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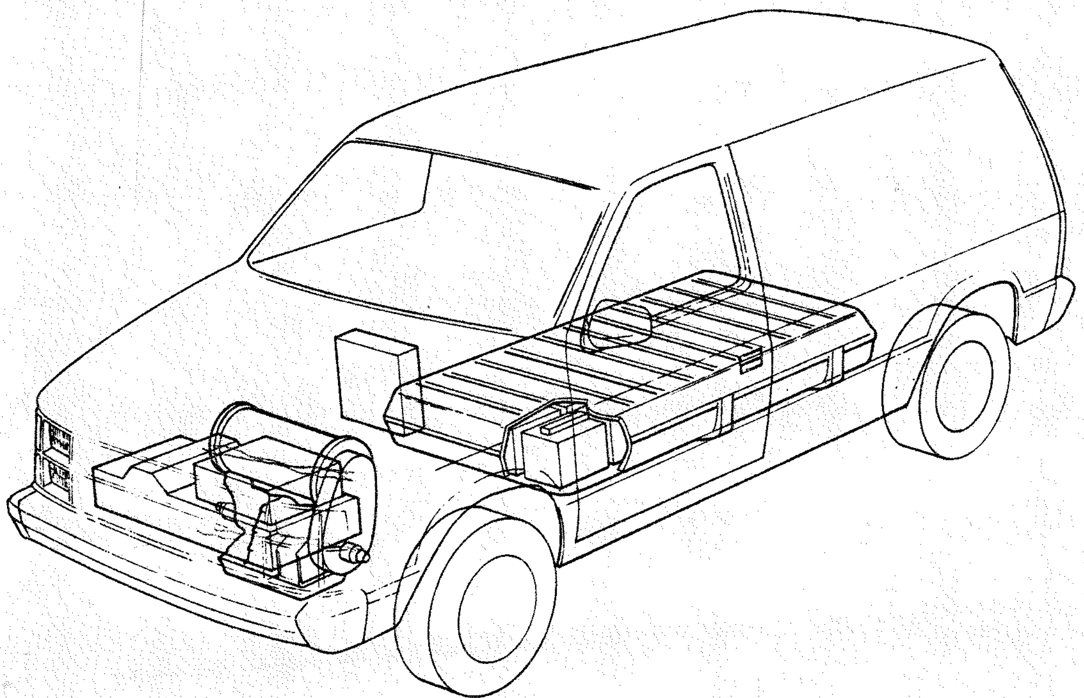

DSEP Advanced Dual Shaft Electric Propulsion System Technology Development Program

Annual III - September 1987

Eaton Corporation — Corporate R&D, Detroit Center

Contract **DE-AC07-84NV10366**
Program Management: Idaho National Engineering Laboratory

U.S. Department of Energy Conservation and Renewable Energy
Office of Vehicle and Engine R&D

MASTER

EATON

ADVANCED DUAL-SHAFT ELECTRIC PROPULSION SYSTEM TECHNOLOGY DEVELOPMENT PROGRAM

DSEP

ANNUAL REPORT - III

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Prepared by

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EATON CORPORATION

Corporate R&D - Detroit Center

Under Contract DE-AC07-84NV10366

Idaho Operations Office

U.S. DEPARTMENT OF ENERGY

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Conservation of Renewable Energy

Office of Transportation Systems

ABSTRACT

This third annual report of the DSEP program summarizes all program activities from September 1986 to August 1987. These activities comprise: completion of dynamometer testing the integrated powertrain of the first test bed vehicle (TB-1), installation of that powertrain in the TB-1 vehicle, the TB-1 vehicle tests to date, new design of some powertrain subsystems for the second vehicle--the NVH (noise, vibration, harshness) test vehicle, construction of a complete powertrain for the NVH vehicle, the DSEP battery subsystem tests and development, and activities related to the program management. A bibliography listing all documentation generated during the period is also included.

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EXECUTIVE SUMMARY

The DSEP (Dual Shaft Electric Propulsion) program is advancing electric propulsion system technology by means of integrated development of a nickel-iron battery, an ac motor and controls, and a two-speed automatic transaxle within a light-weight van suitable for use in an urban/suburban environment (the motor and transaxle are arranged on two parallel axes, hence the term "dual shaft").

The DSEP Program industrial research team includes Eaton Corporate Research and Development, Detroit Center (Southfield, Michigan), the prime contractor, with responsibilities for powertrain technologies and propulsion system integration; Eagle-Picher Industries (Joplin, Missouri) responsible for battery technology; and ASC, Inc. (Southgate, Michigan) responsible for test vehicle modification and integration.

There were several major accomplishments during the third full fiscal year of the program:

- Dynamometer testing of the entire integrated powertrain system for the proof-of-concept test bed vehicle (TB-1) was completed. The tests successfully proved steady state, dynamic, and extreme temperature operations, and assured subsystem compatibility as well as readiness for vehicle installation. However, some inverter-limited shortfall in expected peak power was also indicated.

- The TB-1 vehicle, an extended version of the Chrysler T-115 mini-van, was made operational. Installation of the entire powertrain system into the vehicle, initial shakedown, and basic driveability tests were completed at Eaton, with satisfactory results.

- Extensive vehicle performance tests were conducted at Chrysler Corporation's Chelsea Proving Grounds, reaching or exceeding most original performance goals, except a somewhat reduced acceleration performance due to the peak power shortfall.

- The peak power-limiting system element--the inverter--was redesigned for higher power, and was fabricated for use in the second vehicle that will be built for the DSEP program - the NVH (noise, vibration, harshness) test vehicle. Other subsystems of the NVH vehicle powertrain were similarly revised to correspond to the new inverter design. Fabrication of all subsystems is nearly completed. The assembly will represent a significantly improved powertrain, incorporating many innovations resulting from the TB-1 test and development work.

- A major advance in electric vehicle drivetrain technology was achieved with the development of an advanced control feature that electronically eliminates the effect of driveline torsional resonances by sensing the rate of change of traction motor and transaxle output speeds and then correspondingly modulating the traction motor torque to obtain a smooth transaxle output torque delivery. The feature has effected smooth full-load vehicle starts and transaxle shifts without any hydraulic clutch torque modulation for either function, and without the need for any torsional dampers in the driveline. The feature is fully operational in the TB-1 vehicle powertrain.

- The DSEP battery subsystem underwent extensive developmental and life cycle tests at Argonne National Laboratories, Eaton and Eagle-Picher. The subsystem appears capable of meeting all program goals, called by researchers at Argonne National Laboratory "the most ambitious ever imposed on a vehicle battery". Most importantly, the system is operating at the targeted rate of degradation of energy capacity over 1200 charge/discharge cycles. An area of concern is the subsystem's ability to provide full peak power near the end of each simulated discharge cycle. The cause appears to be the sub-performance of only a few modules rather than the entire pack. Intensive effort is underway to fully diagnose and correct the problem.

INTRODUCTION

The objective of this 48-month program is to advance the state of the art of electric vehicle propulsion system technology using subsystem technologies previously developed under contracts to the Department of Energy by Eaton Corporation and Eagle-Picher Industries. This propulsion system technology is to be integrated into a van for test bed evaluation. The program includes the design, testing and development of two (with an option for a third) complete experimental proof-of-concept propulsion systems installed in vehicles. These vehicles are to be converted, and the powertrains and battery subsystems are to be designed, built and thoroughly tested for performance, reliability and durability. One vehicle is to be delivered to the Government for further independent tests and evaluation.

The powertrain technology, originally developed for passenger cars under contracts to DOE by Eaton, is being upgraded for higher power and starting torque required for van applications. The Ni-Fe battery subsystem was designed and is being furnished by Eagle-Picher; it is a higher voltage adaptation of their battery technology under development for DOE since 1978. These two subsystem technologies are to be jointly advanced as integral parts of a complete propulsion system. Its integration into the recently developed Chrysler T-115 van, a multipurpose front-wheel drive vehicle of low aerodynamic drag, is expected to permit a fair assessment of technical and economic merits of the overall system. Modifications of the T-115 production vehicle chassis are being performed by ASC, Inc.

The first test bed vehicle (TB-1) became operational in March of 1987. It has passed initial dynamometer and driveability tests, and has completed most of the planned road tests at the Chrysler Chelsea Proving Grounds. Initial observations are favorable. Accumulated test data is being processed for inclusion in a comprehensive report covering all TB-1 vehicle tests. Based on test results and development of the TB-1 propulsion system, the design of its several subsystems (inverter, controller, state-of-charge meter) has been revised to assure achievement of all performance goals. Fabrication of this second propulsion system hardware is nearly completed. This report covers in some detail the third year (September '86 to August '87) of these DSEP program activities.

DYNAMOMETER TESTS OF THE INTEGRATED TB-1 POWERTRAIN SYSTEM

The integrated powertrain system tests assured operational compatibility of the subsystems and proved their readiness for installation in the test bed vehicle. However, the tests also indicated an inverter-limited peak power deficiency in the traction motor's operational spectrum above its base speed.

These tests comprised the following operations: steady state, dynamic with gear shifts, high and low temperature, and special conditions such as rolling start-up and safe default. Each subsystem had undergone prior independent testing to determine their individual characteristics.

The steady state tests mapped overall system efficiency across the speed and load spectrum, ranging to 12,000 rpm and between +1085 Nm (800 lb-ft) and -1085 Nm (regenerative) torque. **Figures 1 and 2** show propulsion system efficiencies in high and low gear. The efficiency is better than 70% at dynamometer speeds corresponding to vehicle speeds above 16.1 km/hr(10 mph), and it is above 80% at speeds over 32.2 km/hr(20 mph). **Figure 3** shows overall efficiency of the simulated vehicle system as a function of road speed and load on level ground and no wind. This system efficiency at 88.6km/hr (55 mph) steady speed is 72%, with a road load of 17.5 kW(23.5 hp).

Adequacy of the cooling system was verified with a simulated rated speed 88.6 km/hr (55 mph) run under corresponding load for one hour. With a 32.2 km/hr (20 mph) air flow past the transaxle/motor assembly, maximum oil temperature rose to 79.4°C (175°F) at 29.4°C (85°F) ambient, and to 85°C (185°F) at 50°C (122°F) ambient. These temperatures are well below the recommended maximum of for the oil of about 107°C (225°F), above which accelerated oxidation of the oil begins.

