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Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051

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Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051
Plenary Sessions

SATURDAY: October 26, 1991

9-10 a.m. Opening Plenary:
Welcome: Nancy Hazard, Associate Director of NESEA
Paul Gromer, Commissioner of Energy Resources, State of Massachusetts
Richard King, U.S. Dept of Energy

Bringing Electric Vehicles to Market
Robert Stempel, Chairman and CEO of General Motors Corporation, Detroit, MI

SUNDAY: October 27, 1991

9-10 a.m. Opening Plenary:
Welcome: Dr. Robert Wills, Co-director, American Tour de Sol, and Co-chair of S/EV 91.

Hydrogen Fuel Cells: Key to the Future
Dr. Roger Billings, American Academy of Science, Independence, MO

3:30-5:00 Closing Plenary:
Design for the Ultimate Car:
Session Chair: Dr. Robert Wills, Co-director, American Tour de Sol (603)-878-1600

James Worden, Solectria Corporation, Arlington, MA
Dr. Mike Seal, Director Vehicle Research Institute, W. Washington U., Bellingham, WA
Dr. Robert Wills, Co-director, American Tour de Sol
The Electric Car in the Future of Transportation
A GM Viewpoint

by
Robert C. Stempel
Chairman, General Motors Corporation

In 1986, General Motors received an invitation to participate in an international solar-car race in Australia. GM had recently acquired Hughes Aircraft, a company with expertise in solar cells. The race was an opportunity to use and expand that expertise and to promote technical cooperation between GM divisions and Hughes, and we seized that opportunity. In so doing, we were also able to enlist the participation of AeroVironment, a company with expertise in designing lightweight structures.

We also saw the World Solar Challenge as an opportunity to encourage interest in science and technology among America's young people.

GM found that designing, testing, and racing the GM Sunraycer pushed the boundaries of technology, as we looked for total efficiency. The Sunraycer won the race 2-1/2 days ahead of the nearest competitor, covering 1950 miles using energy from the sun.

We learned a great deal about various technologies from the Sunraycer experience. GM does not see a mass-produced solar car as practical for a long time to come. But our experience with the Sunraycer encouraged us to look at the possibility of a mass produced electric car. To bring such a vehicle up to current safety and comfort standards, manufacture it, and sell it at an affordable price is beyond the capability of current technology.
Most previous electric prototypes built by GM used "conventional" electric and mechanical technology. The Sunraycer used electronics, reducing power losses and making it more efficient. To compete with gasoline-powered cars, an electric car has to use electricity very efficiently.

GM sees the electric vehicle as another step in its energy-conservation and emission-reduction efforts. The electric car is not the total solution for improved air quality, but it is part of the solution. It is the most viable zero-emissions vehicle possible with today's technology.

GM sees the electric vehicle fitting into a spectrum of future transportation alternatives. The gasoline-powered internal combustion engine will continue to have a place, possibly using reformulated fuels that help lower emissions. There will also be vehicles that can operate on a variety of alternatives fuels, such as alcohols and natural gas. Farther out, there may be vehicles powered by new technologies like fuel cells.

GM was the first company to commit to building a consumer-oriented electric vehicle. It will take more than technology to make this vehicle successful. A market must be developed. People need to understand electric transportation and how it can serve their needs. There must also be a dealer system and an energy distribution network to serve these vehicles.

Concerns about the environment, energy conservation, and energy security make an electric vehicle attractive to people all over the world, particularly if such a vehicle is competitive in cost, comfort, safety, and other factors.
The consumer will have to become used to the idea of recharging an electric car, instead of refueling it. An infrastructure will have to be developed to make recharging convenient. The ideal time for recharging would be at night, but there will be situations where people want to recharge electric vehicles at work, while shopping, or on the highway. Quick recharging is possible but requires large amounts of energy. People will have to adjust their behavior to these new realities. People will also want to know that an electric vehicle has warranty coverage like a gasoline-powered vehicle, and that service will be available.

We also want to convince potential buyers that an electric vehicle can provide "good, clean fun." Electricity already has a reputation for being reliable, available, and relatively low-cost. In most respects, an electric car would require less maintenance than a conventional automobile, although the battery pack would require eventual replacement. The GM prototype electric car has already demonstrated acceleration comparable to a sports car. It has a projected top speed of 100 mpg, although a rev limiter keeps the actual top speed at 75 mph. The production model will also offer features that buyers expect, including air bags.

The car will be manufactured in Lansing, Michigan, but GM plans to sell it in many parts of the world. The electric car represents an opportunity to reassert U.S. technical leadership. In contrast to current practices in the U.S., many foreign competitors benefit from cooperative relations between government and industry. The U.S. needs to consider a similar approach. Some of that effort is already in place. GM, Ford, and Chrysler have joined the Department of Energy and the Electric Power Research Institute to speed battery development. This cooperative venture, called the U.S. Advanced
Battery Consortium, will help to identify the most promising technological alternatives. It is not a vehicle development program, nor will it involve battery production.

GM also hopes that the federal government will take a role in demonstration projects and in encouraging development of infrastructure to support electric vehicles. Today's gasoline station will have to become an energy center to support the variety of vehicles available in the future. We also need educators to think about preparing the scientists and engineers who will develop the next generation of electric cars.

General Motors is putting its technical and financial resources behind the electric car. But support from many others groups is essential for the success of this form of transportation.
LaserCell Prototype Vehicle
Billings, R.E.; Sanchez, M.; Cherry, P.A.; Eyre, D.B.
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Abstract
A solid polymer electrolyte fuel cell has been installed in a prototype vehicle to assess the potential of fuel cells in vehicular applications. The fuel cell is based on an advanced technology developed at the American Academy of Science known as the LaserCel. Hydrogen is stored on the vehicle in a safe, metal hydride powder form. Hydrogen is released from the hydride by heat supplied from the exhaust of the fuel cell. Inside the cell, hydrogen is reacted with the oxygen from air to form water. Energy from this reaction is released from the cell in the form of electricity which is used to power an electric motor which is coupled to the wheels through a standard transmission.

Background
For several years, the advantages of utilizing hydrogen as a fuel, have been demonstrated in vehicle prototypes. Hydrogen can be synthesized from water and most of the renewable energy sources. It can be safely stored in its powdered, metal hydride form, and the only resulting air pollution is water vapor and very small amounts of nitric oxide when it is combusted.

Unfortunately, there are several drawbacks which have limited the widespread shift to a "hydrogen energy economy". The most serious disadvantages include:

1. Hydrogen is more expensive to produce than the conventional hydrocarbon fuels in extensive use today.

2. The safest method of storing hydrogen is in the metal hydride form. Though safe, this form of hydrogen storage is very heavy, and therefore has limited the range of hydrogen automobiles to 250 kilometers (150 miles).

3. The existing gasoline infrastructure is not compatible with gaseous hydrogen distribution. In order to begin the implementation of this new fuel, it would be necessary to build an entirely new distribution system.

Recent advances in solid polymer fuel cells, have made possible the application of this technology to vehicle transportation systems. Since fuel cells are two to three times as efficient as the internal combustion engine, and since fuel cells can be operated in reverse as an electrolyzer, their application in an automobile largely overcomes each of the major impediments to widespread application of hydrogen vehicles.

