# HYBRID-ELECTRIC PROTOTYPE TRUCK (HEPT)

## FINAL REPORT • JANUARY 2000

Project Sponsors:

**California Air Resources Board**
**California Office of Strategic Technology**
**Defense Advanced Research Projects Agency (DARPA)**
**South Coast Air Quality Management District**
**U.S. Army — Tank-automotive and Armaments Command (TACOM)**

Project Partners:

**ISE Research Corporation**
**WestStart/CALSTART**
**Kenworth Truck Company**
**Peterbilt Motors Company**
**San Diego Regional Technology Alliance**
**University of California, Riverside**

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# Hybrid-Electric Prototype Truck
# Draft Final Report
# January 2000

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**California Air Resources Board**
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"Hybrid Electric Prototype Truck Project"

and the

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"Develop and Demonstrate Heavy Duty Hybrid Electric Truck
Fueled with Compressed Natural Gas"

# CHAPTER 1
# EXECUTIVE SUMMARY

The ISE Research (ISER) Hybrid-Electric Prototype Truck (HEPT) project was initially funded by DARPA and CALSTART in October 1996, with a matching grant from the California Office of Strategic Technology in January 1997. The initial objective of the HEPT project was to build and test a Class 8 truck using a hybrid-electric drive system. Subsequent to the start of this project, additional funds were obtained from the California Air Resources Board, South Coast Air Quality Management District, and the U.S. Army-TACOM in 1997 and 1998 to augment the initial program by accelerating development and demonstration of certain key technologies, and by funding construction of a second prototype truck.

*Figure 1. Completed Hybrid-Electric Prototype Truck.*

The HEPT project was successfully completed in 1999, with achievement of several major milestones. Early in the year, the first HEPT prototype vehicle was completed, using a Kenworth T-800 chassis (Figure 1). The efforts leading up to completion of this vehicle were initially documented in an interim "Phase 1" Final Report in February 1999.

Subsequent to publication of the interim report, several upgrades were made to this vehicle, and a second hybrid truck was completed, using a Peterbilt 330 chassis (Figure 2). The first HEPT truck, intended to serve as a technology "pathfinder" vehicle, incorporates an advanced AC induction main drive motor and an advanced modular high frequency AC motor controller that were both developed with HEPT project funding. The second HEPT truck, which will be used primarily as a show vehicle, uses a less sophisticated but more commercially mature motor and motor

*Figure 2. Second HEPT truck.*

controller subsystem. Both HEPT vehicles feature advanced vehicle control systems and modular onboard battery charging systems, among other new products. This report documents the results of activities conducted since publication of the interim Final Report, as well as containing all of the prior information which appeared in the earlier document.

The HEPT project resulted directly in development of four major new subsystems, which have market potential in their own right as stand-alone products. These were: (1) an integrated "EVControl" vehicle control subsystem developed under *Task 2, System Controller Development;* (2) an integrated auxiliary power unit (APU) subsystem developed under *Task 3, APU Testing and Integration;* (3) an integrated motive drive subsystem developed under *Task 4, Motor and Motor Controller Development;* and (4) an integrated electric battery subsystem developed under *Task 5, Battery Subsystem Development.* The first four chapters of the main body of this report address each of these tasks, in sequence, and their resulting products.

The original scope of work for the HEPT project was divided into eight technical tasks: a design task, the four subsystem development tasks just listed, two tasks relating to vehicle integration, a test and evaluation task, and a program management task. Highlights of the work accomplished in each of these nine task areas are identified in the following paragraphs.

<u>1.1Task #1: Final Drive System Design</u> — Building on work completed in a prior *Medium and Heavy Duty Hybrid Truck Feasibility Study,* a final drive system design was developed that integrates all major subsystems into Kenworth T-800 and Peterbilt 320 Class 8 trucks. Numerous trade studies were conducted to evaluate alternative motors, motor controllers, auxiliary power units (APUs), and battery options. A relatively high system operating voltage was selected to minimize losses associated with high operating current and to enable use of lower cost motor controllers. The final integrated system design adopted and implemented was similar in most respects to the design envisioned at the start of the program. However, numerous specific changes to the design were made to accommodate unplanned enhancements to key components such as the main drive motor, motor controller, and battery subsystem.

<u>1.2 Task #2: System Controller Development</u> — During the HEPT project, ISER made the decision to utilize an advanced distributed network architecture for its vehicle system controller, based on Echelon Corp.'s LonWorks™ distributed control technology. In this configuration, every major vehicle subsystem has its own dedicated control computer, referred to as a network "node," interconnected via a distributed network. An initial set of nodes essential for achievement of basic vehicle operation were successfully built and demonstrated during Phase 1, including an APU node that controls the vehicle APU and a cabin node that provides the vehicle operator with information on vehicle subsystems. The open architecture of the ISER control system will enable development and seamless

integration of additional vehicle nodes that can help achieve the full potential of the ISER hybrid-electric drive technology.

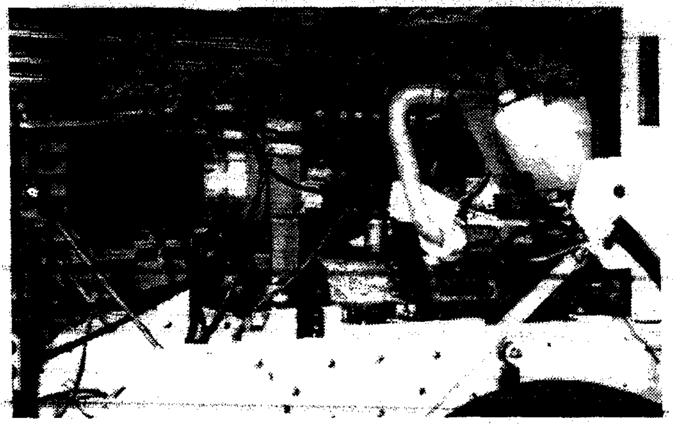

*Figure 3. HEPT auxiliary power unit.*

1.3 Task #3: APU Testing and Integration — A 75 kW APU (Figure 3) was successfully built and demonstrated in the first HEPT vehicle, combining a General Motors Vortec V-6 engine, converted to run on compressed natural gas (CNG), with a 75 kW permanent magnet alternator-generator developed with the assistance of Fisher Electric Technology. The function of this subsystem was initially validated using a load bank built by ISER, and subsequently verified through actual vehicle operation. Basic capability for automated control of the APU, using vehicle bus voltage to determine when the APU is needed, was accomplished. In addition, an APU "load-following" technique was developed, which tailors APU power output to vehicle power requirements. An 80 kW APU utilizing a John Deere 6.8 liter CNG engine was installed into the second HEPT vehicle.

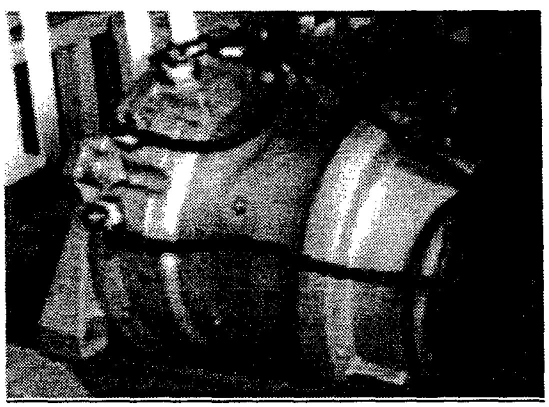

*Figure 4. Advanced AC motor.*

1.4 Task #4: Motor and Motor Controller Development — The HEPT project significantly exceeded its initial expectations in the area of motor and motor controller development, enabled by the acquisition of supplemental funds from the South Coast Air Quality Management District (SCAQMD) and the U.S. Army. The original HEPT plan was to purchase one or more high power AC induction motors from an existing motor supplier such as Westinghouse, General Electric, or Kaman. However, early in the project CALSTART assisted ISER in identifying a promising new motor technology (Figure 4) developed by United Defense LP (UDLP), a former division of FMC Corporation. Following a thorough analysis of this new technology, supported by a prominent consultant referred to ISER by U.C. Riverside, ISER negotiated a series of agreements with UDLP to adapt this motor to the HEPT application and to obtain license to manufacture and market this motor for vehicle applications. One of the first working prototypes of this motor was installed into the Kenworth HEPT truck and successfully demonstrated in late 1998 and early 1999. The motor is controlled by a unique modular motor controller ISER developed under an R&D partnership with Siemens. The ISER-Siemens controller supplies up to 300 kW continuous power, is smaller and lighter in weight than other controllers with equivalent power output, and can be replicated commercially at a much lower cost than similar capacity controllers offered by other firms.

*Figure 5. HEPT batteries in racks.*

<u>1.5 Task #5: Battery Subsystem Development</u> — ISER successfully integrated two sets of 48 batteries into the prototype Kenworth truck (Figure 5). The number of batteries per set was temporarily reduced from 56 to 48 to reduce operating voltage, pending receipt of a new higher voltage Siemens motor control module. In operational testing of the vehicle, the batteries were shown to generate sufficient voltage to supply 261 kW of power to the main drive motor.

When augmented by the output of the APU, this enables the vehicle to run at power levels in excess of 400 horsepower, the peak power limit of the diesel equivalent truck. Use of a similar battery pack in ISER's all-electric Sparkletts delivery truck indicates the prototype Kenworth truck will have an all-electric driving range of between 15 and 50 miles, depending on cargo weight and driving conditions. A single pack of 48 batteries was installed into the Peterbilt truck. Both vehicles were equipped by ISER with onboard charging systems, which use an advanced "constant power" charging technology developed by Coherent Power Ltd. ISER formed a strategic partnership with Coherent Power during the HEPT project to pursue joint development and commercial marketing of advanced electric and hybrid-electric vehicle charging systems.

*Figure 6. Completed HEPT vehicle.*

<u>1.6 Task #6: Integration Planning and Preparation</u> — Plans for integration of the hybrid-electric drive systems into the two HEPT vehicles were developed prior to actual installation, including generation of drawings and development of Work Breakdown Structures (WBS) listing all drive system elements in a

hierarchical structure. In addition to contributing to the successful integration of both prototype hybrid trucks, these plans will facilitate replication of the drive system for future vehicles.

1.7 Task #7: Vehicle Integration — Integration of the hybrid-electric drive system into the first HEPT vehicle was accomplished over a period of about 18 months, beginning in the spring of 1997 and concluding in the fall of 1998. The first subsystem to be successfully integrated was the APU, followed by installation of the CNG fuel system, main drive motor, motor controller, battery racks, batteries, electrically driven accessories, and vehicle control subsystem, in approximately that order. During this process, ISER did not encounter any significant obstacles that would limit integration of hybrid drive systems into future vehicles. Figure 6 is a view of the completed truck with the battery covers removed, showing the battery packs on one side of the vehicle.

1.8 Task #8: Operational Testing — Operational testing goals established at the start of the HEPT project were partially completed during the period of performance. Initial road testing of both the Kenworth and Peterbilt vehicles was performed in the vicinity of ISER's prototype production facility, validating the basic roadworthiness of the vehicles. Professional truck drivers invited to "test drive" the vehicles were very impressed with the trucks' rapid acceleration and smoothness. A two day series of dynamometer tests was also performed on the Kenworth truck at a local Peterbilt truck center (Figure 7), resulting in generation of a substantial data base on vehicle and motor performance. A set of towing tests was conducted at ISER's facilities to augment the dynamometer data. Testing of the truck in actual operational service, which was originally intended to be part of the Operational Testing task, was delayed indefinitely to allow upgrading of the high tech components on the Kenworth and Peterbilt vehicles. However, road testing conducted to date has indicated a high likelihood that hybrid-electric drive systems can achieve projected economic and performance benefits, which include a 50% reduction in fuel consumption and a 90-95% reduction in harmful exhaust emissions.

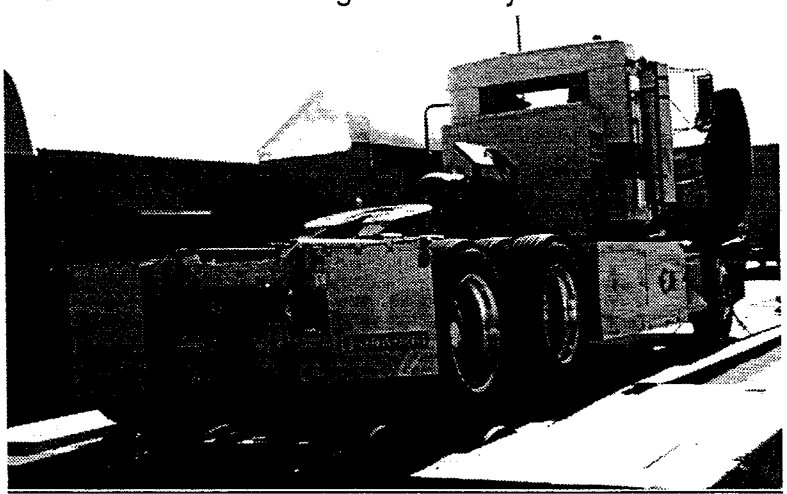

*Figure 7. HEPT in dynamometer testing.*

1.9 Task #9: Project Management — Submittal of this Final Report concludes ISER's project management responsibilities for the HEPT program. The project was completed within the funding allocations supplied by the California Air Resources Board ($350,000), DARPA/CALSTART ($250,000), U.S. Army-TACOM ($240,186), South Coast Air Quality Management District ($200,000), and California Office of Strategic Technology ($180,000). However, the total value of work performed far exceeded the combined project budget of $1,220,186, due partly to the addition of unplanned activities such as advanced motor development, and partly to the fact that several of the HEPT subsystems took significantly more effort to develop than originally expected. The added investment was supplied by additional matching contributions by ISER. In total, ISER's matching contributions to the HEPT project were valued at more than $550,000, and the value of contributions made by Kenworth, Peterbilt, and John Deere are estimated at approximately $200,000. Therefore, the value of the total effort applied to the HEPT project was right in the neighborhood of $2 million.

1.10 Assessment of Project Results — ISER's general assessment of project results is that this has been a highly successful prototype development effort. The paramount goal of basic proof of concept of the ISER hybrid-electric drive system was accomplished. As planned, two fully functional hybrid-electric prototype vehicles were built. In addition, three of the four main vehicle subsystems developed during the project employ more advanced designs, offer greater performance, and have superior market potential (in ISER's estimation) to the concepts envisioned at the start of the project. Specifically:

- The HEPT vehicle control subsystem employs an advanced LonWorks-based distributed network that was not part of the original project plan. This architecture provides greater flexibility and adaptability than the vehicle control network originally planned, and will cost less to replicate for full scale production.

- The motive drive system installed into the Kenworth truck utilizes a new high power AC induction motor with a greater power-to-weight ratio than any other competing motor, and ISER has developed the in-house capability to manufacture this motor. In addition, the customized advanced modular motor control system developed in parallel offers weight and cost advantages over competing products, and which ISER can supply in partnership with Siemens. Both of these components are considerably more advanced technologically than the motors and motor controllers ISER planned to purchase at the start of the project.

- The battery subsystems incorporate lightweight, compact, modular onboard charging systems ISER obtained through negotiation of a partnership agreement with Coherent Power. Operational flexibility of the prototype and future ISER vehicles will be greatly enhanced by this innovation, as contrasted with ISER's original plan to use large offboard chargers. In addition, ISER is approximately 75% complete in developing an advanced battery management system that will further improve the performance of its battery subsystem.

These additional accomplishments required some tradeoffs and sacrifices. Much greater resources were expended during the HEPT project than originally budgeted, and completion of the HEPT trucks was delayed by about a year to accommodate all of the unplanned technology advances. The higher level of complexity of the systems installed into the Kenworth truck makes it necessary to delay testing of this truck in full operational service until the high power motor and modular motor controller can be upgraded. This motive drive subsystem, employing newer and less proven technologies than initially planned, will take longer to perfect and make reliable than if the original plan were pursued and proven "off the shelf" components were utilized.

However, ISER believes these additional costs and sacrifices are justified by the additional long term potential offered by the advanced componentry developed. During the three year time frame of the HEPT project, ISER was able to accomplish a number of "product improvements" that the company envisioned as longer term pursuits. This will shorten the time required to evolve ISER's hybrid-electric drive system into a "market-ready" product. The rugged testing that was not accomplished during the HEPT project will be conducted on future programs and with continuing investments by ISER.

Table 1 summarizes the major accomplishments of the HEPT project, by major vehicle component, and identifies key future improvements ISER believes are required to achieve the full potential of hybrid-electric vehicles. These improvements, such as adoption of turbogenerator or fuel cell APUs, further reducing the size of the motor controller, and use of flywheels or ultracapacitors, are beyond the scope of the HEPT project but will be pursued in the future under separately financed efforts as funds become available.

The following chapters of this report provide a more detailed description of the activities and results of the HEPT project. Chapters 2 through 8 generally follow the sequence of the major project tasks summarized in this chapter.

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*Table 1. Major HEPT accomplishments, and key future improvements required.*

| Component | Primary HEPT Accomplishments | Key Future Improvements Required |
|---|---|---|
| System Controller | Automated APU control<br>APU load-following<br>Smooth acceleration/braking<br>Use of distributed networks | Vehicle efficiency optimization<br>Enhanced operator interface<br>Improved diagnostics<br>Predictive energy algorithms |
| Auxiliary Power Unit | Reduced fuel consumption<br>Reduced emissions<br>Quieter operation | Use of LNG<br>Adoption of turbogenerators<br>Evolution to fuel cells |
| Main Drive Motor | High efficiency AC induction<br>High power to weight ratio | Improve internal liquid cooling<br>Strengthen gears |
| Motor Controller | Unique modular design<br>Compact, lightweight design | Perfect "wye-delta" switching<br>Further reduce system size<br>Enhance system robustness |
| Battery Subsystem | Demonstration of 600 VDC bus<br>Incorporates onboard charger | Perfect battery equalization<br>Improve energy density<br>Augment with flywheels<br>Augment with ultracapacitors |
| General | Rapid acceleration<br>Smooth ride<br>Electrically-driven accessories | Aerodynamic body shaping |

# CHAPTER 2
# FINAL DRIVE SYSTEM DESIGN

Conceptual designs for a Class 8 hybrid-electric drive system were developed by ISER, with the assistance of the Kenworth Truck Company, U.C. Riverside, and several other partners, during a $350,000 *Medium and Heavy Duty Hybrid Truck Feasibility Study* led by ISER in 1995-96. Design work continued between the end of the feasibility study in May 1996 and the start of the HEPT contract in October 1996. The Kenworth T-800B Class 8 truck was used as the basis for these designs, as Kenworth had agreed to contribute one of these vehicles as a contribution to the project.

When the HEPT contract started, initial design work was influenced by major system analyses, such as trade study to determine the optimal operating voltage for the main power bus. Early trade studies determined that, to meet peak power requirements of 300 kW, the drive system operating voltage should be increased from the 240-260 VAC previously planned to 500-600 VAC. While the higher voltage was determined to present some safety and operational issues, it was decided that the higher voltage system would have important advantages, including a reduction in peak operating current to less than 400 amps. This would not only enhance the efficiency of the overall system, but enable use of motor controllers with lower current ratings, which would be less costly to obtain.

The selection of a higher operating voltage had a major impact on the design and selection of several major vehicle components, including the main drive motor, motor controller, and battery subsystem. The operating voltage trade study, and its results on the design of the final drive system, are discussed in more detail in *Chapter 5, Motor and Motor Controller Development.*

Other major drive system design issues evaluated early in the HEPT project related to final selection of locations for the auxiliary power unit (APU), compressed natural gas (CNG) tanks, and batteries. Layouts developed with Kenworth during the previous feasibility study were refined to identify locations, attach points, and mounting hardware in greater detail.

Figure 8 shows the baseline APU and drive motor/controller configuration for the Kenworth truck that was initially used as a point of departure for the HEPT design effort. As indicated, the APU is located toward the front and bottom of the engine compartment, with the generator facing to the rear. The electric drive motor and transmission are located forward of the rear wheels, just above the axle line.

Batteries and battery racks are not shown on this illustration. Various alternatives were considered for accommodation of the more than one hundred batteries that would be required. One option considered was to elevate the APU within the forward engine compartment and use some of the space at the bottom of the engine compartment for battery storage. However, this option was later ruled out in favor of mounting the batteries in racks along the sides of the vehicle, which was determined to provide better weight distribution.

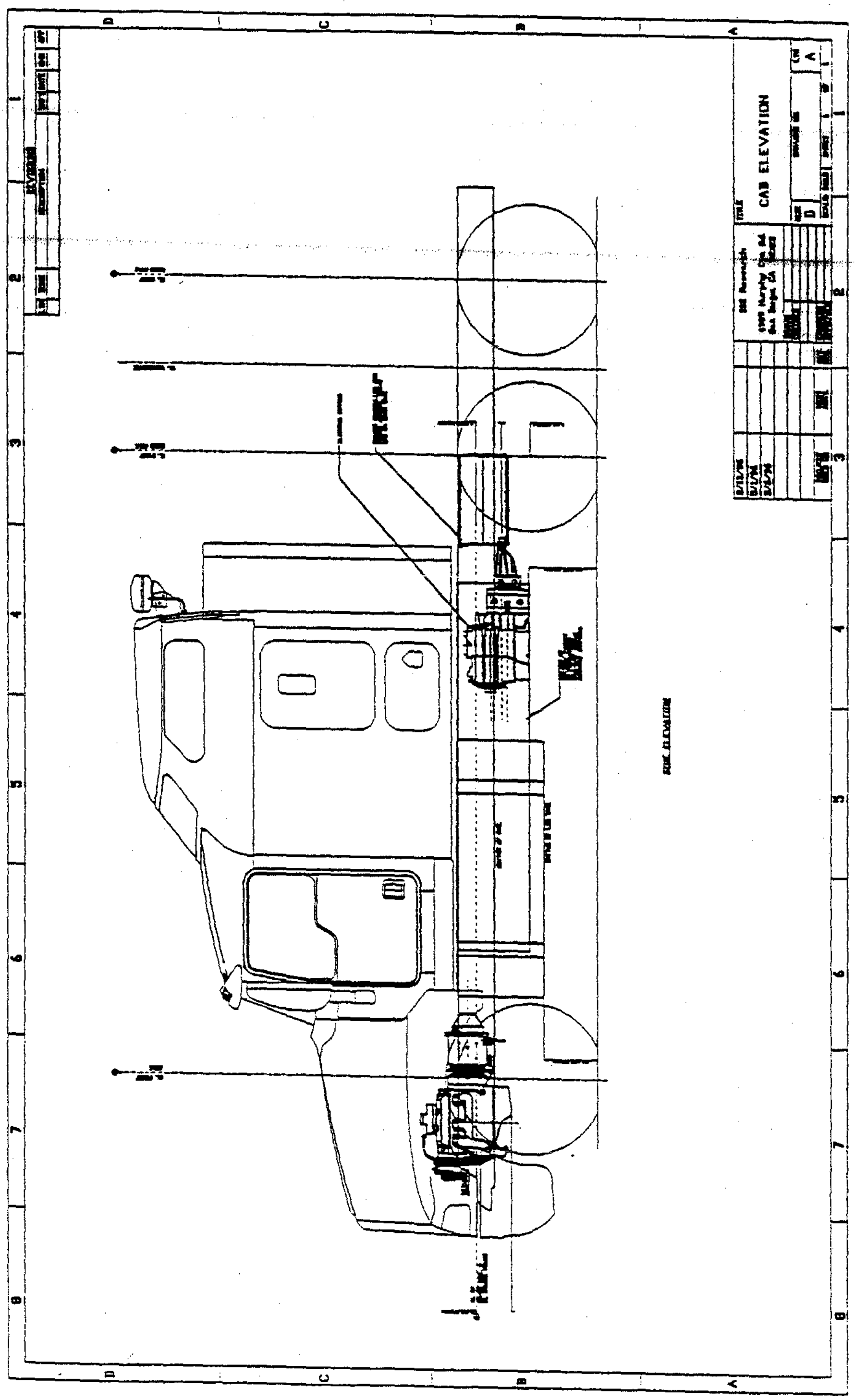


*Figure 8. Drive system layout used as point of departure for HEPT project.*

As the HEPT project proceeded, the drive system design evolved to accommodate the many changes in component selection and design that took place over the course of the program. Specific component changes that had a major impact on the overall drive system design included:

*Development of a new high power AC induction motor, based on the design of a motor recently developed by United Defense, LP (UDLP).* The UDLP-derived motor is substantially smaller and lighter than the motor concepts originally considered. It also has an integral planetary gear reduction system which, combined with the "wye-delta" motor switching system developed by ISER, eliminates the need for a transmission.

*Development of a modular motor control system, using 100 kW power modules manufactured by Siemens.* The modular design of this controller provided greater flexibility than the design of the larger, monolithic controllers initially envisioned. In addition, its total size is smaller and its weight is lower. Use of the Siemens modules, in combination with the UDLP-derived motor, enabled adoption of a 600 volt DC system.

*Increase in fuel storage capacity.* To maximize the range of the HEPT vehicles, a high capacity compressed natural gas (CNG) storage system was selected. In the Kenworth vehicle, this system consists of four cylindrical tanks, each one foot in diameter and seven feet in length. The fronts of the tanks, which were positioned underneath the cab, extend well into the engine compartment. This required elevating the APU to provide clearance for the tanks. In the Peterbilt truck, the tanks were located above the frame rails behind the cab.

*Development of a lightweight onboard battery charging system.* To take maximum advantage of a new, compact and lightweight battery charging system that became available during the HEPT project, ISER switched to an onboard battery charging system featuring sets of 5 kW charge modules, which are situated in the battery racks along with the batteries. This provides substantial operating benefits as compared with the original charging concept, which was based on use of a large offboard charging system. With the new onboard chargers, the vehicle can be "plugged in" to conventional power outlets with essentially no offboard charging infrastructure required.

These modifications, discussed more fully in later chapters of this report, resulted in an integrated drive system design substantially different from the original design. A computer-generated model of the final drive system layout for the Kenworth prototype is shown in Figure 9. As shown, the sleeper cab has been removed, since the vehicle will be used only for local driving cycles. Directly behind the driver compartment is a box containing the motor control system and main wiring junction for the vehicle. The main drive motor can be seen directly below the motor controller box. As compared with the original design, the motor was moved several feet forward, to reduce the angle at which the drive shaft intersects with the rear differential. This will reduce stress on the driveline and increase its operating life.

