336 - 345 Vdc typically
Minimum: 200 Vdc (under load @ 20% SOC) (@ 2/3 Voc)

Power:

Peak: 65 kW (75 hp) at 250 Vdc min. to 60% of useful capacity
(to achieve 80 km/h in less than 20 sec)
Sustained: 35 kW (47 hp) (based on 7% grade at 31 mph)

Energy capacity: 15 kW (goal - optimize to maximum value) measured during
operation of a lightweight vehicle over the FUDS

Weight: 450 kg (990 lb) (maximum including auxiliaries)

Exterior size: Current plans are to package and install the battery
under the load floor

Preliminary battery envelope:

Preferred dimensions:

1. 33.5 (l) x 38.0 (w) x 12.6 (h) inch (mid-vehicle)
(850 x 965 x 320 mm)

Vibration: To meet automotive industry standards

Control system: Compatible with automotive industry practices.

Figure 6-2. Preliminary lead-acid battery specifications

Present sodium-sulfur technology features tubular cell geometries exclusively. This suggests hexagonal packing arrangements for the cells to achieve maximum power and energy densities in these batteries. Depending on the specific electrical circuit used, the series/parallel interconnections between the cells will require clustering of cells, with clearances allowed for internal bus bars. Packaging density will also be affected by the methods used for electrical isolation of each cell and of the bus bars. Routing of the bus bars to comply with requirements for their ultimate connection to the vehicle power cabling may also impact the internal volume requirements. Each battery supplier has their preferred approaches for minimizing battery size while achieving maximum safety against internal ground faults and short circuits.

6.3 Coordination with Battery Suppliers

Two suppliers of sodium-sulfur batteries were contacted and subsequently provided design data to support definition of candidate battery configurations. These data were limited to the 75-hp vehicle design, and extrapolations to 50 and 100-hp designs were made by Ford.

6.4 Battery Configurations

Several sodium-sulfur battery configurations were developed for evaluation of their performance in the candidate vehicles. Each powertrain rating and candidate vehicle was provided with at least one configuration. These batteries were configured to meet the desired power ratings, allowing energy capacity to vary with cell capacity. Both suppliers can achieve comparable specific energy values at the battery level, approximately 100 Wh/kg.

These analyses show the feasibility of the modular concept described above for sodium-sulfur traction batteries. Layouts for three candidate vehicles (see Section 4.0) indicate how the battery enclosures can be packaged.

6.5 Support Systems

6.5.1 Battery Controller

The battery controller will act as the interface between the vehicle system controller and the battery and battery charging subsystems. In the currently proposed vehicle, the target battery technology is sodium-sulfur, although a lead-acid battery technology will be supported.

The battery controller has three main functions. These are

- To monitor the state of the battery, including such conditions as state of charge and internal temperatures, and report relevant conditions to the operator.
- To control the charging of the traction battery, ensure that it occurs in an efficient and safe manner, and inform the user of when charging starts and successfully ends.

- To detect a failure in the auxiliary battery charger or a condition in which the auxiliary battery is too deeply discharged and inform the vehicle system controller of these conditions.

The controller is partitioned into two sections. The intelligent part of the controller holds the microprocessor, memory, digital I/O, and the multiplex network interface. The I/O signal conditioning box holds the input signal conditioning circuitry, the A/D conversion device(s), and the output driver circuits and is located near the batteries. This is done to minimize the length of signal runs between the battery and the signal input sensors.

The two sections communicate over a set of digital, optically isolated signal wires. This interface will allow modulation of the I/O signal conditioning box as new battery technologies require, with only minimal modifications to the structure of the intelligent controller package.

The controller also interfaces with the traction battery charger. This interface supports an interlock function that will prevent the vehicle from operating while connected to ac power and will vary the amount of current supplied to the battery depending on conditions within the battery.

The auxiliary battery charger requires no control from the battery controller. Connections to it are limited to a pair of fault condition indicators for diagnostic and failure prediction purposes.

6.5.2 Battery Charger

The traction battery charger must efficiently supply the battery with energy derived from an external ac service. Currently, the plan is to support both 220-Vac, 30-amp service as the main charging source, and 110-V, 15-amp service for emergency charging.

The charger design will provide greater than 90% conversion efficiency, and will provide a power correction factor of 0.98 or greater. For purposes of safety interlocks, the charger will detect the application of ac power at the input and indicate this to the controller. The level of output current is regulated by the battery controller, which contains all of the intelligence required for charging.

This charger is being designed for use either on board the vehicle or external to it. The interface between the charger and controller will be the same regardless of charger location.

6.5.3 Vacuum Thermal Insulation

Sodium-sulfur and other high-temperature batteries require very high performance thermal insulation to minimize heat losses over their useful life. Such heat losses represent a form of self-discharge, which can impact system efficiency and operating energy cost. A portion of the heat loss can be supplied by waste heat during vehicle operation, but this depends on the vehicle utilization factor. Under-utilized vehicles will have lower operating efficiency due to the need for heating the battery from ac power at the charging location.

Low thermal loss is also important in achieving an acceptable duration for parking the vehicle away from any charging source.

Previous analyses (DOE Contract DE-AC08-80C5-50101) have shown that a 35-kWh sodium-sulfur battery should have a heat loss rate of less than $150 W_{th}$ to achieve 75% overall efficiency, assuming 60% vehicle utilization five days per week. Allowing for $50 W_{th}$ loss due to bus bar and other insulation pass-throughs, the battery thermal enclosure loss should be less than $100 W_{th}$.

This level of insulation performance dictates the use of a double-walled vacuum type of enclosure.

This type of enclosure has been under development at Union Carbide, Linde Division, and other suppliers since 1978. At present, insulation thicknesses of approximately one inch can provide thermal resistance factors of 50 to 60 ($^{\circ}\text{F}\cdot\text{ft}^2\cdot\text{hr}/\text{Btu}$). This is achieved using glass or mineral fiber board sandwiched between stainless steel case walls. These designs yield enclosures with 200 to $300 W_{th}$ at a nominal internal temperature of 300°C .

Development of more advanced insulation designs has continued at Linde, resulting in panels of 1/4-in. thickness with a resistance factor of 15 (i.e., 60 per inch). Independent efforts at the Solar Energy Research Institute (SERI) have resulted in 0.2-in. prototype panels with a resistance factor of 5 (i.e., 25 per inch). Further work at SERI is expected to provide 0.1-in. panels having a resistance factor of 10 (i.e., 100 per inch). These developments could lead to acceptable battery thermal enclosures with lower weight and volume penalties than present enclosure designs. Effective utilization of this improved insulation technology will be supported in coordination activities with the battery manufacturers.

6.5.4 Battery Cooling System

The combination of increased sustained power, reduced heat losses, and reduced battery weight may eventually lead to the need to provide internal cooling of sodium-sulfur batteries. Although forced-air cooling concepts are relatively simple, liquid cooling concepts require less volume, a potentially critical consideration in EV applications.

A candidate liquid cooling concept has been developed for consideration by sodium-sulfur battery manufacturers. A block diagram of this concept is shown in Figure 6-3. Liquid coolant is circulated through a loop by a pump and absorbs waste heat from the battery cells through a cooling plate within the battery thermal enclosure. After leaving the battery, the coolant flows through an air-cooled radiator to return to near-ambient temperature. To avoid chilling or locally overcooling the cells, the coolant will generally need to be preheated before entering the battery enclosure. If the required preheat temperature exceeds the pump environmental rating, a recuperator can be used to perform this function. A fraction of the coolant flow is diverted into the recuperator and is thereby raised, by counter-flow heat exchange, to the temperature of the coolant leaving the battery. A regulator valve controls the amount of recuperator flow to ensure the correct coolant temperature into the battery. The recuperator can be eliminated in favor of a direct bypass line (upstream of the pump) if the pump's temperature limit is higher than the preheat temperature.

Figure 6-3. Liquid-Cooling Concept

Component sizes, weights, and power requirements will vary with the specific heat rejection rate required for the battery. It is likely that such a cooling system would be required for each battery enclosure, rather than a single system for all enclosures combined.

7.0 FAILURE MODE AND EFFECTS ANALYSIS - FMEA

7.1 Introduction

This document states the plan for performing the FMEA effort that will be implemented throughout the DOE/MEVP program and will identify those components and subsystems that play a critical role in overall system safety and reliability.

7.2 Technical Approach

This section will briefly define the technical activities that will be completed in order to perform the FMEA. Table 7-1 lists the components and subsystems that will be the subject of this FMEA. Table 7-2 presents the documents that contain the definitions of the terms used in this section and that govern the activities herein described.

The general technical approach described here follows MIC-STD-1629A, especially paragraph 4.4.2 and task 101. The description of the specific activities to be utilized are presented in the remainder of this section.

Table 7-1. FMEA Subjects.

Ignition switch
Fuse and relay box
Shifter (PRNDL)
Throttle controls
Line pressure switches
Park brake switch
Brake switch
Brake solenoid
Vehicle system controller
12 V auxiliary battery and distribution system
Dc/dc connector
Instrument cluster
Battery controller
Traction battery charger
AC compressor motor
Motor controller
Inverter
Motor & transaxle
Contactactor box
Primary traction battery
Secondary traction battery
Range extender

Table 7-2. Applicable Documents.

MIL - STD - 1629A Potential Failure Mode and Effects Analysis Ford Motor Company Form 1695 Ford Motor Company Engineering Practice #5 Ford Motor Company FMEA plus, Version 2.0 User Guide

7.2.1 Definition of the System to be Analyzed

The purpose of this task is to define, understand, and document the system to a sufficient level of detail as to allow an identification of failure modes and effects. This task consists of identifying and describing internal and external interfaces, expected performance, system restraints, failure definitions, components, and environmental profiles. The form of this description will be written documentation in a variety of forms, including narratives, net lists, and diagrams.

7.2.2 Construct Block Diagrams

The purpose of this task is to highlight by illustration both the hierarchical relationship components and reliability relationship of functions (to enable local failure effects determination and probability of occurrence estimation).

This task consists of reviewing the information compiled in the task described in paragraph 3.1 and abstracting it into these block diagrams. Reliability data is then researched, collected, or estimated and inserted into the reliability block diagrams.

The result of this task is a set of functional and reliability block diagrams that illustrate the operation, interrelationships, and interdependencies of the component level MEVP entities.

7.2.3 Method of Analysis

The purpose of this task is to discover and derive the failure modes and effects. This task consists of the identification of all foreseeable potential item and interface failure modes and the definition of their effects on the powertrain performance.

The hardware analysis approach lists individual hardware items and analyzes their possible failure modes. As the vendors complete their designs, they will be required to perform FMEAs in this manner to support the reliability provision of the hardware's function and to identify potential opportunities for compensating for these failure modes. The result of this task is the completion of the appropriate section, of Ford Design FMEA form #1695.

7.2.4 Severity Classification

The purpose of this section is to define the severity classification evaluation criteria to be used in this FMEA/CA analysis. The severity is the assessment of the seriousness of the effect of the potential failure mode on the powertrain performance.

The severity classification evaluation criteria to be used is as defined in paragraph 12 of Ford's "Potential Failure Mode and Effects Analysis, An Instruction Manual". In addition, the severity analysis results will be used to identify critical characteristics in conformance with Ford Engineering Practice #5.

7.2.5 Occurrence

The purpose of this section is to define the occurrence classification evaluation criteria to be used in this FMEA/CA analysis. The occurrence is the likelihood that a specific cause will result in a failure mode.

The occurrence classification evaluation criteria to be used is as defined in paragraph 15 of Ford's "Potential Failure Mode and Effects Analysis, An Instruction Manual".

7.2.6 Compensation Provisions

The purpose of this task is to identify corrective design or other actions required to eliminate the failure or control the effect/risk. This task consists of first studying the definition of the system to be analyzed together with the failure modes and effects as derived in previous tasks. Based upon this information alternative sets of corrective designs or actions are identified. A trade-off study will then be conducted to identify the most effective set of corrective design changes and actions.

The results of this task are

- A set of written design requirements that specify changes that must be made to the component design.
- A set of written corrective actions to be taken by the vehicle operator, service technicians, etc., to deal with the failure mode effects should they occur.
- A set of written design verification procedures to prevent the design causes of potential failure from occurring or that are intended to detect the design causes of the potential failure or resultant failure mode.

7.2.7 Maintenance of the FMEA

The purpose of this section is to describe the process by which the FMEAs will be maintained consistent with the design. The FMEA will be completely performed at the end of the preliminary design, at the completion of the critical design, and at the end of the final design.

7.2.8 Damage Mode and Effects Analysis (DMEA)

The purpose of this task is to utilize the results of the FMEA to assess the effects of damage such as collision or upset on the powertrain. This task consists of the analysis of the powertrain and its FMEA conducted in order to determine the extent of damage sustained from various possible collisions or

upsets and the effects of such damage modes on: the continued controlled operation of the vehicle, the mission completion capabilities of the vehicle, and the safety of vehicle passengers and pedestrians, rescue workers, and service technicians and retriever crews.

7.3 Documentation

The results of the FMEA/CA will be documented by a set of Ford form 1695's and a summary report.

7.3.1 Ford Form 1695

A set of Ford Form 1695's will be completed at the component level for the MEVP. They will be completed in accordance to Ford's "Potential Failure Mode and Effects Analysis (FMEA), An Instruction Manual".

7.3.2 FMEA Summary Report

A summary report will be prepared at the conclusion of each of the three FMEA analysis. It will include

- A summary of the system description
- A summary of the results including
- Recommended design changes and action
- Failure modes for which no corrective action was recommended and why
- Data sources if any
- Analytical technique used as appropriate
- Reliability critical items
- Descriptions of failure modes to be detected by the vehicle operator.

7.4 Reviews

This section presents the major milestone schedule for this task.

7.4.1 Task Major Milestones

There are two major milestones for this task: the critical FMEA and the final FMEA.

- The critical FMEA is a full FMEA/CA analysis performed when the production representative component design are available, although it should be acknowledged that FMEA is an ongoing part of each component's design process. The milestone is a review of this critical FMEA.

- The final FMEA is a full FMEA/CA analysis performed when the component designs have been finalized. It is in support of production release of the parts. The milestone is a review of their final FMEA.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The preliminary system studies phase (Phase I) of the MEVP program has been completed and the conclusions drawn are as follows

1. Although at present there are only marginal cost differences between ac and dc powertrains, the ac system has efficiency benefits and significant cost reduction potential and has been selected for the MEVP program. (See Section 3.1).
2. The ac induction motor has been selected for the MEVP powertrain in preference to switched reluctance or interior permanent magnet types because of its greater technological maturity and lower production costs. (See Section 5.3).
3. A system voltage of 336 V has been found to offer significant advantages of increased efficiency and system cost reduction. (See Section 3.4).
4. A trade-off analysis including one motor versus multiple motor powertrains warranted the selection of a single motor configuration for MEVP. (See Section 3.2).
5. A single-speed transmission employing two planetary gear sets and a planetary differential offers distinct advantages for MEVP over a multiple-speed version. (See Section 3.3).
6. Air cooling the inverter is possible as a result of more efficient inverter/power components, the use of a higher system voltage, and new packaging concepts. (See Section 5.5).
7. An on-board charger has been selected as the primary option based on market driven requirements. (See Section 2.6).
8. Phase I studies have shown the modularity of powertrain design to be a viable concept. Each of the major powertrain components, (i.e., motor, transmission, system controller, inverter, inverter/motor controller, battery, and battery controller) can be designed to have common features that enable them to be utilized in a range of powertrains, thereby providing the economy of volume production.

8.2 Recommendations

The viability and advantages of a modular powertrain have been demonstrated. It is recommended that the MEVP program continue to Phase II, Component Design, Build, Integration and Test, as set forth in the statement of work.

APPENDIX A

Design Complexity of 1-speed vs. 2-speed

Figure A-1 shows, from a part complexity point of view, why a 1-speed transaxle would be more desirable than a 2-speed. Note, in particular, No. 5, regarding the hydraulic control. Such complexity is typically the cause of a large cost and high scrap rate in a normal multiple speed transaxle.

Design Definition (Base 75 H.P)	Quantity		Comments	
	1 Speed	2 Speed	1 Speed	2 Speed
1. Planetary Units:				
a) Input	1	1	4 simple planets	3 cluster planets
b) Output	1	1	4 simple planets	4 simple planets
2. Differential	1	1	8 spur gears	4 helical gears, 2 pc. carrier.
3. Hydraulic Clutches	-	2	-	Required for shift from one gear to another.
4. One-way Clutch	-	1	-	Required for shift quality
5. Hydraulic Control:				
a) Valves	-	4	-	1) Main regulator valve 2) 1st gear clutch valve 3) 2nd gear clutch valve 4) Solenoid feed valve
b) Solenoids	-	3	-	1) Main regulator 2) 1st gear clutch 3) 2nd gear clutch
c) Bulkhead Connectors	-	3	-	Required for connection between solenoids and power source.
d) Valve Body	-	1	-	Required for housing all valves, solenoids, and lube pump.
e) Pan		1	-	Required for oil reservoir.
6. Hi-Pressure Pump	-	1	-	Supplies high pressure oil to shift system.
7. Low-Pressure Pump	1	1	Cooling & Lubrication	Cooling & Lubrication
8. Transmission Case	2 pcs.	3 pcs.	Protects transmission and electrical motor.	Protects transmission and electrical motor.

Fig. A-1. MEVP Transaxle Design Comparison - 1 Speed vs. 2 Speed

APPENDIX B

The effect of operating temperature on motor efficiency is shown in the maps of Figures B-1 and B-2.

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Inverter Losses (kW)		0	0.438	0.483	0.561	0.652	0.758	0.881	1.019	1.171	1.336	1.514	1.705	1.908	2.123	2.350	2.589
Vs Operating Point		1000	0.615	0.541	0.749	0.973	1.140	1.329	1.533	1.752	1.984	2.227	2.483	2.749	3.027	3.315	3.614
50 Deg	2000	0.717	0.615	0.876	1.126	1.321	1.536	1.768	2.012	2.268	2.535	2.811	30.970	3.391	3.695	4.007	
	3000	0.749	0.665	0.940	1.112	1.298	1.503	1.721	1.950	2.188	2.434	2.687	2.947	3.213	3.485	3.762	
	4000	0.656	0.690	0.941	0.929	1.072	1.228	1.393	1.565	1.743	1.924						
Motor rpm	5000	0.433	0.692	0.876	0.640	0.736	0.846	0.969	1.103	1.248							
	6000	0.392	0.669	0.744	0.647	0.777	0.920	1.075	1.244								
	7000	0.374	0.621	0.557	0.700	0.860	1.047	1.227									
	8000	0.364	0.453	0.595	0.768	0.975	1.174										
	9000	0.354	0.461	0.640	0.844	1.076											
	10000	0.361	0.481	0.690	0.940	1.216											
	11000	0.354	0.503	0.745	1.031												
	12000	0.367	0.528	0.836	1.149												
	13000	0.348	0.554	0.872													

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Motor Losses (kW)		0	0.076	0.126	0.314	0.427	0.664	0.968	1.339	1.778	2.285	2.86	3.503	4.215	4.995	5.845	6.765
Vs Operating Point	1000	0.082	0.143	0.349	0.519	0.767	1.086	1.476	1.937	2.469	3.073	3.749	4.497	5.317	6.211	7.178	
50 Deg.	2000	0.092	0.170	0.402	0.655	0.918	1.255	1.667	2.154	2.716	3.354	4.068	4.859	5.726	6.672	7.696	
	3000	0.105	0.203	0.467	0.822	1.102	1.461	1.899	2.417	3.015	3.695	4.455	5.389	6.222	7.230	8.321	
	4000	0.121	0.241	0.543	1.014	1.313	1.696	2.164	2.717	3.356	4.083						
	5000	0.151	0.284	0.623	1.083	1.442	1.918	2.518	3.252	4.129							
	Motor rpm	6000	0.190	0.332	0.693	1.105	1.678	2.445	3.426	4.646							
	7000	0.208	0.383	0.785	1.374	2.242	3.528	4.978									
	8000	0.220	0.437	0.937	1.788	3.189	4.872										
	9000	0.218	0.473	1.156	2.356	4.224											
	10000	0.231	0.543	1.443	3.190	5.858											
	11000	0.247	0.614	1.812	4.134												
	12000	0.272	0.705	2.511	5.545												
	13000	0.232	0.819	2.889													

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Inverter Losses (kW)		0	0.438	0.449	0.567	0.650	0.754	0.875	1.011	1.161	1.323	1.498	1.685	1.884	2.095	2.318	2.552
Vs Operating Point		1000	0.615	0.546	0.754	0.971	1.138	1.325	1.529	1.746	1.976	2.218	2.472	2.736	3.012	3.298	3.595
25 Deg	2000	0.717	0.621	0.883	1.126	1.320	1.535	1.766	2.011	2.266	2.533	2.809	3.095	3.389	3.693	4.005	
	3000	0.749	0.673	0.953	1.112	1.299	1.504	1.723	1.953	2.193	2.440	2.695	2.956	3.224	3.498	3.778	
	4000	0.656	0.702	0.964	0.931	1.075	1.232	1.399	1.573	1.753	1.937						
	5000	0.433	0.708	0.913	0.640	0.736	0.460	0.968	1.101	1.245							
	Motor rpm	6000	0.392	0.692	0.800	0.647	0.776	0.918	1.073	1.240							
	7000	0.374	0.952	0.560	0.700	0.858	1.043	1.222									
	8000	0.364	0.588	0.595	0.766	0.971	1.170										
	9000	0.354	0.463	0.640	0.843	1.073											
	10000	0.361	0.481	0.689	0.937	1.210											
	11000	0.354	0.503	0.743	1.027												
	12000	0.367	0.527	0.833	1.144												
	13000	0.348	0.554	0.870													

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Motor Losses (kW)		0	0.078	0.124	0.308	0.39	0.606	0.883	1.222	1.623	2.085	2.61	3.197	3.847	4.55	5.335	6.174
Vs Operating Point		1000	0.084	0.141	0.341	0.481	0.708	1.000	1.357	1.778	2.265	2.818	3.436	4.121	4.871	5.689	6.575
25 Deg.		2000	0.092	0.166	0.390	0.617	0.858	1.168	1.546	1.993	2.510	3.096	3.752	4.478	5.276	6.145	7.085
		3000	0.104	0.198	0.452	0.784	1.042	1.373	1.777	2.255	2.808	3.435	4.136	4.914	5.767	6.697	7.705
		4000	0.118	0.234	0.524	0.975	1.252	1.608	2.042	2.555	3.148	3.822					
		5000	0.147	0.275	0.601	1.045	1.378	1.819	2.374	3.051	3.858						
Motor rpm		6000	0.185	0.320	0.672	1.056	1.589	2.301	3.210	4.335							
		7000	0.202	0.369	0.759	1.307	2.117	3.306	4.656								
		8000	0.214	0.421	0.899	1.697	3.000	4.573									
		9000	0.225	0.477	1.107	2.236	3.984										
		10000	0.228	0.529	1.380	3.022	5.523										
		11000	0.242	0.596	1.733	3.924											
		12000	0.266	0.684	2.389	5.260											
		13000	0.227	0.793	2.765												

Figure B-1

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Inverter Losses (kW)		0	0.359	0.436	0.554	0.658	0.767	0.893	1.035	1.192	1.363	1.547	1.745	1.955	2.179	2.415	2.663
Vs Operating Point		1000	0.402	0.536	0.748	0.975	1.145	1.335	1.542	1.764	1.998	2.246	2.504	2.775	3.056	3.349	3.652
100 Deg	2000	0.455	0.609	0.872	1.127	1.322	1.538	1.770	2.015	2.271	2.538	2.814	3.100	3.395	3.698	4.009	
	3000	0.517	0.655	0.925	1.110	1.296	1.499	1.716	1.943	2.179	2.423	2.672	2.928	3.190	3.456	3.728	
	4000	0.602	0.674	0.906	0.926	1.066	1.219	1.381	1.549	1.721	1.306						
	5000	0.729	0.665	0.810	0.640	0.736	0.847	0.971	1.106	1.253							
Motor rpm	6000	0.583	0.628	0.536	0.648	0.779	0.923	1.081									
	7000	0.487	0.565	0.557	0.702	0.863	1.041										
	8000	0.361	0.465	0.596	0.770	0.982	1.184										
	9000	0.343	0.461	0.642	0.848	1.084											
	10000	0.347	0.481	0.692	0.942	1.228											
	11000	0.355	0.504	0.747	1.038												
	12000	0.365	0.528	0.843	1.161												
	13000	0.351	0.555	0.877													

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Motor Losses (kW)		0	0.073	0.131	0.332	0.503	0.782	1.139	1.576	2.093	2.69	3.367	4.124	4.962	5.881	6.882	7.964
Vs Operating Point		1000	0.081	0.150	0.372	0.596	0.888	1.262	1.719	2.260	2.884	3.592	4.384	5.261	6.223	7.270	8.404
		2000	0.095	0.180	0.432	0.733	1.039	1.432	1.912	2.479	3.134	3.878	4.710	5.631	6.642	7.743	8.936
100 Deg.		3000	0.111	0.217	0.506	0.901	1.224	1.639	2.146	2.745	3.437	4.223	5.102	6.076	7.145	8.310	9.573
		4000	0.131	0.260	0.592	1.093	1.436	1.875	2.412	3.047	3.780	4.614					
		5000	0.166	0.308	0.679	1.160	1.572	2.120	2.816	3.668	4.692						
	Motor rpm	6000	0.203	0.357	0.745	1.205	1.861	2.743	3.878								
		7000	0.221	0.413	0.845	1.512	2.501	3.859									
		8000	0.235	0.473	1.015	1.975	3.585	5.499									
		9000	0.235	0.515	1.258	2.606	4.725										
		10000	0.240	0.573	1.572	3.502	6.568										
		11000	0.257	0.651	1.975	4.575											
		12000	0.285	0.749	2.768	6.146											
		13000	0.241	0.871	3.148												