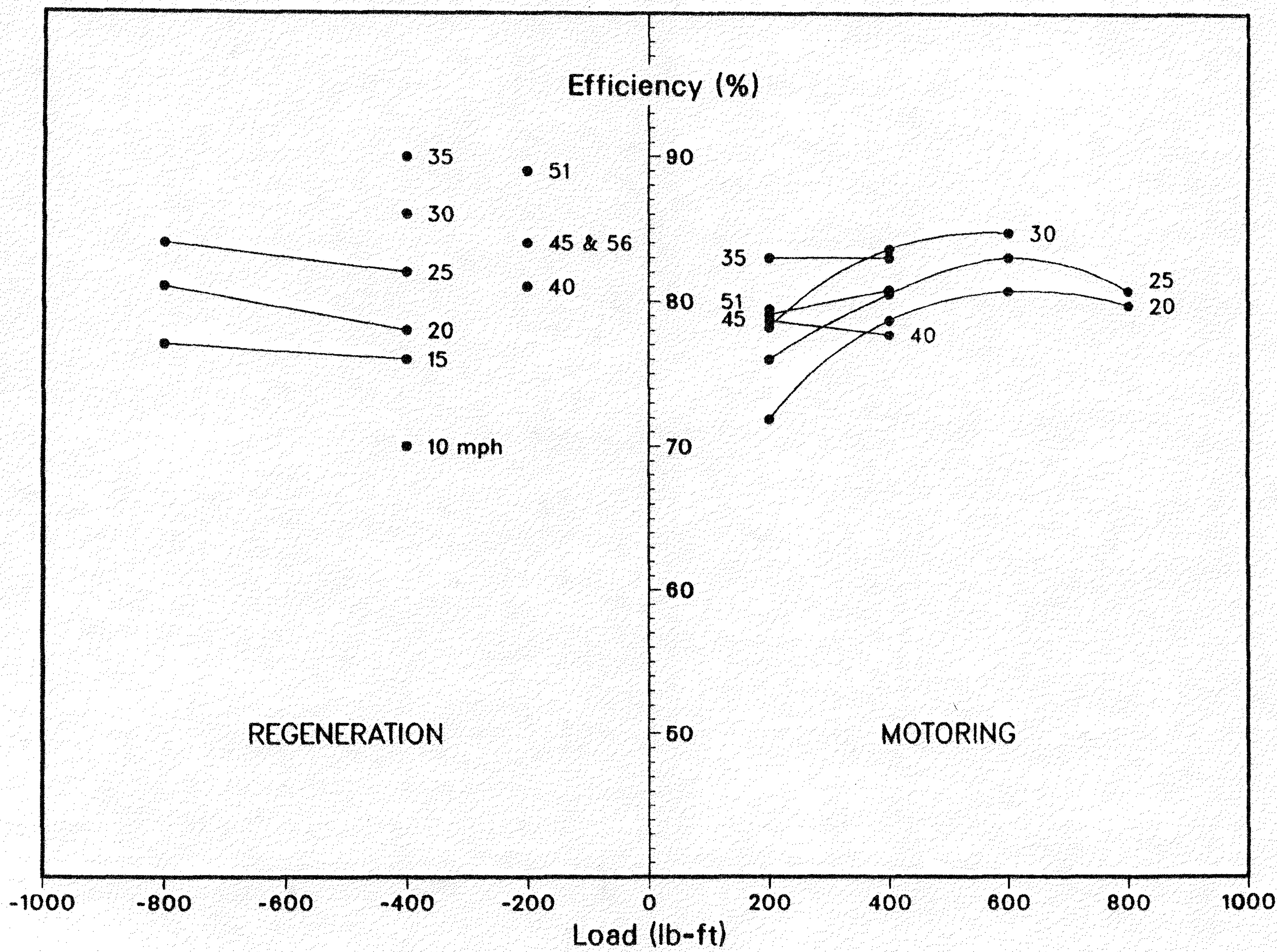

Figure 1 Propulsion System Efficiency in High Gear

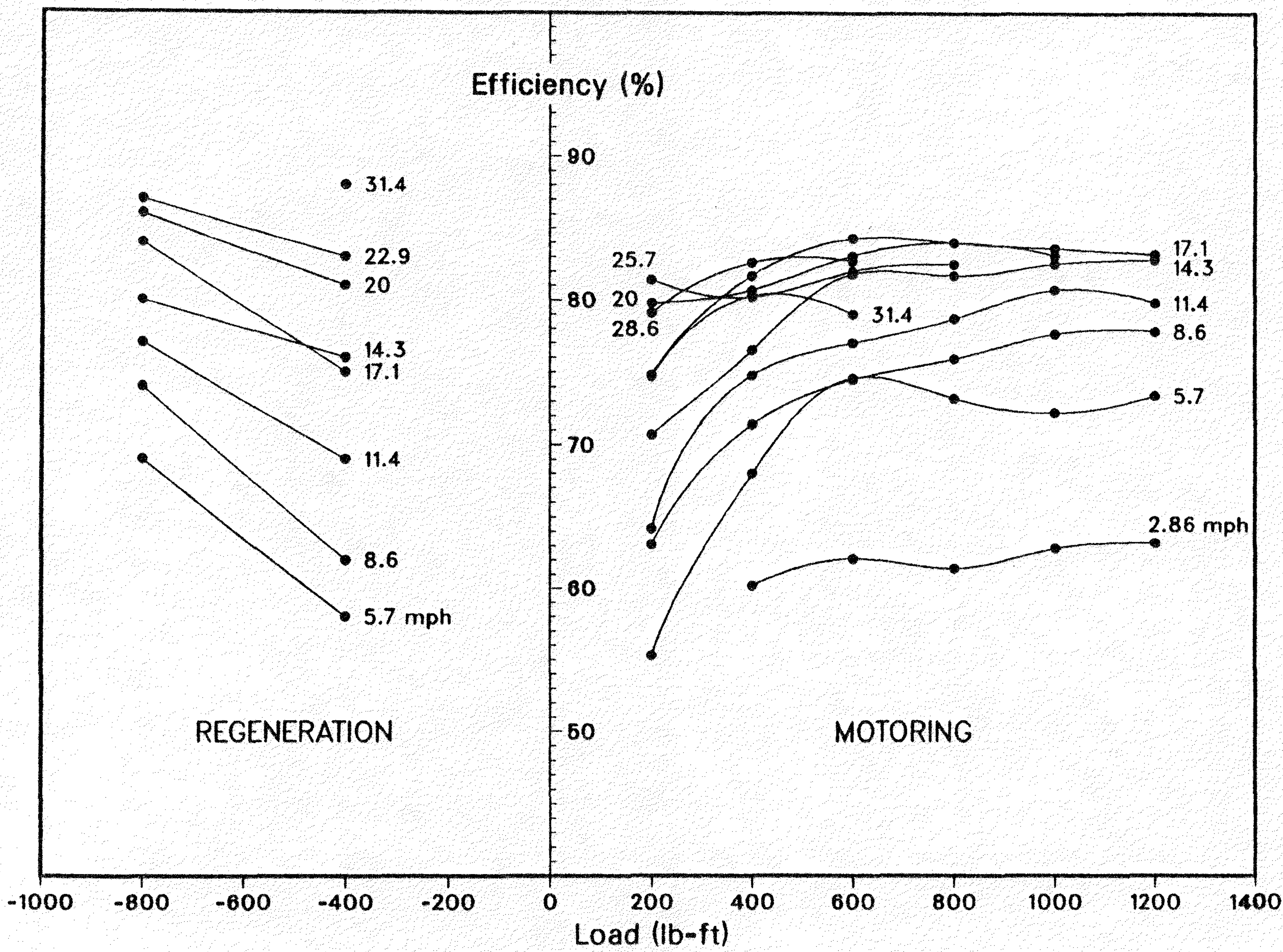

Figure 2 Propulsion System Efficiency in Low Gear

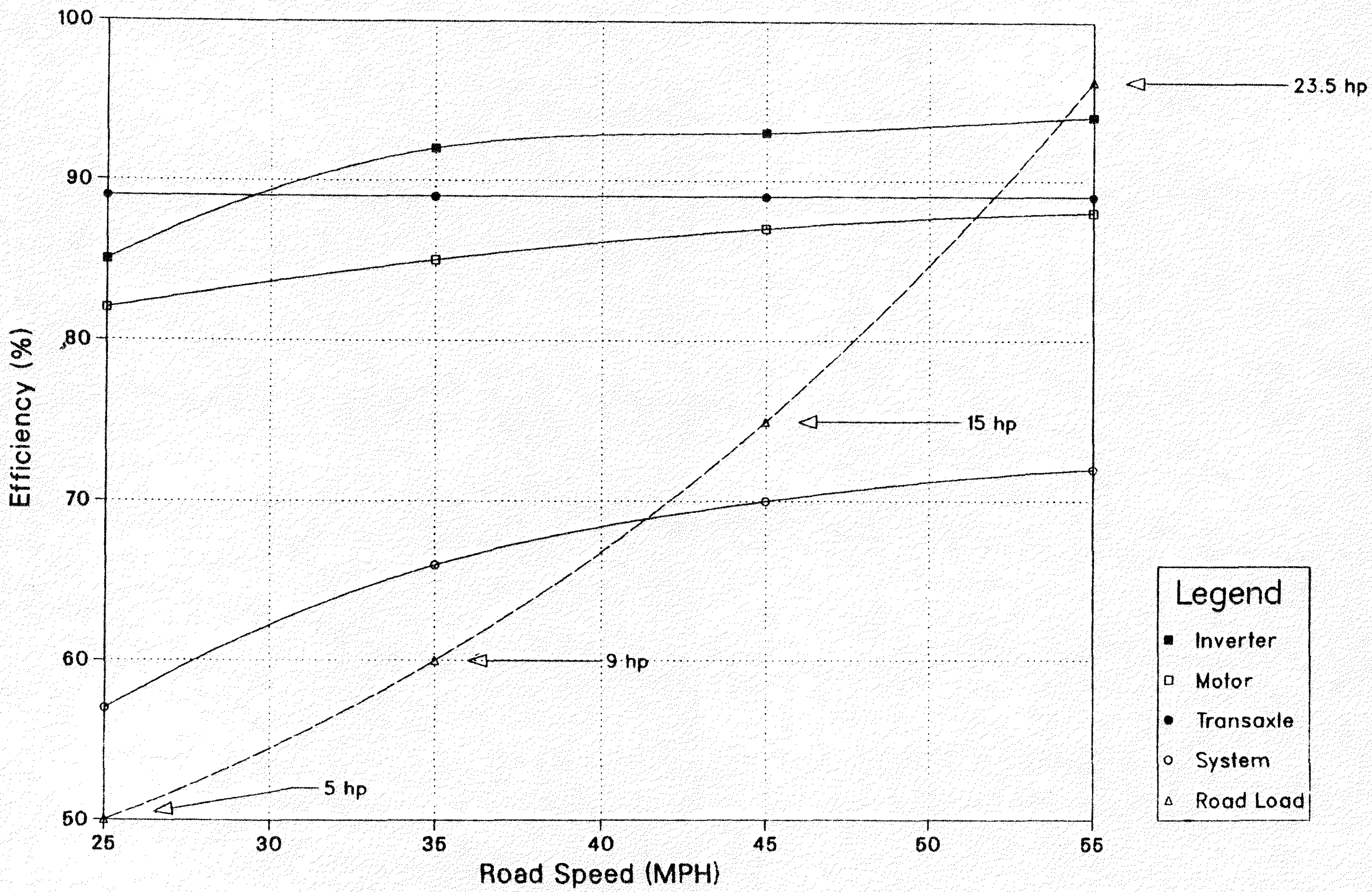

Figure 3 Vehicle System Efficiency vs. Road Speed

Dynamic operation tests comprised measurements of motor slew rates and clutch response times, upshift and downshift routines development tests, and tests of operation under temperature extremes. Motor slew rates were measured in speed-increasing as well as decreasing modes, with the transaxle connected and in neutral position creating the normal drag encountered during a shift. Motor acceleration through 4000 rpm range (5000 to 9000 rpm) took 260 msec, deceleration through the same rpm range--180 msec. These slew rates are compatible with the desired shift times of less than one second. Clutch shift response times are desired not only to be of short but also of consistent duration throughout the operational temperature range. The clutch fill times for the DSEP transaxle were found to be rather stable until well below 0°C (32°F) and repeatable. This facilitates shift programming in the controller for the minimum fill time and then a delay in shift sequence when the oil is cold.

Tests of operation under unusual or partial failure conditions comprised dynamometer simulation of start-ups of the propulsion system while the vehicle is in motion, rocking the vehicle back and forth, and determining default conditions in case of individual component/sensor failure during routine operations. The system startup was smooth in low as well as in high gear, assuring that the system would respond properly should an operator move the selector lever into neutral and back to drive while the vehicle is in motion. A command to reverse the direction of motion under the same circumstances was checked and found to be correctly inhibited until the vehicle speed would drop below 3.2 km/hr (2 mph) to prevent excessive torque reversals. Rocking the vehicle (so as to free it from a rut, in mud or snow) was simulated and found to work well, as the field-oriented motor control allows torque application opposed to the motor rotation. Thus, the gear selector can be shifted at a rapid rate(less than 1 second), with torque applied in each selected position. Continued operation of the system under partial failure was found to be limited. Loss of a single clutch in the transaxle or that of its output speed sensor could be tolerated. Loss of electrical components, sensors or modules is likely to cause complete system shutdown due to absence of critical signals.

The peak power deficiency observed in the traction motor's operational spectrum above base speed ranged as high as 20%. In the speed range below the motor's base speed the torque availability is in excess of required, as the motor is operating with nearly perfect sine wave inputs--the most efficient and desirable condition. Above base speed it becomes impossible to continue to supply the motor with the smooth sinusoidal current desired. The shape of the current waveform begins to show very high peaks, and the average value does not increase in proportion, as it would with a smooth sine wave. The output power of the motor begins to decrease, even though the peak currents are increasing. Precise peak power level, however, could not be ascertained by any means other than testing the motor and inverter together. The magnitude of the shortfall is illustrated with the following measured values from the dynamometer tests. At 8,000 RPM motor speed, the maximum power drawn from the battery by the inverter, limited to 450A in the transistors, was 45 kW. The result is the quotient of 45 kW and 56 kW (goal), or 80%. The 45 kW value is derived from the test data plot of motor speed vs. transaxle output torque, shown in **Figure 4.** The torque values are used for calculating power delivered from the battery terminals, with due consideration for the individual efficiencies of the motor, the transaxle, the inverter, and the transaxle ratio in high gear.