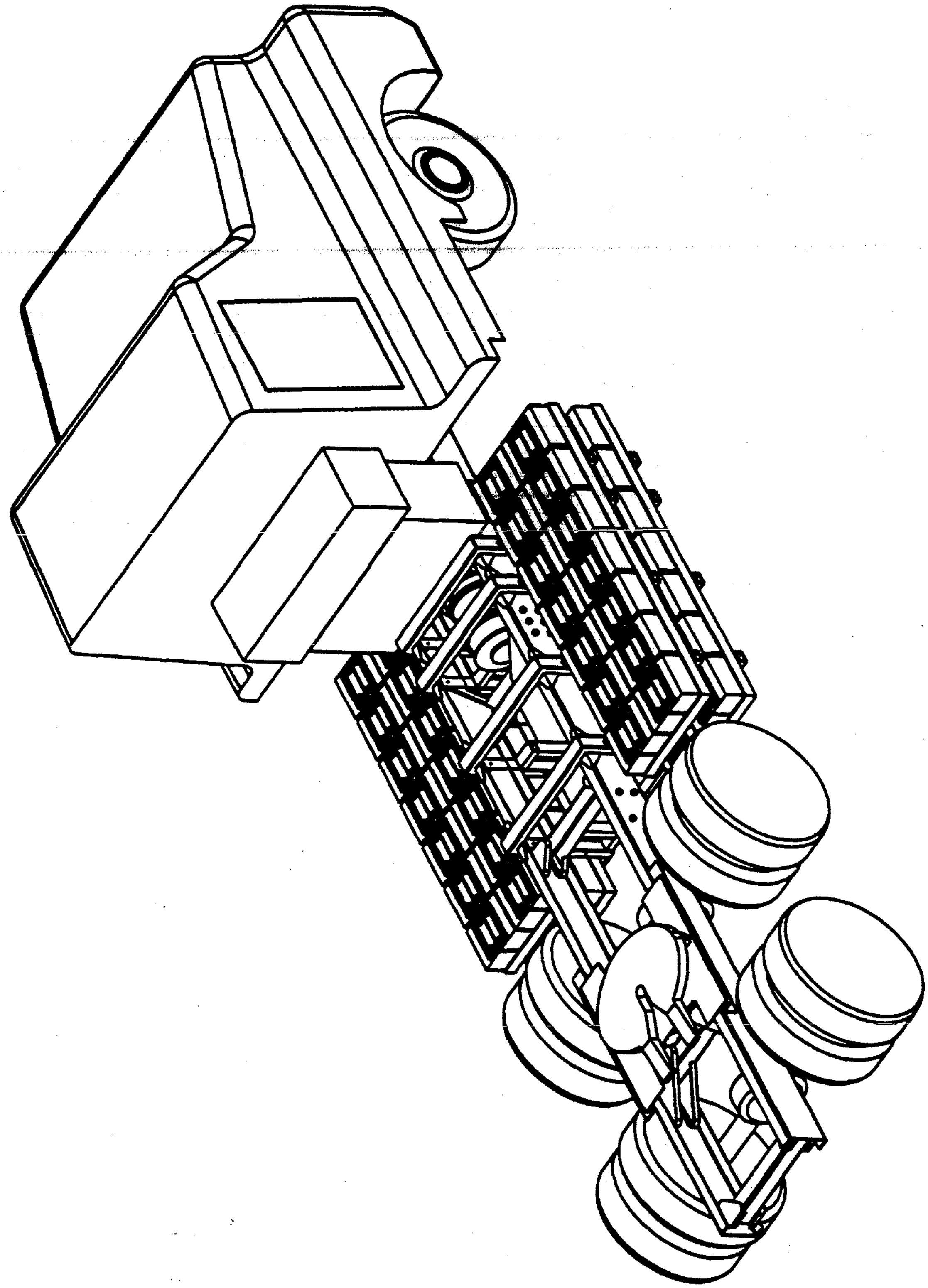

*Figure 9. Computer model of final HEPT drive system configuration.*

As clearly indicated in this figure, the batteries are arranged in four sets of 24, with two sets on each side of the vehicle's rail frames. This configuration is actually fairly close to the original design, except that the number of batteries was reduced from 112 to 96 to reduce operating voltage. While the generally higher operating voltage of 600 VDC was selected for this drive system, it turned out that 112 batteries, arranged in two packs of 56 12-volt batteries, would create peak voltage levels in excess of the capacity of the Siemens motor control module model used in this truck. The final battery subsystem design also accommodates the onboard charging modules, as discussed above.

The APU, not visible in this illustration, is located in the engine compartment about two feet higher than in the original design, with its orientation reversed so that the generator faces forward. This configuration was adopted to provide greater air flow around the generator, thereby improving its cooling.

Figure 10 is an artist's concept of an advanced hybrid-electric truck based on the ISER drive system. Several similarities to the current HEPT configuration are evident, such as the side-mounted battery racks and single electric drive motor. However, the advanced concept features a number of key differences, such as use of a small turbogenerator as the APU, smaller side-mounted liquefied natural gas (LNG) tanks in lieu of larger CNG tanks, and a more aerodynamic body shape. The HEPT project is the first step in a design evolution that can lead to such a future vehicle, which will maximize the benefits of hybrid-electric drive system technology.

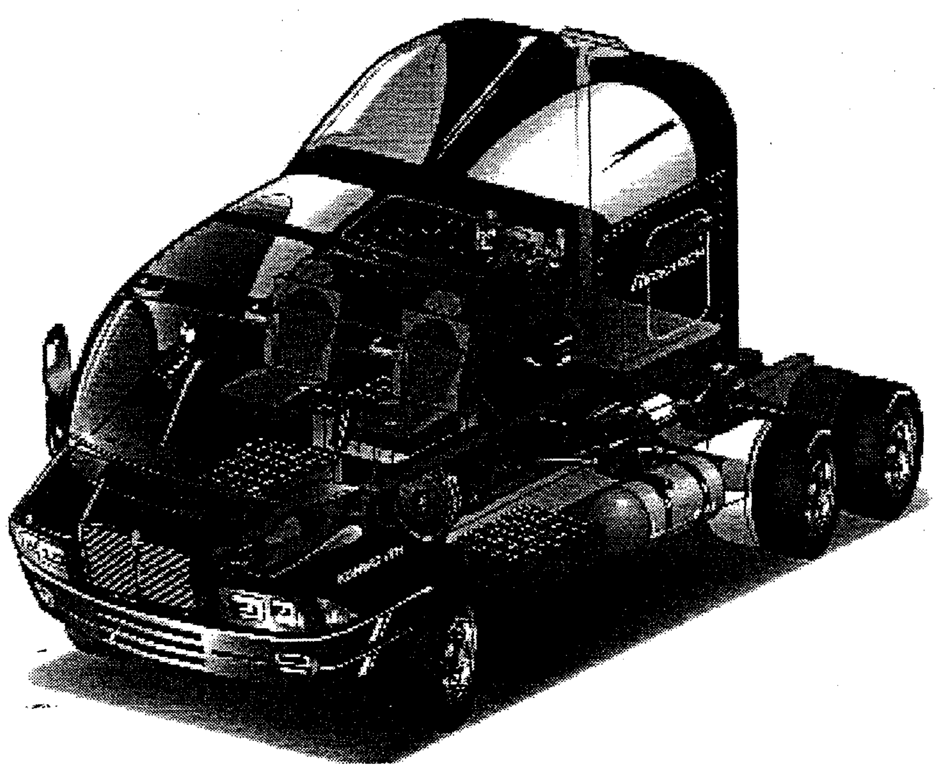

*Figure 10. ISER artist's concept of advanced hybrid-electric truck.*

# CHAPTER 3
# SYSTEM CONTROLLER DEVELOPMENT

## 3.1 Design Approach

The HEPT system controller is the subsystem responsible for: (1) regulating the flow of energy within the drive system, (2) advising the vehicle operator of vehicle operating conditions and the status of the various vehicle subsystems, and (3) facilitating general information transfer among dependent subsystems. From the start, ISER's system controller efforts were guided by three principal design goals, each oriented toward achieving a specific operating objective, as summarized in Table 2.

*Table 2. System controller design goals and operating objectives.*

| Design Goal | Operating Objective |
|---|---|
| 1. Optimize vehicle energy efficiency | Minimize fuel consumption and emissions |
| 2. Maximize autonomous operation | Simplify vehicle operation |
| 3. Maximize modularity and interchangeability of parts | Maximize growth potential |

Early in the HEPT project, working with the College of Engineering - Center for Environmental Research and Technology (CE-CERT) at UC Riverside, we developed a phased strategy for system controller development and then defined the key elements of the initial system controller to be installed into the Kenworth T-800 prototype. While the specific technologies and components selected for the HEPT system controller evolved considerably over the course of the HEPT project, it is interesting to note how similar the operation of the current (1999) HEPT system controller is to the original HEPT concept developed in 1996.

The initial ISER system controller concept was driven by a desire to achieve a level of capability surpassing that of other energy management systems. As reported in ISER's first HEPT quarterly progress report in January 1997, the "Block 1" system controller was planned to have a "load following" feature to reduce inefficiencies caused by repeated microcharging and overuse of the battery subsystem. Our plan was to accomplish this by monitoring the power output of the APU as well as the battery state of charge, and by adjusting APU output to compensate for small fluctuations in vehicle power requirements when determined that this is more efficient than using the batteries as a power leveler.

The ISER system controller was therefore envisioned as a means of extending battery life as well as improving immediate energy efficiency. These goals are not incompatible; in fact, by reducing unnecessary transfers of charge into and out of the battery pack, a controller with a load following feature will minimize the "in and out" inefficiencies associated with battery charge and discharge cycles. The load following feature remains a key element of the ISER system controller.

As indicated in the above table, the ISER system controller was intended to be modular and extendible. With development of new applications and technologies, this would enable the system controller and associated subassemblies to be upgraded with relative ease. The HEPT system controller has therefore been referred to as a "Block 1" controller, incorporating those technologies that could be developed within the scope of the HEPT project, but allowing for seamless upgrades to "Block 2" and subsequent versions over time. From the start, it was an ISER goal to standardize communications between modules so that advanced software algorithms, user interfaces, and unique hardware modules can be installed as needed.

About nine months into the HEPT project, we made the decision to adopt a distributed network technology for the HEPT system controller. To implement this plan, we selected LonWorks, an industrial interface network developed by Echelon, Inc. and Motorola. Prior to adoption of the LonWorks distributed network architecture, our design called for the auxiliary power unit (APU) controls, as well as the main drive controls, to be connected directly to a central computer. The LonWorks technology allows placement of inexpensive computers at the points of control. In this configuration, every major system in the vehicle has its own dedicated control computer, each connected to a central network.

In this architecture, each computer attached to a vehicle subsystem is referred to as a network "node," interconnected via the LonWorks network. By placing a small processor at each control point of the vehicle (e.g., batteries, APU, motor controller), and connecting the nodes with a shared set of wires, we substantially reduced vehicle wiring complexity. This reduced manufacturing time, vehicle weight, and maintenance requirements, while enhancing vehicle functionality.

This configuration is also projected to offer reliability and upgradability benefits. Control of critical vehicle functions is decentralized, so a failure in the central processor is unlikely to affect multiple subsystems. In fact, each module is designed to continue to function in a "safe" mode if separated from other processors for any reason. This network configuration also facilitates the upgrade and replacement of vehicle components with minimal impact to the overall control architecture. For example, upgrading to an improved technology APU (such as a gas turbine) or a higher density battery (such as nickel metal hydride) will be a change transparent to the central processor and the network as a whole, as long as the individual modules linked to each of the upgraded subsystems are replaced or reconfigured in accordance with established network standards. More generally, this will allow vehicle manufacturers and operators to seamlessly "mix and match" a wide variety of components with ISER's ThunderVolt™ powertrains. In addition, customers may eventually be able to inexpensively upgrade their vehicles "in the field;" for example, by downloading new software from our web page that can increase the fuel efficiency of his or her vehicle.

The LonWorks system also has advantages in that the node designs are transportable across different vehicle types. ISER's vehicles share common components, so a LonWorks node developed for the HEPT vehicles can be utilized on other types of vehicles with little or no modification. This was proven over the course of the HEPT project, as we utilized LonWorks nodes identical to the HEPT nodes in two other types of hybrid-electric vehicles, a hybrid tractor developed for the U.S. Air Force and a hybrid transit bus developed for the City of Los Angeles.

Finally, the LonWorks system can support fleet management functions such as Automatic Vehicle Locating (AVL), remote diagnostics and command, expert system maintenance, web-based vehicle monitoring, and other even more advanced functions. All of these capabilities are enabled by the open LonWorks system, and can be supported to varying degrees with off-the-shelf products that are currently available.

### 3.2 System Controller Elements

The basic elements of the ISER system controller remain similar to those envisioned at the start of the HEPT project in October 1996, although the functionality of some of the modules differs in important respects from initial concepts. At the start of the project, ten principal modules were envisioned as comprising the ISER "Block 1" system controller. These modules are described below, along with a discussion of how the design of each module evolved over the course of the contract.

• <u>Energy Management Module</u> — This module was visualized as the heart of the system. Its advanced algorithms would detect energy demand and maximize vehicle efficiency. During the first year of the project we selected the PC-510 single board computer based on the AMD 586 CPU and the OPTi82C465MVB chipset. This board, produced by Octagon Systems in Westminster, Colorado, provides Pentium level performance and low power draw in a very small form factor. However, as the complexity and capability level of other system controller modules was increased over the course of the contract, the need for a powerful central computer diminished. In fact, the central Energy Management Module as originally envisioned does not even exist in the first HEPT prototype, as it was determined unnecessary for basic vehicle operation. It has been replaced by a core set of software routines executing on the Cabin Display Node, which runs the controls and displays on the vehicle dashboard, and the APU Monitoring and Control Node, which determines when the APU should be run and regulates APU power output during its operation. The Energy Management Module will continue to exist only as a software component.

• Drive Motor Control Module — This module was envisioned as the interface with the system's inverter/motor controller that would provide power to the wheels. It would also take commands from the Energy Management Module to control regenerative braking. This device evolved into the ISER "Vehicle Dynamics Controller" (VDC), a custom microprocessor that converts signals from the accelerator and brake pedals into commands recognized by the ISER "ModuDrive" motor controller (see *Chapter 5, Motor and Motor Controller Development).* As the VDC evolved into an independently functioning, highly customized, and particularly vital component of the ISER hybrid-electric drive system, it is presently viewed more as a "stand-alone" component than as an element of the system controller. As this module matures it will retain access to LonWorks network data.

• APU Control Module — This module was intended to work hand-in-hand with the CNG engine to provide auxiliary power to the system while running the engine in the most fuel and emissions efficient manner possible. Over the course of the HEPT project, APU control turned out to be a much more complex undertaking than originally expected. Functions required of the APU controller include continuous real time monitoring of engine speed, temperature, and other operating conditions; ability to physically actuate the engine throttle and maintain engine operation within a desired speed and or generator power output range; ability to modify engine control in response to vehicle power requirements and battery bus voltage; and continuous transmittal of APU status information to the vehicle operator. We developed a new servo mechanism for control of the APU, identifying a more self-contained method for APU operation than the system originally provided by UC Riverside, and devoted substantial effort to researching and testing various means of handling the power surges anticipated during regenerative braking. The APU control configuration we ultimately selected actually consists of two separate network nodes: the APU Monitoring and Control Node, and an Engine Control Node that actuates the engine throttle on the basis of commands received from the APU Monitoring and Control node.

• User Interface Module — The HEPT was recognized to be a complex system with many interacting parts, and our plan was to employ techniques from the field of cognitive science to reduce apparent complexity and information overload. The User Interface Module was envisioned as the means of providing rapid access to the most critical driving information while still allowing service and management personnel access more obscure data. We evaluated different LCD displays and methods of interacting with the system controller, in efforts to help ensure that the system controller is easy to use and adds to the functionality of the vehicle. Each user interface window was described and inter-module communication specifications were solidified. To remain within project budget constraints, a simpler vehicle display was selected than originally envisioned — a four line, single color digital display rather than a large full color monitor. The latter remains a long term desire and will be incorporated into future versions. However, ISER did develop a custom printed circuit board to drive the existing monochrome display, which converts data from several vehicle subsystems into alphanumeric messages that are displayed in various display modes in real time. For example, the power output of the APU in kilowatts can is continuously displayed when this display mode is selected. These capabilities are all incorporated into the Cabin Display Node, which is described more fully in Section 3.5.

• Sensor and Control Network — It was recognized from the outset that to operate a truck as complex as the HEPT, a myriad of sensors and actuators would be required in many different vehicle locations. During the first quarter of the HEPT project we made the decision to select a bus I/O system, as opposed to having dedicated wiring to each sensor. Our initial intent was to use either an RS-485 or a more intelligent bus such as LonWorks or CAN. About nine months into the project we selected LonWorks. As discussed in Section 3.1, every major vehicle subsystem in this architecture has its own dedicated control computer, referred to as a network "node," interconnected via the LonWorks distributed network. To reduce development time and increase reliability, a custom printed circuit board containing common circuitry and power supplies was developed. It is currently being used as the base node for most of the vehicle's LonWorks modules. The "loop" configuration selected for networking the various vehicle modules with the central processor was envisioned as providing the fastest possible data rates, with sufficient redundancy to assure reliable vehicle operation.

• Energy Storage Module — This module concept was designed as the means of handling the intelligent charging and monitoring of batteries or other energy storage devices in the system. It was recognized from the outset that constant monitoring of the energy storage subsystem will increase cycle life and performance. As definition of the system controller architecture progressed, it became evident that the LonWorks "State of Charge" node responsible for this function would have two particularly important roles: monitoring battery state of charge and regulating recharging of the battery pack. About nine months into the HEPT project, ISER received funding under its Air Force tow tractor contract to develop an Advanced Continuous Equalization System (ACES), designed to monitor the state of charge and temperature of each battery individually, and to route energy during operation away from fully charged batteries and toward lesser charged batteries. The main computer for ACES is the "base" node developed for the HEPT project. The inclusion of LonWorks technology into the ACES system will facilitate the retrofit ACES into other vehicles.

• Braking Module — This was envisioned as a relatively simple module that would monitor the vehicle braking system. By working together with the Energy Management Module and the Drive Motor Control Module, we believed we could develop an efficient, multipurpose braking system combining standard and regenerative braking. Ultimately, the functions planned for this module were incorporated into the aforementioned Vehicle Dynamics Controller, whose design and functions are described in detail in Section 3.4.

• Steering Module — Also envisioned as a simple module, the Steering Module was seen as the device for monitoring the status of the electro-hydraulic power steering system. This module was envisioned to be a "place holder" for a more advanced steering system. Unlike software systems, LonWorks does not require the leaving of such "hooks and scars" for future technology. This module as such was thus deleted from our control architecture.

• Diagnostic and Performance Module — This module, by analyzing sensor data, was conceived as a means of monitoring system performance and alerting the vehicle operator to hazardous or inefficient situations. Its basic functions have been incorporated into the Cabin Display Node, which was installed into the first HEPT truck in late 1998. More advanced diagnostic capabilities will be provided by a separate hand-held device to be developed as part of ISER's product improvement effort in 1999-2000. In addition, the data logging function will be incorporated into a separate device. ISER currently uses a stand-alone laptop computer to gather and analyze onboard data.

• Auxiliary Systems Module — This module was seen as the control element responsible for managing other devices not handled by other modules, such as climate control, lighting, and other non-essential power accessories. Some of these functions have been incorporated into the Cabin Control Node. Others have been assigned to the vehicle's original wiring and controls.

As indicated in the preceding paragraphs, all of the functions assigned to the original ten system controller modules in late 1996 have been incorporated into one or more network nodes, or the general LonWorks architecture itself. During 1998, we built eight different network nodes, each using the same "common node" as its central building block, but incorporating auxiliary circuitry and embedded software tailored to its particular functions. Code was written in "Neuron C," a version of C used for the neuron processors utilized in the LonWorks™ system. During the HEPT project, prototypes of all eight nodes were developed, including software development. As indicated in Table 3, four of these nodes were integrated and demonstrated in the HEPT vehicles.

Those nodes not integrated into the HEPT vehicles provide functions that are not yet required, as in the case of the node that will monitor the as-yet-uncompleted ACES battery management system, or that are presently provided by other vehicle subsystems. As determined by future operational requirements, these additional nodes — and others not yet identified — will be incorporated into the network architecture.

*Table 3. Network nodes included in ISER system controller architecture.*

| **Network Node** | **Function** | **Status** |
|---|---|---|
| APU Monitoring and Control Node | Monitors and regulates APU | Installed into HEPT |
| Engine Throttle Control Node | Controls throttle which regulates engine speed | Installed into HEPT |
| Cabin Display Node | Regulates cabin controls and displays | Installed into HEPT |
| Cabin Control Node | Interfaces with Vehicle Dynamics Controller to regulate acceleration and braking | Installed into HEPT |
| Main Drive Node | Monitors status of main drive motor and motor controller | Prototype built |
| State of Charge Node | Monitors status of battery pack and charging operations | Prototype built |
| Battery Equalization System Node | Monitors status of ACES | Prototype built |
| Auxiliary Systems Node | Monitors status of power steering and braking systems | Prototype built |

As indicated earlier in this section, the Cabin Node currently functions as a "surrogate" Master Controller, in lieu of the more complex Pentium-based processor that was determined to be unnecessary for the first generation HEPT vehicles. This Master Controller, programmable in DOS, is complete and available for installation into future vehicles when required. Eventually, we intend to develop a second generation Master Controller, designed to use Microsoft Windows CE as its operating system.

## 3.3 APU Control Methodology

### *3.3.1 APU Role in Achieving Hybrid Operating Benefits*

Beyond assuring the basic functionality of the various vehicle subsystems, the most critical function of the system controller is energy management. A central hypothesis that the HEPT project has sought to validate is that series hybrid-electric systems can be more energy efficient, and produce fewer exhaust emissions, than conventional internal combustion engine (ICE) driven vehicles of equivalent size. According to this hypothesis, these benefits can be expected to be particularly significant for locally driven vehicles such as local delivery trucks and transit buses, which engage in frequent start-stop cycles that are inherently inefficient. ISER's 1995-96 hybrid truck feasibility study postulated that hybrid-electric drive systems could reduce fuel consumption in such vehicles by 50%, and emissions by as much as 95%.

The first step toward achieving these benefits, as postulated by prior ISER studies, is "downsizing" of the engine used in the hybrid drive system. A central thesis the HEPT project sought to demonstrate is that a relatively small engine, augmented by a battery pack, could supply sufficient power and torque to drive a Class 8 truck weighing as much as 80,000 lb. Prior to the HEPT project, this had never been attempted with a series hybrid system; the largest hybrid vehicles in development or trial operation were 40 foot transit buses weighing approximately 40,000 lb. and with much lower speed and power requirements than Class 8 trucks. A series of tests successfully concluded over the course of the HEPT project demonstrated the validity of the ISER approach.

These tests included static tests of the fully assembled Kenworth prototype vehicle in the fall of 1998, which demonstrated the ability of a new, state-of-the-art drive motor and motor controller to work together for the first time (*see Chapter 5, Motor and Motor Controller Development*). Subsequently, during the last several weeks of 1998, we performed a series of initial road trials and dynamometer testing which demonstrated that sufficient power could be generated, in aggregate, by a small engine, capable of producing about 100 horsepower (see *Chapter 4, APU Testing and Integration*), augmented by a pack of 100 lead-acid batteries. Closely monitored dynamometer tests clearly indicated that the batteries alone could supply peak power to the drive motor of more than 260 kilowatts (350 horsepower) — sufficient for most local Class 8 truck applications. Subsequent road testing, in which the APU was shown to generate an additional 60-80 kW of usable power, demonstrated an aggregate peak power availability of well over 400 horsepower, which covers virtually the entire range of local Class 8 truck applications — and most long haul truck applications as well. *Chapter 8, Operational Testing,* provides additional detail on these test results.

Beyond downsizing of the engine, a second important element of ISER's hybrid operating hypothesis was that a sophisticated system controller could manage the power output of the APU in a manner that further optimizes fuel consumption and/or exhaust emissions. Calculations made during ISER's 1995-96 feasibility study suggested that if the APU could be turned on and off at the right times during a vehicle driving cycle, emissions and fuel consumption could be reduced by up to an additional 30%, as compared with running the APU all the time. Based on these projections, a key starting objective of the ISER system controller development effort was to devise some means of turning the APU on and off automatically — a capability never before demonstrated in any hybrid-electric vehicle.

### *3.3.2 Hybrid APU Operating Scenarios*

As indicated at the start of this chapter, subsequent ISER analyses during the first few months of the HEPT project also identified the potential desirability of an APU "load following" feature that could reduce inefficiencies caused by repeated microcharging and overuse of the battery subsystem. Four distinct options for operation and control of the APU emerged by the time the HEPT vehicle took form. These modes, in ascending order of complexity, are:

- Constant APU Operation at Constant Power — The simplest but least efficient of the APU operating scenarios, this mode would run the APU at a constant power level all the time. The key disadvantage of this approach is that the APU would continue to operate, consume fuel, and generate emissions, even at times when the battery pack has a full charge or the vehicle is utilizing little or no power. This mode can also present overvoltage problems caused by the APU supplying excess power when not required, resulting in the need for costly and wasteful means of dissipating waste energy.

- Constant APU Operation at Variable Power — A more efficient APU operating scenario, this mode would run the APU all the time, at a constant speed, but allow the power output of the APU to fluctuate in reaction to varying vehicle power demands. This approach involves continuous fuel consumption and emissions generation, but fuel use and emissions are minimized when vehicle power requirements are low. The variable power mode helps avoid overvoltage problems caused by the APU supplying excess power when not required.

- Periodic APU Operation at Constant Power — The APU operating scenario envisioned prior to the HEPT project, this mode would run the APU at a constant power level whenever it is in operation, but turn the APU off periodically throughout the driving cycle. For this mode to work, the system controller would have to "know" when power from the APU is required, and would require the ability to automatically activate the APU at such times. It would then have to be able to deactivate the APU when not needed, such as when battery charge is full or when the vehicle is consuming very little power for extended periods.

• Periodic APU Operation at Variable Power — The most complex APU operating scenario, this mode would run the APU only when "needed," and would also involve a load-following feature that would tailor the power output of the APU, when in use, to immediate vehicle power requirements. The appeal of this approach is that it offers the potentially large benefits of turning off the APU completely when its power is not required, while also minimizing waste of energy if, during periods of APU operation, vehicle power requirements drop for brief intervals. In the ideal scenario, the system controller would keep the APU running at a reduced power level during brief drops in vehicle power consumption, but turn the APU off completely during longer low power intervals.