		Torque (ft.lb):															
LU Table:	75 Hp	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Inverter Losses (kW)		0	0.438	0.440	0.560	0.660	0.760	0.890	1.030	1.180	1.350	1.530	1.730	1.930	2.150	2.380	2.630
Vs Operating Point	1000	0.615	0.540	0.750	0.970	1.140	1.330	1.540	1.760	1.990	2.240	2.490	2.760	3.040	3.330	3.630	
75 Deg	2000	0.717	0.610	0.870	1.130	1.320	1.540	1.770	2.010	2.270	2.540	2.810	3.100	3.390	3.700	4.010	
	3000	0.749	0.660	0.930	1.110	1.300	1.500	1.720	1.950	2.180	2.430	2.680	2.940	3.200	3.470	3.750	
	4000	0.656	0.680	0.920	0.930	1.070	1.220	1.390	1.560	1.730	1.910						
	5000	0.433	0.495	0.565	0.640	0.740	0.850	0.970	1.100	1.250							
Motor rpm	6000	0.392	0.464	0.540	0.650	0.780	0.920	1.080	1.250								
	7000	0.374	0.459	0.560	0.700	0.860	1.040										
	8000	0.364	0.450	0.600	0.770	0.980	1.180										
	9000	0.354	0.460	0.640	0.850	1.080											
	10000	0.361	0.480	0.690	0.940	1.220											
	11000	0.354	0.500	0.750	1.030												
	12000	0.367	0.530	0.840	1.160												
	13000	0.348	0.550	0.870													

		Torque (ft.lb):															
LU Table: 75 Hp		0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	
Motor Losses (kW)		0	0.075	0.13	0.32	0.47	0.72	1.05	1.46	1.94	2.49	3.12	3.82	4.59	5.44	6.37	7.37
Vs Operating Point	1000	0.083	0.150	0.360	0.560	0.830	1.180	1.600	2.100	2.680	3.330	4.070	4.880	5.770	6.740	7.800	
	2000	0.090	0.170	0.420	0.690	0.980	1.340	1.790	2.320	2.930	3.620	4.390	5.250	6.190	7.210	8.320	
75 Deg.	3000	0.109	0.210	0.490	0.860	1.160	1.550	2.020	2.580	3.230	3.960	4.780	5.690	6.690	7.770	8.950	
	4000	0.126	0.250	0.570	1.050	1.380	1.790	2.290	2.880	3.570	4.350						
	5000	0.161	0.300	0.650	1.120	1.510	2.020	2.670	3.460	4.410							
Motor rpm	6000	0.193	0.340	0.720	1.160	1.770	2.590	3.650	4.970								
	7000	0.216	0.400	0.820	1.440	2.370	3.640										
	8000	0.232	0.460	0.980	1.880	3.390	5.180										
	9000	0.231	0.500	1.210	2.480	4.470											
	10000	0.236	0.560	1.510	3.370	6.210											
	11000	0.251	0.630	1.890	4.350												
	12000	0.280	0.730	2.640	5.840												
	13000	0.239	0.850	3.020													

Figure B-2

Notes on Section I Tests

(Transient Tests)

Battery Voltage. Only the tests designated for a battery voltage of 255 VDC were actually performed. This is the nominal motor rating point and is also close to the average of the battery voltage. The tests designated for 190, 336, and 370 volts were skipped in the interest of the time required to perform this large number of tests. It is expected that little additional information would be gained from their performance.

Motor Temperature. Means of controlling the motor temperature were not available; therefore, only one set of tests were performed. Motor temperature was not recorded. However, due to the time required between tests, it is expected that motor temperature was near ambient (25 deg c) for most of the tests.

Power Supply limitations. The power supply for the setup was limited to 200 amperes which limited the horsepower available with 255VDC to about 65. Some of the torque points were reduced from the test plan to accomodate this limitation. In addition, the charge acceptance of the battery bank limited the regenerative torques below the test plan. Where, these applied, the actual torques used are documented in the individual tests

Flux Regulator. The flux regulator steps were not done as the flux regulator was never enabled in the field oriented control. Acceptable operation was attained without its use.

Test procedure. The following outlines the procedure used for this group of tests.

1. The Dynamometer was set for the speed regulation and adjusted for the motor RPM specified.
2. The power supply/battery was adjusted for the specified input voltage
3. The inverter was adjusted for the specified torque set point.
4. A special set of code was used which allowed a torque step to be added to the torque reference. A 5 ft-lb step was applied and removed to the torque summing junction.

Data. Two types of data were recorded - circular list data and LeCroy oscilloscope data. The following data was recorded in the circular list

1. TQRF (Torque reference which included the step)
2. TQFB (The calcuated torque feedback from the control)

The following data was recorded on the oscilloscope.

1. TQFB (Calculated torque feedback from the DSP D to A)
2. TQRF (From 80196 D to A) on some tests only. This was used as a convenient trigger mechanism.
3. FLUXD - from an analog testpoint.
4. IA - from an analog testpoint on EVDA.
5. Shaft torque from the Himmelstein (with 100 radian filter) on some traces

Response Measurement. The dynamometer was used to hold the desired speed point. A torque value was applied by the inverter. An instantaneous step was added to the torque reference (bypassing the input ramps). The value of the applied step was 5 ft-lbs in most cases. The torque feedback value along with the torque reference value was captured in the circular list and the results plotted. The torque response was measured according to one of the following methods.

1. Critically damped. - $Wc = 1 / (\text{time to 63\% of final value})$
2. Overshoot - $Wc = 3 / (\text{time to peak})$

Transient Response Results

Test Number	Batt. Voltage	Speed (RPM)	Torque (ft-lbs)	Response (Radians)	Comment
3	255	0	5	33	Torque regulator not closed at this speed.
11	255	0	50	?	Too much fundamental torque to determine the response
19	255	0	100	?	Too much fundamental torque to determine the response.
30	255	3,600	0	50	
38	255	3,600	50	30	
46	255	3,600	70	35	
53	255	3,600	-10	100	Originally test was to be done at 100 lb-ft
57	255	7,200	0	50	
65	255	7,200	40	30	Originally test was to be done at 50 lb-ft
73	255	7,200	-10	50	
79	255	11,667	0	50	
87	255	11,667	25	30	
95	255	11,667	-5	30	
101	255	2000rev	0	100	
109	255	2000rev	50	50	
117	255	2000rev	70	50	Originally test was to be done at 50 lb-ft.
124	255	2000rev	-35	50	

Torque Transient Response Sample Result

Torque Step Up

Torque Step Down

TEST II

Description

The object of section II tests is to determine the ability of the inverter/motor combination to produce rated torque (within the limits of the available horsepower) over the battery voltage range and the drive speed range. The following notes apply to the test procedure used to obtain the results in the table.

1. **Power Supply.** The DC power was supplied by the EMHP power supply which is limited to 200 amperes and the battery bank in parallel. For the 336 volt nominal tests, 27 units were used in series. For the 255 volt nominal tests, 22 units in series were used. For the 190 volt tests, 20 units were used. Since many tests required more than 200 amperes, the exact voltage could not always be obtained.
2. **Shaft Torque.** In the results table, motor shaft torque was obtained by measuring the output shaft torque with the Himmelstein torque transducer and dividing by the gear ratio (12.183).
3. **Shaft Speed.** The motor shaft speed was obtained by reading the dynamometer and multiplying by the gear ratio (12.183)
4. **Battery parameters.** The 2510 Tektronix TestLab was used to measure the average battery current, battery voltage, and motor input power.

The "TESTII RESULTS" table is based on the torque available at a particular speed with a particular battery voltage. It is assumed that the battery current can attain any level necessary to attain the 1.0 per unit operating point. (In practice, the battery current was limited to the available in obtaining the data).

In addition to the data given in the table, the following plots were made of system parameters from the 2510 test lab data files.

1. Battery voltage
2. Battery current
3. Each motor phase current
4. Each motor phase line-to-neutral voltage

TEST II RESULTS

Test Number	Shaft Torque	Torque Ref.	Motor Speed	Motor Current	Batt Current	Batt Volts	Motor Power	Comment
1	112.3	120	0	277	63.7	212.1	13.5kw	Rated Torque attained. Unable to adjust Battery for exactly 190 volts
3	123.3	140	0	301	65.8	255.6	13.5kw	Rated torque not attained. Drive in current limit. Flux probably low.
4	119.8	140	0	301	51.4	335.9	13.1kw	Rated torque not attained. Drive in current limit. Flux probably low.
6	94.4	110	3,600	255	310.9	195.6	58.1kw	Rated torque attained.
8	104.2	110	3,600	258.2	263.6	254.2	67.1kw	Rated torque not attained. Power supply in current limit.
10	109.2	115	3,600	273	238.9	306	69.7kw	Rated torque attained
12	37.8	45	7,200	187.5	235.3	194.6	45.8kw	Rated torque not attained. Near square wave mode not enough forcing.
14	55	58	7,200	216.1	268.5	254.4	65.3kw	Rated torque attained.
16	53.9	55	7,200	175	192.4	330.5	61.8kw	Rated torque attained
18	23.5	25	11,667	169	201.4	196.3	39.5kw	Rated torque not attained. Near square wave mode not enough forcing.
20	33.7	37	11,667	233	272.8	254	66.8kw	Rated torque attained.
22	33.2	36	11,667	192	199	334.7	64.5kw	Rated torque attained

TEST II RESULTS

TORQUE ENVELOPE TESTS

Efficiency Tests Results

190v BATTERY

TEST	SPEED (RPM)	TORQUE (LB-FT) REF	TORQUE (SHAFT)	BATTERY VOLTAGE	CHOP FREQ. (KHZ)	BATTERY POWER (WATTS)	MOT IN POWER (WATTS)	SHAFT POWER (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	0	5	5.1	190.3	?	404	283	0	69.9	0	0
7	0	25	23.2	190.2	1.8	1,082	807	0	74.6	0	0
14	0	50	43.3	190.1	2.2	2,336	1,805	0	77.3	0	0
20	0	100	92.4	189.5	3.6	7,740	5,867	0	75.8	0	0
26	0	104	100.2	189.4	3.8	8,422	6,393	0	75.9	0	0
38	3,600	5	3.9	190.6	3.8	3,247	3,016	1,971	92.9	65.4	60.7
44	3,600	25	24	190.3	2.3	14,440	13,968	12,244	96.7	87.7	84.8
50	3,600	50	48.6	193	0.9	29,666	28,584	24,823	96.4	86.8	83.7
56	3,600	*100	86.5	191.1	0.8	55,322	52,854	44,165	95.5	83.6	79.8
62	3,600	*104	82.1	187.9	0.7	52,943	49,603	41,959	93.7	84.6	79.3
68	3,600	-25	-27.7	230.2	2.5	-11,948	-12,125	-14,150	98.5	85.7	84.4
74	7,200	5	3.6	189.6	2.2	5,616	5,446	3,697	97	67.9	65.8
80	7,200	25	23.7	192.1	0.6	28,948	27,868	24,289	96.3	87.2	83.9
86	7,200	*40	33.6	192.8	0.4	41,144	39,613	34,363	96.3	86.7	83.5
92	7,200	#-25	-6.7	226	2.6	-4,594	-4,792	-6,808	95.9	70.4	67.5
98	11,667	5	3.8	189.9	1.3	8,813	8,537	6,250	96.9	73.2	70.9
104	11,667	25	17.2	188.9	0.4	35,439	34,132	28,776	96.3	84.3	81.2
110	11,667	#-10	-3.1	228.1	1	-3,817	-3,883	-5,159	98.3	75.3	74

* Limited due to Power Supply Current Limit

Limited due to excessive battery voltage

Efficiency Tests Results

255v BATTERY

TEST	SPEED (RPM)	TORQUE (LB-FT) REF	TORQUE (SHAFT)	BATTERY VOLTAGE	CHOP FREQ. (KHZ)	BATTERY POWER (WATTS)	MOT IN POWER (WATTS)	SHAFT POWER (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
3	0	5.3	53	256.7	?	622	597	0	96	0	0
9	0	25	21.8	256.8	4	1,332	1,150	0	86.3	0	0
16	0	50	41.8	256.6	3.5	2,819	2,366	0	83.9	0	0
22	0	100	91.5	256.2	5	8,425	6,531	0	77.5	0	0
28	0	140	118.2	255.7	5.2	12,859	9,807	0	76.3	0	0
40	3,600	5	3.6	256.4	4.9	3,332	3,269	1,845	98.1	56.4	55.4
46	3,600	25	23.9	256	2.8	14,745	14,363	12,210	97.4	85	82.8
52	3,600	50	47.9	255	2.3	29,750	28,770	24,500	96.7	85.2	82.4
58	3,600	*100	76.4	254.7	2	48,490	46,534	39,050	96	83.9	80.5
64	3,600	*110									
70	3,600	#-25	-15.8	330.4	6.2	-6,154	-6,249	-8,093	98.5	77.2	76
76	7,200	5	3.5	258.1	3.8	6,041	5,775	3,528	95.6	61.1	58.4
82	7,200	25	24.1	255.2	1	28,064	27,322	24,621	97.4	90.1	87.7
88	7,200	*54	43.3	254.3	0.6	51,744	50,293	44,406	97.2	88.3	85.8
94	7,200	#-25	-10.7	340.4	2	-9,625	-9,819	-10,933	98	89.8	88
100	11,667	5	3.6	256	2.2	9,040	8,715	5,980	96.4	68.6	66.2
106	11,667	25	23.2	255	0.9	46,024	44,586	38,461	96.9	86.3	83.6
112	11,667	-10	-11.7	372.6	2.2	-16,628	-16,710	-19,299	99.5	86.6	86.2

* Limited due to Power Supply Current Limit

Limited due to excessive battery voltage

Efficiency Tests Results

336v BATTERY

TEST	SPEED (RPM)	TORQUE (LB-FT) REF	TORQUE (SHAFT)	BATTERY VOLTAGE	CHOP FREQ. (KHZ)	BATTERY POWER (WATTS)	MOT IN POWER (WATTS)	SHAFT POWER (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
5	0	5	3.2	336.6	10	1,069	907	0	84.8	0	0
11	0	25	23.5	336.5	6	1,534	1,454	0	94.8	0	0
18	0	50	41.2	336.2	6.5	3,750	3,492	0	93.1	0	0
24	0	100	91.3	335.9	6.8	9,872	7,844	0	79.5	0	0
30	0	140	118.2	336.2	7.2	15,406	11,704	0	76	0	0
42	3,600	5	3.4	336	7.7	3,946	3,823	1,764	96.9	46.1	44.7
48	3,600	25	24	335.9	4.3	15,297	15,136	12,252	98.9	80.9	80.1
54	3,600	50	47.7	335.6	4.1	30,291	29,736	24,362	98.2	81.9	80.4
60	3,600	100	94.3	334.7	4.3	62,474	59,866	48,195	95.8	80.5	77.1
66	3,600	110	103.6	334.5	4.2	69,181	66,068	52,916	95.5	80.1	76.5
72	3,600	-25	-26.6	361.3	5.3	-10,805	-10,913	-13,604	99	80.2	79.4
78	7,200	5	3.3	336.9	5.6	6,383	6,126	3,363	96	54.9	52.7
84	7,200	25	23.7	336.7	2.1	28,765	28,073	24,326	97.6	86.7	84.6
90	7,200	54	52	335.7	2	61,978	60,248	53,138	97.2	88.2	85.7
96	7,200	#-25	-21.3	362.3	3.3	-20,083	-20,306	-21,845	98.9	93	91.9
102	11,667	5	3.4	336.9	3.8	9,533	9,177	5,705	96.3	62.2	59.8
108	11,667	33	31.2	333.7	1.2	60,805	59,246	51,649	97.4	87.2	84.9
114	11,667	-10	-10.8	356.5	1.2	-16,807	-16,872	-17,802	99.6	94.8	94.4

* Limited due to Power Supply Current Limit

Limited due to excessive battery voltage

Transaxle Efficiency at 3600RPM **Transaxle Efficiency at 7200RPM** **Transaxle Efficiency at 11,667RPM**

Transaxle Efficiency at 255VDC **Transaxle Efficiency at 190VDC** **Transaxle Efficiency at 336VDC**

Inverter Efficiency 255 Volt Battery

Motor Speed	
✕	4000 RPM
◆	5000 RPM
▲	6000 RPM
⊗	7000 RPM
⊙	8000 RPM
	9000 RPM
☆	10000 RPM

4000 RPM	88.2	91.3	94.2	93.9	94.6	94.9	95.4	95.8	96.2	96.5	97.4	97	96.8	96.6	96.4	96.3	96.3	96.2
5000 RPM	90.4	94.1	95.3	95.7	96.1	96.3	97.1	97.2	97.4	97.7	98	98	97.3	97	96.9	96.6		
6000 RPM	90.8	94.6	95.4	96.3	96.7	97.1	97.3	97.5	97.6	97.8	98.1	97.5	97.3	97	96.6			
7000 RPM	93.7	94.7	95.9	96.4	97.2	97.2	97.5	97.6	97.6	97.7	98.2	97.1	97	96.6				
8000 RPM	91	93.2		95.6		96.6		97		97.3	96.9	97	96.7					
9000 RPM	93.3	94.9		96.6		97.2		97.6		97.9	98.1	97.1	96.4					
10000 RPM		96		97.4		97.6		98.1		98.1	97.3	97.1						

Torque in ft-lbs

Inverter Efficiency

190 Volt Battery

0 RPM	69.9	74.6		77.3			75.8	75.9
3600 RPM	92.9	96.7		96.4		95.5		
7200 RPM	97	96.3	96.3					
11,667 RPM	95.9	96.3						

Torque in ft-lbs

Inverter Efficiency

255 Volt Battery

0 RPM	96	86.3		83.9			77.5	76.3
3600 RPM	98.1	97.4		96.7	96			
7200 RPM	95.6	97.4	97.2					
11,667 RPM	96.4	96.9						

Torque in ft-lbs

Inverter Efficiency

336 volt Battery

0 RPM	84.4	94.8		93.1					
3600 RPM	96.9	98.9		98.2				79.5	75.9
7200 RPM	96	97.6			97.2			95.8	
11,667 RPM	96.3	97.4							

Transaxle Efficiency

190 Volt Battery

3600 RPM	65.4	87.7		86.8		84.6
7200 RPM	67.9	87.2	86.7			
11,667 RPM	73.2	84.3				

Transaxle Efficiency 255 Volt Battery

4000 RPM	42.5	58.8	63.6	73.2	75	77	78.4	79.6	79.9	81.3	85.7	87.4	87.2	87.1	86.7	86.6	86	85
5000 RPM	45.3	64.6	70.9	74.9	78.9	80.5	81.5	81.2	82.6	84.7	88.7	89.5	89.2	89.1	88.4	87.1		
6000 RPM	49	68.7	73.9	78.2	81.8	81.1	83.1	84.2	85.5	86	89.2	90	89.4	88.7	86.7			
7000 RPM	57.8	69.6	74.7	78.9	80.7	83.4	83.7	84.6	86.1	87.5	91.1	90.4	88.9	86.2				
8000 RPM	59.5	68.4		78.8		82.3		85.3		86.8	90.6	90.5	87.7					
9000 RPM	55.5	69.4		80.9		84.2		86.2		89.1	89.7	88	84.7					
10000 RPM		69		80.7		84		87.4		88	89.1	87.7						

Torque in ft-lbs

Transaxle Efficiency

255 Volt Battery

3600 RPM	56.4	85		85.2	83.9
7200 RPM	61.1	90.1	88.3		
11,667 RPM	66.2	83.6			

Transaxle Efficiency

336 Volt Battery

Torque-Speed Matrix for Determining Efficiency

Motor Torque in LB-FT																							
Motor RPM	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	70	80	90	100	110	120	130	140
500		*		*		*		*		*	*	*	*	*	*	*	*	*	*	*	*	CL	CL
1,000		*		*		*		*		*	*	*	*	*	*	*	*	*	*	*	*	CL	CL
2,000		*		*		*		*		*	*	*	*	*	*	*	*	*	*	*	BC	BC	BC
3,000		*		*		*		*		*	*	*	*	*	*	*	*	*	*	*	BC	BC	
4,000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				
5,000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*							
6,000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*								
7,000	*	*	*	*	*	*	*	*	*	*	*	*	*	*									
8,000	*	*		*		*		*		*	*	*	*										
9,000	*	*		*		*		*		*	*	*	*										
10,000		*		*		*		*		*	*	*											
11,000	*	*		*		*		*		*	*	*											
12,000		*		*		*		*		*	*	*											
13,000		*		*		*		*		*	*	*											
14,000	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB	AB											

* Test Completed

CL- excessive motor current

BC- Excessive DC current (>250 amps)

AB- Above speed range

EFFICIENCY AND LOSS DATA AT 500 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	40.5	23	132.3	674	793	119	541.7	85	19.6	16.7
3										
4	40.5	47	270.4	931	1,069	138	660.6	87.1	29	25.3
5										
6	40.5	70	402.7	1,145	1,315	170	742.3	87.1	35.2	30.6
7										
8	40.5	100	575.3	1,429	1,613	184	853.7	88.6	40.3	35.7
9										
10	40.5	125	719.1	1,732	1,915	183	1,012.9	90.4	41.5	37.6
20	40.5	246	1,415.2	2,738	2,984	246	1,322.8	91.8	51.7	47.4
30	40.5	367	2,111.3	4,137	4,400	263	2,025.7	94	51	48
40	40.5	486	2,795.9	5,171	5,635	464	2,375.1	91.8	54.1	49.6
50	40.5	606	3,486.2	6,576	7,236	660	3,089.8	90.9	53	48.2
60	40.5	729	4,193.8	7,948	8,855	907	3,754.2	89.8	52.8	47.4
70	40.5	855	4,918.7	9,618	10,814	1,196	4,699.3	88.9	51.1	45.5
80	40.5	973	5,597.5	11,399	12,882	1,483	5,801.5	88.5	49.1	43.5
90	40.5	1,094	6,293.6	12,983	14,845	1,862	6,689.4	87.5	48.5	42.4
100	40.5	1,224	7,041.5	14,703	16,917	2,214	7,661.5	86.9	47.9	41.6
110	40.5	1,344	7,731.8	17,038	19,656	2,618	9,306.2	86.7	45.4	39.3
120	40.5	1,456	8,376.1	19,085	22,101	3,016	10,708.9	86.4	43.9	37.9
130	cur lim									

EFFICIENCY AND LOSS DATA AT 1000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	82.1	27	314.9	937	1,056	119	622.1	88.7	33.6	29.8
3										
4	82.1	51	594.8	1,343	1,477	134	748.2	90.9	44.3	40.3
5										
6	82.1	75	874.6	1,728	1,892	164	853.4	91.3	50.6	46.2
7										
8	82.1	99	1,154.5	2,087	2,252	165	932.5	92.7	55.3	51.3
9										
10	82.1	124	1,446.1	2,466	2,620	154	1,019.9	94.1	58.6	55.2
20	82.1	244	2,845.5	4,319	4,520	201	1,473.5	95.6	65.9	63
30	82.1	362	4,221.6	6,388	6,636	248	2,166.4	96.3	66.1	63.6
40	82.1	487	5,679.4	8,449	8,888	439	2,769.6	95.1	67.2	63.9
50	82.1	607	7,078.8	10,414	11,076	662	3,335.2	94	68	63.9
60	82.1	729	8,501.5	12,670	13,598	928	4,168.5	93.2	67.1	62.5
70	82.1	850	9,912.6	14,901	16,105	1,204	4,988.4	92.5	66.5	61.6
80	82.1	975	11,370.4	17,464	18,968	1,504	6,093.6	92.1	65.1	59.9
90	82.1	1,090	12,711.5	19,733	21,532	1,799	7,021.5	91.6	64.4	59
100	82.1	1,213	14,145.9	22,669	24,832	2,163	8,523.1	91.3	62.4	57
110	82.1	1,331	15,522	25,189	27,702	2,513	9,667	90.9	61.6	56
120	82.1	1,460	17,026.4	28,207	31,174	2,967	11,180.6	90.5	60.4	54.6
130	cur lim									