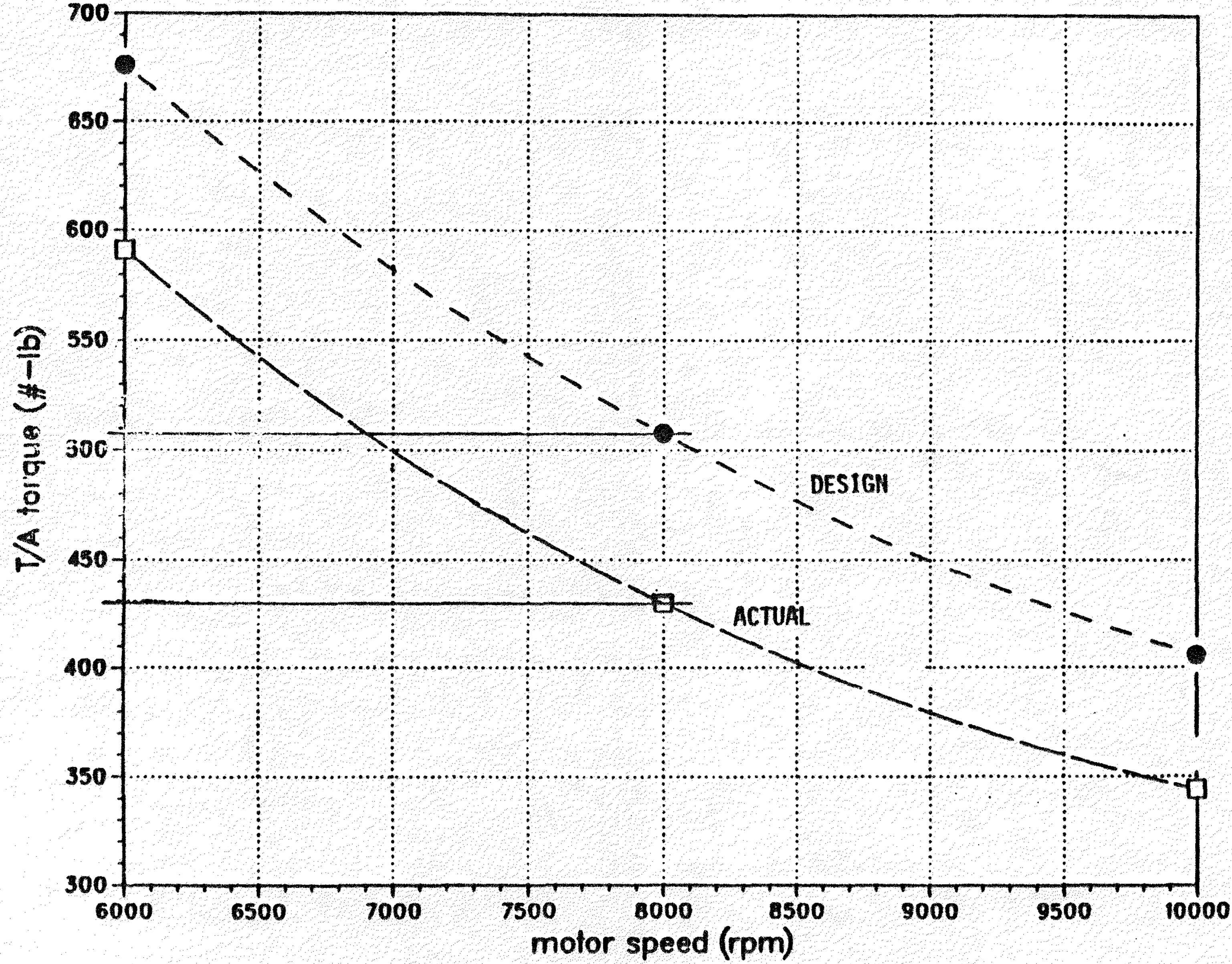

Figure 4 DSEP System Output Torque; Design vs. Actual

POWERTRAIN INSTALLATION IN THE TB-1 VEHICLE

The TB-1 vehicle, an extended (by 17.8 cm or 7 in.) version of the Chrysler T-115 minivan, was received from the ASC, Inc. ready for installation of the Eaton-developed DSEP powertrain. All powertrain subsystems had been dynamometer tested individually and then as an integrated, complete system. New cable and wiring harnesses were fabricated and installed to connect the components of the TB-1 test bed vehicle powertrain. Installation of the subsystems was rather straightforward, as most mounting brackets and fixtures had already been fabricated and installed in the vehicle. Start-up of the system, however, required considerable effort to diagnose and resolve problems arising from the differences in the wiring and interconnects from those on the test stand. Cable lengths and proximity to one another caused new problems and necessitated substantial modifications in the harness. The primary area of difficulty was in the communication link between the microprocessor-based controller and the power inverter. The very high currents switched by the inverter affected nearby components with the radiated energy. The generated noise interfered with the low-voltage signals between the controller and the inverter. Modifications to the controller, inverter and the wiring harness resolved the noise problems, resulting in reliable controller/inverter communications.

One secondary subsystem not previously evaluated was the vehicle-installed version of the battery pack watering and venting system. It is controlled by solenoid valves that admit water to and vent gases from the pack. The system was made operational and the battery was successfully watered in the vehicle.

Other secondary subsystems were checked out, namely, the hydrogen detection system, the vacuum boost of the power brake system, and the combined transaxle/power steering hydraulic system. All were made to operate properly. The dc-to-dc converter for charging the 12V battery was successfully operated at currents up to 70A.

TB-1 VEHICLE TESTS

These tests comprised initial shakedown tests on the chassis dynamometer, general driveability tests around Eaton Research Center, and road tests at Chrysler Corporation's Chelsea Proving Grounds.

The shakedown tests started with sustained running-in operation in each gear across the vehicle's load and speed spectrum, watching for any anomalies such as excessive noise, vibrations, leakage or overheating. The propulsion system proved to be free of these problems, except for the high acoustical noise levels emanating from the hydraulic and vacuum pump systems. Considerable sound-deadening effort was required to quiet these two systems. **Figure 5** shows the TB-1 vehicle on the chassis dynamometer.

The shift control signals were checked out next, and up and down-shifting and shift tuning was performed. Due to the relatively rigid connection in the DSEP powertrain between the motor and vehicle wheels, (no torque converter, slipping clutches or torsional dampers), the motor torque and speed control, and its synchronization with vehicle speed is critical during a shift to prevent violent torsional oscillations.