1. Although hydrogen is more expensive to produce than the conventional fossil fuels, the higher utilization efficiency of the fuel cell more than compensates for this difference making the cost of operating a vehicle on hydrogen less than operating on gasoline.
2. Since hydrogen is utilized two to three times as efficiently in the fuel cell as in an internal combustion engine, vehicle range is extended to 500 kilometers (300 miles) or more without increasing the weight of the hydride storage vessel or the quantity of the hydrogen stored.

3. By operating the fuel cell in reverse as an electrolyzer, it is possible to produce hydrogen for storage in the metal hydride vessel by connecting the vehicle to a source of electric power and water. Since both are readily available, the problem of an incompatible infrastructure is overcome.

For these reasons, hydrogen fuel cells are the “key” to the commercial implementation of hydrogen as a vehicular fuel.

LaserCel1 Prototype

The U.S. Postal Service donated a Ford Fiesta which had been retrofitted for operation as an electric vehicle by JET Industries, and had been used for five years to deliver the mail in El Paso, Texas. Upon receipt, the vehicle was in poor condition, and, after three years of storage, was nonoperational.

In postal service, the vehicle was heated with a gasoline-fueled furnace. As the first step in preparing the prototype for the fuel cell conversion, the gasoline heater, and fuel tank were removed. Also, the special equipment installed on the vehicle for mail delivery, such as a large hood-mounted mirror and a mail shelf, were removed from the vehicle. New seats were installed but no effort to switch the steering column to the left side was attempted.

Modifications to the vehicle body styling were conceived and implemented by Design Factory of Kansas City. Included in the design changes were the installation of European-style headlights, sport mirrors, high performance tires, and body skirting on all four sides to lower the vehicle profile.

The electrical system of the car was redesigned to incorporate a new controller and various monitoring and regulating equipment were installed for added safety.

The hydrogen system consisted of a metal hydride storage vessel mounted in the rear of the vehicle, a heat exchanger, gas compressor, control system, and the hydrogen fuel cell. A schematic diagram of the hydrogen system is presented as Figure 1.

Hydrogen Fuel Cell

The fuel cell is located in the forward “engine compartment”. It is based on a cell geometry developed at the American Academy of Science, referred to as the LaserCel. This name is applied to the geometry because of the utilization of a high-powered YAG laser in the fabrication of the anodes and cathodes used in the cell.
The cell utilizes a solid polymer electrolyte produced by the Asahi Chemical Company of Japan. In operation, hydrogen is applied to the anode side of the cell at a pressure of approximately two atmospheres (absolute). The hydrogen molecule is broken down on the surface of a noble metal catalyst (platinum) forming hydrogen ions or protons and releasing electrons to the anode. A proprietary method of catalyst application provides satisfactory results with loading densities of less than 1.0 milligrams per square centimeter. The hydrogen ions are transported through the membrane to the cathode side where they react with oxygen to form water. See Figure 2. The reactions involved in the fuel cell are as follows:

- **Anode Reaction**: \( H_2 \rightarrow 2H^+ + 2e^- \)
- **Cathode Reaction**: \( 2H^+ + 2e^- + 1/2 O_2 \rightarrow H_2O \)
- **Overall Reaction**: \( H_2 + 1/2 O_2 \rightarrow H_2O \)
FIGURE 2. SPE FUEL CELL

Anode (−)

Cathode (+)

Hydrogen

Oxygen

Hydrogen Exhaust

Exhaust

Solid Polymer Electrolyte

FIGURE 3. SPE FUEL CELL POWER CURVE

Voltage (Volts)

Current (Amps/cm²)
In order for the electrons to travel from the anode to the cathode side of the cell, they must flow through an external load. In the case of the fuel cell vehicle, they pass through the electric motor providing the source of propulsion power.

In the LaserCel prototype, the fuel cell consists of two stacks of cells inside of a single enclosure. The small stack consists of 16 cells, and produces 12 volts to power the vehicle's accessories. The large stack, consisting of 135 cells, outputs 100 volts to power the drive motor. It is not necessary to balance the output of the two stacks because they are electrically isolated.

The cell operates at a current density of about 0.5 amps per square centimeter at 0.75 volts per cell. The cell voltage as a function of load is presented in Figure 3. The dimensions and mass of the LaserCel fuel cell shown in Figure 4 are:

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measurement</th>
</tr>
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<tbody>
<tr>
<td>Height</td>
<td>0.23 meters</td>
</tr>
<tr>
<td>Length</td>
<td>0.25 meters</td>
</tr>
<tr>
<td>Width</td>
<td>0.16 meters</td>
</tr>
<tr>
<td>Mass</td>
<td>34.0 kilograms</td>
</tr>
</tbody>
</table>

In order to achieve adequate cell performance, reaction kinetics dictate that hydrogen flow through the cell must be 0.5 times greater than actual cell consumption. Surplus hydrogen is captured upon exiting the cell and is recirculated. Oxygen is supplied to the cell at a rate of 2.5 stoichiometry, and at a pressure of 1.15 atmospheres (absolute).
The hydrogen gas pumping needed for recirculation and the air compression required for the fuel cell are provided by the proprietary gas compressor shown in Figure 4. The compressor utilizes hydrogen pressure from the metal hydride storage vessel to activate a gas piston. The piston actuates a diaphragm air compressor and circulates hydrogen through the cell. The design of the gas compressor is depicted in Figure 5 and Figure 6 shows the system gas recirculation. The gas compressor is controlled electronically, as detailed in Figure 7, by a time delay circuit and a gas pressure switch. As hydrogen is consumed by the fuel cell, gas pressure drops. The drop in pressure is detected by the switch which initiates a new cycle. In this way, the gas compressor automatically is load following.

Cooling System

The fuel cell has heat plates interspersed every three cells to provide temperature control for the system. The heat plates are cooled by water which is circulated to the system heat exchanger. The heated water is utilized to provide the hydrogen gas humidification required by the cell through a technique which is proprietary and therefore not disclosed in this discussion.
FIGURE 6. GAS RECIRCULATION SYSTEM

Compressor

Metal Hydride Vessel

LaserCel Fuel Cell

Air

Hydrogen

Pressure Switch

3-Way Solenoid

Hydrogen

FIGURE 7. COMPRESSOR CONTROL SCHEMATIC

Pressure Switch

Time Delay Control

Trigger

Time Delay Relay

Fuse

Relay

Fuse

3-Way Solenoid

+12
In the system heat exchanger, heat from the heat plates as well as from the cell exhaust gases is transferred into an ethylene glycol water solution which is used to heat the vehicle and to supply heat of dissociation for the metal hydride storage vessel. The heat exchanger is equipped with eight thermoelectric heat pumps which are automatically energized should the fuel cell overheat. In actual operation, these heat pumps have not been required to date. The heat exchanger design is outlined in Figure 8.

Metal Hydride Storage Vessel

The hydrogen for the vehicle is stored in a metal hydride storage vessel located near the rear of the automobile. See Figure 9. This hydride vessel stores 2.3 kilograms of hydrogen and has a total mass of 136 kilograms. With this quantity of hydrogen, the vehicle has a range of 300 kilometers. (By modernizing the electrical propulsion system of the car, it is estimated that the range could be extended to 400 kilometers.)