EFFICIENCY AND LOSS DATA AT 2000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	165	27	632.8	1,373	1,508	135	740.2	91	46.1	42
3										
4	165	52	1,218.8	1,977	2,166	189	758.3	91.3	61.6	56.3
5										
6	165	76	1,781.3	2,695	2,857	162	913.8	94.3	66.1	62.3
7										
8	165	100	2,343.8	3,288	3,460	172	944.3	95	71.3	67.7
9										
10	165	124.5	2,918	3,984	4,151	167	1,066	96	73.2	70.3
20	165	244	5,718.8	7,309	7,530	221	1,590.3	97.1	78.2	75.9
30	165	368	8,625	10,925	11,217	292	2,300	97.4	78.9	76.9
40	165	488	11,437.5	14,345	14,827	482	2,907.5	96.7	79.7	77.1
50	165	607	14,226.6	17,889	18,568	679	3,662.4	96.3	79.5	76.6
60	165	729	17,085.9	21,482	22,412	930	4,396.1	95.9	79.5	76.2
70	165	851	19,945.3	25,548	26,750	1,202	5,602.7	95.5	78.1	74.6
80	165	969	22,710.9	29,428	30,877	1,449	6,717.1	95.3	77.2	73.6
90	165	1,094	25,640.6	33,313	35,385	2,072	7,672.4	94.1	77	72.5
100	165	1,209	28,335.9	37,378	39,793	2,415	9,042.1	93.9	75.8	71.2
110	165	1,331	31,195.3	41,375	44,162	2,787	10,179.7	93.7	75.4	70.6
120	cur lim									
130										

EFFICIENCY AND LOSS DATA AT 3000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	247.5	26	914.1	1,673	1,860	187	758.9	89.9	54.6	49.1
3										
4	247.5	51	1,793	2,606	2,793	187	813	93.3	68.8	64.2
5										
6	247.5	76	2,671.9	3,613	3,822	209	941.1	94.5	74	69.9
7										
8	247.5	99	3,480.5	4,532	4,749	217	1,051.5	95.4	76.8	73.3
9										
10	247.5	123	4,324.2	5,552	5,787	235	1,227.8	95.9	77.9	74.7
20	247.5	242	8,507.8	10,286	10,609	323	1,778.2	97	82.7	80.2
30	247.5	364	12,796.9	15,397	15,808	411	2,600.1	97.4	83.1	81
40	247.5	488	17,156.3	20,511	21,093	582	3,354.8	97.2	83.6	81.3
50	247.5	607	21,339.8	25,485	26,227	742	4,145.2	97.2	83.7	81.4
60	247.5	727	25,558.6	30,285	31,655	1,370	4,726.4	95.7	84.4	80.7
70	247.5	847	29,777.3	35,440	37,068	1,628	5,662.7	95.6	84	80.3
80	247.5	969	34,066.4	40,925	42,885	1,960	6,858.6	95.4	83.2	79.4
90	247.5	1,090	38,320.3	46,910	49,248	2,338	8,589.7	95.3	81.7	77.8
100	247.5	1,216	42,750	52,618	55,355	2,737	9,868	95.1	81.2	77.2
110	247.5	1,330	46,757.8	58,272	61,420	3,148	11,514.2	94.9	80.2	76.1
120	cur lim									
130										

EFFICIENCY AND LOSS DATA AT 4000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	328.4	9.5	443.2	1,042	1,182	140	598.8	88.2	42.5	37.5
2	328.4	21	979.6	1,668	1,827	159	688.4	91.3	58.7	53.6
3	328.4	38.5	1,795.9	2,662	2,826	164	866.1	94.2	67.5	63.6
4	328.4	51	2,379	3,250	3,463	213	871	93.8	73.2	68.7
5	328.4	63	2,938.8	3,917	4,143	226	978.2	94.5	75	70.9
6	328.4	75	3,498.6	4,545	4,787	242	1,046.4	94.9	77	73.1
7	328.4	86.5	4,035	5,150	5,398	248	1,115	95.4	78.4	74.8
8	328.4	99	4,618.1	5,800	6,055	255	1,181.9	95.8	79.6	76.3
9	328.4	111	5,177.9	6,484	6,738	254	1,306.1	96.2	79.9	76.8
10	328.4	124	5,784.3	7,117	7,378	261	1,332.7	96.5	81.3	78.4
20	328.4	243	11,335.4	13,221	13,576	355	1,885.6	97.4	85.7	83.5
30	328.4	366	17,073.1	19,543	20,158	615	2,469.9	96.9	87.4	84.7
40	328.4	489	22,810.7	26,173	27,046	873	3,362.3	96.8	87.2	84.3
50	328.4	609	28,408.5	32,639	33,793	1,154	4,230.5	96.6	87	84.1
60	328.4	732	34,146.1	39,383	40,849	1,466	5,236.9	96.4	86.7	83.6
70	328.4	850	39,650.6	45,769	47,539	1,770	6,118.4	96.3	86.6	83.4
80	328.4	977	45,574.8	52,979	55,015	2,036	7,404.2	96.3	86	82.8
90	328.4	1,094	51,032.6	60,060	62,445	2,385	9,027.4	96.2	85	81.7
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 5000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	410.4	9	524.7	1,159	1,282	123	634.3	90.4	45.3	40.9
2	410.4	26	1,515.7	2,345	2,493	148	829.3	94.1	64.6	60.8
3	410.4	38.5	2,244.4	3,166	3,324	158	921.6	95.2	70.9	67.5
4	410.4	50	2,914.8	3,890	4,064	174	975.2	95.7	74.9	71.7
5	410.4	63	3,672.6	4,657	4,844	187	984.4	96.1	78.9	75.8
6	410.4	75	4,372.2	5,430	5,639	209	1,057.8	96.3	80.5	77.5
7	410.4	86	5,013.4	6,148	6,335	187	1,134.6	97	81.5	79.1
8	410.4	98	5,713	7,032	7,232	200	1,319	97.2	81.2	79
9	410.4	110	6,412.5	7,767	7,972	205	1,354.5	97.4	82.6	80.4
10	410.4	123	7,170.3	8,463	8,663	200	1,292.7	97.7	84.7	82.8
20	410.4	248	14,457.3	16,296	16,634	338	1,838.7	98	88.7	86.9
30	410.4	364	21,219.5	23,706	24,203	497	2,486.5	97.9	89.5	87.7
40	410.4	489	28,506.5	31,976	32,862	886	3,469.5	97.3	89.1	86.7
50	410.4	608	35,443.6	39,763	40,992	1,229	4,319.4	97	89.1	86.5
60	410.4	726	42,322.5	47,878	49,396	1,518	5,555.5	96.9	88.4	85.7
70	410.4	848	49,434.5	56,773	58,793	2,020	7,338.5	96.6	87.1	84.1
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 6000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	492.5	9	629.6	1,286	1,417	131	656.4	90.8	49	44.4
2	492.5	25.5	1,783.9	2,595	2,744	149	811.1	94.6	68.7	65
3	492.5	37.5	2,623.4	3,551	3,721	170	927.6	95.4	73.9	70.5
4	492.5	50	3,497.9	4,472	4,645	173	974.1	96.3	78.2	75.3
5	492.5	62	4,337.4	5,303	5,482	179	965.6	96.7	81.8	79.1
6	492.5	74	5,176.8	6,380	6,568	188	1,203.2	97.1	81.1	78.8
7	492.5	85.5	5,981.4	7,198	7,398	200	1,216.6	97.3	83.1	80.9
8	492.5	98	6,855.8	8,136	8,347	211	1,280.2	97.5	84.3	82.1
9	492.5	110	7,695.3	9,000	9,224	224	1,304.7	97.6	85.5	83.4
10	492.5	122	8,534.8	9,927	10,153	226	1,392.2	97.8	86	84.1
20	492.5	241	16,859.7	18,911	19,287	376	2,051.3	98.1	89.2	87.4
30	492.5	366	25,604.4	28,451	29,182	731	2,846.6	97.5	90	87.7
40	492.5	485	33,929.3	37,961	39,023	1,062	4,031.7	97.3	89.4	86.9
50	492.5	608	42,534.1	47,980	49,475	1,495	5,445.9	97	88.6	86
60	492.5	728	50,929	58,775	60,842	2,067	7,846	96.6	86.7	83.7
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 7000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	575	14	1,143.5	1,979	2,112	133	835.5	93.7	57.8	54.1
2	575	25	2,041.9	2,936	3,100	164	894.1	94.7	69.5	65.9
3	575	37	3,022	4,044	4,216	172	1,022	95.9	74.7	71.7
4	575	49	4,002.1	5,074	5,264	190	1,071.9	96.4	78.9	76
5	575	61	4,982.2	6,176	6,356	180	1,193.8	97.2	80.7	78.4
6	575	74	6,044	7,248	7,457	209	1,204	97.2	83.4	81.1
7	575	85	6,942.5	8,297	8,508	211	1,354.5	97.5	83.7	81.6
8	575	97	7,922.6	9,365	9,596	231	1,442.4	97.6	84.6	82.6
9	575	109	8,902.7	10,346	10,596	250	1,443.3	97.6	86	84
10	575	121	9,882.8	11,301	11,563	262	1,418.2	97.7	87.5	85.5
20	575	240	19,602.3	21,507	21,902	395	1,904.7	98.2	91.1	89.5
30	575	365	29,811.8	32,978	33,956	978	3,166.2	97.1	90.4	87.8
40	575	483	39,449.6	44,389	45,784	1,395	4,939.4	97	88.9	86.2
50	575	603	49,250.7	57,170	59,177	2,007	7,919.3	96.6	86.1	83.2
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 8000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	656.5	14	1,305.5	2,194	2,412	218	888.5	91	59.5	54.1
2	656.5	24	2,238.1	3,272	3,511	239	1,033.9	93.2	68.4	63.7
3										
4	656.5	49	4,569.4	5,800	6,066	266	1,230.6	95.6	78.8	75.3
5										
6	656.5	73	6,807.5	8,272	8,563	291	1,464.5	96.6	82.3	79.5
7										
8	656.5	96	8,952.3	10,491	10,819	328	1,538.7	97	85.3	82.7
9										
10	656.5	120	11,190.3	12,896	13,258	362	1,705.7	97.3	86.8	84.4
20	656.5	246	22,940.2	25,312	26,117	805	2,371.8	96.9	90.6	87.8
30	656.5	363	33,850.8	37,419	38,570	1,151	3,568.2	97	90.5	87.8
40	656.5	484	45,134.4	51,450	53,188	1,738	6,315.6	96.7	87.7	84.9
50										
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 9000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	739	13	1,364.6	2,459	2,635	176	1,094.4	93.3	55.5	51.8
2	739	24	2,519.3	3,629	3,829	200	1,109.7	94.8	69.4	65.8
3										
4	739	49	5,143.6	6,356	6,581	225	1,212.4	96.6	80.9	78.2
5										
6	739	73	7,662.9	9,099	9,357	258	1,436.1	97.2	84.2	81.9
7										
8	739	96	10,077.3	11,631	11,914	283	1,553.7	97.6	86.6	84.6
9										
10	739	126	13,226.4	14,849	15,168	319	1,622.6	97.9	89.1	87.2
20	739	245	25,718	28,673	29,227	554	2,955	98.1	89.7	88
30	739	367	38,524.6	43,765	45,090	1,325	5,240.4	97.1	88	85.4
40	739	492	51,646	60,948	63,213	2,265	9,302	96.4	84.7	81.7
50										
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 10000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	821	23	2,682.2	3,888	4,051	163	1,205.8	96	69	66.2
3										
4	821	48	5,597.7	6,940	7,126	186	1,342.3	97.4	80.7	78.6
5										
6	821	71	8,280	9,855	10,094	239	1,575	97.6	84	82
7										
8	821	95	11,078.8	12,683	12,923	240	1,604.2	98.1	87.4	85.7
9										
10	821	125	14,577.4	16,557	16,874	317	1,979.6	98.1	88	86.4
20	821	244	28,455.1	31,937	32,836	899	3,481.9	97.3	89.1	86.7
30	821	363	42,332.8	48,270	49,706	1,436	5,937.2	97.1	87.7	85.2
40										
50										
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 11000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1	905	12	1,542.6	2,848	2,993	145	1,305.4	95.2	54.2	51.5
2	905	23	2,956.7	4,322	4,489	167	1,365.3	96.3	68.4	65.9
3										
4	905	47	6,041.9	7,512	7,709	197	1,470.1	97.4	80.4	78.4
5										
6	905	72	9,255.7	10,726	10,956	230	1,470.3	97.9	86.3	84.5
7										
8	905	95.5	12,276.6	14,082	14,374	292	1,805.4	98	87.2	85.4
9										
10	905	119	15,297.6	17,496	17,845	349	2,198.4	98	87.4	85.7
20	905	242	31,109.4	35,058	36,068	1,010	3,948.6	97.2	88.7	86.3
30	905	351	45,121.4	53,835	55,870	2,035	8,713.6	96.4	83.8	80.8
40										
50										
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 12000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	986	22	3,081.3	4,647	4,813	166	1,565.8	96.6	66.3	64
3										
4	986	52	7,283	8,961	9,183	222	1,678	97.6	81.3	79.3
5										
6	986	71	9,944	11,764	12,021	257	1,820	97.9	84.5	82.7
7										
8	986	100	14,005.7	16,036	16,342	306	2,030.3	98.1	87.3	85.7
9										
10	986	124	17,367	19,827	20,197	370	2,460	98.2	87.6	86
20	986	244	34,173.9	39,264	40,494	1,230	5,090.1	97	87	84.4
30	986	358	50,140.3	61,135	63,368	2,233	10,994.7	96.5	82	79.1
40										
50										
60										
70										
80										
90										
100										
110										
120										
130										

EFFICIENCY AND LOSS DATA AT 13000 RPM

TORQUE	DYN SPEED (RPM)	DYN TORQUE (LB-FT)	SHAFT POWER (WATTS)	MOTOR POWER (WATTS)	INVERT. POWER (WATTS)	INVERT. LOSSES (WATTS)	TRANS LOSSES (WATTS)	INV EFF (%)	TRANS EFF (%)	TOTAL EFF (%)
1										
2	1,068	22	3,337.5	4,946	5,201	255	1,608.5	95.1	67.5	64.2
3										
4	1,068	46	6,978.4	9,015	9,308	293	2,036.6	96.9	77.4	75
5										
6	1,068	75	11,377.8	13,758	14,096	338	2,380.2	97.6	82.7	80.7
7										
8	1,068	99	15,018.8	17,321	17,717	396	2,302.3	97.8	86.7	84.8
9										
10	1,068	123	18,659.7	21,381	21,895	514	2,721.3	97.7	87.3	85.2
20	1,068	246	37,319.3	43,420	44,765	1,345	6,100.7	97	85.9	83.4
30	1,068	342	51,883	64,887	67,364	2,477	13,004	96.3	80	77
40										
50										
60										
70										
80										
90										
100										
110										
120										
130										

INVERTER LOSSES

255 V Battery

INVERTER EFFICIENCY 255 VOLT BATTERY

TRANSAXLE LOSSES

255 Volt Battery

LOSSES (WATTS)

TRANSAXLE EFFICIENCY

255 VOLT BATTERY

Motor Speed

- 500 RPM
- ▲ 1000 RPM
- ▼ 2000 RPM
- ◆ 3000 RPM
- 4000 RPM
- ⊙ 5000 RPM
- 6000 RPM
- ▲ 7000 RPM
- ▼ 8000 RPM
- ◆ 9000 RPM
- ⊙ 10,000 RPM
- 11,000 RPM
- 12,000 RPM
- ▲ 13,000 RPM

Motor Efficiency

$EFF = [(Shaft\ Power + Gear\ Losses) / motor\ power] * 100$
 Motor output power calculated by adding the gear losses to the shaft power
 Gear Loss data only available to 6000 RPM

GEAR LOSSES

GEAR LOSSES WERE OBTAINED FROM EFFICIENCY DATA SUPPLIED BY FORD

FILE GLOSS.SPW
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Gear Losses VS SPEED

Test IV Heatruns

Test Setup.

The inverter was configured for the hardware presently being shipped with the final design. The major components being:

1. Toshiba IGBTs MG300J2YS45, 300 ampere, 600 volt design.
2. Philips electrolytic capacitors (3186GH5025400KHA2 5000MFD), 400 volts
3. Ford supplied muffin fans identical with those supplied in the vehicle. (Air flow 300CFM, .5")
4. A radiator for cooling the motor oil was used since no ram air from vehicle motion was available.

The inverter was fitted with thermocouples as defined in the data tables. A Ford cover was installed with tape used to seal around openings needed for wiring/thermocouples. The transaxle contains an AO Smith motor representative of those shipped by Ford.

For all tests, the following special hardware was used.

1. Capacitor with a thermocouple in its core and another attached to the outside of the can.
2. IGBT with a hole drilled in its base for attaching a thermocouple
3. Motor oil temperature was measured by inserting a thermocouple through a small hole in the filler cap.

Test I.

The following parameters define test I.

1. 35 HP continuously
2. 3600 RPM (at motor)
3. 255 volts battery voltage

3600 RPM was chosen because this is the motor corner point for a 75HP rating with 110 lb-ft of torque. Since the motor flux continues to rise until 5000 RPM, the maximum motor current required for 35 HP occurs at 3600 RPM.

The Tektronix 2510 Testlab was used to measure the inverter losses which allowed the IGBT junction to case temperature to be calculated.

$$P_{IGBT} = [Inverter_losses] \cdot \frac{1}{6} \cdot \frac{2}{3} = [1300] \cdot \frac{1}{9} = 140W$$

$$\Delta T_J = (.1 \text{ deg } C/W) \cdot (140W) = 14 \text{ deg}$$

Results

1. Capacitor - Maximum core rise was 7 deg C, well within expected values
2. IGBT - Maximum junction rise was 59 deg C, well within expected values
3. Electronics - The maximum rise approached 85 deg C but did not exceed it.
4. Motor - The maximum rise was well within expected values

Test II.

The following parameters define Test 2.

1. 140 ft-lbs torque for a duty cycle of 30 seconds on and 30 seconds off repeated continuously.
2. Stall (0 RPM).
3. 255VDC battery voltage

This point was chosen, in part, because it represents a worse case from the standpoint of capacitor ripple current. The Tektronix 2510 Testlab was used to measure the inverter losses which allowed the IGBT junction to case temperature to be calculated.

$$P_{IGBT} = [Inverter_losses] \cdot \frac{1}{6} \cdot \frac{2}{3} = [2100] \cdot \frac{1}{9} = 230W$$

$$\Delta T_J = (.1 \text{ deg C/W}) \cdot (230W) = 23 \text{ deg C}$$

Results.

The IGBT junction temperature would not support the current required for 140 lb-ft with this duty cycle. The torque requirement was reduced to 100 lb-ft to allow the test to be completed.

1. Capacitor - The maximum core rise was well within expected values
2. IGBT- The IGBT rise was more than originally calculated. Operation in the application is not affected.
3. Electronics - The maximum rise was well within safe limits
4. Motor temperatures - The motor temperatures within limits. The divergence of winding temperature from oil temperature indicates diminished cooling capability at zero speed.

HEATRUN - 30 SEC ON, 30 SEC OFF 100LB-FT TORQUE AT STALL

Time Minutes	Dis- charge Air	Phase C Wire	Air Around Caps	Above Heatsnk	Cap #2 Exterior	Cap #2 Interior	IGBT End of Full TQ	IGBT End of Zero TQ	Above the B- board	Ambient	Motor Oil	Heat Sink	Motor Winding
0	24.7	28.4	27.9	26.3	29.5	35.5	24.7	24.7	31.5	24.8	33.1	31.6	28.8
5	30.6		29.9	28.2	32.6	35.9	74.5	49.2	31.2	26.1	36.1	57.8	59.1
10	33.5		33.3	30.4	35.7	37.8	87.5	58.2	31.6	28.2	42.6	65.4	66.9
15	35.1		35.7	31.3	38.2	39.4	93.5	63.8	33.5	29.6	47.8	73.2	75
20	36.3	36.9	37.6	32.6	40.3	41	95.7	66.2	35.2	30.7	52.2	72.4	78.9
25	36.7	37.4	39.1	33.7	41.8	43.2	97.1	67.6	35.4	31.6	56.1	76.4	81.8
30	37.4	38.1	40.3	35.1	43.4	45.8	97.7	68.3	37.4	31.9	59.2	77.3	83.9
35	37.8	38.7	43.5	35.3	44.6	47.3	97.8	68.8	38.3	32.6	62.4	76.9	86.1
40	38.1	39.7	43	36.9	45.8	49.2	98.1	69	39.6	32.8	64.8	77.7	88.1
45	38.1	39.7	43.6	35.6	46.8	50.6	98.3	69.2	40	33	67.2	78.3	90.4
50	38.2	40	44.4	37.7	47.4	52.2	98.4	69.5	41.7	33.3	68.9	77.7	90.8
55	38.6	40.4	47	38	48.6	53.9	98.7	69.9	42	33.9	71	80.4	95.3
60	38.2	40.6	46.2	39.1	48.8	55	98.8	69.9	42.7	33.9	72.3	80.4	94.9
65	38.7	40.7	46	39.3	49.5	56.3	99	70.1	42.7	33.9	73.5	80.8	96.8
70	38.8	40.8	46.5	41	49.8	57.8	99.1	70	43	34.1	74.6	79.7	96.1
75	38.7	41.5	47.2	40.6	50.4	58.1	99.2	70.3	43.4	34.4	75.3	79.5	97.5
80	38.8	41.3	47.6	41.2	50.7	59.4	99.2	70.2	43.6	34.3	76	78.9	97.5
85	39.2	41.6	47.8	42	51	60.1	99.4	70.1	44	34	76.5	81.4	99.2
90	38.8	42.1	47	42.8	51	60.4	99.3	70.4	45.8	33.9	77.5	81.3	99.6
95	39.5	41.8	48.5	42.8	51.6	61.4	99.7	70.6	46	34.5	78	80.7	98.4
100	39.6	42.4	49.2	43.4	52.2	61.8	99.7	70.9	46	34.7	78.6	80.8	99.8
105	39.6	42.6	50.1	43	52.8	62.4	100.3	71	46.8	34.8	78.8	81.8	99.8
110	39.6	42.6	48.8	44.1	52.6	62.9	99.7	71	47	34.6	79.3	81.8	100.6
115	39.4	43.1	48.4	43.9	52.7	63.3	99.7	71	48.1	34.8	79.5	80.8	100.6

Time Minutes	Dis- charge Air	Phase C Wire	Air Around Caps	Above Heatsnk	Cap #2 Exterior	Cap #2 Interior	IGBT End of Full TQ	IGBT End of Zero TQ	Above the B- board	Ambient	Motor Oil	Heat Sink	Motor Winding
120	39.4	41.9	52	42.8	53.8	63.4	99.9	71	47.3	35.1	80.5	81	102.3
125	39.2	44.2	51.6	42.8	53.9	63.9	100.5	71.2	48.2	34.9	80.5	80.8	102.3
130	39	43	51.8	41.4	53.9	64.2	100.1	71.2	47.1	34.9	80.5	79.7	103.1
135	39.2	43.9	51.8	41.8	53.6	64.4	100.3	71.2	47	34.9	80.5	80.8	103.3
140	40.1	42.8	52	42.7	54.1	64.8	100.6	71.5	47.6	35.3	80.8	81.8	103.1
145	39.6	43.2	51.2	42.9	54.3	65.3	100.7	71.6	47.5	35.4	81.1	80.8	103.3
150	39.4	43.8	51.4	43.6	54.3	65.8	101	71.8	48.1	35.4	81.6	79.7	103.1
155	39.3	43.9	52.1	42.8	54.8	66.1	101	71.8	48.4	35.7	81.9	81.8	103.3
160	39.4	43	50.5	42.6	53.9	65.5	100.5	71.3	48.1	35.1	81.6	80.8	103.7
165	40	43.5	51.3	43	54	65.8	101	71.5	49.2	34.9	81.4	81.8	104.3
170	39.6	43.6	51.4	43	53.7	66	100.7	71.5	48.8	35.1	82.2	81.8	103.7
175	39.6	43.8	50.8	42.9	53.8	66.5	100.7	71.6	48.2	34.9	82.2	81.8	105.4
180	40.2	43	52	42.1	54.2	66.6	101.2	71.5	49	35.1	82.6	80.8	105.8

* All temperatures in the above table are in degrees Centigrade

35 HP Continuous Heatrun

Time Minutes	Ambient	Dis- charge Air	Above B-Board	Above Heatsnk	Above Power Supply	Phase C Wire	Cap Exterior	Cap Core	IGBT Base	Motor Oil	Heatsnk	Motor Winding
0	23.2	23.1	22.9	23.2	23	23.1	22.9	22.8	23	23.9	27.9	28.7
5	24.1	28.7	28.4	25.6	28.6	39.6	25.9	24.1	57.3	36	52.9	45.9
10	25.6	30.8	31.2	27.3	28.4	51.3	29	24.9	65.9	51.3	58.9	59.2
15	26.5	32.4	32.5	28.7	31.2	60.1	31	26.3	68.9	59.1	62.3	67.2
20	27.5	33.5	35	31.5	33.6	65.5	33.3	28.2	71.4	68.8	64.6	74
25	28.1	34.4	37.7	34.1	35.7	70	35.4	29.9	72.9	73.8	67.2	79.9
30	28.9	34.8	40.1	34.6	38.2	72.2	36.8	32	74	79	68.4	84.4
35	29.3	35.3	43.6	35.5	40.4	74	38.3	34.3	74.4	81.6	68.7	87.1
40	29.8	35.5	44.7	36.8	42.1	76.2	39.3	36.7	74.8	84.8	70.3	89.1
45	30.1	35.9	46.8	37.2	44	77.4	40.2	38.4	75.2	86.5	69.3	90.4
50	30.4	35.9	49	37.8	45.8	78.9	40.9	40	75.5	88.4	70.1	91.6
55	30.7	36.2	51.2	39.1	47.5	79.6	41.9	41.8	75.6	89.9	70.1	92.9
60	31	36.4	52.6	38.9	48.5	80	42.7	43	75.9	90.9	71.1	94.3
65	31.2	36.6	53.8	39.6	49.9	81.2	43.2	44.5	76.1	91.6	72.1	95.3
70	31.5	36.6	55.6	40.4	51	81.6	43.8	45.3	76.3	92.8	71.7	95.9
75	31.6	36.8	56.1	40.8	52	81.4	44.4	46.5	76.5	93.4	72.1	96.9
80	31.7	36.7	57.8	40.6	53.3	81.9	45.2	47.5	76.9	94.4	72.1	97.1
85	31.9	37.1	59.3	42.2	54.3	81.5	45.8	48.4	77	94.4	72.1	97.5
90	31.9	37	59.7	42.6	54.6	83.1	45.8	49.3	77	95	72.1	97.5
95	32.1	37.1	60.2	42.7	55.4	83.5	46.3	49.8	77.2	95.2	72.5	98
100	32.3	37.2	61.3	42.6	55.9	83.4	46.5	50.8	77	95.5	72.5	98.2
105	32.3	37.6	61.7	43	56.7	84.3	47	51.3	77.4	95.8	72.5	99.2
110	32.3	37.6	62.1	43.4	57.2	86.5	47	52	77.4	96	72.5	99.6
115	32.5	37.6	63	43.6	57.9	85	47.4	52.5	77.7	96.4	72.5	99.6