While the last of these operating modes was recognized early in the HEPT project as likely to be the most efficient operating mode, ISER's initial plan was to pursue the third option listed above: periodic operation at constant power. Operating the APU at a constant power level would be simpler than incorporating a load-following feature, which we initially planned to incorporate at a later time. However, regardless of which of the four operating modes we were able to employ, it was expected that substantial operating benefits would be demonstrated, based on the small size of the engine, its use of clean CNG fuel, and performance-related benefits of the high power AC drive motor (such as rapid acceleration and smooth ride).

*3.3.3 Limitations of Periodic Operation, Constant Power APU Operating Mode*
HEPT efforts toward the end of 1998 focused on fine tuning the APU Monitoring and Control Node to achieve the targeted operating mode, periodic operation at constant power. However, several unexpected problems were encountered in this pursuit.

The most severe and frustrating of these problems was creation of overvoltage problems if energy was created by regenerative braking during APU run times. With the high power capacity of the main drive motor and motor controller, very large energy spikes could be created by the regenerative braking feature built into the ISER system. If battery state of charge were low, the battery pack would absorb the excess energy. However, as the APU raised battery state of charge to higher levels, the battery pack would eventually become unable to absorb all of the regenerative braking energy. This would then cause auxiliary systems such as the power steering system to shut down, as their electric controllers were set to fault at high voltage levels to protect their circuits.

Numerous potential solutions to this problem were considered, but all had major shortcomings.

For example, we considered temporarily disabling the regenerative braking function, or limiting the percentage of braking achieved with "regen," when the overall bus voltage was at a high level. However, this option was ruled out because the braking "feel" would be much different during disabling of the regen, and for safety reasons we felt it essential that the brakes respond the same way at all times. Another potential solution to the overvoltage problem was to install a resistor bank to "bleed off" some of the excess energy during regen. Resistor banks capable of dissipating up to 30 kW were built and successfully demonstrated in other ISER vehicles. Unfortunately, the high power levels that could be generated by the Class 8 hybrid truck far exceeded the capacity of these banks, and installing resistors of sufficient capacity was determined to be prohibitively expensive, as well as adding excessive weight and complexity to the vehicle.

More advanced energy absorption devices, such as flywheels or ultracapacitors, were also considered as means of handling excess regen energy, but such devices are far too expensive for practical application to HEPT.

Another potential overvoltage solution was to keep battery state of charge very low, by turning the APU off before battery state of charge could reach an overvoltage level. However, this was not an optimal solution because, with the ability of the advanced motor and controller to generate high potential power surges, the APU would have to be turned off any time the battery charge level rose to much more than about 50%. This would result in a larger number of APU start-stop cycles, and limit our ability to make most effective use of the energy storage capacity of the batteries. More important, the perpetually low battery state of charge and resultant low bus voltage would limit vehicle performance.

The most practical solution to the overvoltage problem was determined to be configuring the Engine Throttle Control Node (see Section 3.2) to monitor and govern engine speed, and to maintain a constant engine speed somewhat lower than originally planned. With this methodology, when a sudden increase in bus voltage results in a sudden decrease in engine load, the controller immediately detects the tendency of the engine to speed up in response to the reduced load, lowers the throttle, reduces fuel flow, and keeps the engine RPM from rising. This in turn limits the output of the generator, both in terms of total power and voltage, preventing the APU from raising vehicle bus voltage and creating the overvoltage situation. This approach is similar to the engine control method used in aircraft engines, where it is essential to keep propellers rotating at a constant speed.

*3.3.4 Achievement of Periodic Operation, Variable Power Capability*

By governing engine speed and effectively limiting the output voltage of the APU generator, we were able to solve the perplexing overvoltage problem that had confronted us in our efforts to fix APU power output at a constant level. This approach has turned out to have additional benefits, resulting from the tendency of vehicle bus voltage to rise and fall in response to instantaneous vehicle power consumption. As addressed in greater detail *Chapter 8, Operational Testing,* vehicle bus voltage not only spikes suddenly during regenerative braking, but also drops by substantial amounts as power draw from the drive motor increases. Since governing engine speed was shown to have the effect of causing the power output of the APU to vary in inverse correlation to bus voltage, and bus voltage is inversely correlated with vehicle power use, APU power output in this control methodology becomes directly correlated with vehicle power use. In effect, controlling the APU in this manner represents the variable power "load-following" technique we had identified in 1996 as the ideal APU control technique.

Through experimentation, we determined that our system achieved a desirable load following pattern with the engine kept at a constant speed of approximately 1500 RPM. This is significantly slower than the 2400 to 2800 RPM range identified as optimal for emissions reduction during our 1995-96 hybrid truck feasibility study. However, in practical application the 1500 RPM speed has been shown to be much quieter, as well as resulting in a power output easier for the ISER hybrid-electric system to manage. There are also indications that the economic and environmental benefits of operating in the 1500 RPM range may be comparable to the benefits observed at higher speeds. 2400-2800 RPM was shown to be the optimal range for the GM V6 engine under constant engine power loads of 60 to 80 kW. However, as engine power load declines from 60 kW, optimal engine speed declines as well. In fact, running the engine at 1500 RPM under a 40-50 kW load is virtually as efficient and clean burning as running at 2400-2800 RPM in the previously targeted 65-75 kW range.

Therefore, by maintaining constant engine speed, and taking advantage of the vehicle bus voltage variability, we were able to not only solve the overvoltage problem, but also achieve a generally more advanced load following APU capability — the Periodic Operation, Variable Power ("POVP") APU control method.

One question raised by this control method, as compared with the constant power technique, is the long run impact of lowering the average APU power output. When the APU is running in the load following mode, its average power output is only about half of the 60-80 kW we have previously envisioned as the ideal APU power output. In our earlier studies we recognized that 60-80 kW was probably "overkill," as local heavy duty vehicles typically have average power requirements of only about 40 kW. Our rationale for initially selecting the higher APU power output was that it provided additional operating margin, and would allow the APU to be used less often than if the power output were lower. However, in practical application, the ability of the hybrid drive system to effectively utilize surplus APU power is limited by the bus voltage problem and the general limitations of the battery pack. In effect, we have learned from our operating prototype that we cannot efficiently "force feed" a higher APU power output into the system, at least not with current energy storage technologies.

In considering APU power requirements, it should also be noted that our hybrid vehicles, in preliminary road tests, have shown that they recapture between 20%

and 30% of the energy they use through regenerative braking. If this trend is indicative of future operational performance, the hybrid truck APU will need to produce an average of only about 30 kW over the course of a typical local driving cycle, especially if operated in a "charge depleting" mode with a daily energy contribution from the battery pack.

One other question raised by the "POVP" operating mode is whether up and down cycling of the APU power output is less efficient or clean burning than running the APU at a constant power level. It was our initial hypothesis was that stabilizing APU output would make the engine operate more efficiently. However, it is unclear whether this is more efficient than the POVP approach, where power output varies but engine speed kept constant. If the engine is less fuel efficient in the POVP mode, any resultant reduction in engine efficiency could be partially or completely offset by reducing the amount of energy running in and out of the batteries, as discussed below. Extensive road testing will be required to conclusively determine the fuel economy and emissions characteristics of the POVP load following technique.

*3.3.5 Summary of APU Control System Status*

The POVP control technique was first demonstrated in early 1999, and efforts to refine this control technology were ongoing as of the writing of this report. These efforts, along with extensive efforts to measure fuel economy and emissions during actual vehicle operation, will continue well into the year 2000. However, the APU control work ISER has accomplished during the HEPT project has clearly resulted in an advanced APU control system, based on the POVP operating principle, that has demonstrated several key operational benefits. These include:

- <u>Achievement of the basic capability to turn off the APU when it is not required</u> — The current ISER APU control system turns off the APU when the measured power output of the APU drops below a specified level for a specified time duration. Both the power level and the time interval are variables that can easily be modified with the control software. This means that if the vehicle is stationary or using low power for any length of time, the APU does not use any fuel or generate any emissions. The APU is commanded to turn back on automatically when the overall bus voltage drops below a given level for a specified time duration (see *Section 4.2, APU Control).* The consideration of a time duration variable prevents the APU from turning on if bus voltage is dropped momentarily, such as in response to rapid acceleration or climbing a steep but short hill.

- <u>Elimination of overvoltage events</u> — The APU control system has the ability to instantaneously drop the engine to an idle, and effectively eliminate output of power from the APU, when regenerative braking results in surges of energy into the system. This allows regenerative braking to be used consistently and maximizes the amount of regenerative braking energy that can be effectively utilized, as well as eliminating the problems experienced earlier in the program that were caused by overvoltage spikes.

• Minimization of unnecessary cycling of the battery pack — With the ISER load following technique, the system controller's first response to an increase in vehicle power requirements is to raise the power output level of the APU. This reduces the number of times energy is drawn from the battery pack, which will extend battery life. It is also more electrically efficient to transfer power directly from the APU to the motor, rather than to use the APU to recharge the batteries, and then draw the same power from the battery pack. By increasing the load on the APU without altering engine speed, and by limiting the peak power draw from the APU to between 50 and 80 kW, the power draw from the APU is accomplished efficiently and without a major increase in emissions.

• Maintenance of a high bus voltage level — The ISER APU control system keeps the overall bus voltage constant at a sufficiently high level to assure adequate vehicle power in all situations — approximately 620 VDC. In both road testing and dynamometer testing, the HEPT vehicles were shown to incur a major reduction in available power when bus voltage is allowed to drop. The problem becomes more acute as battery state of charge declines over the course of each driving cycle. Maintenance of high bus voltage in the POVP method overcomes a major drawback of constant APU power operating modes, which do nothing to compensate during periods of peak power usage. The ISER load following system, by automatically elevating APU power output in response to such power requirements, helps maintain the high bus voltage required for peak accelerating and hill climbing capabilities.

• Ability to tailor APU control to specific driving cycles — The high degree of programmability of the ISER APU control system enables the APU control technique to be customized to particular vehicle applications. In particular, operating flexibility is provided by the ability to vary the time intervals for activation/deactivation of the APU, the APU power output threshold at which the APU is deactivated, and the vehicle bus voltage at which the APU is reactivated. "Deep cycling" of batteries can be achieved by programming the APU controller to keep the APU inactive for longer intervals — such as by deactivating the APU more frequently and/or elevating the bus voltage at which the APU is reactivated. This may be desirable for congested urban driving cycles, where fuel economy is lowest, emissions are most critical, and high power APU-assisted performance is least vital. It might also be the preferred approach in areas with high fuel costs. Conversely, a reverse approach may be taken, with the APU relied upon more of the time, when average vehicle power requirements are comparatively high. In an extreme case, such as a large transit bus operating on a hot day with a continuously high air conditioning load, it could be most efficient to keep the APU running essentially all the time. To account for the variances in driving cycles, the overall APU power output range can be varied as well as the frequency of use.

Table 4 summarizes the features and benefits, and disadvantages of the POVP load following technique and the alternative APU control methods investigated by

ISER. As indicated, the selected POVP method is believed to offer the best combination of advantages, which we are verifying through continued operation of the HEPT vehicles and other hybrid vehicles we have built with this technology.

*Table 4. Summary of APU control methods.*

| **Technique/Features** | **Key Advantages** | **Key Disadvantages** |
|---|---|---|
| Constant Operation/ Constant Power - COCP (APU operated at all times at constant power output) | Maximum aggregate APU power output<br>Simplest control method | Overvoltage problem<br>No all-electric operation<br>Greatest wasted power |
| Constant Operation/ Variable Power - COVP (APU operated at all times, variable power output) | Enables load following<br>Solves overvoltage problem<br>Maintains constant bus voltage | No all-electric operation<br>Some wasted power (APU at least idles at all times) |
| Periodic Operation/ Constant Power - POCP (APU periodically shut off, power output constant when on) | Maximum all-electric operating time<br>High aggregate APU power output | Overvoltage problem<br>Maximizes battery cycling |
| Periodic Operation/ Variable Power - POVP (APU periodically shut off, variable power output) | Enables load following<br>Solves overvoltage problem<br>Maintains constant bus voltage<br>Some all-electric operation | Most complex control method |

In addition to continuing to characterize and refine the APU control system, future work will address advanced APU capabilities, identified at the start of the HEPT project and in previous studies, that turned out to be beyond the scope of the HEPT effort. For example, use of Global Positioning System (GPS) locator data and pre-programmed route maps to optimize future vehicle energy consumption will be examined and implemented, on a trial basis, when practical. As an example of a capability that would be enabled in this scenario, the APU might be turned on if the locator data indicated that the vehicle would have to climb a steep hill in the near future. As reliability of the APU control system on the basis of real time data is improved, advanced capabilities such as this can be pursued. ISER also intends to integrate turbogenerators and, ultimately, fuel cells, into its hybrid drive systems as such opportunities arise.

## 3.4 Acceleration and Braking Control

As indicated in Section 3.2, a second key function of the hybrid system controller is control of acceleration and braking functions. In the original HEPT system controller architecture, this function was assigned to the "Drive Motor Control Module," which evolved into a device ISER presently refers to as its "Vehicle Dynamics Controller" (VDC) and an associated LonWorks network node designed to interface with the VDC. The functions of acceleration and braking were considered to be sufficiently complex and important to justify development of a separate microprocessor, unconstrained by the common architecture of the LonWorks network nodes, to oversee these functions. In fulfilling this role, the VDC serves as the critical interface between the vehicle operator and the motor controller. ISER's two guiding principles in development of the VDC were to: (1) provide for safe and predictable acceleration and braking, and (2) simulate, as closely as possible, the "feel" of the accelerator and brake pedals on conventional ICE-driven vehicles. With respect to this latter point, it was our belief that acceptance of hybrid-electric vehicles in the commercial marketplace would be enhanced if the responses of the accelerator and brake pedals resembled those of traditional vehicles.

To augment the fine control provided by the VDC, we assigned to the LonWorks "Cabin Control Node" (CCN) the top-level control functions of forward-neutral-reverse and safety interlocks to prevent the vehicle from being driven with the parking brake activated or during recharging. The operator interface with the CCN is a push-button panel that allows the driver to select forward, neutral, or reverse simply by pressing a button.

The driver's foot pedals and the CCN both interface directly with the VDC, as illustrated in the basic block diagram of the ISER acceleration and braking control system (Figure 11). The VDC interfaces with a Motor Control Module (MCM) supplied by Siemens via analog input and output, utilizing numerous programmable parameters incorporated into the MCM control logic. The MCM in turn provides the control signals governing the Siemens 100 kW power modules used as the basis for the ISER motor control subsystem. The MCM was developed by Siemens expressly for precision industrial motor applications, so the controllability offered by the MCM parameters is more than adequate for the fine control required in vehicle applications.

The VDC, in essence, translates traditional foot pedal and gear shifter controls into the precision operating commands expected by a computer numerically controlled (CNC) type device such as the Siemens MCM. In the process, it simulates torque limitations, engine braking, hill holding, and creeping — capabilities all standard on modern motor vehicles.

The power modules are the high frequency inverters that control the main drive motor. Not shown in Figure 11 are the Synchronization Module and inductors that are also elements of the ISER motor control system. A description of these components, along with a more detailed discussion of the functionality of the MCM and power modules, is presented in *Chapter 5, Motor and Motor Controller Development.*

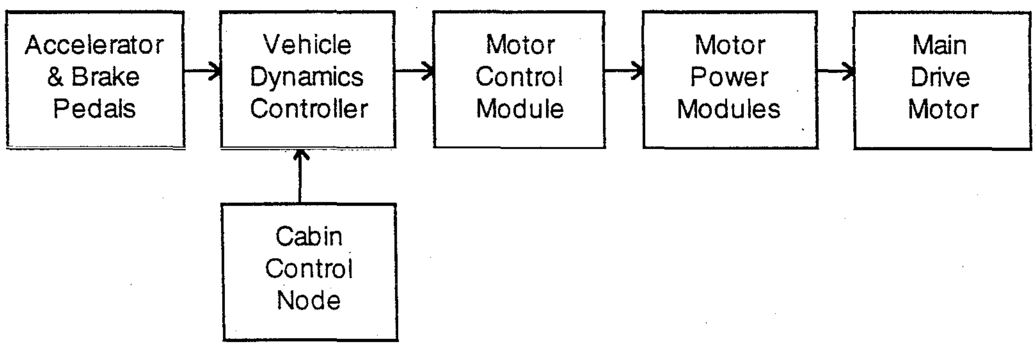


*Figure 11. Acceleration and braking control system.*

The VDC design is based on the Motorola 8051 processor, a proven device that offers the high degree of reliability required of this subsystem and which is readily available in the marketplace. ISER has written a set of proprietary VDC programs tailored to the acceleration and braking requirements of heavy duty vehicles. A set of "gear stages" is written into the program to provide the appropriate level of motor control, smoothness, and acceleration within specified motor speed ranges.

The VDC (Figure 12) also regulates the regenerative braking function. The percentage of braking energy supplied by "regen" is a programmable VDC variable that can range from zero (complete reliance on conventional brakes) to 100% (maximum regen). Regenerative braking energy is converted from AC to DC power by the Siemens power modules and routed to the DC bus, where as much energy as possible is returned to the battery pack. Any excess regen energy is dissipated using a resistor bank. ISER's Sparkletts electric truck, equipped with a similar system, was equipped with a dashboard dial that allow the driver to adjust the regen level in real time, even in the middle of braking.

Both the VDC and the MCM can be programmed with conventional laptop computers. This enables ISER engineers to modify acceleration and braking functions “on the fly.” The VDC has been adapted for use in ISER’s other electric and hybrid-electric vehicles, all of which employ the Siemens-based motor control products with which the VDC is programmed to interface. Through experience gained on the HEPT and several other vehicles since early 1998, the design of the VDC has progressed through several generations. Current versions of the VDC product, used in conjunction with the Siemens modules, offer a degree of controllability ISER believes is unsurpassed in any other heavy duty vehicles, ICE or electrically driven.

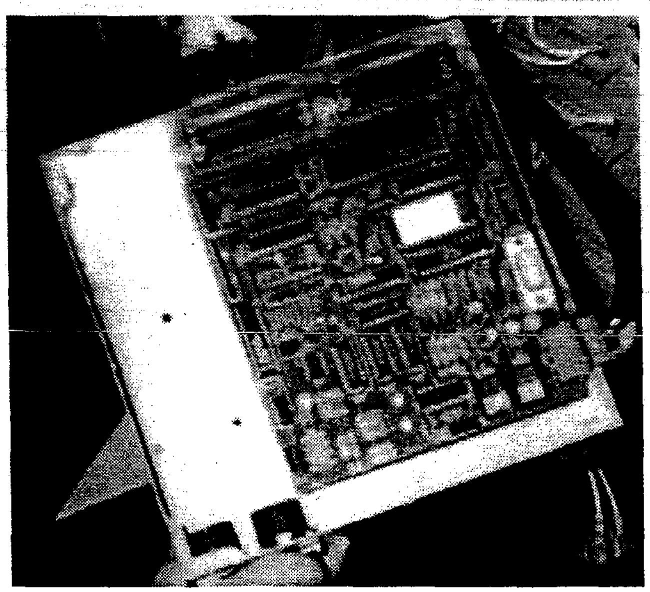

*Figure 12. Vehicle Dynamics Controller.*

### 3.5 Cabin Controls and Displays

The ISER “Cabin Display Node” (CDN), as discussed in Section 3.2, is the LonWorks node responsible for regulating the dashboard display that shows the status of the hybrid-electric drive system, and which enables the vehicle operator to control various vehicle functions. While the cabin display itself is relatively simple — a Noritake vacuum fluorescent 4 x 20 character monochrome display — the engineering effort during the HEPT project that went into making this display a functioning element of the ISER system controller network was substantial.

A large part of this ISER effort centered around development of a Display Interface Program, written in ANSI-C, which facilitates the design of pages that display network information. Such information can be shown either in the alphanumeric mode used in the current Noritake display or in other formats that may be enabled by more sophisticated displays, such as plots and icons. The availability of the in-house display program will make it easier to accommodate these types of future upgrades to the display system, as well as enabling rapid development of new pages for the existing display as additional network nodes are brought on line.

The current cabin display supplies the driver with essential information on the operation of the hybrid system, including:

- APU power output, in kW
- APU current output, in amperes
- Vehicle bus voltage level, in VDC
- Battery state of charge
- Fuel level

• Engine conditions, including coolant temperature and oil pressure

Currently, battery state of charge is approximated on the basis of measured bus voltage. In the absence of any commercially available devices for measuring battery state of charge, this was selected as an interim method, pending ISER development of more sophisticated state of charge measurement techniques. ISER plans to develop an improved battery state of charge measurement system as part of an advanced electric tractor program that was recently initiated.

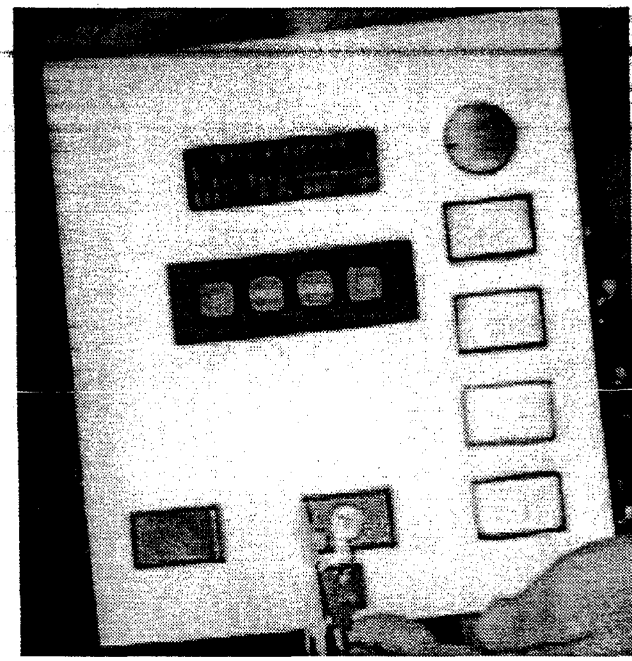
*Figure 13. Cabin display used in HEPT.*

A simple push-button interface on the cabin display panel (Figure 13) allows the driver to scroll among the various types of information available via the CDN. In addition, the driver can select between two basic vehicle operating modes: all-electric and hybrid-electric operation. As the names suggest, in the all-electric mode the APU is only turned on if manually activated by the driver. In the hybrid-electric mode, the APU follows the automated control methodology described in Section 3.3. The driver can also select a diagnostics mode, via which information can be accessed on the status of individual vehicle components. When necessary, driver access to the diagnostics mode can be limited through use of a separate hand-held device for accessing this information.

The CDN also constrains the sole electrical connection to the original vehicle wiring harness. Items such as back-up lights, brake lights, and accessory power are all integrated into one plug. The addition of two 12-volt power cables and a fuel sensor brings to three the total number of chassis electrical points. ISER believes the simplicity of this interface will facilitate introduction of new vehicle types. Even though the design of the CDN may change, the interface to the vehicle will remain the same.

The current HEPT cabin display is considered adequate for prototype demonstration vehicle purposes. More sophisticated displays, including large color monitors, have been evaluated and are compatible with the LonWorks network as future upgrade options. Such displays were ruled out for the HEPT project due to budgetary limitations, as their costs can run into the several thousands of dollars apiece when purchased individually.

# CHAPTER 4
# APU TESTING AND INTEGRATION

## 4.1 APU Design and Development

The engine selected for the first APU for the first HEPT prototype vehicle is a General Motors Vortec V6 engine converted to run on compressed natural gas (CNG) by Clean Air Partners, a San Diego company which supported the prior ISER hybrid truck feasibility study. Before the start of the HEPT project, ISER obtained one of these engines and, in collaboration with Clean Air Partners and CE-CERT, conducted a series of efficiency and emissions tests with the engine run at various power levels. Analyses of the data from the ISE Research-Clean Air Partners-CE-CERT test program indicated that this engine should meet or exceed the performance and emissions levels that were predicted analytically at the start of our 1995-96 feasibility study.

During the summer of 1996, the GM engine was delivered to the ISER assembly bay at the CALSTART facility in Burbank, where ISER initiated integration of the first HEPT vehicle. During the second quarter of the HEPT project, with the assistance of CE-CERT, we installed an actuator mechanism onto the GM engine. The accessory uses a servo motor to actuate a throttle, whose settings are calibrated to engine speeds up to 2,800 RPM and are correlated with discrete engine control commands from the system controller.

Also during the second quarter, we completed the design of the compressed natural gas (CNG) tank system to be used in conjunction with the HEPT APU. A set of four 1400-standard cubic feet (scf) CNG tanks was selected, each tank seven feet in length and one foot in diameter. The tanks, which collectively hold the energy equivalent of 44 gallons of diesel fuel, were installed in a cluster on the undercarriage of the vehicle between the frame rails, about midway between the front and rear axles. The tanks were obtained from NGV Systems, Inc., and installed into the vehicle in the CALSTART Burbank facility in April 1997.

During the third quarter we successfully installed the GM engine into the HEPT vehicle. An air intake system, exhaust system, and engine thermal management system were designed, fabricated, and installed. The entire engine installation fits neatly into the space under the stock vehicle hood previously occupied by the diesel engine and transmission. On 11 June 1997, the APU engine operation in the Kenworth test vehicle was successfully demonstrated in view of an audience consisting of representatives of the SCAQMD, ARB, and the San Diego Regional Technology Alliance. The engine was shown to start simultaneously without vibration, noise, or noxious exhaust emissions.

To accommodate integration of an electric generator with the GM engine, an alternator mounting and drive coupling system was designed around an industry standard SAE No. 3 flywheel housing, SAE 10" clutch flywheel, and a commercial Lovejoy Centaflex vibration isolation coupling. A design heritage for this mounting was established on the HEPT vehicle, enabling the mounting/coupling to be used on any reciprocating piston internal combustion engine power unit selected for subsequent applications.

Earlier in the project, following completion of the final HEPT bus voltage and current requirements trade study (discussed in *Chapter 5, Motor and Motor Controller Development),* we selected a generator concept proposed by the Fisher Electric Company in Florida. The generator was designed to produce a constant 75 kW at a nominal DC bus voltage of 672 VDC. This customized permanent magnet generator was ordered in early 1997 and arrived in Burbank in July of that year. Unfortunately, the generator was determined to have sustained damage during shipping from Fisher's plant in Florida. The fan cover was crushed and the unit had been shipped vertically, placing large axial loads on the bearings. After initial testing it was returned to Fisher for replacement of the cover and bearings. The repaired unit was subsequently returned to ISER and reinstalled into the vehicle in September 1997. Figure 14 shows the completed APU assembly, with the cylindrical shaped generator to the left of the engine.