The hydride alloy utilized is Fe$_{44}$Ti$_{51}$Mn$_5$. This alloy was selected for its ease of activation, and tendency to inhibit decrepitation. The alloy has a useable weight percent of 1.9 and operates at temperatures ranging from approximately 10$^\circ$ to 90$^\circ$ C.
A recharge "quick" connect is installed on the left side of the vehicle. To recharge the hydride, hydrogen is supplied at a pressure of 17 to 20 atmospheres. Heat must be removed from the hydride bed to achieve a quick recharge. This is accomplished by connecting an external heat exchanger to the vehicle through the twin "quick" connects installed on the rear of the vehicle to the right of the hydride storage vessel. The external heat exchanger consists of a finned tubing coil through which cooling fluid is pumped as air is forced over the fins to dissipate the heat. The design of the external heat exchanger is shown in Figure 10.

Accelerator Battery

To minimize the fuel cell capacity required for the prototype, an accelerator battery was installed in the vehicle. The accelerator battery is utilized to provide part of the power during periods of high acceleration, and then is recharged during cruise. The vehicle accelerator battery is lead-acid, and has a total capacity of 25 horsepower-hours. The 13, 6-volt batteries were provided for the project by the Exide Corporation.

A safety analysis of the prototype design and construction was performed by Air Products of Allentown, Pennsylvania. The Pennsylvania State Energy Office provided part of the funding
for the construction of the prototype. The LaserCel1 prototype will undergo extensive testing during the next 18 months.

**LaserCel Implementation**

The advantages of the LaserCel become more evident when combined with the improved technology electric vehicles which will soon be in production. The innovative GM Impact is a remarkable electric vehicle into which the hydrogen fuel cell could easily be implemented. This state-of-the-art automobile offers an acceleration rate of 0 to 60 mph in eight seconds and a projected top speed of 110 mph. The current design, however, employs 870 pounds of lead-acid batteries, and offers a 120-mile cruising range. Thus, one could travel from the research laboratories of the American Academy of Science located in Independence, Missouri to Junction City, Kansas where the vehicle would require recharging. If, alternatively, these 870 pounds of batteries in the Impact were replaced by a hydrogen fuel cell system and metal hydride storage vessel of equivalent weight, vehicle range could be extended 8.6 times that of the current design, giving the driver the ability to travel from Independence, Missouri to Washington D.C. before requiring refueling. This comparison can be seen in Figure 11.

Implementation of the hydrogen fuel cell into the GM Impact would also significantly reduce the cost of operating this vehicle. In the conventional Impact, the operating cost is estimated to be 2¢/mile for electricity and 5¢/mile for battery depreciation, for a total cost of 7¢/mile. In the
case of the hydrogen fuel cell, however, the electricity cost would be increased to 4¢/mile, but
the amount for battery depreciation would be eliminated; thereby cutting the cost per mile
almost in half. Alternatively, the hydrogen could be produced by natural gas reformation, which
would reduce the total operating cost to less than 2¢/mile.

Conclusions

With the advent of the Laser:Cell automobile, each of the major disadvantages of the
"hydrogen energy economy" have been overcome. Natural gas reformation is one of the
interesting alternatives available to provide some of the fuel required by the hydrogen fuel cell
vehicle. If 1 GJ of natural gas were processed through such a reformation, sufficient hydrogen
would be produced to give a hydrogen fuel cell vehicle a 340-mile range. On the other hand,
if an equivalent amount of natural gas were compressed or liquefied, placed in tanks, and
burned in an internal combustion engine, such a CNG-LNG vehicle would travel only 130 miles
as shown in Figure 12. In other words, a hydrogen-electric vehicle would consume only one-
third the fuel required by a CNG-LNG vehicle travelling the same distance.

Besides better resource utilization, the hydrogen fuel cell vehicle offers a significant reduction
in emitted CO₂. The CO₂ given off by a CNG-LNG vehicle directly to the atmosphere is
approximately 450 grams per mile. On the other hand, the hydrogen fuel cell vehicle produces
zero emission on the road. The 170 g CO₂ per mile that is produced at the reformation plant
is almost one-third that emitted from a CNG-LNG vehicle. Thus, by implementing the CNG-Hydrogen option, our limited natural resources can better be utilized and emission of environmental pollutants notably diminished.

The hydrogen fuel cell prototype vehicle demonstrates that an SPE-type fuel cell is technically capable of powering a standard automobile. Before such systems become a commercial reality, several design improvements should be incorporated into the design. An intelligent power controller should be developed to manage charging and discharging of the accelerator battery. This would greatly reduce the accelerator battery capacity required by the vehicle. A reduction in vehicle operating cost could also be realized if reliable operation could be achieved at a current density of 2 amps per square centimeter.

In general, the boost to the advantages of hydrogen energy resulting from the application of a fuel cell to a vehicular system are exciting and warrant considerable attention.
INTRODUCTION

The Solectria Force has been designed as the most efficient producible practical electric vehicle and is now commercially available. The Force is based on the Geo Metro, the most efficient gasoline driven, crash certified US car today. We have taken out more than most conversions so we can achieve greater efficiency throughout the system. The motor, controller, transmission, etc. have been carefully set up to achieve by far the best efficiency of any commercially available EV!

However, if the designer is allowed to start from the ground up, there is greater freedom for efficient design and there are much less limitations. .......... The Flash has been designed with efficiency in mind for every single component; however, practical consumer use and safety have helped to guide many of the decisions.

FRAME, BODY DESIGN, AERODYNAMICS CONSTRUCTION AND ASSEMBLY

A lightweight but strong and safe frame and body are needed for the success of a ground up car. There is no metal frame in the Flash. The frame, is really one with the body - a classic monocoque design. A main structural beam box runs down the center of the car and keeps the batteries in the safest possible place, in the center of the car. This box extends from the front to the rear of the car to give a crushable, structure reaching in front of and behind the passenger compartment for front and rear end collisions. The rest of the structure is then built out to and all around the body making the body a key structural component for side impacts and roll-over protection. The design of these structural body components are as simple as possible to facilitate producibility. The simple aerodynamic shape is designed with minimal protrusions and an all convex shape.

The end result of the simple aerodynamic body design, is low drag and minimal power consumption.

FLASH SPEED VS POWER GRAPH: (next page)
THREE WHEELED VS. FOUR WHEELED

Although the three wheeled design of a vehicle has never received popular acceptance in adults (perhaps children can relate to it more), it will always offer the opportunity for somewhat superior efficiency while providing adequate handling and plenty of safety. The Flash is a new approach that could capture appeal from a considerable percentage of people. The Lightspeed was a four wheel design, and surely as a sports performance Electric car it needs four wheels for more than just style. Flash being a prototype designed for efficiency uses 30% less power, 10% of which is attributed to the 3 versus 4 wheels.

The drive system is the most simple part of the car. A Solectria brushless motor is linked to the wheel by a single chain. The 35lb motor is driven by the 12 lb. Solectria brushless controller. (a 47 lb drive system)
DRIVE SYSTEM

Motor Efficiency at 60mph: 93%
Controller Efficiency @ 60 mph: 98%

Because the motor and controller are so efficient and because so little power is required to move the Flash, very little cooling is required, in fact no active cooling is needed and no directed passive cooling. The motor & controller together, emitting about 300W of heat at 50 mph are kept cool simply because they are in still air just inside the rear wheel well.