Time Minutes	Ambient	Dis- charge Air	Above B-Board	Above Heatsnk	Above Power Supply	Phase C Wire	Cap Exterior	Cap Core	IGBT Base	Motor Oil	Heatsnk	Motor Winding
120	32.5	37.8	63.2	43.3	58.3	87	47.5	52.7	77.6	96.7	72.8	99.6
125	32.6	37.6	64.1	43.6	58.3	86	47.6	53.1	77.7	96.9	72.8	99.8
130	32.6	38	64.2	44.2	59.3	86.2	48	53.1	77.8	97.1	72.8	100.2
135	32.7	38	65.1	44.4	59.2	86.2	48	54	78	97.4	73	100.2
140	32.8	38.1	64.8	44.7	59.7	87.5	48.2	53.9	77.9	97.5	73	100.2
145	32.7	38	65.2	44	59.5	86.2	48.2	54.5	78.1	97.8	72.5	101.4
150	33	38.1	65.5	44	60.3	87.9	48.6	54.8	78.3	98.1	73	101.4
155	33.1	38.2	65.5	45.6	60.1	90.7	48.7	54.7	78.3	98.2	73	101.4
160	33.1	38.4	65.8	45.4	60.4	89.9	48.8	55.2	78.5	98.5	73.2	101.6
165	33.3	38.4	65.7	45.4	60.7	88.7	48.9	55.4	78.4	98.7	73.2	101.4
170	33.1	38.4	66.7	45.5	60.7	89.9	49	55.3	78.4	98.7	73.2	101.4
175	33.3	38.5	66.1	45.9	60.9	89.8	48.9	55.9	78.6	98.9	73.2	101.4
180	33.4	38.2	66.6	45.4	61.5	89.8	49	55.8	78.6	99.1	73.2	101.4

* All temperatures in the above table are in degrees Centigrade

Measured Capacitor Temps

Capacitor Delta Temp Rise

Predicted Rise 50 deg C Ambient

Stall Heatrun 100 lb-ft TQ

Measured IGBT Base Temps

IGBT Temp Deltas

Predicted Rise 50 deg C Ambient

Heatsink Temperature

Stall Heatrun 100 lb-ft TQ

Stall Heatrun 100 lb-ft TQ

Measured Capacitor Temps

Capacitor Delta Temps

Predicted Rise, 50 deg C Ambient

35 HP HEATRUN

Electronic Temperatures

Electronics Temp Deltas

Predicted Rise, 50 deg C Ambient

35 HP HEATRUN

35 HP HEATRUN

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SUNDSTRAND POWER SYSTEMS
MODULAR ELECTRIC VEHICLE PROGRAM

**DEMONSTRATION TESTING AND
PRELIMINARY DESIGN OF A GAS TURBINE
RANGE EXTENDER AUXILIARY POWER UNIT
FOR THE FORD MODULAR
ELECTRIC VEHICLE**

FINAL REPORT

**PREPARED FOR
FORD MOTOR COMPANY AND THE
UNITED STATES DEPARTMENT OF ENERGY**

**CONTRACT NUMBER DE-AC07-90ID13019
FORD P.O. NUMBER 47-Y-112726**

Power
Systems

Sundstrand Corporation

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ENGINEERING REPORT

FORD MEVP RANGE EXTENDER APU DEMONSTRATOR TEST AND PRELIMINARY DESIGN STUDY

FINAL REPORT

DOCUMENT NO: **ERR 2219**

ISSUED:
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APPROVAL SIGNATURES:

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Advanced

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1.0 INTRODUCTION

This report describes the demonstration testing of a gas turbine APU and the preliminary design of a 24KW recuperated turboalternator prepared by Sundstrand Power Systems (SPS) under the DOE/FORD Electric Vehicle Range Extender Auxiliary Power Unit (APU) subcontract. The FORD Modular Electric Vehicle Program (MEVP) is sponsored by the US Dept. of Energy, Office of Transportation Technologies.

As part of the subcontract, Sundstrand has built and tested a 20kW APU using the T-20G-10C4 Gemini Gas Turbine. A Sundstrand Electric Systems, AC Generator, P/N 976J827-1 is driven at 12,000 RPM through a speed reduction adapter. After completion of performance, emissions, and noise tests, the unit was delivered to FORD for further testing.

The results of the APU testing at Sundstrand are described in the MEVP Demonstrator Test Report (ERR 2145) Appendix IV.

The preliminary design effort included the development of design concepts for the aerodynamic components, the low emissions combustor, the heat exchanger, and the high speed alternator-integrated with the turbine. Two different engine layouts were prepared reflecting alternative structural arrangements of the engine components. Concurrent with the layout design work producibility and cost studies were made to develop a rough order of magnitude estimate of the projected engine cost. This effort was supported by the FORD "Alpha Simultaneous Engineering Dept." to benefit from that organization's experience in estimating cost for automotive production volumes.

The preliminary design reflects previous experience at Sundstrand with similar products, such as, a regenerated truck turbine, a 10KW high speed turboalternator, and the recently developed small low cost ceramic turbojet (TJ-50). Consultations with FORD resulted in the decision that the design should be based on current state-of-the-art component technologies, already demonstrated at SPS. The maximum cycle temperature was limited to the temperature capabilities of the metallic turbine wheel and heat exchanger. However, the design of the turbine nozzle was based on silicon nitride ceramic material reflecting Sundstrand's design and development experience with ceramic components in several engines.

Using the FORD performance requirements Aerothermal Conceptual Design Studies were performed to optimize the cycle parameters and to define the aerodynamic flow path. The thermodynamic cycle was based on demonstrated aerodynamic component efficiencies, and well known heat exchanger and alternator characteristics. The final aerothermal design evolved as a compromise between performance/fuel economy, emissions, cycle temperatures, etc., and size. Methods to optimize fuel economy and emissions at part load were also evaluated. The results of the preliminary aerothermodynamic design study are summarized in Engineering Report No. ERR 2212, and are included here in APPENDIX I.

The preliminary design of the combustor was driven by the FORD requirement that the range extender equipped vehicle should meet the California ULEV pollution emission levels. Based on previous experience and emission test data, it was obvious that with conventional combustors, ULEV emission levels cannot be met if the engine has to operate at full load all the time. However, as a range extender, the engine will run only part of the vehicle operating time; therefore, a simple, conventional combustor may be satisfactory and the complexities and cost associated with ultra low emission catalytic combustors may be avoided. Based on this assumption, two simple low cost combustor concepts were studied, both of which are very familiar to SPS: a well stirred lean burn partial premix can combustor, and a rich primary zone "Tornado" annular combustor. Emission predictions made from test data on the can combustor showed that with the present can combustor configuration, the engine could not meet the ULEV requirements. ULEV requirement could be met if the engine is operated for 25% of the vehicle running time. Due to lack of emissions test data, no emission prediction was made for the "Tornado" annular combustor. The Preliminary Combustor Design Report TRR 1349 in APPENDIX II discusses the combustor design approach and the emissions predictions.

The structural design of the engine addressed two different recuperator arrangements: wrap around and aft mounted. Both arrangements can satisfy the FORD specifications for volume and weight.

The results of the producibility and cost study are shown in APPENDIX III.

2.0 24KW TURBOALTERNATOR PRELIMINARY DESIGN

During the Conceptual Design phase of this program several alternative turboalternator concepts have been analyzed for their suitability to the role of range extender for the MEVP electric vehicle. Sub-component selection was based on Sundstrand's extensive knowledge of small, high speed, Auxiliary Power Units (APUs). Of considerable importance to the cost equation is the high degree of similarity between the chosen turboalternator design and Sundstrand's low cost thrustjet, TJ-50.

The design concept chosen to perform manufacturing and cost analysis was selected using the following criteria:

- Capability to meet the Range Extender performance requirements
- Capability to meet low cost, high volume production expectations
- Simple compact design with low parts count
- Low technical risk to meet production schedule
- Growth potential through technology development
- Logical evolution of existing Sundstrand sub-systems

2.1 PRELIMINARY DESIGN CONSIDERATIONS

The turboalternator concept is based on Sundstrand's TJ-50 thrustjet, a four inch diameter jet engine, and the 10Kw Gemini Turboalternator. Whilst the basic turbomachinery configuration is similar to existing engines the components have been optimized for the range extender application. In designing the new turbomachinery elements care has been taken to stay within demonstrated results. The use of ceramic components was restricted to low stressed stationary turbine components to minimize technical risk.

A State of the Art approach has been utilized throughout the design of the turboalternator. To achieve volume production capability within a reasonable time frame it was deemed necessary to use only demonstrated technology and processes. Technological advancements could later serve to improve performance and reduce weight and cost.

For this relatively small size gas turbine power plant to achieve a low Brake Specific Fuel Consumption (BSFC) a heat recovery device is required. A metallic recuperator has been chosen for this application based on present day technology. Ceramic regenerators offer an alternative, however, there is still high technical risk associated with structural integrity of the ceramic disk, leakage, and seal wear. Cost and complexity of the rotating disk drive is also a major factor in this decision.

2.2 TURBOALTERNATOR CONFIGURATION

The baseline configuration for the turboalternator shown in Figure 1, is essentially a monorotor turbine with annular combustor, a shaft speed generator and an integrated wrap around recuperator. The monorotor design combines the compressor and turbine wheels in a one piece rotor, which is manufactured as a single component. The monorotor concept has been demonstrated successfully on several Sundstrand products, and proved to be a significant cost saving feature, the most recent monorotor application is in the 50 LB thrustjet which utilizes Silicon Nitride ceramic components for the turbomachinery and the turbine nozzle.

The turboalternator design is based on a single stage 5:1 compression ratio compressor. The radial impeller discharges air into a wedge diffuser where static pressure recovery is achieved. The compressed air from the diffuser enters the recuperator radially before being directed axially rearward while increasing in temperature. Exiting the recuperator the air is premixed with fuel before entering the primary zone of the combustor and ignited. The hot gas mixture is then accelerated through the nozzle and impinges upon the radial inflow turbine rotor to drive the impeller and the alternator. The exhaust is then directed to the recuperator to minimize waste heat losses, and improve the SFC. The use of the recuperator helps to reduce the exhaust gas temperature as well as the engine noise.

2.3 TURBOALTERNATOR PERFORMANCE

The Ford Range Extender specification identifies the system design point to be 24 kWe (electric) output with a SFC of 250 g/kWh (electric), which corresponds to a BSFC of 0.368 lb/hr/shp at 89.4% generator efficiency.

Performance trade studies were run on a range of configurations. The chosen design, with a pressure ratio of 5:1, accepts a slight drop in turbine efficiency for the improved reliability gained by reducing the running speed. The size and operating temperature limits of the recuperator also had a major impact on the aero-thermal design and engine performance.

The proposed design with a running speed of 93,882 rpm and air mass flow of 0.63 lb/sec has a calculated SFC of 374 g/kWh (electric). Although this is higher than with the design goal, it is realistic based on the size and simplicity dictated by the application. It was felt important to stay within tested component efficiencies, rather than create a theoretical design that is unachievable in production.

The relationship between Electrical Power and SFC is shown in Figure 2. From the curves, it can be seen that an SFC of 350 g/kWhr is achieved at an output of 20 kWe, assuming a constant 1750°F TIT.

2.4 AEROTHERMODYNAMIC DESIGN

The preliminary aero thermodynamic design of the engine is discussed in Appendix I.

2.4.1 Compressor Design

Design point cycle studies indicate an optimized performance for the compressor at the 24 kW(electric) match point of:

Pressure ratio (total-static)	5.0
Inlet air flow (ppm)	37.8
Peak Efficiency (total-static) %	75.2

General cycle analysis was performed to develop relationships for the leading performance indicators. Having established the optimized system a more detailed computation was performed which, through an iterative process, refines the turbomachinery design. A wedge diffuser with 17 vanes of high length to throat ratio was chosen to obtain maximum pressure recovery. The major design point parameters are contained in table I below.

TABLE I.
Turboalternator Compressor
Major Aerodynamic Performance Parameters
25% margin, 59°F, sea level condition.

PARAMETERS	VALUES
Rotational Speed	93,882 (rpm)
Airflow	0.63 (pps)
Inducer Tip diameter	2.305 (in)
Inducer Hub diameter	1.45 (in)
Impeller Tip diameter	4.625 (in)
Impeller Tip Speed	1894 (fps)
Impeller Tip width	0.115 (in)
Diffuser Entry diameter	5.0 (in)
Diffuser Exit diameter	7.0 (in)
Diffuser Exit Mach No	0.1
Diffuser Vane Height	0.125 (in)
Overall Efficiency	75.2 (%)
Pressure Ratio	5.0
Specific speed	0.571
Work Factor	0.673

2.4.2 Turbine Design

The design point turbine performance requirements for the turboalternator are:

- Expansion Ratio 4.02
- Efficiency (total-static) 85.0%
- Velocity Ratio 0.67

Baseline performance was established using the MPSPU test data and a tip speed limit of 2000 fps. The computer program 'RADTURB' was then used to develop the leading parameters and match the two turbomachinery components. The Turbine design point performance parameters are contained in table II.

TABLE II.
Turboalternator Turbine
Major Aerodynamic Performance Parameters
25% margin, 59°F, sea level condition

PARAMETERS	VALUES
Inlet Temperature	2210 (°R)
Inlet Pressure	64.22 (psia)
Pressure Ratio	4.02
Rotational Speed	93,882 (rpm)
Nozzle Entry diameter	6.1 (in)
Nozzle Exit diameter	5.3 (in)
Number of Nozzles	11
Nozzle Width	0.11 (in)
Nozzle Throat Area	0.9 (sq in)
Turbine Tip diameter	5.9 (in)
Turbine Tip Speed	2000 (fps)
Nozzle Width	0.11 (in)
Velocity Ratio	0.67
Exducer Tip diameter	2.85 (in)
Turbine Efficiency	85 (%)

2.4.3 Combustor Design

Sundstrand has two combustors that operate at similar mass flows to the requirements of the range extender, one is an annular construction, the other is a can type. Both can be used as the baseline in the development of a combustion system for this application. Also applicable is Sundstrand's patented 'TORNADO', swirl stabilized combustor which offers a simple design with minimal wall cooling.

The untreated emission levels from gas turbines are typically lower than reciprocating engines after the catalytic conversion. However, this application invokes ULEV emission levels which will require some additional development. The complexity of the combustor will be heavily dependent upon the method used to convert the gas turbine emissions into weighted system emission levels, and how the turboalternator is operated. For the preliminary design it has been assumed that a simple fixed geometry combustor can be used. Predicted emissions as a function of engine load at 100% speed are shown in Figure 3. Since flame temperature has a major influence on the Emission Indices, a final design will optimize, based on vehicle driving cycle.

The configuration chosen for the baseline design is an annular, reverse flow combustor, with four fuel injectors. This type was selected based on trade study comparisons with the single can configuration. Packaging was a major factor, but also overall design simplicity for recuperator integration was another consideration. The liner is a brazed assembly of 0.032 Hasteloy X sheet, with primary and secondary air swirl tubes. Its physical dimensions are; outside diameter 7.2 inches, inside diameter 3.6 inches, length 5 inches.

A detailed discussion of the combustor design is given in Appendix II.

2.4.4 Recuperator Design

There are many recuperator configurations that have the potential to satisfy this design. The type chosen for the study is an annular primary surface recuperator (PSR). It was selected because of its superior power density and low volume and weight. The PSR is a compact, highly efficient heat exchanger well suited to high volume production. The final size of the recuperator will be dictated in trade off studies involving weight, cost, and effectiveness.

The 'C-Type' configuration, which, due to the inlet and exit geometry lends itself to radial turbomachinery, results in a very compact and simple design. The core is assembled from stacking a number of air cells together, and welding them around the inlet and exit manifolds. Sheet metal welded around the outside and inside diameters completes the core assembly. Attaching flanges and an inner seal land completes the recuperator module.

Performance cycle temperature limits of 1175°F max recuperator exhaust gas inlet temperature have been imposed to stay within the material properties of 300 series stainless steel. Further increase of TIT above 1750°F would require a higher grade alloy steel, probably an Inconel 600 series alloy, with a significant increase in raw material cost.

Based on preliminary analysis the recuperator core will weigh less than 50lbs, and have an effectiveness of 80%, see Figure 4. This analysis used a standard internally developed code that is used to size Sundstrand's APU mounted heat exchangers. Since the code is based on the characteristics of a plate fin heat exchanger the results are conservative. PSRs offer significant reductions in weight with a corresponding improvement in effectiveness when compared to plate fin type designs, published reports indicate weight reductions of 50% are not uncommon.

2.5 STRUCTURAL DESIGN

The Range Extender has been designed to fit within the envelope defined in the specification, 38.9" wide, by 22.4" deep, by 12.5" high. With a wrap around recuperator overall length of the unit is significantly reduced, however, it's diameter starts to push the limits of the specification. Going to an aft mounted recuperator (see Figure 5) reduces the diameter from 12.5 ins to 9.4 ins, the length, however, is increased from 20.5 ins to 29.5 ins.

Ease of assembly is achieved through modular design practices. The rotor is inserted into the air intake housing as a finished module, being retained by radial screws. The air intake housing is a cast aluminum structure with minimal machining content. The temperature profile of the turbine is such that the aluminum terminates at the diffuser outside diameter and is connected to the recuperator by a flanged joint. Keeping the flange in the relatively cool location maintains the integrity of the aluminum structure and saves weight.

The turbine static structure is connected to the compressor static structure by the recuperator. Having flange attachments at both ends it ties the air intake housing to the combustor housing. The core of the recuperator, with its layers of thin sheet, provides an excellent containment shield.

The combustor housing forms a seal with the turbine nozzle at the exducer to form a pressure container for the compressor delivery air. The combustor housing is fabricated from Hastelloy X, which affords good elevated temperature strength and resistance to oxidation. The turbine nozzle is a two piece Silicon Nitride component, similar to one successfully run in the ceramic Gemini program, where temperatures of 2400°F were demonstrated.

Figure 6 shows the cavity between the compressor and the turbine and the two static components that together control leakage and minimize heat transfer. The knife seal is a standard component on radial turbomachinery. It limits compressor air leakage flow by means of maintaining a slight clearance with the shaft. Due to the single piece cast wheels the seal plate is in two halves, with a feather seal arrangement eliminating leakage along the axial split line. The thermal shield is a composite ceramic with extremely low thermal conductivity. Both of these components have been demonstrated in other engine programs.

An axially compliant static seal sits between the diffuser and the turbine nozzle. Being a full ring it also serves to radially locate the split knife seal, and thermal shield segments. A degree of redundancy has been built into the interstage seal arrangement due to the performance penalty of leakages on small turbomachinery. In development it is hoped to simplify this group of components.

2.6 ROTATING ASSEMBLY

An Inconel 713LC monorotor (see Figure 7) inertia welded onto an alloy steel shaft is a low cost patented Sundstrand design. The rotor is the principle component in the rotating assembly. The joint forward of the inducer improves the producibility of the monorotor casting, increasing the yield quantity for a given pour weight. Inertia welds are in use on several production engines, they provide strong reliable structural joints, and are well suited to volume production.

The alternator rotor and shaft bearings are axially clamped by a nut, which together with the monorotor form the complete rotating portion of the assembly. Upon insertion into the capsule containing the alternator stator, the rotating assembly becomes a module that is built and balanced as a replaceable sub-assembly.

2.7 ALTERNATOR DESIGN

A two pole permanent magnet generator (PMG) was selected for this application, due to its inherent simplicity and ruggedness of construction. The leading parameters of this concept design are listed below in table III.

TABLE III
PMG DESIGN PARAMETERS

PARAMETERS	VALUES
Speed	93,882 rpm
No of poles	2
Frequency	1565 Hz
Voltage (output)	250 volts, DC rectified.
Inducted current	100 Amps
No of phases	3
Turns per phase	8
Current density	16040 Amp/sq. in
Magnet material	Sm2Tm17

The high speed of this application dictates a very small rotor diameter to keep the tip speed below 650 FPS. Packaging constraints imposed by the modular concept eliminated the option of an Electromagnetic Generator (EMG), which requires rotating rectifiers and field winding cooling. The PMG has no rotor winding losses or rectifier losses to dissipate and is more efficient.

To compliment the small rotor a toothless stator design has been utilized. With a toothless design the windings are more compact since they now occupy the space previously taken by the steel teeth. Instead of the teeth carrying the flux to the AC windings the main flux penetrates the conductors. Winding eddy current losses are minimized by using Litz-wire.

2.8 SHAFT DYNAMICS

A model of the rotor system was created and analyzed using a PC program 'DYROBES'. For the purpose of this preliminary study composite stiffness's were used to characterize the bearings and support system.

The results of the baseline rotor analysis are shown in Figure 8.

Based on this preliminary analysis the rotor system appears to exhibit robust stability characteristics. There is a 29% margin for the second critical, and a 60% margin for the third. The high margins indicated can be attributed to the high shaft stiffness and the relatively low mass of the turbomachinery.

2.9 SYSTEM CONCEPT

The range extender interface with the vehicle systems has been limited to the physical envelope constraints, and the electrical output power. Integration of the gas turbine with the vehicle will have an impact on the turboalternator design.

For the next phase it is recommended that a full systems management flow chart be created to fully integrate the range extender with the system. This will address energy management, thermal management, secondary flow management, and integration of control functions.

Compartment shape, location, and configuration of inlet and exhaust are also important considerations since they will effect installation orientation, ducting losses, noise suppression, thermal insulation, etc. Careful installation design can minimize flow losses, reduce cost, and have a significant effect on assembly and maintenance.

2.10 GROWTH CAPABILITY

The baseline turboalternator has a Turbine Exhaust temperature (TET) limit of 1175°F imposed due to recuperator cost impact. Future growth could be achieved within the same envelope if the recuperator material was changed to IN 600 series steel, and a ceramic monorotor was incorporated; thus permitting the TET to increase to 1500°F, with a corresponding 18% increase in power.

2.11 EXHAUST SYSTEM

Exhaust system ducting has not been considered in this phase of the design. How the exhaust is directed will depend heavily on the installation requirements imposed by vehicle configuration. Since the exhaust gas exits the recuperator at 674°F, it will be necessary to reduce its temperature prior to final exit from the vehicle. A simple ejector system, that mixes the combustion gasses with air, could be designed to achieve the desired final exit temperature.

2.12 ENCLOSURE

The range extender APU should be accessible for servicing, but enclosed to isolate noise and vibration. It can therefore be envisioned that a compartment built around its unique requirements should be integrated into the vehicle. The enclosure should have quick disconnect electrical sockets, and simple attachments for any fluid or air filtering and ducting systems.

Final design of the enclosure will require a sound understanding of the proposed maintenance plan.

3.0 PRODUCIBILITY AND DESIGN TO COST

Many design features of the 24Kw Turboalternator, the monorotor, shaft speed alternator, and cold end bearings are representative of the traditional Sundstrand low cost approach that has been successfully used in the design and fabrication of our thrustjet family of products. The simplicity of geometry, low parts count, and elimination of hot end bearing lubrication and sealing requirements all serve to reduce cost.

Some trade-offs have been performed in the derivation of the baseline engine. Nevertheless some of the design considerations were driven by Aerospace technologies and practices, a greater integration with Automotive practices may result in a lower cost approach.

Production rates of 100,000 units a year forces the cost estimates to include a complete facilitation for most components, at a minimum it would require a dedicated cell. It is Sundstrand's experience that Aerospace suppliers, typically, do not support this activity, and tend to quote based on factored historic data, completely ignoring any resultant modifications to their rate structure.

The approach taken for this phase of the program was to team with Ford Alpha Group and derive a combined estimate using Automotive costing practices and Aerospace knowledge of the technology. This approach provides the added benefit of increasing our understanding of each others business philosophy. It was also felt that the combined approach would improve the quality of supplier participation.

