

DOE/GO/10017--T1

# **The \$2000 Electric Powertrain TRP Project**

**Baseline Program**

**Final Report**

**Project Period - June 22, 1994 through January 21, 1996**

**Program Manager: Timothy J. Winter**

Northrop Grumman Corporation  
Electronic Sensors and Systems Division  
Baltimore, Maryland 21203

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## **1.0 Program Summary**

Northrop Grumman (which acquired the Westinghouse division responsible for this project on March 1, 1996) was the project lead and performed the majority of the tasks. Chrysler was the only other significant performer of tasks.

The Statement of Work (SOW), dated May 23, 1994, set forth the activities to be accomplished under this program. The work breakdown structure was fundamentally followed with some variations in funding for the individual tasks. The Northrop Grumman responsibilities were Task A (Improved Powertrain) and Task C (Advanced Powertrain); the Chrysler responsibility was Task B (Vehicle Engineering).

The project period was from June 1994 to January 1996. The total cost of the project was \$15,360,770. The amount of DOE funding was \$7,680,000 and the amount of recipient funded activities was \$7,680,770.

### **1.1 Program Objective**

Develop and test technologies which improve the Northrop Grumman electric powertrain and lead to the volume production of an electric powertrain with the power, smoothness, and cost of an internal combustion engine.

### **1.2 Overall Program Accomplishments**

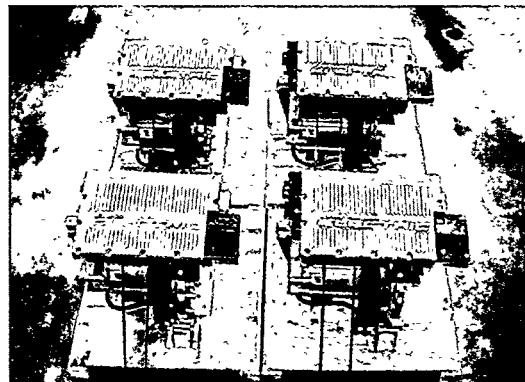
Accomplishments for this program can be summarized in six topic areas and selected figures are shown in the following pages.

1. The 100 hp powertrain was commercialized.
2. The Chrysler EPIC minivan was commercialized.
3. The 230 hp powertrain was commercialized.
4. The Blue Bird electric school and commercial buses were commercialized.
5. Related developments were initiated for DoD and energy systems applications.
6. Several key powertrain technologies were researched and advanced.

**Accomplishment 1 - The 100 hp powertrain has commercialized.**



*Figure 1 - The 100 hp drivetrain is configured like a standard V6 internal combustion engine for easy vehicle insertion.*



*Figure 2 - Northrop Grumman has shipped preproduction powertrains to Chrysler for vehicle testing.*

**Accomplishment 2 - The Chrysler EPIC minivan was commercialized.**

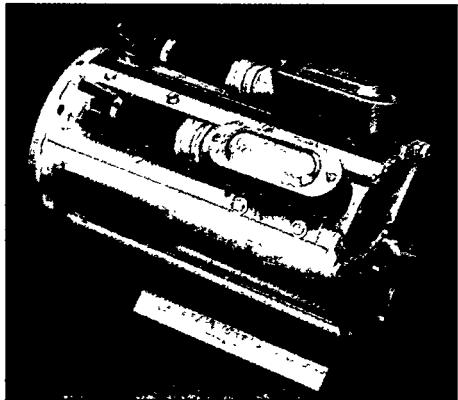


*Figure 3 - The EPIC has been offered for sale and the DoD, among others, has agreed to purchase several for their fleet.*

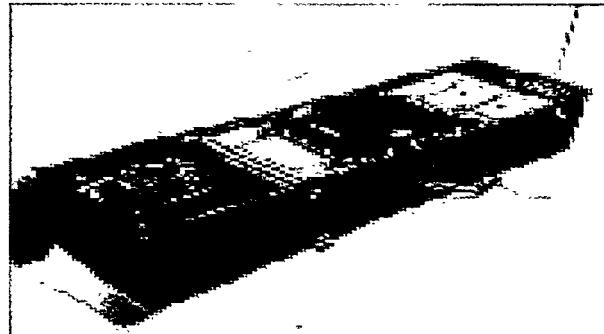
EPIC Electric Minivan Performance	
0-60 mph	16 Seconds
Top Speed	80 Miles Per Hour
Range	60 Miles (Estimated SAE J1634 Combined City/Highway with No Accessories)
Batteries	Sealed, Advanced Lead Acid - 324 Volts On-Board Charger 208/240 Volt, 40-Amp Circuit
Warranty	Vehicle - 3 Year/36,000 Miles