OVERALL VEHICLE EFFICIENCY

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
</tr>
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<tbody>
<tr>
<td>Total Drag at 60 mph</td>
<td>3600W</td>
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<tr>
<td>Aerodynamic</td>
<td>1650W</td>
</tr>
<tr>
<td>Rolling Resistance</td>
<td>1460W</td>
</tr>
<tr>
<td>Drive Train</td>
<td>180W</td>
</tr>
<tr>
<td>Motor &amp; Controller</td>
<td>310W</td>
</tr>
</tbody>
</table>

INTERIOR
A very simple but comfortable interior makes the car more enjoyable but is designed to add minimal weight. The seats are 6 lbs each and are made of carbon graphite for strength.

ACCESSORIES

Accessories: All the accessories have been designed to use as little power as possible. Night time driving, with the headlights on, uses just 78W extra power thereby decreasing the range by
Lightweight accessories are used to ensure that extra weight is kept to a minimum. Do not forget that you will have 1% range reduction if the radio is turned up high. (In a heavier car, a radio does not have a perceived affect on range since the vehicle uses much more power than the radio).

INTERIOR, CONTROLS AND DISPLAYS

The Flash controls and instrumentation are as simple as possible. One central accessory control panel runs lights, blinkers, hazard lights, fan etc. The amp-hour counter is the only battery and system meter to monitor the battery level. A speedometer-odometer bike unit is used to keep this essential tool lightweight. The accelerator pedal controls the motor in drive and regenerative braking modes while the brake pedal is used only for the hydraulic disc brakes.

SOLAR ARRAY AND CHARGING SYSTEM

The solar charging system on the Flash provides 250W through a maximum power point tracker which optimizes the solar cells' output. This provides enough energy for 4-5 miles of driving for every hour that the car sits in good sun. The body is curved in only one direction to facilitate solar panel application. It is designed to minimize the change in angle that the solar array goes through from front to back of the car.

CONCLUSION

Although we are not currently planning any production of this car, we are hoping for project funding to build a production prototype which will make the car a professional, producible and practical commuting vehicle. The concept of two people cruising at 60 mph, using less energy per mile than a 60W light bulb uses in an hour is spectacular. The benefits of such a vehicle which can drive the average American commute right off solar power and without being plugged in is truly what America needs to solve its pollution problem and heavy foreign oil dependence.
DESIGN FOR THE ULTIMATE VIKING CAR 1972–1991

Michael R. Seal
Director, Vehicle Research Institute
Western Washington University

INTRODUCTION

Since 1972 more than twenty vehicles have been designed and built by undergraduate students and faculty at the Vehicle Research Institute at Western Washington University in Bellingham, Washington. Thirteen of these vehicles have been quite distinctive in design from each other and were built to meet specific criteria, for example, to meet rules of a competition or fulfill the goals of a grant. I believe that innovative vehicle design starts with a specific goal or need to meet a design criteria. A free-wheeling brainstorming session is used to look at as many possibilities as can be dreamed up, regardless of whether that idea has ever been used before or how outlandish. Each idea must be examined to see how closely it meets the goals. Only after the very best solution has been found do you begin to eliminate, change or make compromises to utilized the resources available. Things such as time, budget, material availability, etc. now begin to influence the final design.

EARLY VEHICLES BUILT AT THE VRI

![Figure 1](image)

VIKING I - A car for the 1972 urban environment
The first car designed and built at the Vehicle Research Institute was Viking I. (As most of the early settlers in this northwest area were of Scandinavian descent the various sports teams at Western Washington University are called Vikings). This vehicle was designed to win the Urban Vehicle Design Competition held at G.M. Proving Grounds in Milford, Michigan. Major design considerations were centered around low speed maneuverability and parkability. After considering rear steer which we rejected because it does not help at all in parallel parking, we finally arrived at what we called "extreme Ackerman steering".

![Extreme Ackerman Steering](image)

Figure 2
Extreme Ackerman Steering

This system makes use of an extra steering link so that correct Ackerman steering angles can be maintained to extreme steering lock. The inside front wheel can be turned perpendicular to the centerline of the vehicle. The inside rear wheel remains stationary while the differential allows the outside wheel to drive through the differential. Another important consideration for this contest was exhaust emissions. A Toyota engine was converted to run on propane. At that time the VRI had no emission test equipment and it was not possible to do much development in this area and the car did not win in this category. Viking I did win the maneuverability and parkability awards and finished 3rd overall in the competition behind the University of British Columbia and the University of Florida.
Thus the die was cast and the next vehicle, Viking II used a similar propane system for the 1975 Student Engineered Economy Design Rally which ran from Bellingham, Washington to Los Angeles, California. By this time the VRI had acquired an early Non-Dispersive Infra Red (NDIR) unit to measure HC and CO and an Chemiluminescent Monitor to measure NOx and a chassis dynamometer to run simulations of the "LA-4" emission test cycle. The Viking II was our first essay into aerodynamic design for automobiles. A series of 1/10 scale wind tunnel models were built based on the early work by Leon Jaray, Wunnibald Kamm and Zagato. The design chosen had low frontal area with a well rounded front and tapered back to a minimum area on the rear. The $C_d$ was .34 which was considered very good for the time, especially as most automotive designers were of the opinion that drag aero below 200 MPH was insignificant with regard to fuel economy. Viking II won the SEED rally against opposition from schools in the U.S.A, Canada and Japan with a fuel economy of 58 MPG on LPG and established the lowest exhaust emissions measured in the contest, even ahead of a Japanese entry powered by hydrogen.

Viking III was a conversion to propane on a Datsun B-210 fastback with add on aerodynamic modifications. This has been the only non scratch-built car to receive a Viking number.

Viking IV is an aluminum monocoque streamlined coupe originally built to win its class at the Bonneville National Speed Trials with an 1146 cc Wankel rotary engine. At one point
this car was fitted with a 500 cc Wankel and achieved 55 MPG. Later it was fitted with a 1500 cc turbocharged diesel engine. In this guise it entered the Sea to Sea Econorally winning awards for lowest emissions and best economy as well as 1st overall. One of the unique features of this car was a special 5 speed transaxle with overdrive on both 4th and 5th and freewheel on fifth gear. We began our investigation of low rolling drag radial tires with this car which is now fitted with a 998 cc 3 cylinder turbo diesel. This car can achieve highway fuel economy of more than 100 MPG at 50 MPH in cross county rallies.

Viking V is a lightweight version of Viking IV using a fiberglass aerodynamic shell in place of the aluminum one on Viking IV. This car had been fitted with a variety of engines and drive trains in the last few years including:

1. Subaru diesel engine built at the VRI
2. Isuzu 2 cylinder 800 cc diesel
3. Honda/50 cc single and a 2 cyl/4 cyl Subaru. (In this form the car could run with five different displacements)
4. Turbocharged, intercooled natural gas 4 cylinder Subaru which set a record at Bonneville Salt Flats for methane fuel.
5. V6 2400 cc Mercury outboard power head mounted up to a Subaru 5 speed transaxle.