3.1 PROCESS REVIEW

High volume for the Aerospace Industry is typically measured in the hundreds of units per year, for the Automobile Industry a million units per year is not untypical. This application has a projected volume somewhere between the two, we are using 100,000 units per year.

To arrive at a reasonable probable cost for the preliminary design Ford and Sundstrand have 'TEAMed' to combine the knowledge of both Industries. Indeed without the involvement of Ford it is unlikely Aerospace suppliers would address, with the same level of effort, unit costs for production rates of 100,000. Even the costs we have today are probably high due to the volume exceeding their custom and practice, but never-the-less, Fords involvement has added credibility to the volume requirement, and will make future inquiries easier.

In order to obtain a homogeneous cost picture the data has been compiled by Ford 'Alpha Group'. The TJ-50 baseline at, 3,000 units per year, was used to formulate a 'low-volume' Automotive cost. Using the responses from the supplier base a high volume cost estimate has also been obtained. These two numbers represent the degree of scatter for the probable cost before 'Value Engineering' and 'Cost Reduction'.

3.2 COST DRIVER SUMMARY

For a list of the Sundstrand Turboalternator cost drivers, refer to Appendix III, Component Estimates for Production Quantities, prepared by FORD, (Alpha Group).

By comparing columns B and C of the cost summary shown in Appendix III, it is readily observed that the major differences are associated with machining operations and metal forming. These differences represent the gap between Aerospace and Automotive Industries. The automotive estimate is achieved by a higher degree of tooling and automation consistent with volume production.

TABLE IV

COMPONENT	% TOTAL COST*
Alternator	11.3
Recuperator	41.3
Turbine Nozzle	17.9
	TOTAL 70.5

*FORD Alpha Estimate @ 100,000 units/yr.

The FORD Alpha estimate is governed by the components shown in Table IV. Together these three components represent over 70% of the total cost. These components will be the focus of evaluation and further trade studies in the future. The recuperator and the turbine nozzle will offer the greatest potential, since the alternator has already been rigorously pursued internally.

The cost of the recuperator was driven by material cost associated with an assumed core weight of 122 lbs. The design target weight is 50 lbs, achieved by balancing weight and effectiveness. This compromise, which will still achieve a 80% effectiveness, should result in a 50% cost reduction for this one component.

SPS is strongly encouraging the Government to support the development of ceramic recuperators for vehicular applications. Ceramic recuperators would facilitate operation at higher cycle temperatures and would result in substantial weight savings.

The nozzle cost is dictated by its process. Ceramics are now mass produced for automotive turbocharger applications at competitive cost. However, the cost estimate for this component does not take into account the necessary process maturity required. There are many current programs geared towards process improvement, cost reduction, and volume production of ceramic components. We therefore believe substantial cost reductions will be achieved in the near future.

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Figure 1. FORD Range Extender

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Figure 2. SFC vs Electrical Power

Figure 3. Emission Predictions at 100% Speed

Figure 4. FORD Hybrid Recuperator

Figure 5. AFT Recuperator Scheme

Figure 6. Knife Edge Interstage Seal Configuration

MONOROTOR, CAST IN 792
MACHINED SURFACES LIMITED TO SHROUD AND PILOT.
QUOTE BASED ON TJ-50 DETAIL DRAWING
QUANTITIES OF 100,000 PER YEAR

Figure 7. Monorotor, Cast In. 792
Machined Surfaces Limited to Shroud and Pilot

ERR 2219

Figure 8.

APPENDIX I

SUNDSTRAND REPORT ERR 2212

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ENGINEERING REPORT

Preliminary Aero-thermodynamic Design of a 24 kW APU for the FORD
Range Extender

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1.0 SUMMARY

This report documents preliminary findings on the aero-thermodynamic design of a 24 kWe APU for the Ford MEVP Range Extender. A background and objective of the given topic are presented, followed by the methodology. The design is based on customer requirements, guidelines and all necessary assumptions (listed in the Background Section). Design point cycle analysis and engine component performance programs were used to find the optimum pressure ratio using a regenerated Brayton cycle. After finding the optimum pressure ratio, a design comparison was carried out on the two rotational speeds. The slower speed (93882 rpm) was favored over the higher speed (120,000) for reliability reasons assuming that the slightly larger physical size of slower engine was acceptable. As a result the preliminary engine design was based on the lower speed. An engine cycle deck was built to reflect the preliminary design. Methods for improving part load specific fuel consumption (SFC) hence emissions were also examined. Maximum turbine inlet temperature was assumed limited to 1750°F (954°C) to facilitate the use of low cost material for the recuperator.

The preliminary results for the nominal sea level standard day design point are summarized below:

Turbine Powerhead Performance

100% Mechanical Speed, rpm	93882
T amb	59
P amb	14.7
powerhead output, shp (kWe)	45.3 (33.6)
Specific Fuel Consumption, lb/hr/shp, (kg/hr/kWe) (after rectifier)	.624 (.379)

2.0 BACKGROUND

The electric vehicle propulsion is actively being pursued as an alternative to the reciprocating internal combustion engine. The most prominent reasons for this research are those of reducing emissions and dependence on fossil fuels for transportation. Although the electric vehicle uses energy from its batteries, the energy source used to charge the batteries can vary. Large stationary power plants are capable of generating the electrical energy to charge the batteries at lower emission levels than current vehicular engines. However, there are still prevailing technical issues that need be overcome before electric vehicle use becomes widespread. The limitation for which this study seeks a solution is the one of vehicle range. Instead of waiting for battery technology to sufficiently improve vehicle range, a hybrid electric car is being considered in which an auxiliary energy source may be temporarily activated to provide electric power and/or recharge the batteries. The intent of this study was to define the basic aero-

thermodynamic configuration of a turboalternator that will meet or exceed the performance design goals outlined below.

An internal SPS meeting held on June 22, 1993, established preliminary performance guidelines for the MEVP hybrid electric vehicle. These guidelines will be used by the various engineering groups to develop the preliminary design of the range extender APU. The design assumptions are listed below and followed by a summary of the resulting project goals. It should be noted there are existing cost-benefit incentives associated with system characteristics that exceed minimum requirements.

Design Assumptions

- Turboalternator output power is based on a flat rated 24kWe generator output at sea level up to 100°F.
- Turboalternator will operate at modest TIT conditions (not to exceed 1750 °F).
- Inlet heating $\cong 0.73 \times (\text{Generator losses})$.
- $\eta_{\text{gen}} = 0.894$ with 8% being released as heat energy. (η after rectification)
- All performance evaluations are based on installed engine conditions. (2% inlet, 3% exhaust loss)
- Engine must fit inside an envelope size measuring 38.9" wide, by 22.4" deep, by 12.5" high.
- The mass of the turboalternator system should not exceed 88 lbs. (40 Kg).
- Regenerator effectiveness = 0.8

Design Goals

- The design shaft power output of the engine is 45.3 shp, 25 % higher than the required steady state electric (24kWe) power at 59°F, sea level condition. (Consequence of flat rating and electrical losses)
- The turboalternator should achieve a Specific Fuel Consumption (SFC) of 0.55 lbm/hr/shp based on shaft output power.
- Engine emissions should not exceed existing reciprocating engines running with a catalytic converter.
- APU must demonstrate a 250 millisecond fall time between full generator output power (24 kWe) and no load

3.0 METHOD

The first design was based on a compressor operating at an optimum specific speed. However, the rotational speed of the compressor based on an optimum specific speed was determined to be too high risk. As a result, the second of the two designs was chosen as the baseline, operating at the same speed as the Gemini APU. A small decrease in the compressor performance was accepted.

High Speed Design:

The following describes the methodology used to used to derive an optimum design based on SFC and weight, to meet the requirements outlined in the Background section. The analysis begins with a generic design point cycle analysis program that has been modified to take into account the effect of recuperation. All necessary assumptions for the first iteration were taken from existing data on the Gemini engine.

Table I shows tabulated data of SFC against pressure ratios of 4:1, 5:1 and 6:1. The mass flow rate was adjusted such that the engine yielded a power output of approximately 45 hp. From the results of Table I, it can be seen that there is negligible reduction in SFC in going from a pressure ratio of 5:1 to 6:1.

TABLE I - Preliminary Powerhead Design Point Air Flow Rate and SFC Vs. Compressor Pressure Ratio.

<i>Pressure Ratio</i>	4.0	5.0	6.0
<i>Air Flow Rate, lbm/s</i>	0.60	0.56	0.54
<i>(kg/s)</i>	(0.272)	(0.254)	(0.245)
<i>SFC (lbm/hr/shp),</i>	0.502	0.481	0.480
<i>kg/kWhr</i>	(0.305)	(0.292)	(0.291)

A similar analysis using an off design point, (36 shp, sea level, 100°F) also confirmed that there is no benefit in fuel economy by exceeding a pressure ratio of 5:1 for the given power requirement at the selected turbine inlet temperature (TIT). Equation 1 was used to obtain an approximate 100% design point speed of the engine, which turned out to be 118,000 rpm.

$$N_s = \frac{N \cdot \left(\frac{\dot{W}}{\rho_{a1}} \right)^{1/2}}{\left[g \cdot C_p \cdot T_1 \cdot \left(R_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \right]^{3/4}} \quad (\text{Eq. 1})$$

To obtain a more refined estimate of optimum speed as well as the scantling dimensions of the compressor, an SPS computer code called NS1 was used. Using the required mass flow rate, pressure ratio, 100% engine speed the compressor diameter was adjusted to produce a realizable work factor. The output total to total efficiency from NS1 was then reused in the cycle analysis to obtain a more refined estimate of the required mass flow rate. The converged solutions using NS1 and the cycle analysis programs are provided in the Appendix.

After defining the compressor, the turbine wheel was sized. To accomplish this, the test data from a similar turbine rig (shown in Figure 1) was used at a pressure ratio of 5:1. The turbine diameter was adjusted so that the U/V matched that corresponding to the peak in Figure 1. However, a mechanical stress constraint on tip speed prevented the design from reaching the optimum U/V. The constraint on turbine tip speed was set at 2000 ft/s and was active for both designs. This constraint resulted in a loss of only 1.4% on turbine efficiency.

To complete the turbine sizing and check for accuracy on turbine efficiency, it was necessary to run the one-dimensional analysis program called 'RADTURB'. RADTURB was used to confirm that the turbine efficiency assumed in the cycle analysis program was correct and to size the remaining scantling dimensions including the turbine nozzle throat area and rotor throat area. The RADTURB output is shown in the Appendix.

Gemini Speed Design:

The other option that was ultimately the chosen design, operates at the same nominal speed as the proven Gemini APU. To meet endurance goals the engine was designed around the selected nominal engine speed of 93,882 rpm for the intended application.

The same process was carried out for this design as the one for the high speed case. The only difference was that the compressor could not be optimized for adiabatic efficiency on specific speed. With a near optimum pressure ratio still at 5:1, the compressor needed to be sized to match the required mass flow rate producing the required power. All other aspects of the design and iteration process were the identical.

4.0 RESULTS

A preliminary APU design was carried out using the slower speed approach. For preliminary design purposes, the lower speed design was selected because of lower risk. Table II shows the final dimensions for the preliminary design. Figure 2, shows a schematic of the basic scantling dimensions of the compressor and turbine sections. The efficiencies predicted and used in the sizing of this engine are based on SPS experience and are realistic.

Table II, Basic Engine Dimensions

Compressor	
D1h, in	1.450
D1s, in	2.350
D2, in	4.625
Specific Speed	73.6
N. D. Specific Speed	0.57
Turbine Nozzle	
LE Diameter, in	6.10
TE Diameter, in	5.30
Vane Height, in	0.110
Ath, in ²	0.919
Vane #	19
Turbine Rotor	
Tip Diameter, in	4.90
Exducer Hub Dia., in	1.20
Exducer Shroud Dia., in	2.85
Ath, in ²	2.95
Blade #	16
Exhaust Diameter	4.20

A preliminary cycle deck (RECUPERF.FOR and MEVP.DAT) was made to evaluate on and off design performance. The flat rated power requirement (36 shp) at a sea level 100°F day is equivalent to 45.3 shp on a 59°F day with constant TIT. Therefore the 59°F design point is 45.3 shp. Generator heating causes the inlet temperature at the compressor to increase from 59°F to 76°F. The results show a powerhead SFC of 0.558 lbm/hr/shp that is marginally higher than the goal of 0.55 lbm/hr/shp. The TIT is 1780°F. This is 30° higher than the goal of 1750°F and is considered acceptable. The electric SFC at the flat rated power requirement is approximately 0.62 lbm/hr/shp. The cycle deck output for the nominal design point, 36 shp at 59°F, and 36 shp at 100°F ambient are included in the Appendix.

Table III, Engine Design Point Performance

100% Mechanical Speed	93882
Gen. Output Power (flat rated up to 100°F)	24 kW
T0, °F	59
P0, psia	14.7
Intake Press. Loss, %	2.0
T2, °	76
w, lb/s	0.63
$w\sqrt{T/p}$, lb/s $\sqrt{^\circ R/psia}$	1.012
Rc	5.00
η_c , %	75.2
qw	0.694
Comb. Press. Loss, %	4.0
TIT, °F	1780
Rt	3.91
η_T , %	85.0
Utip, ft/s	2007
U/V	0.672
Recup. Effec., %	80.2
Cold Recup. Press. Loss, %	3.9
Hot Recup. Press. Loss, %	10.9
Exhaust Press. Loss, %	3.0
EGT, °F	1241
Gen. Input Power, shp	45.3
wf, lbm/hr	25.3
SFC, lbm/hr/shp (kg/kWhr) (generator output after rectifiers)	0.624 (0.379)

Optimization for Part Load Efficiency:

To optimize part load efficiency, an attempt was made to maintain a constant TIT using the engine model. Reducing the engine airflow at the inlet or running at a slower speed is the easiest way to maintain a constant TIT. Variable geometry diffuser and turbine nozzle could also be used but will be more costly. Table IV shows SFC at a lower speed, and at reduced air flow. Part load SFC was evaluated using a 10kWe load.

Table IV, Part Load SFC, 10 kWe (42% Design Power)

Power Reduction Mode	% Speed	Air Flow, lb/s	Inlet Pressure Drop, %	TIT, °F	SFC, lbm/hr/shp (kg/kWhr) Gen. Output
Constant Speed	100	0.64	2%	1373	1.355 (0.824)
Reduced Speed*	77	0.38	2%	1472	0.749 (0.455)
Reduced Air Flow	100	0.47	26%	1742	1.212 (0.737)

*Speed reduction limited by cycle deck, in practice speed can be reduced further

Reducing the speed has the lowest part load SFC but requires robust, vibration tolerant rotor and blade dynamics as free turbine aero engines do now. The speed can probably run between 60 and 100% of design speed. The predictions in this study were limited by the capabilities of the cycle deck below 77% mechanical speed. Reducing the airflow with a throttling valve provides 10% reduction of SFC. Cycle deck output for the part load conditions analyzed are in the Appendix.

5.0 CONCLUSIONS

- SFC on the higher speed engine is not significantly less than the lower speed engine (<3%).
- The selected engine design would be approximately 1.7 inches larger in diameter than the faster engine.
- It is unknown at this point what the weight difference would be between the two designs.
- The selected engine design is not projected to have a problem fitting inside the specified envelope.
- The SFC at the nominal design point is 0.56 and approximately 0.62 at the flat rated power conditions.
- The component efficiencies assumed in the analysis are neither conservative or optimistic but rather realistic.
- SFC at part load conditions can be reduced by throttling the airflow fairly easily.
- Speed reduction at part load provides substantial reduction in SFC. Rotor dynamics and blade dynamics must be made satisfactory over full speed range

6.0 RECOMMENDATIONS

- Unless packaging or weights become a limiting factor, the 93,882 rpm design appears to be an adequate design.
- More work needs to be done to see if a recuperator can be realistically made to provide the assumed effectiveness within the given space and weight constraints.
- Follow on work in subsequent contracts should address the shaft and blade dynamics to avoid resonant frequencies.
- Follow on work outside the scope of this contract should address the electromagnetic geometry for the alternator rotor and stator.
- Control System development should address optimization of the control functions including sensors based on automotive technology and cost approaches.
- The current lack of high temperature, low cost recuperator technology limits the turbine cycle operating temperature. Higher cycle temperature would result in better fuel economy, lower emissions and smaller, lower weight engines.

Figure 1, Turbine Rig Data

Figure 2, Preliminary Design

APPENDIX

NSI OUTPUT
PRELIMINARY CYCLE ANALYSIS
RADTURB OUTPUT
CYCLE DECK OUTPUT

NSI OUTPUT

INPUT DATA FOR

T1 DEGR 519	P1 PSI 14.7	GAMMA 1.395	D1H/D2 .3135	REY # EXP .2
N 93882	P2/P1 5	W PPS .63	D2 4.625	M2 .1
U2/RT1 83.1625	C1/RT1 22.7512	PHI .273575	DELTA T AD 299.622	
D1H 1.44994	D1S 2.31463	Q .673376	RE2 .521572E+07	
ETA POL .863757	ETAD 1 .830823	ETAD 2 .752075	ETAD 3 .752075	
NS 73.5752	M1S .990279	ETAD 4 .752075	A1 2.55664	

PRELIMINARY CYCLE ANALYSIS

RUN AT 3-AUG-1993 08:56:19

TSOF	PSO	MODE	SHPIN	PTO		
76.0	14.700	0	0.0	14.70		
DP12/P1	DP70/P7	ETAG	E HE	DP33A	DP67	
0.020	0.030	0.990	.800	0.032	0.089	
MNO.	PT1/PTO	PT1	PT2	TT2F		
0.000	1.000	14.70	14.41	76.0		
W2	RC1	ETAC1	PT21	TT21F		
0.6300	5.000	0.752	72.03	487.2		
W21	RC2	ETAC2	PT3	PT3A	TT3F	TT3AF
0.6300	1.000	1.000	72.03	69.7	487.2	1055.6
W3	DP34/P3	ETAB	PT4	TT4F	UQVO	VTIP
0.6174	0.040	0.990	66.94	1750.0	0.670	2007.222
W4	RT	ETAT	PS6	TT5F		
0.6242	4.024	0.850	16.64	1212.0		
W5	WL/W1	W6	ETAM	TT6F	TT7F	
0.6242	0.020	0.6368	1.000	1197.6	674.1	
WF	SHPOUT	WB1	WB2	SFC		
24.59	45.2	0.00	0.00	0.544		
W1RT1QP1	W3RT3QP3	W3RT3AP3	W4RT4QP4	W6RT6QP6	W7RT7QP7	
0.992	0.264	0.345	0.438	1.558	1.415	

UNITS:psia,deg R,in,ft/s

INPUT FOR CASE: MPSPU 50HP RIG

```

-----
      PT0      TT0      GA
      66.90    2209.7    1.330

      D0      D1      D2      D3H      D3S      D4
      6.100    5.300    4.900    1.200    2.850    4.200

      B0      B1      B2      ZN      CNOZZ      ATN      TN1
      0.250    0.250    0.250    19.    0.900    0.900    0.020

      ZR      CROT      BET2INF      TN3      ATR      WGAS      TGAS
      16.     1.800    0.000    0.030    2.950    0.000    459.7

      WCOOL      TC1      TC2      TC3      DS      D3R
      0.020      0.015    0.015    0.015    3.250    2.187

```

```

OUTPUT FOR:  PR04(T-S)= 4.025  U2/V04= 0.672
-----      PR03(T-T)= 3.902  U2/V03= 0.678

```

MASS FLOW= 0.625 WRTT0/PT0= 0.439 RWT= 0.934 CP= 0.276

RPM= 93882. NS= 64. DELTAT= 542.6 RE NOZZ=.65E+05

```

STATION  TT      TS      PT      PS      MACH
1        2209.7    0.0    64.22   41.20   0.840
2        2209.7    1949.5  62.36   37.63   0.899
2R       1966.0    1949.5  38.93   37.63   0.227
3R       1732.7    1635.0  20.08   15.89   0.602
3        1666.2    1635.0  17.15   15.89   0.340
4M       1667.1    1662.0  16.79   16.62   0.124

STATION  V/W      Vr/Va    Vth/Wth  Alp/Bet  U      rVth(fts/s)
1        1785.3    384.8    1743.3   77.55
2        1897.4    448.9    1843.5   76.32    376.4
2R       477.8     448.9    -163.7   -20.04   2007.2
3R       1162.7    653.5    -961.7   -55.80   895.7
3        656.9     653.5    -66.0    -5.76    -6.0
4M       245.5     240.6    -48.6

```

ENTHALPY LOSS COEFFICIENTS

```

ENNOZZ= 0.0867
EVS = 0.0546
EINC = 0.0012
ELOAD= 0.0488
ECOOL= 0.0240
ECL = 0.0816
EFRI = 0.3217

```

EFFICIENCIES

```

DRVT/RVT V.SPACE = 0.022
DP/P NOZZ+V.SPACE = 0.068
ROTOR ONLY (T-T) = 0.896
ROTOR EXIT (T-T) = 0.857
DIFFUSER EXIT (T-S) = 0.841
DIFFUSER CP = 0.583
DEL ETA WINDAGE = 0.001
VA DIST. = 1.136
DP/P DIFFUSER = 0.021
DUMP LOSS = 0.010

```

```

NOZZLE CH. FLOW= 0.634 AT NOZZ EX. MN= 0.939
ROTOR CH. FLOW = 0.631 AT NOZZ EX. MN= 0.911 AND PR04= 5.985

```

NOMINAL DESIGN POINT 59°F

OUTPUT FOR RECUPERATED ENGINE USING DATAFILE: MEVP
CASE: T40-1 ATP MINIMUM S.F.=.5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MNO	RRF	N(RPM)	V0 (FT/S)
76.000	14.700	0.000	2.000	93882.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
76.000	14.700	0.6301	0.6312	0.0200	14.406
T2	WRT2/P2	RC	ETAC	QWC	PHI
76.00	1.0124	4.999	0.7523	0.6941	0.3633
URTC	PHI/PHIMX	BETA	P3	T3(F)	
81.856	0.9598	5.863	72.011	487.03	
P3P	T3P	P6P	T6P	DT3P4	EFF
69.23	1091.50	15.14	662.89	688.21	0.8020
DP34	P4	T4(F)	WF	UVT	RT
0.0401	66.45	1779.72	25.2584	0.6719	3.910
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8503	0.9292	0.6247	0.4449	1243.71	16.99
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
1240.70	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.95	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	45.26	0.000	0.0000	0.0200	0.5581

SURGE MARGIN = 9.6%

36 shp SLSD

OUTPUT FOR RECUPERATED ENGINE USING DATAFILE: MEVP
CASE: T40-1 ATP MINIMUM S.F.=.5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MNO	RRF	N(RPM)	VO (FT/S)
76.000	14.700	0.000	2.000	93882.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
76.000	14.700	0.6344	0.6389	0.0200	14.406
T2	WRT2/P2	RC	ETAC	QWC	PHI
76.00	1.0193	4.894	0.7429	0.6913	0.3674
URTC	PHI/PHIMX	BETA	P3	T3(F)	
81.856	0.9708	5.326	70.506	485.41	
P3P	T3P	P6P	T6P	DT3P4	EFF
67.74	1016.21	15.14	640.08	632.36	0.8005
DP34	P4	T4(F)	WF	UVT	RT
0.0404	65.00	1648.56	23.0121	0.6963	3.841
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8475	0.9266	0.6280	0.4437	1151.14	16.92
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
1148.47	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.95	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	36.02	0.000	0.0000	0.0200	0.6389

SURGE MARGIN = 12.12

36 shp, SL 100°F

ERR 2212

OUTPUT FOR RECUPERATED ENGINE USING DATAFILE: MEVP
CASE: T40-1 ATP MINIMUM S.F.=.5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MNO	RRF	N(RPM)	VO (FT/S)
117.000	14.700	0.000	2.000	93882.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
117.000	14.700	0.5828	0.5883	0.0200	14.406
T2	WRT2/P2	RC	ETAC	QWC	PHI
117.00	0.9716	4.633	0.7637	0.6932	0.3530
URTC	PHI/PHIMX	BETA	P3	T3(F)	
78.893	0.9498	6.188	66.741	527.51	
P3P	T3P	P6P	T6P	DT3P4	EFF
63.99	1113.97	15.14	694.60	655.64	0.8050
DP34	P4	T4(F)	WF	UVT	RT
0.0408	61.38	1769.62	22.2358	0.6889	3.641
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8519	0.9275	0.5773	0.4441	1258.87	16.86
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
1256.00	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.95	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	36.02	0.000	0.0000	0.0200	0.6173

SURGE MARGIN = 9.27

PART LOAD - NO CHANGE

OUTPUT FOR RECUPERATED ENGINE USING DATAFILE: MEVP
CASE: T40-1 ATP MINIMUM S.F.=.5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MNO	RRF	N(RPM)	V0 (FT/S)
76.000	14.700	0.000	0.000	93882.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
76.000	14.700	0.6392	0.6479	0.0200	14.406
T2	WRT2/P2	RC	ETAC	QWC	PHI
76.00	1.0270	4.668	0.7186	0.6884	0.3722
URTC	PHI/PHIMX	BETA	P3	T3(F)	
81.856	0.9834	4.612	67.246	483.70	
P3P	T3P	P6P	T6P	DT3P4	EFF
64.54	862.29	15.14	594.09	511.13	0.7974
DP34	P4	T4(F)	WF	UVT	RT
0.0405	61.92	1373.42	18.2307	0.7560	3.696
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8294	0.9116	0.6313	0.4365	960.46	16.75
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
958.51	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.94	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	15.04	0.000	0.0000	0.0200	1.2123

