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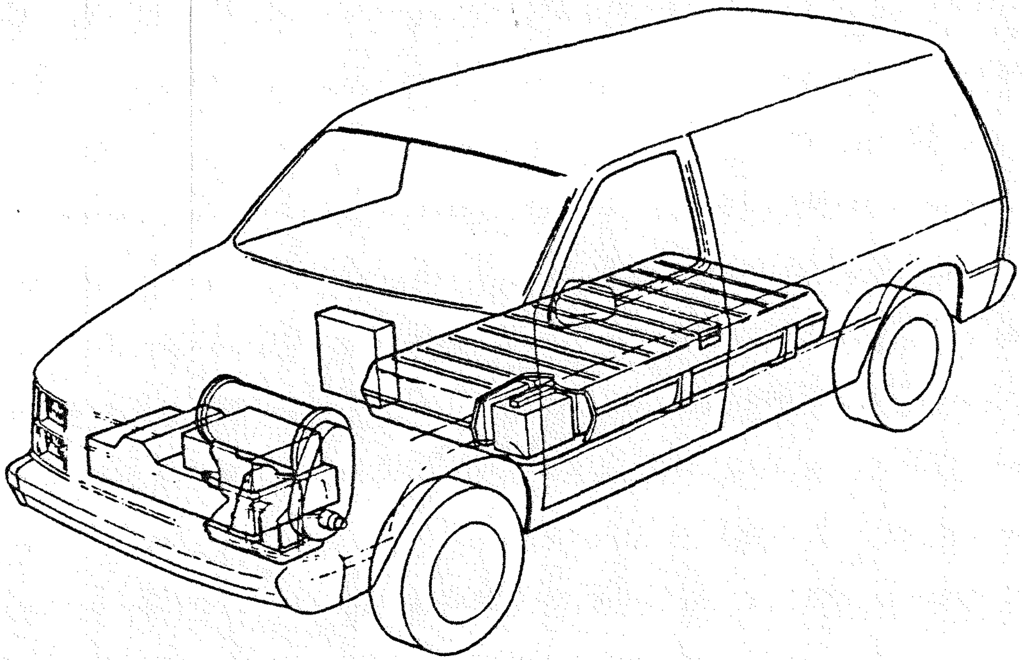

DSEP Advanced Dual Shaft Electric Propulsion System Technology Development Program

ANNUAL REPORT IV - October 1988

Eaton Corporation — Corporate Research & Development-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

EATON

DOE/NV/10366--6
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ADVANCED DUAL-SHAFT ELECTRIC PROPULSION SYSTEM TECHNOLOGY DEVELOPMENT PROGRAM

DSEP

ANNUAL REPORT - IV

OCTOBER 1988

Prepared by
Ilmar Kalns

EATON CORPORATION
Corporate R&D - Detroit Center

Under Contract DE-AC07-84NV10366
Idaho Operations Office
U.S. DEPARTMENT OF ENERGY
(Program Management by Idaho National Engineering Laboratory)

for

U.S. DEPARTMENT OF ENERGY
Conservation of Renewable Energy
Office of Transportation Systems

MASTER

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ABSTRACT

This fourth annual report of the DSEP program summarizes all program activities from September 1987 through August 1988. These activities comprise:

- Successful completion of the first test-bed, proof-of-concept vehicle (TB-1) tests, achieving performance comparable to that of IC engine powered vehicles. Results are in good (±8%) agreement with those obtained by EG&G, Idaho in simulated dyno tests.

- Completion of conversion of the second test-bed, durability test vehicle (NVH), dyno tests of its powertrain, vehicle installation of the powertrain, shakedown tests of the complete system, and problems encountered in the process. A revision in DSEP program scope is in process that designates this vehicle as a deliverable to DOE and reduces the extent of its durability testing.

- Completion of conversion and start of subsystem installation of the third complete vehicle (TB-2) to be constructed on the DSEP program; it is a deliverable to DOE.

- Battery life test results to date, battery performance in the TB-1 vehicle, and an assessment of battery system status.

- Analysis of the DSEP vehicle/propulsion system manufacturing cost and life cycle cost, and the start of future planning.

- Program administration and management.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The DSEP (Dual Shaft Electric Propulsion) program is dedicated to advancing electric propulsion technology through 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 urban/suburban commercial service. The motor and transaxle are arranged on two parallel axes, hence the term "dual shaft".

The program's industrial research team comprises Eaton Corporation (Corporate R&D, Detroit Center, Southfield, MI) as the prime contractor with responsibilities for overall program management, powertrain technologies and propulsion system integration; Eagle-Picher Industries (Joplin, MO) responsible for the battery technology, and ASC (Southgate, MI) responsible for test bed vehicle conversion to accept an electric propulsion system.

The objectives of this 54-month program are to design, test and develop three advanced experimental proof-of-concept propulsion systems installed in vehicles. Two of these are to be thoroughly tested for performance, reliability and durability. The third complete vehicle/propulsion system--incorporating the technology developed under this program--is to be built, function-tested and delivered to the Government for further independent tests and evaluation.

The program in its fourth year has continued to make solid progress toward achieving those objectives.

All tests of the first test bed vehicle (TB-1) were satisfactorily completed in early '88, exceeding most of its ambitious performance goals. The goals are comparable to those of an internal combustion engine-powered vehicle. The following table lists the goals vs. actual performance:

	Goals	Actual
Acceleration:		
0-80.4kmh (50 mph)	20 sec.	20.5 sec.
0-48.3kmh (30 mph)	10 sec.	8.0 sec.
Top Speed:	90.6kmh (60mph)	112kmh (70mph)
Gradeability:		
from rest	>20%	28%
maintain 88.5kmh (55mph)	on 3% grade	4%
Range:		
at 40 kmh (25mph)	----	129.0km (80mi)
72.4 (45)	104.7km (65)	93.3 (58)
88.4 (55)	----	78.8 (49))

These results were achieved with first-generation hardware and without any disabling breakdowns.

The second test bed vehicle (NVH) was converted to accept the electric powertrain. A propulsion system with a revised and improved inverter/controller design was dyno-tested, encountering development problems that caused significant program schedule slip. Subsequently, the system was installed in the NVH vehicle and made ready for the originally planned durability and NVH (noise, vibration, harshness) tests at Chrysler Corporation's Chelsea (MI) Proving Grounds.

At that point, however, DOE management refocused program goals, placing higher priority on having two deliverable vehicles in virtually new condition (for site placement and further independent tests) instead of only one--with the other vehicle consumed in extensive durability testing. Thus, the DSEP program scope is being revised to specify two complete vehicle/powertrain systems as deliverables, and to eliminate the accelerated life/durability testing of the NVH vehicle.

The third vehicle (TB-2) is under construction. Its completion is pending resolution of all remaining NVH powertrain control problems. These are being simultaneously addressed on the dynamometer (TB-2 hardware) and in the operational NVH vehicle to expedite solutions.

Life tests of the Ni-Fe battery subsystem were continued with two battery packs and with one single module. Each of the two packs (nominally with 28 modules in each) have accumulated more than half of the 1200-cycle goal. Both packs continue to test satisfactorily, however, several modules have had to be removed or replaced in these packs due to their inadequate performance. The single-module test was terminated just short of the goal for the same reason. Examination of all removed modules indicates a predominant single assignable cause--a manufacturing quality control problem with the iron electrode. The deficiency has surfaced now, after years of testing and the completion of manufacture of all six packs plus spare modules required for the program. The battery packs in the test bed vehicles have performed satisfactorily in over-the-road and proving grounds tests, enabling the vehicle to be fully characterized relative to its very ambitious performance goals.

The task of the complete vehicle life cycle cost analysis and future planning for the product was addressed this year. The life cycle cost will focus on electric vs. gasoline-powered light delivery van comparison; a detailed manufacturing cost estimate is nearing completion for three different annual production quantities. Indications are that DSEP program subcontractors may be interested in taking a role in long term commercialization of the product.

INTRODUCTION

The objective of this 54-month program is to advance the state of the art of electric vehicle system technology using subsystem technologies previously developed under contracts to the Department of Energy by Eaton Corporation and Eagle-Picher Industries.

The powertrain technology, originally developed for passenger cars by Eaton, is to be upgraded for higher power and starting torque required for van applications. The Ni-Fe battery subsystem is to be designed and furnished by Eagle-Picher, and 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 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 to be performed by ASC.

This propulsion system technology is to be integrated into the Chrysler mini-van for test bed evaluation. The program includes the design, testing and development of three experimental proof-of-concept propulsion systems in vehicles. The vehicles are to be converted to receive the electric propulsion systems, the powertrains and battery subsystems are to be installed and tested for performance, reliability and durability. The third complete vehicle and propulsion system incorporating the technology developed under this program is to be delivered to the Government for further independent tests and evaluation. A revision of DSEP program scope is currently in progress; it will provide for two of the three vehicles to be delivered to the Government, and will eliminate planned extensive durability testing of one of the deliverable vehicles.

This report covers in some detail the fourth year, September 1987 to August 1989, of the DSEP program activities.

COMPLETION OF THE TB-1 VEHICLE TESTS

This section of the report covers only those TB-1 vehicle tests not reported on in the last annual report, Ref. 1. These consist of road tests corresponding to Section 6.0 in the TB-1 Vehicle Test Plan, and comprise the following individual tests:

- coastdown test
- acceleration characteristics
- braking characteristics with and without regeneration
- range at constant speeds
- range under SAE J227 schedules C and D
- tractive force and gradeability
- rough road test

The TB-1 vehicle completed all planned over-the-road tests. It has approached or exceeded all performance goals--with first-generation powertrain hardware. About 8000km (5000mi) have been accumulated in city traffic and at the Chrysler Corporation Chelsea Proving Grounds, experiencing some system glitches (trip-outs) but no disabling breakdowns.