*Figure 4 - The EPIC performance, including range, satisfies fleet requirements for many applications.*

*Accomplishment 3 - The 230 hp powertrain was commercialized.*



*Figure 5 - The heavy-duty motor uses flow through cooling to help maximize the power density and provide the required performance.*



*Figure 6 - The double bridge inverter provides 640 amps of current in an electronics assembly which includes much of the vehicle's auxiliary equipment.*

*Accomplishment 4 - The Blue Bird electric school and commercial buses were commercialized.*

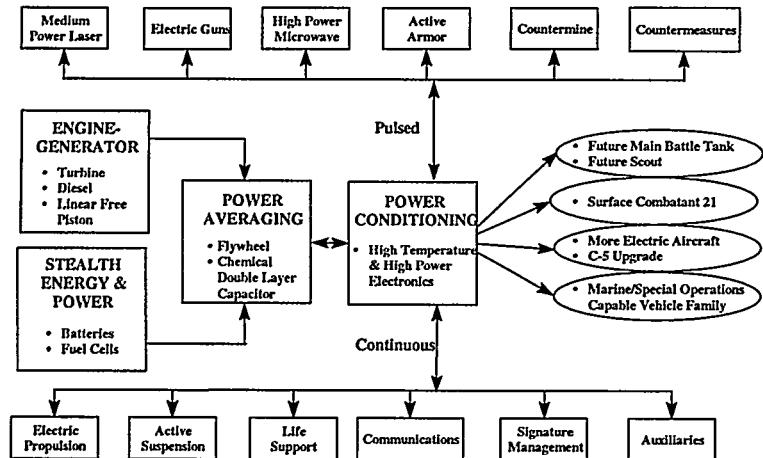


*Figure 7 - School buses represent 70% of the U.S. bus market and the electric bus satisfies many of the routes.*

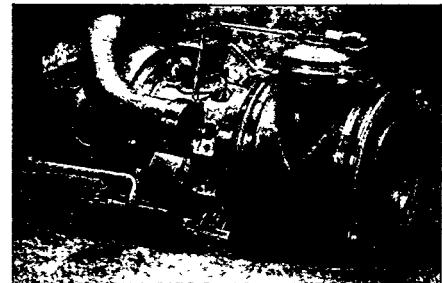


*Figure 8 - The commercial bus uses the same chassis and can be used for transit service.*

**Accomplishment 5 - Related developments were initiated for DoD and energy systems applications.**

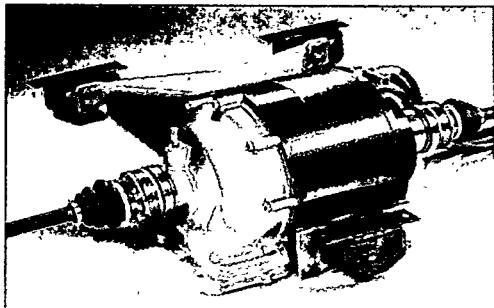


**Figure 9 - The powertrain technologies are being applied to the DoD More Electric Military including DARPA's Combat Hybrid Power Systems.**

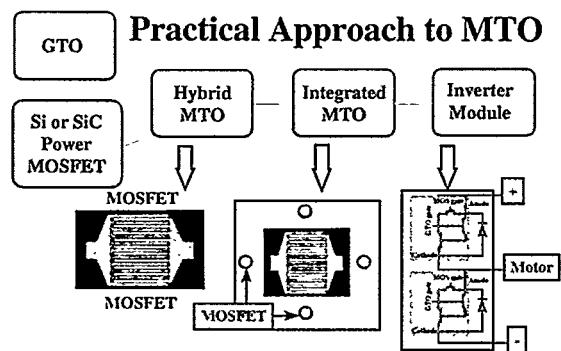


**Figure 10 - The power electronics have been integrated with a turbogenerator to pursue high manufacturing volumes in the portable power field.**

**Accomplishment 6 - Several key powertrain technologies were researched and advanced.**



**Figure 11 - A relationship was established with Unique Mobility to help productize their brushless DC permanent magnet system.**



**Figure 12 - A silicon carbide switch roadmap was developed and low current and voltage silicon carbide diodes and switches were designed, manufactured, and evaluated.**

### **1.3 Task A Summary Highlights - Improved Powertrain**

Throughout 1994, the 100 hp induction motor powertrain including controller, charger, and DC/DC converter was developed, fabricated, and tested. Several of these prototypes, which were designated F1 or design verification units, were built and delivered for test and evaluation at both Northrop Grumman and Chrysler. Product assurance tasks analyzing safety, performance, reliability, and quality were accomplished. Manufacturing processes were created and documented for the expected levels of production. Design verification occurred through functional, performance, and environmental testing. Enough changes were expected in the design and manufacturing processes that life testing was postponed until the process verification units were completed in 1995. Throughout 1995 and 1996, Northrop Grumman continued to productize the powertrain for use in the Chrysler electric minivan and other applications. Multiple process verification units and preproduction units have been delivered to Chrysler and other customers. Value engineering and preparation for increasing levels of production are still continuing.