MURGE MARGIN = 16.8%

PART LOAD - REDUCED SPEED

OUTPUT FOR RECUPERATED ENGINE USING DATAFILE: MEVP

CASE: T40-1 ATP MINIMUM S.F.=.5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MN0	RRF	N(RPM)	V0 (FT/S)
76.000	14.700	0.000	0.000	72289.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
76.000	14.700	0.3813	0.3229	0.0200	14.406
T2	WRT2/P2	RC	ETAC	QWC	PHI
76.00	0.6126	2.907	0.7544	0.7134	0.2481
URTC	PHI/PHIMX	BETA	P3	T3(F)	
63.029	0.8374	7.925	41.877	326.49	
P3P	T3P	P6P	T6P	DT3P4	EFF
39.86	1004.77	15.14	502.88	467.48	0.8209
DP34	P4	T4(F)	WF	UVT	RT
0.0418	38.19	1472.25	10.0209	0.6781	2.384
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8625	0.9050	0.3765	0.4333	1155.80	16.02
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
1152.80	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.95	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	14.95	0.000	0.0000	0.0200	0.6701

SURGE MARGIN = 7.9%

PART LOAD - THROTTLED

OUTPUT FOR RECUPER USING DATAFILE: MEVP
CASE: T40-1 ATP MINIMUM 5

***** SINGLE SHAFT ENGINE OUTPUT *****

T0(F)	P0(PSIA)	MNO	RRF	N(RPM)	VO (FT/S)
76.000	14.700	0.000	0.000	93882.0	0.000
T1(F)	P1	W1	MN2	DP12	P2
76.000	14.700	0.4724	0.6232	0.2600	10.878
T2	WRT2/P2	RC	ETAC	QWC	PHI
76.00	1.0052	5.022	0.7535	0.6954	0.3590
URTC	PHI/PHIMX	BETA	P3	T3(F)	
81.856	0.9486	6.067	54.633	487.85	
P3P	T3P	P6P	T6P	DT3P4	EFF
52.17	1150.83	15.14	667.96	591.13	0.8136
DP34	P4	T4(F)	WF	UVT	RT
0.0412	50.02	1741.97	16.2032	0.7399	3.037
ETAT	RWT	W4	WRT4/P4	T5(F)	P6
0.8392	0.9161	0.4676	0.4386	1305.79	16.47
T6(F)	DP67	PSCRL	WRTH/DEL	TB (F)	PB
SCRL					
1302.72	0.0300	0.00	0.00	0.00	0.000
WRTH/DEL	ETAB	HPACC	HPFAN	ETAM	
B					
0.00	0.95	0.000	0.00	1.00	
A TURB	HPSHAFT	WB	WAS	DWSP	SFC
0.919	14.95	0.000	0.0000	0.0200	1.0837

SURGE MARGIN = 8.7%

APPENDIX II
SUNDSTRAND REPORT ERR 2239

Power
Systems

SUNDSTRAND
AEROSPACE

Sundstrand Corporation

4400 RUFFIN RD., P.O. BOX 85757 • SAN DIEGO, CA 92186-5757

CAGE 55820

ENGINEERING REPORT

PRELIMINARY COMBUSTOR DESIGN REPORT FOR THE 24KW APU FOR THE
FORD MEVP RANGE EXTENDER ENGINE

DOCUMENT NO:

ERR - 2239

ISSUED:

(DATE)

2/17/94

REVISION:

(LETTER AND DATE)

REV A 2/24/94

APPROVAL SIGNATURES:

PREPARER

STUART GREENWOOD, COMBUSTION ENGINEER

APPROVER

ROBERT THOMPSON, TECHNOLOGY DEVELOPMENT
MANAGER

REPORT ON:**PRELIMINARY COMBUSTOR DESIGN FOR THE 24KW APU FOR THE
FORD MEVP RANGE EXTENDER ENGINE****1. INTRODUCTION**

SPS report ERR 2212 details the design point combustor operating conditions of a range extender engine for a hybrid vehicle being developed by FORD. The engine is flat rated at 24kW generator output up to an ambient of 100 °F. Off design combustor operating conditions were determined using the engine cycle computer code.

FORD requires that the engine meets the Californian ULEV pollutant emission levels hence low emissions are a major consideration for the combustion system.

This report describes two possible design concepts for the combustor which are similar to combustors which SPS already has experience of. The combustors do not incorporate ultra low emission technology, for instance fully premixing/prevaporising or catalytic systems which would be needed if the engine was the prime mover. It was felt that, at this point in time, it was more appropriate, for a range extender engine, to examine the ability of less complex, more conventional combustors to meet the ULEV requirements.

2. EMISSION REQUIREMENTS TO MEET ULEV

Automotive emissions requirements are quoted in grams/mile based on a driving cycle which includes starting, idling, accelerating etc. For combustor design purposes it is necessary to convert these requirements into emission indices; that is grams of pollutant produced per kilogram of fuel burnt. To a first approximation this can be accomplished by using the following formula which assumes gasoline fuel:-

$$\text{Emission index(EI)} = (\text{emission in grams/mile}) \times (\text{miles/gallon}) / 2.787$$

This is a very simple expression which only requires knowledge of the vehicle fuel consumption. For the ULEV emission requirements of 1.7 grms/mile CO, 0.04 grms/mile HC and 0.20 grms/mile NOx this expression gives the following emission indices:-

TABLE I

Miles/gal	Emission indices grms/kg fuel		
	CO	HC	NOx
10	6.1	0.2	0.7
20	12.2	0.3	1.4
40	24.3	0.6	2.9
60	36.5	0.9	4.3

It can be seen that the allowable EI values increase as vehicle fuel consumption reduces. This means that the emission levels required from the combustor are determined not only by the fuel consumption of the engine but just how the engine is operated in the hybrid vehicle.

The following table shows typical emission levels measured on three of our gas turbine engines:-

TABLE II

ENGINE	FUEL TYPE	LOAD	CO		HC		NOx	
			ppm	EI	ppm	EI	ppm	EI
Gemini 20 kW Pr = 3.5	Kerosene	Full	316	16.7	2.5	0.08	43	3.8
		Idle	137	14.8	5.9	0.36	16	2.8
	Gasolene	Full	311	16.9	7.0	0.22	42	3.7
		Idle	168	17.9	17.8	1.08	17	2.9
APS1000 250 kW Pr = 5	Kerosene	Full	50	2.3	1.3	0.04	72	5.6
		Idle	55	7.4	8.3	0.64	29	6.5
APS3200 400kW Pr = 7	Kerosene	Full	58	3.0	2.9	0.08	94	7.9
		Idle	70	7.0	2.0	0.11	51	8.3

where Pr is the pressure ratio.

Apart from visible smoke, none of these engines have combustors which have been designed for low emissions.

As can be seen the NOx emission increases with engine pressure ratio, a fact that is already well known in combustor technology. HC emissions levels are similar on all three engines but the Gemini combustor suffers from high levels of CO emissions which, it is believed, could be reduced to the level attained by the other engines by suitable combustor modifications.

Our existing Gemini engine is very close to the power output required for the range extender engine so it is informative to compare its measured emissions (Table II) with the values required to

meet the ULEV(Table I). Taking the Gemini full load gasoline fueled emissions, the engine meets the CO ULEV requirements providing the fuel consumption is better than 30 mpg, the HC requirements if better than 12 mpg and the NOx if better than 50 mpg. As it is probable that a fuel consumption better than 40 mpg will be expected of the hybrid vehicle the Gemini emission performance looks, at first sight, to be in the required range to meet ULEV.

However the brake specific fuel consumption of the proposed engine is approximately 420 grms/kW.h at 24kW load, see section 8 of the report, which is equivalent to a fuel burn of 3.6 gals per hour. Assuming the engine is either operating at 24kW output or is in-operative, i.e a simple two mode control, and the vehicle covers 20 miles in one hour under conditions similar to the Federal Urban Driving Schedule(FUDS) then the engine must only operate 15% of the time in order to achieve 40 mpg. This "on Time" would increase to 20% if the engine output was limited to 7.5 kW.

Intermittent operation of the engine invalidates somewhat the assumptions used to derive Table I since start-up emissions have to be considered. For a pure gas turbine driven vehicle a rough rule of thumb is that the steady state emissions indices targets need to be half those quoted in Table I in order to achieve the ULEV limits to allow for engine start-up, idle and acceleration modes demanded by the FUDS. For a hybrid vehicle range extender engine transient operation should be much less important, for instance in the two step mode assumed above there is no idle or acceleration requirement, but nevertheless the values in Table I will have to be factored down to some degree.

This first order analysis suggests therefore that the current Gemini engine would not be able to meet the ULEV requirements, because it has no margin to absorb any factoring down of the Table I emission indices, and hence the range extender engine must have a combustor capable of giving lower emissions.

It is clear that a much better appreciation of the conversion of the ULEV limits into combustor emission indices is needed before one can be sure of having selected the most appropriate type of combustor. Since the engine has to be low cost it is also important, at this stage at least, that the combustor is not made unnecessarily complex in pursuit of ultra low emission goals.

For this report therefore a NOx emission index target of 2 was chosen as a design goal since it is believed that this level is attainable without resort to a complex ultra low NOx design.

3. COMBUSTOR OPERATING CONDITIONS

At this time the method of controlling the engine for power modulation has not been decided, hence it is not possible to derive for certain the overall operating requirements of the combustor.

Consideration is being given to modulating the engine power by varying the engine speed. This allows the combustor to run at near constant air/fuel ratio over the whole operating range. This is very attractive when a very lean mixture strength is used for NO_x control since it avoids the difficulty of achieving adequate combustion stability, i.e mixture strength burning range. The technique does however introduce two problems. The first is combustor pressure loss which would reduce as engine speed decreases hence adversely affecting the fuel and air mixing efficiency leading to less homogenous combustion. The second is transient operation where it is suspected that the combustor lean blow out air/fuel ratio would have to be lower than with a constant speed engine to cater for rapid load shedding.

It is likely however that the engine will be controlled as per the Gemini, that is constant speed operation. In this case combustor steady state operating points will be as given in the following table and these conditions have been used as the basis for the work reported here:-

TABLE III

	Full load	75% load	50% load	25% load	No load
Air mass flow kg/s	0.283	0.285	0.286	0.286	0.286
Inlet air temp K	861	810	763	718	693
Outlet gas temp K	1243	1154	1070	990	933
Inlet air pressure kPa	478	465	453	442	436
Air/fuel ratio	93	105	120	138	158
Fuel flow kg/h	11.0	9.8	8.6	7.5	6.5

Starting conditions have not been looked at in any detail. With our experience in producing small APUs the problems of achieving adequate fuel atomization with the very small light-off fuel flows are well known to us. Indeed the Gemini engine itself brought about the development of the spinning cup atomizer as one solution to the problem which has proved itself in service, see Ref. 1.

4. ESTABLISHED KNOWLEDGE:

Combustor performance and emissions levels are related to operating conditions, combustor mixing processes and fuel injection method. Burning a premixed prevaporized lean mixture of air and fuel produces the lowest combustion system emissions. Usually, the design of the combustor primary zone dictates most of the combustion system emission because this is the region where the fuel and air interact, combine, release heat, and produce the different chemical species.

The three major emission species are oxides of nitrogen(NO_x), carbon monoxide(CO), and unburnt hydrocarbons(HC). The desired level of NO_x emission is the most important factor in determining the type of combustor to use.

NO_x is principally dependant on flame temperature. If temperature increases above 1800 K, NO_x formation increases rapidly. This is due to thermal NO_x formation described by the Zeldovich mechanism which takes into account the following reactions:

The first reaction is assumed to be the most dominant and is encouraged by higher temperatures; for this reason, it is a good practice to keep the temperature below 1800 K.

It has also been found that NO_x is formed in the flame region due to other non-Zeldovich mechanisms. This is called Prompt NO_x and is not as dependant on temperature as thermal NO_x. Prompt NO_x formation is accentuated in poorly mixed systems and concentration levels are typically below 30 ppm (part per million by volume). However for ultra low NO_x systems Prompt NO_x represents a major proportion of the total NO_x emission. Prompt NO_x formation is governed by the following reactions:

Figure 1 shows typical characteristic emission values for lean mixture combustors. The top graph shows data taken from Ref. 2 which is for a well, though not perfectly, mixed combustor which did not achieve complete fuel evaporation and mixing homogeneity. The lower graph is from

Ref. 3 which is for lean premixed prevaporized combustors(LPP). The classic combustor problem of CO and HC emissions being in inverse relationship to NO_x emission is well illustrated. This problem forces the adoption of the lean burn concept and brings with it the difficulty of coping with a narrow mixture strength operating range which can necessitate fuel staging or variable combustor geometry.

Figure 2 shows emission values derives from classical equilibrium theory which illustrates how NO_x can be controlled by burning richer than stoichiometric. This fact has led to interest in rich quench lean (RQL) combustors where after a rich burning stage to suppress NO_x the temperature of the reactants is quickly brought down(the quench process) to a level which ensures low levels of NO_x production then the reaction is continued at lean conditions to burn out, in particular, the high CO levels produced in the rich stage.

5. COMBUSTOR CONCEPTS AND EVALUATION

For the reasons explained above most low emission combustors are designed to operate away from the stoichiometric air to fuel ratio. Some concepts use the lean side, others the rich side. Reducing NO_x must not be done at the expense of increasing CO. Therefore, a well designed combustor produces low levels of NO_x, CO, and HC. Staged combustion, variable geometry, catalyst combustors, premixed prevaporized combustors, lean and rich-quench-lean combustors are all concepts that are directed at low emissions.

Most of the combustor types mentioned impose complications of some sort; for instance a more complex fuel control or the need for hardware management. For this preliminary design we decided to examine the capabilities of simple, near conventional combustors. When a better understanding of the actual level of emissions needed for a range extender is available a more complex combustor may be found to be needed.

Two concepts that we have studied are the lean premixed-prevaporized concept and the well-stirred lean primary zone combustor. It is apparent that these systems need to operate at an equivalence ratio between 0.35 to 0.6. In that band, the temperature levels are between 1600 K and 2100 K, and the emission levels are moderate for all three mentioned species.

The premixed prevaporized system gives the lowest levels of emissions because it provides the greatest level of homogeneity. Figure 3, from Ref. 3, compares emissions from a premixed-prevaporized system to the of a conventional diffusion flame system. It is obvious that the

premixed system has a much better emission levels. However this system has a narrow operating range. The combustor suffers from poor stability limits and from lean blow out problems. The solutions to this are variable geometry or staged fuel injection. These solutions produce too complex a system for consideration at this stage.

The well-stirred lean primary zone combustor concept seems to be the most attractive for the range extender and is along the lines of our current Gemini combustor. We realize that our Gemini combustor does not provide the emission levels needed for the MEVP project but they are nevertheless of the same order of magnitude as the goal need be achieved. The main improvement to be introduced is to mix the fuel and air so that it approaches, as close as possible, homogeneity. The Gemini combustor does not achieve the level of mixing and fuel preparation that is needed since emissions were not the most important design criteria.

The new concept of a well stirred lean primary zone combustor will feature fuel injection into the blade passages of the swirler. We believe that this fuel injection method will result in partially premixed and prevaporized air and fuel approaching homogeneity. This type of fuel injection has been studied in the SPS combustion group when the company existed as the Radial Engine Division of Solar Turbines Inc. and the work undertaken has been reported at past technical conferences, see Refs. 1,4 and 5. More recently this type of combustor has been studied at Leeds University in England, Ref 6., and was shown to approach the emission levels of a premixed-prevaporized system as shown in figure 4 taken from Ref. 6. A discussion of the combustor design is provided in the next section.

Within the last three years at SPS a development of our current in-service "Sidewinder" combustion system called the "Tornado" has been conceived, designed and tested. This is a unique combustor which can be loosely described as a rich quench lean system. This system is low cost and this makes it very attractive for APU/RPV engine applications. For this reason the system is being actively pursued. Three Tornado combustors have been the subject of development testing and one is currently used in our TJ50 turbojet engine. Another is just beginning its development program and will be used in a military APU. Whilst the emission performance of this system is as yet un-quantified we believe that it may well have good potential and hence be a good candidate for the range extender engine. It has the advantage that it is an annular combustor, indeed the TJ50 combustor at 100mm diameter is believed to be the smallest annular combustor ever to be developed to a satisfactory level of performance.

Therefore, for this report, we have concentrated on :-

- (a) a well stirred lean burn can type combustor, similar in concept to previous experimental work done on our Gemini combustor, with swirler vane passage fuel injection to provide partial premixing and prevaporization
- (b) a Tornado annular combustor, similar to those already produced by SPS and being actively worked on for other projects.

As an alternative annular combustor to the Tornado, should its promise not be fulfilled, we would adapt the well stirred can concept to annular form. This has been done and tested by Solar turbines, Refs 5 and 7, but it is obvious that this conversion to annular form is not easy. In this report we do not describe the annular well stirred lean burn concept for which the reader is referred to Ref. 7.

6. WELL STIRRED LEAN BURN PARTIAL PREMIX CAN COMBUSTOR

This combustor is similar to the current Gemini system and is shown in figures 5 and 6. The system was the subject of a research project aimed at producing low emissions without the need for variable geometry and was given the name CIVIC, Concept In Vortex Induced Combustion. Since the Gemini objectives did not include gaseous emission control the knowledge gained from this research was not fully implemented in the Gemini combustor.

The proposed combustor is similar to the existing Gemini in terms of overall size, aspect ratio (length to width) and air admission port through area. This is because (a) the addition of a recuperator increases the combustor inlet temperature and hence leans out the overall combustor mixture strength (the current Gemini has a full load air/fuel ratio of 54 compared with 93 for the current design) therefore producing a lean primary burning zone with a similar sized radial swirler and (b) the higher pressure ratio of the current design (5 compared with 3.5 for the Gemini) reduces the combustion loading without the need to substantially change the combustor volume.

The primary air admission is all through the radial swirler. Figure 6, as per the CIVIC concept. Figure 5 shows the combustor sized to burn at a full load primary zone equivalence ratio of approximately 0.5, that is 30 air/fuel ratio, which with completely homogeneous fuel air mixing would result in a maximum flame temperature of 1920 K. Based on the emission work undertaken in Ref. 6 this would give a NO_x emission index of about 2. A higher equivalence ratio

would be used it tests showed this to be possible since this would be beneficial for combustor operating range.

The design uses a radial inward flow swirler with a flat combustor back plate to generate an inner and outer recirculation zone separated by a high shear layer. The swirler shown, which is similar in construction to the Gemini, may lack aerodynamic efficiency(as suggested by the work in Ref. 6) and might, to advantage, be replaced by a curved blade swirler. At the downstream extremity of the burning zone the combustor diameter reduces to help (a) promote and define the axial limit of the inner recirculation and (b) prevent upstream migration of the dilution air into this zone.

No film cooling devices are shown on the combustor walls since this type of cooling adversely influences, in particular, the CO reaction in the near wall region and in the extreme case the establishment of the desired recirculation patterns. For a metallic combustor cooling will be affected in the areas requiring it by either enhancing back side convection (that is on the air side of the wall) or by the use of transpiration cooling (a pattern of small 0,50 mm dia holes laser drilled at an acute angle through the wall) as used on one of our current APU combustors or a combination of both.

Fuel is injected into the air passages of the swirler using a simple air blast injector concept. The momentum of the combustor air generated by the combustor pressure loss is used to atomize the fuel rather than fuel pressure. This allows the use of a low pressure fuel system which is less costly and more reliable than a high pressure one. Air blast fuel injectors are the main-stay of most SPS combustors so we have a lot of experience with them. The important consideration is to maximise the mixing of the fuel and air so that as near to an homogenous mixture as possible exits the blade passage. In Refs. 1 and 4 the effectiveness of swirl passage air blast atomization was explained in part by the action of the centrifugal forces generated by the swirling action. The centrifugal forces act on the fuel droplets and tend to inhibit them from leaving the swirler until they are either very small or completely evaporated.

The more successful in achieving mixture homogeneity the less NOx but also the less combustor operating air/fuel ratio range in the premix mode. Hence there is a need to enhance this range and figure 5 shows a central fuel injector which creates a diffusion type flame inside the burning zone by injecting the fuel just in-board of the turbulent shear layer created by the swirler outflow. This diffusion flame gives the required extension in mixture strength burning range but does increase NOx. The fuel split between the central and swirler passage fuel injection would be determined by combustor tests.

For starting the engine, fuel atomization and placement within the burning zone are critical. The Gemini swirler cup atomizer was born out of the need to be able to start the engine with highly viscous cold diesel fuel(25 cs kinetic viscosity) since a conventional fuel pressure atomized injector is incapable of providing the needed atomization performance at the low fuel flow rates demanded. For the current design we are dealing with a much less viscous and more volatile fuel(gasolene) and hence the problem is much less severe. We favor the use of an external air assisted injector using a small electrically driven air pump. The air assist would be applied to the central injector.

Light-off would best be achieved by a low tension low energy spark plug similar to that used in current automobiles. At SPS we use low tension high energy systems which can be dangerous to unskilled people working on the machine. This is not a problem in the aerospace field but would be of concern for an automobile used by the general public. Another potential ignition source is an electrically heated ceramic glow plug.

7. RICH PRIMARY ZONE "TORNADO" ANNULAR COMBUSTOR

Figures 7,8 and 9 show the Tornado type combustor system currently the subject of development at SPS. It is a fully annular axisymmetric combustor. The concept is to set up a total swirling flow pattern inside the combustor by admitting air into it through angled tubes positioned on the outer wall. Hence a series of jets is used to establish and drive an intense swirling vortex system. In a small diameter combustor, such as the one proposed, extremely high centrifugal forces are set up within the combustor which have a significant effect on the combustion process in that they strongly influence the mixing of the hot, less dense, combusted gases with the cool, more dense, incoming fuel air mixture. We attempt to use this phenomenon to control the combustion process to advantage.

The primary zone (the zone where the fuel comes in) equivalence ratio of 1.5(10 air/fuel ratios) is controlled by correct sizing of the first(primary) row of angled tubes. This zone is followed by the secondary zone where the equivalence ratio is brought down to approximately 0.35 by admittance of air through the second row of angled tubes. The fuel is injected into three of the six primary air tubes and hence it is atomized and mixed with the primary air. It may be necessary to inject fuel into all six tubes to gain good mixing.

Downstream of the secondary zone there is a conventional dilution system with air being admitted through plain circular holes on both the inner and outer combustor walls.

No cooling air admission devices are shown on the combustor and indeed none are used on any of the Tornado combustor at SPS. Like the well stirred can combustor these devices are to be avoided in the burning zone. With the engine being recuperated, transpiration cooling will be needed in certain regions for a metallic combustor.

For engine starting, this combustor would use either external air assist on one or all three fuel injectors or, if the cranking speed is high enough, light directly off the air blast injectors without any need for atomization enhancement by other means.

As has been stated previously the emission levels of this type of combustor have not been quantified so this is a major unknown area which of course is critical to this engine design. It would be necessary to establish emission levels on a Tornado type system to demonstrate that it has potential before firming up on the use of this concept. It does have the advantage that its annular configuration makes the packaging of the recuperator much easier than the can combustor.

8. EMISSION PREDICTIONS

For emissions predictions we have restricted ourselves to the use of practical test data rather than a purely theoretical assessment. Hence we have only considered the well stirred lean burn passage injection CIVIC combustor for which data exists, Refs. 1 and 6. In this case we have utilised the data provided in Ref. 6 since this is the more recent and more comprehensive work. Figure 10 shows emission data taken from Ref. 6 with the combustor burning aviation kerosene, Jet A-1, and operating at a combustor inlet air temperature of 600 K and atmospheric pressure. The emission values in figure 10 are at primary zone exit and hence are higher than would be measured at combustor exit.

This data has been used to predict combustor exit emission levels for our proposed lean burn combustor. In doing this we had to take into account the higher air inlet temperature, lower residence time and higher operating pressure of our combustor. Two methods have been used to allow for the effect of combustor operating pressure on NO_x production hence our NO_x

prediction has a band width. This was done because of the difficulty in handling both Prompt and Thermal NOx by the same scaling process. The HC emissions are shown as methane equivalent.

The predictions, see figure 11, are based on operating exclusively using swirler passage fuel injection hence in terms of Nox represent the lowest values attainable. The predictions show that the operating range of the combustor is not sufficient to prevent excessive HC/CO emissions at no load conditions. This can be dramatically improved if the NOx level at full load can be allowed to increase since then the primary zone equivalence ratio can be increased which, as figure 10 shows, brings a big reduction in HC/CO emission at the very lean no load conditions. Alternatively, as already described, a central fuel injector can be included to reduce HC/CO emission at weak conditions at the expense of some increase in NOx production.

If desired the predictions can be converted to volumetric concentrations by the following formula:-

$$\text{Emission in ppm by vol} = \frac{1000 \times (\text{Emission index figure 11}) \times (\text{Molecular Wt of exhaust gas})}{(\text{Molecular Wt of pollutant}) \times (1 + \text{overall air/fuel ratio})}$$

to a first approximation exhaust gas Molecular Wt is 29.