The following table summarizes the original performance goals and actual test results:

	Goals	Actual
Acceleration:		
0-80.4kmh (50mph)	20 sec.	20.5 sec.
0-48.3kmh (30mph)	10 sec.	8.0 sec.
40-88kmh (25-55mph)	20 sec.	20 sec.
Top Speed:	96.5kmh(60mph)	112kmh(70mph)
Cruising Speed:	88kmh(55mph)	88kmh(55mph)
Range:		
At 40 km/hr (25 mph)	90 @ 30mph	129.0km(80miles)
" 56.3 " (35 ")	--	115.8km(72 ")
" 72.4 " (45 ")	65	93.3km(58 ")
" 88.5 " (55 ")	--	78.8km(49 ")

FUDS:

Energy Consumption:

At 40 km/hr (25 mph)	.23kwh/mi@30mph	.17kwh/km(.28kwh/mi)
" 56.3 " (35 ")	--	.20kwh/km(.32kwh/mi)
" 72.4 " (45 ")	.31kwh/mi	.23kwh/km(.37kwh/mi)
" 88.5 " (55 ")	--	.28kwh/km(.45kwh/mi)

Gradeability:

From rest	>20%	28% (est.)
Maintain 88.5kmh(55mph) on	3% grade	4% grade
Sustained Thermal	TBD	TBD

Fig. 1 shows the TB-1 vehicle undergoing high speed tests. Results of all other tests are shown graphically in Figures 2 to 8.

The rough road test accumulated 145km (90mi) over an appropriate test route at the Chrysler Chelsea Proving Grounds at speeds in the 48kmh (30mph) range to obtain a rough measure of the vehicle's structural and propulsion system adequacy to withstand harsh road conditions and handling. The results were satisfactory. Occasional electrical system trip-outs were experienced, but with no greater incidence than encountered under less strenuous conditions.

Results of electromagnetic compatibility tests indicated that both radiated and conducted modes of interference exist, mainly emanating from accessories and the inverter.

After completion of tests at Eaton, the TB-1 vehicle was transported to EG&G Idaho, Inc. for further dynamometer and battery characterization testing. Results of simulated dyno tests of energy consumption, range and aceleration are in good (±6 to 8%) agreement with Eaton-obtained test track results (Ref. 9).