### **1.4 Task B Summary Highlights - Vehicle Engineering**

Throughout 1994, Chrysler developed the F1 or design verification units for the planned production electric minivan. Vehicle planning, packaging, and subsystem development were accomplished in parallel. Vehicle subsystems, which were primarily subcontracted to suppliers, included the battery systems/HVAC, speed reducer, motor/controller/charger, chassis/cooling systems, and electrical/electronic systems. Vehicle builds and testing occurred on these prototype vehicles and have continued through the current time on those and subsequent vehicle configurations. Chrysler has offered for sale the EPIC, or Electric Powered Interurban Commuter, and customers, including the Department of Defense, have agreed to purchase these production minivans.

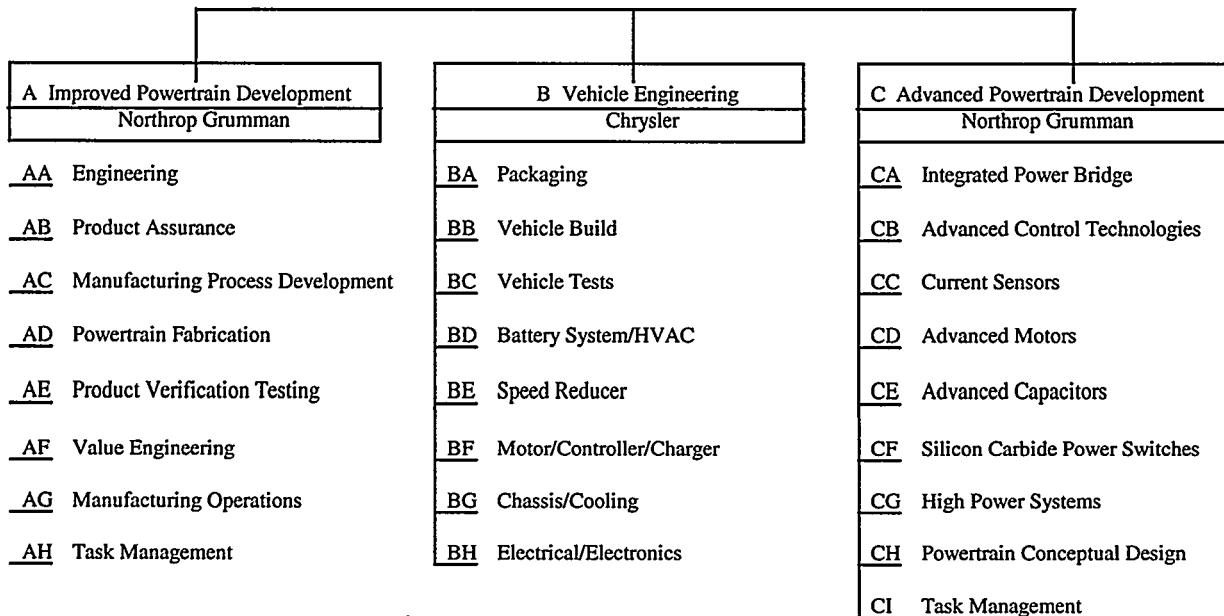
### **1.5 Task C Summary Highlights - Advanced Powertrain**

From 1994 though 1996, technologies which could reduce the production price of the powertrain were investigated and evaluated. Most noteworthy was the development of a 230 hp powertrain for use in school buses, commercial buses, and other heavy vehicles. Advanced cooling techniques and aggressive manufacturing processes were developed to achieve the required torque, power, reliability, and cost. In addition to the higher power system, Northrop Grumman also evaluated technologies for lower power systems and determined that a brushless DC permanent magnet powertrain was most suitable for numerous applications. An agreement was reached with Unique Mobility to help market and commercialize their 70 hp system as production opportunities with major OEMs were identified. Novel concepts for evolutionary and revolutionary advances were studied including resolverless control techniques, current sensor integrated circuits, integrated power bridges, advanced motor fabrication methods, and silicon carbide power devices.

## 2.0 Program Structure

The program was laid out and fundamentally implemented according to the following work breakdown structure.