Viking V remained in the shadow of Viking IV always finishing second to Viking IV in the cross country economy runs.
Viking VI was developed under a contract with NHTSA to show that a fuel efficient, low emission vehicle could meet or exceed federal crash-worthiness standards. Two of these vehicles were built. The first unit was fitted with anthropomorphic dummies and crashed at 43 MPH into a concrete barrier. The dummies survived with HIC numbers of 552 and 286 with no injuries. The second Viking VI was further developed into a show car to demonstrate fuel economy and compliance with exhaust emission standards. At present the car can achieve 118 MPG at 50 MPH. The exhaust emissions are: CO - .89, HC - .09, NOx - .86 when running on unleaded gasoline. The primary emission control on this car is a 3 way catalyst system. Viking VI won the Three Flags Econorally (Canada to Mexico) and was 2nd in the Three Flags Econorally (Mexico to Canada) behind an independent VRI graduate student built car, the AVION.
Viking VII is a high performance sports car built to determine if high fuel economy and clean exhaust could be maintained while offering "Supercar" levels of performance. Although fuel economy on the highway is only 50 MPG and less on the L.A. 4 cycle the car accelerates to 60 MPH in 5.3 seconds and can generate over 1 G in cornering power. The car has won the A-Modified class in local autocross competition two years running.
Viking VIII was an effort to capitalize on the success of Viking VII and introduce a limited production sports car to be built in Costa Rica and sold in the USA. Although the car would look like the successful Viking VII it would incorporate an American built engine transaxle assembly from Chrysler and use an all composite monocoque body-chassis unit. A single experimental prototype was built along with plastic tooling suitable for an initial production run. Unfortunately the client ran into financial difficulties and the initial production run never materialized.

![Composite Chassis - Viking VIII](image)

Viking IX was a prototype for an autocross type competition. A vehicle that students could build for themselves at low cost. Each student in the summer session of 1989 paid a $1,600 lab fee and purchased a 1970-1980 vintage rotary engine (RX3, RX4, or RX7) car to serve as a donor car for the engine transmission rear axle for their Viking car. Viking numbers 10-19 were assigned to the autocrossers built that summer. Although these cars are socially irresponsible, we all learned a good deal about efficient limited production as the cars were constructed on student built tooling in nine weeks.
THE SOLAR ELECTRIC ERA BEGINS AT THE VRI

With announcement of the GM Sunrayce USA, the VRI entered a new phase, the search for the ultimate solar powered race car that would be capable of winning not only the GM Sunrayce but could also be a viable competitor in the World Solar Challenge in Australia 1990. This was to be the most complex and challenging project that the VRI had attempted to date. Over half a million dollars and gifts-in-kind were raised and a team of over 50 people worked on various parts of the design and construction. A team of 32 went to the GM Sunrayce and 18 to Australia.

How do you begin a project of this magnitude? You break it up into small manageable pieces. It was obvious to the Viking XX Solar Car Team that no matter how good your design was, if you didn't have funds to buy the state of the art components and materials to execute the design you would not win in either competition. A major fund raising campaign would be critical to the success of the project.
Solar technology was a completely new field to both the students and faculty at the VRI. It seemed a good idea to build a simple solar powered car quickly to gain experience and credibility with potential sponsors. The students selected one of the previously built super mileage marathon cars as a basis for the new car. They removed the 46 cc internal combustion engine and transmission system and replaced it with an electric motor from an automobile cooling system fan, driving a rear wheel with a direct friction drive to the tire. A simple flat solar panel 4' by 12' was mounted above the aerodynamic body shell to provide power. No battery was fitted to the system. The vehicle would achieve 15 MPH on the level in bright sunlight. Our visual communications group prepared a video of this car and previously successful Viking cars to use in our fund raising effort. Fund raising was now underway and the search for a winning design could begin.

**DESIGNING AND BUILDING A UNIQUE AND WINNING SOLAR CAR**

We had discovered during the history of university competitions that a reliable machine would be of the utmost importance. To this end we resolved to build only components that we understood thoroughly and buy components beyond our capability. (The Department of Technology over the past 20 years has made a gradual shift from teacher education to Industrial Technology and Engineering Technology. It is not an engineering school and lacks...
expertise in the construction of electronics and of motor control systems used on solar cars.) We realized that thorough testing would be necessary for all components whether built or bought, and the time line must reflect this need for thorough testing of components and complete systems. Once a preliminary time line has been established, intermediate milestones must be established. If these dates are not perceived to be real they will not be met and the project is likely to fail. Devices such as tying the first trial of the complete car to a major irrevocable media event will usually work. An earlier competition with one or two nearby competitors months in advance of the major competition definitely helps ensure that the time line is followed. As the time line slips, new time lines that reflect actual progress must be substituted and posted or despondency will set in and progress stops.

The actual design of the solar car should assign priorities to the various design considerations. For world solar challenge type competition the prime design consideration must be solar power input. The total power input is very small so it is important to get as much of it as possible. Quite often solar cars are designed as if every day of the contest will have ideal solar conditions. This is extremely unlikely! A design that is optimum at full sun may prove to be inferior at .7 sun. The second most important consideration is aerodynamic drag if speeds are above 30 MPH. Low vehicle weight is the third most important. Many competitors seem to have their priorities mixed up and have built extremely fine vehicles for some other power source than photovoltaic. Although it is very important for most road going vehicles to have good road-holding characteristics, a solar racing car can assign a relatively low priority to them.

Figure 12
Viking XX - A Solar Racer Designed to Maximumize Solar Power
Given the previous priority of design consideration our entire solar car team participated in a brainstorming session with regard to overall vehicle design. All ideas no matter how outlandish were recorded without comment during the 1st brainstorming session. In the 2nd session we analyzed the different designs to see which one had the most positive features and the fewest negative ones. We chose the configuration which eventually evolved into the Viking XX design, which was a two person vehicle, driveable in either direction, with fore and aft symmetry instead of side to side. It certainly satisfied the first criteria. It would be difficult to imagine any way of providing a greater solar strike area within the 2 meter wide by 6 meter long by 1.6 meter high design limits. There were obvious difficulties. As the car must drive in either direction the controls must be duplicated, although the removable steering wheel can easily be transferred to the other end. The 50% increase in solar strike area which was allowed in the rules for a two person vehicle must be paid for by the additional weight of a passenger and the attendant structure to hold the passenger. The frontal area due to the passenger would not increase at all however, in the Viking XX design. The aerodynamic compromise due to the requirement that the vehicle travel in both directions was investigated. Preliminary analysis suggested that weight increase would be less than 50% over previous best single seaters. We built a 1/10 scale model of the GM Sunraycer and 1/10 scale model of Viking XX to test in our wind tunnel.

![Wind Tunnel Model - Viking XX](image)

Although the Sunraycer has a superior Cd its frontal area is substantially greater than Viking XX. In fact the overall drag aero of Viking XX is only 8% higher than the Sunraycer. Further analysis showed that if Viking XX were equipped with 13.25% efficient terrestrial grade solar cells the performance would be slightly better above 30 MPH and should somewhat worse below 30 MPH than the Sunraycer. As we had no hope of obtaining satellite grade solar cells at this time we determined to build our car to this design.
as it was the only one that looked to be competitive with Sunraycer using lower grade solar cells. Most schools elected to take a lower risk approach by trying to make small beneficial modifications to the Sunraycer design and build near copies of the most successful solar car in the world up to that time. We felt there was an additional reason for taking the two passenger approach. We know there would be a separate class for two seat cars in the World Solar Challenge and we might while be able to win that class. We did!