It became obvious in the course of testing that a means of damping these oscillations would be necessary to obtain smooth vehicle starts and transaxle shifts. A control feature, named the "estimator" (described in the next section of this report), was incorporated in the controller and underwent considerable development and fine tuning before achieving remarkably smooth vehicle starts and transaxle shifts throughout the load range.

Vehicle tests on the dynamometer also confirmed that there is an approximate 20% peak power shortfall with this propulsion system, which would adversely affect the acceleration performance of the TB-1 vehicle.

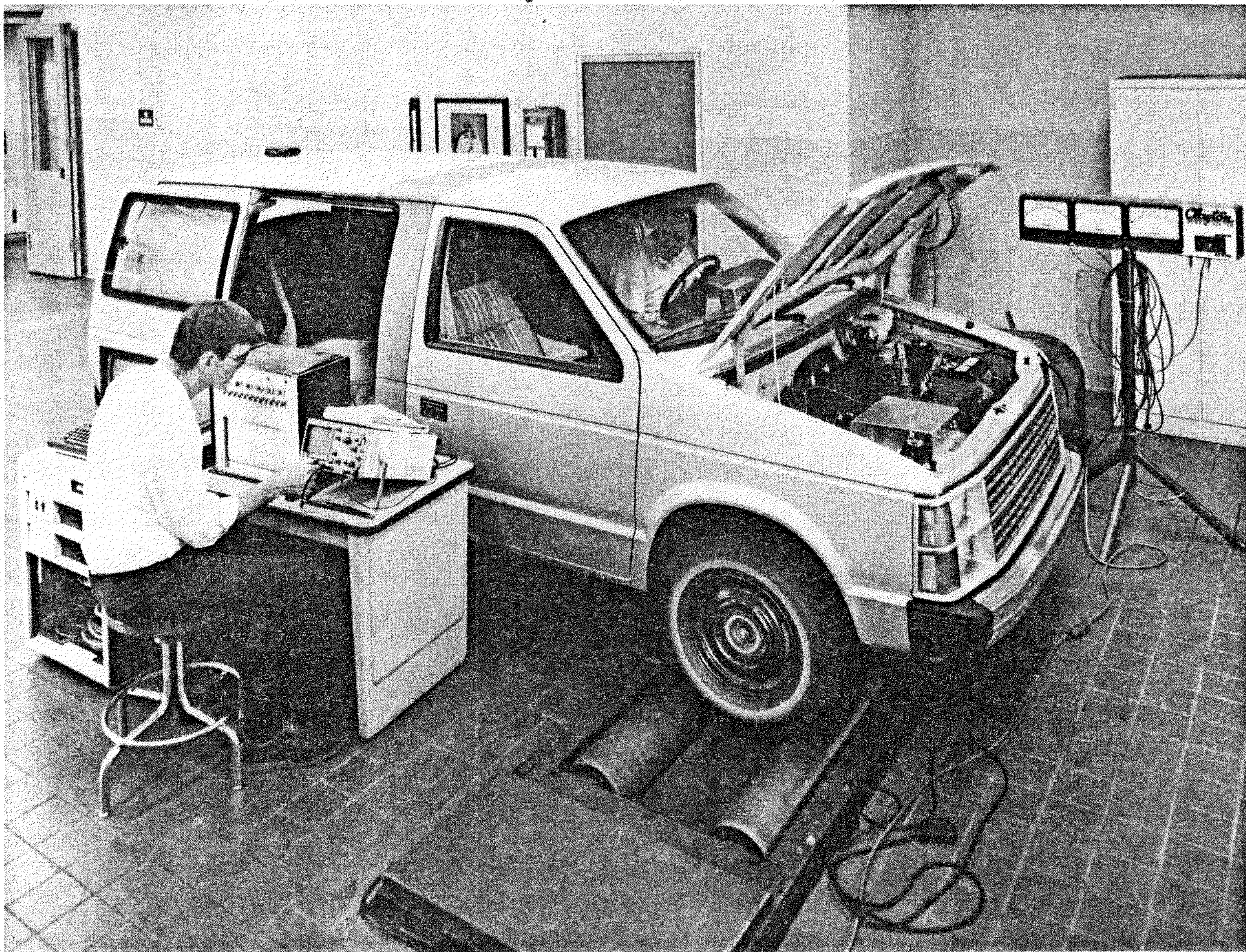

Figure 5 TB-1 Vehicle Test on Chassis Dynamometer

Satisfactory forward/reverse shifting, up and down shifting, braking, and regeneration control capability was established, readying the vehicle for the next round of tests comprising basic static and general driveability tests.

Basic static tests consisted of checking vehicle weights, the static steering effort with power assist, and the vehicle chassis characteristic angles of approach, departure and ramp breakover.

The weights of the TB-1 are as follows:

	Actual Sept.,1987		Projected Jan.,1986	
The van (stretched), less batteries	1374 kg	(3027 lbs)	1327	(2922)
The 28 Ni-Fe battery modules	708	(1560)	699	(1540)
Battery box and support systems	92	(203)	121	(266)
Curb weight	2174	(4790)	2146	(4728)
Maximum payload	545	(1200)	545	(1200)
Gross Vehicle Weight	2720	(5990)	2691	(5928)
Weight distribution, front to rear	48% / 52%			

The characteristic chassis angles measured greater than SAE recommended minimums. The static steering effort was comparable to that of the production van, when tested in accordance with the Chrysler test procedure.

The general driveability tests comprised braking effectiveness, shift quality, response time to driver inputs, and subjective handling evaluation.

Braking effectiveness was checked at speeds up to 88.5 km/hr (55 mph), exhibiting positive feel and freedom of imbalance. Braking characteristics of this vehicle are consistent with braking performance of the production van at maximum load.

Shift quality is smooth at all accelerator pedal positions. Upshift time duration is perceptible; that of the downshifts is barely so. The upshift duration is being being improved upon.

Test of vehicle response to driver inputs was started with checking of the dynamic steering response. It compares well to that of the production van. Slight loss of power steering assist is noticeable if the transaxle shift occurs during a turn, as hydraulic pressure is momentarily diverted to clutch actuation. This will be corrected in the revised hydraulic system for the NVH vehicle by separating the transaxle hydraulics from the power steering hydraulics.

The accelerator pedal travel has an initial deadband after which the pedal feel is smooth and responsive. The deadband is considered unacceptable and will be corrected in the NVH vehicle system.

Brake response is comparable to that of the production van brake system. The electrically driven vacuum pump appears to have enough capacity for all but a rapid series of pedal applications.

Road tests were performed at Chrysler Corporation's Chelsea Proving Grounds. Subjective handling test comprised high speed steering response check; it was deemed positive and comparable to that of production van steering feel and response time. Pitch, bounce, roll and yaw characteristics were similarly found acceptable. Ride quality evaluation was assisted by Chrysler Proving Grounds vehicle dynamics engineering personnel. Ride quality compared well with that of the production van, due to the higher sprung mass of the DSEP van. No improvements were deemed necessary, hence, no changes in spring rates or shock absorber damping characteristics were suggested.

Vehicle gradeability was checked and found adequate to start on a 20% grade; the start was smooth and without hesitation. **Figure 6** shows the vehicle undergoing gradeability tests.

As of this writing, a number of road tests are either incomplete or must be re-run to confirm repeatability. These tests comprise the coast-down, acceleration, regenerative braking, range at constant speed, and range under C & D schedules of SAE J227 tests.

Figure 6 TB-1 Vehicle Gradeability Test

Final chassis dynamometer tests to establish vehicle range under the FUDS cycle will complete the TB-1 vehicle tests.

IMPACT OF TB-1 TESTS ON NVH POWERTRAIN/VEHICLE DESIGN

The TB-1 tests revealed several areas in the propulsion/vehicle systems in need of improvement to achieve DSEP program goals and/or make the vehicle more user-friendly. These areas comprise:

- the peak power shortfall
- vehicle start-up and shift smoothness
- hydraulic system noise and efficiency
- vacuum assist for power brake

The <u>peak power shortfall</u> was first measured in the propulsion system dynamometer tests and later confirmed in vehicle tests. It was recognized that the shortfall was due to peak current limitations of the double Darlington transistors. A redesign of the inverter to incorporate higher current capability transistors and associated componentry was in order; it was proposed to and approved by DOE program management, March 1987.

The inverter, controller and the SOCM redesign effort is described in the next section.

While <u>vehicle start-up and shift smoothness</u> were much improved through the use of the field-oriented motor control in place of the PWM control used in earlier ac systems, the TB-1 tests indicated a need for further improvement. Thus, an advanced control technique called the "estimator" was developed. The "estimator" is a closed-loop electronic control system that monitors the rate of change of the traction motor and transaxle output speeds, estimates their imminent incompatibility and then correspondingly modulates the motor current to inhibit driveline torque build-up in excess of the demand torque. The estimator algorithm is a significant feature of the control as it involves a mathematical dynamic model of the mechanical system residing in a microprocessor, that predicts the incipient torque level. The algorithm is, in effect, an extra program routine in the controller that substitutes for an expensive conventional torque sensor.

The "estimator" control technique is fully operational in the TB-1 vehicle powertrain. It effects smooth vehicle starts and transaxle shifts, even at full load, without any hydraulic clutch torque modulation for either function, and without any torsional dampers in the driveline. This control technique represents a significant advance in electric vehicle powertrain technology.

Based on observations from the TB-1 vehicle tests, separation of the transaxle and the power steering hydraulic systems in the NVH vehicle powertrain is advisable for a number of reasons. The momentary, small, though perceptible loss of power steering assist upon a transaxle shift during cornering is to be avoided. Independent hydraulic system for the power steering function will also allow greater freedom for that unit's placement within the front compartment, avoid pump cavitation and higher continuous noise problems encountered with the present system. Planned future replacement of the entire power steering hydraulic system by an all-electric system (when these become commercially available) would be possible without any revisions in the transaxle hydraulics.

The TB-1 vehicle tests also indicated that the substitution of hydraulic power brake assist for the vacuum assist used in the TB-1 vehicle is advisable. This is based on the fade of the power assist on repeated brake application with the vacuum system, and the relatively higher noise level with that system.