# Electric Powertrain Program



## 3.0 Task Objective and Accomplishment Summaries

For each of the detailed tasks in the work breakdown structure, the task objective with planned milestones and the summary accomplishments are listed. Detailed technical specifications are not provided for proprietary and brevity reasons. More information can be requested from the contracts or program points of contact at Northrop Grumman.

### 3.1 Task A: Improved Powertrain

#### Objectives: Task AA - Engineering

This task provides for the engineering development effort of a production prototype electric powertrain. The effort includes, but is not limited to, full description of the architecture of the system, generation of system specifications, customer interface, and specification flowdown. Coordination of design engineering, product assurance, manufacturing engineering, and software engineering is included in this task. This task includes electrical, mechanical, and drafting design of

the production prototype powertrain. Software design and test are included under this task. All manufacturing drawings for the powertrain will be generated under this task. The milestone schedule for this task is as follows:

System Specification	Q1-94
Module Preliminary Design Reviews	Q1-94
Software Specification	Q1-94
Module Testing Complete	Q2-94
System Failure Mode and Effects Analysis	Q3-94
Drawings Complete	Q3-94
Complete Software Build	Q3-94
Software Failure Mode and Effects Analysis	Q4-94

#### **Accomplishments: Task AA - Engineering**

Specifications were written, design reviews were held, analyses were completed, and drawings were created. The ultimate accomplishment of this task was that the improved powertrain design was finished and hardware was delivered on schedule to the powertrain test program and to Chrysler for vehicle integration. The results of Tasks AB (Product Assurance), AE (Product Verification Testing), and AF (Value Engineering) were also later used to enhance the design of the improved powertrain.

#### **Objectives: Task AB - Product Assurance**

Evaluate and guide system reliability and quality through the use of Failure Mode and Effects Analysis (FMEA), software FMEA, and criticality analysis. Provide engineering guidelines for stress, FMEA, performance, and CALCE analysis. Work as an integral member of the design team to guide component selection and long-term life of the system. Develop a data base on components that will support manufacturing analysis, stress analysis, performance analysis, and FMEA. The milestone schedule for this task is as follows:

Product Assurance Plan	Q1-94
Stress Analysis	Q3-94
Module FMEA	Q3-94
Product Assurance Assessment	Q4-94

### **Accomplishments: Task AB - Product Assurance**

A plan was created and followed, although not all task schedules were met on time. Powertrain reliability and quality were evaluated and improved through the use of FMEAs and other analyses. Components engineering was integrated with the design team to ensure optimal parts selection for the life of the powertrain. The focus was on meeting the specification at the lowest possible cost.

### **Objectives: Task AC - Manufacturing Process Development**

Provide manufacturing expertise to integrated product team. Develop manufacturing process flows for all powertrain components. Identify all tooling and capital equipment required to manufacture the powertrain in the anticipated volumes. Initiate procurement of the capital and tooling. Budgets for tooling and capital are not included in this task. The milestone schedule for this task is as follows:

Preliminary Process Flow	Q2-94
Identify Tooling and Capital	Q3-94
Process Development Activity Plan	Q3-94
Baseline Production Plan	Q4-94

### **Accomplishments: Task AC - Manufacturing Process Development**

Detailed process flows were created for the motor, system control unit, on-board battery charger, and oil pump assembly. Suppliers were selected and processes and capability plans were established for the expected business volume. Tooling and capital requirements were identified for the subassemblies for both Northrop Grumman and the suppliers. The baseline production was created with plans for continual updates.

### **Objectives: Task AD - Powertrain Fabrication**

Procure and build eight powertrains and spares for design verification testing. Includes all labor associated with fabrication and manufacturing follow. All material for the eight systems and spares is included. The milestone schedule for this task is as follows:

Units Available (#1-#3)	Q2-94
Units Available (#4-#8)	Q3-94

### **Accomplishments: Task AD - Powertrain Fabrication**

More than eight powertrains were fabricated for use in design verification testing. These systems were delivered to the powertrain test facility at Northrop Grumman for extensive bench and dynamometer testing as well as to Chrysler for extensive vehicle road testing.

### **Objectives: Task AE - Product Verification Testing**

This task includes development and tracking of all product verification test plans and schedules that conform to Chrysler's program. Verification testing includes, but is not limited to, functional verification, environmental testing, life testing, maintenance testing, and failure mode testing. All equipment rental and fixture design and fabrication are part of this task. The milestone schedule for this task is as follows:

Verification Test Plans	Q3-94
Complete Functional Tests	Q3-94
Complete Performance Tests	Q3-94
Complete Environmental Tests	Q4-94
Complete Life Tests	Q4-94

### **Accomplishments: Task AE - Product Verification Testing**

The enhanced version of the improved powertrain underwent extensive product verification testing. Functional, performance and environmental tests were all performed on schedule. Due to the extent of planned changes for the process verification units, life testing was delayed until those units were available. The process verification units have since undergone durability and life testing. Tests were accomplished for hot and cold temperature, vibration, shock, altitude, conducted and susceptibility EMI, and salt spray.