An additional problem with our design centered around cross wind stability and increase in drag during cross winds. Initially the car was designed with four wheels and the two occupants sat back to back in the driver pod. Late in the design process the organizers of the GM contest decided to add a requirement that the driver be able see upwards at 10°. Our configuration did not allow this.

The occupants had to be moved toward the ends of the driver pod past where the wheels were to go. The only remaining place for wheels was between the two occupants. We considered two partially overlapping wheels in this space but finally opted for a single overloaded tire between the two occupants. This change allowed a 26" wheel which gave slightly less rolling drag and slightly better load carrying ability.

As steering system was devised in which the two wheels on the battery pod side, counter-steer and the remaining wheel between the occupants became the drive wheel. Early tests showed that spoke wheels and standard bicycle forks wouldn't be stiff enough, so we made
carbon fiber wheels and larger tube forks and double wishbone suspension systems. Performance was good enough to continue with development.

We considered structure between the two hulls of the vehicle but wind tunnel tests on a model suggested unacceptable aerodynamic losses. The structure selected was a carbon fiber composite shell and wing structure. Steering was initially by rod and lever linkage system. This was replaced by a cable and bobbin system that proved lighter and more direct. As the car had to go in both directions we could not depend on castor action to give self centering to the steering. We developed a spring loaded self centering cam at each steering wheel to assist straight running. The braking system used was a composite of two different systems. The drive wheel was fitted with a small disc brake and motorcycle caliper plumbed up to a centrally mounted master cylinder. The other two steering wheels have hydraulic bicycle brake calipers plumbed into two more master cylinders mounted on a plate with the motorcycle master cylinder. The three units are mechanically linked together and to actuating levers in both cockpits. The levers are like hand brakes but are pushed not pulled so that driver weight gives a self servo action. In addition, the drive motor controller is set up to provide regenerative braking in a proportional fashion whenever the left pedal is pushed in each cockpit. The right pedal controls a potentiometer that signals the motor control box so the pulse width modulator responds to provide control over motor speed and load. A silver zinc battery in the maximum allowable Watt hour size (5KW hours) was chosen as it appeared likely that in good sunshine the full capacity could be regained during allowable evening and morning charging time. This power could then be expended during the day climbing hills, outrunning bad weather or simply driving faster than input sun would allow. The relatively modest weight (118 lbs) made this a viable option particularly as ballast was needed on that side of the car to avoid overturning. Light drivers and passengers were recruited as their ballast weight could be carried behind the front wheel where it was most needed to provide side wind stability. In the interest of providing maximum reliability, we managed to drive the car 850 test miles before the Sunrayce USA. During testing a number of components failed. We were able to design more reliable components or find supplies of better units which improved reliability of the whole system. We determined that we would make or buy a spare part for every component in the car except the main monocoque structure.

These parts were stored in our follow truck complete with the tools necessary for replacing each part. We spent quite a bit of time practicing part replacement until we felt confident that we could carry out any repair in minimum time. A number of design changes were incorporated to facilitate rapid repair. We carried a complete workshop in the Sunrayce and the World Solar Challenge including a lathe/mill, TIG welder, drill press, and extensive supply of hand tools. It became evident that a supercargo was necessary as someone had to know where everything was when needed or there was no point in carrying it halfway round the world anyway. As we live in a wet part of the world it seemed necessary to weatherproof everything which turned out to be a substantial advantage as many teams found out during the contest. It always seems to rain during a solar car race.
We paid particular attention to airflow inside the car. The electric motor sometimes requires considerable cooling. Both inlet and outlet must be provided. A NACA duct is often a suitable means for inducing air into the vehicle. An exit duct that brings the warm air up to free stream velocity before ejecting it can actually provide thrust instead of drag. Although turbulent flow is needed at the cooling site, non-stalled flow is greatly to be preferred both before and after the heat transmission zone. Our design tended to keep the occupants cooler than most designs because they were both always in the shadow of the panel. An inlet and an outlet port is provided for each cabin and each cabin is provided with a biscuit fan controlled by a push button so that an occupant could move air through whenever it became unendurable. These system ensures that a minimum of electrical power is used cooling the occupants. Air flow entered the ballast boxes through NACA ducts set in the removable doors. When the car direction is reversed the doors are replaced the other way around. The air in the battery ballast and battery boxes rises by convection through the wing to cool the underside of the cells before escaping through holes in the upper wing edge. Silicon solar cells lose their efficiency as the temperature rises.

After the first race in which we were second overall to the University of Michigan "Sunrunner" We received GM sponsorship for the World Solar Challenge. GM paid all expenses for 8 of the 18 person team, shipped both our solar car and the 40' container containing the workshop as well as providing us with enough satellite grade cells to make a new array. This array was 15% more efficient than the previous array and produced 1.8 KW making it the most powerful solar car array in the world.

We began preparation for the World Solar Challenge running from Darwin on the north coast of Australia across the outback to Adelaide on the south coast. As we had experienced some side wind difficulties across Ohio in the Sunrayce we determined to improve side wind stability. We discovered through testing, that the addition of a fin at the rear between the solar wing and bubble at the end of the cockpit, moved the lateral center of pressure aft. Removing the front side window on the battery pod side allowed cross winds to escape from the front further improving cross wind stability. Another modification for the Australian race was to alter the steering of all three wheels so that the car could yaw towards the apparent wind which dramatically reduced drag and improved stability. Conditions during the Australian race turned out to have extremely severe side winds. In fact one of our competitors, the Danish car, was picked up by a "Willi Willi" and carried 50 meters off the road and destroyed. Although the drivers of Viking XX sometimes had to exercise intense concentration, they were able to keep the car on the road even during the most severe conditions. Incidentally the wind blast from the "road trains" never gave Viking XX any problem but another competitor was blown over seven times yet finished the race. However, cross winds did cause the tires on Viking XX to wear out at a greater rate than expected and tire changes were being made nearly every hour in order to insure that blowouts would not occur.
As many changes were needed to be made to the Viking XX each time it was turned around the team practiced the procedures over several weeks prior to the race. During the race the full team could complete the turn-a-round in less than two minutes.

The Viking XX was 5th in the World Solar Challenge behind the Swiss Car, Honda of Japan, University of Michigan, and Hoxan of Japan which were all single person cars. Viking XX was first of the two person cars.

![Viking XX With Aerodynamic Aids](image)

Figure 15
Viking XX With Aerodynamic Aids

For the California Clean Air Race held in June 1991 from Sacramento to LA we made some further modifications. Because of the nature of this race there would be more likelihood of good sunshine and with a relatively short driving range each day and ample charging time, therefore, we could expect the speeds to be higher. In addition the race route went through Pacheco Pass where there is a wind mill farm. In a further attempt to improve cross wind stability we decided to carry more ballast than was required to compensate for light drivers and thus reduce the steering effect at the rear wheel, and increase the front wheel steer. Due to the nature of the course direction we could reverse direction each night while charging and make the next day's run during the morning. During the actual race everything was as expected, although we did get lost in LA on the last 40 mile leg of the course, however we were able to retrace our route and finish a cumulative 5 hours ahead of the next finisher to win the event.
VIKING 21 - A CAR FOR THE TWENTY FIRST CENTURY

Following our success with Viking XX we decided to see if it would be possible to put the lessons learned in the previous 20 years of Viking cars into a prototype for the 21st century. Viking 21 has been designed and is now fully funded by the Washington State Ecology Department, The Boneville Power Authority and Puget Sound Power and Light Co. The construction stage of this car is now underway and it is expected to be completed over the next two years.