NVH POWERTRAIN DESIGN

As a result of the peak power shortfall in the TB-1 propulsion system above the traction motor's base speed and the associated reduction in the TB-1 vehicle's acceleration performance, major revisions were necessitated in the inverter, controller and SOCM (state-of-charge-meter) design for use in the powertrain of the (NVH) vehicle. A brief description of the function of these devices and the design changes relative to their TB-1 system counterparts is given in the following.

The DSEP inverter uses six bipolar power transistors in three half-bridge legs to convert the dc battery current to the variable voltage and frequency ac current required by the induction motor. The inverter package also contains the low-voltage power supply for the entire propulsion system, the interface circuitry to communicate with the controller that commands and monitors the inverter, and the voltage-isolating base drivers and current sensors.

The inverter redesign for the NVH vehicle propulsion system was undertaken with the following objectives:

- handle 600A peak motor current per phase (300A rms)
- increase voltage, noise and thermal margins, and
- reduce cost and weight of the inverter assembly

The double Darlington transistors of 450A peak current capability were replaced by the triple Darlingtons capable of 600A peak current. Circuit problems encountered in the original debug and test of the TB-1 inverter were corrected for the NVH inverter. All printed circuit boards were revised to accommodate these corrections. Significant improvements were achieved in the areas of noise sensitivity of the interface board, the regulation of the power supply board, and the over-voltage stress of components on the base drive boards. **Figure 7** shows the physical layout of the inverter assembly, **Figure 8** the nearly completed assembly.

As the dynamometer tests of the TB-1 inverter at elevated ambient temperatures registered inverter internal air temperatures approaching the limit of some components, modifications were incorporated in the NVH inverter package and cooling system design to effectively reduce these internal temperatures. The

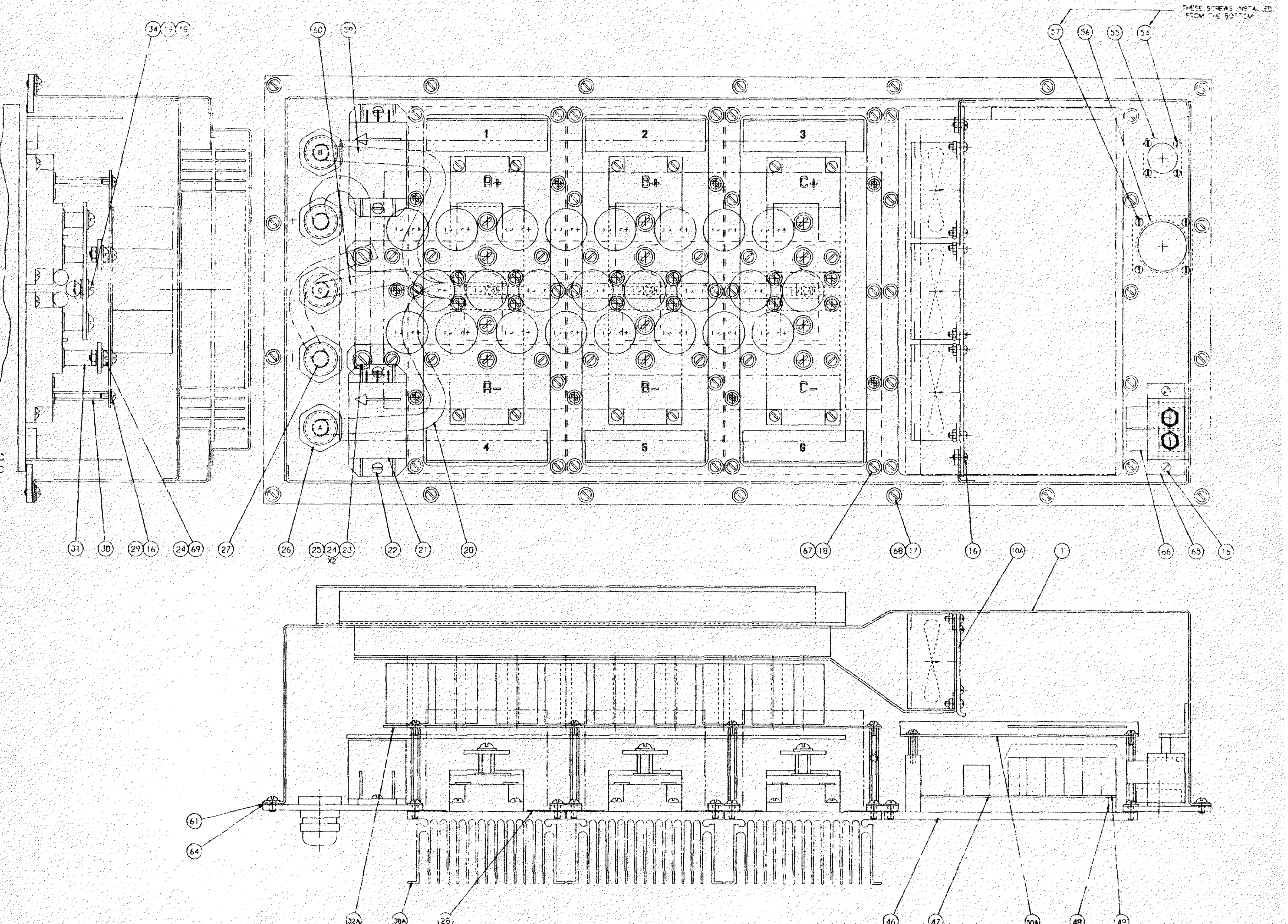

Figure 7 NVH Inverter Layout

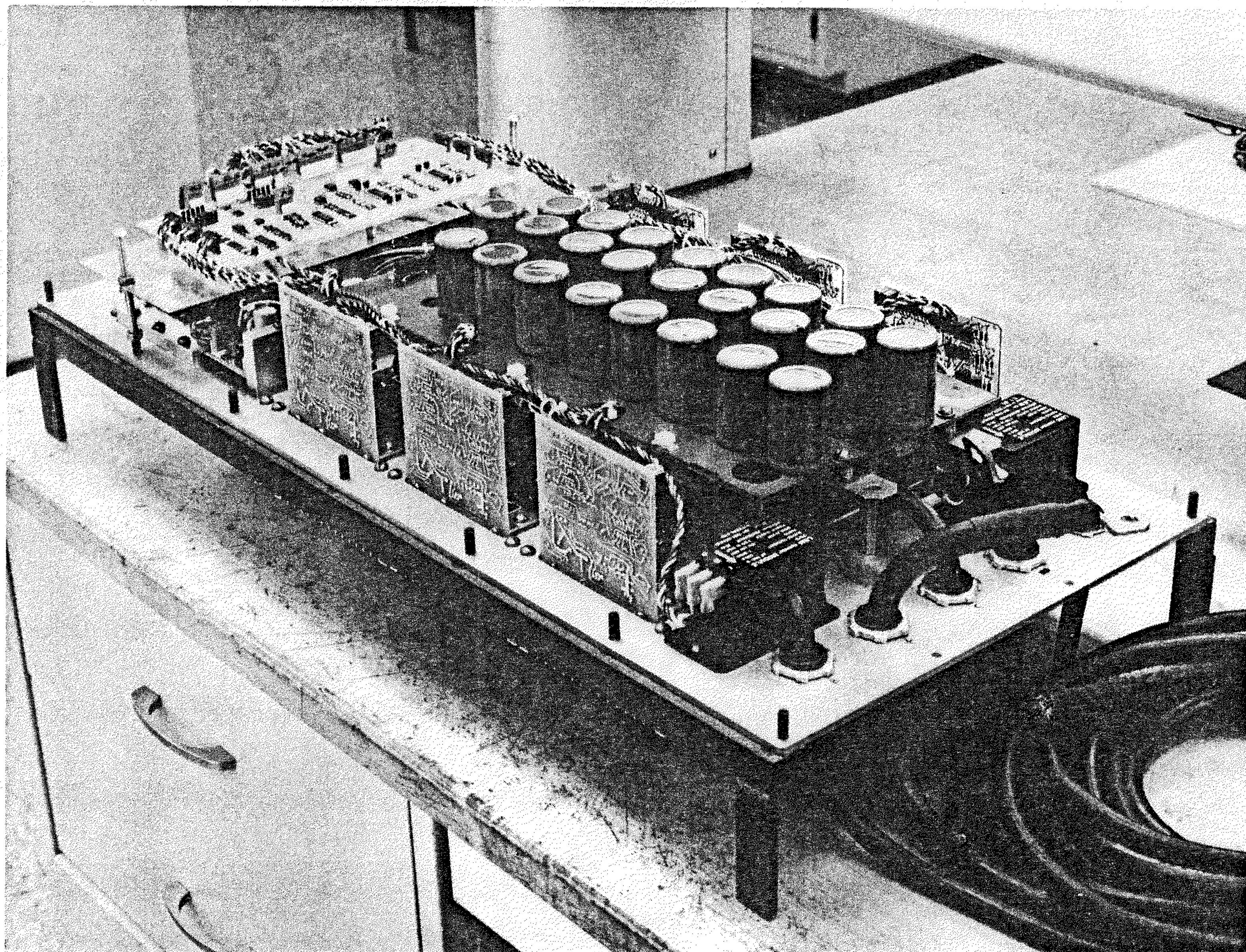

Figure 8 NVH Inverter Assembly

measures included:

- increasing the volume of the inverter package
- adding a third internal air-circulating fan
- ducting the the airflow close to the heat exchanger fins, and
- isolating the three main heatsinks from the internal air.

A significant cost reduction was achieved in the design revision of the power bus assembly. Stamped conductors, power transistor interconnectors and four circuit boards of the TB-1 inverter were replaced by a single circuit board and two bus bars to interconnect these components.

The NVH controller performs these functions related to vehicle and motor control:

- Field oriented control for fast motor torque response
- Control of an outer torque loop for stabilization of vehicle resonances
- Gear shift coordination and shifting operations
- Fault monitoring and protection
- Dashboard display
- Diagnostics communication

The NVH Controller is a redesign of the original DSEP TB-1 Controller. The modifications have been aimed at matching the new NVH inverter design, reducing component count, improving the overall flexibility of the previous design through modularization, and reducing the overall package size. The components chosen will meet a wider temperature specification than their TB-1 counterparts, and will also be readily available, off-the-shelf, devices. **Figure** 9 shows a block diagram of the controller.

The DSEP NVH Controller is made up of two modules, the Power Module and the Logic Module. The function of Power Module is to supply the operating and reference voltages for the Controller system. The Logic Module contains all hardware required for proper operation and support of the microcontroller.

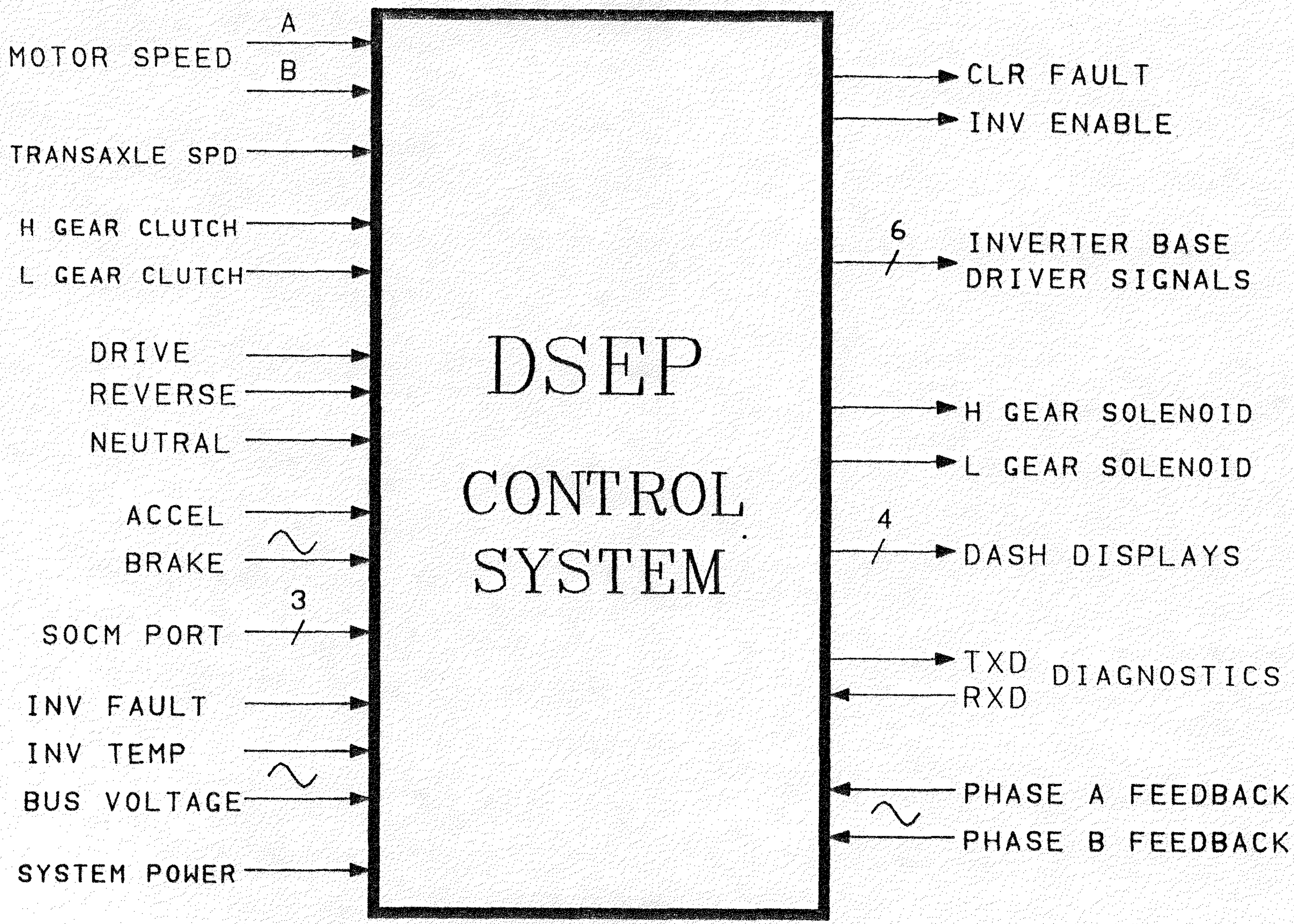

Figure 9 NVH Controller System Block Diagram

The processor functions are performed by a microcontroller device contained within the Logic Module. This device integrates many of the functions of a control environment onto one chip, comprising a 10-bit analog to digital converter, a serial communications port, a high speed I/O (input/output device), a digital I/O device, and timer/counters for event handling.

The State-of-Charge Meter (SOCM) measures and tracks the level of charge contained in the battery pack at all times and reports this to the operator via the fuel gauge in the dash panel. The SOCM integrates amp-hours into, and out of, the battery in determining the level of charge and range remaining. The SOCM also calculates self-discharge of the battery during open circuit operation as a function of level of charge and time. The SOCM interacts with the Lester charger to properly charge the battery and monitor conditions that may be improper for charging, such as excessive battery temperature or abnormal hydrogen generation. The SOCM and the charger communicate via a serial link. Information relative to charging is passed between the two, as each is constantly monitoring the conditions that may adversely affect the charging of the battery pack. **Figure 10** shows a block diagram of the SOCM.

The design improvements over the TB-1 SOCM version have been aimed at increasing reliability, improving the noise immunity within the system, and reducing component count through development of a digital display system. The NVH SOCM differs from the TB-1 version through increased modularization; it contains: a logic module, an isolated interface module, and a display module. The SOCM logic module contains the major componentry required for operation of the SOCM system. It houses a microcontroller and support hardware. The isolated interface module will be located in the interface box (under the hood) and will be responsible for collection of the analog information required by the system (bus voltage, current). The display module will replace the analog fuel gauge with 16 discrete led's to report battery state-of-charge. This module will be located in the vehicle dash panel area.

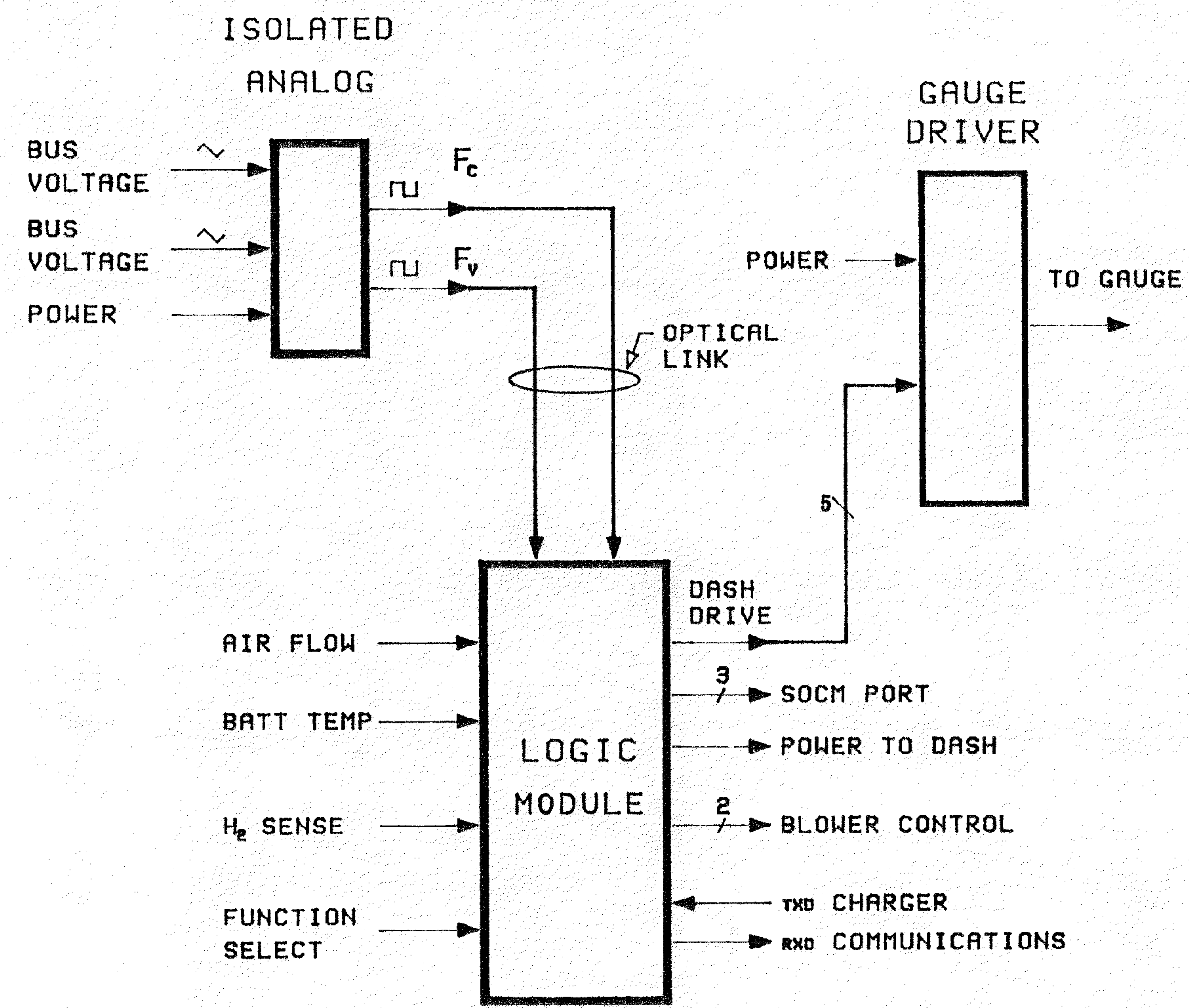

Figure 10 NVH SOCM Block Diagram

DSEP BATTERY SYSTEM STATUS

Based on lab tests of a limited number of subsystem elements, the DSEP nickel-iron energy system at its present stage of development appears likely to satisfy most of its goals, except peak power availability at deep depths of discharge over a prescribed number of cycles. Causes for the shortfall are being investigated, and potential remedies are being assessed for their merits.

The DSEP energy system goals are the most demanding ever imposed on a vehicle battery, yet they are realistically mission-oriented to enhance user acceptance and the likelihood of commercial success. DSEP battery packs #1 and #2, when new, exhibited the peak power and energy capacity necessary to meet the DSEP vehicle acceleration and range requirements. Pack #3 is presently satisfactorily powering the TB-1 vehicle. While the energy capacity of the batteries undergoing testing at ANL and Eagle-Picher have thus far degraded at expected rates commensurate with the cycle life goal, the test results of these two batteries show that their continued capability to deliver the peak power envisioned in one of the DSEP mission-derived goals is inadequate. This goal--to deliver full peak power for 20 seconds near the end of the 80.4 km (50 mi) FUDS cycle range for 1200 such cycles--was, however, promulgated without the support of fully proven battery technology necessary to achieve it, and without an assurance by the battery manufacturer of its feasibility.

Life cycle testing at ANL on pack #1 reveals that if the pack current/voltage variations on maximum power draw are limited to the range acceptable to the DSEP motor and inverter, this battery has ceased to deliver the peak power necessary to meet the acceleration goal. This occurred after about 300 cycles, or one-fourth of the cycle life goal of 1200. Even if gross peak power (current/voltage combinations unacceptable to the electrical system but yielding 52 kW) is considered, a shortfall appears certain to occur at about the mid-point of the desired life. **Figure 11** shows a plot of this peak power degradation vs. accumulated cycles in ANL tests.

The shortfall in achieving this DSEP battery system goal with pack #1 at ANL is presently believed to be due to premature individual degradation of some modules of the battery system, rather than the gradual, unavoidable degradation of the battery system as a whole. The suspected individual module degradation may be due to possible non-uniformities in the manufacture of the modules themselves, or perhaps a design deficiency in the watering/venting or cooling systems of the pack. The graph in **Figure 12** shows the peak power deficiency of some modules relative to others, at various depths of discharge of the pack.

Orderly approach to resolution of the problem requires that the pack #1 at ANL is first examined for any anomalies in the pack and its ancillary systems. This is currently in progress. Electrolyte analysis has been completed and indicated normal chemical composition. Based on preliminary, non-destructive examination of suspect modules of pack #1, the watering system appears to function satisfactorily. However, electrolyte samples were taken from only the end cells of a limited number of modules and the electrolyte levels were observed at the end of only one complete cycle after watering. Closer examination of this and pack #2 may still reveal significant electrolyte migration, occasional overwatering, or electrolyte levels below normal in individual cells. All of these malfunctions can cause a loss in performance and may result in damage to the cells.

Pack #3 in the TB-1 vehicle has an improved watering system; its performance has not as yet been sufficiently observed to draw any conclusions. The time required for watering needs to be reduced. Watering after every 10 to 12 cycles presently takes about 1 hour instead of the desired 30 minutes; a development effort is in progress at EPI to improve this operation.

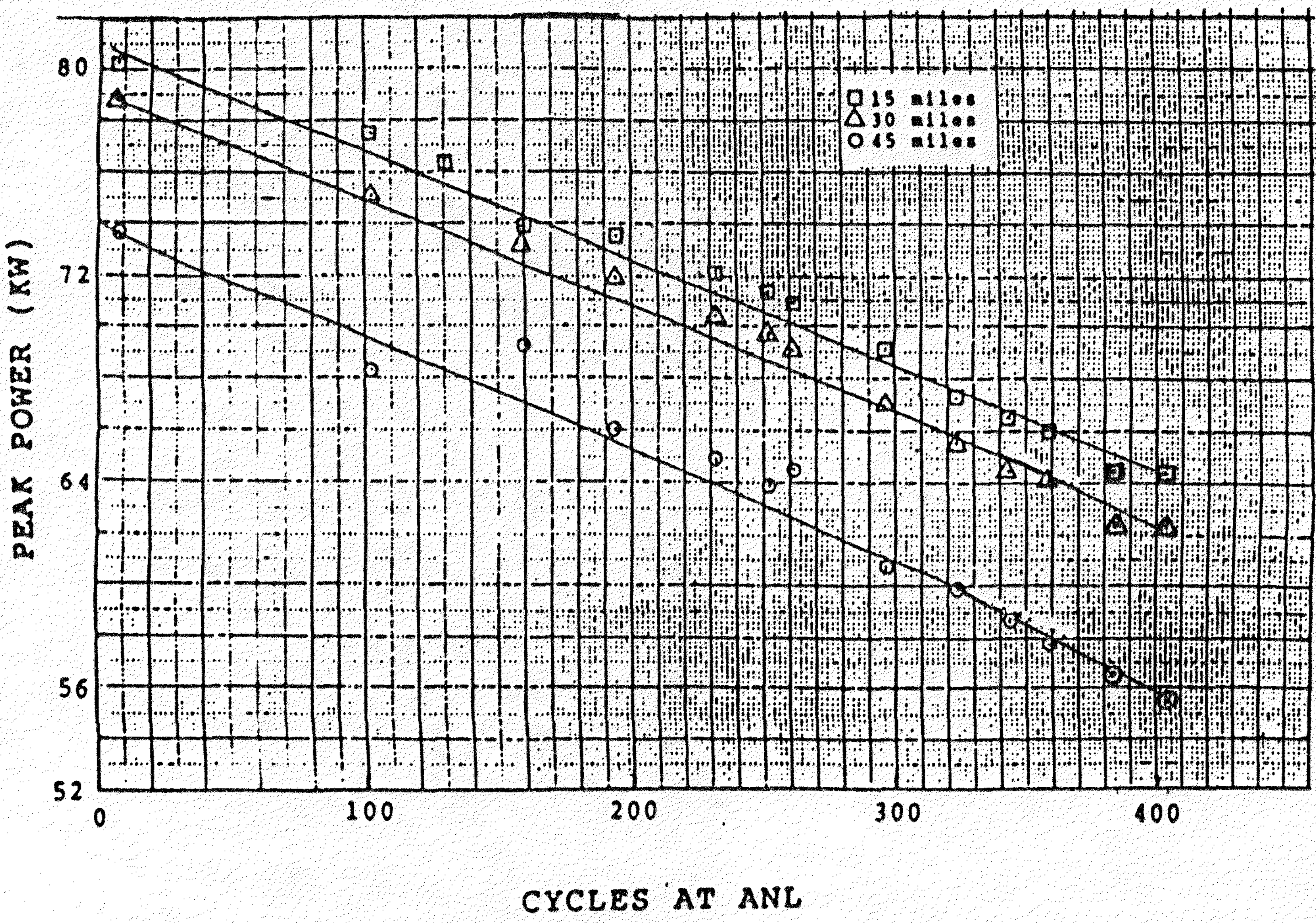

Figure 11 Peak Power Degradation of Pack #1 in ANL Tests

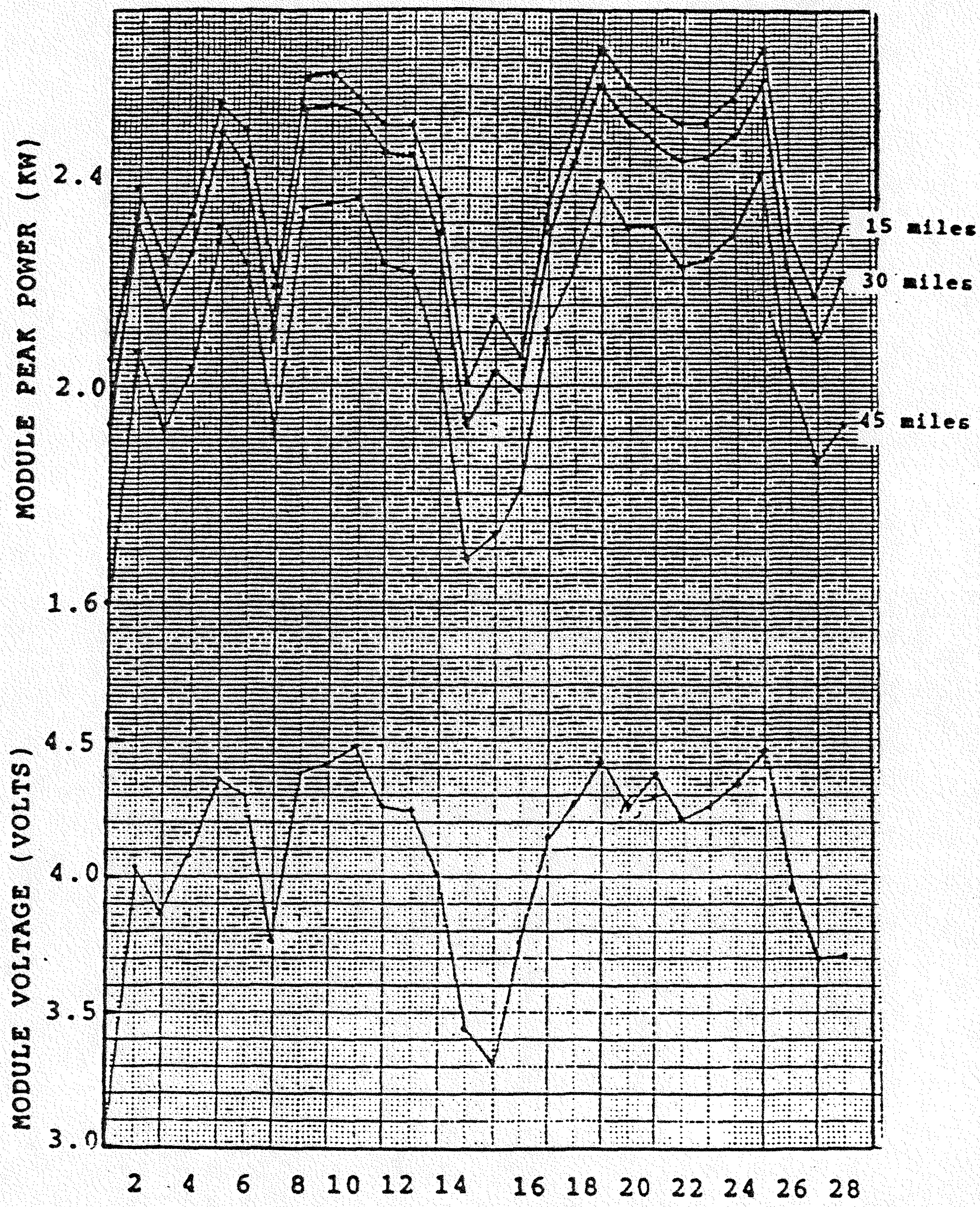

Figure 12 DSEP Pack #1 Module Variations

Temperature mapping indicates about 5°C gradient in module temperature from the front row to the rear. This may significantly affect peak power delivery. Light thermal insulation is now experimentally applied to modules receiving more cooling in order to effect more uniform temperature distribution among the modules and thus maximize power output from the pack.

The present safety system has been effective in preventing safety-related incidents on all three operating battery systems. On-board hydrogen detectors, however, have picked up minor leaks in the #3 pack's (installed in the TB-1 vehicle) solenoid valve/trap area. Remedial action was taken in this area to increase reliability. Incorporation of a newer simpler, externally (to DSEP program) developed system for inhibiting flame propagation is being considered for the future.