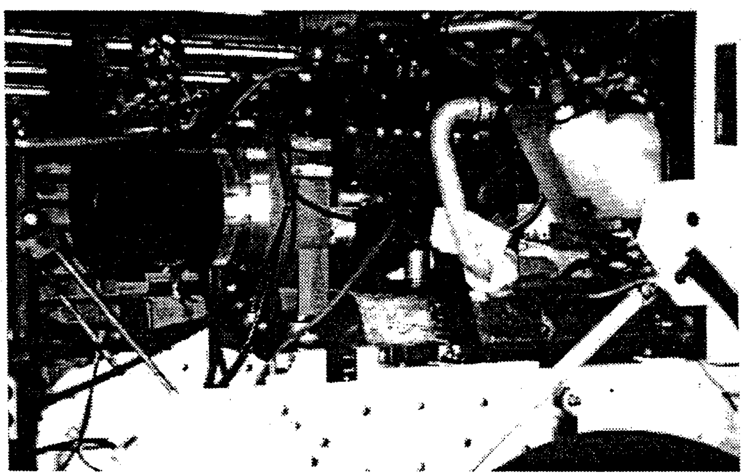

*Figure 14. HEPT auxiliary power unit.*

Following integration of the APU, we constructed a load bank to accommodate full power testing of the APU. The load bank was completed during the fifth quarter of the contract. Subsequent testing of the generator with the load bank validated the APU's ability to produce a constant 75 kW at a nominal DC bus voltage of 672 VDC. However, the GM V6 engine used as the power plant exhibited a tendency to overheat when run at the full 75 kW power level for extended periods. We concluded that the radiator that we had installed into the vehicle was unable cool the engine at high power levels while the vehicle is stationary due to insufficient air flow. While it is possible that the vehicle could have functioned with this radiator under a variety of conditions, we replaced the radiator with a larger capacity unit as an added precaution. Subsequent testing of the APU prior to vehicle operational testing indicated that the upgraded cooling system would be sufficient.

Since the initial HEPT application, we have adapted the basic HEPT APU design to several other hybrid-electric vehicles. 80 kW Fisher generators were integrated

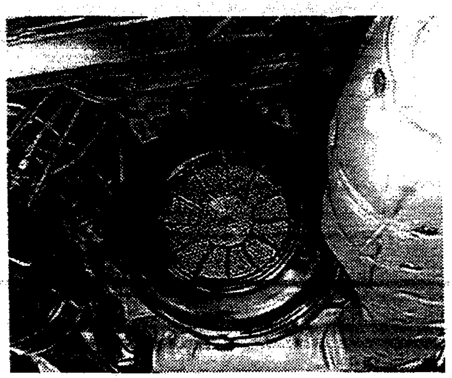

*Figure 15. Peterbilt APU.*

with Cummins 5.9 liter diesel engines in three hybrid tow tractors we built for the Air Force in 1998-99, and with GM 5.7 liter propane engines in four transit buses we built for the City of Los Angeles during the same time period. A further upgraded version of the HEPT generator, with a continuous power rating of 120 kW, was integrated into APUs in 1999 for the Peterbilt HEPT truck (Figure 15) and an International Class 8 hybrid-electric truck we built for UC Riverside.

## 4.2 APU Control

As discussed in *Chapter 3, System Controller Development,* a key objective of the HEPT project was to achieve a more sophisticated level of APU control than demonstrated in other hybrid-electric vehicles. In particular, the ability of the vehicle control system to automatically turn the APU on and off in response to vehicle power needs was a key driving requirement of the design of the APU control system. A second key design requirement was for the APU control system to be compatible with the ISER LonWorks-based system control architecture. A third design requirement was to establish a standard controller design that can be replicated on a commercial basis.

A substantial engineering effort was devoted to developing an APU control system capable of meeting these requirements. The electronic engine controller and the engine throttle control originally delivered with the GM engine were both highly customized units, the former developed by Clean Air Partners and the latter by CE-CERT. To assure compatibility with the ISER system controller and future producibility, it was determined that both of these systems would have to be replaced. The functions of the Clean Air Partners engine interface were eventually taken over by the ISER APU Monitoring and Control Node, and those of the CE-CERT throttle controller were assumed by the ISER Engine Throttle Control Node.

### *4.2.1 APU Monitoring and Control*

The APU Monitoring and Control Node is the microprocessor developed by ISER to regulate the following five functions:

- Engine start and shutdown
- Engine warm-up and cool-down
- Engine speed control
- APU output
- Manual APU testing

Engine start, as discussed in *Section 3.3.5 Summary of APU Control System Status,* is triggered by a sustained drop in vehicle bus voltage. While the APU Monitoring and Control Node continuously measures bus voltage, it is the job of the central computer within ISER's system controller, presently located within the Cabin Display Node, to run the time-based bus voltage algorithms used to, in effect, calculate battery state of charge. In other words, when the Display Node sees that bus voltage has been depressed for a certain period of time, it rules out the possibility that bus voltage has been momentarily reduced by a vehicle power surge, and instead reaches the conclusion that the battery charge level has been diminished. At this point the Display Node sends a command to the APU Monitoring and Control Node (MCN) to begin the engine start sequence. The MCN responds by activating the starter motor and engine coolant pump, and enabling operation of the engine's fans. The MCN validates engine "turnover" and adequate oil pressure.

The MCN then initiates an engine warm-up sequence. This involves running the engine at a low idle for three minutes. The warm-up sequence is designed to lubricate the engine before running it at high speed and to heat the catalytic converter before burning large quantities of fuel. These steps should extend engine operating life and reduce vehicle emissions.

Once the warm-up period is ended, the MCN raises the engine to its normal operating speed. As discussed in *Chapter 3, System Controller Development,* the power output of the APU is regulated in a modified "load following" manner by regulating engine speed. In the HEPT application, engine speed is currently held constant by the MCN at 1500 RPM. A tachometer sensor supplies the MCN with continuous engine speed readings, enabling the MCN to rapidly adjust to changes in engine speed caused by variations in the vehicle bus voltage and the resultant effects on APU and engine load.

The tachometer sensor is one of several sensors utilized by ISER in a standardized set of APU sensors used in all of our hybrid-electric vehicles. Other sensors included in this suite monitor engine oil pressure, coolant temperature, and fuel level. Standardizing the sensor suite provides a common system for interfacing with the wide variety of engines used in ISER's APUs. During the HEPT project this was determined to be a more commercially viable approach than relying on the factory-installed sensors provided with each engine. Had we adopted the latter approach, a different engine control interface would be required with each different type of engine. Standardizing the controller and sensor interface makes it less expensive for us to integrate our own set of sensors into the engine, even if they merely duplicate sensors already provided by the engine manufacturer.

The MCN sensor suite also includes two generator temperature sensors, a voltage sensor, and a generator current sensor, which are utilized in support of the MCN's fourth main function, regulation of generator output. Voltage and current readings are used to continuously calculate generator power output. A sustained drop in

APU current and power output, indicative of an elevation in vehicle bus voltage, will result in the MCN commanding the engine and APU to be turned off. A sudden spike in bus voltage, interpreted as an indication of regenerative braking, results in the MCN commanding the engine to temporarily slow down to an idle. Hence overvoltage situations are avoided and the APU is turned off when it is not needed. When the central computer determines that a sustained drop in vehicle bus voltage is indicative of a low battery state of charge, the MCN is instructed to begin the engine start sequence and the cycle is repeated.

*4.2.2 Engine Throttle Control*

The MCN regulates engine speed by sending throttle position commands to the Engine Throttle Control Node (ETCN). The desired throttle position is characterized as a "desired" percent throttle value and updated by the MCN at approximately 1.5 second intervals. This time interval, while fairly long by computer standards, was found to correct engine speed and APU output with sufficient speed, while avoiding ETCN overcompensation in response to MCN throttle commands. The ETCN uses a Hewlett Packard optical encoder to provide information on the mechanical position of the engine throttle, which is translated by the ETCN into an "actual" percent throttle value. The actual throttle value is continuously compared with the desired throttle position values received from the MCN. The ETCN corrects for throttle position by actuating the engine throttle with a 24 volt DC Pittman servo motor. An off-the-shelf Microchip chipset is used to "servo" the motor using pulse width modulation feedback control.

*4.2.3 APU Control Interaction*

A simplified schematic of the interaction of the APU control components is illustrated in Figure 16. The dashed line linking the Dashboard Display Node and the Engine Throttle Control node indicates that engine throttle control is regulated from the dashboard computer only when the APU is under manual control — an override diagnostic and maintenance function designed into the system.

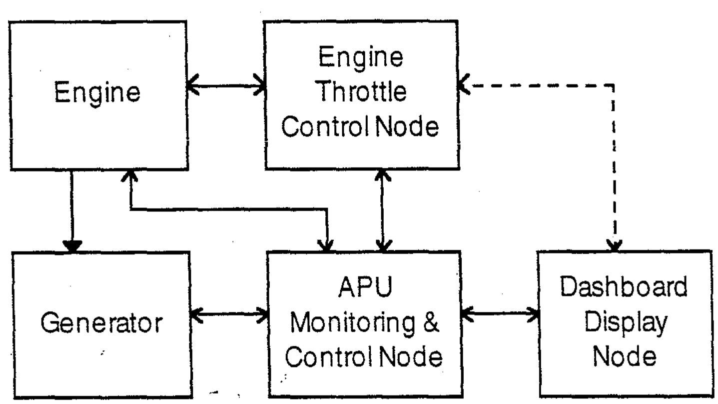


*Figure 16. Interaction of APU control components.*

At all other times, with the APU under automated control, the dashboard computer interacts only with the MCN, which forwards commands to the ETCN reflecting the state of charge information received from the display node. The MCN also interacts directly with the engine, receiving and processing information on engine speed, oil pressure, and coolant temperature.

Future versions of the ISER APU control system will rely on a more sophisticated State of Charge node to calculate battery state of charge. As mentioned earlier in this report, R&D aimed at developing improved SOC calculation methods is being performed by ISER as part of an advanced electric tractor program that was recently initiated. As discussed in *Chapter 3, System Controller Development,* future versions of the ISER vehicle control system may also incorporate predictive algorithms to estimate future energy consumption. The devices and software used to make these calculations, such as GPS receivers and stored maps of vehicle driving routes, will be incorporated into the APU control architecture as appropriate.

## 4.3 APU Evaluation

As discussed in *Chapter 3, System Controller Development,* the APU control system used in the HEPT vehicle employs a load-following technique that varies APU power output in accordance with vehicle bus voltage and, hence, vehicle power utilization. Fuel efficiency and emissions produced while operating the APU in this manner have not yet been measured, but since the engine is still operated at a constant speed, we do not expect fuel efficiency or emissions levels to depart radically from the levels measured during static testing of the GM V6 engine in 1996. Figure 17 summarizes the results of these 1996 tests.

As indicated in the top plot in Figure 17, optimal fuel efficiency is achieved while running the engine at the low end of the speed range tested (2,000 RPM), and at a power output of 60-65 kW. Efficiency is slightly degraded as power levels decline from 60 kW, but the engine continues to operate as efficiently as it would at higher speeds and power levels. Extrapolating from these results, we would expect that in the HEPT application, with the engine run at 1,500 RPM, efficiency would be along a curve 10% or so more efficient than at the 2,000 RPM level shown. This would seem to indicate we can expect efficiency in the 8,000 Btu/Hp-hr range or lower, which is clearly at the most efficient operating range for this engine.

As indicated in the lower plot of Figure 17, NOx emissions are lowest at the 2,000 RPM level if power output is constrained to 50 kW. The general trend of this curve seems to indicate that emissions will continue to decline at power levels below 50 kW before leveling off. This also bodes well for the HEPT application of this engine, as average power levels under the load-following regime are projected to be 50 kW or slightly lower.

One question yet to be resolved is whether the V6 engine is appropriately sized for the Class 8 truck application. One issue that needs to be addressed is overheating. During full operational testing of the HEPT vehicle, excessive venting of steam from the engine radiator was exhibited. The immediate cause of this problem was a loose-fitting radiator cap. In addition to venting steam, the poor fit of the radiator cap made it impossible for the cooling system to achieve full pressurization, thereby causing the engine to run at above-normal temperatures.

This problem was exacerbated by a failure of one of the engine fans to turn on. Once these relatively minor problems were solved, the APU functioned sufficiently for the truck to be operated for brief intervals. However, if the APU is run constantly at full power (75 kW) for extended periods, we suspect that the V6 engine might be taxed beyond its comfortable limits. At minimum, the longevity of the engine may be degraded. Extensive operational testing of the vehicle will be required to determine conclusively whether an engine this size provides an effective long term solution to accommodating the APU power requirements of a locally driven 55,000 lb. Class 8 truck. Therefore, for Class 8 applications we intend to utilize larger engines, at least until more definitive data are available on engine performance in this type of operating environment. This is one reason why a much larger John Deere 6.8 liter CNG engine was installed into the second HEPT vehicle.

The above concerns notwithstanding, we believe the V6 engine was an appropriate selection for the first HEPT vehicle is warranted because a goal of this project was to "push the limits" of APU down-sizing to see how small an engine can be used in this type of drive system. By comparing the performance of this engine with that of the larger Deere engine in the Peterbilt truck, we will eventually acquire sufficient data to help us optimize engine size for these types of applications.

A second, related issue raised by HEPT test results is whether the 75 kW output of the HEPT APU is sufficient for Class 8 truck applications. The calculations used to size the HEPT APU at 75 kW simply added the peak power output of the APU to the peak power computed to be available from the battery pack. However, as discussed in *Chapter 6, Battery Subsystem Development,* the peak power output of the battery pack declines significantly as battery state of charge is reduced. To allow sufficient discharging of the battery pack to achieve maximum hybrid-electric operating benefits, it may turn out that a more powerful APU is required to sustain a higher bus voltage. To validate this hypothesis, we utilized the larger 120 kW APU in the second HEPT Class 8 vehicle, which will enable a long term comparison of APU power output to be made.

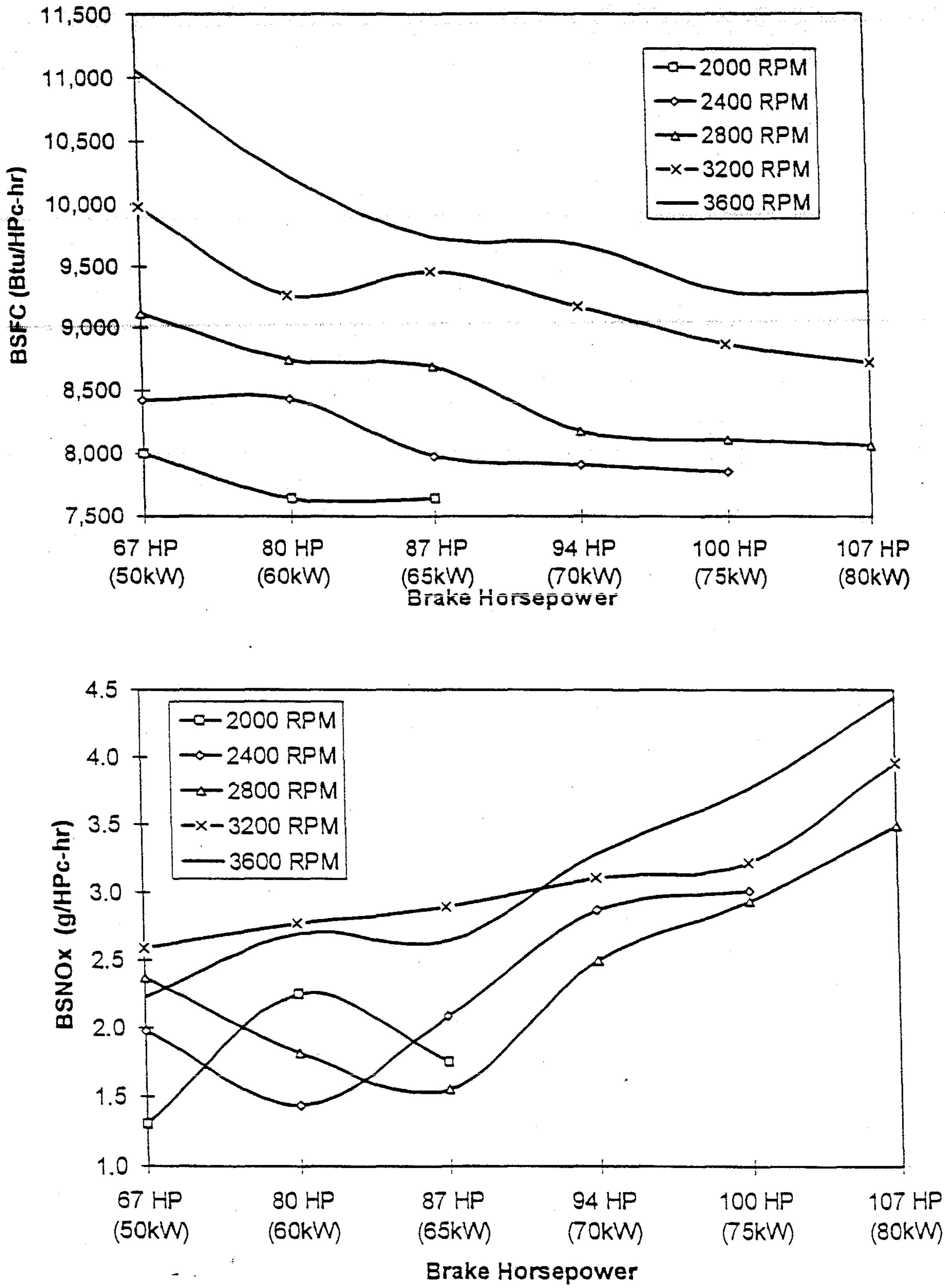


*Figure 17. Measured fuel efficiency (top graph) and NOx emissions (lower gra[illegible] with GM V6 engine.*

# CHAPTER 5
# MOTOR AND MOTOR CONTROLLER DEVELOPMENT

## 5.1 Motor-Controller Strategy and Trade Studies

During the hybrid truck feasibility study that preceded the HEPT project, ISE Research had concluded that the HEPT should use a commercially available AC induction motor, most of which were designed to operate at nominal bus voltages in the range of 300 to 360 VDC. However, company-funded analyses conducted between the feasibility study and the HEPT project in mid-1996 resulted in two major conclusions: (1) that the high power levels associated with heavy duty vehicles provide a strong case for adopting higher voltage systems than initially planned; and (2) that existing AC motors are inadequate for Class 8 truck applications, or at best, very expensive alternatives.

These conclusions were driven by concerns regarding achievement of the high start-up torque required by fully loaded trucks. Figure 18 shows power and torque requirements for a heavy duty truck as a function of vehicle weight and operating speed. The middle curves, corresponding to the 54,000 lb. GVW vehicle baselined for the HEPT local trash-hauling application, indicate a peak power requirement of about 250 kW and a maximum torque at start-up of just under 1,500 Nm. These data help illustrate why existing motors — generally in the 60-180 kW class — were determined to be undersized for the HEPT application. While a few motors at the larger end of this range, such as the 172 kW (peak) Northrop-Grumman WPT-230, could potentially have been combined to meet desired performance, such a dual motor configuration would have been prohibitively expensive and inefficient. To meet the power requirement for the 54,000 lb. vehicle with a single motor, a peak power rating of at least 250 kW was required, and the 80,000 lb. vehicle application would require at least 300 kW peak.

In addition to indicating serious power shortcomings in existing motors, our analyses also indicated that the 300-360 VDC bus voltage would present motor controller difficulties. At the low motor speed and voltage conditions at start-up, it was determined that the current required to drive the traction motor in a 300-360 VDC system would be over 1,000 amperes. Handling this current load would reduce system efficiency (due to $I^2R$ losses) and require a prohibitively expensive motor controller.

When the HEPT project started in October 1996, the initial focus of the Motor and Motor Controller Development task was to address these issues in a broad reconsideration of our design strategy with respect to the motor, motor controller, and vehicle operating voltage. By the second quarter of the project, we had developed two unique approaches to resolving these issues.

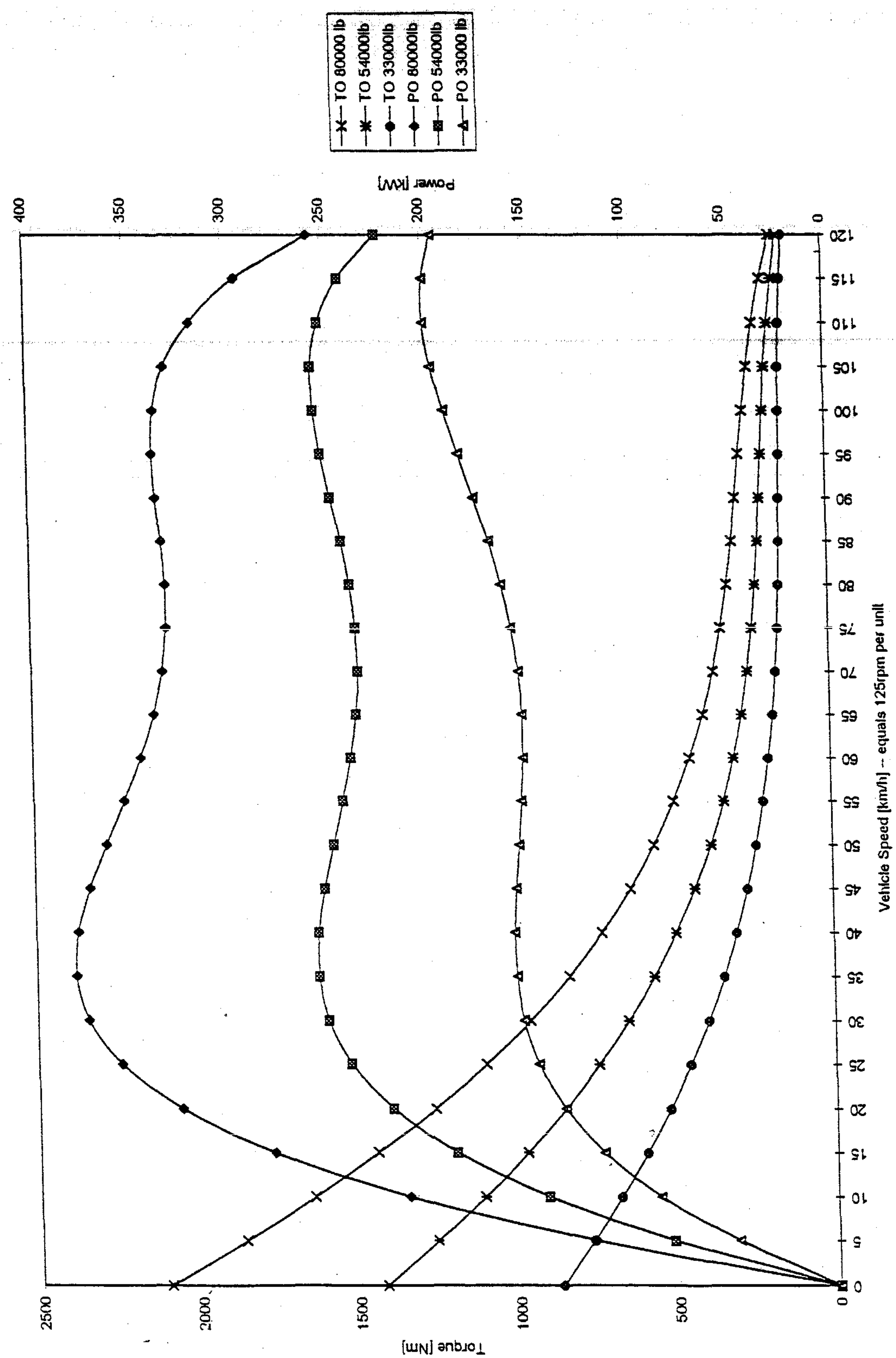


*Figure 18. Torque and power requirements as functions of vehicle weight and speed.*

The first component of this approach was to utilize of a unique motor winding and switching method, for which ISER has applied for a patent. In this "wye-delta" switching approach, current can be routed through the motor windings two different ways — one way providing maximum motor efficiency during nominal operations, but in the second way enabling higher torque to be achieved during start-up conditions with about 30% less current than would be required in the other winding configuration.

The second element of our strategy was to adopt a motor developed by United Defense, LP (UDLP) as the base motor for the hybrid application. During our motor assessment, CALSTART had provided ISER with an introduction to UDLP, which had developed a technologically advanced, high power induction motor for hybrid variants of tracked military vehicles. This motor was determined to offer the high power and current-carrying capability required for the HEPT application, while utilizing innovative winding, cooling, and other techniques to minimize size and weight. By the end of the first quarter of the HEPT project in late 1996, it had become evident to our team that such a motor could offer substantial advantages over commercially available motors. By combining ISER's "wye-delta" winding method with UDLP's innovative motor design, we felt we could produce a high performance custom drive motor that not only meets the near term requirements of the HEPT project, but which also has excellent commercial applications potential.

## 5.2 Advanced Motor Development

*5.2.1 Motor Design and Development*

During the second quarter of the HEPT project in early 1997, we worked with UDLP to develop a preliminary motor design, based on the UDLP motor, with a projected torque capability 10% greater than the 2,100 Nm ISER design requirement, and capable of generating 388 kW (520 horsepower) at speeds between 1,650 and 10,000 RPM. With these performance characteristics, the UDLP-ISER motor would meet HEPT requirements, and might also be highly sought-after for other heavy duty electric and hybrid-electric vehicle applications. Based on these conclusions, we developed a new motor-controller concept designed to use a modified version of the UDLP motor with an electronic controller sized to provide 220-300 kW and operating at about 540 VAC.

The main obstacle to implementation of this plan was the added investment required for this improvement — at least $200,000 each for the motor and the motor controller — which was well beyond the scope of the HEPT project at that time. To allow time to seek these additional funds, we adopted a dual-track strategy that enabled us to defer final selection of the HEPT vehicle motor and controller until the second quarter of 1997, by which time we felt we would know whether funding for a custom motor-controller system could be obtained.

In June of 1997, ISER was awarded a $200,000 R&D contract by the South Coast Air Quality Management District (SCAQMD) to enable development of the new HEPT motor, based on the UDLP design. Combined with the HEPT funds previously allocated for motor acquisition (approximately $50,000), we determined that this sum would be sufficient to cover most of the costs of a production article of this motor for the Kenworth T-800 vehicle; any shortfall we would make up. Also in June of 1997, ISER was awarded a $350,000 contract from the California Air Resources Board, the primary purpose of which would be to build a second prototype hybrid truck. There would therefore be a requirement for two motor-controller sets.