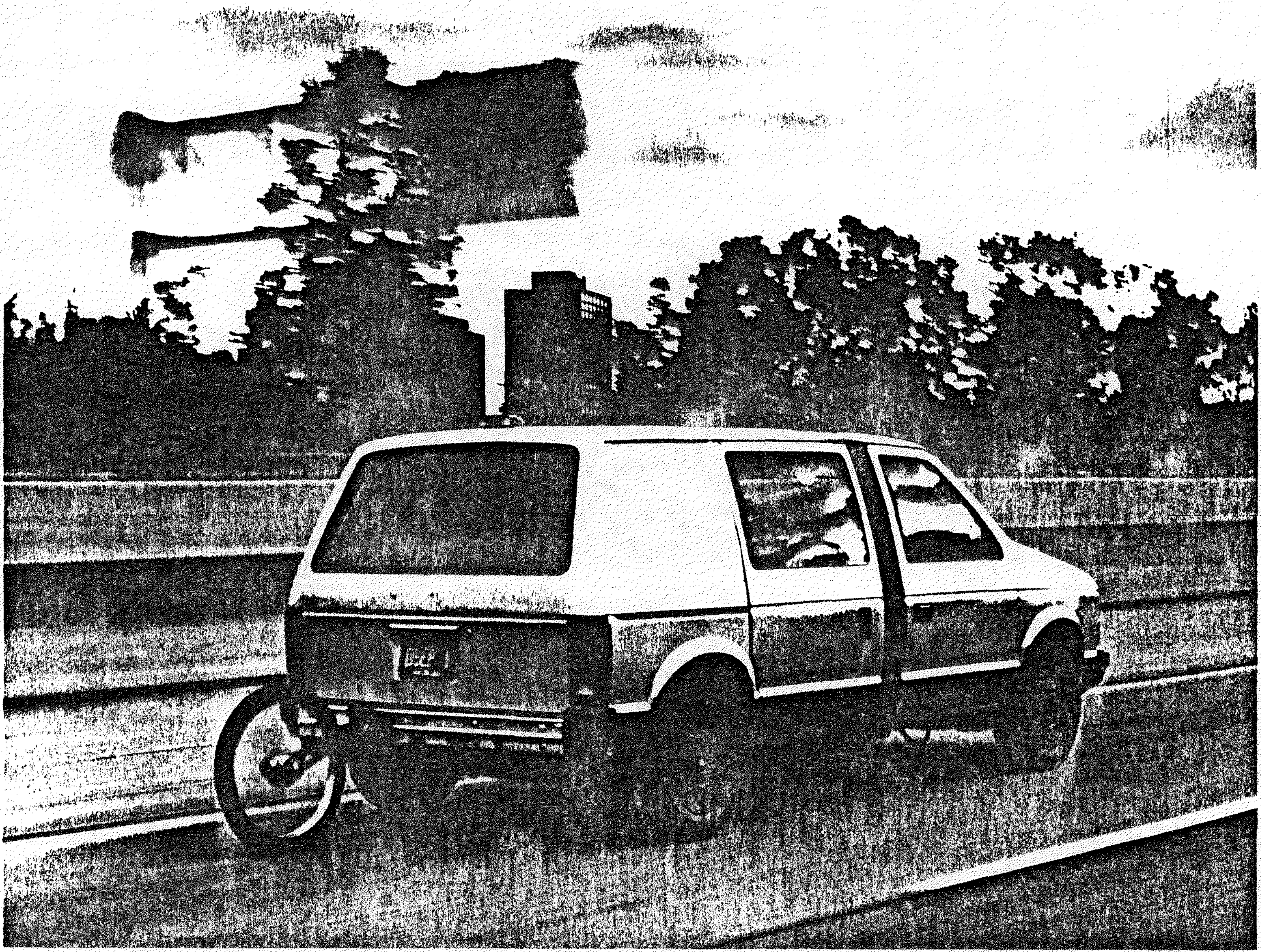


FIG. 1: TB-1 VEHICLE HIGH-SPEED TEST

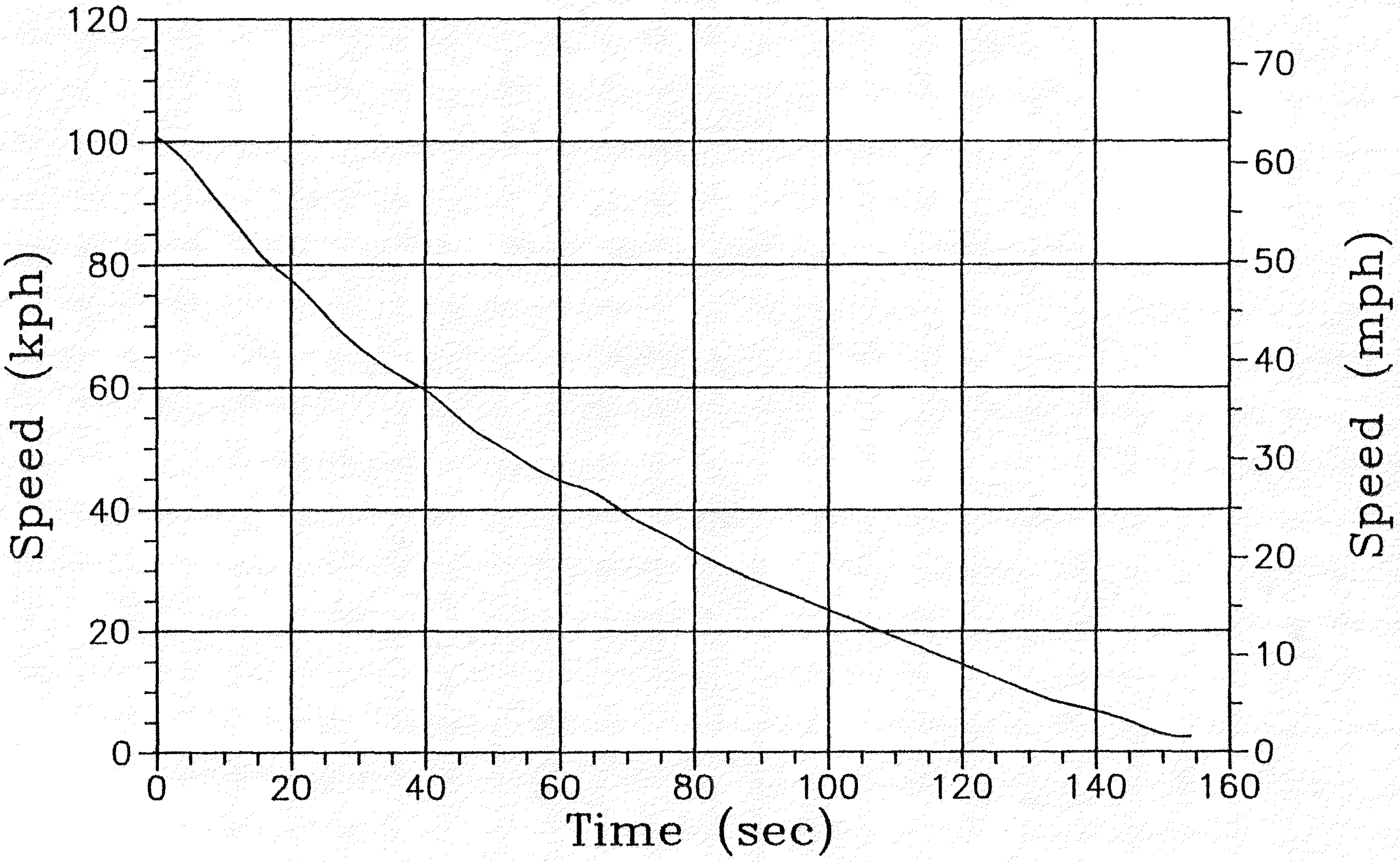


FIG 2 : Vehicle Coast Down Test

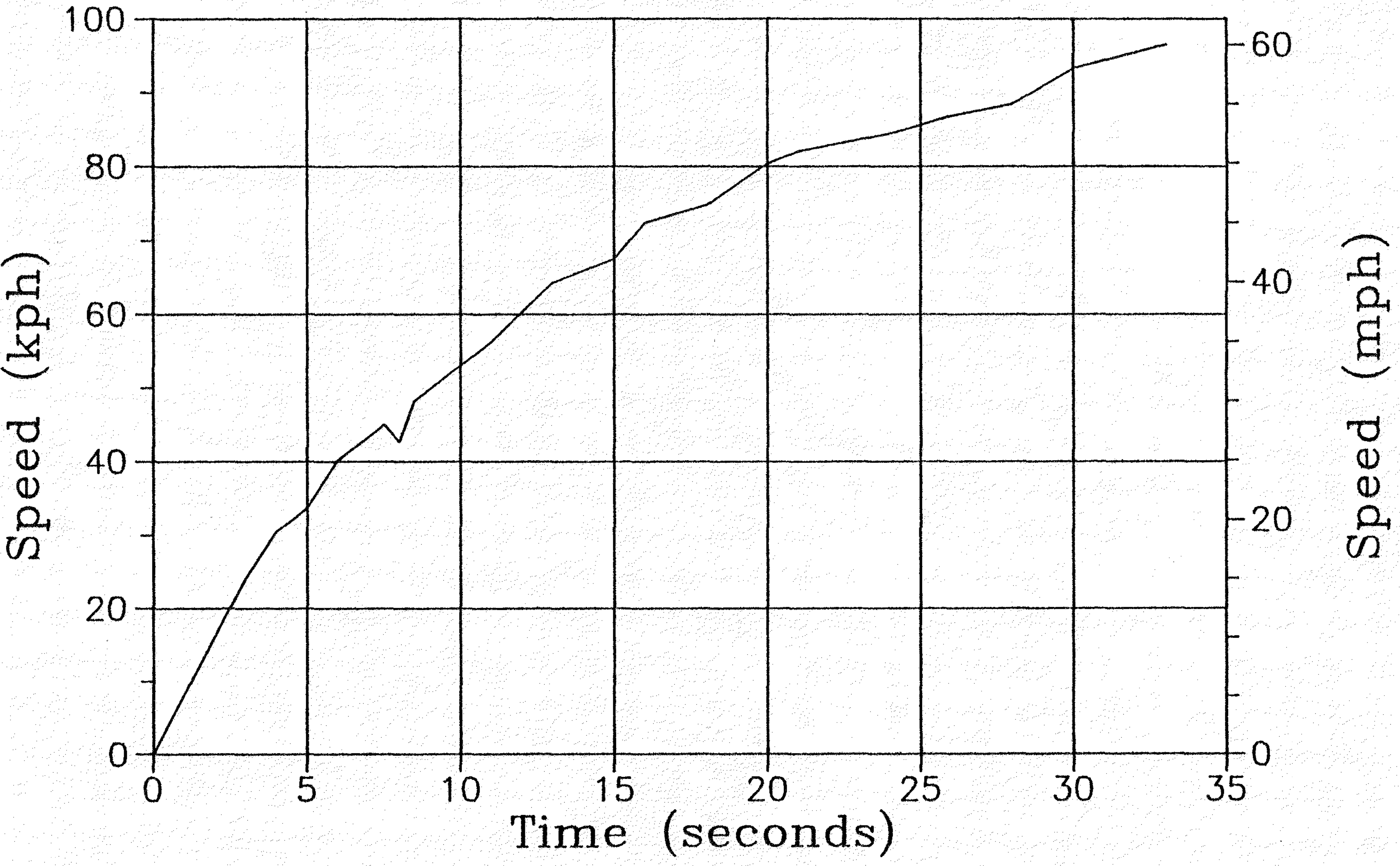


FIG 3 : TB–1 Vehicle Acceleration Profile
(Track Test Data; Fully Charged Battery)

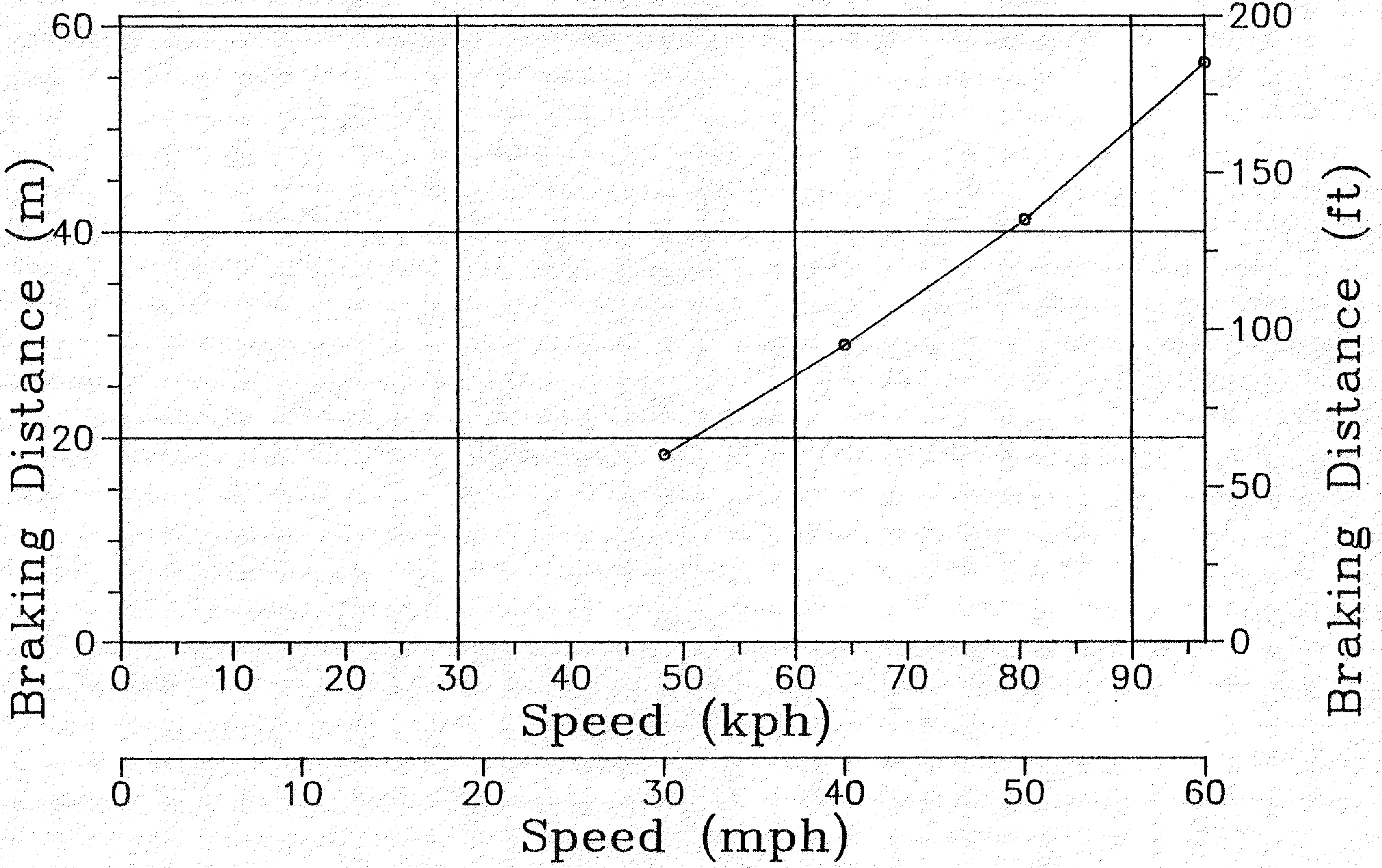


FIG 4 : Braking Distance from Various Speeds
(with 1/2 Payload; GVW = 2400)