### **Objectives: Task AF - Value Engineering**

Continue cost reduction and process improvement activities after the production prototype powertrain design is frozen. Incorporation of all lessons learned on verification testing is covered under this task. Analysis not completed prior to freeze of production prototype design including, but not limited to, FMEA and performance analysis. The milestone schedule for this task is as follows:

Baseline Design Review	Q3-94
Design Status Review	Q3-94
Production Design Intent Design Review	Q4-94
Production Prototype Software Release	Q4-94

### **Accomplishments: Task AF - Value Engineering**

The initial design verification units were assembled and tested. The manufacturing and engineering team jointly performed value analyses on the powertrain, subsystems, and components. Significant modifications were made to improve the performance as well as prepare the production tooling and processes. As a result of the value engineering task, additional verification units were fabricated and tested.

### **Objectives: Task AG - Manufacturing Operations**

Implement manufacturing process and quality controls in the factory. Provide manufacturing engineering and design support to establish factory processes and capability. Continue the process improvement efforts to reduce the manufacturing cost of the system. The milestone schedule for this task is as follows:

Manufacturing Test Requirements	Q3-94
Factory Layout	Q4-94
Supplier Process Review	Q4-94
Factory Process Review	Q4-94

### **Accomplishments: Task AG - Manufacturing Operations**

The powertrain manufacturing operations were transitioned from our prototype assembly factory to our production manufacturing facility. Manufacturing tests were created to identify manufacturing defects. The factory layout included an incoming parts storeroom and kitting area, multiple electronics assembly stations, a motor assembly area, a test and engineering evaluation area, and a final assembled parts storeroom and shipping area. Supplier and factory processes were reviewed and documented.

## **3.2 Task B: Vehicle Engineering**

The milestones associated with all the activities included as part of the Vehicle Engineering tasks were completed during the fourth quarter of 1994 or the first quarter of 1995.

### **Objectives: Task BA - Packaging/Planning/Task Management**

This task includes the construction review and updating of a mock-up. This includes ensuring proper fit and packaging of vehicle components and subsystems, designing for serviceability, and planning vehicle build sequence. Task Management is also included in this task. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Program Vehicle Release	Q4-94
Program Mockup Complete	Q4-94
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BA - Packaging/Planning/Task Management**

The packaging of the first program vehicle was completed. The major packaging issues were resolved initially with the help of a mock-up vehicle and finally with the first program vehicle. Issues relating to serviceability and manufacturing were generated in order to be addressed in future builds. The subassemblies were positioned on the manufacturing pallets to assure proper vehicle installation.

#### **Objectives: Task BB - Vehicle Build**

Two mule vehicles will be built in the summer of 1994. Coordination of vehicle parts supply and vehicle build are part of this task. These vehicles will be built from the ground up with the mule vehicle parts. Slight modifications to the body are anticipated during this phase of the program.

During the first half of 1995, additional vehicles will be assembled. These vehicles will be pilot vehicles which will require some rework to outfit them with the EV components. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Mule Vehicle Complete	Q3-94
Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BB - Vehicle Build**

Mock-ups were built to verify all packaging issues. The first program vehicle was built to perform design verification testing. The build was slightly behind schedule due to late receipt of vehicle bodies. Some vehicles were built in the plant to confirm the manufacturing assembly process.

## **Objectives: Task BC - Vehicle Tests**

Thorough testing of the electric powertrain and surrounding vehicle subsystems is necessary to produce a consumer product. To achieve this, component integration and testing among the various high voltage parts is a very large part of this task. In addition, thermal testing of the vehicle and components is planned under various driving and environmental conditions. Vehicle test also includes durability and endurance testing, battery testing, and ride and handling testing. The milestone schedule for this task is as follows:

Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Cold Tests	Q1-95
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95
Program Vehicle Testing Begins	Q2-95

## **Accomplishments: Task BC - Vehicle Tests**

The mule vehicles were extensively tested. Cold testing provided good data on oil flow through the powertrain. Issues with the battery system were addressed prior to completion of the cold testing. Hot testing provided valuable data on component extremes and the cooling system efficiency. Vehicles were tested at the Chrysler Technology Center, prior to being tested at alternate locations. Testing of the program vehicles was initiated and ultimately completed with the results factored into the production vehicle designs.