Following award of the advanced motor funding from the SCAQMD, ISER negotiated three separate agreements with UDLP. The first agreement was a contract employing UDLP to redesign their motor for compatibility with our wye-delta winding method. This effort was initiated in July 1997 and completed by the end of the summer. The second UDLP agreement was a contract enlisting UDLP support in production of the prototype motor units to be installed into the HEPT vehicles. This activity was formally initiated in August 1997, and began with UDLP delivery to ISER of a complete set of motor drawings and a list of vendors employed by UDLP to fabricate motor components. The third agreement was a long term licensing agreement granting ISER exclusive rights to market the UDLP motor and its derivatives for vehicle applications; this agreement was signed in October 1997.

One of the project compromises that had to be made to accommodate incorporation of a high technology, UDLP-derived engine into the HEPT design was a stretch-out of the project schedule. Had we followed our initial plan and purchased an existing, commercially available motor for this application, the motor could have been procured during the spring or summer of 1997. This would have allowed the Kenworth truck to be completed on or close to its original completion schedule of late 1997. However, inclusion of major motor redesign and production efforts as new HEPT tasks was recognized from the start as an activity that would delay completion of the first HEPT vehicle until 1998. Initially, 31 March 1998 was established as the revised completion date for the first HEPT vehicle. Delays in the advanced motor development, production, and integration process later resulted in further delay of vehicle completion to late 1998.

The first of these delays was a delay in receipt of funding for the motor redesign and production effort. The nonrecurring engineering effort to redesign the UDLP motor for the HEPT application was originally scheduled to be completed by the end of May 1997. However, this effort was delayed by three months because the funding to pay for this activity — the $200,000 R&D contract from the South Coast Air Quality Management District (SCAQMD) — was not made available until the end of June 1997, even though the contract had been awarded to ISER in March.

Following final signing of the SCAQMD contract, the nonrecurring effort went rapidly, as did procurement of parts for three motors (two for the HEPT vehicles and one for an electric Sparkletts delivery truck that we had determined could also use this motor). With UDLP support under the prototype motor production agreement, ISER placed orders with vendors for all major motor components during the summer and early fall of 1997. Deliveries of motor parts to ISER were carefully inspected and generally determined to be of high quality. For example, the rotor bars were measured to be within 1/1000th of an inch of their specified thickness, versus a design tolerance of 15/1000ths. This is especially noteworthy because the production process was changed from machining to extrusion. This will result in long term cost reductions. Other key components, which were delivered to ISER and UDLP in the fall of 1997, included bearings, rotor and stator laminations, and rotor end plates. Estimates submitted by vendors for production of motor components in large quantities provided increased confidence that we would be able to substantially reduce overall motor production costs following completion of the prototype phase.

Some delays were encountered in the process of fabricating motor components. The motor shell casing was one key part delivered late by its vendor, Reuland Electric. This resulted in a delay in final machining of the casing, which had to be delayed until early 1998. The most critical delays were experienced in build-up and qualification of the rotor subassemblies. The rotors were assembled in December 1997, but attempts by UDLP to seal the rotor stacks sufficiently to prevent leakage of oil coolant carried well into 1998. This problem came as a surprise, because we were led to believe by UDLP that the processes for motor construction had been perfected prior to initiation of the HEPT motor production effort.

By February 1998, the rotor sealing problem was solved, with maximum leak rates of 1/2 ml per minute at over 1,000 psi, using alcohol as a test fluid. In the actual application, the fluid to be used in the rotor is lubricating oil, which leaks at rates equal to or less than the rates experienced with the alcohol. The leak rates exhibited with alcohol therefore provided confidence that the rotors were sufficiently sealed and ready to for shaft "splining," the last major step prior to integration of the rotors into the motors. The rotors were shipped to a machinist in Miami to spline the rotor shafts, after which the "splined" rotor assemblies were returned to UDLP in San Jose for spin balancing and integration with the stator assemblies.

Following leak-proofing of the first stator, this process was completed for the first motor in mid-March, with the motor completely assembled and delivered to San Diego at the end of March. The process was subsequently repeated for the second motor. The delays in leak-proofing of the rotor and stator prevented ISER from receiving its first working UDLP-derived motor until April 1998. It was decided to install and test this first motor in the electric Sparkletts truck, which was a less demanding application than the larger HEPT vehicles. Initial run testing of the

30,000 lb. Sparkletts truck during the spring of 1998 validated the basic functionality of the new motor. The second completed motor was received in May 1998 and installed into the first HEPT vehicle by the end of June.

*5.2.2 Motor Design and Performance Characteristics*

ISER believes the extra effort in adapting the UDLP motor to the HEPT application is justified by the performance and long term economic benefits offered by this component. The UDLP motor offers a power-to-weight ratio a factor of five to ten greater than any of the other high power motors ISER investigated prior to and during the first few months of the HEPT project. The ISER adaptation of this motor has a continuous power rating of 388 kW and weighs about 300 kg., including the weight of the integral gear reduction system incorporated into the motor design. The resultant power density is approximately 1.3 kW/kg. By comparison, the Siemens motors utilized in ISER's other vehicles, weighing approximately 600 kg. and providing between 100 to 205 kW of continuous power, offer power densities of between 0.17 and 0.34 kW/kg.

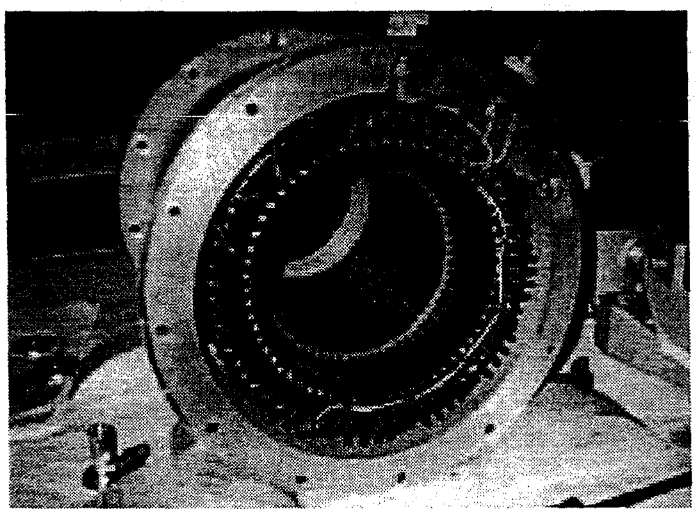

*Figure 19. Stator of the UDLP motor, which was slightly redesigned for HEPT.*

The UDLP motor incorporates several unique features that make this high power density possible. Formed copper coils in the stator (Figure 19) carry more electrical current than conventional wire windings. A unique internal liquid cooling system, in which cooling fluid flows through the interior of the motor, provides superior heat rejection capacity.

In addition, to these features, the UDLP motor includes a custom designed 4.4:1 gear reduction system (Figure 20) already integrated into the motor package. This matches the output speed of the motor shaft to the input speed of the differential used in heavy duty vehicles. Combined with the "wye-delta" switching technology described later in this chapter, this eliminates the need for a separate gear reduction system, reducing the weight and cost of the overall motive drive subsystem.

The versions of this motor built by ISER in 1997-98 are identical in most respects to the base motor design developed by UDLP. The one significant difference is that the stator coils and leads were modified in the ISER design to accommodate the "wye-delta" switching technology, which requires, in effect, that the motor be wound in a way that permits it to be operated in both the "wye" and the "delta" modes. ISER also changed some suppliers of motor components in efforts to reduce the cost of manufacturing the motors.

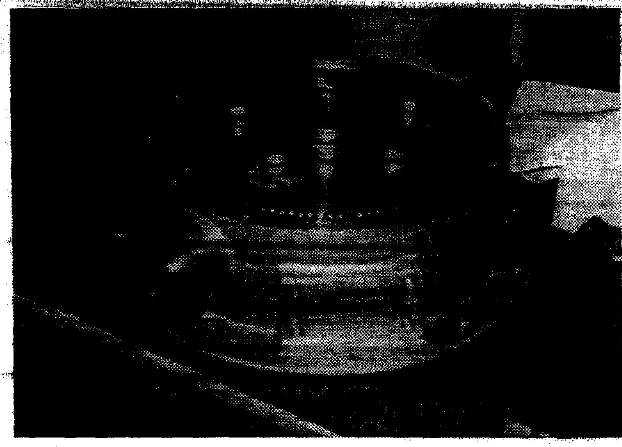

*Figure 20. Integral planetary gear system used with the UDLP motor.*

Initial tests of the ISER versions of the UDLP motor, both in the first HEPT vehicle and in ISER's Sparkletts electric truck, have validated the basic operation of this motor. The motors have been spin tested up to 12,000 RPM, which equates to a vehicle speed of approximately 75 miles per hour, and the HEPT motor has been tested under load to 261 kW on a dynamometer. Additional information on motor test results is contained in *Chapter 8, Operational Testing.*

In separate but coordinated activities, ISER and UDLP are working to improve the design of this motor. Following initial testing of the first HEPT prototype, we redesigned the output bearing of the high power drive motor to improve its mechanical strength. High priority future focus areas include modifying the cooling system to reduce internal leakage and improving the stator coil design or manufacturing process to alleviate the type of short circuit problem that emerged in the first HEPT motor. In late 1998, ISER received a follow-on funding commitment from DARPA that will help fund these efforts. The first improved version of this motor will be produced by ISER in early 2000 and installed into one of three hybrid-electric buses ISER will build for the City of San Bernardino later that year.

Meanwhile, ISER is utilizing more proven, mass-produced Siemens industrial motors in most of its other electric and hybrid-electric vehicles. The Siemens motor utilized in the second HEPT truck is a 100 kW continuous/140 kW peak air cooled motor, of the same design used previously in our hybrid-electric military tow tractors and Los Angeles buses. Our analyses and vehicle performance to date indicate this motor provides sufficient power and torque for vehicles with gross weights up to about 35,000 lb., which is the fully loaded weight of the Peterbilt 330 HEPT truck. Larger Siemens motors, with continuous power ratings of 190-205 kW and peak power ratings of about 275 kW, are available as a near term solution for more demanding Class 8 applications. However, one drawback of all of the Siemens industrial motors is there relatively heavy weight — 1,400 lb. for the 100 kW version and 1,600 lb. for the 190 and 205 kW versions. Therefore, perfection of the UDLP-derived motor will offer a major weight benefit and a better long term solution.

## 5.3 Motor Controller Development

In parallel with our advanced motor development activities, we engaged in an R&D project to develop a modular electronic, variable frequency controller that could economically supply the high power levels required by the UDLP-derived motor and the higher power Siemens motors. As in the case of the drive motor, our initial approach to motor controller development was to acquire a commercially available inverter. However, as in the case of the motor, all of the readily available motor controller products identified by ISER at the required power levels were too large, heavy, and/or expensive for practical application in a commercial vehicle. Compatibility with the ISER "wye-delta" switching technology was another consideration that limited the field of acceptable motor controllers.

The practical power limit for motor controller products, in terms of size and affordability, was about 100 kW. This was the highest power rating we could find among controllers using insulated gate bipolar transistors (IGBTs), which provide the fastest and most reliable means of performing the high frequency modulation required for our selected AC induction motor. Motor controllers rated at more than 100 kW also were typically as large as telephone booths and priced in the tens of thousands of dollars.

During the second quarter of the project in early 1997, our focus shifted from a line of controllers developed by Asea Brown Boveri (ABB) to the Siemens controller product line. Our analyses concluded that the Siemens controllers are more compatible with the expected HEPT torque regimen because they can achieve a higher field weakening factor, thereby allowing a lower motor base speed design point and requiring lower current at a given torque level. The Siemens controllers also employ sensors to continuously monitor motor speed whether or not the motor is under direct control. This allows monitoring of motor speed during the switch-over between the high torque and nominal operating modes, increasing the speed and efficiency of the transition.

During the third quarter of the HEPT project we devised a motor controller approach, in collaboration with Siemens, involving use of a Siemens high frequency 100 kW controller as a "building block" for assembly of higher power controllers. In theory, two 100 kW modules could be used together to supply 200 kW, three 100 kW modules could jointly supply 300 kW, and so on. Siemens manufactures a line of 100 kW power modules that are relatively small and inexpensive, so using two or three such modules in a "modular" controller configuration appeared to be a practical alternative to purchasing larger, monolithic chargers in the 200-300 kW range. The main obstacle to this approach was developing a means of synchronizing the power output of the three controllers in a way that simulates the output of a single controller.

In late 1997, we began working with Siemens to develop a "synchronization module" that could perform the required output phasing. A contract awarded to ISER by the U.S. Army Tank-automotive and Armaments Command (TACOM) provided the increment of funding needed to pursue this R&D in earnest. In addition, the TACOM contract provided funds to enable development of a prototype wye-delta switching mechanism and an environmental enclosure to protect the modular motor controller from damage during vehicle operation.

This synchronization module development effort was led by Siemens in Germany, with occasional visits from ISER engineers. During the first half of 1998, ISER and Siemens conducted a series of motor controller power module tests with a 600 volt DC bus, utilizing one synchronization module driving up to three power modules, in a configuration similar to the one designed for the HEPT application. These tests were conducted at increasing current and motor speed levels.

During the first phase of testing in early 1998, Siemens successfully demonstrated a three-module controller configuration up to a combined power level of 120 kW (40 kW per module), at which point a failure occurred in the output stage of one of the controllers. The failure was traced to a section of the IGBT gate driver circuitry which had been incorrectly biased. Subsequently, the synchronization board was redesigned to improve the gate timing circuit, turn-off voltages, and several other parameters. Fabrication of the improved board was completed in the Spring of 1998, and testing was successfully achieved at HEPT operating power levels by June 1998.

The synchronization module interfaces seamlessly between the ISER Motor Control Module (discussed in Section 3.4) and as many as four of the Siemens 100 kW power modules, supplying continuous power levels of up to 400 kW, in 100 kW increments. The synchronization module consists of two circuit boards, a power/communications board and an interface/sensor board, and is extremely compact. Following the successful demonstration of this board in June 1998, the first operational module was delivered to ISER in July 1998 and was immediately integrated onto the first HEPT vehicle in a three power module (300 kW) configuration.

A custom enclosure was built to house the synchronization module, Motor Control Module, and three power modules. Illustrated in Figure 21, the enclosure consists of steel cabinets mounted on a shock attenuation system consisting of four 2-axis dampers attached to an L-plate. The enclosure is designed to withstand forces of up to 12 g while insulating the peak load experienced by the controller to less than 1g. The system is splash proof and nearly watertight. An evaluation of temperature requirements determined that air cooling of the modules would be sufficient. The controllers' fan inputs/outputs are sealed to the aluminum case to prevent any moisture from the airflow from entering the electronics area. The main controller cooling fan(s) are mounted to the side of the box. All external parts are aluminum or stainless steel to preclude corrosion. Wiring is also corrosion and petroleum resistant. Also shown in Figure 21 is a set of three 3-phase 400 micro-henry inductors integrated into the motor control system. The inductors, situated directly beneath the power modules in the HEPT configuration, are required to minimize phase error due to the low inductance of the UDLP-derived high power drive motor.

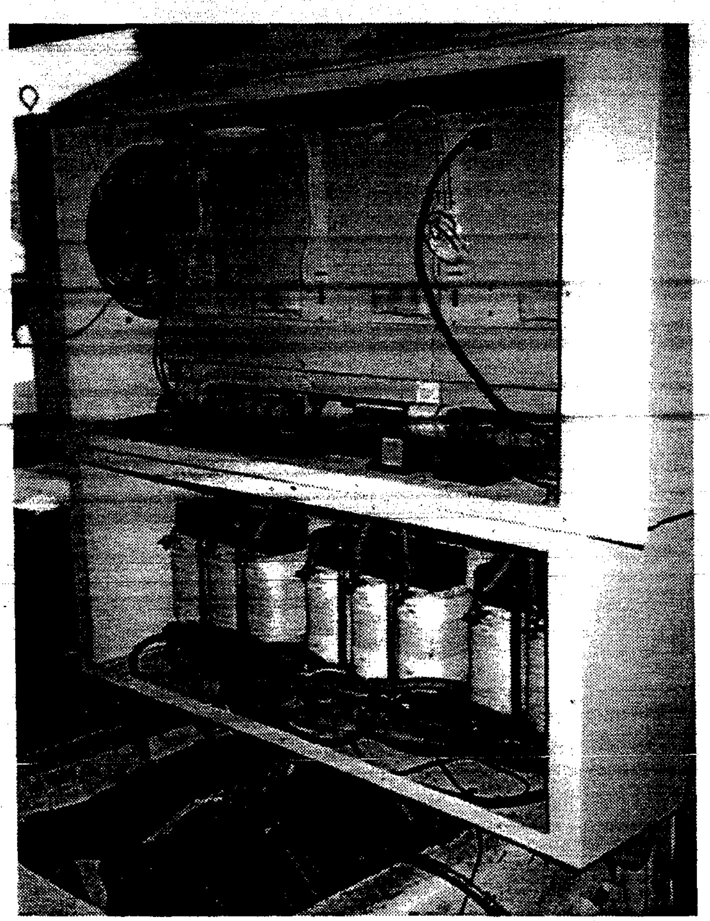

*Figure 21. HEPT motor controller system, illustrating three 100 kW power modules..*

In parallel with build-up of the prototype modular motor control system, a first generation wye-delta switching mechanism was designed by ISER with the assistance of engineering students from the University of California, San Diego (UCSD). The requirements for the switch are extremely challenging, as up to 1,000 amps has to be switched at up to 700 VAC with less than 250 msec total switching and debounce time. The prototype switch utilizes a combination of an air actuator and heavy duty springs to provide the quick response required to minimize "shifting" time and to aid in quenching the large arc produced in switching these high currents. To augment the fast switching time in quenching the arc, the entire prototype switching mechanism was submersed in a bath of non-conductive oil (same as that used in high voltage transformers). Following its construction, the unit was tested in an unpowered state and achieved switching times of 40 ms, a factor of 6 better than the design specification. The switch was then tested under load.

While heavier and bulkier than the switch envisioned as being used in operational vehicles, the prototype wye-delta switch demonstrated the functionality of this key ISER concept. A second wye-delta switch design phase was initiated following development of the first prototype device, with the goal of optimizing physical connections and reducing total system weight. However, early in this effort we determined that the wye-delta switch could not be perfected within the budgetary or schedule constraints of the HEPT project. For future vehicle applications, the switching system must be environmentally sealed and proven compatible with a truck operating environment, as well as reduced in size and weight. Custom hardware and software must also be developed to operate the wye-delta switching mechanism within the ISER system controller network. A daughter board must be developed to interface with the LonWorks node being developed to monitor and control motor operation. Software must be added directly to the motor control node software, unless the code becomes too large to fit in the EPROM. If this occurs, a separate LonWorks node will have to be created solely to service the wye-delta switch. The hardware will consist of a number of analog and digital inputs and outputs to monitor and control various switch actions. It will also be capable of monitoring motor controller status and providing control signals to enable/disable pulse operation.

ISER hopes to secure funding to pursue these follow-on wye-delta switch activities in 2000. Meanwhile, the UDLP-derived motor will be utilized primarily in its "delta" winding mode, which provides efficiency at high speeds, with a reduction in starting torque. If torque limitations become a problem, a two speed transmission can be used as an interim solution until the wye-delta switch concept can be perfected.

### 5.4 Motor-Controller Testing

By early August 1998, both the high power UDLP-derived AC induction motor (Figure 22) and the three-module "ModuDrive" motor control system were successfully installed into the first HEPT vehicle. By this time, as indicated in Section 5.2, a similar motor had been built and successfully demonstrated in ISER's electric Sparkletts bottled water delivery truck over a period of more than three months. However, during the first high power, no-load testing of the HEPT motor on 7 August 1998, damage to several of the stator coils was sustained. The damage was sustained after approximately one hour of testing.

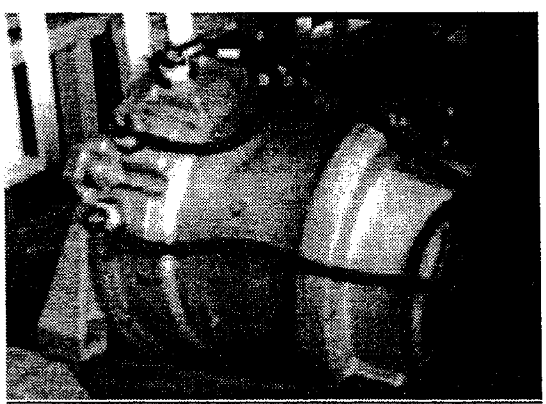

*Figure 22. Fully assembled motor.*

Two possible causes for this motor damage were identified and investigated:

1) A flaw in the manufacture of the stator, such as a crack in one of the copper coils or a physical condition capable of causing a short circuit between two poles.

2) A voltage spike or other unusual condition caused by the three-module motor controller configuration.

From the start of the investigation, it was our belief that the first of these two causes, a manufacturing defect, was the most likely cause of the damage. Physical flaws were previously found in at least two stators built by the same vendor, Advanced Industries — one of ISER's three motors and a smaller UDLP motor of similar design. The damaged ISER motor had not been run previously, so a manufacturing defect could have gone undetected until the time of the 7 August test. Given the motor's electrical ratings, an extremely high voltage spike or current level would have been required to cause the damage that was incurred.

To validate this hypothesis, a 100 kW Siemens motor was temporarily connected to the multi-module motor control system and run several times at full power. No voltage spikes or other anomalies approaching the magnitude required to damage the UDLP motor were observed during any of these tests. These tests, combined with the fact that the motor control system was successfully tested by Siemens prior to ISER's tests, strongly suggested that the motor control system was sound and that the stator coil damage resulted from a flaw in motor construction.

To expedite a resumption of HEPT vehicle completion and testing, parts previously built for a third motor, earmarked for the second HEPT vehicle, were "borrowed" to rebuild the second motor. Meanwhile, the damaged stator was returned to Advanced Industries for inspection and repair. Engineers at Advanced Industries later confirmed that a flaw in the coils was the most likely cause of the motor damage.

The rebuilt second motor was completed and installed into the Kenworth truck in October 1998. Initial spin testing of the motor later that month was successful, and validated that the previous motor's stator short circuit problem was an isolated instance. The motor was subsequently connected to the vehicle drive shaft, and initial spin-up of the vehicle's wheels was achieved in November. All-up run testing of the completed HEPT truck was initiated in December, and at the end of December a series of dynamometer tests were conducted at a local Peterbilt truck center to characterize the performance of the motor and controller (Figure 23).

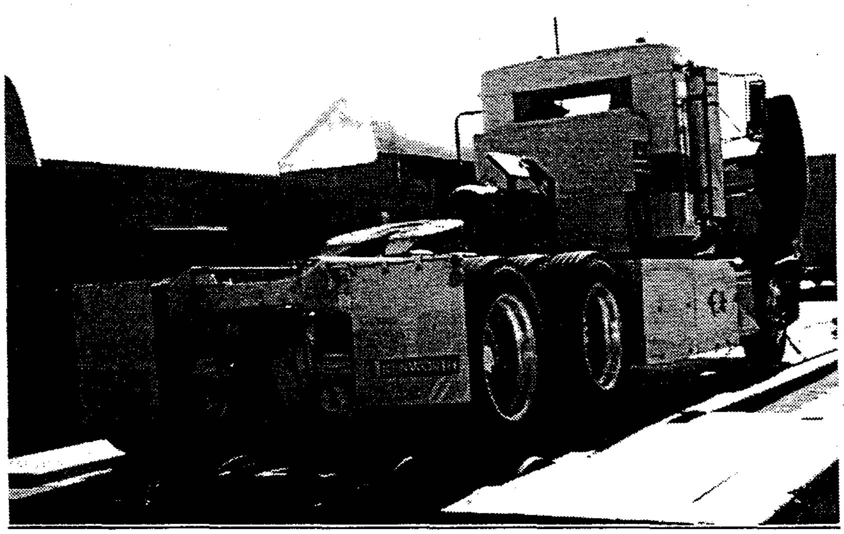

*Figure 23. HEPT truck #1 undergoing dynamometer testing in December 1998.*

As discussed in greater detail in *Chapter 8, Operational Testing,* the motor and controller were shown to perform in accordance with project expectations, reaching a peak power output of 261 kW before power output dropped off due to the drawing down of vehicle bus voltage. Due to logistical constraints during testing we were unable to boost the bus voltage by running the APU. However, subsequent road testing with the APU operational demonstrated the ability of the APU to elevate bus voltage by 30 to 50 VDC, which our analyses indicate is sufficient to achieve motor power levels in excess of the targeted 300 kW. This was validated during follow-on testing of the vehicle in 1999.

The motive drive system utilized in the first HEPT vehicle remains a highly experimental system, even though it has successfully demonstrated basic operability, including the use of a new high power induction motor and a new modular motor control concept employing a synchronization module to phase the output of two or more power modules.

The main drive motor has demonstrated the potential to improve the state of the art in motor technology by increasing power density by a factor of five or more. The basic operational properties of the motor, as demonstrated by our Sparkletts electric truck as well as the HEPT Vehicle #1, appear to validate the basic motor concept. However, even after having strengthened the design of the output shaft bearing, we believe that the experimental version of this motor presently in use in the first HEPT truck will require three additional structural improvements for it to be used as a long life asset. These are:

1) Redesign of the rotor and stator to eliminate internal leakage of cooling fluid.
2) Redesign of the gear reduction system to strengthen the gears and reduce the cost of this component.
3) Improvement of stator coil manufacturing and/or installation techniques to eliminate incidences of short circuits.

The most critical of these improvements, Item 1, is already being addressed through ISER and United Defense projects funded by the Department of Defense and our two companies. Funding for Items 2 and 3 has not yet been secured, but it is our intention to implement these changes as soon as such funding does become available.

In our judgment, the UDLP-derived motor in its current configuration is sufficient to enable HEPT Vehicle #1 to continue to be tested under close supervision, as special steps were taken to seal the rotor and stator of this motor and it has not yet exhibited any signs of internal leaking. However, to assure sufficient longevity for prolonged operation in a "real world" environment, we believe the motor will have to be enhanced, at minimum, by Item 1, and possibly by Item 2. Item 3 relates to future production articles.

Following initial testing of the HEPT vehicle in early 1999, we incorporated a new Siemens digital control module into the motor controller. This enabled control of the UDLP-derived motor at the higher base speeds characteristic of the "delta" mode. This work, which was completed in May 1999, enabled the HEPT vehicle to be operated in the "delta" mode and to achieve "freeway speeds" for the first time.