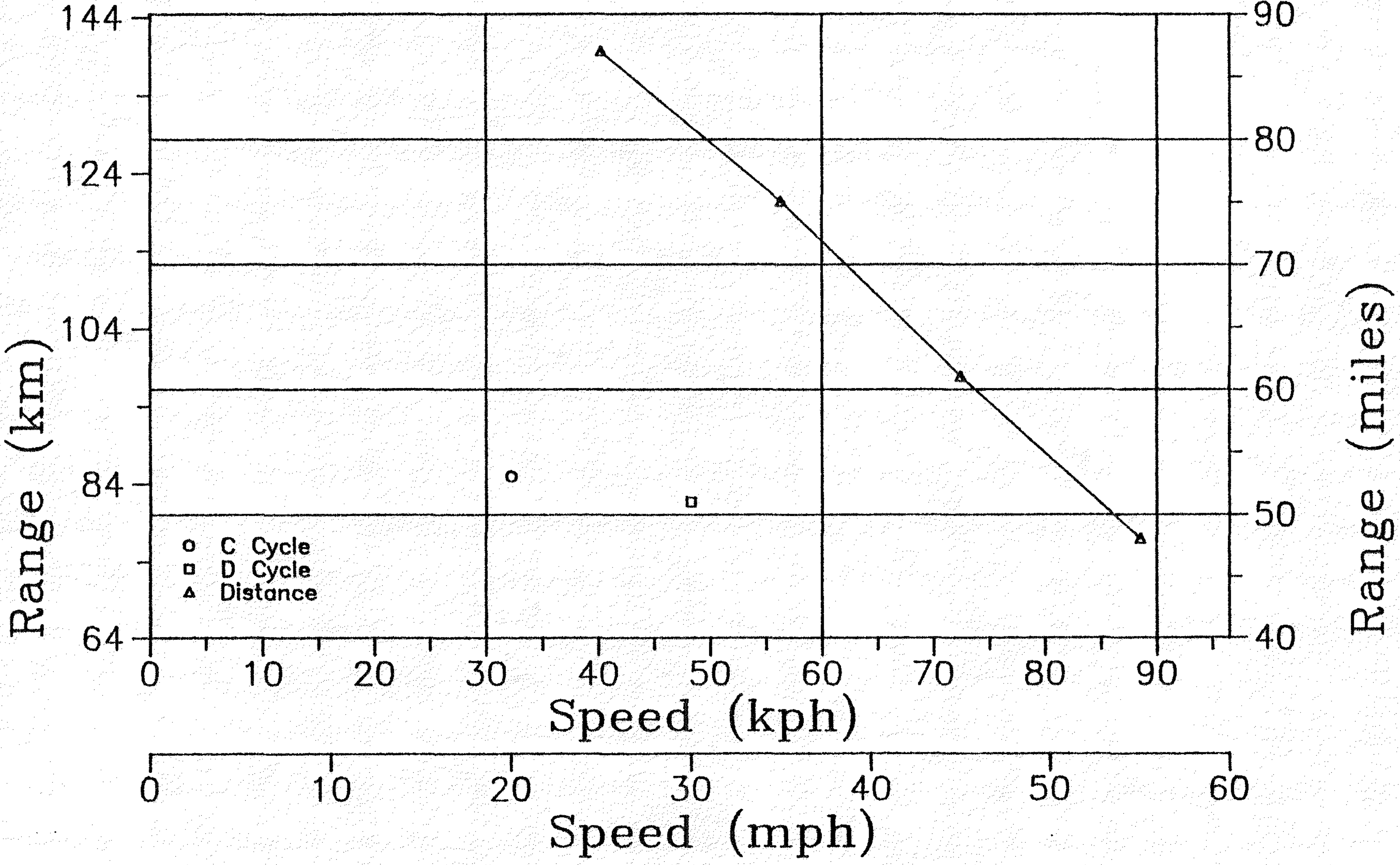


FIG 5 : Range at Constant Speeds

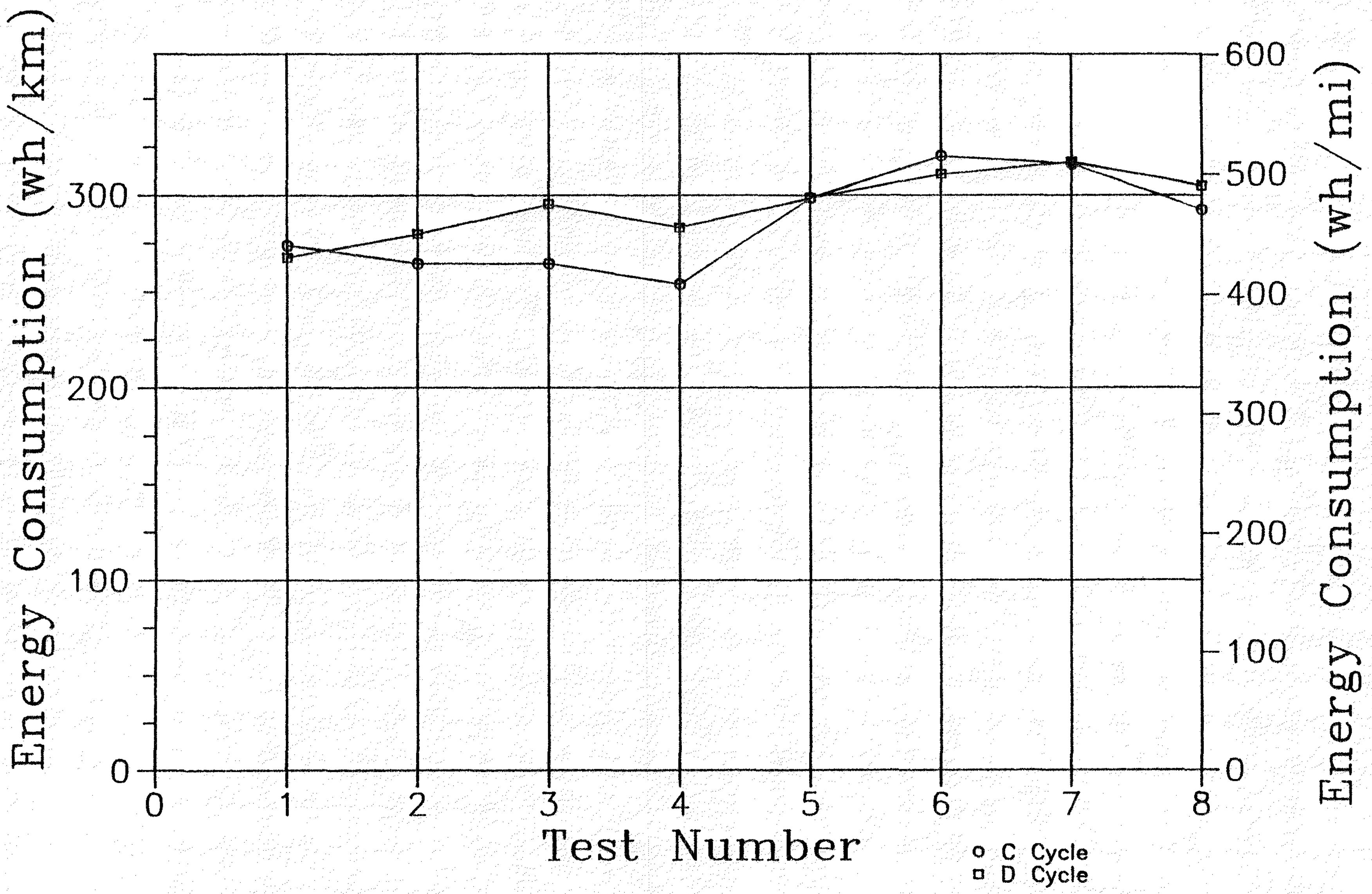


FIG 6 : Energy Consumption Under C and D Cycles

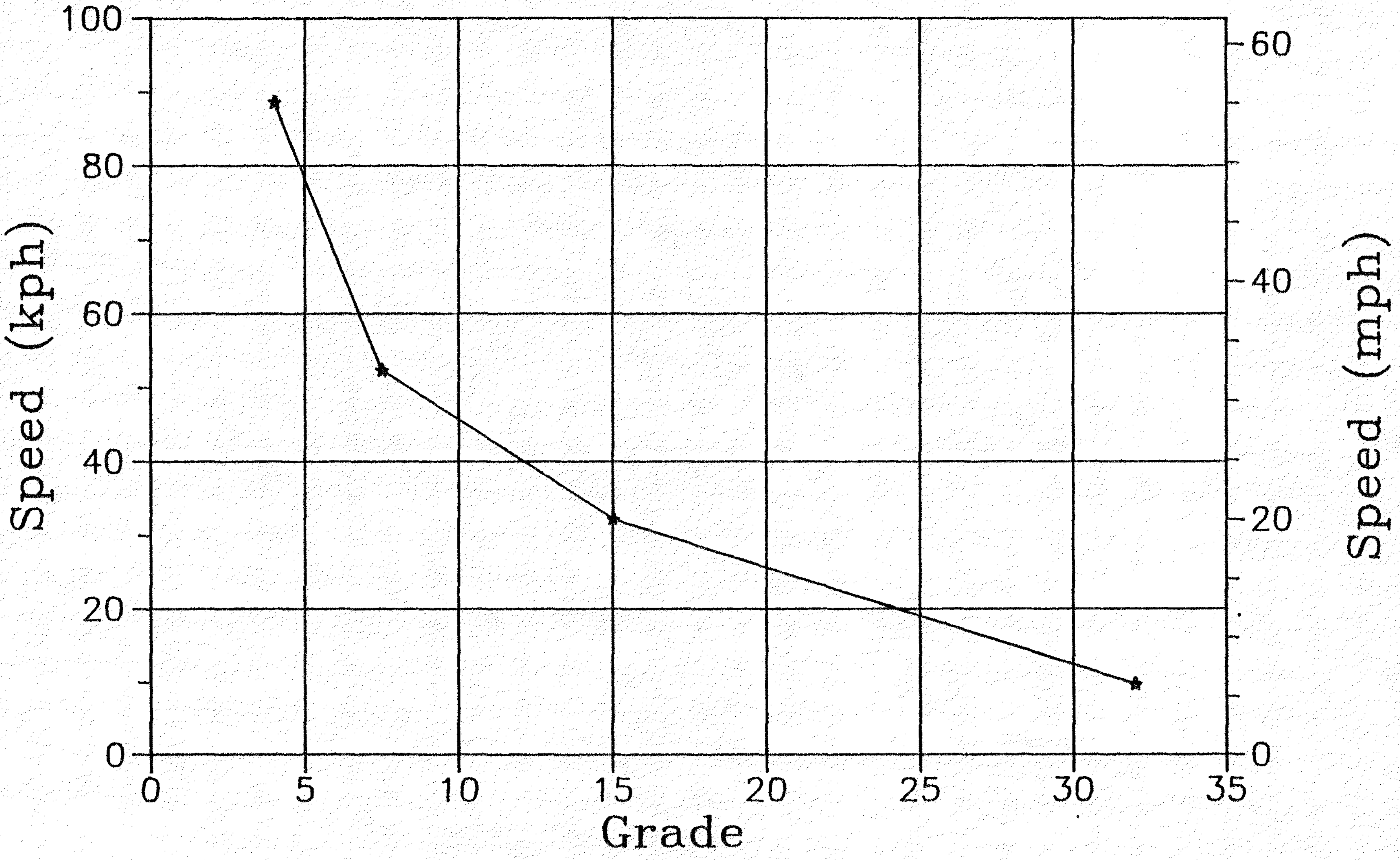


FIG 7 : Gradeability vs. Speed

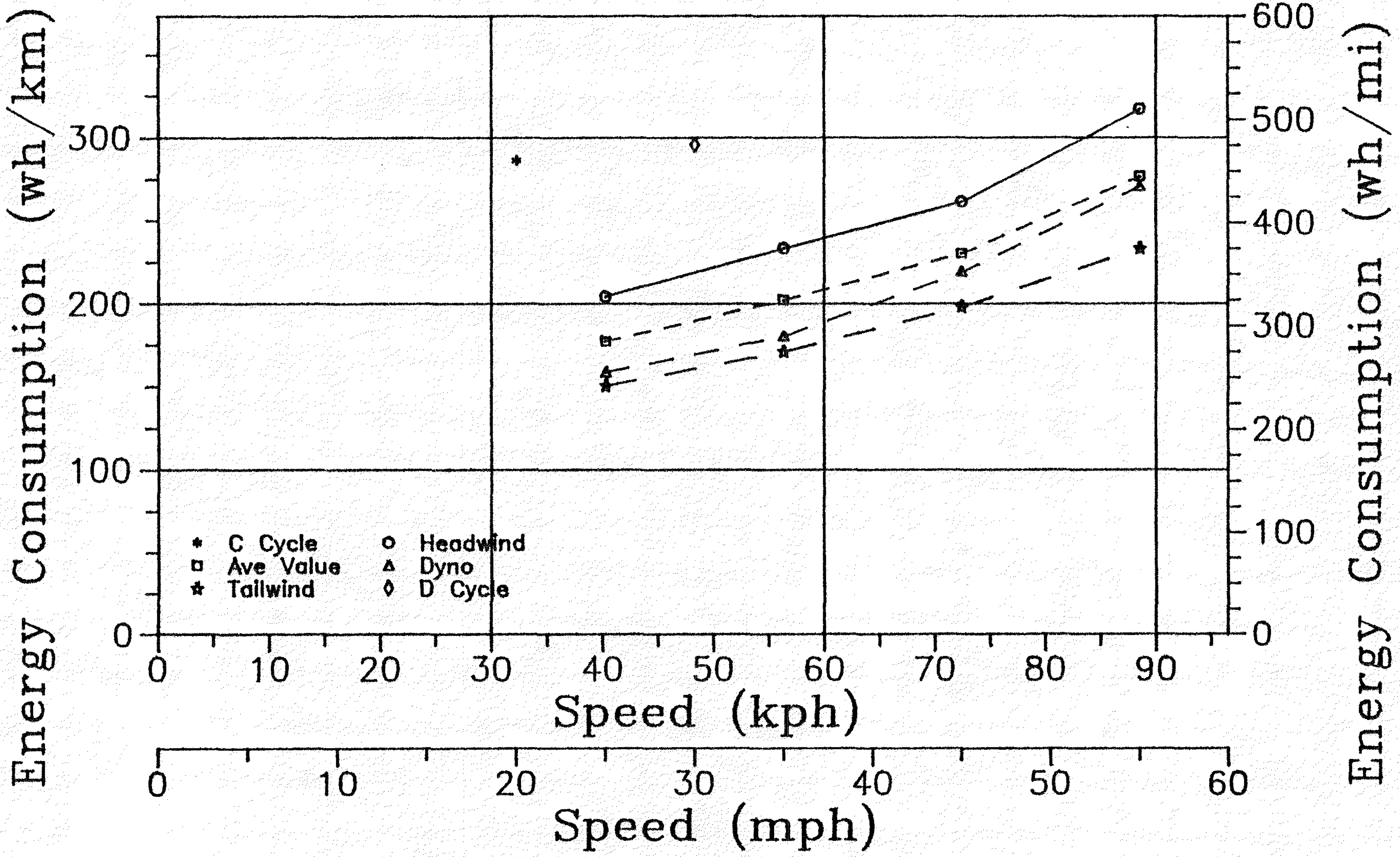


FIG 8 : Energy Consumption at Constant Speed

The TB-1 dyno and road tests impacted the NVH powertrain/vehicle design by indicating areas in need of improvement, namely: peak power shortfall, insufficient smoothness in vehicle start-up and transaxle shifts, hydraulic system noise and efficiency, and the fade in vacuum-assisted brake system.

NVH SYSTEM

Build, Dyno Tests and Vehicle Installation

Fabrication of the redesigned inverter/controller and other subsystems of the powertrain was completed in October of '87.

Dynamometer tests of the new system indicated a number of electronic noise problems that were gradually eliminated from the inverter, the interface module and the controller. The latter, however, underwent another revision in overall circuit layout before the noise problems were resolved. The initial dyno performance of the new system still was below expected levels in terms of peak power and torque. Substantial effort was expended to balance and control critical system parameters throughout the operational spectrum, as the system response appeared markedly different from that of the first-generation TB-1 system. Fig. 9 shows the NVH propulsion system undergoing dynamometer tests.

Installation of ancillary systems in the NVH vehicle was started in January of '88 and completed with the installation of the propulsion system in June to start shakedown tests. Fig. 10 shows motor/transaxle assembly installation in the NVH vehicle.

NVH Vehicle Shakedown Tests

The shakedown testing is underway at Eaton's Southfield location and at Chelsea proving grounds. Fig. 11 shows the NVH vehicle undergoing the tests at Chelsea. A number of unresolved problems have surfaced in the vehicle environment: the stall torque and