Figure 16
Viking 21 - A Solar/Electric CNG Hybrid

If the greenhouse effect is real and I have little reason to doubt it, then all the rules for low emission vehicles have changed. The only viable automobiles will be electric cars and the power to run them must come from non-fuel burning sources. The solar/electric car is rapidly becoming a viable alternative as an urban commuter but has little hope with the current battery and solar cell technology of being acceptable for intercity use.

Viking 21, a parallel hybrid, is the Vehicle Research Institute's solution to the consumers desire to do what they can to help the environment yet not give up the freedom to travel by personal transport over long distances. The Viking 21 does not, of course, eliminate CO₂ production but should go a long way towards reducing these emissions. It will use presently
available technology and will require a minimum of adjustment on the users part. In the urban environment it will have a 100 mile range on solar/electric power while converting to a clean, fuel efficient internal combustion powered vehicle with an additional 200 mile range on compressed natural gas.

Figure 17
Viking 21 - Component Layout

Figure 18
Viking 21 - Plan and Side View
The solar/electric hybrid will be a two seat coupe with both occupants seated side by side. The front wheels would each be powered by a 13 lb brushless D.C. motor. The rear wheels would be powered by the I.C. engine through a 5 speed gearbox and differential.

All four wheels could be driven during ice and snow to enhance traction. Solar cells will be mounted on the upper body panels and would collect solar energy to store in the fiber-nicad batteries while the car is stopped at a stop light or parked. The turbo charged, intercooled, fuel injected, natural gas engine will power the car at speeds above 50 MPH. The chassis will be of composite materials with one of the two filament wound natural gas tanks down the center backbone providing additional torsional stiffness.

A unique feature of Viking 21 will be wheels that mount two tires on a single rim much like a dual truck tire assembly. The two tires will be very different however, as the inner tire will have a hard compound rubber and round section giving a very small contact patch. The outer tire will have a wider tread patch and use very soft high grip rubber.

The wheels would normally run at negative camber so the outer tire does not quite touch the road. During cornering, normal chassis roll causes the outer wheel to become perpendicular to the road surface. The outer tire now grips the road securely allowing higher
cornering power. When the brakes are applied a micro switch sends a signal to a solenoid high pressure valve which allow high pressure from the fuel tank to pressurize a central hydraulic system. Slave cylinders mounted at the outer end of each wishbone cause all four wheels to become perpendicular to the road greatly increasing traction when stopping.

As the car is designed to demonstrate near term viability it will have automatic safety belts, full road lighting equipment, heater, defroster and radio/tape deck. It is also hoped to included air-conditioning.

Although Viking 21 doesn't have all the answers, I believe that it will demonstrate to the public and to the world's auto makers that an advanced concept car that is comfortable and easy to drive can significantly reduce CO, CO₂, HC and NO₃ emissions and as well as reduce fuel consumption to minimum levels.
The Fundamentals of Electric Vehicles, Parts I & II

Fundamentals of Electric Vehicles-Part I
A comprehensive approach to designing, understanding or building a solar electric vehicle

10:30-noon:
Session Chair, Bruce Burk, St. Johnsbury Academy, St. Johnsbury VT (802)-748-8171

The Challenge of Building Solar Cars
James Worden, President, Solectria Corporation, Arlington, MA

Photovoltaics for Electric Vehicles
Steve Strong, President, Solar Design Associates, Harvard, MA

Battery Choices and Considerations
David Reisner, Reisner Group, Inc., Bristol CT

LUNCH: 12 NOON-1:45PM EXHIBIT HALL

1:45-3:15
Session Chair: George Bradford, Champlain College

Motors, Transmissions, and Power Electronics
Gill Pratt, Research Scientist, MIT, Cambridge, MA

Instruments
Doug Fraser, Dartmouth College, Hanover NH

BREAK 3:15-3:40PM

3:40-5:10
Session Chair: Ed Clark, Worcester Polytechnic Institute, Worcester, MA

Radio Communications
Carl Pietrzak, Engineer Group Leader, Motorola Paging and Telepoint Group, Schaumburg, IL

Fundraising
Lee Weinstein, Co-advisor, MIT Solar Car Club, MIT, Cambridge MA

Car Categories, and Racing Strategy
Dr. Robert Wills, Co-director, American Tour de Sol

Fundamentals of Electric Vehicles-Part II
A comprehensive approach to designing, understanding or building a solar electric vehicle

10:30-NOON
Session Chair: Bob Larsen, Argonne National Laboratories, Argonne, IL

Conversions
Mike Brown, Electro Automotive, Sana Cruz, CA

Conversion Case History: St. Johnsbury Hilltopper
Bruce Burk, St. Johnsbury Academy, St. Johnsbury, VT

Safety Issues for Conversions
Gary Carr, Vehicle Development Group, Cambridge, MA

LUNCH: 12 NOON- 1:45PM EXHIBIT HALL

1:45-3:15
Session Chair: Michael Hackleman, Alternative Transportation News, Mariposa CA (213)-396-1527

Chassis, Steering and Suspension
Erik Vaaler, Research Scientist, MIT, Cambridge MA

Wheels, Tires and Brakes
Catherine Anderson, Mechanical Engineer, MIT, Cambridge, MA

Mechanical Design for Safety
Norman Asper, Ph.D., Professor of Mechanical Engineering, Trenton State College, Trenton, NJ

BREAK 3:15-3:30 PM

3:30-5:00 Closing Plenary: see plenary sessions
THE CHALLENGE OF BUILDING SOLAR AND ELECTRIC CARS

James D. Worden
CEO/Director of R & D
SOLECTRIA CORPORATION

Why build a solar or electric car?

After building and working with some 20 electric cars, a rush of excitement and enthusiasm runs wild every time I think about a new electric vehicle project. Is it the technological challenge, the push for helping the environment, man’s desire to create, our love of cars and speed, the new learning experiences, or the glory and exhilaration of rolling out that shiny, newly finished car and being an active part of driving into the future? It is probably a combination of all of these that brings us all together today.

My first practical solar-electric vehicle—Solectria 2, was a small, two seat vehicle designed for city commuting and charged by the sun. Although the biggest challenge was building a working vehicle, before I started, and throughout the design and construction phases of the car, I was always searching for ways to make it better — better than other electric cars at the time. In the early 1980’s, most of the books about electric cars (there was really nothing about solar cars) described huge, heavy conversions with short ranges which were not very practical. A few of them were exotic, expensive looking hand built vehicles but they were still heavy and impractical. Each of these vehicles also had a huge battery pack. I knew that the vehicle I built had to be light, aerodynamic and have a better drive train; this would make it much more efficient so that it could be charged from the sun (given the fact that solar cells are a fairly weak power source). The big question was:

How can you design a vehicle that can travel at least 50 miles, be charged from solar panels, keep up with city traffic, be visible enough on the road, have all the requirements to be legally registered on the road, and most of all, be inexpensive enough so that you could afford to build it???

The answer was:

Solectria 2— with the resources and technology that I could lay my hands on at the time and just two thousand dollars, it was completed.