To allow easier manipulation of the emission predictions the data in figure 11 is given below in terms of grms/kW.h:-

TABLE IV

Load kW	Fuel flow kg/h	Bsfc grms/kW.h	Emission grms/kW.h		
			CO	HC	NOx
30	11.0	366	0.84	0.07	0.81
22.5	9.8	433	0.52	0.06	0.61
15	8.6	572	0.63	0.06	0.57
7.5	7.5	998	2.30	0.64	0.80

The combustor emissions are, of course, directly influenced by the engine brake specific fuel consumption hence it is important that the engine is optimised to provide the best Bsfc at the most predominant load condition for the range extender. The above table and figure 11 show that the combustor, when operating exclusively with swirler passage fuel injection, has not sufficient air/fuel ratio range to keep clear of the region of rapidly rising CO and HC at the lean, low load conditions. The combustor can be re-balanced to prevent this occurring by reducing the primary zone air flow but this will increase NOx emission at full load. If the engine spends only a very short

time at full load then this would be a viable option. However for this report we have suggested the use of a central, pilot, injector to prevent excessive low load emissions.

In order to calculate the emissions produced over the FUDS assumptions have to be made about the vehicle and engine control. The following have been assumed in order to perform the calculations:-

- (a) the vehicle achieves an average speed of 20 mph over the Federal Urban Driving cycle.
- (b) the engine runs at one constant load condition
- (c) the engine operates for a certain percentage of the cycle duration, i.e engine "on" time.
- (d) No allowance is made for start-up emissions

Note that these are additional to the assumption already made that the engine power modulation is achieved without varying engine speed.

TABLE V

Load kW	100			Engine "on" time % 50			25		
	Emission g/mi			Emission g/mi			Emission g/mi		
	CO	HC	NOx	CO	HC	NOx	CO	HC	NOx
30	1.26	0.10	1.21	0.63	0.05	0.60	0.32	0.03	0.30
22.5	0.59	0.06	0.68	0.30	0.03	0.34	0.15	0.01	0.17
15	0.47	0.04	0.43	0.24	0.02	0.21	0.12	0.01	0.11
7.5	0.86	0.24	0.33	0.43	0.12	0.17	0.21	0.06	0.08

(The ULEV limits are 1.7 CO, 0.04 HC, 0.20 Nox)

The figures in "bold" show the regions where the engine meets the ULEV requirements . It must be concluded therefore that if the assumptions used to derive the above values are reasonably valid then a simple, near conventional, well stirred partial premix can combustor will be able to achieve the ULEV requirements providing the engine "on-time" is less than 25%. and the start-up emissions are not significant. This level of engine operating time would be consistent with achieving a reasonable vehicle fuel consumption.

9. EFFECT OF REBALANCING THE CAN COMBUSTOR

The emissions predictions in section 8 above are with the can combustor aerodynamics balanced towards limiting NO_x emission at the 30kw full load condition. With the combustor operating purely in the partial premix mode, i.e no central fuel injection, the operating range of the combustor for low emissions is not large enough to prevent relatively high levels of HC emissions at low power conditions. This can be seen in figure 11 and Tables IV and V.

The combustor can be rebalanced, that is the air admission into the combustor primary zone can be changed, to favor the mid power operating range at the expense of producing higher emissions at full load. This has a very beneficial effect on the HC emission at low power.

To illustrate this, emissions predictions have been made for the can combustor with the primary zone full load equivalence ratio increased from 0.49 to 0.56. The Table below shows these predictions:-

TABLE VI

Load kW	Emissions grms/kW.h		
	CO	HC	NO _x
30	2.43	0.09	1.22
22.5	0.88	0.08	0.85
15	0.64	0.06	0.76
7.5	1.26	0.13	0.87
5	3.58	0.57	1.14
2.5	19.14	1.84	2.19

A comparison of this table with Table IV at the same power levels will show how the emissions have increased at 30kw but reduced at 7.5kW. In Table VI emissions have been predicted for powers lower than 7.5kW in order to demonstrate how the problem of lack of combustor range in the partial premix mode again causes high emissions if the power level is reduced sufficiently. It should be recognised that Brake specific emissions(Bse) are influenced by the engine thermal efficiency. At low load conditions the Bsfc is high, at the limit becoming infinite at no load, and this fact of course has a great effect on the Bse values which the combustor designer has no power to prevent. For this reason emissions indices are a far better expression of combustor performance. Figure 12 shows the emission indices for the rebalanced combustor which can be

compared with the emission indices, figure 11, from the previous predictions unfettered by the effects of the engine thermal efficiency.

The effect of the rebalancing on the combustor on the predicted ULEV for the FUDS are shown below:-

TABLE VII

Load	Engine "on" time %								
	100			50			25		
	Emissions g/mi			Emissions g/mi			Emissions g/mi		
kW	CO	HC	NOx	CO	HC	NOx	CO	HC	NOx
30	3.65	0.14	1.83	1.82	0.07	0.92	0.91	0.04	0.45
22.5	0.99	0.09	0.96	0.50	0.04	0.48	0.25	0.02	0.24
15	0.48	0.05	0.57	0.24	0.02	0.29	0.12	0.01	0.14
7.5	0.47	0.05	0.33	0.24	0.02	0.16	0.12	0.01	0.08

(The ULEV limits are 1.7 CO, 0.04 HC and 0.20 NOx and the "bold" figures meet this)

This rebalancing exercise demonstrates how the design of the combustor for the range extender engine must take into account the demands placed on the combustor by the engine and vehicle control system.

9. CONCLUSIONS

- 1) The selection of the most cost effective combustor design to meet the ULEV standards for the range extender engine is dependant on the engine duty demanded by the vehicle control system and how the engine power output is modulated by the engine control system in response to those demands.
- 2) Extensive use will have to be made of computer modelling of the vehicle/engine dynamics in order to facilitate (1)

- 3) Since emissions are so important the combustor characteristics must be a major consideration in engine design and operation. This is a distinct change in philosophy compared with our current APU engines.
- 4) The analysis undertaken indicates that, if the assumptions on engine/vehicle operation are realistic, a near conventional combustor can meet the ULEV requirements
- 5) It is important to recognise that the emissions are strongly influenced by the combustor design point chosen. In this report the engine full load conditions have been used for the combustor design point. This is illustrated by the change in the emissions predictions which occurs when the combustor was rebalanced to more favor the mid power range.
- (6) Emission measurements must be taken on a Tornado combustor as soon as possible to determine its suitability as a candidate system for the range extender.
- (7) Ultra low emission combustor concepts must be studied since they will provide more flexibility in vehicle/engine control options.

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Experimental effect of primary zone flame temperature on CO and NO_x emissions

Experimental effect of primary zone flame temperature on hydrocarbon and oxides of nitrogen emissions

Emissions from premix/prevaporize combustors

FIGURE 1

Equilibrium concentrations of CO and NOx at the full load conditions of the range extender engine

FIGURE 2

Co-NO_x-ranges for automotive gas turbine combustion systems

FIGURE 3

Emission Levels Reported by Leeds University Using the Different Fuel Injection Systems

FIGURE 4

Design Details of Lean, Partially Premixed Can Combustor

FIGURE 5

ERR 2239

Combustor Swirler and Fuel Passage Design Details

FIGURE 6

Design Details of Rich Primary Zone "Tornado" Annular Combustor

FIGURE 7

**Cross Section of the Annular Combustor
Showing the Primary Air Inlet Tubes**

FIGURE 8

**Cross Section of the Annular Combustor
Showing the Secondary Air Inlet Tubes**

FIGURE 9

Ref 6: Emission Measurements

Test data for swirler passage fuel injection at combustor inlet conditions of 600 K and atmospheric pressure

FIGURE 10

Emissions Predictions for Can Combustor Design

Predicted emissions levels for the well stirred lean burn
partial premix can combustor for the range extender engine

FIGURE 11

Predicted emission levels for the well stirred lean burn partial premix can combustor with rebalanced primary zone

FIGURE 12

The attached schedule is a compilation of estimated costs and quotations for the "Range Extender" TurboAlternator as proposed by the Sundstrand Corporation.

Column "A" is an attempt to look at costs from the current perspective of the Aircraft Industry. While the costs shown for a 3,000 piece annual run may seem high, they are actually quite low by standards in this industry where \$10,000 to \$20,000 would be more typical for even lower volumes such as 100 to 300 pieces per year.

Column "B" is also an approximation derived from values provided by Sundstrand in an attempt to project costs at 100,000 pieces per year (a volume level unheard of in this industry).

Column "C" is Alpha's estimate, done by traditional Auto Industry methods and which reflects the best thinking and processing that can be brought to bear on this conceptual design. The major cost drivers; the ceramic nozzle, the monorotor, the recuperator, the alternator and the high speed bearings are supported by supplier quotations.

It should be noted that the cost of one of the major components, the recuperator, is based on 85% effectiveness which is directly related to the weight of materials used in it's construction. With materials accounting for approximately 40% of the cost, if it can be determined that less efficiency is acceptable, the total cost and weight of the turbine assembly could be reduced significantly.

While much development work remains to be done towards the ultimate design, and some new innovative manufacturing techniques will be required for emerging materials, such as ceramics, it is believed that the estimated costs developed in column "C" are firmly within the realm of what can be achieved by bringing high volume processing to the Aircraft Industry.

Sundstrand - Turbo Alternator - "Range Extender"					Sundstrand Cost \$ To 3,000/ yr	Sundstrand Cost \$ 100,000 / yr	Alpha Estimated Cost \$ 100,000 / yr	Alpha Estimated HI Vol Tool (\$000)
Purchased Parts	Material	Process	Weight lbs.	Source				
				b)				
1 Assembly & Test				Sundstrand	120	90	100	500
2 Inlet Housing	C-356 Alum	Castling	2.67	Alpha Est.	300	198	19	200
3 Stator Housing	C-356 Alum	Castling	0.42	Alpha Est.	50	20	8	200
4 Monorotor	IN713 LC	Castling	3.88	Cast Masters	800	548	75	124
5 Shaft	S.S. 15-5	Machined Bar	0.64	Alpha Est.	60	40	5	50
6 Roller Bearing	Steel	Assembly	0.10	Split Ball Bearing	75	40	23	0
7 Alternator Rotor/Stator	Steel/Copper	Assembly	4.69	Sundstrand, Lima	300	197	220	300
8 Ball Bearing	Steel	Assembly	0.10	Split Ball Bearing	55	40	37	0
9 Nut	4340 Steel	Machined Bar	0.06	Alpha Est.	20	18	2	10
10 Diffuser	Cres S.Steel	Castling	2.00	Alpha Est.	100	71	47	175
11 Recuperator	S.Steel	Stamped	122.00	Solar Turbine	900	395	805	750 a)
12 Deflector	Hast x S.Steel	Stamping	2.24	Alpha Est.	25	18	8	150
13 Combustor Housing	Hast x S.Steel	Stamping	2.01	Alpha Est.	55	40	10	200
14 Combustor Liner	Hast x S.Steel	Stamping	3.01	Alpha Est.	150	118	14	300
15 Turbine Nozzle (2 pc)	Ceramic	Molded	1.67	Saint-Gobain	1,700	500	350	500
16 End Cap	S.Steel	Stamping	0.27	Alpha Est.	10	4	1	25
17 Static Seal	S.Steel	Machined ring	0.19	Alpha Est.	25	16	3	20
18 Knife Seal	S.Steel	Stamping	0.43	Alpha Est.	55	40	6	50
19 Thermal Shield	Ceramic	Molded	0.38	Alpha Est.	35	24	33	50
20 Ring Seal, Diffuser	Steel	Machined ring	0.18	Alpha Est.	8	4	5	20
21 Ring Seal, Nozzle	Steel	Machined ring	0.09	Alpha Est.	15	8	2	20
22 Thrust Washer	Steel	Stamping	0.02	Alpha Est.	8	4	2	20
23 Fuel Nozzle	S.Steel	Assembly	2.00	Alpha Est.	40	28	75	400
24 Misc. Fasteners	S.Steel	Headed	1.50	Alpha Est.	25	18	30	25
25 Insulation	Ceramic Fiber	S.M.C.	3.00	Alpha Est.	40	20	15	100
26 Bearing Lube System	Steel	Assembly	1.50	Alpha Est.	65	38	50	300
Subtotal, Ass'y + Purchased Material					5,038	2,529	1,945	
Mark Up					3,030 c)	388 d)	210 e)	
Totals					8,068	2,917	2,155	4,489

- a) Solar Turbine quotation of tooling & facilities @ \$100,000,000 requires further analysis.
b) Where suppliers are identified, a quotation has been received.
c) Typical A/D industry, low volume markup of 28% on components + 20% G & A and 15 % profit.
d) A/D industry markup revised to 15% on components and 25% G & A and profit.
e) More typical auto industry markup of 25% on value added and 10% on components,
Note! - These costs do not include warranty or amortization of Facilities or Tooling.

APPENDIX III

FORD ALPHA GROUP, COST ESTIMATES FOR THE 24W APU FOR THE FORD MEVP RANGE

APPENDIX IV

SUNDSTRAND "GEMINI" APU DEMONSTRATION TEST REPORT

Power
Systems

SUNDSTRAND
AEROSPACE

Sundstrand Corporation

4400 RUFFIN RD., P.O. BOX 85757 • SAN DIEGO, CA 92186-5757

CAGE 55820

ENGINEERING REPORT

MEVP DEMONSTRATOR TEST REPORT

DOCUMENT NO: ERR-2145

ISSUED: 28 SEPTEMBER 1993
(DATE)

REVISION: N/A
(LETTER AND DATE)

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MANAGER, DEVELOPMENT TEST

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1.0 INTRODUCTION

As outlined by Ford Motor Company purchase order number 47-Y-112726, Task 2.0, a Sundstrand Power Systems (SPS) Gemini engine, model number T-20G-10C4, serial number 813202, was tested at the SPS Development Test Facility in San Diego. The tests performed were:

- 1) A "shakedown" test to check-out the engine, generator, controls and instrumentation
- 2) Performance tests
- 3) Emission tests
- 4) Noise tests

2.0 INSTRUMENTATION

All measuring and test equipment for this test shall be calibrated in accordance with MIL-STD-45662. Unless otherwise specified, a typical instrumentation list is included in the appendix. In addition, a strip chart recorder has been used to record engine speed, EGT, fuel flow and vibration (1st E.O.).

3.0 TEST ARTICLE

The Auxiliary Power Unit (APU), Sundstrand Power Systems T-20G-10C4, was built in accordance with drawing 161920. The APU was equipped with an Electronic Sequencing Unit (ESU), P/N 160935-203. The engine was driving a Sundstrand Electric Power Systems AC generator, P/N 976J827-1, at 12,000 RPM through a speed reduction gear drive.

4.0 SHAKEDOWN AND CALIBRATION TESTING

4.1 Introduction

The purpose of these tests was to identify the "baseline" engine conditions and to verify the mechanical integrity of the APU with and without the generator installed. The test plans are documented in SPS technical reports TRR-1726 and TRR-1740.

4.2 Procedure

The engine was operated at no-load conditions with and without the generator installed. A water dynamometer was then installed and the engine was operated at various loads to an Exhaust Gas Temperature (EGT) of 1300°F. All instrumentation, wiring and facilities were checked out during these tests.

4.3 Results

4.3.1 Run-In Tests

The following checks were made during the initial run of the engine without the generator or dynamometer installed:

- Checked instrumentation at ambient conditions.
- Cold cranked engine to verify starter operation and harnessing.
- Cold cranked engine to verify oil pump operation.
- Bled fuel lines to remove air.
- Attempted starts to verify ESU sequencing.
- Attempted starts to verify fuel system.
- Started engine. Checked ESU operation.
- Checked cup motor (fuel atomizer) current.
- Checked all instrumentation at operating conditions.
- Checked rotor vibration.
- Checked engine for leaks.

Engine starts were timed at 8.5 to 10 seconds to full speed. A no-load EGT of 718°F was measured with an inlet temperature of 75°F. This is normal for the Gemini engine.

4.3.2 Generator Check-Out

The generator was installed and the engine was started to full speed. The generator vibration and cooling were checked. The engine vibrations were examined. The no-load EGT remained at basically the same level. There was no significant change in the operation of the APU with the generator installed.

4.3.3 Dyno Loading Check-Out

As a final check of the engine before performance testing, the generator was removed and a water dynamometer installed to test the engine to its full load capability. Per the test plan, documented as SPS technical report TRR-1740, the engine was operated through a series of step loads from no-load to a full load of 1300°F EGT. The dynamometer hook-up and controls were also checked out at this time. A maximum of 32.5 HP was achieved at 1300°F EGT with the engine running at 100% corrected speed. For reference, the un-reduced data for this data point is included in the appendix.

5.0 PERFORMANCE TESTING

5.1 Introduction

The purpose of this test was to identify the performance characteristics of the APU. The goal of this test was to provide performance calibrations at 100% corrected speed. The test plan is documented in SPS technical report TRR-1747. The engine was operated through a full load cycle using both JP-5 and unleaded gasoline.

5.2 Procedure

All data taken during this test was obtained with the engine running at 100% corrected to a 59°F inlet temperature. The APU was stepped through a cycle from no-load to a full load of 20 KWe and back to no-load in steps of approximately 100°F changes in EGT. One load cycle was performed using JP-5 fuel and one load cycle was performed using unleaded gasoline.

5.3 Results

The APU performance test results showed no significant change in performance between the tests run on JP-5 and unleaded gasoline. These results are summarized as Figure 5.1 and Figure 5.2, included. Attached as Table 5.1 is the reduced data from a typical data point taken at 1223°F EGT. This is the maximum load point taken under electric load. This point shows a Specific Fuel Consumption of 1.98 lb/KWe/hr at a corrected shaft load 20.1 KWe.

Figure 5.1 presents the performance test results from the tests run on JP-5 fuel and Figure 5.2 presents the result from the tests run on unleaded gasoline. Each figure has curves for Engine Inlet Air Flow, Compressor Pressure Ratio, Fuel Flow, and Generator Output plotted as functions of the EGT. These curves show some typical characteristics of constant speed gas turbines: 1) The air flow decreases and the pressure ratio increases as the EGT increases and 2) The fuel flow and power output increase with increasing EGT.

6.0 EMISSION TESTING

6.1 Introduction

Continuous emission testing was performed on the APU to determine the transient start characteristics, the steady state characteristics and the transient effects of sharp off-loading on the exhaust emissions. All samples were analyzed for HC, CO, CO₂ and NO_x. The APU was operated through a full test cycle using both JP-5 fuel and unleaded test gasoline (UTG93). The test plan is documented in SPS technical report TRR-1764. Instruments were calibrated to California Air Resources Board (CARB) Method 100 for continuous emissions monitors.

6.2 Test Set-Up

The engine was installed in an indoor test cell with the exhaust duct sealed to prevent leakage and dumped into a 16"Ø low pressure drop exhaust stack. The emissions samples were taken through a 1/4"Ø probe custom designed to take an average sample across the stack. The sampling line was electrically heated to prohibit condensation between the sampling location and the analyzer. Except the exhaust probe installation and sealing the engine exhaust duct, the set-up was a typical test cell installation for the APU. Emissions' analyzer calibrations were performed before each test.

6.3 Results

All of the data presented in this section is for the tests using UTG93 fuel. As stated above, all emissions tests were also performed with the engine run on JP-5 fuel. Comparable figures and tables like those presented below were constructed for the tests using JP-5 fuel and these data are included in the appendix. All raw data obtained during the emission testing is on file at SPS in hard copy and on floppy diskette.

6.3.1 Steady State Testing

The test results for the steady state emissions with the engine run on UTG93 fuel are included as Figures 6.1 and 6.2 and Table 6.1. The data was taken in load steps of 5 KWe from no-load to 20 KWe and back to no-load. Figure 6.1 shows the emissions indices as a function of engine load. The same data is presented in Figure 6.2 as a function of fuel/air ratio. Table 6.1 presents the data from which the figures were plotted. Table 6.1 also shows the calculated combustion efficiency at each point.

6.3.2 Transient Load Testing

The test results for the transient emissions with the engine run on UTG93 were recorded during start-up conditions and during sharp-off loading conditions and are presented below. The data for a typical start are included as Figures 6.3, 6.4, and 6.5. These figures show the transient concentrations, during start-up of the engine, of NO_x, CO and unburned hydrocarbons, respectively.

The test results for the transient emissions with the engine run on UTG93 were recorded during sharp off-loading conditions. This test was performed for off-loads from 5, 10, 15 and 20 KWe to no-load condition by opening the main load contactor to the load bank. The off-load time was only limited by the mechanical switch time required to open the load contactor. The engine performed as expected under these conditions with no mechanical or electrical problems from sharp transient effects. Presented as Figures 6.6, 6.7 and 6.8 are the data for the transient emissions for a sharp off-load of 20 KWe to no-load. The data for the lower power off-loading are on file at SPS, this point has been taken as the "maximum" condition. Figures 6.6, 6.7 and 6.8 show the transient concentrations, during sharp off-loading, of NO_x, CO and unburned hydrocarbons, respectively.

7.0 NOISE TESTING

7.1 Introduction

Free field acoustic measurements of the APU were made and documented. Noise levels for no-load and 20 KWe load is summarized in Table 7.1, attached, at key angles for the exhaust and inlet. Case radiated sound power is also shown. Background noise levels were at or below 65 dB(A)

for all 1/3 octave bands during the tests. SPS technical report ERR-2110, Noise Measurements of the Ecostar Range Extender APU Demonstrator, contains the detail data obtained during the tests discussed below.

7.2 Test Set-Up

The inlet and exhaust measurements were made at the SPS Ruffin Road facility in the back parking lot. A 3/4" plywood wall, 8 feet high and 20 feet wide was erected. The APU was placed behind one side of the plywood barrier while the noise source penetrated the wall into measurement area as shown in Figure 7.1. During the inlet noise tests, the exhaust noise was silenced behind the barrier with an experimental silencer. One third octave pole and ground plane measurements were made on 14 positions on the 10 foot radius away from the source to determine the effects of directionality and distance. Measurements were made at every 15° on the semicircular arc. The pole microphone was placed at 6 feet above ground level and the ground plane microphone was placed 1/4" above ground level for the ground plane measurements. The 10 foot radius was taken from the centerline of the noise source exit. The noise source was vibration isolated from the wall and a good acoustic seal was made at the interface. Microphone calibrations were made before and after each test.

Case radiated noise measurements were made on the opposite side of the plywood barrier with the exhaust penetrating the barrier. The exhaust silencer was placed over the APU inlet to isolate case radiated noise. Case radiated sound power levels were calculated from space averaged sound pressure measurements made over a 10 foot radius quarter sphere.

7.3 Conditions and Instrumentation

Meteorological conditions that existed during the test were as follows:

Wind	3-5 kts
Temperature	71-80°F
Humidity	55-65%
Precipitation	none
Barometric Pressure	29.95-29.97 inHg

Relative humidity was taken from nearby Montgomery Field airport services. Barometric pressure was taken from the test cell log book in which readings are recorded twice a day. A list of the instrumentation used to acquire acoustic data is included as Table 7.2.

7.4 Results

The test data was free field corrected to take out the ground plane reflections. Table 7.3 shows a summary of free field corrected overall A-weighted sound pressure levels for for both the inlet and the exhaust versus measurement angle. Case radiated sound power is also shown.

7.4.1 Exhaust Noise

Figure 7.2 and Figure 7.3 show free field corrected one third octave band exhaust noise levels for 15° (maximum noise angle) for no-load and 20 KWe load. The exhaust noise spectrum is fairly broad band with a tone near 800 Hz. The tone is higher when the mechanical speed droops with higher shaft load. Therefore, this tone is believed to be related to the can combustor since is not mechanical. Exhaust noise was loudest at 20 KWe load. Estimated sound power for the exhaust is 127 dB(L) at full load.

7.4.2 Inlet Noise

Figures 7.4 and Figure 7.5 show free field corrected one third octave band inlet noise levels for 90° (maximum noise angle) for no-load and 20 KWe load. Contrary to the exhaust noise, the inlet noise was highest at no-load but much lower than the exhaust noise levels. This characteristic is typical of small gas turbine radial compressors and is probably associated with the higher inducer Mach numbers at no-load condition. At no-load the compressor mass flow rate is higher. Estimated sound power for the inlet was 114 dB(L) at no-load.

7.4.3 Case Radiated Noise

Figure 7.6 and Figure 7.7 show one third octave band sound power levels for case radiated noise at no-load and 20 KWe load. Case radiated noise was fairly broad band with tones near 200, 800 and 1600 Hz. The 800 and 1600 Hz tones are believed to be associated with combustion. The 200 Hz tone is probably due to a gearbox frequency.