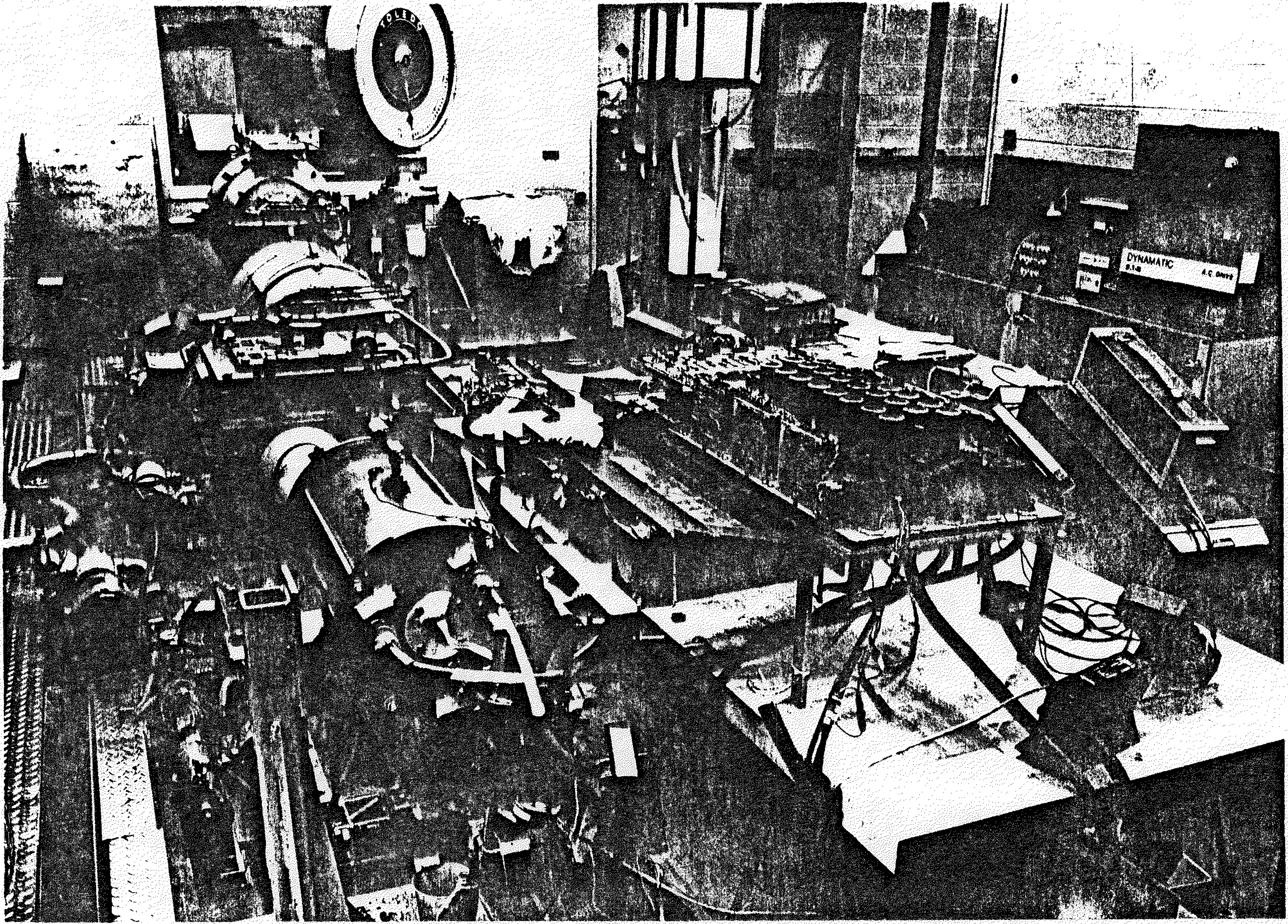


FIG. 9: NVH PROPULSION SYSTEM
DYNO TEST

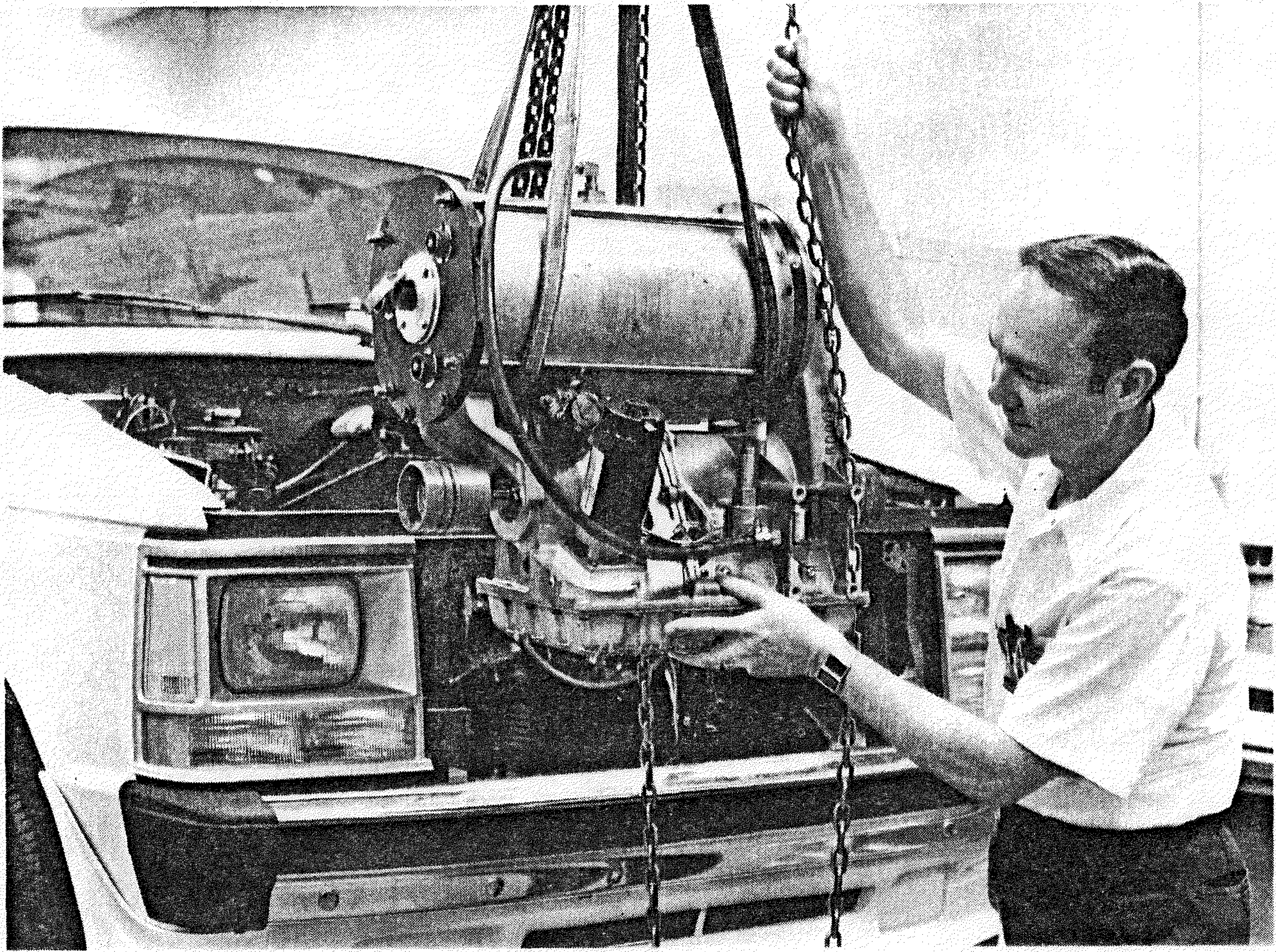


FIG. 10: MOTOR/TRANSAXLE ASSEMBLY
INSTALLATION IN THE NVH
VEHICLE

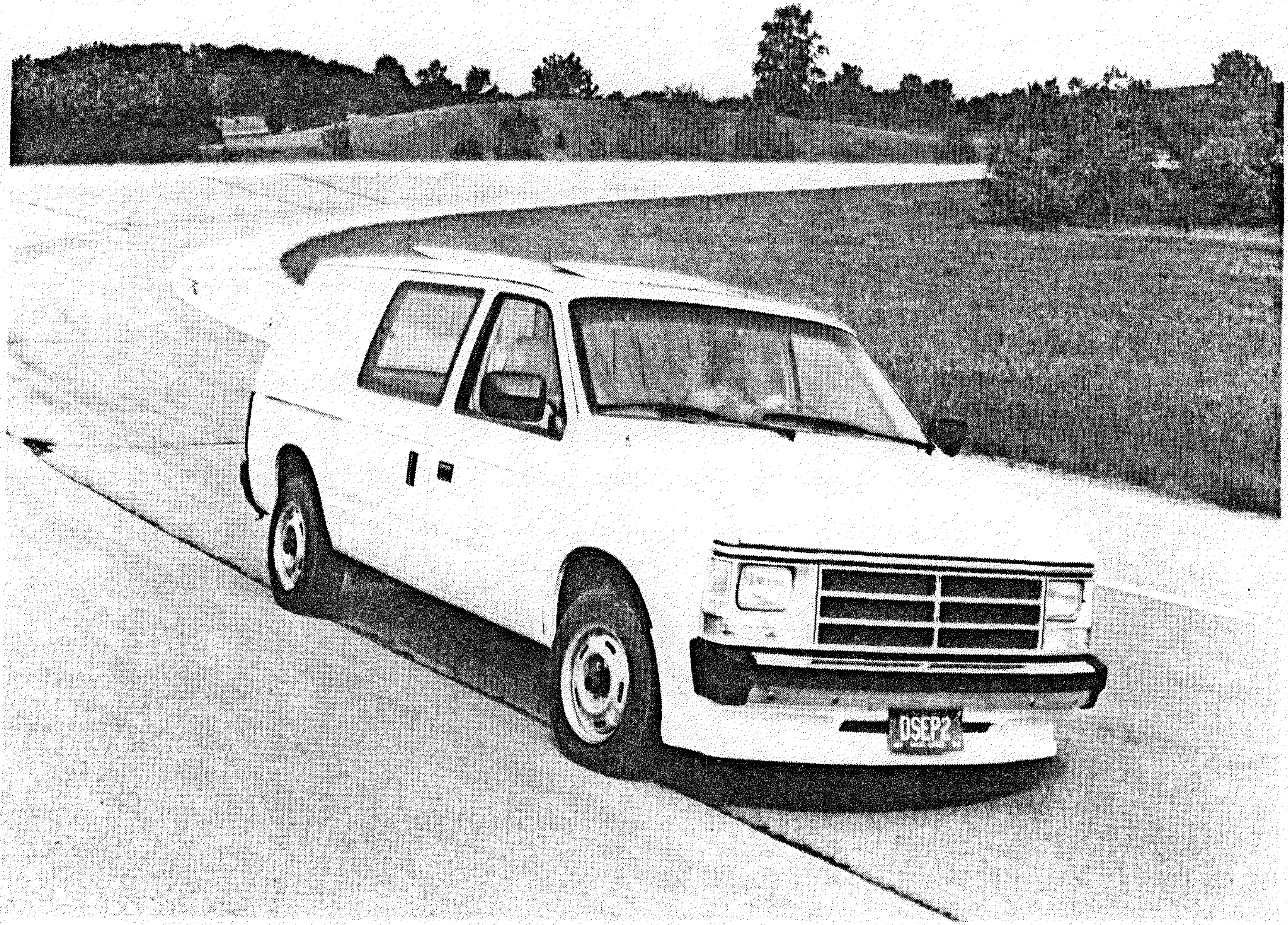


FIG. 11: NVH VEHICLE SHAKEDOWN TEST AT CHRYSLER CHELSEA PROVING GROUNDS

peak power are still unsatisfactory, the inverter occasionally trips out on high torque demand, the shifts at high torque are unsatisfactory, some system instability is still present, and the power steering system is still too noisy.