Continued diagnostic effort of pack #1 at ANL is necessary for determining further action that must be taken to bring the battery's peak power capability in line with the DSEP mission goals. It may well be that no more than a routine overhaul on a limited number of modules would be necessary to accomplish this, thus possibly obviating more costly and unattractive measures, such as adding extra modules or revising the battery design.

If substantial improvement is not obtained in the peak power capability of pack #1 through the maintenance of more uniform module temperatures currently being attempted at ANL, the next orderly step is to remove and closely examine the suspect modules in the pack. External means are to be employed first in an attempt to restore these modules to normal operation. Failing that, the module cases are to be opened for an in-depth failure analysis and morphological examination.

Cycle testing of pack #1 at ANL is to be resumed either with the removed modules replaced with new ones in the pack, or else, with an incomplete pack consisting of only the remaining modules and the test parameters adjusted accordingly. The true degradation profile of peak power and energy capacity of this battery design is necessary for its complete characterization, design improvements, and eventual generation of superior designs.

PROGRAM MANAGEMENT

Eaton Corporation has continued through the third year of the program to provide all necessary personnel, equipment, facilities, materials and services required to plan, manage, implement and control the technical progress and costs of the contract and subcontracts. **Figure 13** illustrates the financial history of the DSEP program.

Proper attention has been given to ensuring personal safety of everyone working on the program or coming into any contact with its activities, particularly with respect to proper ventilation of flammable gases and safequards around high voltage equipment.

Contractually required design and test review meetings were held, presentations made as requested, and weekly/monthly progress reports furnished on schedule. An extensive report on TB-1 propulsion system tests was issued, a TB-1 vehicle test plan was generated, and a situation paper on the DSEP battery system status was written.

Technical progress of the NVH vehicle build is nearly on schedule; TB-1 vehicle test completion is about 3 months behind. A program funds addition and schedule extension (to furnish a new deliverable vehicle rather than a refurbished former test vehicle) has been submitted and is awaiting approval. The master schedule network chart of **Figure 14** reflects the proposed extension.

Following the successful management of the DSEP program for the last 2 1/2 years, Jeffrey Skorupski accepted an engineering management position at Eaton CoRD-DC. Ilmar Kalns was appointed 2/1/87 to succeed Jeff as the DSEP Program Manager.

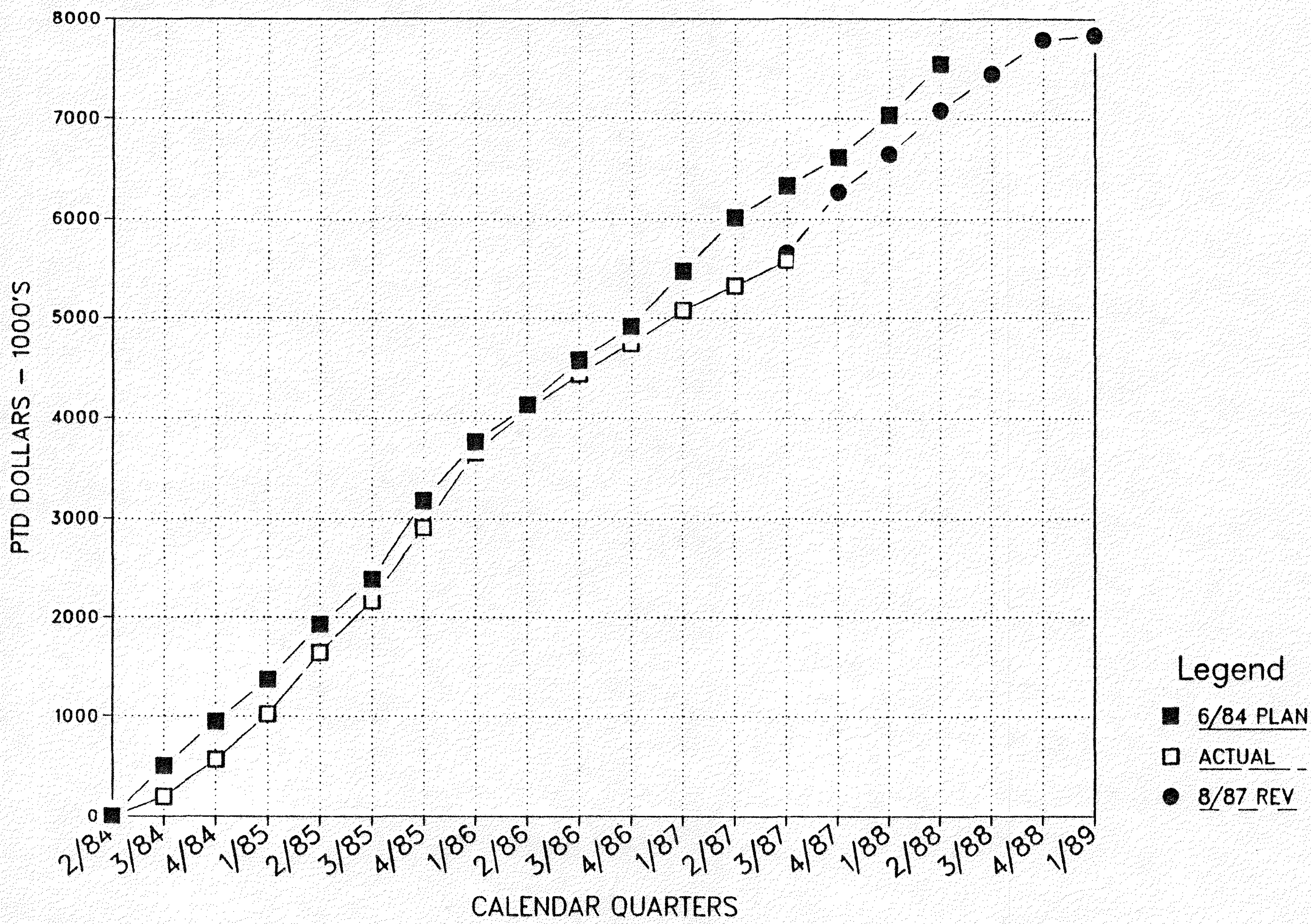

Figure 13 DSEP Program Financial History

EATON ENGINEERING & RESEARCH CENTER

DSEP ADVANCED DUAL SHAFT ELECTRIC PROPULSION SYSTEM TECHNOLOGY DEVELOPMENT PROGRAM

DE-AC07-84NV10366

9-16-87

57870

△ DELIVERY ITEM OR CONTRACT DUE DATE
⊛ OPTIONAL TASK
I-III GO-NO GO DECISION POINTS

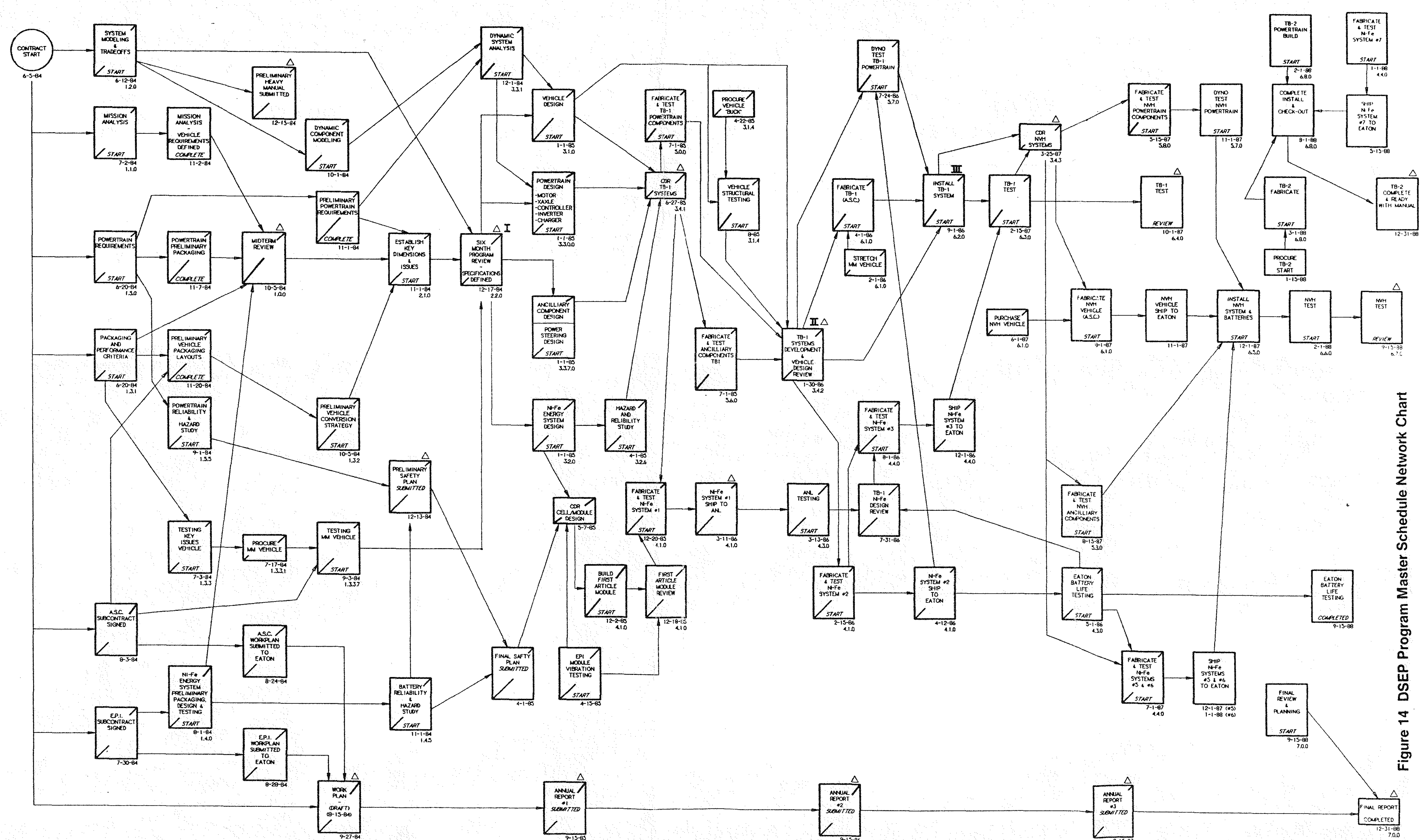

Figure 14 DSEP Program Master Schedule Network Chart

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