The second HEPT vehicle, with a much lower gross vehicle weight rating and designed for use principally as a show vehicle, was equipped during the summer of 1999 with a single Siemens 100 kW motor and 100 kW motor control module. This vehicle is capable of a top speed of approximately 60 miles per hour.

# CHAPTER 6
# BATTERY SUBSYSTEM DEVELOPMENT

## 6.1 Battery Analyses and Trade Studies

Our movement toward a higher voltage system, as discussed at the beginning of the preceding chapter, prompted us to begin investigating battery subsystems toward the end of the first quarter of the HEPT project, about two months ahead of schedule. In general, operation at higher voltages did not appear to preclude any of the battery options identified prior to the HEPT contract. Our early battery subsystem analyses focused on three different broad options:

• Sealed lead-acid batteries. Such batteries are relatively inexpensive, and offer energy densities ranging from 25 to nearly 40 watt-hours per kilogram. An advanced "Horizon" sealed lead-acid battery manufactured by Electrosource was advertised as offering energy densities of 40-45 watt-hours/kilogram.

• Nickel metal hydride batteries. The leading manufacturer of such batteries for automotive applications, GM Ovonic, offers a nickel metal hydride (NiMH) battery rated at about 70 watt-hours/kilogram.

• Other near term alternatives. These include lead-cobalt batteries, whose energy density is in the range of lead-acid batteries. Their maintenance is more complex, but their acquisition cost may be significantly lower on a cost/kW-hour basis.

During the second quarter of the HEPT project we conducted an integrated battery subsystem trade study to determine the best of these options and to define the number and configuration of cells to be utilized.

As of the end of the second reporting period, our selected HEPT battery option was an inexpensive "Champion" sealed lead-acid battery manufactured by GNB. This battery type was determined to be considerably less expensive — by at least a factor of five to ten — than the more advanced Horizon lead acid and GM Ovonic nickel metal-hydride batteries. The Champion offers about 20% less energy density than the Horizon lead-acid battery (39 watt-hours per kilogram for the Champion vs. about 45 Wh/kg for the Horizon) and about 55% of the density of the Ovonic nickel metal-hydride batteries (39 Wh/kg vs. about 70 Wh/kg), but is projected to satisfy HEPT driving cycle requirements in the sets of 112 batteries that were initially envisioned for the HEPT battery subsystem.

During the second quarter of the HEPT project we designed racks capable of housing these batteries in four sets of 28. Our rack concept consisted of inexpensive aluminum trays with raised tabs on the bottom to keep the batteries in place. The racks would be slid into place alongside the vehicle frame rails between the front and rear axles, in the same area previously occupied by the diesel fuel tanks.

About one year into the HEPT project, ISER delivered an electric tow tractor to United Airlines utilizing a set of 96 of the GNB Champion lead-acid batteries. While these batteries exhibited the basic advantages of sealed lead-acid batteries, particularly low maintenance, we were not satisfied with the quality of the product, and were further disappointed when GNB raised the price of this battery model. Following delivery of the United tow tractor, were able to identify a competing product that offered comparable performance at a lower price — a "Chairman" series of sealed lead-acid batteries offered by Concorde. These Concorde batteries, rated at about 37 watt-hours per kilogram, were subsequently purchased and used in the electric Sparkletts bottled water delivery truck we built in late 1997 and early 1998.

Experience with the Sparkletts truck validated the feasibility of using the Concorde batteries in our drive systems. While the Sparkletts truck is an all-electric vehicle, it uses the same advanced AC induction motor as the HEPT trucks and was designed to run at the same bus voltage. However, during operational testing of the Sparkletts truck in mid-1998, we discovered that the two parallel sets of 56 batteries used in this vehicle, when fully charged, supplied more voltage than could be handled by the Siemens motor controller power module. While the nominal bus voltage was 672 VDC (56 times the nominal single battery voltage of 12 VDC), fully charged batteries were measured to be at 13.2 VDC, resulting in an actual total bus voltage of more than 739 VDC. This exceeded the 708 VDC fault threshold of the Siemens power module. A higher voltage, 800 VDC Siemens module is being developed and is expected to be available later in 1999, but in the interim we were forced to solve this problem by reducing the number of batteries in each set on the Sparkletts truck from 56 to 50. When this was shown to help eliminate the Siemens module overvoltage problem, the design for the HEPT vehicles was modified to include two sets of 48 batteries instead of the twin 56 battery sets previously planned.

### 6.2 Battery Subsystem Integration and Testing

During the summer of 1998, the battery racks for the first HEPT truck were fabricated and successfully installed onto the vehicle. A first set of 48 batteries was integrated into the truck during the summer and used for initial testing of the motor. Toward the end of the year, ISER successfully integrated a second set of 48 batteries into the prototype Kenworth truck, completing the full complement of 96 batteries. A slightly smaller number of batteries was selected than the 100 batteries used in the Sparkletts truck to reduce weight and provide greater protection against overvoltage problems. With its hybrid-electric drive system, the HEPT vehicle is not as dependent as the all-electric Sparkletts truck on batteries to extend operating range.

the motor controller is adversely impacted when bus voltage declines to the 500-520 VDC range. If the batteries are fully (100%) charged, this occurs when vehicle power consumption reaches 400 kW, and at lower states of charge, controller malfunction can occur at vehicle power levels as low as 150 kW.

This means that for high power Class 8 truck applications, battery charge level cannot be drawn below the 500-520 VDC range, requiring more frequent use of the auxiliary power unit (APU) to either keep battery state of charge high or to augment bus voltage when state of charge is low. It also makes it less likely that such trucks will be able to operate at high power levels with single packs of 48 batteries. When augmented by the output of the 75 kW APU installed into the Kenworth prototype, the vehicle with two packs of 48 batteries should be able to run at power levels in excess of 400 horsepower, the peak power limit of the diesel equivalent truck. However, as discussed in *Chapter 5, Motor and Motor Controller Development,* operation of the main drive motor in the "delta" winding mode is required for effective running of the HEPT vehicle at higher power levels.

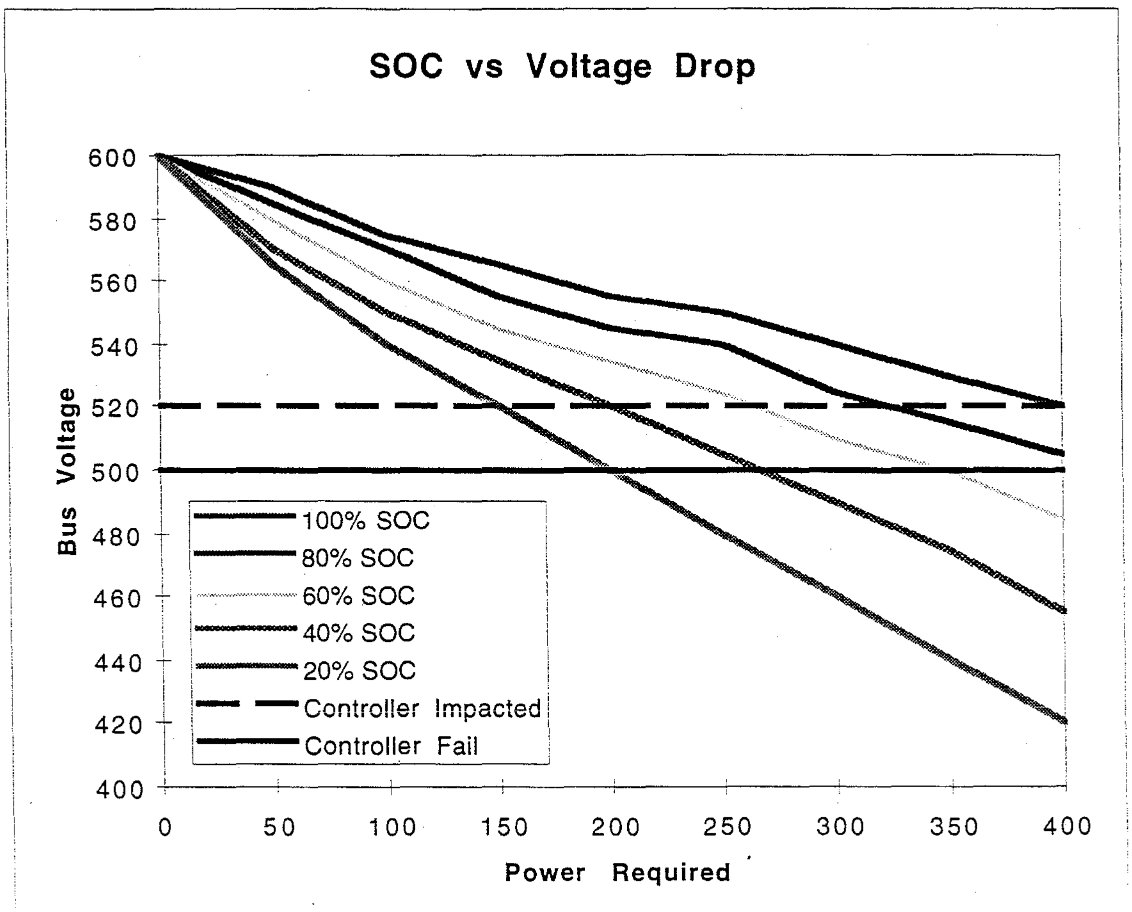


*Figure 26. Reduction in vehicle bus voltage as a function of vehicle power consumption.*

Operational experience to date indicates the prototype Kenworth truck will have an all-electric driving range of 15 to 25 miles, depending on cargo weight and driving conditions.

For the Peterbilt prototype truck, we elected to test a different type of battery, manufactured by Optima. The Optima batteries offer higher power densities than the GNB Champion or Concorde batteries, but have about 15% lower energy density. Our goal in switching to the Optima was to see if we could sustain higher vehicle power levels at lower battery states of charge. Preliminary run testing of the Peterbilt truck, which was equipped with only 48 batteries, indicates that we are obtaining higher power at a given state of charge than with the Kenworth truck, and that this benefit may offset the lower energy density of the Optima batteries. Further testing will be required to validate this preliminary conclusion.

### 6.3 Future Developments

ISER continues to develop a prototype battery management system, an Automatic Continuous Equalization System (ACES) funded under ISER's Air Force tow tractor contract. ACES is designed to continuously route power during battery recharging away from batteries with high charge levels and toward batteries with low charge levels. This would represent an advantage over currently available alternatives, which protect higher charge batteries from overcharging, but typically use resistive elements to dissipate the surplus energy in the form of heat, thereby reducing system efficiency. ACES also provides a means of monitoring the temperature and state of charge of each battery individually, facilitating replacement of bad batteries before damage to the battery pack results.

While the ACES system was not baselined for the HEPT vehicles, its eventual completion may offer an upgrade option for the HEPT vehicles and their commercial successors which will address common problems with electric and hybrid-electric vehicles — battery pack failures due to undetected failures of individual batteries, and overcharging and/or undercharging of individual batteries during recharging (which can accelerate failures). Completion of the ACES development effort, and subsequent retrofitting of an ACES system into the first HEPT vehicle, was expected during 1999. However, due to unforeseen problems in ACES development, by mid-1999 we were forced to acknowledge that it would be at least early 2000 before we could complete development of an ACES system sufficiently robust and reliable for every day use on a vehicle. We therefore elected to substitute a commercially available battery monitoring system called eXtend™ on our Air Force tractors. We still hope to complete development of ACES some time in 2000, with the goal of merging the eXtend™ monitoring function with the ACES continuous charge equalization function. If we are successful in combining these two capabilities, we will have an integrated battery management system superior to any other product that we are aware of on the market today.

Upgrades to improved batteries are planned as such technologies become more affordable. The NiMH batteries discussed earlier in this chapter are presently offered at prices ranging from ten to twenty times the price of the Concorde sealed lead acid batteries, which is a price reduction as compared with a few years ago, but still far too expensive for cost-effective use in Class 8 hybrid truck applications. Lithium polymer batteries have been identified which offer energy densities as great as 155 watt-hours per kilogram. A lithium polymer battery pack the same weight as the current HEPT lead-acid battery pack would supply four times as much stored energy. Alternatively, the same amount of energy currently available could be supplied by a lithium polymer battery pack weighing one quarter as much — a total weight saving close to 5,000 lb. To obtain these benefits, ISER looks forward to adapting the HEPT drive system to NiMH, lithium polymer, or other advanced batteries as soon as such battery technologies become affordable.

# CHAPTER 7
# VEHICLE INTEGRATION

## 7.1 Integration Approach

ISER's approach to vehicle integration evolved substantially during the HEPT project. At the start of the project in October 1996, the company had completed some feasibility and design studies, but had not yet built any prototype vehicles. The 27-month period during which the first HEPT vehicle was built was therefore characterized by a significant amount of learning. Much of this learning was accomplished on other, less complex vehicles, such as the electric United Airlines tow tractor and Sparkletts bottled water delivery truck mentioned in previous chapters. Experience was also gained on two other hybrid-electric vehicle models whose development paralleled the HEPT project in late 1997 and through much of 1998: hybrid-electric tractors built for the U.S. Air Force and hybrid-electric transit buses built for the City of Los Angeles.

The most significant change in the ISER integration approach was an evolution from a pure prototyping, "trial and error" based approach to one incorporating much greater production control, documentation, and standardization. The first components to be integrated into the HEPT vehicle — the APU and fuel tanks — were installed on the basis of general conceptual drawings and engineering analyses. Precise mounting locations and interfaces with vehicle components were developed almost in "real time." Completed installations were documented only in the most general sense, if at all. However, by the time the final vehicle components were installed into the HEPT vehicle in late 1998 — the LonWorks nodes and final wiring connections — ISER had evolved a much more sophisticated process. Detailed engineering drawings are now developed and approved by at least one senior manager before any part is installed onto an ISER vehicle, and drawings are meticulously updated whenever any installation is modified. A number of additional configuration management tools have been put in place, including use of "Work Breakdown Structure" (WBS) parts hierarchies to track every part used in the vehicle drive system or its installation.

We have adopted these improvements in our vehicle integration and configuration management processes to support our transition from a builder of one-of-a-kind prototype vehicles to an integrator of drive systems into large numbers of similar vehicles. Our Los Angeles bus program, which called for integration of hybrid-electric drive systems into five identical 30-foot transit buses, was the principal catalyst for these changes. Our greater attention to documentation and the consistency and repeatability of our integration processes is already showing benefits. Between the summer of 1998 and the Spring of 1999, we reduced the time required to integrate a drive system into one of the L.A. buses from three and a half months for the first bus to six weeks for the second bus and just over four weeks for the fourth bus. During the Summer of 1999, our improved integration methods enabled us to integrate the drive system into the second HEPT vehicle in just over two months — about eight times faster than the integration period required for the first prototype. This improvement in integration time was achieved despite the fact that the second vehicle used a completely different chassis than the first.

Our long term objective is to simplify and standardize the drive system integration process to the extent that vehicle manufacturers can be trained to install hybrid drive system components at their own production sites. To facilitate this process, ISER will "pre-integrate" drive system components into "kits" that the manufacturers can integrate into the vehicles on their own production lines. Pre-integrated kits will consist of five major subsystems:

1) Vehicle Control Subsystem (LonWorks nodes, network cabling, dashboard display, and central computer)
2) APU Subsystem (engine, generator, and interface and control hardware)
3) Motive Drive Subsystem (motor, motor controller, and gear reduction systems)
4) Battery Subsystem (batteries, charger, racks, cables, and connectors)
5) Accessory Subsystem (electrically driven power steering, braking, and air conditioning units)

The first four of these subsystems, and their integration into the first HEPT vehicle, were described (in essentially the order listed) in Chapters 3 through 6 of this report. The only major components and integration tasks not addressed in these chapters relate to the fifth subsystem listed above, the Accessory Subsystem.

## 7.2 Accessory Subsystem

During the HEPT project, ISER developed a line of multi-use electrically-driven accessories that can be used on a variety of heavy duty vehicles, including both the company's Class 7 and Class 8 trucks. In conventional vehicles, and in most other hybrid-electric vehicles, accessories such as power steering, braking, and air conditioning are driven by hydraulic or pneumatic pumps connected to the vehicle's internal combustion engine. Such conventional "power take-off" (PTO) units require the engine to be run continuously, or power will be lost for critical vehicle functions such as power steering and braking. However, as discussed in *Chapter 2, System Controller Development,* the ISER hybrid-electric drive system has the unique feature of enabling an all-electric operating mode, in which the engine and APU subsystem are completely shut down for extended periods. During these intervals, any accessories dependent on the vehicle engine for power would be inoperable. To assure continuous operation of accessories such as power steering and braking, it was therefore necessary for ISER to develop a line of electrically-driven accessories. These ISER accessories derive power from the vehicle's batteries when the APU is not running, and can thus be operated at any time.

*Figure 27. Hydraulic motor/pump.*

A custom motor hydraulic pump supporting both the power steering and motor cooling systems was integrated and installed on the first HEPT truck. In the HEPT vehicle, pneumatic fluid for power steering is pumped through the system using a 10 horsepower electric motor (Figure 27). In an innovative combination of functions, the same fluid is pumped through the interior of the main electric drive motor as the cooling fluid for the motor.

To maintain the 12 volt system for powering vehicle accessories such as lights and the horn, 300 VDC to 12 VDC DC-DC converters were installed. Two 600 watt modules were installed, one on each half of the 600 VDC main bus. The output are fully isolated and were paralleled to enable a total 1.2 kW supply to support the 12 VDC system.

With two separate DC-DC converters, the output can never be exactly matched, so one of the converters always draws more power than the other. This eventually leads to imbalances in the packs. Currently we solve this problem one of two ways. We either add some logic that always turns off the DC-DC converter attached to the low pack until they are equalized, or design a new converter which operates off the full bus voltage. A better solution would be to develop a DC-DC converter that could operate directly on the 600 VDC bus, which would be a simpler, cheaper, and more reliable solution. ISER has been pursuing this as a near term product improvement under an advanced tractor project that was initiated in July 1999, and we expect to have a completed system ready for testing on one of our vehicles by the end of this year.

During the HEPT project, an overvoltage protection circuit for all items on the main 600 VDC bus was also developed. As discussed in previous chapters, during regenerative braking, large amounts of energy are generated by the motor and placed on the DC bus. These amounts can exceed the levels of energy the batteries are capable of accepting, especially when the batteries are fully charged. When regenerative braking supplies energy in excess of that which the batteries can absorb, the bus voltage can rise above acceptable levels. Although this only happens for very short periods of time (from a few milliseconds to a few seconds at the most), it can cause damage to components if not addressed. To eliminate this issue, a large resistive heater bank was developed and installed. A fully isolated voltage sensor was also developed which has an integral switch to actuate the resistor bank. When the voltage exceeds allowable levels, the switch actuates the 30 kW resistor bank, which provides an additional load on the bus, thereby limiting any rise. The bank automatically turns off when the voltage returns to a safe level.

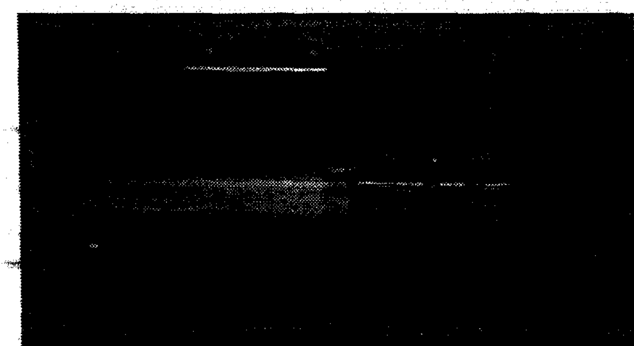

*Figure 28. Air conditioning pump.*

In addition, a prototype motor and air conditioning compressor unit was developed and integrated (Figure 28). Future versions will utilize a close-coupled compressor to eliminate external moving parts and to reduce the size of the assembly.

Finally, a custom motor/pneumatic pump unit which provides air for truck braking systems was designed and installed into the first HEPT vehicle (along with installation of a similar unit into the Sparkletts water truck), including shuttle valves, purge valves, and a parallel circuit to allow computer actuation of the brakes (Figure 29). Testing of the first actuator, which was composed of an electromagnetic actuator driving a conventional brake valve, was tested and the response was determined to be too slow. A new servo brake actuator with faster response was subsequently selected.

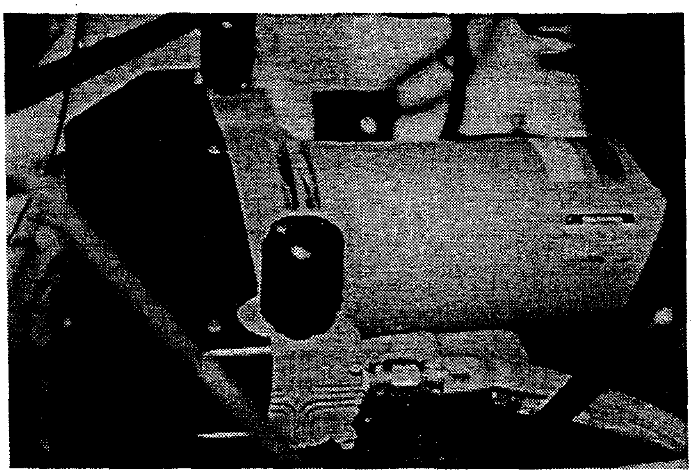

*Figure 29. Braking system air compressor.*

Figure 30 shows the fully integrated Kenworth HEPT vehicle at the end of 1998 during dynamometer testing at the Pressley Peterbilt truck center in San Diego. As discussed in more detail in the following chapter, the dynamometer and initial road testing of the vehicle in late 1998 and the first half of 1999 demonstrated the basic functionality of the ISER integrated hybrid-electric drive system.

Efforts to refine the Kenworth vehicle continued throughout the first half of 1999. In addition to upgrading specific components such as the motor and motor controller, we improved wiring harnesses and connections. As experience is gained testing the vehicle under a variety of conditions, these and other elements of the vehicle will continue to be upgraded to improve their longevity. Lessons learned in integration of the first vehicle were applied during the Summer of 1999 to integration of the second HEPT vehicle, using a Peterbilt 320 truck. As indicated previously, this vehicle was integrated extremely rapidly. Equally important, the vehicle demonstrated reliable performance right from the start of run testing.

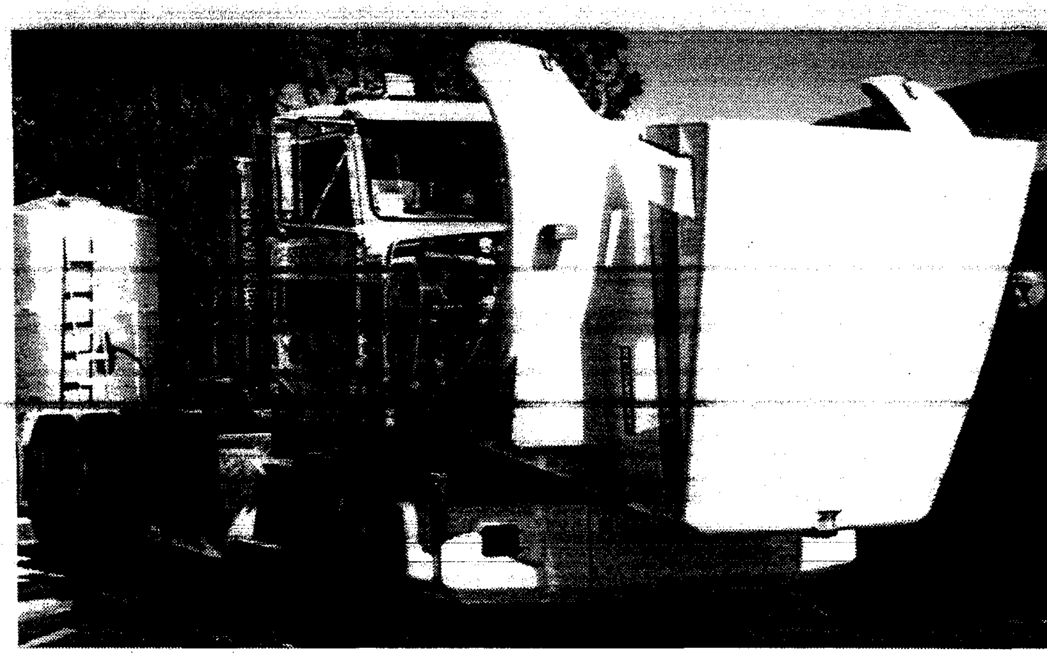

*Figure 30. Fully integrated vehicle.*

ISER has also been selected to integrate a hybrid-electric drive system into a Class 8 Volvo truck for Norcal Waste of San Francisco. This activity is expected to begin in November 1999 and extend for a period of about one year. The drive system installed into the Norcal truck will be similar to the HEPT drive system, though adaptations will obviously have to be made to accommodate the differences in vehicle models. A modified version of the HEPT drive system will also be integrated into three 40-foot hybrid-electric transit buses ISER will be building for the City of San Bernardino in 1999-2000.

Finally, ISER has continued to seek private and public funding, to finance major upgrades to the HEPT drive system. As mentioned briefly at the end of *Chapter 2, Final Drive System Design,* ISER has developed future hybrid truck concepts that employ a variety of advanced components, including turbogenerators in lieu of conventional combustion engine-driven APUs and more compact LNG fuel systems in lieu of CNG. The aerodynamic vehicle shape shown at the end of Chapter 2, enabled by use of compact components and the inherent flexibility of hybrid drive system geometry, could improve vehicle performance by as much as 15%. Such advanced vehicles can also utilize other performance-enhancing improvements as they are demonstrated and become affordable, such as higher energy density nickel metal hydride and lithium polymer battery technologies (see *Chapter 6, Battery Subsystem Development).* Flywheels or ultracapacitors may eventually be used in ISER drive systems to augment the main battery packs. In the more immediate future, ISER's highest priority product improvements will focus on the main drive motor and motor controller systems, which have shown exceptional promise during the HEPT project, but which require substantial evolution before they can be relied upon in routine vehicle applications.

# CHAPTER 8
# OPERATIONAL TESTING

## 8.1 Overview

ISER's original testing plan called for a two month series of "Phase 1" operational tests to demonstrate the basic roadworthiness of the Kenworth truck, followed by at least six months of more rigorous "Phase 2" tests, including placement of this vehicle into operational service. Crown Disposal, a refuse collection firm in Burbank that operates a fleet of 100 refuse trucks agreed at the start of the program to test the first HEPT vehicle in its fleet during this phase of testing. For most of the duration of the project, it was ISER's intention to follow through on this entire test plan. However, by the time the Kenworth truck was completed and upgraded to meet basic performance specifications in May 1999, it had become evident that the very advanced technologies incorporated into this vehicle were not quite ready to be demonstrated under every day operational conditions.

As discussed in preceding chapters, the first HEPT vehicle was completed at the end of 1998, at which time a series of operational tests was immediately initiated. Within days of physical completion of the vehicle, a series of dynamometer tests was conducted at a local Peterbilt truck center. These tests were not part of the original project plan, but were performed at ISER expense to maximize the value of ISER's own testing of the vehicle. Several months of road testing followed during the first half of 1999. During these tests, it became apparent that a much longer, more staged process of testing and vehicle improvement would be required before a vehicle of the complexity of the first HEPT truck could be placed into regular, reliable operational service. In particular, as discussed in *Chapter 4, Motor and Motor Controller Development,* HEPT results indicate that at least one or two additional motor and motor controller improvements will be required before a vehicle using the advanced Kenworth motive drive subsystem can be placed into reliable operational service.

The second HEPT vehicle, the Peterbilt 330 truck, was tested by ISER and Peterbilt engineers during the last three months of 1999, in a process that is still on-going as of the date of this report. Since the Peterbilt truck utilizes a less complex motive drive system, consisting of a Siemens motor and single module motor controller, and a more powerful engine, it is closer to operational readiness than the Kenworth truck. The greater reliability and robustness of the Peterbilt vehicle has been clearly demonstrated in testing to date. In fact, during its first public demonstration of the Peterbilt truck in September 1999, ISER received a commercial offer to purchase this vehicle.

Based on the results of HEPT testing, ISER is proceeding with commercial marketing of trucks using the technology incorporated into the Peterbilt truck. In many respects, the Peterbilt drive system is closer to what ISER envisioned in its original HEPT development plan, which was based on use of "off the shelf" hardware in most of the vehicle's subsystems. By contrast, the high power AC induction motor, modular motor controller, and APU control systems employed in the Kenworth HEPT vehicle are all substantially newer and more advanced than their counterpart systems in most other electric or hybrid-electric vehicles. Refining the basic designs of these components to meet vehicle requirements in all foreseeable operating conditions is a major task that will require further development. Therefore, in parallel with marketing of the Peterbilt truck's technology, ISER is initiating a "HEPT-2" technology development program aimed at refining the more complex technologies incorporated into the Kenworth truck.

The following two subsections summarize the results of operational tests performed on the Kenworth and Peterbilt trucks. Section 8.2 focuses on the dynamometer tests performed on the Kenworth truck in late 1998. Section 8.3 focuses on the road tests of the Peterbilt truck that were performed the following year. These results provide many insights into the potential of hybrid-electric drive technology.

## 8.2 Kenworth Truck Testing Results

The objective of the streamlined HEPT test program was to evaluate, under closely controlled conditions, the ISER advanced motive drive subsystem and its ability to propel a Class 8 truck in a manner comparable to that of a conventional diesel drivetrain. Specific goals of this subsystem included:

Goal 1) 215 kW continuous power
Goal 2) 288 kW peak power
Goal 3) 1,000 NM continuous torque
Goal 4) 1,500 NM peak torque
Goal 5) 12,000 rpm maximum speed
Goal 6) 92% peak efficiency
Goal 7) Characterize power, torque and efficiency across operating range
Goal 8) Evaluate ability of electric drive system to propel the vehicle in a manner consistent with a conventional diesel

Dynamometer testing of the first HEPT truck was preceded by bench testing and a few days of preliminary on-road testing, and was followed by several months of additional road testing. These tests were then augmented with analyses to compile the required data to meet the program goals.

Bench testing was conducted using the Kenworth HEPT vehicle as a stationary "bench." This was done for two reasons; first the United Defense test set-up originally planned for use was unavailable, and secondly, this provided the most realistic operating conditions for the motor and controller. As will be shown, using the first HEPT vehicle as a stationary test bench provided valuable data on the characteristics of hybrid systems which would not have been obtainable on a conventional test bench. Dynamometer testing was conducted at the Pressley Peterbilt Truck Center in San Diego, using a chassis dyno, and was conducted by independent Peterbilt operators.

On-road testing, both before and after the dyno tests, was conducted utilizing ISER and Sparkletts drivers to obtain both an internal and external perspective on the vehicle's capabilities. The road testing conducted after the dynamometer tests enabled us to obtain performance results that could not be obtained on a chassis dynamometer due to the inherent limitations of such devices. Specifically, since chassis dynos generally use water brake turbine systems to provide loads, they are not capable of generating large loads at slow speeds. Since electric motors can generate maximum torque at zero rpm, the dyno was not capable of capturing this data, so an alternate method had to be devised.

*8.2.1 Bench Testing*

As described above, bench testing was performed utilizing the Kenworth HEPT vehicle as a stationary test bench. The motor and controller were mounted in place and the motor was connected to the drive shaft. The vehicle was raised on jack stands to allow the wheels to freely rotate. This allowed the motor to see the rotational inertia to which it would normally be subjected during operation. The HEPT vehicle utilizes a set of 48 series connected 12V batteries for a nominal DC bus voltage of 576 VDC. The APU, while connected to the bus, was not utilized during this test period. As shown in Figure 31, the power begins at approximately 4 kW at very low speeds, dips down to near zero from 500 to 2000 rpm and then increases back to about 3.5 kW at 6,000 rpm. The high initial peak is expected due to the control methodology utilized. The motor begins in open loop torque control which allows for smooth slow speed operation, however, requires large initial currents to generate the induced fields at slow speeds. There is some fluctuation in the curves which we believe was due to the no-load condition of the motor, allowing vibration and backlash in the 4.4:1 gear reduction. While these are AGMA 12 or better gears, some variation must be expected due to heat expansion. These fluctuations were not seen under loaded conditions. The fluctuations in the power curve allow the controller to maintain precise speed control. A polynomial trend line is also shown to display the average power usage.

*8.2.2 On-Road Testing*

Following physical completion of the HEPT vehicle in late 1998, the motor was attached to the drive shaft and the vehicle was raised up on jack stands to allow free rotation of the drivetrain. Software "smoothing" of the drivetrain was then conducted by a team of engineers to ensure that the vehicle would run smoothly in all gears and under most conditions. The largest challenge in this process is to ensure smooth braking, utilizing a combination of regenerative braking and standard air brakes. Once this was accomplished on jack stands, the vehicle was lowered and initial on-road testing was performed. First, ISER personnel drove and further "smoothed" the operation of the motor control system to minimize any non-linearities, and attempted to find operating conditions which would cause undesirable performance. Once these were corrected, the vehicle was ready for on-road trials.

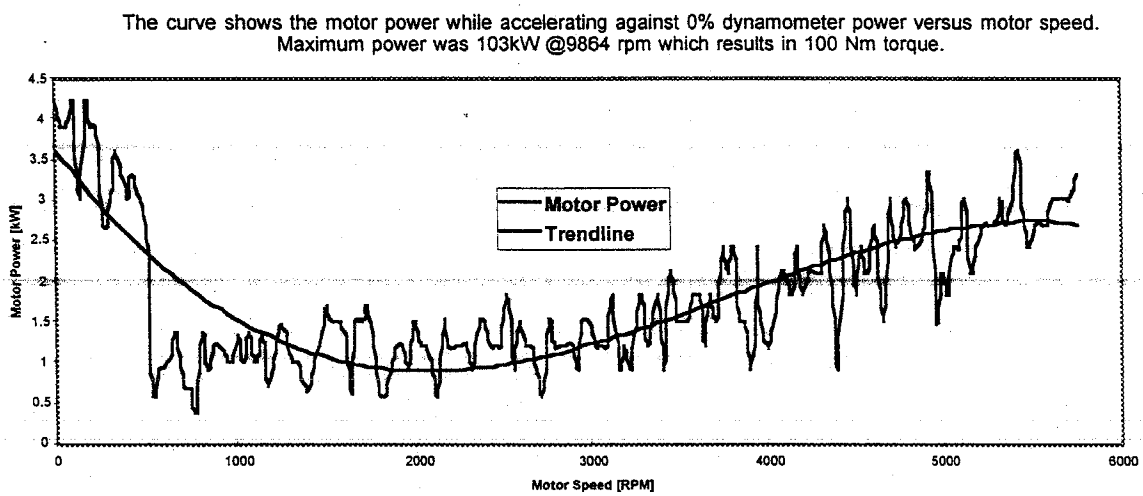


*Figure 31. Motor power curve under no load.*

Road testing was first assigned to an ISER mechanic who has worked for Peterbilt for 12 years. He was immediately impressed with the smooth acceleration and the quietness of the cab. He felt that these advantages alone would be strong incentives for people to purchase such vehicles. Then, to obtain an outside, independent opinion, a driver from Sparkletts agreed to evaluate the vehicle. He was also impressed with the rapid acceleration and excellent performance. He felt that the truck was much quicker than a conventional diesel and appreciated the fact that there were no gears to shift. All in all, both the ISER and independent drivers thought that the HEPT vehicle was capable of performing the duties of a conventional tractor and in most cases was superior to a diesel vehicle.

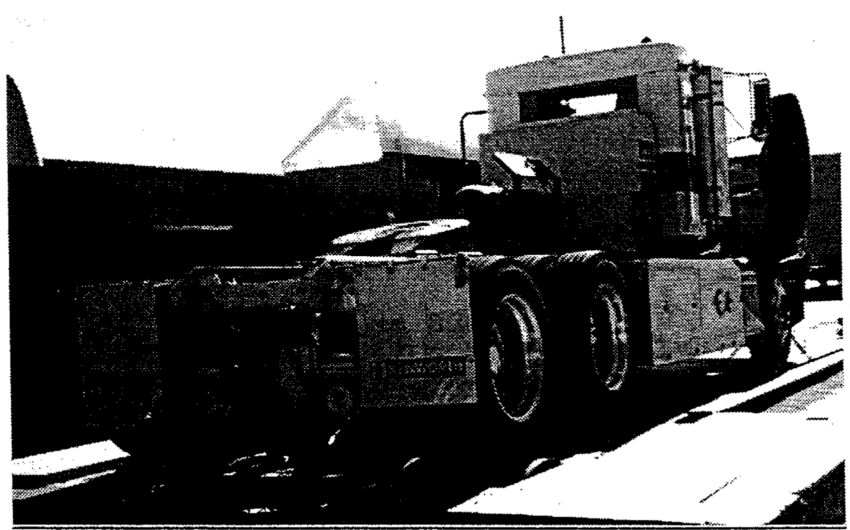

*Figure 32. HEPT in dynamometer testing.*

*8.2.3 Dyno Testing*

Following these initial road tests, the HEPT vehicle was taken to Pressley Peterbilt for independent dyno testing. The vehicle was driven onto a chassis dynamometer and prepared for testing (Figure 32). It was fully instrumented and operation of the vehicle was under computer control by

ISER personnel. The dyno and instrumentation were under Peterbilt control. The dyno utilized was a conventional water turbine design normally utilized to test vehicles of this type. However, one of the shortcomings of this type of dynamometer is that it must build up speed to be capable of exerting a load on the rolling drums and therefore the vehicle. For conventional vehicles this is not a problem, because the engine must speed up to generate torque as well. However, for the electric motor-driven HEPT vehicle, near peak torque is generated from zero rpm to the peak power point. Therefore, as will be seen in the charted data, high torque numbers at lower speeds could not be captured on this dyno.

The vehicle was operated in an all-electric mode during testing as this was the worst case condition where the bus voltage and power is not supported by APU operation. The objective of this first run was to determine a baseline power draw for future "loaded" runs. The first run was conducted with no load on the dynamometer, meaning the dynamometer was not placing additional loads on the system. However, the additional inertia and friction of the rolling drums would be a factor in the measurements taken. In addition, the inertia of the truck driveline and the losses in the differential would also be measured. As show in Figure 33, power was shown to ramp up from approximately 4 kW (as seen in the motor-only run during bench testing) and then increase with speed to nearly 135 kW at 12,090 rpm. The 4 kW starting power was expected, as there are nearly no losses in the drivetrain at very low rpm. There is a small instability in the power at approximately 4,000 rpm, which appears to be one of the modal frequencies of the drivetrain. As will be shown, this disappears in all loaded tests. The power then continues on up to a peak of 135 kW at 12,090 rpm or a vehicle speed of approximately 90 mph. This is higher than expected, but just shows that the differential has higher losses than predicted.

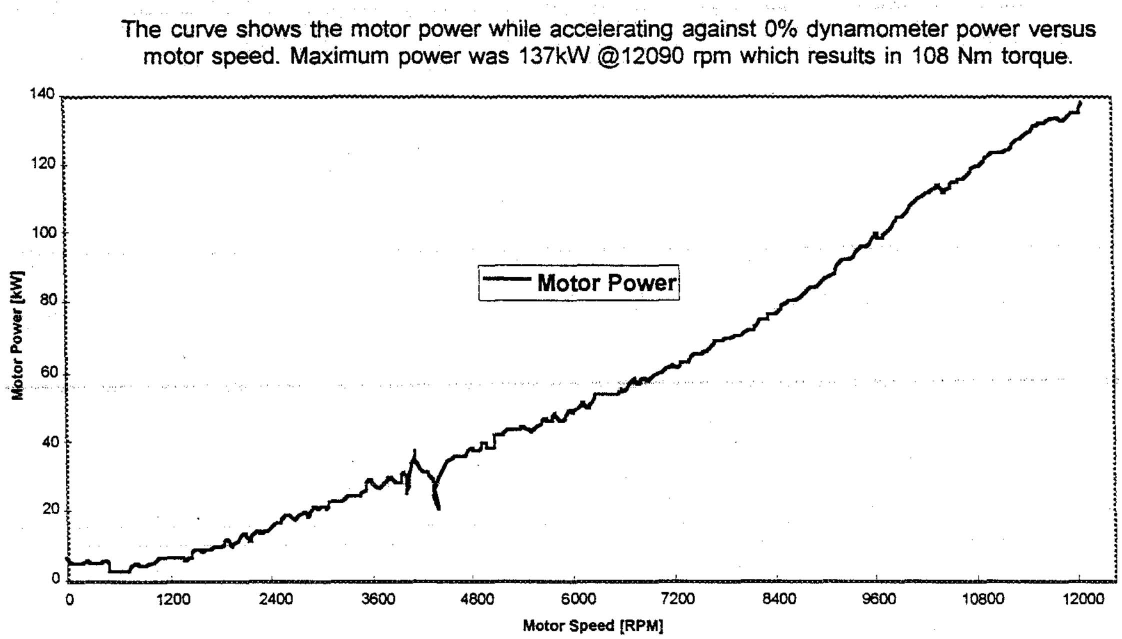


*Figure 33. Motor power with 0% dyno load.*

Figure 34 shows the corresponding torque required to accelerate the entire drivetrain and dyno rollers according to the power levels shown in Figure 33. These numbers were used to form the baseline, upon which other readings were normalized. This test also provides evidence that Goal 5 (12,000 rpm maximum speed) was achieved.

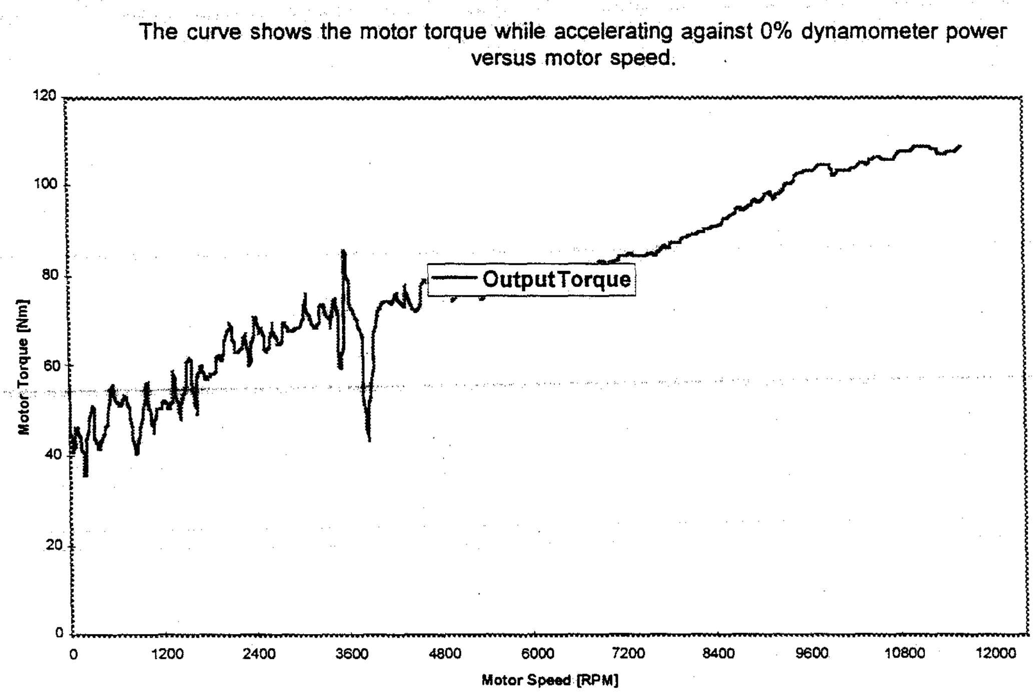


*Figure 34. Motor torque with 0% dyno load.*

For the next test, the dynamometer was set to load the system with 50% of its capability. As shown in Figure 35, The motor power starts at about 4 kW and then increases fairly smoothly to a peak of 198 kW at 4,447 rpm. Figure 36 shows the corresponding torque required to achieve the speeds and power levels demonstrated in Figure 35. Notice that a high starting torque is required to overcome initial rolling resistance. Once moving, the torque required reduces to less than 40NM and then gradually increases with speed.

The dyno was then set to 75% of its capability. Figure 37 shows the power utilized in accelerating the dyno from zero to approximately 3,600 rpm. As shown, the motor power again starts from about 4 kW and ramps up to a peak of 231 kW at 3,606 rpm. Figure 38 shows the corresponding torque, which reaches about 650 NM at 3,500 rpm.

The curve shows motor power while accelerating against 50% dynamometer power versus motor speed. Maximum power was 198kW @ 4447 rpm which results in 425 Nm torque.

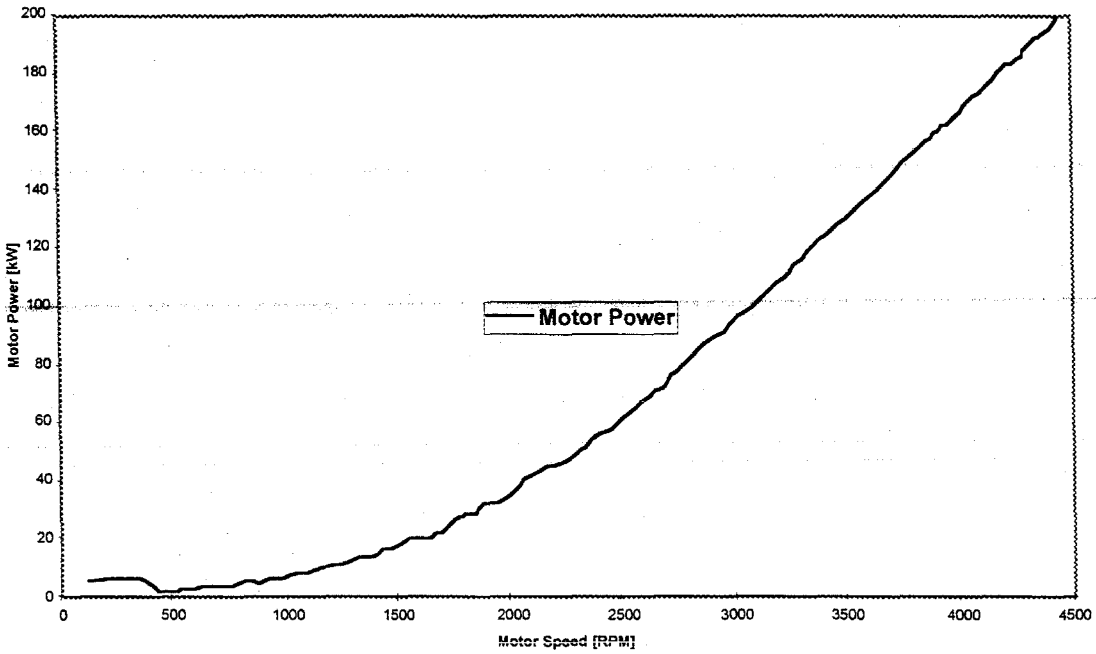


*Figure 35. Motor power with 50% dyno load.*

The curve shows the motor torque while accelerating against 50% dynamometer power versus motor speed.

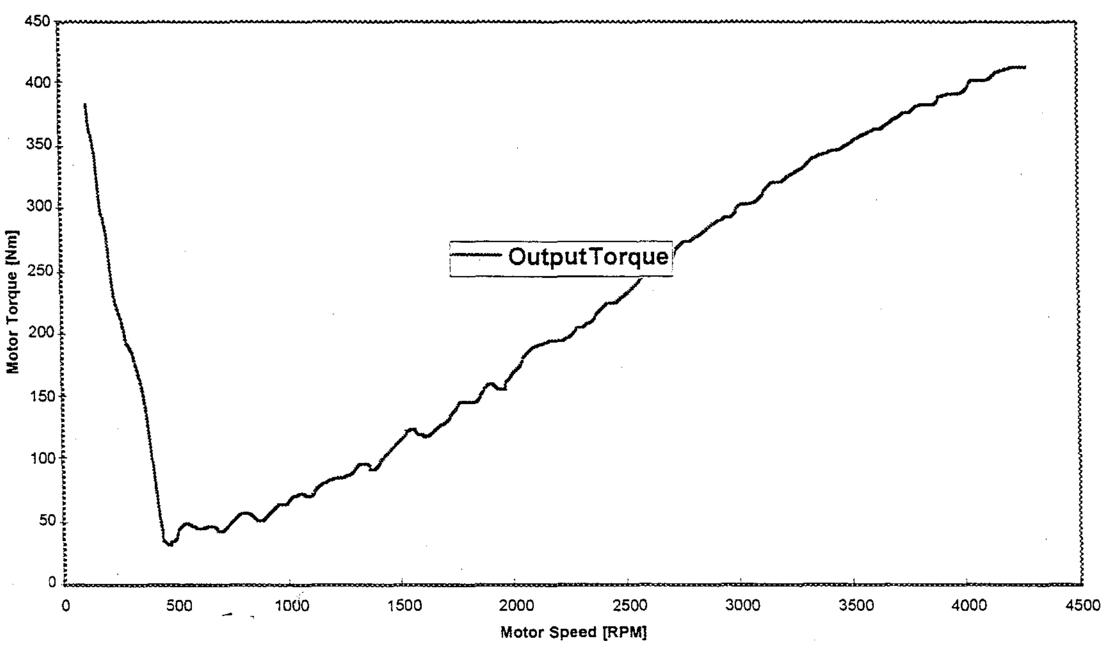


*Figure 36. Motor torque with 50% dyno load.*

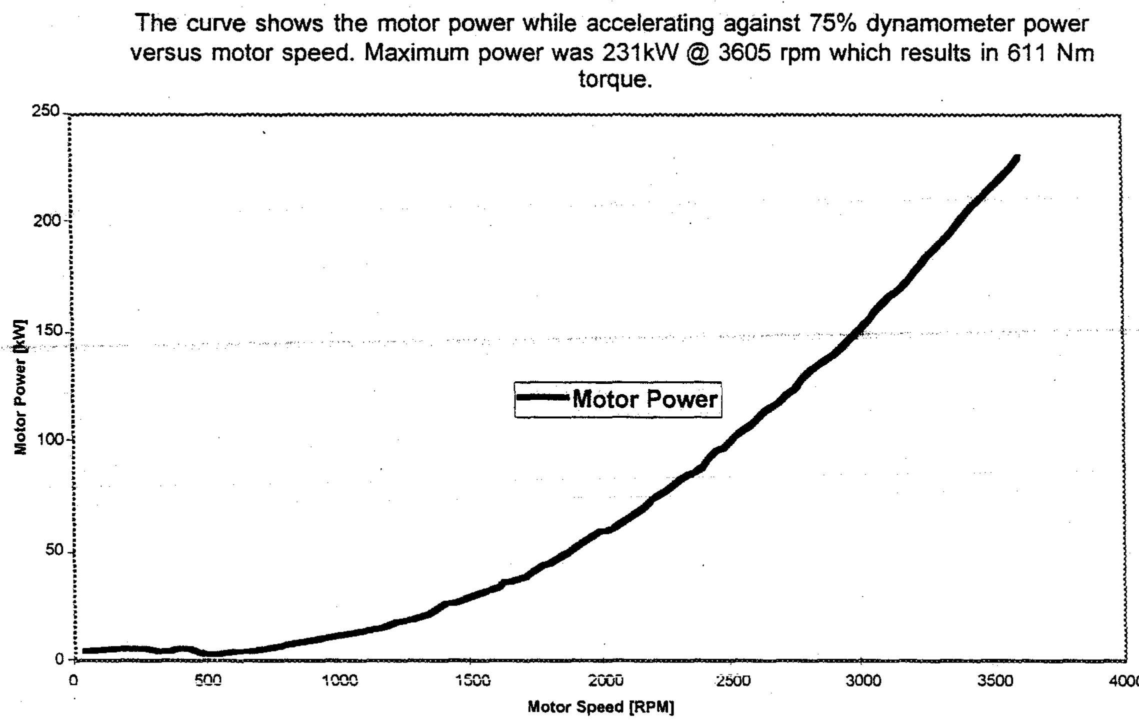


*Figure 37. Motor power with 75% dyno load.*

Finally, the dyno was set to 100% of its capability. Figure 39 shows the power utilized in accelerating the dyno from zero to approximately 3,200 rpm. As shown, the motor power again starts from about 4 kW and ramps up to a peak of 261 kW at 3,144 rpm. Figure 40 shows the corresponding torque, which reaches 792 NM at 3,144 rpm. It should be noted that the torque numbers are not the motor peak capability, but are the maximum load that the dyno is capable of putting on the motor.

The curve shows the motor torque while accelerating against 75% dynamometer power versus motor speed.

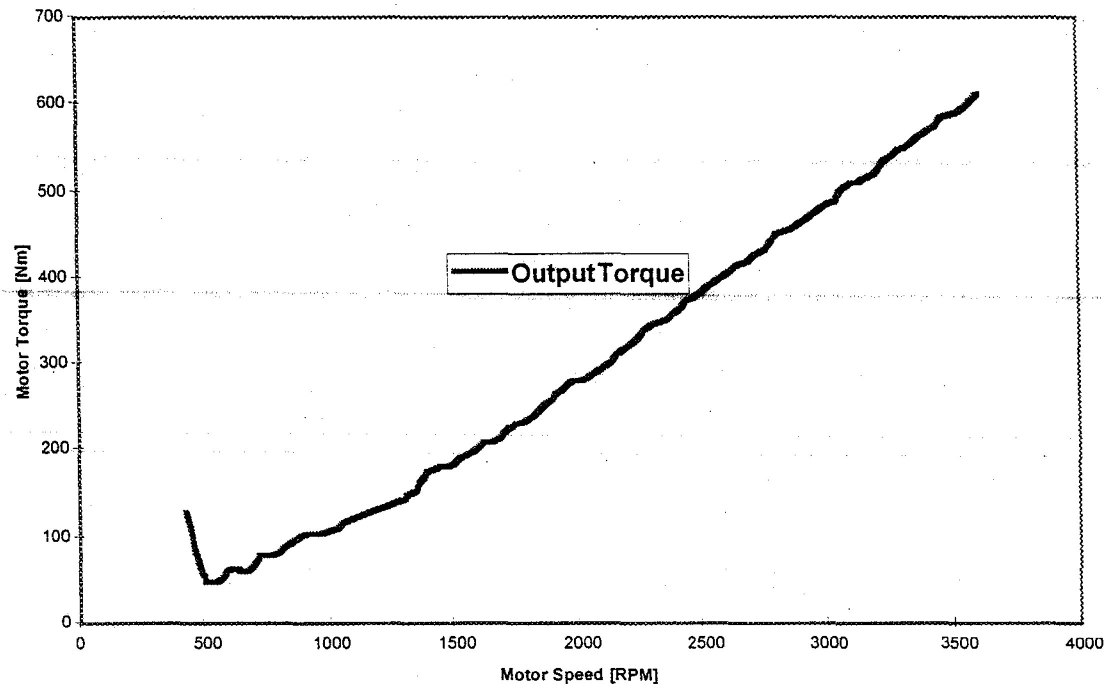


*Figure 38. Motor torque with 75% dyno load.*

The curve shows the motor power while accelerating against 100% dynamometer power versus motor speed. Maximum power was 261kW @ 3144 rpm which results in 792 Nm torque.

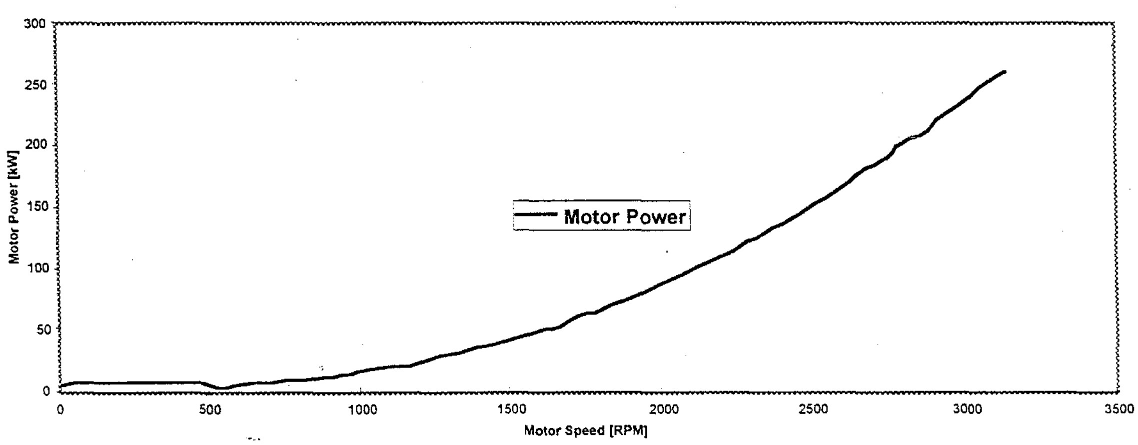


*Figure 39. Motor power with 100% dyno load.*

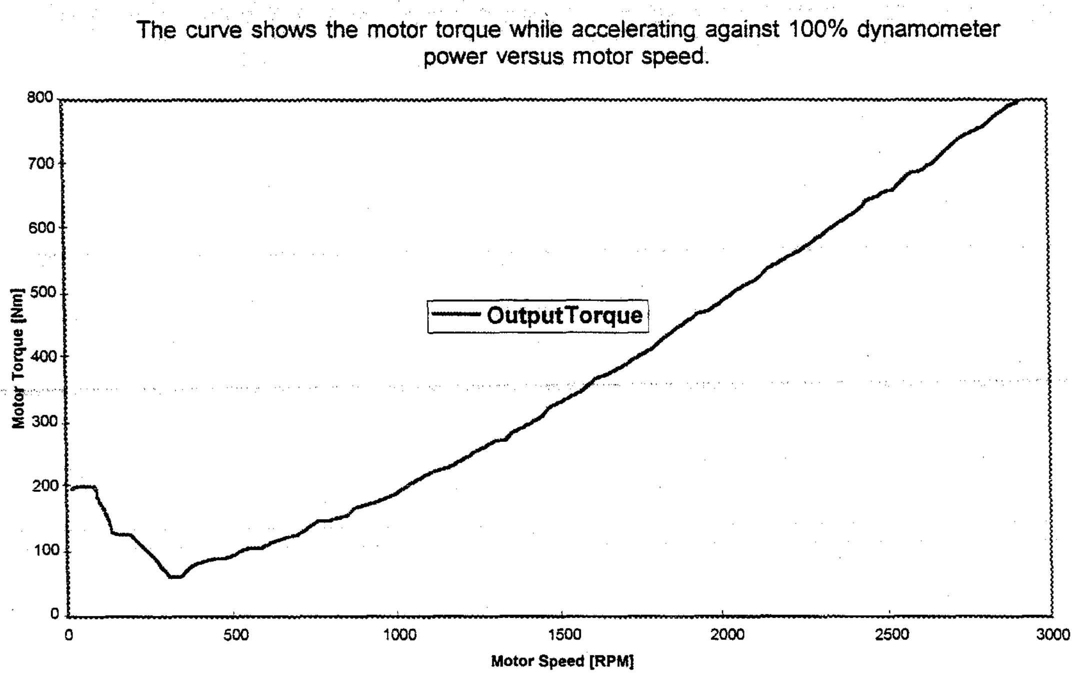


*Figure 40. Motor torque with 100% dyno load.*

As previously shown in Figure 39, the motor peak power was limited to 261 kW. However, this was not the peak capability of the motor, it was limited by the bus voltage at the time of testing. Figure 41 shows the bus voltage, motor voltage, and the motor power. The motor voltage has been converted from its AC value to the corresponding rectified DC value by multiplying by 1.32 (standard 3-phase AC to DC). The power curve ramps up from 4 kW and zero rpm toward its peak of 261 kW after about 57 seconds. While this is occurring, it can be seen that the DC bus voltage begins at approximately 580 and decreases to about 500 VDC at peak power. During this period, the normalized motor voltage is increasing from about 150 VDC to a peak of 500 VDC. At the point where the DC bus voltage has decreased to the 500VDC and the motor voltage has increased to 500 VDC, there is no margin left and the controller has no choice but to reduce power. This power reduction is shown in the Motor Power curve exactly at the point the both other curves meet. The important data this yields is that with two parallel packs of 48 lead-acid batteries, it is impossible to obtain more than 261 kW (348 hp) without turning on the APU. However, with the vehicle's 75 kW APU activated, the DC bus will be boosted by approximately 30 VDC, which we have analytically determined would allow the motor to produce about 321 kW before again being limited by the DC bus.

Since a power level of 321 kW equates to approximately 430 horsepower, the HEPT drive system has demonstrated the ability to match the power output of most large Class 8 trucks, which typically have engines rated at 350 to 400 Hp. The power output of the HEPT drive system can be increased to the 450-500 Hp range by adopting a larger APU, such as the 120 kW versions we plan to utilize in our next Class 8 prototypes. This would provide a power output matching the largest Class 8 trucks on the road today.

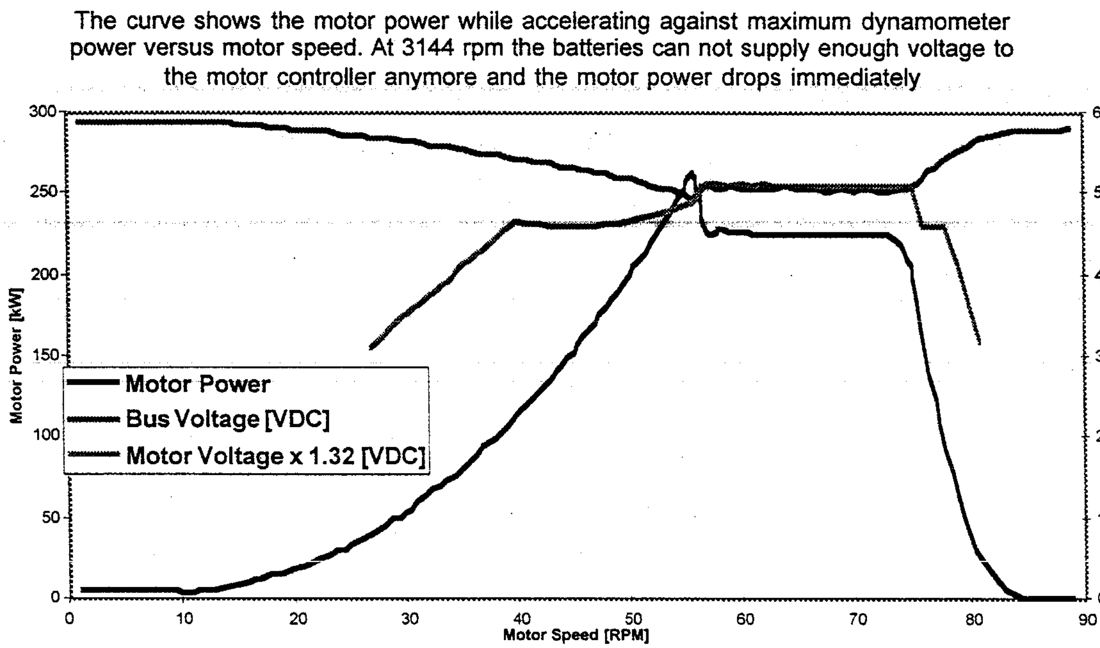


*Figure 41. Bus voltage vs. motor voltage and power.*

Also shown in Figure 41, after the power peaked, it was reduced to 225 kW and operated for 20 seconds to demonstrate the motor's continuous power capability. The 225 kW was again not the motor's peak capability, but rather the level which allowed the AC and DC buses to remain even. This provides evidence that the motor is capable of exceeding Goal 1 (215 kW continuous power) by at least 10 kW and likely more with the APU activated and a higher bus voltage maintained. In the absence of an APU to boost bus voltage, Goal 2 (peak power of 288 kW) was not achieved in this particular test, due to the dip in the bus voltage, but, as discussed above, we extrapolate significantly higher peak power levels with the APU running.

Figure 42 demonstrates the efficiencies of the motor and drivetrain. The power required at no load was divided by the power required at full load to obtain the mechanical efficiency of the drivetrain. The power utilized by the motor was compared to the output readings on the dyno (full power minus no load power to eliminate drivetrain losses) to obtain the motor efficiency. As shown, the motor reaches a peak efficiency of 96% at from 2,400 to 2,600 rpm, which correlates to the base speed of the motor. This exceeds Goal 6 of 92% motor efficiency. Goal 7 of characterizing the power torque and efficiency is met as shown in Figures 39, 40, and 42.

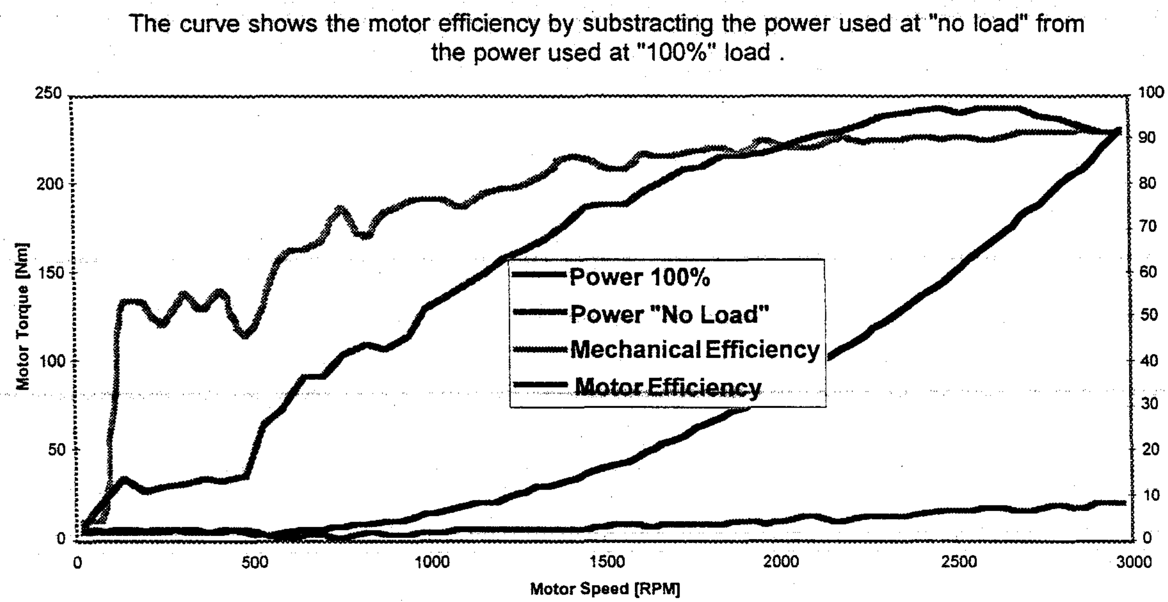


*Figure 42. Motor and drive system efficiency.*

### *8.2.4 Follow-on Road Testing*

Since the dyno was not capable of generating or measuring the torque of the motor at low speeds, an alternate test was devised to determine the peak and continuous torque ratings of the motor. The HEPT vehicle was attached via a chain to an 18,000 lb tow tractor produced by the Entwistle Company. The objective was to have the HEPT vehicle tow the Entwistle tractor and gradually increase brake application on the tractor until the HEPT motor stalled. Figures 43 and 44 show the Motor Torque and Speed during these tests. The first (left most) hump on Figure 43 was a warm up and can be ignored. The right hump on Figure 43 first shows the torque as the HEPT is accelerating the tow tractor. There is then a flat section while both vehicles are gliding at constant speed. Then, as the tow tractor brakes are applied, the HEPT torque is increased to maintain speed. The speed actually kept increasing because the motor torque overpowered the tow tractor maximum drag. The motor reached a peak of over 1,600 NM when the HEPT vehicle started dragging the tow tractor along with locked brakes. At this point the HEPT was commanded to rest. This exceeds the Goal 4 peak of 1,500 NM. During this test, the torque also exceeded 1,000 NM for over 20 seconds and could have continued indefinitely if allowed to continue to drag the tow tractor. Therefore, Goal 3 (continuous torque of 1,000 NM) was also achieved.

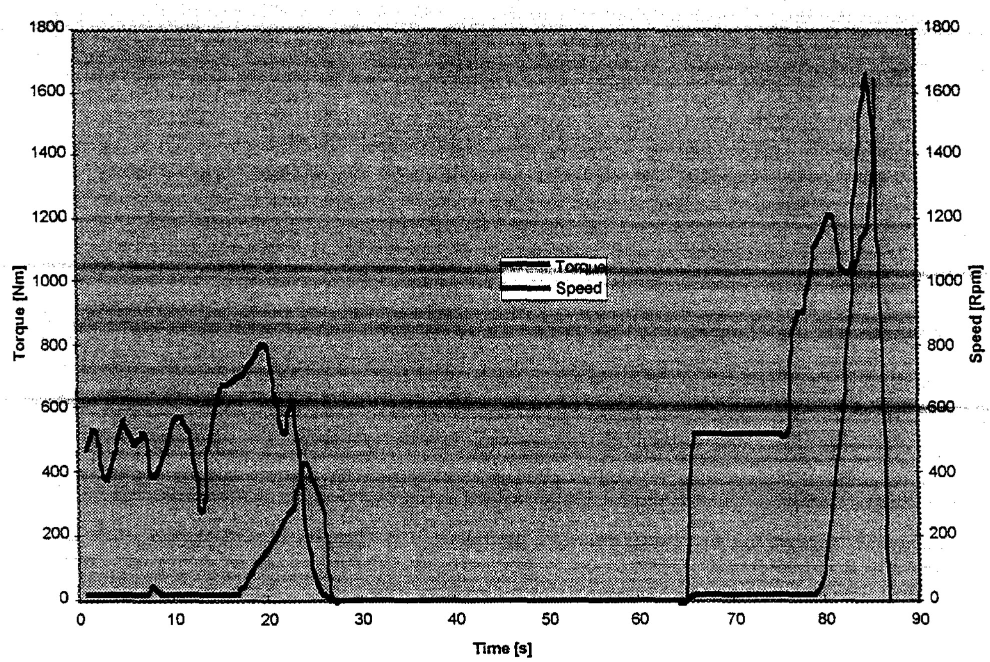


*Figure 43. HEPT pulling tow tractor - first test.*

Figure 44 shows two additional torque tests using the same test setup. By this time, however, the tires were hot and sticky from being dragged so the coefficient of friction was lower and therefore lower torque was required to drag the vehicle.

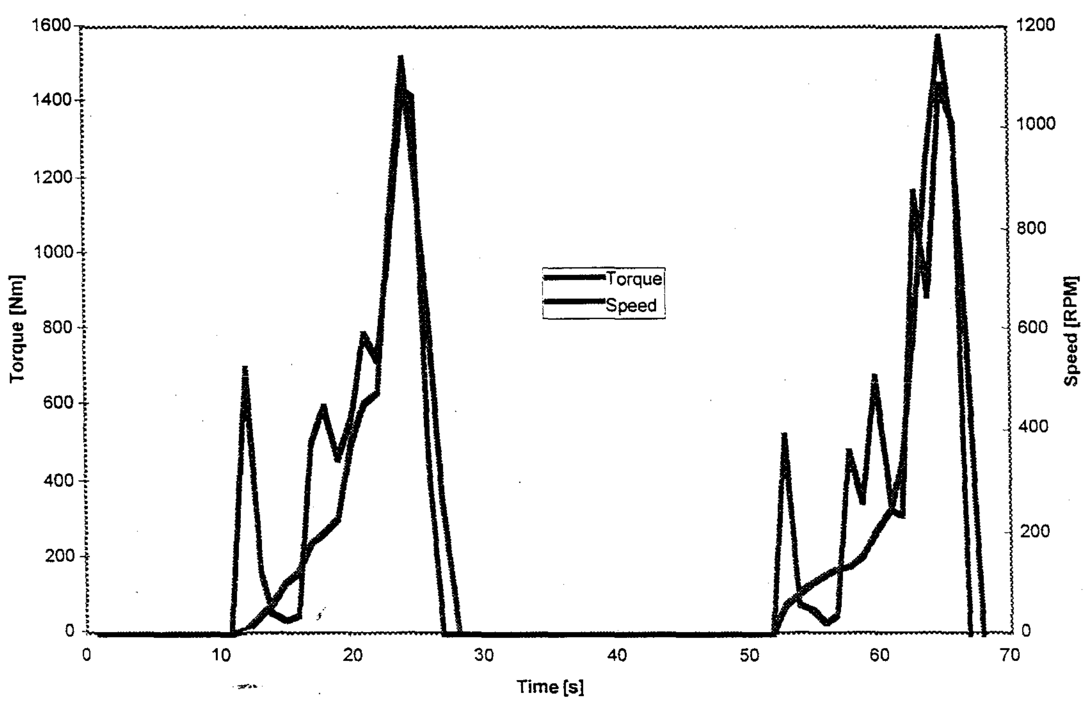


*Figure 44. Dual HEPT pulling tow tractor torque tests.*

#### *8.2.5 Test Summary*

In summary, the HEPT motive drive subsystem proved to be an equivalent, if not superior drive system for its intended service as a local Class 8 truck. The system operated very smoothly and was liked by all drivers of conventional vehicles. All performance goals were met or exceeded. While observed peak power was 261 kW (vs the 288 kW goal), it was limited only by the batteries' ability to maintain DC bus voltage, not due to any limitation of the motor or controller. Based on calculations of our 75 kW APU's ability to augment DC bus voltage, the extrapolated peak power of the motor in the HEPT vehicle is 321 kW (430 hp). The following list summarizes achieved performance vs program goals.

| | | |
|---|---|---|
| Goal 1) | 215 kW continuous power | 225 kW achieved |
| Goal 2) | 288 kW peak power | 261 kW measured/321 kW calculated with APU on |
| Goal 3) | 1000 NM continuous torque | 1000 NM measured |
| Goal 4) | 1500 NM peak torque | 1600 NM achieved |
| Goal 5) | 12,000 rpm maximum speed | 12,000 rpm achieved |
| Goal 6) | 92% peak efficiency | 95% achieved |
| Goal 7) | Characterize power, torque and efficiency | Complete |
| Goal 8) | Evaluate acceptability of electric drive system | Drivers preferred HEPT |

While the testing addressed in this subsection focused on the performance of the Kenworth motive drive and battery subsystems, the other main vehicle subsystems clearly performed at levels equal to or greater than initial project expectations. In road testing conducted throughout 1999, both the Kenworth and Peterbilt vehicle control subsystems demonstrated the ability of the APU to turn on and off automatically, which was a key program objective. Also demonstrated was an APU load-following capability, which addresses both the dips in bus voltage discussed in this chapter and the spikes caused by regenerative braking, as discussed in *Chapter 3, System Controller Development.* The APU subsystem itself, both in static and road tests, has demonstrated the ability of both the GM and John Deere engines, combined with permanent magnet generators, to work together to supply desired voltage, current, and power levels. The accessory drive subsystems on the Kenworth and Peterbilt vehicles successfully support power steering, braking, and other accessories when the APUs are not running.

### 8.3 Peterbilt Truck Testing

In late 1999 we performed a series of basic tests of the Peterbilt prototype truck to gain a preliminary understanding of the performance of this vehicle. A series of acceleration tests were performed, and drawbar pull tests were conducted to determine the truck's approximate towing capacity. Since a trailer was not available, these tests were performed with the tractor itself, which had a total weight of 16,740 lb. and a rear axle weight of 6,755 lb. However, the performance of a fully loaded truck of this class can be roughly extrapolated from our results.

Specific results of the Peterbilt truck tests were as follows:

| | |
|---|---|
| Acceleration time, 0 to 30 mph: | 13.8 seconds |
| Acceleration time, 0 to 55 mph: | 55.3 seconds |
| Maximum speed: | 85 miles per hour |
| Drawbar pull, low gear: | > 6,600 lb. |
| Drawbar pull, high gear: | 2,750 lb. |

The drawbar pull tests were conducted using a load cell and one of ISER's hybrid tow tractors (weighing 26,000 lb.) as a stationary object. Following the low gear drawbar measurement of 6,600 lb., the Peterbilt truck began to move the tow tractor, so the upper limit of drawbar pull remains unknown. However, the 6,600 lb. capability that was measured equates to the ability to tow a trailer weighing more than 80,000 lb., the legal Class 8 truck weight limit in California. This is fairly remarkable, as the 100 kW motor in the Peterbilt truck has only a fraction of the power and torque of the more advanced motor in the Kenworth vehicle.

In addition to these specific test results, road testing of the Peterbilt truck indicated superior hill climbing ability. The vehicle appears capable of meeting its design requirement, which is to travel a 12% grade with a 55,000 lb. load.

### 8.4 Future Plans

ISER is continuing to make improvements in all of the technologies incorporated into the Kenworth truck, both under separately funded programs and at the company's own expense. A 190 kW Siemens motor and dual module controller was installed into a Class 8 truck built by ISER for UC Riverside and the U.S. Army in late 1999, and this vehicle is demonstrating superior power to the Peterbilt truck, and a similar level of reliability. A second generation United Defense-derived motor is being built and will be demonstrated in a 40-foot hybrid bus in the second half of 2000. Improved hybrid control systems are being developed and will be demonstrated in this bus, as well as the Norcal Waste hybrid-electric refuse collection truck to be built by ISER in mid-2000. Some time in late 2000 or 2001, we will also follow through on our original goal of transporting at least one of the HEPT vehicles to the PACCAR Technical Center in Washington, where it will be further tested for endurance and performance.

ISER has developed a "HEPT-2" technology plan aimed at elevating all major components of the Kenworth truck to levels of reliability and robustness sufficient to allow this vehicle, with its more advanced technology, to perform in operational service with Crown Disposal or a similar firm. The budget for this activity is approximately $1.3 million, and ISER has recently begun the process of soliciting external funding to support this activity in 2000-2001. Toward the end of the HEPT project, we also received an initial funding commitment for a proposed turbine-driven hybrid Class 8 truck project, which is aimed at placing a Class 8 line haul truck, using a turbine-based APU subsystem, into operational service in the Los Angeles in 2001.

In conclusion, the year of vehicle testing concluded during the final year of the HEPT program seem to validate the basic premises of the Hybrid-Electric Prototype Truck project; namely, that a down-sized combustion engine, working in concert with an electric motor and energy storage system, can meet the basic operating requirements of vehicles in the Class 8 truck range. Road testing with professional truck drivers at the wheel has further indicated that the HEPT drive system offers several performance features that compare favorably with those of conventional diesel trucks, including more rapid acceleration, absence of diesel emissions and associated odors, and a smoother, quieter ride. Testing of the HEPT prototypes and/or future demonstration vehicles incorporating reliability and robustness improvements will be required to validate the ability of the HEPT drive system to function in a "real world" environment and to produce large reductions in fuel consumption and total exhaust emissions. However, preliminary indications of fuel efficiency with the HEPT vehicle, and exhaust emissions measured by ISER from the HEPT engine and engines used in our other hybrid-electric drive systems, provide confidence that these objectives will also be met.

Based on the results of the HEPT project, ISE Research strongly advocates continued research and development in the application of hybrid-electric drive systems to large vehicles. In our company's opinion, no other currently foreseeable motor vehicle technology offers the combination of potential economic, performance, and environmental benefits indicated by the HEPT drive system.