Corrective Action

Due to DSEP program schedule slip of nine months as of August 1, 1988, it became imperative to resolve these problems without further delay in order to allow satisfactory completion of the program. A task force was formed and is addressing the remaining issues. As a result, the problems have been defined, their causes individually explored, potential solutions proposed and some successfully tried. The process is continuing; substantial improvement has been achieved at this writing in a number of problem areas.

Perceived Causes

Inverter Tripping

There are two classes of inverter trips:

- predictable trips, caused by set limits
- random trips, which are usually caused by induced R.F. or electromagnetic noise in a gross manner through interference into critical susceptible logic circuits.

Predictable trips are being addressed. Random trips are more difficult to deal with because they occur infrequently and unpredictably. The strategy will be to first correct the predictable trips and then turn to what others remain.

Drivetrain Instability

The outer, estimator-based, sensorless torque control loop works very well at start and when the drive is below base motor speed.

TB-1 and NVH are indicating a small but significant amount of instability at high battery voltage conditions after the shift into high gear.

The probable cause is that the motor FOC (Field Oriented Control), being short of battery voltage in this region, does not have enough V/hz "headroom" to force the motor to respond rapidly enough with bandwidth to let the first estimator outer loop function.

Plans are to measure this frequency bandwidth on the TB-2 dyno tests. An optimal balance is to be determined here, since reducing the working V/hz to give more "headroom" and wider bandwidth also reduces the peak torque envelope above base speed.

Rough Shifts

Rough shifts have several possible causes:

- torque not sufficiently ramped before a clutch is disengaged;
- new clutch is reengaged in new ratio with the road speed and motor speed not adequately synchronous;
- a possible cause of the above is for the timing to be off;
- some problems with the rapid motor slew during the shift when both clutches are disengaged.
- mechanical problems are also possible but not likely in this case.

Planned Corrective Action Tasks

The problem solutions are being worked on simultaneously with the NVH vehicle on the road and the TB-2 system on the dyno. When a problem is resolved in one system, the solution is verified by and incorporated into the other system, significantly accelerating the corrective action.

In NVH Vehicle:

- confirm that self-oscillating feedback loops are stable in all motor regimes
- resolve problem with high torque/high speed
- achieve stalled torque expected
- current demand/current limit/current trip strategy
- FOC V/hz etc. optimization
- inverter corroboration--freedom from trips, full current capability, correct ripple component
- cold motor starting
- outer estimator loops--driveline stability
- shift final optimization
- driveability development and tuning
- traces, observations for final report

With TB-2 System on Dyno:

- ambient temperature verification of inverter and controller
- final tuning of FOC algorithm for highest performance/ efficiency balance; try measured V/hz signal integration into controller
- heat sink temperature integration into software (reduce current at excessive heat sink temperatures)
- motor temperature compensation if necessary (to deal with cold motor start)
- torque frequency response and stall, below and above base speed
- torque envelope and efficiency map data
- data reduction, final graph preparation

THE TB-2 SYSTEM BUILD, DYNO TESTS AND VEHICLE INSTALLATION

Most of the TB-2 subsystem fabrication closely followed the build of the NVH propulsion system, as these subsystems had performed satisfactorily in the TB-1 vehicle and thus could be built identical for the NVH and TB-2 vehicle systems. The only exceptions were the inverter and controller, whose redesigned versions were dyno tested to assure functionality of hardware before committing to building second copies for the TB-2. Further development was correctly anticipated to be confined to the software--motor control algorithm--area. This assumption has proved correct, as most development has indeed been in the software. Further program delays as a result of the NVH propulsion system problems have been avoided.

Vehicle delivery by Chrysler and subsequent vehicle conversion by ASC was completed on schedule. All ancillary subsystems have been installed at Eaton, except the propulsion system itself. The latter is on the dynamometer, continuing tests of system characterization and software development in parallel with the NVH vehicle testing.

DSEP BATTERY SYSTEM STATUS

Life tests of the Ni-Fe battery subsystem were continued with two battery packs (at Argonne Labs and Eaton, respectively), and with one single module (at Eagle-Picher). Each of the two packs (nominally with 28 modules in each) have accumulated more than half of the 1200-cycle goal in the past two and a half years of testing.

The pack at Argonne has been subjected to accelerated life testing and has suffered some accidental heavy overcharge. While the rest of the pack continues to test satisfactorily, seven modules have recently been removed due to inadequate individual performance.

The single-module test was terminated just short of the goal, at 1060 cycles, for the same reason.

Examination of the removed unsatisfactory modules indicates a predominant single assignable cause--a manufacturing quality control problem with the iron electrode. The deficiency has surfaced now, after years of testing. It is being addressed with the off-shore, Swedish Nife source. However, the manufacture of all six packs and spare modules required for the program has already been completed.

The battery packs in the test bed vehicles have performed satisfactorily in over-the-road and proving grounds tests, enabling the vehicle to achieve its demanding performance goals. However, four modules were recently replaced in the #3 battery pack of the TB-1 vehicle before the vehicle was to undergo final dynamometer tests at EG&G in Idaho Falls. Analysis of the causes for unsatisfactory performance of these four modules is not complete.

MANUFACTURING COST, LIFE CYCLE COST ANALYSIS, AND FUTURE PLANNING

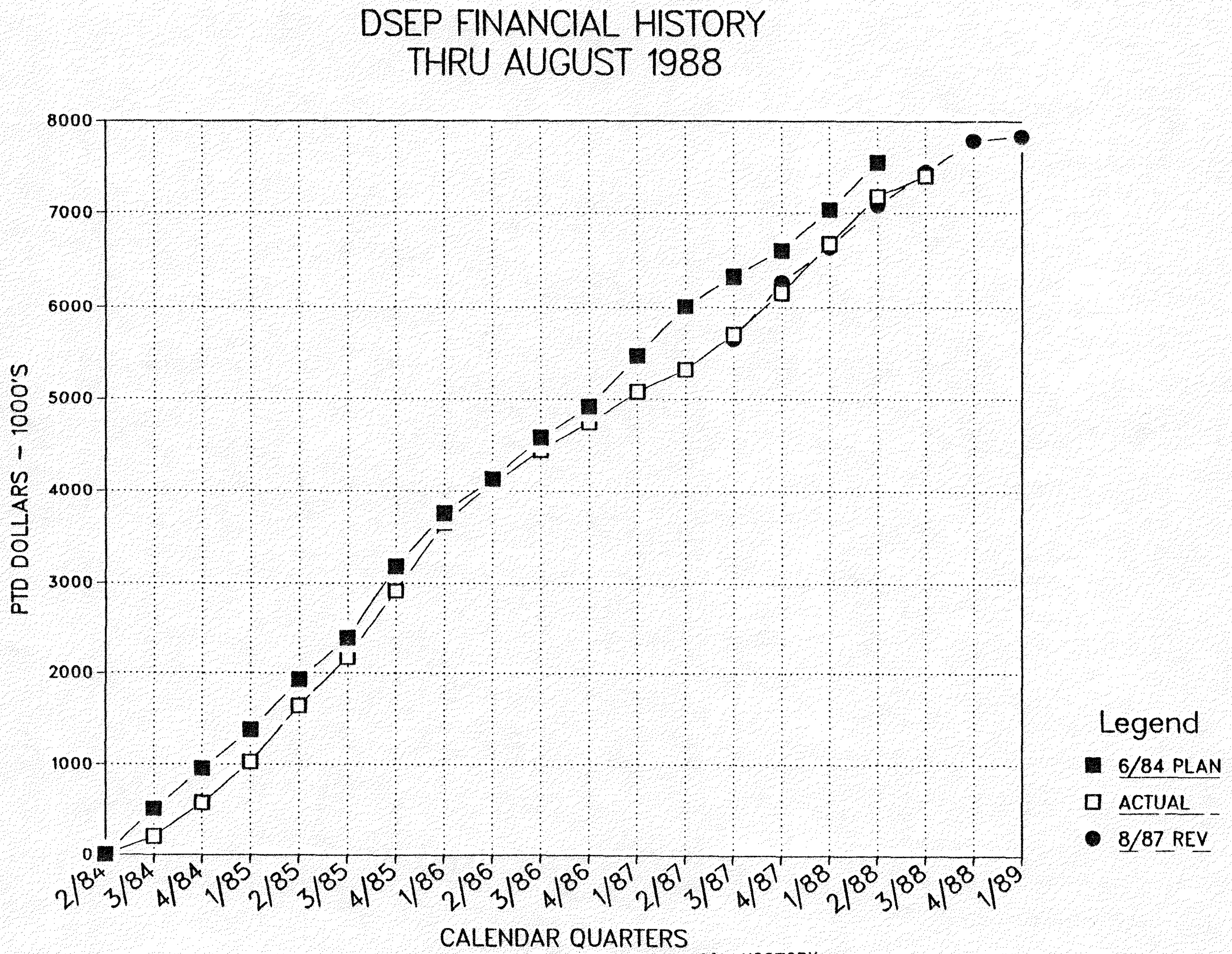
Vehicle life cycle cost analysis and future planning is underway.