Solectria 2

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Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051
Solectria 2 raced in the American Solar Cup, the first American Tour de Sol, and the Canadian Solar cup. Although it did exceptionally well (mostly by default) in these inaugural races, it would probably not be able to finish today’s solar and electric car races because of newer technology and better competition (it is now in a Boston museum.)

Just like the challenges that faced me with the Solectria 2 project, you will have to face these challenges for the first time as you build or improve your first car.

The First Challenge:

The biggest challenge and the most obvious one is building a working vehicle, with your given time frame, budget, and set of resources; and building a safe, working car with good handling, visibility, ease to drive and safety. It is very easy to get lost in the technology (and efficiency), fundraising, publicity and excitement and to forget about doing the hardest part—designing and building a successful vehicle.

Keep in mind these key issues:

- **Reliability**
  - Keep the car as simple as possible.
  - Use proven assembly techniques and proven components.

- **Budget**
  - Plan and spend money where it will help your car the most - don’t buy an expensive battery before you have an efficient, reliable drive train figured out.
  - Don’t buy expensive communication radios before you have instrumentation so the driver knows where the battery level is, what his speed is, etc.

- **Time and work force**
  - Figure out how many hour it might take to do tasks (multiply this by 3) and make sure you and your team have the hours, and can spend time on the most important items first. A breathtaking body is nice, but if you want a good car, the working frame and drive train should come first.

- **Driver visibility / comfort**
  - An ultra-aerodynamic shape is good but make sure the driver can comfortably sit and adequately see for several hour stretches.
• Safety

Most important for vehicle success is safety.
Adequate over design of all structural and safety-related components is of utmost concern for the safety of the driver, the public and the future of solar-electric car racing.

The Second Challenge:

The second challenge, once you have planned how to build your car in your given timeframe, is to plan the following: vehicle efficiency, creative design and optimum component selection. You may want to optimize the overall efficiency of your vehicle - your goal is to make the energy consumption of your vehicle as low as possible. The most important areas to look at are:

• aerodynamics,
  slick overall vehicle shape, minimal cross sectional area, reduction of protrusions and anomalies.
• weight and rolling resistance,
  lightweight chassis/ body, lightweight drive components, batteries and accessories, good suspension/steering geometries, tires and brakes.

The graph below represents how many watts of additional power is required to overcome weight added to a vehicle (@50 mph) with a low rolling resistance tires.

• drive train efficiency
  motor / controller efficiency, gear reduction
Example: Characteristics for an 8 horsepower (continuous) motor

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Efficiency (peak)</th>
<th>Weight (lbs.)</th>
<th>cooling needed</th>
<th>regen available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush, Wound Field</td>
<td>84%</td>
<td>65</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Brush Perm Magnet</td>
<td>90%</td>
<td>54</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>AC Induction</td>
<td>90%</td>
<td>39</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Brushless Perm Mag</td>
<td>93%</td>
<td>25</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

The Third Challenge:

Probably the most important part of a vehicle project after a good design, good component selection and good construction techniques is testing, testing, testing. The challenge will be to get the car running on the ground as soon as you possible can. More important than anything else is that the car works - smoothly, safely and properly. As soon as the frame or chassis is built, roll it around, test the brakes, steering, suspension etc. Then, get the drive system installed and find yourself a large open parking lot and go for a spin, checking the whole car as often as possible - for parts which may come loose, underdesigned components, poor tuning of suspension, etc.. Leave time for needed changes and redesigns.

Instrumentation: In order to optimize driving efficiency, some basic instrumentation is all that you need. A speedometer, odometer, amp-hour meter are basics. Battery current and voltage meters, and possibly motor current and temperature meters would be nice, however, you do not want things to be overly complex or too complicated for the driver. The amp-hour meter allows you to know exactly how many ampere-hours you have removed from the battery. It also allows you to test your car to find how much energy per mile it takes to travel at different speeds and vehicle adjustments. It gives you an idea of precious acceleration and hill-climbing energy.

Conclusion: Solectria Flash - a vehicle success

The Flash is Solectria's fourth ground-up developed two-seat commuter vehicle. It included, however, several firsts for Solectria - a monocoque chassis-body, a new, more powerful motor and controller, new suspension. The whole car was considerably different in many areas than any other vehicle that we have built. Using the guidelines above, the Flash was completed in May 1991, and finished first in the 1991 American Tour de Sol. Now the challenge is yours. I'll see you when the flag drops!
Photovoltaics for Electric Vehicles

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Electric vehicles hold considerable promise as a cost-effective and environmentally-acceptable alternative to gasoline-powered transportation. However, EV’s will, in the near term, still rely on the combustion of fossil fuels to produce the electricity to recharge their batteries. To reduce and eventually eliminate CO2 emissions and other air pollution from fossil fuel combustion, the long-term goal must be to increase renewable sources of electricity.

When environmental benefits, reliability, O&M and life-cycle costs are taken into consideration, employing solar photovoltaics for the direct recharging of electric vehicles is very attractive in many applications.

Photovoltaics are solid-state devices made from silicon and/or other semiconductor materials which exhibit the unique ability to convert light energy directly into electricity with no moving parts, no waste or by-products and no maintenance.

Electricity produced from photovoltaics (PV) is still more expensive than most sources of utility grid power. However, cost have come down dramatically in the past 20 years from over $2,000 per peak watt to around $5.00/Wp today. Moreover, major research, development and commercialization efforts now underway in the U.S., Europe and Japan assure the cost of photovoltaics will continue to drop (while “conventional” sources of electricity continue to escalate).

The potential for PV and electric vehicles is significant for EV designers and manufacturers as well as for the PV industry. Photovoltaics will support EV’s in three key areas: Home-base recharging, en route recharging and on-board systems for recharging and accessory use.

In the “average daily driving cycle”, people commute to work for 20-30 minutes, leave their car parked in the sun all day and then drive home 8-9 hours later. An on-board, PV-powered charging system can contribute a
good portion of the energy needed for this daily commute, especially in areas
of the country with high annual insolation.

In addition, on-board PV will provide a consistent topping-off charging
current to the battery bank, which can extend the life of lead-acid batteries.
On-board PV systems will also power ventilation fans, keeping cars cooler
when parked to reduce the size of the AC unit required.

These on-board PV arrays have, in the past, been comprised of standard,
framed PV modules mounted on the vehicle. EV manufacturers such as
Solectria, Solar Car Corporation and others have begun to incorporate
laminations of conventional, thick-crystal silicon PV cells onto the body
panels of the vehicles. This approach is aerodynamically superior and far
more elegant.

Future EV's will have their PVs integrated into the manufacture of light-
weight, high-strength composite body panels. The PV devices will conform
to the curved body surfaces employing technologies such as Texas
Instruments' novel Spheral solar cells; ultra-thin, dendritic-web silicon
ribbon from Westinghouse or perhaps high-efficiency, multi-junction thin
films of silicon or other materials.

As EV's gain in popularity, en route recharging stations will become
desirable and available. In the not-to-distant future, light-weight, space-
frame support structures will span over parking lots at office parks and
shopping centers supporting large PV arrays. The New York Power
Authority has recently announced plans to design such a PV system as an
initial demonstration.

The PV system would provide electricity to recharge EV's while their owners
shop, work or play. