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Performance Testing of the Ford/GE Second Generation Single-Shaft Electric Propulsion (ETX-II) System

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ABSTRACT

System-level-operational testing of the ETX-II test-bed electric vehicle is described and the results discussed. Because the traction battery is a major factor in the performance of an electric vehicle, previously reported work on the sodium-sulfur battery designed for use with the ETX-II is reviewed in detail. Chassis dynamometer performance of the test-bed vehicle met or exceeded design goals and compared reasonably well with SIMPLEX computer modeling results. Areas are identified wherein further work is needed to establish a firmer basis for comparison of the simulation and the observed results.

SUMMARY

In 1981, Ford Motor Company (Ford) and General Electric Company (GE) developed a concept for an advanced electric vehicle powertrain that was subsequently presented to the U.S. Department of Energy (DOE) as an unsolicited proposal. The concept involved a combination of technology from Ford and GE that would result in a novel powertrain based on a motor and transmission concentric with the drive wheel axis. Initial work suggested that the entire motor/transaxle combination could be expected to be smaller and lighter than the dc motors that were currently in use in electric vehicles at that time, and that the powertrain could be expected to be more efficient than other available powertrains. A contract for this program (ETX-I) in support of the DOE Electric and Hybrid Vehicle Program (EHVP) was awarded to Ford on April 15, 1982. During the course of the ETX-I program, it was determined that the most likely introduction of an electric vehicle (EV) to the nation would be in the form of a fleet of small commercial vans. In response to this need, the Second Generation Single-Shaft Electric Propulsion System (ETX-II) Program was proposed.

The objective of the ETX-II research and development program was to upgrade the ETX concept in order to make it suitable for use in a small commercial van and to advance ac propulsion system technology for electric vehicles, another step nearer to production so that industry would have additional information from which to make decisions regarding applicability for commercialization. The resulting contract, No. DE-AC07-85NV10418, was awarded by the DOE, and the effort commenced March 14, 1985. The contract was administered by the DOE Idaho Field Office and was technically monitored by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL).

The ETX-II Program focused on the design, construction, test, and refinement of an experimental advanced electric vehicle propulsion system suitable for packaging in a Ford Aerostar minivan. The program effort was directed toward advancing the technology by improving the size, weight, efficiency, reliability, and cost characteristics of the ETX-I powertrain and by integrating advanced battery technologies compatible with the powertrain to

form a complete propulsion system. Novel developments within the ETX-II program included the transaxle, a two-speed automatic transmission, and three-phase interior permanent magnet ac motor on a common axis integral with the rear axle of the test bed van; a compact water-cooled inverter to operate up to 500 A from a 200 V battery pack; a system controller that included digital inverter/motor controls to generate the necessary motor drive signals, microprocessor-based vehicle controls that interface with the driver, all of the vehicle subsystems to control motor torque, regenerative braking, transmission shifting, and other functions. The scope of the ETX-II program was broadened to include a plug-compatible, MOS-controlled thyristor- (MCT) based inverter to test the MCT technology in the ETX-II system.

The traction battery that Ford selected for this propulsion system was the sodium-sulfur (NaS) battery. It was determined that this was the only advanced technology that had been developed to a point that would allow the test vehicle to achieve a range of over 160 km (100 mi), as determined on the Federal Urban Driving Schedule (FUDS), without the battery exceeding 25% of the vehicle's gross weight.

A suitable NaS battery was supplied to DOE by Chloride Silent Power, Limited, of the United Kingdom, for all necessary evaluation and testing, both apart from and in the test-bed vehicle. Under the terms of the contract with DOE, CSPL retained ownership of the battery and was kept aware of test activities and results which would indicate any degradation of the battery's capabilities (i.e., end-of-life).

This report describes the system-level operation of the ETX-II test bed vehicle during the engineering tests designed to characterize and evaluate its performance. The vehicle was tested at steady-state speeds and on several drive cycles, including SAE J227a/C and the FUDS. For all of the dynamometer tests, detailed measurements of the energy flow throughout the system were recorded. Table S-1 summarizes the test results. It should be noted that the NaS battery was removed from the ETX-II by CSPL before dynamometer testing was

completed. As a consequence, the J227a/C and FUDS cycle tests were powered by a sealed lead-acid battery. Vehicle performance was not battery-limited in either case.

Table S-1. ETX-II test results summary.

Constant Speed (km/h)	Energy Consumption (W·h/km)
48 ^a	155
56 ^a	159
72 ^a	172
80 ^a	200
88 ^a	218 ^c
96 ^a	242
SAE J227a/C ^b	218 (196) ^d
FUDS ^b	233 (212) ^d

-
- a. Tests performed with the CSPL NaS battery.
 - b. Tests performed with the sealed lead-acid battery.
 - c. Measured range of 185 km.
 - d. Gross (net) energy consumption.
-

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ACRONYMS

A	amperes, unit of current
ac	alternating current
A·h	ampere-hours
ANL	Argonne National Laboratory
BMS	Battery Management System
C-Cycle	SAE J227a Driving Cycle C
C _D A	drag-area product
CSPL	Chloride Silent Power Limited
dc	direct current
DOD	depth-of-discharge
DOE	U.S. Department of Energy
DSEP	dual-shaft electric propulsion
EHVP	Electric and Hybrid Vehicle Program
EMI	electromagnetic interference
ETX	electric transaxle
ETX-I	First Generation Single-Shaft Electric Propulsion System
ETX-II	Second Generation Single-Shaft Electric Propulsion System
EV	electric vehicle
EVTL	Electric Vehicle Testing Laboratory at the INEL
Ford	Ford Motor Company
FUDS	Federal Urban Driving Schedule
GE	General Electric Company
gpm	gallons per minute
I	electric current
IDSEP	improved dual-shaft electric propulsion
IGBT	insulated gate bipolar transistor
INEL	Idaho National Engineering Laboratory
IPM	interior permanent magnet
IR	current-dependent voltage drop
JCI	Johnson Controls, Incorporated
JPL	Jet Propulsion Laboratory
LED	light emitting diode

MCT	MOS-controlled thyristor
MEVP	Modular Electric Vehicle Program
MLC	multi-layer ceramic
MOS	metal-oxide semiconductor
N·m	newton-meter (unit of torque)
NVH	noise, vibration, and harshness testing
OEM	original equipment manufacturer
PWM	pulse width modulation
RAM	random access memory
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SFUDS	Simplified Federal Urban Driving Schedule
SNL	Sandia National Laboratory
SOC	state-of-charge
TB-1	DSEP Test Bed-1 Vehicle
TB-2	DSEP Test Bed-2 Vehicle
U.K.	United Kingdom
V	voltage in volts
W/kg	battery power density in watts per kg
W·h/kg	battery energy density in watt-hours per kg
W·h/km	test bed energy consumption in watt-hours per km
WORM	"write-once-read-many" optical storage medium

PERFORMANCE TESTING OF THE FORD/GE SECOND GENERATION SINGLE-SHAFT ELECTRIC PROPULSION (ETX-II) SYSTEM

INTRODUCTION

In 1985, the Ford Motor Company (Ford) was placed under contract to the U.S. Department of Energy (DOE) to develop the Second Generation Single-Shaft Electric Propulsion (ETX-II) System. This research effort concentrated on technologies that would adapt the ETX concept to a small commercial van. General Electric Company (GE) was a major subcontractor and was responsible for the electric subsystem, comprising the motor, its controls, and the inverter, including the power modules. Technological advances that were made included: a new interior permanent magnet (IPM) motor for the transaxle assembly that was integrated into the rear axle of the van, development of the algorithms required for control of the interior permanent magnet motor, development of the power modules, improvements to the inverter to reduce its size and weight, and integration of the vehicle controls and the electric subsystem controls into a single component that controlled the entire propulsion system. Design details are presented in Reference 1. In addition, specification and integration of an advanced sodium-sulfur (NaS) traction battery was included in the program to ensure that this portion of the propulsion system was included in all of the system design trade-offs. Powerplex Technologies, Inc. (Powerplex), a subcontractor, supplied a NaS traction battery for the program. An additional NaS traction battery (built to ETX-II specifications under a separate contract with the DOE) for test in the ETX-II propulsion system was supplied by Chloride Silent Power Limited (CSPL).

In FY 1990, GE delivered three types of inverters for the ETX-II propulsion system, although the program was originally planned for only two types of inverters. The first type was a bipolar transistor-inverter that used the Darlington transistor developed in the ETX-I program. The second type was the more advanced MCT-based inverter that utilized the MOS-(metal oxide-semiconductor) controlled-thyristor(MCT) technology developed at GE, and a high voltage multi-layer ceramic (MLC) capacitor available from Olean

Advanced Products. Because of several unresolved failures in one of the phase legs of the Darlington inverter, an additional more rugged inverter replacement was provided by GE with their own funds. This third inverter type was developed by GE for fan drives and uses Insulated-Gate Bipolar Transistors (IGBTs). It was repackaged to fit the vehicle and also interfaced directly to the ETX-II controls. The IGBT inverter is expected to be a viable contender for use in the production of EVs.

Initially, two of the advanced MCT inverters were planned; however, program cost constraints and availability of hardware allowed for only a single MCT inverter to be built and functionally tested on the dynamometer at GE. The advanced MCT inverter has significant advantages over the other transistor inverters: elimination of the driver circuits and the power supplies that are required for bipolar switching devices; reduction of snubber circuits and the attendant operating losses; greater power efficiency; and better thermal management. Use of a ceramic capacitor permits a large reduction in required volume for the dc bus capacitor and in energy lost as heat. These improvements allow the MCT inverter to be 50% smaller, 50% lighter, and more efficient than the other transistor inverters for the same power rating. Tests on the MCT-based inverter² (conducted at GE under full-power operation) indicated very high (95%) efficiencies, as evidenced by the absence of a temperature rise of the coolant (water at 1 gpm). The inverter was subjected to intensive testing, including regenerative operation. Notable goals achieved include 60 kW (81 hp) at 7,000 rpm and 41 N·m (30 lb-ft) of regeneration torque at 5,000 rpm.

The ETX-II program was completed in FY 1990, and the DOE took delivery of the ETX-II test bed vehicle in October 1990. The ETX-II was subsequently shipped to the INEL for extensive laboratory testing of the test bed vehicle and the CSPL NaS battery in November of 1990. Battery and vehicle testing were completed in April 1992.

The purpose of the work reported here was to examine the system-level operation of the ETX-II test bed vehicle during the engineering tests designed

to characterize and evaluate its performance. Procedures to determine the levels of performance of the ETX-II test bed vehicle were based on the final draft revision of the Society of Automotive Engineers (SAE) Electric Vehicle Test Procedure SAE J227a, dated May 8, 1986. Tests of the ETX-II were performed in the INEL Electric Vehicle Testing Laboratory (EVTL) at Idaho Falls, Idaho. Supporting tests to characterize and evaluate a state-of-the-art sodium-sulfur traction battery (a candidate power source for this vehicle) were conducted in the INEL Battery Test Laboratory. The test data were analyzed in detail and compared with other test results and computer simulations of the ETX-II vehicle under various operating conditions.

A substantial portion of this report is concerned with the details of the CSPL NaS battery, both construction and performance. Many of these details were reported in an earlier document³. Nonetheless, since vehicle performance is largely dependent upon battery performance, the authors felt it desirable to present an adequate review of this information in the context of vehicle testing. It should also be noted that, under the terms of the contract with DOE, CSPL retained ownership of the battery and was given full access to the data from all testing activities, in order to monitor the service behavior for end of useful life through potential degradation. Withdrawal of the NaS battery from test-bed vehicle service by CSPL was based on such degradation.

ETX-II SUBSYSTEMS

Powertrain

In August 1985, the 50 hp induction-motor-based ETX-I Advanced Electric Vehicle Powertrain Program was completed. Testing performed under that program (Contract No. DE-AC08-82NV-10308) verified that the vehicle met its program targets for energy consumption, acceleration, gradeability, and automotive-industry-acceptable driveability. This successful contract that involved three years of extensive effort by Ford Motor Company (Ford) and the General Electric Company (GE) (a major subcontractor), significantly advanced the state-of-the-art in electrically-powered vehicles.

An advanced 70 hp ac electric-drive system was then to be developed under the DOE-sponsored Second Generation Single-Shaft Electric Propulsion System Development Program (ETX-II). This contract was placed in March 1985. ETX-II research efforts concentrated on the development of highly efficient electric-drive system components, and associated controls with application to a small commercial van. Transaxles developed for both the ETX-I and ETX-II contained two-speed automatically shifted transmissions with the oil-cooled ac electric motor mounted concentrically with the drive axle axis. ETX-I was designed for a small front-wheel drive passenger car, while the ETX-II was designed for a rear-wheel drive minivan.

Performance goals for the ETX-II propulsion system are shown in Table 1. These performance goals are for a vehicle weight of 2,050 kg, corresponding to the vehicle plus half of the maximum payload capability.

Table 1. ETX-II propulsion system performance goals.

Energy Consumption (FUDS)	250 W·h/km
Maximum Speed	96 km/hr
0 - 80 km/hr acceleration	< 20 s
Gradeability	30%

Electric Drive System

The advanced ac electric drive system consists of a 70 hp interior permanent magnet (IPM) synchronous motor, a three-phase transistor inverter, and microprocessor-based inverter/motor controller. Power is supplied from the nominal 204 V battery to the pulse-width-modulated (PWM), current-regulated transistor inverter for delivery to the three-phase IPM motor as adjustable frequency ac power. This dc-ac power conversion is controlled by the inverter/motor controls that regulate drive operation using motor phase current and rotor position feedback. A brief description of the IPM motor, inverter, and controls is provided in the following paragraphs.

IPM Motor

The efficient (96%) 70 hp IPM motor was designed by GE Motors, Ft. Wayne, Indiana. Based on the system performance goals shown in Table 1, the motor was designed for a maximum output torque of 110 N·m (81 lb·ft) in the constant torque region and 70 hp from its base speed range of approximately 4,500 to 11,000 rpm while operating from a 135 V battery. During the motor design process, detailed motor simulations were used to project the motor output torque/speed envelope for operation at rated voltage and several values of motor phase current. Total weight of the motor rotor and stator is 50.9 kg (112 lb).

PWM Inverters

Three liquid-cooled inverters were designed and tested as part of the 70 hp ETX-II program effort. These inverters convert the 204 V nominal battery voltage to an adjustable ac voltage and frequency with either positive or negative phase sequence. The power circuit is a three-phase, full-wave bridge with power semiconductor switches and reverse-connected feedback diodes. The inverter developed in the base program utilizes three custom power modules, each comprising a full-phase Darlington transistor with associated feedback diodes and snubber circuits, and represents the entire complement of power semiconductors for the 70 hp inverter. The inverter is designed to operate from 135 to 264 V dc link with peak device currents of 525 A. Rated ac output current for this inverter is 315 A rms in PWM mode and 325 A rms in square-wave mode of operation. Dimensions of the Darlington inverter are: 60.6 x 29.5 x 25.1 cm (23.875 x 11.625 x 9.875 in.), not including vehicle mounting brackets. The Darlington inverter weighs 36.4 kg (80 lb.).

Two additional prototype three-phase inverters were developed by GE to directly interface with the ETX-II controls and IPM motor. The first advanced inverter uses MOS-controlled thyristors (MCTs) and multi-layer ceramic capacitors. The goal for the MCT inverter development effort was to cut the volume in half and to obtain higher efficiency than the original Darlington inverter. (MCT device losses are about 50% of the Darlington device losses.) The second prototype inverter uses Insulated-Gate Bipolar Transistors (IGBTs) and electrolytic capacitors in approximately the same volume as the Darlington inverter.

Advanced MCT-Based Inverter Development

The MCT-based inverter design is based upon two new technological advances: the MCT power switch and its driver, originally developed at the GE Corporate Research and Development Center (CRD), and the high-voltage multi-layer ceramic capacitor product available from Olean Advanced Products. The MCT power switch provides the following important advantages: elimination of bulky power driver circuits and their power supplies as required for bipolar

power switches, elimination of bulky snubber circuits, and a significant reduction in operating losses that permits attaining greater power efficiency and better thermal management. The use of ceramic capacitors permits a large reduction in the volume required for the dc bus capacitor and a significant reduction in capacitor loss as heat.

An MCT switch is comprised of three MCT modules (with four MCTs per module connected in parallel), each module having its own free-wheeling diode, snubber resistor, and capacitor in a tightly connected configuration. These module assemblies are built on individual alumina substrates and clamped into intimate contact with the base plate. Each module is provided with anode and cathode copper straps to connect them in parallel to the positive and negative dc bus.

A single gate-driver card is mounted directly above the three MCT modules and drives the three gates in parallel through balancing resistors.

The MCT inverter contains six MCT switches, series-connected across the dc bus as three independent phases. The inter-switch connection comprises the phase output to the motor. The worse-case instantaneous peak current in each phase leg MCT switch is 525 A, based upon ETX-II specifications and electric drive system measurements. The worst-case instantaneous peak voltage experienced by the MCT is constrained to less than 375 V by the incorporated RC snubber.

The 1200 uF dc bus capacitor bank employs twenty-four MLC capacitors (600 V, 50 uF each). The low value of reactance for these capacitors results in a negligible temperature rise and an improvement in inverter efficiency compared to aluminum electrolytic capacitors.

The ETX-II MCT inverter is designed as a "drop-in" replacement for the existing bipolar Darlington-transistor-based inverter. By definition and design, it is physically and electrically compatible with the existing mechanical and electrical connections to the ETX-II Darlington transistor inverter. However, the reduction in volume by a factor of more than 50%

forced the relocation of supporting hardware.

Direct liquid cooling technique, as used successfully in the ETX-II baseline inverter, is also utilized in the MCT inverter. Six 2-mm (0.080-in.) depth "tubs," connected in series from the coolant input to output ports, are located at each MCT half-phase switch position. Liquid coolant is sealed using O-rings between the switch base-plate and heat sink. Dimensions of the liquid-cooled MCT inverter are 52.6 x 23.6 x 16.8 cm (20.7 x 9.3 x 6.6 in.). The MCT inverter volume is 0.021m³ (0.73 ft³), and the weight 28.6 kg (63 lb). Inverter output power at the nominal 204 V dc link is 87.3 kVA; therefore, the power density of this inverter is 4.2 MVA/m³ (119 kVA/ft³)².

Advanced IGBT-Based Inverter Development

The advanced IGBT-based inverter power circuit was initially developed for a higher voltage/higher power (600-V dc link) application. Design peak semiconductor switch current for this inverter is 800 A. Operation of this inverter at its designed value of 600-V dc link produced 300 hp when interfaced to the appropriate three-phase motor. The IGBT inverter volume is 1.75 ft³, and its weight is 45 kg (100 lbs). ETX-II controller torque and current limits were increased with the IGBT inverter. This provided improved vehicle acceleration performance compared to the performance with the original Darlington and MCT inverters. The IGBT inverter was installed in the ETX-II vehicle when it was delivered to the U.S. Department of Energy and subsequently tested at the INEL.

Digital Inverter/Motor Controls

The control system has essentially two different modes of operation. In the constant torque region, the inverter is current-controlled using field-oriented vector control techniques (PWM mode). In the constant power region, control is based on torque angle orientation of the applied square-wave voltage (square-wave mode). In the PWM mode, the machine phase currents and rotor angle are sampled and used to estimate and regulate the IPM motor torque

and flux. Inner current loops provide independent regulation of both the torque and flux-producing current vectors. Flux is programmed as a function of torque level to optimize drive system efficiency. Instantaneous control of the sinusoidal three-phase currents is accomplished with three independent hysteresis band current regulators. In the constant power region, the controller detects saturation of the current regulators and reconfigures the control laws to weaken the machine flux to establish the desired torque. Key feedback variables as well as estimators remain the same as in the PWM mode, and the output flux estimator is utilized to detect an over-flux condition and then initiate and control a smooth transition back to the PWM control schemes⁴.

Transaxle

The components of the ETX-II motor/transaxle assembly are uniquely arranged concentric with the drive wheel axis, resulting in a highly compact and efficient design. The ETX-II motor/transaxle configuration is a natural evolution of the arrangement that was successfully designed, built, developed, and tested as part of the ETX-I Program. Unlike the ETX-I powertrain, which was designed to replace the conventional internal combustion engine and transmission in a front-wheel drive Mercury LN7 passenger car test bed, ETX-II was designed for use in a rear-wheel drive Ford Aerostar minivan. The major powertrain differences from ETX-I are summarized as follows:

- ETX-II incorporates an IPM ac traction motor (synchronous machine) as compared to the ETX-I ac induction motor.
- The motor/transaxle is arranged as a rigid rear-wheel drive axle, eliminating the need for four constant-velocity joints that are necessary for front-wheel drive and spring applications.
- ETX-II is designed for a much larger and heavier vehicle than ETX-I. As a result, higher torque and power are required to meet the vehicle objectives for gradeability and acceleration performance.
- ETX-II incorporates new gear ratios to satisfy the vehicle and motor requirements for performance and energy efficiency.

Two planetary gear sets are connected such that two rather large ratios are obtained, providing both gear steps and the final drive ratio. The motor rotor shaft is hollow, which allows the right-hand axle shaft to pass through its center from the differential bevel gear assembly. The transmission input sun gear is cut directly into the rotor shaft. This completely integrated motor and transaxle concept results in a very compact arrangement, which is packageable under the rear cargo floor of the Aerostar, in place of the normal rear axle assembly.

Figure 1 is a montage of the ETX-II program and shows all of the major portions of the program. Pictured clockwise, starting from the top left-hand corner, are the following: ETX-II Concept Vehicle; unsprung motor/transaxle assembly; cross-section of the motor/transaxle and rigid axle assembly; one-third portion of the full CSPL NaS battery; the Powerplex Technologies, Inc. B11 battery (one-half of a full battery); IPM motor (stator and rotor); inverter; and transistor and power module.

Table 2 contains the specifications for the vehicle and its major propulsion system components.

Figure 1. ETX-II propulsion system components.

Table 2. ETX-II vehicle and powertrain specifications.

Curb weight (kg)	1,795
Test weight (kg)	2,050
Gross weight (kg)	2,310
Aerodynamic drag coefficient	0.37
Frontal area (m ²)	2.92
Drag area product-C _D A (m ²)	1.08
Rolling resistance coefficient (kg/kg)	0.0095
Motor:	
Weight (kg)	51 (112 lb)
Type	ac interior permanent magnet (IPM)
Peak output power (kW)	52.5
Maximum speed (rpm)	11,000
Stall torque (Nm)	110 (81 lb-ft)
IGBT Inverter:	
Type	3-phase, variable voltage, variable frequency
Maximum current (A)	800 peak rms
Maximum voltage (V)	600
Volume (L)	49.6 (1.75 ft ³)
Weight (kg)	45 (100 lb)
Transmission:	
Type	2-speed automatic transaxle
Gear ratios	Low: 21.2 High: 13.8
Motor/transaxle assembly weight	110 kg (243 lb)
Traction Battery:	
Type	Sodium-sulfur
Weight (kg)	750 (24 8-V banks)
Voltage (nominal system)	200
Capacity (new):	
A-h at C/3	300
kW-h at C/3	60
Maximum power (kW)	60
Manufacturer	CSPL
DC-dc converter	4-Vicor 200 V to 15 V converters in parallel

THE CSPL NaS BATTERY

A NaS traction battery designed to meet the requirements of the ETX-II minivan was developed and manufactured by CSPL of the United Kingdom, under a DOE-sponsored contract to Sandia National Laboratory. The battery was assembled in late 1989, and thus represents the state of cell, packaging, and enclosure technology at that time. The key consideration was that the battery operate reliably and safely, and have sufficient life (cyclic and calendar) to evaluate NaS battery technology with the advanced electric driveline in the ETX-II test bed vehicle. Battery weight and volume were to be the minimum possible consistent with specified operational constraints. The product reflected CSPL experience with large assemblies of cells up to the time of manufacture. No attempt was made to minimize weight, size, and complexity of the auxiliary equipment; that was, for the most part, maintained off-board of the vehicle.

The battery was tested in the INEL Battery Laboratory and then in the ETX-II vehicle (in the INEL EVTL). This report sets forth the test results and puts them in perspective for future development of NaS battery technology for electric vehicle applications. The CSPL NaS battery tested at the INEL represented the best CSPL technology available in 1989. The ETX-II test results indicated the system improvements needed to realize the full potential of NaS battery chemistry in EV applications.

Battery Description

The battery (Figure 2) is made up of three modules connected in series, each containing eight banks (also series-connected) of 30 parallel strings of four series-connected cells, for a total of 2,880 cells. Cell and battery designs are described in Reference 5. The open-circuit voltage of the battery (24 banks) is 200 V and its rated energy capacity is 60 kW·h. Peak power capacity is 60 kW.

Figure 2. ETX-II CSPL sodium-sulfur battery.

Table 3 summarizes the key features of the cell and the bank components of the CSPL battery.

Table 3. Key features of the Mark III cell, the 120-cell bank, and the 8-bank module.

	<u>Cell</u>	<u>Bank</u>	<u>Bank</u>
Weight	131 g	31.25 kg	250 kg
Volume	70 cm ³	23.1 L	185 L
Rated capacity to 1.9 V open-circuit cut-off	10 A·h	300 A·h	300 A·h
Open-circuit voltage at full charge	2.08 V	8.3 V	66.4 V

The weight and dimensions of the modules, and the weights of the various battery system auxiliary components are given in Table 4. Photographs of the heater controller, the charger, and the watchdog are shown in Figures 3 through 5. The weight of the three modules is 750 kg; the weight of the cells alone is 377 kg. The volume of the three modular containers is 556 L, with a total cell volume of 201 L. Therefore, the fraction of battery weight that is cells is 0.5 and the fraction of the volume that is cells is 0.36.

Improvements in these packaging factors would result in better battery system performance based on specific energy and specific power densities because the cells are the electrochemically active part of the system. Throughout the present discussion, the energy and power characteristics of the battery will be given in terms of both the cell and battery weights and volumes. In the final analysis, the weights and volumes of auxiliary equipment that is on-board the vehicle must be included in the determination of the energy and power densities of the NaS battery system, but that determination must await further development of those components and the battery itself.

Table 4. CSPL NaS battery, control, and auxiliary component information.

Module weight (avg)	250 kg	(550 lb)
Module footprint		
Length	1065 mm	(41.9 in.)
Width	560 mm	(22.0 in.)
Height	311 mm ^a	(12.2 in.)
Control and Auxiliary Component Weights		
Watchdog	18.6 kg	(41.0 lb)
Heater control unit	78.6 kg	(173.0 lb)
Module rack	18.9 kg	(41.6 lb)
Thermal pad	6.8 kg	(15.0 lb)
Charger	246 kg	(541.0 lb)
Vacuum pump	42.9 kg	(94.5 lb)
Connection box & cables	37.3 kg	(82.0 lb)
Shunt box & cables	17.5 kg	(38.5 lb)
Laptop computer	2.8 kg	(6.2 lb)
Vacuum lines	1.8 kg	(4.0 lb)

a. Enclosure height excluding support frame and junction boxes.

Figure 3. NaS battery heater controller.

Figure 4. Nas battery charger.

Figure 5. NaS battery watchdog monitor.

Laboratory Testing

The battery as tested was not in a "like new" condition. The cells had experienced 2.5 electrolyte freeze/thaw cycles (that is 3 heat-ups and 2 cool-downs) before the initiation of testing at the INEL. However, the battery temperature was continuously maintained at $>300^{\circ}\text{C}$ for approximately 18 months after delivery to Ford in August 1990. The battery was tested at the INEL until the end of February 1992 when it was allowed to cool to ambient temperature (frozen) and shipped back to CSPL for detailed inspection. The capacity of the battery had degraded to 225 Ah and CSPL felt it had reached the end of its calendar life and further testing of the battery would not be prudent.

The series of tests performed on the CSPL battery in the INEL Battery Test Laboratory consisted of constant-current and constant-power discharges, and simulated driving cycle discharges based on the FUDS and the SFUDS. A total of 38 charge/discharge cycles were run on the battery over a 6-month period. This testing is discussed in detail in Reference 3. The results are summarized in Table 5.

Table 5. CSPL NaS battery test data.

TOTAL SUMMARY BATTERY DATA SHEET										PACK NO. 62 CHLORIDE SILENT POWER SODIUM/SULFUR													
DISCHARGE										CHARGE													
TOTAL CYCLES	I.N.E.L. CYCLES	DATE	DR (A,P,F)	ABOD (AH)	EBOD (KWH)	DCV* (VOLTS)	EDT (AVG.)	MAX.TEMP. (C)	TTD	DATE	CHARGE RATE	ABIR (AH)	EBIR (KWH)	CC (amps)	% CHARGE	ECT (AVG.)	MAX.TEMP. (°C)	TTOC	NOTES				
Cycle 1		02/07/90	80	300	---	---	---	---	---	NO CHARGE DATA AVAILABLE										CYCLES 1 THRU 14 WERE CONDUCTED AT FORD BATTERY RETURNED TO CSPL FOR REPAIR VEHICLE TESTING AT FORD VEHICLE TESTING AT FORD VEHICLE TESTING AT FORD VEHICLE TESTING AT FORD TEST CONDUCTED BY CSPL 3 INEL- NO DATA PROGRAM DEZZB11 INSTALLED NEW PROGRAM ETX2012 LOADED BEFORE DIS. (NEW PROGRAMS WERE LOADED BECAUSE OF DECREASING AND/OR FLUCTUATING CAPACITY) NEW PROGRAM ETX2012M LOADED BEFORE DIS. DISCHARGE TERMINATED DUE TO CABLE TEMP BATT. TEMP= 310 C START OF CYCLE 15 DIS. CYCLE 18 DISCHARGE ACCEPTED BASED ON WATCHDOG READINGS WITHIN 22 DISCHARGE TERMINATED MANUALLY - OVERTEMP BATT. TEMP= 310 C START OF CYCLE 21 DIS. BATT. TEMP= 310 C START OF CYCLE 22 DIS. SFUDS = 12 CYCLES - 10MIN. 24SEC. SFUDS = 13 CYCLES - 21MIN. 59SEC.			
Cycle 2		02/12/90	FUDS	296	---	---	---	---	---														
Cycle 3		02/13/90	35KW	199	---	---	---	---	---														
Cycle 4		02/14/90	FUDS	295	---	---	---	---	---														
Cycle 5		02/15/90	FUDS	296	---	---	---	---	---														
Cycle 6		08/22/90	80	237	---	---	---	---	---														
Cycle 7		08/30/90	FUDS	240	---	---	---	---	---														
Cycle 8		09/17/90	75	291	---	---	---	---	---														
Cycle 9		09/18/90	35KW	222	---	---	---	---	---														
Cycle 10		09/19/90	FUDS	297	---	---	---	---	---														
Cycle 11		UNK	FUDS	270	---	---	---	---	---														
Cycle 12		UNK	TRACK	UNK	---	---	---	---	---														
Cycle 13		UNK	TRACK	UNK	---	---	---	---	---														
Cycle 14		UNK	TRACK	UNK	---	---	---	---	---	NO CHARGE DATA AVAILABLE													
Cycle 15	Cycle 1	12/01/90	100.0	272.0	---	---	---	---	---	12/01/90	---	---	---	---	---	---	---	---	---				
Cycle 16	Cycle 2	12/10/90	100.4	266.0	48.5	172.1	358.8	363.9	2HR 39M	12/10/90	32.4	261.6	53.4	30.7	98.3	323.8	360.8	8HR 05M					
Cycle 17	Cycle 3	12/12/90	100.0	260.1	47.4	172.4	358.1	363.0	2HR 36M	12/12/90	31.7	261.5	53.3	30.5	100.5	323.4	361.0	8HR 15M					
Cycle 18	Cycle 4	12/14/90	100.0	245.1	44.8	174.6	356.6	361.5	2HR 27M	12/14/90	30.7	253.1	51.6	28.9	103.3	323.8	359.9	8HR 15M					
Cycle 19	Cycle 5	12/18/90	150.2	247.8	43.5	167.3	368.9	373.7	1HR 39M	12/18/90	30.3	250.0	51.0	28.3	100.9	323.3	373.1	8HR 15M					
Cycle 20	Cycle 6	12/20/90	150.2	225.3	39.7	170.3	363.9	369.3	1HR 30M	12/20/90	29.4	226.2	46.2	28.7	100.4	323.7	368.5	7HR 42M					
Cycle 21	Cycle 7	01/02/91	150.0	247.5	43.4	167.3	369.5	374.4	1HR 39M	01/02/91	31.3	247.1	50.4	30.8	99.8	323.6	374.9	7HR 54M					
Cycle 22	Cycle 8	01/04/91	100.1	260.1	47.4	172.7	358.0	362.2	2HR 36M	01/04/91	31.3	265.7	54.1	29.1	102.1	322.7	361.9	8HR 30M					
Cycle 23	Cycle 9	01/08/91	100.1	260.2	47.4	172.4	357.9	362.1	2HR 36M	01/08/91	31.3	264.6	53.9	29.5	101.7	323.1	362.0	8HR 27M					
Cycle 24	Cycle 10	01/10/91	100.0	260.1	47.4	172.5	358.6	363.0	2HR 36M	01/10/91	31.4	263.8	53.8	27.7	101.4	323.0	361.8	8HR 24M					
Cycle 25	Cycle 11	01/14/91	150.1	225.2	39.6	170.2	363.8	367.9	1HR 30M	01/14/91	30.5	225.6	46.1	30.0	100.2	323.1	366.3	7HR 24M					
Cycle 26	Cycle 12	01/17/91	150.2	240.3	42.2	168.1	366.3	371.3	1HR 36M	01/17/91	30.8	243.1	49.7	27.8	101.2	323.7	371.3	7HR 54M					
Cycle 27	Cycle 13	01/21/91	150.3	240.4	42.2	168.2	367.2	372.0	1HR 36M	01/21/91	30.7	242.2	49.4	29.2	100.7	323.0	370.3	7HR 54M					
Cycle 28	Cycle 14	01/23/91	150.1	240.1	42.2	168.0	366.6	371.1	1HR 36M	01/23/91	30.4	240.4	49.0	27.9	100.1	323.1	370.3	7HR 54M					
Cycle 29	Cycle 15	01/25/91	301.1	143.0	22.1	154.5	357.1	365.9	28.5M	01/25/91	30.6	143.9	29.4	29.5	100.6	334.8	358.6	4HR 42M					
Cycle 30	Cycle 16	01/28/91	14 W/KG	269.5	51.0	177.8	340.9	345.5	5HR 24M	01/28/91	30.8	272.2	55.5	29.7	101.0	323.6	341.9	8HR 50M					
Cycle 31	Cycle 17	01/30/91	14 W/KG	267.1	50.6	178.1	340.8	344.8	5HR 21M	01/30/91	30.8	269.3	54.9	30.1	100.8	323.8	340.3	8HR 50M					
Cycle 32	Cycle 18	02/01/91	21 W/KG	262 ON WATCHDOG, COMPUTER QUIT, LAST 31 RIMS DATA ONLY	---	---	---	---	---	02/01/91	31.5	260.0	53.1	29.9	---	323.5	356.4	8HR 15M					
Cycle 33	Cycle 19	02/05/91	21 W/KG	255.1	47.3	175.2	350.7	354.6	3HR 19M	02/05/91	30.6	257.3	52.5	29.8	100.9	323.4	353.0	8HR 20M					
Cycle 34	Cycle 20	02/07/91	42 W/KG	229.4	39.8	166.0	368.6	376.1	1HR 24M	02/07/91	31.0	229.6	46.9	27.8	100.1	323.2	370.9	7HR 25M					
Cycle 35	Cycle 21	02/11/91	42 W/KG	234.6	40.2	163.5	359.5	366.3	1HR 25M	02/11/91	31.6	231.8	47.4	30.4	98.8	308.9	365.3	7HR 20M					
Cycle 36	Cycle 22	02/12/91	42 W/KG	230.3	39.5	163.7	359.6	367.4	1HR 23M	02/12/91	31.0	232.6	47.6	29.1	101.0	308.8	360.6	7HR 30M					
Cycle 37	Cycle 23	02/14/91	SFUDS	212.0	41.4	139.6	---	354.4	4HR 58M	02/14/91	30.1	218.4	44.7	29.6	103.0	324.0	354.5	7HR 15M					
Cycle 38	Cycle 24	02/19/91	SFUDS	238.0	41.5	136.1	---	358.2	5HR 34M	02/19/91	30.3	242.5	49.6	29.2	101.9	324.4	359.9	8HR 00M					

Table 5. (continued)

TOTAL SUMMARY BATTERY DATA SHEET										PACK NO. 62 CHLORIDE SILENT POWER SODIUM/SULFUR									
DISCHARGE										CHARGE									
TOTAL CYCLES	I.N.E.L. CYCLES	DATE	DR (A,P,F)	ABOD (Ah)	EBOD (KWh)	DCV* (VOLTS)	EDT (AVG.)	MAX.TEMP. (C)	TTD	DATE	CHARGE RATE	ABIR (Ah)	EBIR (KWh)	CC (amps)	% CHARGE	ECT (AVG.)	MAX.TEMP. (C)	TTCC	NOTES
Cycle 39	Cycle 25	03/04/91	SFUDS	222.0		136.8	---	---		03/04/91	29.5	229.0	46.8	29.2	103.1	324.1	358.5	7HR 45M	SFUDS = 12 CYCLES + 22MIN. 40SEC.
Cycle 40	Cycle 26	03/07/91		100.1	235.2	42.9	174.6	354.9	359.4 2HR 21M	03/07/91	31.1	235.7	48.2	29.9	100.2	324.1	358.5	7HR 35M	DISCH. TERMINATED MANUALLY, LOW BANK V.
Cycle 41	Cycle 27	03/18/91		100.4	234.2	42.7	174.3	355.7	360.4 2HR 20M	03/18/91	30.4	233.0	47.6	29.1	99.5	324.1	359.1	7HR 40M	DISCHARGE AFTER 10 DAY STAND TEST
Cycle 42	Cycle 28	03/25/91		100.2	241.6	43.9	173.2	357.5	361.8 2HR 25M	03/25/91	30.5	236.3	48.3	28.7	97.8	324.9	360.0	7HR 45M	DISCHARGE AFTER NEW RESISTANCES INSTALLED
Cycle 43	Cycle 29	03/26/91		100.1	240.1	43.7	173.6	357.3	361.4 2HR 24M	03/26/91	30.8	235.5	48.4	29.1	98.1	324.1	356.7	7HR 40M	DISCHARGE AFTER NEW RESISTANCES INSTALLED
Cycle 44	Cycle 30	03/27/91		100.0	241.7	44.0	173.2	357.0	362.0 2HR 25M	03/27/91	30.8	238.5	48.7	29.2	98.6	325.1	359.0	7HR 46M	DATA INTERRUPT @ 455 H. TO INC. SCAN RATE
Cycle 45	Cycle 31	03/28/91		150.3	224.2	39.2	168.5	366.7	373.5 1HR 29.5M	03/28/91	30.5	226.5	46.3	29.0	101.0	333.7	366.4	7HR 08M	DATA INTERRUPT @ 410 H. TO INC. SCAN RATE
Cycle 46	Cycle 32	03/29/91		150.2	227.9	39.9	168.1	366.9	374.8 1HR 31M	03/29/91	31.3	227.2	46.4	30.8	99.7	335.1	369.8	7HR 13M	DATA INTERRUPT @ 420 H. TO INC. SCAN RATE
Cycle 47	Cycle 33	04/01/91		149.9	227.4	39.8	168.1	367.0	374.3 1HR 31M	04/01/91	30.9	227.0	46.4	30.2	99.8	334.9	369.3	7HR 13M	DATA INTERRUPT @ 420 H. TO INC. SCAN RATE
Cycle 48	Cycle 34	04/25/91	FUDS		244.0	42.6			6HR 11M	04/25/91	30.0	230.1	47.0	29.7		323.2	358.0	7HR 40M	PACK DISCHARGED 20AH'S BEFORE START OF
Cycle 49	Cycle 35	05/03/91		100.1	238.6	43.4	173.1	357.2	361.6 2HR 23M	05/03/91	29.8	240.8	49.2	28.1	100.9	323.6	359.5	8HR 05M	FUDS TO AVOID OVERVOLTAGE ON REGEN.
Cycle 50	Cycle 36	05/07/91	FUDS		250.0	38.9			5HR 47M	05/07/91	29.9	217.0	44.4	29.1		324.2	355.9	7HR 15M	PACK DISCHARGED 30AH'S BEFORE START OF
Cycle 51	Cycle 37	05/09/91		99.9	238.2	43.3	173.0	357.0	361.5 2HR 23M	05/10/91	30.9	242.2	49.5	29.4	101.7	323.8	360.2	7HR 50M	FUDS TO AVOID OVERVOLTAGE ON REGEN.
Cycle 52	Cycle 38																		

Acronyms:

ABOD Amp-hours Battery Out Discharge
 EBOD Energy Battery Out Discharge
 EDT Avg. Ending Discharge Temperature
 DR Discharge (A-Amps, P-Power Kw, F-FUDS Cycle)
 DCV Discharge Cutoff Voltage (* varies due to time interval spacing)
 TTD Total Time of Discharge
 ABIR Amos Battery In Recharge
 EBIR Energy Battery In Recharge
 CC End of Charge Current
 ECT Avg. Ending Charge Temperature
 TTCC Total Time of Charge

BATTERY WEIGHT IS 750 KGS. (250 KGS/MODULE)
 BATTERY CONSISTS OF 3 MODULES, 24 BANKS, 2880 CELLS
 EACH MODULE HAS 8 BANKS & 960 CELLS
 EACH BANK HAS 120 CELLS

CHARGER EFFICIENCY, CHARGE 25 = 81.7%
 AVERAGE POWER DRAW TO KEEP BATTERY HOT IS 709 WATTS

CHARGES THRU CYCLE 27 WERE INTERRUPTED, CYCLES 28 THRU 29 WERE CONTINUOUS.
 Ah and KWh values include the C/3 discharge before the FUDS test was started.

BATTERY PERFORMANCE TEST RESULTS

Discharge Characteristics

Constant Current Discharge. The battery was discharged at constant currents of 100, 150, and 300 A. At the outset of the testing in the INEL Battery Laboratory, the battery had a capacity of 260 A·h at the C/3 (100 A discharge) rate and 240 A·h at the C/2 (150 A discharge) rate. Unacceptable temperature increases in the cables and the battery itself precluded a discharge at the C/1 (300 A discharge) rate to 100% of the battery capacity. The discharges at the C/3 and C/2 rates were terminated when the watchdog, that monitors the battery discharge, determined that the inferred open-circuit voltage of one of the 24 banks had reached 7.6 V (4 times the open-circuit cut-off voltage of 1.9 V/cell). The effect of bank variability on battery capacity and the effect of aging on the variability are discussed later in this report.

The measured energy capacity of the ETX-II battery was 45 to 48 kWh at the C₃/3 rate. An energy capacity as high as 51 kWh was measured at the C₃/5 rate. These energy capacities correspond to energy densities of 60 to 68 Wh/kg based on the battery weight (750 kg) and 119 to 135 Wh/kg based on the cell weight (377 kg). The nominal energy density of the battery is often stated to be 80 Wh/kg based on a capacity of 60 kWh (2.08 V · 96 cells in series · 300 A·h = 59.9 kWh). The energy density of any NaS battery in practice will be less than the nominal value because of cell variability and the reduced voltage caused by the internal IR drop during the discharge. The volumetric energy density of the ETX-II battery is 81 to 92 Wh/L based on the battery enclosure volume and 224 to 254 Wh/L based on cell volume.

Constant Power Discharge. Constant power tests of the ETX-II battery were performed in the Battery Laboratory at power densities of 14, 21, and 42 W/kg, based on the battery weight of 750 kg. The corresponding power densities, based on the cell weight of 377 kg, are 28, 42, and 84 W/kg. The results of the constant power tests are given in Figure 6 as a Ragone plot.

The result of testing the battery with the ETX-II vehicle at 88 km/h is also shown in Figure 6. Based on battery weight, the energy densities vary between 52 and 68 Wh/kg; the corresponding values are 106 to 135 Wh/kg when the cell weight is used. On a cell basis, the battery has attractive performance, but the packaging weight significantly detracts from that performance. From a volumetric standpoint, the effect of packaging is even more important. The volumetric energy densities are 70 to 90 Wh/L based on battery volume and 200 to 250 Wh/L based on the volume of the cells. Note that the dependency of the energy density of the NaS battery on discharge rate is relatively small.

The INEL data (2,880 cells) are compared in Figure 6 with data taken at Sandia National Laboratory (SNL) on a 4-cell string⁶ and at Argonne National Laboratory (ANL) on 120-cell⁷ and 960-cell⁸ battery units. The 960-cell unit at ANL was air-cooled. The same bank (120-cell unit) weight of 31.25 kg was used to present both the INEL and ANL data. A cell weight of 130 gm was used for both the INEL and SNL cell data presentations. The agreement between the three sets of data is quite good. The lower INEL energy density values are caused by the fact that they represent the average performance of 2,880 cells, and the tests were terminated by the watchdog that used inferred values of bank resistance to calculate open-circuit voltage, rather than the measured values used at ANL. In addition, the INEL battery was showing the effects of aging.

SFUDS and FUDS Discharges. The power profiles used for the SFUDS and FUDS cycles in the INEL Battery Laboratory tests were for the IDSEP vehicle as is required by the SFUDS test procedure. Because of the difficulties encountered with the vehicle, the NaS battery was not tested with the ETX-II on the FUDS cycle. The voltage-versus-time trace for the SFUDS test is shown in Figure 7. The battery capacities on the cycles are given in Table 6.

Figure 6. Ragone plots for the CSPL NaS battery.

Figure 7. Voltage-versus-time traces for the SFUDS test.

Table 6. SFUDS and FUDS discharge characteristics of the CSPL NaS battery.

Test	Cycle Number	Gross out		Gross in		Net (modified)	
		A·h	kW·h	A·h	kW·h	A·h	kW·h
SFUDS	24	278	48.8	37	7.35	241	42.4
FUDS	34	323 ^a	57.0 ^a	69	14.4 ^b	254	44.8

- a. These values account for the A·h and kW·h taken from the battery before the FUDS test was started (see Table 2).
- b. The high regeneration energy into the battery was the result of an error in setting up the power profile for the FUDS test.

Both the gross A·h and kW·h taken from the battery and the A·h and kW·h returned to the battery during regenerative braking steps are given in this table. When calculating the net energy, the energy returned to the battery during regeneration was corrected (based on the ratio of the measured average voltages during discharge and regenerative braking) to account for the losses associated with charge and discharge of the battery. This value is given in Table 6 in the column designated as "net modified." Using the modified net energy, the energy densities for the SFUDS and FUDS cycles are 56 and 60 W·h/kg, respectively, based on battery weight and 112 and 119 W·h/kg based on cell weight. The peak power density required to meet the FUDS cycles is 80 W/kg based on battery weight and 160 W/kg based on cell weight. The data indicated that the ETX-II battery could meet these power requirements (57 kW) at a minimum voltage of 135 V, but this draw represented nearly the peak power capability of the battery. The net A·h capacity of 220 to 240 A·h for the battery on the SFUDS and FUDS cycles is in reasonable agreement with values found in the constant power test at the same average power. The effect of the magnitude and the variability of the power required during the SFUDS and FUDS cycles on the ability of the watchdog to properly terminate the test (utilizing filtered values of the calculated open-circuit voltages of the banks) is somewhat uncertain. Further testing is required to resolve this issue.

A 120-cell unit (equivalent to a single bank in the ETX-II battery) has been tested at ANL on the SFUDS cycle.⁷ The net (gross out minus in) A·h and kWh measured were 295 and 2.14, respectively. The resultant net energy density is 68.5 Wh/kg, based on a battery unit weight of 31.25 kg. The corresponding value for the INEL battery test (2,880 cells) is 55.3 Wh/kg. The difference between the ANL and the INEL results is accounted for by the lower A·h capacity measured at INEL (241 A·h compared to 295 A·h). Part of this difference stems from the fact that the watchdog terminated the tests at the INEL based on a calculated end-of-test voltage, while ANL utilized a measured bank resistance to terminate tests.

Voltage-Current Characteristics

The voltage-current characteristics of the NaS ETX-II battery can be determined from SFUDS and constant-power discharge data. The results from the SFUDS data are shown in Figure 8 as a function of the net A·h discharged from the battery. This figure also shows that the NaS battery is "stiff" in that the relationship between voltage and current is nearly independent of state-of-charge (SOC) (net A·h) except near charge depletion. Even near the end of discharge, the dependency on SOC is less than for other battery types. The linearity of the V, I plots (even at high currents) indicates the effects of polarization on battery performance are small. The voltage-current characteristics of the CSPL battery were also determined from the energy economy tests of the ETX-II vehicle on the dynamometer. As shown in Figure 9, the data obtained from constant power discharges of the battery in the INEL Battery Laboratory³ are consistent with those obtained with the battery powering the vehicle. The small downward shift of the curves is caused by battery aging (that is, a decrease in A·h capacity caused by a loss of strings in a few banks of the battery).

The V, I plots and the SFUDS/FUDS data were used to determine the average battery/cell resistances and the open-circuit voltage as a function of SOC. The resistance is given by the slope of the "A·h = constant" lines. The battery and cell resistances (Ω) calculated from the V, I plot, Figure 8, are

Figure 8. Voltage-versus-current, Ah plot from SFUDS data.

Figure 9. Voltage-versus-current, Ah plot from constant-power data.

given in Table 7. The cell resistance given by CSPL⁵ is 0.039 Ω at 350°C. Utilizing the temperature correction relationship recommended by CSPL, this corresponds to cell resistances of 42 to 45 milli-ohm for the average temperatures of 332 to 342 °C of the INEL tests. One would expect the cell resistances in the ETX-II battery to be higher than the single cell values because of connections between cells and banks and the effects of battery aging. Therefore, the INEL resistance values appear to be reasonable. The present data also clearly showed the expected higher battery resistance near full charge.⁵

Table 7. Battery, bank, and cell resistances of the CSPL NaS battery.

Test	Battery Resistance ^a	Bank Resistance	Cell Resistance ^a
Constant Power	0.16	0.0066	0.050
SFUDS	0.145	0.0060	0.045
FUDS	0.153	0.0064	0.048

a. All resistances in Ohms.

The open-circuit voltage of the battery as a function of net Ah was determined from the FUDS data (Figure 10). Knowing the configuration of the cells in the battery, an average open-circuit voltage curve for the cells can be determined from Figure 10. The result, shown in Figure 11, indicates good agreement with cell data from the literature.

Charging and Regenerative Braking Characteristics

The NaS battery was charged using the Charger (Figure 3) and software provided by CSPL. The charge was monitored by the watchdog (Figure 4). The charging algorithm is very simple—a constant 30 A charging current with charge termination when one of the banks reaches a voltage of 9.1 V. The charging time is 8 to 10 h after a complete discharge. The battery exhibited a coulombic efficiency of 100% as would be expected for the NaS chemistry. The energy efficiency of the battery is 85 to 90%, depending on the discharge rate profile. The battery cools 6 to 8°C/h during charging, reaching the set point

Figure 10. Battery open-circuit voltage as a function of net Ah from FUDS test data.

Figure 11. Cell open-circuit voltage as a function of net Ah.

temperature of 325°C well before the end of charge. The bank voltage is near 8.5 V (2.125 V/cell) during most of the charge. During the last 10 to 15 minutes of the charge, the voltage of one or more of the banks increases rapidly to the cut-off value of 9.1 V. The charging data indicate that the strongest bank (or banks) in the battery terminate the charge, unlike the discharge, which is terminated by the weakest banks. Therefore, the variability in the banks tends to be increased by the charge/discharge processes.

The regenerative braking characteristics of the NaS battery were determined from SFUDS and FUDS data. The average bank voltage as a function of regenerative braking power (and W/kg in the regeneration step) is given in Figure 12. The voltage is nearly independent of SOC (net A·h) except near full charge and near charge depletion. The battery accepted the regeneration power (10 W/kg) on the SFUDS cycle even near full charge at a voltage well below the 9.1 V limit. On the FUDS cycle, the regenerative braking powers used were much higher (up to 33 kW) and it was necessary to discharge 20 to 30 A·h from the battery before initiating the cycle. Otherwise, the watchdog terminated the test because of the 9.1 V limit being exceeded. Figure 12 indicates that the NaS battery can accept high regenerative braking power after as little as 20 A·h has been used from the battery. A more detailed study of the regenerative braking limit near full charge is needed.

Thermal Characteristics

The NaS battery is intended to operate in the temperature range 300 to 380°C. When the battery is inactive, it is maintained at a temperature of 300 to 325°C by the heater controller. For the ETX-II battery, the heater energy required to compensate for the heat loss of the battery is 700 W. When the battery is discharged, the temperature of the battery increases because of heat generated within the cells. When the battery is charged, the battery temperature decreases because the heat loss from the battery is greater than the heat generated during charging. The primary thermal questions regarding

Figure 12. Regenerative charging characteristics of the ETX-II CSPL NaS battery.

the battery are the heat loss during periods of inactivity and the rate at which the battery temperature increases during high power discharges. The ETX-II battery is uncooled and the watchdog terminates the discharge when the temperature of any bank exceeds 380°C.

The thermal behavior test results³ are summarized in Figure 13 for various constant power discharges and for the SFUDS cycle. The battery temperature rise during the 88 km/h test of the ETX-II vehicle on the dynamometer is also shown in Figure 13. Note that the rise measured during the vehicle test is consistent with that found during the constant-power discharge tests in the INEL Battery Laboratory. The relatively high rate of temperature increase in the present battery is of some concern. For future battery designs, limiting the rate of temperature increase to a specified value at a particular power level will likely be a design requirement. However, the temperature rise during SFUDS and FUDS tests is not a problem. For those tests, the temperature rise was 32°C with a maximum temperature of 358°C at the end of the test.

The heat loss from the battery to the environment can have an important effect on the overall energy efficiency of the battery/vehicle system. As an example, consider a typical day on which the ETX-II vehicle is driven 80 km. Assuming an energy consumption of 200 Wh/km on the FUDS cycle, the energy used from the battery would be 20 kWh over a period of approximately 2.5 h. For a charging efficiency of 80% (including charger losses of 10%), the wall plug energy required to recharge the battery is 25 kWh. The charging time would be 4.1 h, after which the battery would be maintained at the set point temperature of 325°C by the heater. The energy required to do this is $18.4 \cdot Q_{\text{loss}}/1,000$ kWh. For $Q_{\text{loss}} = 700$ W, the daily efficiency for this example is 52.8%; for $Q_{\text{loss}} = 250$ W, the daily efficiency is 67.6%. In either case, the efficiency is significantly less than the 80% for battery charging alone. The effect of heat loss on the relative attractiveness of NaS batteries, compared to ambient-temperature batteries, in various types of electric vehicles is discussed by Bentley⁹.

Figure 13. Temperature rise characteristics of the ETX-II CSPL NaS battery at constant power.

Bank Variability at End-of-Test

The useable capacity of the battery in any test is limited by the variability among banks, because the watchdog terminates the test when a calculated value of the open-circuit voltage of any single bank falls below 7.6 V for a specified time. The open-circuit voltage of each bank is calculated by adding the IR voltage drop to the instantaneous voltage calculated from the measured current and a bank resistance determined during the charging of the battery. In the ETX-II battery, the variability between banks at end-of-test is significant, and as shown in Figure 14, the variability increases as the battery ages. When the open-circuit voltage of the weakest bank reaches 7.6 V, the other banks still have unused capacity and the useable Ah capacity of the battery is then less than the rated value of 300 Ah. The larger the battery (that is, the greater number of cells in the battery), the more important bank variability is likely to be in limiting battery capacity. As discussed by Burke³, there is some doubt regarding the accuracy with which the watchdog calculates the open-circuit voltage and whether the values taken immediately at end-of-test accurately reflect the true open-circuit voltage as a measure of Ah discharged from the battery. Bank variability in NaS batteries and its relationship to the measurement techniques requires additional study.

Battery Condition During Aging

A method utilizing the bank variability at end-of-test to infer the number of 4-cell strings that are inoperative in each of the banks in the battery at any particular time in its life is discussed in Reference 10. The method is based on the dependency of the open-circuit voltage on Ah withdrawn from the battery (see Figure 10). For the configuration of the ETX-II NaS battery (30 parallel, 4-cell, strings), a change of 0.067 V in the bank open-circuit voltage at end-of-test implies a loss of a single 4-cell string in a bank and a resultant loss of 10 Ah in battery capacity. The method neglects the effect of the loss of a 4-cell string on the resistance of the

Figure 14. Variability of the bank open-circuit voltage at end-of-test as the battery ages.

bank. Theoretically this can contribute, at most, 30% of the calculated change in bank open-circuit voltage.

The method was applied after two 100 A discharges of the battery (Table 5, cycles 3 and 29 in the INEL Battery Laboratory tests) and after a constant-speed test (88 km/h) of the ETX-II vehicle (cycle 49) on the dynamometer. The results are graphically shown in Figures 15 and 16 and summarized in Table 8. A steady degradation of the battery over the 15-month period of the INEL tests is evident in the table as a greater number of the 4-cell strings in the banks progressively become inoperative. The method illustrated appears to be a promising, non-intrusive approach to assessing the condition of the NaS battery, but more experience with the method is needed before its usefulness can be fully assessed with confidence. In particular, results such as those shown in Table 8 should be compared with the actual condition of the battery found when it is torn down for inspection of the banks and cells.

Figure 15. Number of inoperative strings of the CSPL NaS banks-cycles 3 and 29.

NAVS BATTERY CYCLE 49 2/11/92
ETX-II TEST NO. X2D882

Figure 16. Number of inactive strings of the CSPL NaS banks - cycle 49.

Table 8. Summary of ETX-II CSPL NaS battery aging data.

Date	Cycle Number ^a		
	3	29	49
	12/12/90	03/26/91	02/11/92
Ah Capacity	260	240	220
Strings inoperative			
Best Bank	1	1	3
Worst Bank	4	6	8
Number of banks with "N" inoperative strings			
N-0	0	0	0
1	1	1	0
2	13	9	0
3	8	3	0
4	2	9	5
5	0	0	7
6	0	2	5
7	0	0	5
8	0	0	2

a. Cycle number at INEL. Add 14 to get total cycles on battery.

CHASSIS DYNAMOMETER TESTING

Facility, Instrumentation, and Test Setup

Dynamometer tests of the ETX-II test bed vehicle were performed in the INEL Electric Vehicle Testing Laboratory in Idaho Falls. Figure 17 shows the ETX-II on the Clayton chassis dynamometer. The dynamometer is an electromechanical device with road load — of the form $A + B \cdot V + C V^2$ — provided by a computer-controlled dc motor. The A, B, and C parameters, which are input from the dynamometer control keyboard, are varied during the calibration procedure until the coastdown curve of the vehicle on the dynamometer matches that measured on the track^{11,12}.

The primary quantities measured in the ETX-II dynamometer tests were battery voltage, current, power, dynamometer roll torque, and rpm. The electrical quantities are obtained using Xitron, Model 2503H, Power Analyzers developed especially for electric vehicle testing. Battery voltage and current signals are fed to the Xitron, which processes them and outputs digital or analog signals proportional to battery voltage, current, and power. The current sensor is either a coaxial shunt or a Hall-effect transducer (LEM, Model LT-100). Measurements of the dynamometer torques and rpm are used in its control system, and therefore these signals are readily available during vehicle tests.

The dynamometer laboratory data acquisition system (DAS) is based on the Imagination Systems, Inc., Autonet Data Acquisition System software, in conjunction with a Neff System 470 data acquisition unit and a 32-bit Intel 80386-based workstation. The DAS is configured for monitoring 125 measurement channels. The data are archived on an optical (WORM) storage medium. The ETX-II instrumentation is listed in Appendix A.

Considerable care is required in setting up the dynamometer for electric vehicle tests and then confirming that the setup yields the road load appropriate for the vehicle being tested. In principle, all that is required

Figure 17. ETX-II test-bed vehicle on the INEL EVTL Chassis dynamometer.

is that the dynamometer be set at the proper inertia weight (2,050 kg for the ETX-II) and that the values of A, B, and C be determined for which the coastdown of the vehicle on the dynamometer matches that measured on the track. (INEL used Ford coastdown data.) This determination requires a number of test runs on the dynamometer at various values of A, B, and C.

However, since the effective vehicle road forces¹¹ on the dynamometer are the sum of those from the tires on the rolls and the dc motor, care must be taken to ensure that the tire temperature is the same for all dynamometer coastdown runs and that the tire temperature selected is close to the average expected for the vehicle dynamometer tests to be done later. The force of the tires on the rolls at a given vehicle speed can be determined by measuring the dynamometer parasitic losses with and without the vehicle on the rolls. The total road load for the test is then obtained by adding the tire force to that of the dc motor, which includes the dynamometer spin losses (see Figures 18 and 19, and Table 9).

As shown in Figure 19, there is good agreement between the on-track and dynamometer coastdown data, and it was concluded that the dynamometer setup was satisfactory.

Figure 18. Calculated road load power of the ETX-II test-bed vehicle.

Figure 19. ETX-II coastdown curve-fit results.

Table 9. Aerodynamic and rolling resistance loads calculated from coastdown data.

km/h	Aero (kW)	Rolling (kW)	Total (kW)
94	13.899	5.368	19.266
93	13.204	5.277	18.480
91	12.533	5.186	17.718
90	11.884	5.095	16.979
88	11.259	5.004	16.263
86	10.656	4.913	15.569
85	10.075	4.822	14.897
83	9.515	4.731	14.246
82	8.977	4.640	13.617
80	8.459	4.549	13.008
78	7.962	4.458	12.420
77	7.484	4.367	11.851
75	7.026	4.276	11.302
74	6.587	4.185	10.772
72	6.167	4.094	10.261
70	5.765	4.003	9.768
69	5.380	3.912	9.293
67	5.014	3.822	8.835
66	4.664	3.731	8.395
64	4.331	3.640	7.971
62	4.014	3.549	7.563
61	3.713	3.458	7.171
59	3.428	3.367	6.795
58	3.157	3.276	6.433
56	2.901	3.185	6.086
54	2.660	3.094	5.754
53	2.432	3.003	5.435

Table 9. (continued)

km/h	Aero (kW)	Rolling (kW)	Total (kW)
51	2.218	2.912	5.129
50	2.016	2.821	4.837
48	1.827	2.730	4.557
46	1.650	2.639	4.289
45	1.486	2.548	4.034
43	1.332	2.457	3.789
42	1.189	2.366	3.555
40	1.057	2.275	3.332
38	0.936	2.184	3.120
37	0.823	2.093	2.916
35	0.721	2.002	2.723
34	0.627	1.911	2.538
32	0.541	1.820	2.361
30	0.464	1.729	2.193
29	0.395	1.638	2.033
27	0.332	1.547	1.880
26	0.277	1.456	1.733
24	0.228	1.365	1.594
22	0.186	1.274	1.460
21	0.149	1.183	1.332
19	0.117	1.092	1.209
18	0.090	1.001	1.091
16	0.068	0.910	0.978

Dynamometer Test Results

The ETX-II vehicle was tested on the chassis dynamometer, first with the NaS battery developed by CSPL and then with the JCI 12 V (69 A-h @ C/3) sealed lead-acid battery. The chassis dynamometer tests indicated that the vehicle functioned well with the NaS battery. The peak power (60 kW) from the battery was sufficient to permit full use of the maximum power of the ETX-II driveline, even at low SOC.

Energy economy tests at speeds up to 96 km/h (60 mph) were performed without difficulty. The limited testing conducted to battery depletion indicated that vehicle ranges in excess of 150 km (100 mi) could be expected for the FUDS cycle. The CSPL NaS battery powered the ETX-II for 185 km (115 mi) at 88 km/h (55 mph) on the dynamometer before testing with this battery was terminated. This performance was achieved despite the fact that the NaS battery had degraded to approximately 225 A-h from its 300 A-h rated capacity.

The J227a/C and the FUDS cycle energy economy tests of the ETX-II vehicle were conducted using the JCI sealed lead-acid battery.

The results of the ETX-II tests are summarized in Table 10 and presented in more detail in Appendix B. A summary of all INEL electric vehicle tests can be found in Appendix C. A comparison of the measured energy consumption (Wh/kg) of the ETX-II with that predicted by the SIMPLEV code¹³ is also presented in Table 10.

The battery support equipment (watchdog, charger, and heater) functioned well during the tests. The equipment, as well as the battery itself, was off-board; the weight and size ruled against their accommodation on board the vehicle.

Table 10. Summary of ETX-II dynamometer test results and comparison with SIMPLEV predictions.

Driving Mode	Energy Consumption (Wh/km)	
	Dynamometer Test	SIMPLEV
Constant-Speed		
48 km/h ^a	155	158
56 km/h ^a	159	165
72 km/h ^a	172	203
80 km/h ^a	200	227
88 km/h ^a	218 ^a	253
96 km/h ^a	242	279
Driving Cycles		
SAE J227a C ^b	218 (196) ^d	237 (225) ^d
FUDS ^b	233 (212) ^d	251 (238) ^d

a. Test performed with the CSPL NaS battery sodium-sulfur battery.

b. Test performed with the sealed lead-acid battery.

c. Measured range of 185 km.

d. Gross (net) energy consumption.

CONCLUSIONS

Performance testing of the ETX-II test-bed vehicle on a dynamometer resulted in the following conclusions:

- Component and system configurations for the drivetrain and the power and control subsystems are practical and adequate for a rear-wheel drive service vehicle.
- The vehicle operated well with the CSPL NaS battery, which readily met the maximum power requirements (52.5 kW) of the powertrain.
- Vehicle performance goals were achieved or exceeded (see Table 11).

Table 11. ETX-II performance versus program goals

	GOAL	RESULTS
Acceleration (sec) [0 to 80 km/h]	<20	17.35
Gradeability limit (%)	30	30
Top speed (km/h)	96	105
Payload (kg)	545	590
Energy consumption (kW-h/km) [on FUDS]	0.250	0.212
Range on FUDS (km)	>160	>160

Extensive separate tests to characterize the NaS battery and evaluate its suitability for electric vehicle service were also performed. It was concluded that:

- The observed lower-than-rated ampere-hour capacity appeared to be a consequence of cell/cell-string degradation.
- While battery calendar life appeared adequate, the capacity and service life may have been sensitive to both battery aging processes, i.e., effects that could be accentuated by the very large number of cells (2,880) in the battery, and thermal cycling.
- Battery performance based solely on cell weight and volume is attractive, but overall system test results indicate a need for further system (e.g., packaging) development.

- **Certain topics need further study:**
 - **Bank variability, as it limits the useful Ah capacity of an assembly of cells in a series-parallel arrangement. The results of the nonintrusive cell evaluation technique can only be verified by tear-down examination data.**
 - **High-power regenerative braking presents a problem with a fully charged (or nearly so) battery, and unquestionably should be studied in future testing.**

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APPENDIX A
ETX-II Instrumentation List

Table A-1. ETX-II instrumentation list.

Measurement	Symbol	Range	Response Time	Upper Cut-Off Frequency	Sensor Location	Output to Computer	Computer Input	Description
Battery Temperature	TBAT1	0-100	1 s	0.5 Hz (Computer)	Battery Module	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Battery Temperature	TBAT2	0-150	1 s	0.5 Hz (Computer)	Battery Module	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Battery Temperature	TBAT3	0-150	1 s	0.5 Hz (Computer)	Battery Module	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Battery Temperature	TBAT4	0-150	1 s	0.5 Hz (Computer)	Battery Module	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Electric Motor Temperature	TEM1	0-100	1 s	0.5 Hz (Computer)	Electric Motor	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Transaxle Temperature	TRCS	0-100	1 s	0.5 Hz (Computer)	Transmission	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Ambient Temperature	TAMB	0-100	1 s	0.5 Hz (Computer)	Dyno Room	0-9.708 MV Analog	+10 MV Analog	24-30 gauge ungrounded TC, ice point reference junction (Type E)
Battery Voltage	BV	0-300 V	—	5 Hz (PMI Box)	Vehicle	+10 V FS	+10.24 V Analog	Xitron
Motor Phase A, B, C Voltage	MVA MVB MVC	0-100 V	—	5 Hz (PMI Box)	Vehicle	+10 V FS	+10.24 V Analog	Xitron
Battery Amps	BA	0-500 A	—	5 Hz (PMI Box)	Vehicle	+10 V FS	+10.24 V Analog	500 A shunt, Xitron
Motor Phase A, B, C Amperage	MAA MAB MAC	0-500 A	—	5 Hz (PMI Box)	Vehicle	+10 V FS	+10.24 V Analog	500 A shunt, Xitron
Dyno Torque	DT	0-3580 n	—	5 Hz (Computer)	Dyno	0-10 V FS	+10.24 V Analog	Daytronics Power Supply and Signal Conditioning
Dyno Idle Roll	DIR	0-3000 rpm	—	—	Dyno	0-25 kHz	Pulse Accumulator	Digital Encoder
Dyno Load Roll	LDSPD	0-150 km/h	—	5 Hz (Computer)	Dyno	0-6.43 V @ 96.56 kph	+10.24 V Analog	Clayton System Controller

Table A-1. (continued)

Measurement	Symbol	Range	Response Time	Upper Cut-Off Frequency	Sensor Location	Output to Computer	Computer Input	Description
Accessory Battery Voltage	AUXBV	0-20 V	—	5 Hz (PMI)	Vehicle	+10 VFS	—	Xitron
Accessory Battery Current	AUXBI	0-50 A	—	5 Hz (PMI)	Vehicle	+10 VFS	—	Xitron
Energy Out of Battery	EBOD PBOD	0-50 kWh 0-150 kWh	— —	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron
Energy Into Battery	EBI PBI	0-50 kWh 0-90 kWh	— —	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron
Power/Energy Into Motor	EMIA PMIA EMIB PMIB EMIC PMIC	0-50 kWh 0-150 kWh	— —	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron
Total Ah Out of Battery	ABO	0-500 kAh	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron Voltage input set at 10 V.
Total Ah Into Battery (Regenerative)	ABI	0-500 kAh	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron Voltage input set at 10 V.
Power Out of Battery	PBO	0-100 kW	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron Average power is software calculated.
Power Into Battery	PBI	0-100 kW	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron Average power is software calculated.
Energy/Power Out of Motor	EMOA PMOA EMOB PMOB EMOC PMOC	0-50 kWh 0-150 kW	— —	10 kHz (PMI Box)	Vehicle	0-10 kHz Digital	Pulse Accumulator	500—A Shunt, Xitron Average power is software calculated.
Energy Out of Accessory Battery	EAUXB	0-10 kW	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	—	50—A shunt, Xitron.

Table A-1. (continued)

Measurement	Symbol	Range	Response Time	Upper Cut-Off Frequency	Sensor Location	Output to Computer	Computer Input	Description
Power Out of Accessory Battery	PAUXB	0-1 kW	—	50 kHz (PMI Box)	Vehicle	0-10 kHz Digital	—	50—A shunt, Xitron. Average power software calculated.
Distance	DIST	0-322 km	—	—	Idle Roll	5-V Pulse	Pulse Accumulator	Digital encoder
Cycles Driven	—	—	—	—	—	—	—	Computer calculated
Elapsed Time	—	—	—	—	—	—	—	Computer generated
kph	—	—	—	—	—	—	—	Computer calculated
Battery Recharge Amps	BAR	0-50 A	—	5 kHz	Vehicle	+10 VFS	—	Xitron
Battery Recharge	EBIR	0-500 kWh	—	5 kHz	Vehicle	0-10 kHz	—	Xitron
Energy/Power	PBIR	0-15 kW	—	—	Vehicle	5 V Pulses	—	Xitron
Battery Recharge	ABIR	0-500 Ah	—	50 kHz	Vehicle	0-10 kHz 5 V Pulses	—	Xitron
Battery Recharge Amps-Hours	ABIR	0-500 Ah	—	50 kHz	Vehicle	0-10 kHz 5 V Pulses	—	Xitron
Energy Battery Recharge (ac wall power)	EBCI	0-500 kWh	—	50 kHz	Charger	0-6829 Hz 5 V Pulses 6144 Pulses = 1 Wh	—	Xitron
Battery Recharge Volts	BVR	0-300 V	—	5 Hz	Vehicle	+10 Vdc	—	Xitron

Appendix B
ETX-II Test Data Summary

Table B-1. ETX-II Test Data Summary

Test number	X2D881	X2D561	X2D722	X2DC01	X2D883S
Test type	88 km/h	56 km/h	72 km/h	C-Cycle	88 km/h
Test date	7/30/91	7/31/91	8/5/91	8/7/91	2/6/92
Range (km)	21.8	45.2	34.4	32.9	60
Number of cycles	—	—	—	68	—
Test time (minutes)	15.6	48.7	29.0	90.2	45.6
Battery type ^a	Pb-Ac	Pb-Ac	Pb-Ac	Pb-Ac	NaS
ac energy consumption (W h/km)	—	—	—	—	—
dc energy consumption gross (W h/km)	229.3	147.8	181.0	217.8	225.9
dc energy consumption Net (W h/km)	—	—	—	196.2	—
Battery discharge energy (kW h)	5.0	6.7	6.2	8.5	13.5
Battery regeneration energy (kW h)	—	—	—	0.8	—
Battery discharge A h (gross)	27.2	34.8	32.4	45.5	76.8
Battery discharge A h (net)	—	—	—	41.7	—
Average battery temp test start (°C)	—	—	—	—	324.9
Average battery temp test end (°C)	—	—	—	—	338.5
Recharge energy dc (kW h)	—	—	—	—	32.9
Recharge energy ac (kW h)	—	—	—	—	44.4
Recharge A h	—	—	—	—	163.7
Battery energy recharge efficiency (%)	—	—	—	—	33.4
Battery coul recharge efficiency (%)	—	—	—	—	—
Recharge time (min)	—	—	—	—	315.8
Average battery temp recharge start (°C)	—	—	—	—	334.8
Average battery temp recharge end (°C)	—	—	—	—	323.8
<p>a. Pb-Ac is lead-acid, NaS is sodium-sulfur</p>					

Table B-1. (continued)

Test number	X2DE01	X2D882	X2DE02	X2DF01
Test type	EE	88 km/h	EE	FUDS
Test date	2/10/92	2/11/92	2/13/92	4/6/92
Range (km)	193.9	185.3	193.6	24.4
Number of cycles	—	—	—	2
Test time (min)	161.5	126.5	191.7	56
Battery type ^a	NaS	NaS	NaS	Pb-Ac
ac energy consumption (W h/km)	—	—	—	—
dc energy consumption gross (W h/km)	212.4	214.2	— ^b	232.5
dc energy consumption net (W h/km)	—	—	—	212.1
Battery discharge energy (kW h)	41.2	39.7	— ^b	5.7
Battery regeneration energy (kW h)	—	—	—	0.5
Battery discharge A h (gross)	226.7	222.8	219.4	30.5
Battery discharge A h (net)	—	—	—	28.3
Average battery temp test start (°C)	324.8	324.9	—	—
Average battery temp test end (°C)	350.9	353.5	—	—
Recharge energy dc (kW h)	45.4	45.5	—	—
Recharge energy ac (kW h)	—	—	—	—
Recharge A h	221.1	222.3	—	—
Battery energy recharge efficiency (%)	90.8	87.3	—	—
Battery coul recharge efficiency (%)	97.5	99.8	—	—
Recharge time (min)	395.7	381.4	—	—
Average battery temp recharge start (°C)	334.7	347.6	—	—
Average battery temp recharge end (°C)	324.8	330.8	—	—
a. Pb-Ac is lead-acid, NaS is sodium-sulfur.				
b. Intermittent power measurement.				

Equations

Equations used to calculate vehicle and battery performance as provided in the dynamometer test summary tables:

$$\text{ac energy consumption} = \frac{\text{ac energy into charger}}{\text{distance traveled}} \quad (1)$$

$$\text{Vehicle dc energy cons. (gross)} = \frac{\text{TB energy out} + \text{aux bat energy out}}{\text{distance traveled}} \quad (2)$$

$$\text{Vehicle dc energy cons. (net)} = \frac{\text{TB energy out} - \text{TB energy regen} + \text{aux bat energy out}}{\text{distance traveled}} \quad (3)$$

$$\text{TB energy recharge efficiency} = \frac{\text{TB energy out} - \text{TB energy regen}}{\text{charger output energy}} (100\%) \quad (4)$$

$$\text{TB coulombic recharge efficiency} = \frac{(\text{TB amp-h out}) - (\text{TB amp-h regen})}{\text{recharge amp hours}} (100\%) \quad (5)$$

$$\text{Wall ac efficiency} = \frac{\text{TB energy out} - \text{TB energy regen} + \text{aux bat energy out}}{\text{charger ac energy input}} (100\%) \quad (6)$$

$$\text{Charger efficiency} = \frac{\text{dc energy out of charger}}{\text{ac energy into charger}} (100\%) \quad (7)$$

Note: TB in all equations = traction battery

$$\text{Auxiliary battery energy consumption} = \frac{\text{aux battery energy}}{\text{distance traveled}} \quad (8)$$

$$\text{TB specific energy gross} = \frac{\text{TB energy out}}{\text{battery weight in kg}} \quad (9)$$

$$\text{TB specific energy net} = \frac{\text{TB energy out} - \text{TB energy in}}{\text{battery weight in kg}} \quad (10)$$

$$\text{TB specific power gross} = \frac{\text{TB energy out}}{\text{time (h)} \times \text{battery weight in kg}} \quad (11)$$

$$\text{TB specific power net} = \frac{\text{TB energy out} - \text{TB energy in}}{\text{time (h)} \times \text{battery weight in kg}} \quad (12)$$

APPENDIX C

INEL ELECTRIC VEHICLE TESTING SUMMARY

Table C-1. INEL electric vehicle testing summary.

Vehicle specifications

Vehicle designation	<u>Bedford Van</u>	<u>Eaton AC-3</u>	<u>Eaton DC</u>
Weight (kg)			
Test	3490	1651	1723
Curb ^a	2658	1352	1588
Gross vehicle ^b	3500	— ^c	— ^c
Rolling resistance coefficient (kg/kg)	0.0104	0.0098	0.0098
Frontal area (m ²)	3.35	1.84	1.84
Aero drag coefficient (C _D)	0.47	0.43	0.43
Drag area product—C _D A (m ²)	1.57	0.79	0.79
Power-to-weight ratio (W/kg) ^d	12	21	17
Motor	dc	ac	dc
Peak output power (kW)	40	33.6	29.8
Maximum speed (rpm)	6,000	12,500	4,500
Transmission	single-speed	two-speed	three-speed
Road load power @88 km/h (kW)	21.20	12.40	12.34
Powertrain efficiency @88 km/h (%)	79 ^e	76	79

Battery specification

Manufacturer	Lucas Chloride (EV5T)	Sears Die Hard	ALCO 2200
Type	Tubular lead acid (36 x 6 V)	Lead acid (16 x 12 V)	Lead acid (18 x 6 V)
Weight (kg)	1134	385	545
Battery mass fraction	0.32	0.23	0.32

Vehicle performance data

Acceleration (s)			
0-48 km/h	11.6	11.2	12.5
0-80 km/h	64.8	22.0	36.4
0-88 km/h	—	28.5	47.5
Energy consumption (W·h/km)			
48 km/h (vehicle net dc)	183	—	—
72 km/h (vehicle net dc)	233	159	145
C-cycle (vehicle net dc)	299	179	—
D-cycle (vehicle net dc)	311	188	241
FUD-cycle (vehicle net dc)	313 ^f	192	—
Range (km)			
48 km/h	182	— ^g	—
72 km/h	109	— ^g	79
C-cycle	97	— ^g	—
D-cycle	82	55.5	41
FUD-cycle	77 ^f	— ^g	—
Gradeability @32 km/h (%)	11	18	14

a. Based on weighing the vehicle.

b. Assigned by developer/manufacturer.

c. Means no weight assigned because vehicle was a test bed.

d. Propulsion system peak power-to-weight (vehicle) ratio.

e. At 80 km/h (top speed of this vehicle is 84 km/h).

f. Best effort.

g. Only minimal range data taken because of the use of marine batteries in place of EV batteries.

Table C-1. continued.

<u>Vehicle Specifications</u>			
Vehicle designation	<u>Chrysler/GE ETV-I</u>	<u>Ford/GE ETX-I</u>	<u>Solar Escort</u>
Weight (kg)			
Test	1723	1705	1968
Curb ^b	1522	1566	1836
Gross Vehicle ⁱ	1822	— ^j	— ^j
Rolling resistance coefficient (kg/kg)	0.0095	0.0097	0.0011
Frontal area (m ²)	1.84	1.78	1.90
Aero drag coefficient (C _D)	0.32	0.42	0.42
Drag area product—C _D A (m ²)	0.59	0.75	0.79
Power-to-weight ratio (W/kg) ^k	17	25	16
Motor	dc	ac	dc
Peak output power (kW)	30	43	32
Maximum speed (rpm)	5,000	9,000	6,000
Transmission	single-speed	two-speed	five-speed
Road Load power @ 88 km/h (kW)	9.60	10.40	12.50
Powertrain efficiency @ 88 km/h (%)	84	74	84
<u>Battery specification</u>			
Manufacturer	JCI Phase 3 Gel/Cell	Lucas Chloride	Concorde
Type	Lead acid (18 x 6 V)	Tubular lead acid (16 x 12 V)	Sealed lead acid (18 x 6 V)
Weight (kg)	539	520	672
Battery mass fraction	0.31	0.31	0.34
<u>Vehicle performance data</u>			
Acceleration (s)			
0-48 km/h	10.4	7.4	8.3
0-80 km/h	23.6	21.3	25.6
0-88 km/h	28.8	29.8	32.5
Energy consumption (W·h/km)			
48 km/h (vehicle net dc)	94	129	119
72 km/h (vehicle net dc)	108	140	144
C-cycle (vehicle net dc)	163	201	201
D-cycle (vehicle net dc)	154	181	—
FUD-cycle (vehicle net dc)	174	208	212
Range (km)			
48 km/h	172	128	154
72 km/h	126	92	108
C-cycle	85	65	75
D-cycle	82	58	—
FUD-cycle	75	60	68
Gradeability @ 32 km/h (%)	18	25	17

h. Based on weighing the vehicle.

i. Assigned by developer/manufacturer.

j. Means no weight assigned because vehicle was a test bed.

k. Propulsion system peak power-to-weight (vehicle) ratio.

Table C-1. continued.

<u>Vehicle specifications</u>			
Vehicle designation	<u>Solex Dual Battery Van</u>	<u>Eaton DSEP</u>	<u>Ford/GE ETX-II</u>
Weight (kg)			
Test	3713	2614	2050
Curb ⁱ	3510	2459	1795
Gross vehicle ^m	3860	2710	2310
Rolling resistance coefficient (kg/kg)	0.00963	0.0095	0.0095
Frontal area (m ²)	3.52	2.97	2.92
Aero drag coefficient (C _D)	0.48	0.375	0.37
Drag area product—C _D A (m ²)	1.65	1.11	1.08
Power-to-weight ratio (W/kg) ⁿ	18	21	25
Motor	dc	ac	IPM
Peak output power (kW)	67	55	52.5
Maximum speed (rpm)	4,500	12,000	11,000
Transmission	three-speed	two-speed	two-speed
Road load power @ 88 km/h (kW)	23.77	15.24	16.26
Powertrain efficiency @ 88 km/h (%)	77	83	85
<u>Battery specification</u>			
Manufacturer	JCI Phase 4 Gel/Cell	Eagle-Picher	CSPL
Type	Sealed lead-acid (36 x 6 V)	Nickel-iron (28 x 6 V)	Sodium-sulfur (24 x 8 V, banks)
Weight (kg)	1188	816	750
Battery mass fraction	0.32	0.31	0.37
<u>Vehicle performance data</u>			
Acceleration(s)			
0-48 km/h	8.7	7.5	6.98
0-80 km/h	24.4	20.0	17.35
0-88 km/h	30.9	24.3	—
Energy consumption (W·h/km)			
48 km/h (vehicle net dc)	235	157	155
72 km/h (vehicle net dc)	290	180	172
C-cycle (vehicle net dc)	441	298	196
D-cycle (vehicle net dc)	463	276	—
FUD-cycle (vehicle net dc)	463	296	212
Range (km)			
48 km/h	102 ^p	107 ^p	—
72 km/h	70 ^p	94 ^p	—
C-cycle	43 ^p	53 ^p	—
D-cycle	29 ^p	51 ^p	—
FUD-cycle	28 ^p	50 ^p	—
Gradeability @ 32 km/h (%)	18	17	—

i. Based on weighing the vehicle.

m. Assigned by developer/manufacturer.

n. Means no weight assigned because vehicle was a test bed.

o. Propulsion system peak power-to-weight (vehicle) ratio.

p. There is significant uncertainty in the range values because of the poor state of the traction batteries.

q. The measured range of ETX-II with the CSPL NaS battery at 88 km/h constant speed was 185 km.

DATE

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8/24/94

END