FORD/GEMINI PERFORMANCE

SN 813202, FUEL = JET-A

Figure 5.1: Performance Test Results Run on Jet A

FORD/GEMINI PERFORMANCE

SN 813202, FUEL = UNLEADED GASOLINE

Figure 5.2: Performance Test Results Run on Unleaded Gasoline

SHAFT/BLEED ENGINE DATA ANALYSIS

T-205-10C4 FORD/DOE TESTS W/ JET-A

DATA FILE NAME =FORD2

ORIFICE BLEED MEASUREMENT

TEST POINT 107

RAW DATA

N (RPM)	WF (LB/HR)	LOAD (KW)						
96530.0	40.3	20.3						
PBARO (IN HG)	PSV (IN H2O)	PSB (PSIG)	DPB (IN H2O)	PSPLIT (IN H2O)	PS3 (PSIG)	PS4 (PSIG)	PS6 (IN H2O)	PS6CL (IN H2O)
29.3	0.0	0.0	0.0	0.0	37.2	0.0	-6.2	0.0
T1 (DEG. F)	TB (DEG. F)	T3 (DEG. F)	T6 (DEG. F)	PELD (PSIG)	TBLDF (DEG. F)	DPBN (IN H2O)	PS1 (IN H2O)	QBY
91.0	0.0	0.0	1223.	0.0	0.	0.0	0.0	0.000

UNCORRECTED RESULTS

SPEED	%SPEED	HP	WF	SFC	(U/FT)T	P4/PS6		
96530.0	102.8	27.3	40.3	1.48	39.2	3.46		
P0	F1	P2	P3	P4	PR	PS6		
14.29	14.26	14.26	51.59	45.01	14.29	14.17		
T1 F	TCD F	T3 F	TBEX F	T4W F	T4F F	T6 F	TB F	
91.	401.	401.	1641.	1641.	1632.	1223.	0.	
W1	W3	WN	W4	WBORF	WBNOZ	FB	(WRT/P)B**2	TTEX
0.624	0.590	0.602	0.602	0.000	0.000	0.0190	0.112	1235.

RESULTS CORRECTED TO P0= 14.7 PSIA, T0= 59.0 DEG F, ZERO DUCT DELTA-P'S & LEV=18540. BTU/LBM

% N/RTH	W1	WF	SFC	WB	KW	FF1SL	ETACSL	PHI	
99.8	0.662	39.9	0.198E+01	0.00	20.1	1.026	0.780	0.296	
W1RT1/G2	F2	P3/P2	TCD	T3	ETAC	QWC	PB	TB	QWCSL
1.026	14.700	3.62	351.	351.	0.779	0.679	14.63	-27.	0.678
P4/P3	TBEX	T4P/TN	ETAB F	ETABW	P4QP2	LEERDPB	W3	W4	BLD FLOW FCN
0.950	1524.	0.996	0.971	0.979	0.950	0.000	0.627	0.638	0.00
(WRT/P)N	P4/PS6	T4W	ETAT	U4/V4	RWTN	RWT TH	ETAT TB	LEERET	LEERRWT
0.563	2.44	1524.	0.730	0.647	0.909	0.909	0.779	6.7	0.0
T6	TTEX								
1132.	1142.								

Table 5.1: Reduced Data for a Full Electric Load Data Point
Fuel: Unleaded Gasoline

Figure 6.1: Steady State Emissions Indices as a Function of Load
 Fuel: UTG93

Figure 6.2: Steady State Emissions Indices as a Function of Air/Fuel Ratio
 Fuel: UTG93

GEMINI_UTG 27R x 5C

0 Engine Load, kW 1 Fuel/Air Ratio 2 Efficiency, % 3 EI CO 4 EI UHC 5 EI NOX

1	0	0.00904	99.3743	20.69	1.40	2.34
2	0	0.00936	99.4959	17.53	0.92	2.84
3	0	0.00936	99.4959	17.53	0.92	2.84
4	5	0.01113	99.6218	14.03	0.49	3.71
5	5	0.01113	99.6242	13.99	0.47	3.68
6	5	0.01112	99.6347	13.59	0.46	3.68
7	10	0.01314	99.5242	18.82	0.34	4.33
8	10	0.01304	99.5246	18.87	0.32	4.37
9	10	0.01304	99.5246	18.87	0.32	4.37
10	15	0.01577	99.4579	22.02	0.25	4.01
11	15	0.01577	99.4618	21.85	0.25	4.01
12	15	0.01592	99.4750	21.33	0.24	3.94
13	20	0.01854	99.5785	17.13	0.19	3.66
14	20	0.01864	99.5899	16.66	0.19	3.60
15	20	0.01874	99.5975	16.35	0.18	3.59
16	15	0.01558	99.4385	22.95	0.22	4.05
17	15	0.01553	99.4425	22.79	0.22	4.10
18	15	0.01553	99.4412	22.86	0.22	4.09
19	10	0.01321	99.4901	20.64	0.25	4.37
20	10	0.01315	99.4963	20.49	0.22	4.35
21	10	0.01315	99.4948	20.49	0.24	4.36
22	5	0.01098	99.6265	14.62	0.30	3.85
23	5	0.01108	99.6378	14.30	0.26	3.83
24	5	0.01117	99.6396	14.14	0.28	3.83
25	0	0.00921	99.5342	17.54	0.54	2.96
26	0	0.00911	99.5425	17.20	0.53	2.93
27	0	0.00911	99.5420	17.20	0.54	2.92

Table 6.1: Steady State Emissions Data, Including Combustor Efficiency
Fuel: UTG93

GEMINI APU TURBINE ENGINE
SOURCE TEST RESULTS
NO_x CONCENTRATION vs TIME
START-UP TRANSIENTS
UTG 93 FUEL

Figure 6.3: Start-Up Transient NO_x Concentration
Fuel: UTG93

SOURCE TEST RESULTS
TOTAL HYDROCARBON CONCENTRATION vs TIME
START-UP TRANSIENTS
UTC 93 FUEL

Figure 6.4: Start-Up Transient THC Concentration
Fuel: UTC93

ENGINEING
SOURCE TEST RESULTS
CARBON MONOXIDE CONCENTRATION vs TIME
START-UP TRANSIENTS
UTG 93 FUEL

Figure 6.5: Start-Up Transient CO Concentration
Fuel: UTG93

Gemini Turbine Source Test
 UTG 93 Fuel
 Drop-Test
 20KW Load To Baseline No-Load

—■— NOx

Figure 6.6: Sharp Off-Load Transient NOx Concentration
 Fuel: UTG93

Gemini Turbine Source Test
UTG 93 Fuel
Drop-Test
20KW Load To Baseline No-Load

—■— THC

Figure 6.7: Sharp Off-Load Transient THC Concentration
Fuel: UTG93

Gemini Turbine Source Test
UTG 93 Fuel
Drop-Test
20KW Load To Baseline No-Load

Figure 6.8: Sharp Off-Load Transient CO Concentration
Fuel: UTG93

Angle, °	Inlet -No Load, dB(A)	Inlet -20kW, dB(A)	Exhaust -No Load, dB(A)	Exhaust - 20kW, dB(A)
0	79.9	80.5	98.0	102.4
15	81.3	79.1	99.2	102.7
30	83.5	83.1	98.7	101.1
45	87.0	87.0	96.3	99.7
60	89.9	88.6	96.1	96.7
75	91.9	89.1	93.4	96.5
90	92.0	89.8	94.2	95.9
105	90.7	89.9	94.4	98.3
120	89.5	88.1	92.9	97.6
135	87.6	85.9	94.7	97.8
150	84.6	83.2	97.8	100.5
165	81.3	80.6	99.4	102.4
180	83.2	83.8	101.4	103.9

	No Load, dB(A)	20 kW, dB(A)
Case Radiated Sound Power	115.1	114.3

Table 7.1: Summary of APU Noise Levels at 10 Feet

Figure 7.1: Acoustic Measurement Set-Up

Description	Call. Number	Serial Number	Last Call.	Call. Exp.
B&K 2143 Freq. Analyzer	T203031	1516990	5/11/92	5/20/93
B&K 4133 1/2" free field mic.	T203004	1423973	4/28/92	5/22/93
B&K 2639T pre amplifier	T203007	1497408	4/28/92	5/22/93
B&K 4230 Calibrator	T203009	1511328	4/28/92	5/22/93
B&K A00029 30 meter mic cable	T203008	---	---	---
Dwyer R523 Wind Meter	---	---	---	---

Table 7.2: Instrumentation Used for Acoustic Measurements

Sound Pressure Levels dB(A) at 10 feet
(Free Field Corrected)

	Angle	No Load	20kW
Exhaust	180°(max.)	101	104
Inlet	90°(max.)	92	90

Sound Power Levels dB(A)

	No Load	20kW
Case	115.1	114.3

Table 7.3: Free Field Corrected Sound Pressure Levels at 10 Feet and Case Radiated Sound Power Levels

Figure 7.2: Free Field Corrected Exhaust Noise Levels for 15°
No-Load Condition

Figure 7.3: Free Field Corrected Exhaust Noise Levels for 15°
20 KWe Load Condition

Figure 7.4: Free Field Corrected Inlet Noise Levels for 90°
No-Load Condition

Figure 7.5: Free Field Corrected Inlet Noise Levels for 90°
 20 KWe Load Condition

Figure 7.6: Case Radiated Sound Power Levels
No-Load Condition

Figure 7.7: Case Radiated Sound Power Levels
20 KWe Load Condition

APPENDIX

Parameter	Qty	Expected	Device	Readout	DAS Chn
PRESSURE					
P baro	1	30 inHg	Barometer	DAS	081
Ps pcd	1	42 psig	Transducer/Gage	DAS/Gage	065
Ps Venturi	1	-15 inH2O	Transducer/Mano	DAS/Mano	066
Ps Inlet	1	-20 inH2O	Transducer	DAS	067
Ps Exhaust	1	30 inH2O	Transducer	DAS	069
Ps Oil	1	40 psig	Transducer/Gage	DAS/Gage	070
Ps Fuel Boost	1	15 psig	Transducer	DAS	071
T Cell Ambient	1	75 °F	K-Type T/C	DAS	029
T Exhaust	6	1300 °F	K-Type T/C	DAS	001-006
T Venturi	4	75 °F	K-Type T/C	DAS	015-016
T Inlet	6	75 °F	K-Type T/C	DAS	007-012
T Fuel	1	75 °F	K-Type T/C	DAS	019
T Oil Sump	1	190 °F	K-Type T/C	DAS	020
T Eng Exhaust	1	150 °F	K-Type T/C	DAS	025
T Gen Exit	2	200 °F	K-Type T/C	DAS	021-022
Engine Speed	1	3600 Hz	Mag Pickup	DAS	121
Fuel Flow	1	25 lb/hr	Micro Motion	DAS	124
Power Head Vib	1	7 g's	Accelerometer	DAS	083
Generator Vib	1	1 g	Accelerometer	Analyzer	084
Generator Output	1	20 kWe	Load Bank	DAS	
Shaft Load	1	28.6 HP	Dynomometer	DAS	162
Emission Sample	1		Outside Vendor		

Typical SPS Engine Instrumentation List

SUNDSTRAND	FORD GEMINI TEST	D/P #	73	PAGE 50
ENG. SPEED 101.7 % N	T. CELL AMB.	75 F	T. INLET # 1	75 F
ENG. SPEED 95490 RPM			T. INLET # 2	80 F
ENG. SPEED 3673 HZ	T. EXH. # 1	1310 F	T. INLET # 3	79 F
CORR SPEED 99.5 %	T. EXH. # 2	1313 F	T. INLET # 4	78 F
	T. EXH. # 3	1304 F	T. INLET # 5	78 F
	T. EXH. # 4	1284 F	T. INLET # 6	78 F
EST AVE 1-6 1293.5 F	T. EXH. # 5	1264 F		
PS PCO 38.8 PSIG.	T. EXH. # 6	1264 F	DYND SPEED	12246 RPM
PS VENT. -5.4 INH2O			LOAD	32.1 HP
PS INLET -3.4 INH2O	T. ENG EXH	1244 F		
PS EXH. -5.7 INH2O			P/H VIBS	5.2 G's
PS OIL 21.0 PSIG.	T. VENT. # 1	77 F		
PS FUEL B. 0.7 PSIG.	T. VENT. # 2	77 F	FUEL FLOW	44.4 PPH
P BARD 29.36 INHG	T. FUEL	75 F		
	T. OIL SUMP	199 F		
04/05/93	12:33:52			

SUNDSTRAND	FORD GEMINI TEST	D/P #	74	PAGE 50
ENG. SPEED 101.7 % N	T. CELL AMB.	75 F	T. INLET # 1	79 F
ENG. SPEED 95490 RPM			T. INLET # 2	79 F
ENG. SPEED 3673 HZ	T. EXH. # 1	1310 F	T. INLET # 3	78 F
CORR SPEED 99.9 %	T. EXH. # 2	1313 F	T. INLET # 4	78 F
	T. EXH. # 3	1305 F	T. INLET # 5	78 F
	T. EXH. # 4	1294 F	T. INLET # 6	79 F
EST AVE 1-6 1293.9 F	T. EXH. # 5	1267 F		
PS PCO 38.8 PSIG.	T. EXH. # 6	1266 F	DYND SPEED	12250 RPM
PS VENT. -5.4 INH2O			LOAD	32.8 HP
PS INLET -3.4 INH2O	T. ENG EXH	1247 F		
PS EXH. -5.6 INH2O			P/H VIBS	5.4 G's
PS OIL 19.9 PSIG.	T. VENT. # 1	77 F		
PS FUEL B. 0.7 PSIG.	T. VENT. # 2	77 F	FUEL FLOW	44.5 PPH
P BARD 29.36 INHG	T. FUEL	75 F		
	T. OIL SUMP	200 F		
04/05/93	12:34:24			

SUNDSTRAND	FORD GEMINI TEST	D/P #	75	PAGE 50
ENG. SPEED 101.7 % N	T. CELL AMB.	75 F	T. INLET # 1	79 F
ENG. SPEED 95490 RPM			T. INLET # 2	79 F
ENG. SPEED 3673 HZ	T. EXH. # 1	1313 F	T. INLET # 3	78 F
CORR SPEED 99.7 %	T. EXH. # 2	1315 F	T. INLET # 4	79 F
	T. EXH. # 3	1307 F	T. INLET # 5	79 F
	T. EXH. # 4	1287 F	T. INLET # 6	79 F
EST AVE 1-6 1295.9 F	T. EXH. # 5	1266 F		
PS PCO 38.5 PSIG.	T. EXH. # 6	1266 F	DYND SPEED	12248 RPM
PS VENT. -5.2 INH2O			LOAD	32.7 HP
PS INLET -4.0 INH2O	T. ENG EXH	1248 F		
PS EXH. -5.7 INH2O			P/H VIBS	5.2 G's
PS OIL 19.7 PSIG.	T. VENT. # 1	79 F		
PS FUEL B. 0.7 PSIG.	T. VENT. # 2	78 F	FUEL FLOW	44.4 PPH
P BARD 29.36 INHG	T. FUEL	75 F		
	T. OIL SUMP	201 F		
04/05/93	12:34:40			

Un-Reduced Data at Maximum Dynamometer Load

Steady State Emissions Indices as a Function of Load
Fuel: JP-5

Steady State Emissions Indices as a Function of Air/Fuel Ratio
Fuel: JP-5

0 Engine Load, kW 1 Fuel/Air Ratio 2 Efficiency, % 3 EI CO 4 EI UHC 5 EI NOx

1	0	0.00922	99.6256	14.52	0.32	2.75
2	0	0.00932	99.6305	14.35	0.31	2.71
3	0	0.00917	99.6259	14.54	0.31	2.76
4	5	0.01115	99.6411	14.52	0.17	3.83
5	5	0.01115	99.6398	14.54	0.17	3.86
6	5	0.01110	99.6426	14.45	0.17	3.84
7	10	0.01322	99.5047	20.54	0.11	4.56
8	10	0.01327	99.5049	20.53	0.11	4.47
9	10	0.01332	99.5066	20.46	0.11	4.45
10	15	0.01573	99.4556	22.72	0.09	4.10
11	15	0.01578	99.4563	22.66	0.09	4.07
12	15	0.01578	99.4623	22.43	0.09	4.13
13	20	0.01919	99.6019	16.61	0.06	3.66
14	20	0.01920	99.5980	16.72	0.08	3.66
15	20	0.01929	99.6128	16.15	0.06	3.62
16	15	0.01573	99.4649	22.35	0.08	4.23
17	15	0.01573	99.4597	22.52	0.09	4.23
18	15	0.01563	99.4569	22.70	0.08	4.26
19	10	0.01332	99.5106	20.35	0.10	4.60
20	10	0.01332	99.5090	20.36	0.11	4.57
21	10	0.01115	99.4097	24.55	0.11	5.37
22	5	0.01110	99.6552	14.10	0.12	3.97
23	5	0.01110	99.6515	14.22	0.13	3.95
24	5	0.01115	99.6545	14.14	0.12	3.91
25	0	0.00922	99.6292	14.68	0.25	2.89
26	0	0.00922	99.6264	14.73	0.26	2.94
27	0	0.00918	99.6230	14.91	0.25	2.88

Steady State Emissions Data, Including Combustor Efficiency
 Fuel: JP-5

GEMINI APU TURBINE ENGINE
SOURCE TEST RESULTS
-NO_x CONCENTRATION vs TIME
START-UP TRANSIENTS
JP5 FUEL

Start-Up Transient NO_x Concentration
Fuel: JP-5

GEMINI APU TURBINE ENGINE
SOURCE TEST RESULTS
TOTAL HYDROCARBON CONCENTRATION vs TIME
START-UP TRANSIENTS
JP5 FUEL

Start-Up Transient THC Concentration
Fuel: JP-5

GEMINI APU TURBINE ENGINE
SOURCE TEST RESULTS
CARBON MONOXIDE CONCENTRATION vs TIME
START-UP TRANSIENTS
JP-5 FUEL

Start-Up Transient CO Concentration
Fuel: JP-5

Gemini Turbine Source Test
JP5 Fuel
Drop-Test
20KW Load To Baseline No-Load

Sharp Off-Load Transient NOx Concentration
Fuel: JP-5

Gemini Turbine Source Test
JP5 Fuel
Drop-Test
20 KW Load To Baseline No-Load

—■— THC

Sharp Off-Load Transient THC Concentration
Fuel: JP-5

Gemini Turbine Source Test
JP5 Fuel
Drop-Test
20 KW Load To Baseline No-Load

—■— CO

Sharp Off-Load Transient CO Concentration
Fuel: JP-5

Original Sundstrand Gemini APU Test Plan

Ford proposes to conduct the following tests as part of the evaluation of the Sundstrand turbo alternator auxiliary power unit (APU). Note that during all testing the following information will be recorded :

Turbine inlet and exhaust temperatures, fuel flow, exhaust gas O₂ and CO₂ levels (%), HC and NO_x emissions (ppm's), pressure ratio across the APU, engine speed, and alternator output.

Initial APU Evaluation :

- a) Operate the APU at rated speed and load. Record all data.

Objective : To determine if APU, as delivered, meets original goals of output power, fuel efficiency, and emissions.

- b) Operate the APU at the same steady-state load points used by Sundstrand in their initial test and check-out of the engine, i.e., 5, 10, 15, and 20 kW. Record all data.

Objective : To have a basis to compare Ford test results to the data taken by Sundstrand.

Operating the APU as a Range Extender :

- a) Operate the APU at the following steady-state output points, which correspond to those points representative of the hybrid Ecostar vehicle operated over the FUDS driving cycle :

7.00 kW _E (start)	4.00 kW _E
5.41	5.62
10.8	4.34
7.03	4.57
6.31	4.00 (end)

The preceding operating points will be tested in order, beginning with engine start-up from cold conditions. Before changing load, data will be taken at each point after the engine has reached steady-state. Changes in load will be accomplished as soon as possible, consistent with engine control strategy and hardware. Data will be recorded during load changes to the extent possible.

Objective : Operate the APU using the current hybrid Ecostar strategy, i.e., by running the APU at a power level which represents the average power consumption over the preceding two minutes of vehicle operation. The goal of this strategy is to maintain a given battery state of charge while providing sufficient generating capacity to continue to drive the vehicle.

Operating the APU as a Series Hybrid :

- a) Using the programmable electronic load bank, operate the APU over the FUDS driving cycle in such a manner as to simulate the instantaneous power requirements of the hybrid Ecostar vehicle. Power update requests will be given to the APU on a second-by-second basis. Data will be recorded over the entire length of the test.

Objective : To determine the fuel consumption and emissions characteristics of this APU when operated in a series hybrid mode.

Transient Operation :

- a) Using the programmable electronic load bank, operate the APU between two output power levels, varying the time required to make the transition between the lower level and the higher level, and then back again. Repeat for a different set of power levels.

For example, operate the APU at 5 kW output. Over a period of 1 second, increase the output to 10 kW. Record data during transient period. Decrease output to 5 kW. Record data during transient period. Refer to Figure D-1 for an illustration of this transient test procedure. Actual power levels to be used will be specified at test time.

Objective : To characterize the transient emissions behavior of the APU, and to assess the ability of the APU control system to accurately follow power command requests, including a command to go to zero output power from full load.

Effect of Hot Restarts :

- a) Start the APU and bring to a specified steady-state output power level. Command the APU to shut down. After the APU has stopped completely, issue another command to start again and return to the original steady-state output power level. Repeat this test for various output power levels and time intervals between shutdown and restart. Refer to Figure D-2 for an illustration of this test procedure. Actual power levels to be used will be specified at test time.

Objective : To determine the effects on emissions of engine shutdown and restart for various output power levels and restart time intervals, and to determine how quickly the engine can respond to a shutdown command. Results of this series of tests could help determine the viability of alternate gas turbine APU control strategies.

Figure D-1. Transient Loading

Figure D-2. Hot Restart

Programmable Load Bank Control

The programmable load bank is controlled by a zero to ten volt signal generated by a D/A converter that connects to the parallel port of a PC. A QuickBasic program was written to control the D/A convertor according to the desired APU testing applications.

The operation of the APU can not be precisely anticipated in the areas of voltage and losses. For this reason, a linearization is established by an initial test of the APU to calibrate the program. This method is valid because the last equation on the governing equations, page 3 of this Attachment, shows that V_i is a function of P and several constants. This linearization is used throughout the program to determine an output byte that yields the desired power level of the APU. Some deviation may occur when the values that are taken as constants do not remain constant.

Several methods remain continuous throughout the program. The "F1" key will always return the voltage to a no load condition, and then continue the program. The "F2" key will return the voltage to a no load condition, and return to the main menu. After the "F2" key has been used it is recommended that the program be quit and restarted. At user prompts ("?" and cursor) the function keys must be followed by the <enter> key to be activated. When a prompt receives an invalid entry, the cursor will remain on the line and the user should type a new value over the old value. The program sets the no load condition whenever the routine is ended and the menu is requested.

Main Menu

1 Calibration

This enables the user to establish the linearization used throughout the program. It can be saved and loaded from this menu option.

2 Steady State

The current power level is displayed and a new level is established when the user presses <enter> from the prompt.

3 Sudden Drop

A power level is established as soon as <enter> is pressed at the prompt. The APU should be allowed to stabilize before the no load drop occurs.

4 Transients

Given a starting power level, the user is prompted for a second power level and a time for the transition. Separate these entries by a comma for proper entry. The second power level becomes the starting level if the routine is continued. CAUTION: The prompt must see a comma for the "F1" and "F2" keys to operate when <enter> is pressed.

5 Cycle

This option requires a data file consisting of two columns. The first column contains the time in seconds at which the power level in the second column is to be started. At the end of the cycle a no load signal is sent, but the display retains the previous power and time settings.

Startup with Calibration

- Analytically estimate load bank voltage range
- Turn alternator field off
- Select menu option 1, and a new calibration
- Select starting byte outside of the anticipated no load condition
- Use right arrow (-->) key to toggle between byte 0 and 255 for adjusting pots to the analytical values, while observing D/A convertor output on a voltmeter.
 - Pot 1: Offset, the location of the window on the 0 to 10 volt scale. CCW moves toward 10 volts, CW moves toward 0 volts
 - Pot 2: Gain, the window size. CCW increases size, CW decreases size
- Set byte to starting voltage
- Start generator field, and confirm no load
- Use up and down arrow key to change byte value
- NOTE: Range should be maximized. If the no load and full load conditions do not have a large range then:
 - Turn the generator field off.
 - Adjust the pots to correspond with the D/A converter signal voltages where the load points occurred.
 - Set the byte value to the no load condition
 - Turn the generator field on.
- When a load is first observed, move to a byte just outside that load and establish the zero load condition by pressing the left <-- arrow key
- Change the byte value until power is close to the full load condition, and press the left arrow (<--) key.
- The program will prompt for the power level at this point. After the power is entered the APU will resume the no load condition.
- A maximum power level will be determined based on the maximum remaining resolution, and the user will be prompted to enter a limit. If the limit is outside of the resolution, then the calibration should be performed again with a different operating range. This maximum power will be used throughout the program as the limiting voltage, where power requests above this value will be truncated.

Startup from a file

- Turn generator field off
- Select menu option 1, and select "F"
- Enter path and name of file
- When the menu appears, the generator field can be activated.

Governing Equations

$$P = I^2 R = VI = \frac{V^2}{R}$$

Definition of Terms

V_s = rms voltage of fully rectified three phase source

V_l = voltage setting on the load bank

V_d = voltage losses (copper, diodes, etc.)

R_{eq} = equivalent resistor from parallel configuration

Determination of V_s

$$V_s = 0.9557 V_{\max} \quad V_{\max} = \sqrt{2} V_{rms\phi}$$

Maximum possible power dissipation in systems

$$P = V_{\lim} * I_{\lim}$$

Power dissipation

$$P = \frac{V_s(V_s - V_d - V_l)}{R_{eq}}$$

Load bank voltage as a function of Power in circuit

$$V_l = \frac{V_s^2 - PR_{eq} - V_s V_d}{V_s}$$