A number of market studies (EVDC's; Detroit Edison's; Booz, Allen, Hamilton's) relative to electric van commercialization were examined for methodology and results. The DSEP van life cycle cost analysis is focusing on electric vs. gasoline-powered light delivery van comparison, using the method and algorithm employed in the initial life cycle cost analysis. A detailed manufacturing cost estimate for use in the final life cycle cost analysis of the DSEP van is nearly completed for annual production quantities of 300, 3000 and 100,000.

A number of scenarios for commercialization of the DSEP van have been promulgated and subcontractors contacted about their potential role and interest in them. While there are indications of their interest in the long-term, uncertain market potential and the lack of a volume customer committment leaves this program still at "high risk".

PROGRAM MANAGEMENT

Eaton Corporation has continued through the fourth 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 12 illustrates the financial history of the DSEP program.



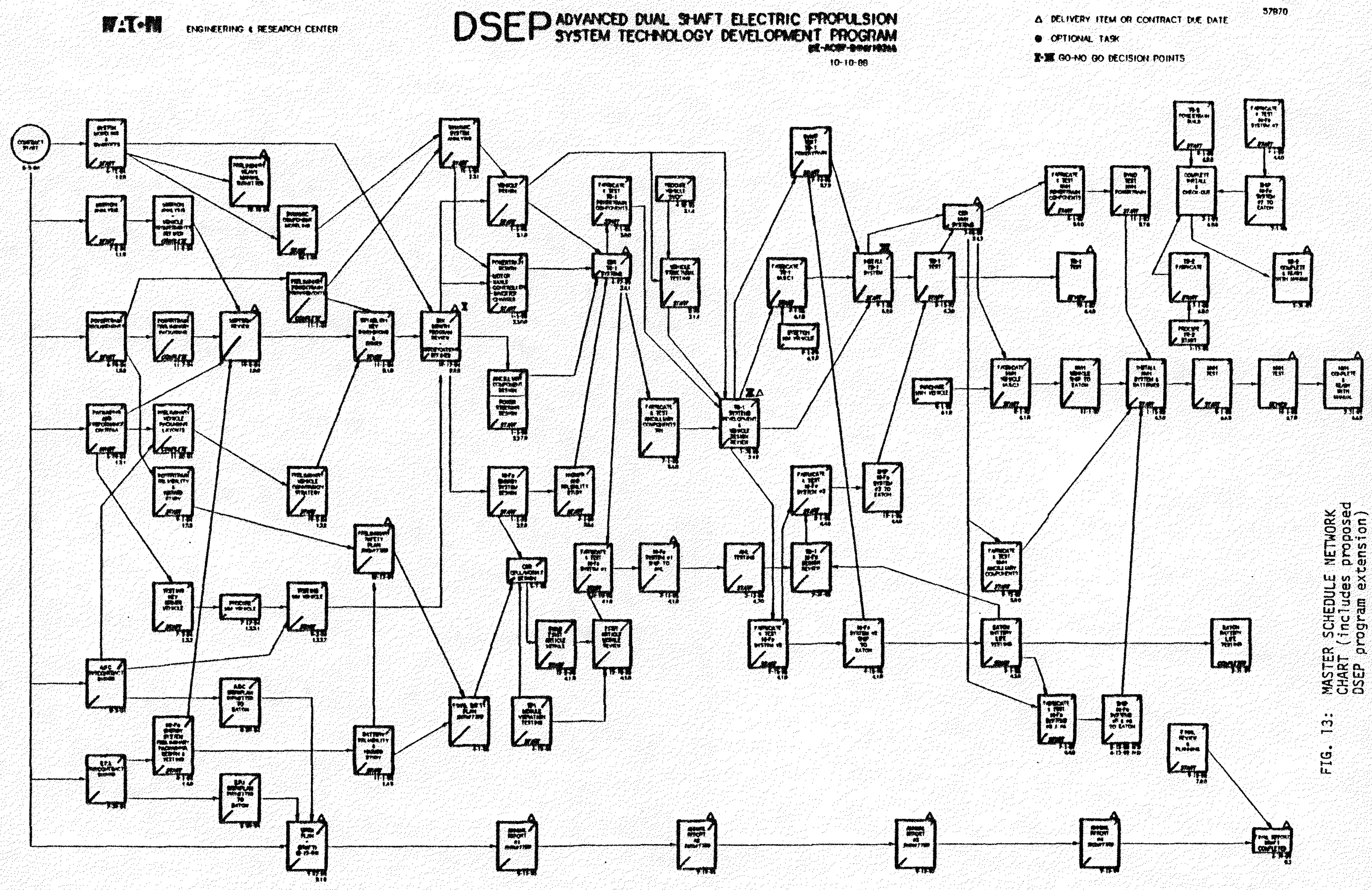
DSEP FINANCIAL HISTORY
THRU AUGUST 1988

FIG. 12: DSEP FINANCIAL HISTORY

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, safeguards around high voltage equipment, and safe handling of the two operational vehicles.

Contractually required review meetings were held, presentations made as requested, and weekly/monthly progress reports furnished on schedule. A complete TB-1 vehicle test report was issued. An endurance test plan for the NVH vehicle was written, along with operation and maintenance instructions for the TB-1 vehicle. Also, three technical papers have been prepared for presentation at the 9th International EV Symposium in Toronto in November 1988.

Due to the delay in solving NVH control problems, technical progress of the NVH vehicle has fallen six months behind schedule (Master Schedule Network Chart, dated 9/16/88, in last year's Annual Report). As the completion of the TB-2 vehicle is dependent on solution of the same problems, its progress is two months behind as of 10/1/88. A $592,000 and seven-month program extension to June 30, 1989 has been submitted for approval to DOE; this extension would permit satisfactory completion of the program. The attached graph of DSEP financial history, the master schedule network chart, Fig. 13, and a detailed (by task and subtask) Gantt chart, Fig. 14, of the schedule reflect the proposed program extension and scope changes.



EATON ENGINEERING & RESEARCH CENTER

DSEP ADVANCED DUAL SHAFT ELECTRIC PROPULSION SYSTEM TECHNOLOGY DEVELOPMENT PROGRAM

10-10-88

△ DELIVERY ITEM OR CONTRACT DUE DATE

● OPTIONAL TASK

I-III GO-NO GO DECISION POINTS

57870

FIG. 13: MASTER SCHEDULE NETWORK CHART (includes proposed DSEP program extension)

```
Program: PHASE2     DSEP PROGRAM SCHED./FUND. EXTENS.9/26/88                                                 Starting Date: 10/14/88
 Task         Description           OCT88   DEC88   FEB89   APR89   JUN89   AUG89   OCT89   DEC89   FEB90   APR90   JUN90   AUG90

 3201 DSGN AUTO BATT WTR SYST         ------>.
 3202 FABR AUTO WTR SYST                      <-->.
 3203 INSTALL&TEST WTR SYST                       <---.....
 3301 UPDATE TR/AXLE DWGS             ----.
 4301 BATT LIFE TEST                  --------------------..
 4401 ASSY OF BATT PACKS              ----...
 5601 DEFINE SOCM MALFUNCT            -->.
 5602 REVISE SOCM ALGRTHM                 <-->.
 5603 TEST SOCM PERFORM                         <-------....
 5604 FAB 2 PWR STR UNITS             ->..
 5605 INSTALL&TEST PWR STR UNITS          <---...
 5701 TUNE FOC ALGRTHM ON DYNO        ---->.                                    S :  Start of Program
 5702 HT SNK TEMP INTEGR              -->...
 5703 ROTOR TEMP COMPENS              ---->......                               F :  End of Program
 5704 TORQUE FREQ.RESPONSE                     <>..
 5705 MAP TORQUE & EFFICNCY                       +.                              = :  Critical Task
 5706 DATA REDUCTION                                <--..
 6601 DETERM.CURRNT LIM STRAT         ---->.                                    < :  Task has a Predecessor
 6602 OPTIMIZE PARAMTRS               ---->.
 6603 INVERTER CORROBOR.                      <--..                             > :  Task has a Follower
 6604 COLD STARTS                             <--..
 6605 DRIVELINE STABILITY                      <>...                            + :  Single Week Task with both Predecessors and Followers
 6606 SHIFT OPTIMIZ.                                <.
 6607 DRIVEABILITY TUNING                           +.                          * :  Zero Duration Event
 6608 RECORD TRACES                                   <---....
 6609 ACCUMULATE MILEAGE                              <-->...                     : :  Portion of Task which is Complete
 6610 DELIVER VEHICLE                                         *
 6801 MOUNT TB-2 PWR STR ASSY             <-..
 6802 INSTALL WATER SYST              --.                                       . :  Slack Time
 6803 INSTALL BATTERY                 ----..
 6804 INSTALL DRIVER CONTRLS            -------..                               ^ :  Either a Missed Start Time or Delayed Finish
 6805 INSTALL MTR/TRANS ASSY                        <->..
 6806 INSTALL CABLING                                 <->.
 6807 VEHICLE SHAKEDOWN                                   <>
 6808 ACCUMUL MILEAGE                                       <=====>
 6809 DELIVER VEHICLE                                               *
 7001 MFG COST ESTIMATE               ---->.
 7002 LIFE CYCLE COST ANAL                    <----->.
 7003 ASSESS COMERC POTENTIAL                             <>..
 8001 EXEC COMM MTG                                              *
 8002 PARTICIP EVS-9 TORONTO              -.
 8003 DRAFT FINAL REPORT                                    ----------..
 8004 PROGRAM MANAGEMENT              =================================^F
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FIG. 14: GANTT CHART OF PROPOSED DSEP PROGRAM EXTENSION