## **Objectives: Task BD - Battery Systems/HVAC**

Development of an efficient heating, ventilation, and air conditioning system for an electric minivan. Objectives are to provide an energy efficient system which focuses on meeting customer comfort expectations and satisfying the existing government standards for HVAC.

This task includes the development of battery tubs which retain, cool, and ventilate the batteries. This effort includes the design and development of the tubs, cover, rail reinforcement plates, bracketry, blower motors, and ductwork. Objectives are to maximize available volume for battery packaging, provide flexibility for different battery configurations, and meet customer requirements.

In addition to the battery packaging and environmental control is the Battery Energy Management System (BEMS). It is designed to provide the optimal maintenance and charging of a large pack of batteries. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Supplier FMEA	Q3-94
Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BD - Battery Systems/HVAC**

The design of the battery system and HVAC was complete. The units were installed into the first program vehicle. Work continued on the optimization of these two systems to ensure efficient operation. The battery tub and ancillary equipment underwent a design for manufacturing review.

#### **Objectives: Task BE - Speed Reducer**

Develop a low-cost, low-weight, single-speed transaxle which meets the established corporate reliability standards and exhibits “best-in-class” absence of gear noise. This is a unique transaxle designed specifically for the Northrop Grumman A/C induction motor and Chrysler’s electric minivan. Objectives of this task are to optimize the vehicle’s performance while meeting warranty targets and best-in-class noise characteristics. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Supplier FMEA	Q3-94
Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BE - Speed Reducer**

The development and build of the speed reducer was complete and the unit has met all the cost, weight, and noise characteristics. The unit was installed on the first program vehicle.

### **Objectives: Task BF - Motor/Controller/Charger**

To integrate the Northrop Grumman powertrain into the next-generation minivan. Numerous details of the integration include: electrical system compatibility, vehicle communication requirements, ensuring auxiliary power requirements are defined and achieved, sizing the battery charger, vehicle build and test coordination, system specification, and electromagnetic compatibility. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Supplier FMEA	Q3-94
Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

### **Accomplishments: Task BF - Motor/Controller/Charger**

The powertrain was installed into the first program vehicle. The system completed the compatibility checkouts and the charger was able to supply power to the batteries using the BEMS system. The supplier's FMEA process was completed including documentation.

### **Objectives: Task BG - Chassis/Cooling**

The major efforts of this task are directed toward development of suspension, power steering, braking, and cooling. Suspension efforts are directed at providing proper ground clearance and adequate springs for accommodating battery weight while ensuring vehicle build at the production plant. The vehicle will be equipped with a high voltage electrohydraulic power steering system targeted toward consumer expectations. The braking system will provide a blending of ABS and regenerative braking incorporating the latest technology. The cooling module has the following objectives: provide required oil cooling under all operating conditions, meet all R134A refrigerant condensing requirements for the vehicle air conditioning system, provide heat scavenging for the heat pump, minimize noise, vibration, and harshness. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Supplier FMEA	Q3-94

Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BG - Chassis/Cooling**

The development of the suspension was completed. The vehicle provided adequate clearance and proper load balance to carry the battery system. The electrohydraulic power steering was installed in the program vehicle. Testing at cold temperatures was performed. The braking system blended the regenerative with the ABS braking system. The cooling module provided adequate cooling and good flow at hot and cold temperatures.

#### **Objectives: Task BH - Electrical/Electronic**

To develop a reliable electrical system for the electric minivan that conforms to all applicable corporate, SAE, and UL standards. This will be a unique Chrysler system due to the high voltage potential of the electric minivan. The objectives of this task are to design an electrical system which fulfills the CARB ZEV requirements. The milestone schedule for this task is as follows:

Initial Design Complete	Q1-94
Mock-up Complete	Q2-94
Mule Vehicle Parts	Q3-94
Hot Tests	Q3-94
Supplier FMEA	Q3-94
Program Vehicle Release	Q4-94
Start Program Build	Q1-95
First Program Vehicle Complete	Q2-95

#### **Accomplishments: Task BH - Electrical/Electronic**

The electrical system was installed in the program vehicle and initial checkout was completed. Special care had been taken to identify all high voltage and cable connections. The electric minivan conforms to all applicable corporate, SAE, and UL standards.

### **3.3 Task C: Advanced Powertrain**

#### **Objectives: Task CA - Integrated Power Bridge**

The activities performed under this task will focus on developing a new approach for packaging the motor controller power bridge (inverter electronics). Northrop Grumman will package bare Integrated Gate Bipolar Transistor (IGBT) dies into custom hybrid modules to form an integrated power bridge. The integrated power bridge is projected to 25% lower cost, 20% lower weight, 50%

smaller volume, and 400% more reliable than the discrete power bridge utilized by the Improved Powertrain (Task A). The new power bridge will be installed into the improved powertrain and then fully tested. Due to the reliability improvement, the cooling system for the controller can be reduced and this results in additional cost reductions. Investigations will also evaluate quick disconnect connectors for high current and liquid interconnects, gate drive circuits integrated into the bridge, and a quick disconnect mounting plate. The milestone schedule for this task is as follows:

Verify Prototype Performance	Q1-95
Complete Pre-production Design	Q2-95
Power Bridge Test & Evaluation	Q3-95
Advanced Design Analysis Complete	Q4-95

#### **Accomplishments: Task CA - Integrated Power Bridge (IPB)**

Several IPBs were assembled and tested (in a lab environment). A revised design was completed but the performance and cost improvements did not initially justify the investment required to productize that design. A more aggressive concept for the next-generation IPB was developed as part of the technology assessment program.

#### **Objectives: Task CB - Improved Control Technologies**

The activities performed under this task will focus on improving the current state-of-the-art technology in monitoring the position of the rotor. Successful completion of this task will allow for the elimination of the resolver (located in the motor), a cable between the motor and the controller, and resolver to digital interface circuitry. Upon completion of bench testing, the resolverless control techniques will be tested in a vehicle. The milestone schedule for this task is as follows:

Bench Test Complete	Q3-94
Vehicle Test Complete	Q4-94

#### **Accomplishments: Task CB - Advanced Control Technologies**

The hardware and software required to evaluate resolverless control options were developed and tested. An electric powertrain was updated to include this updated hardware and software. Dynamometer testing was scheduled at the research facility in Pittsburgh with a planned transition to vehicle testing in Baltimore. This task was not completed due to availability of the correct human resources.

#### **Objectives: Task CC - Current Sensors**

The activities performed under this task will focus on developing a new type of alternating current (AC) sensors. These AC sensors use a shunt-based sensing element with an Application-Specific Integrated Circuit (ASIC). When measuring a 300A current (typical for an electric vehicle motor), the shunt-based current sensor provides superior performance with a digital output for three-

fourths the cost, one-fourth the volume, and one-fifth the weight of comparable industry standard Hall effect sensors. The milestone schedule for this task is as follows:

Sensor Design Review	Q1-94
ASIC Layout Complete	Q2-94
Design Complete	Q2-94
ASICs Available	Q2-94
Sensors Available	Q3-94

#### **Accomplishments: Task CC - Current Sensors**

The digital current sensor was designed and the ASIC was laid out. Errors were uncovered in the design of the ASIC. Due to the timing and cost required to completely fix the errors, this activity was put on hold. Estimates of production costs (primarily due to the cost of the ASIC) have indicated that volumes of several hundred thousands would be required in order to make this product price competitive with the state-of-the-art Hall effect current sensors that are currently used in electric drive applications.

#### **Objectives: Task CD - Advanced Motors**

The activities performed under this task will focus on improving the design of the current AC induction motor and investigate long-term motor designs. The current AC induction motor will be analyzed to determine if it can be manufactured (recurring and non-recurring) more cost effectively without sacrificing performance. The resulting motor will be similar to our existing AC induction motor and this new motor will be both bench tested and tested in a vehicle. The other major effort of this task will be the investigation of motor architectures that have the potential to be more cost effective with the same performance of AC induction motors. This effort will focus on analyzing and evaluating brushless DC motors and reluctance motors to determine their long-term potential as motors for electric and electric hybrid vehicles. Required power circuits and vector control algorithms for these types of motors will also be studied. The milestone schedule for this task is as follows:

Improved AC Induction Motor Identified	Q3-94
Design Complete - Improved AC Motor	Q4-94
Improved Motor Available	Q1-95
Analyze Advanced Motor Concepts	Q3-95
Specify Advanced Motor Designs	Q4-95

#### **Accomplishments: Task CD - Advanced Motors**

The design and development work was completed on an improved version of our higher power motor. Progress was made in the areas of spray oil nozzle design, cooling design, slot keeper design and oil foaming analysis. The technology assessment program identified several areas of advanced motor work. The further development of in-place cooling techniques for existing motors

was proposed. The technology would provide high conductivity pathways to carry heat out the rotor/stator stack to the rear of the stack where it could be more easily cooled. Evaluation of prototype motors (non AC induction) from the University of Wisconsin and Rensselaer Polytechnic Institute was identified for further analysis. Net shape fabrication was identified as a key process to lower the cost of EV motors. A process (microlams), developed at the Northrop Grumman research facility a number of years ago, could be developed and may considerably lower the cost of the stator.

### **Objectives: Task CE - Advanced Capacitors**

The activities performed under this task will focus on evaluating film capacitors that are capable of replacing the current state-of-the-art bulky, high voltage, high ripple current, and high-temperature capacitors. The physical properties of film capacitors allow for customized form factors suitable for surface-mount installation into the IPB developed under Task CA. This fully-integrated power bridge has the potential to provide significant cost, performance, weight, and volume advantages over state-of-the-art technology available today. These advanced capacitors will be bench tested in a modified powertrain. This task will also evaluate high-temperature capacitors for use with silicon carbide power switches (Task CF) in the integrated powertrain (Task CH). The milestone schedule for this task is as follows:

Analyze Alternative Capacitors	Q1-95
Capacitor Testing Complete	Q3-95

### **Accomplishments: Task CE - Advanced Capacitors**

A path for the development of capacitors (required for the development of a low-cost integrated power block) was scoped out as part of the technology assessment program. This capacitor most likely will use parallel plates which minimize parasitic inductance and is closely coupled to the switch network. Requirements are for 100 uF of capacitance operating at 300 volts occupying a 3" x 10" footprint (considerably less than 1" thick).

### **Objectives: Task CF - Silicon Carbide Power Switches**

The activities performed under this task will focus on developing silicon carbide power switches that will be capable of replacing industry standard silicon power switches. These devices can operate at significantly higher temperatures than silicon devices which in turn allows for the reduction or elimination of cooling systems that are required by present silicon devices. The development efforts performed under this task range from the growing of silicon carbide crystals through to the final packaging and testing of the power switch devices. The end result of this effort is targeted to be 600V 10A power switches that can operate at over 250°C. The milestone schedule for this task is as follows:

Device Evaluation Complete	3Q-94
3A Device Model Complete	4Q-94
Material Characterization Complete	1Q-95
Demonstrate 3A Devices	2Q-95

10A Device Model & Design Complete	3Q-95
Demonstrate 10A Devices	4Q-95

### **Accomplishments: Task CF - Silicon Carbide Power Switches**

Small diodes and switching devices have been fabricated and tested to varying degrees. The first Schottky diode and GTO cells have been produced and tested with outstanding results. A detailed plan for the development of increasing power levels of diodes and a MOS TurnOff (MTO) thyristor including strategic industry partners was created and is awaiting further funding.

### **Objectives: Task CG - High Power Systems**

The purpose of this task is to integrate higher power electric powertrains into larger vehicles such as school buses, shuttle buses, and utility bucket trucks. The main emphasis of this task is to double the power of the electric motor to over 200 hp and to increase the current rating of the controller to 640 amps. A verification program to evaluate these electrically driven vehicles is a part of this task. The milestone schedule for this task is as follows:

Controller and Motor Design Complete	Q1-94
Motor and Controller Testing Underway	Q1-94
Demonstrate Electric School Bus	Q2-94
Demonstrate Electric Bucket Truck	Q3-94
Demonstrate Electric Shuttle Bus	Q3-94

### **Accomplishments: Task CG - High Power Systems**

A higher powered or heavy-duty system which produces 230 hp of peak power was designed and tested. This system uses many of the same manufacturing processes and tools as the medium-duty system. These processes include spray oil cooling nozzles in the casted end bells, lightweight magnesium extrusion dies, cast copper rotors, and semi-automated stator winding. The 230 hp powertrain was productized and integrated into multiple vehicle types including an electric bucket truck, a school bus, and a shuttle bus. All of these vehicle styles were tested and demonstrated.

### **Objectives: Task CH - Powertrain Design**

The activities performed under this task will focus on performing the conceptual design of the next-generation electric powertrain (the integrated electric powertrain) that is based on the technologies developed via Tasks CA through CG. The milestone schedule for this task is as follows:

System Design Review	2Q-95
Complete Top-level Design	4Q-95

### **Accomplishments: Task CH - Powertrain Conceptual Design**

A technology assessment program to look at design/architecture of future powertrains was completed. A multidisciplined team of scientists and engineers from the Northrop Grumman research facilities in Pittsburgh were the primary investigators. Assistance from the EV team in Baltimore, coupled with outside experts from the University of Wisconsin, Rensselaer Polytechnic Institute, and the University of South Africa completed the team. The following technologies were investigated: integrated power block (next-generation of the integrated power bridge), power electronics, conductive polymers, motor architectures, microlams for motor manufacturing, and silicon carbide. Each technology was evaluated using production cost as being the discriminator in determining which technologies to develop. Development plans were created to advance each of these technologies.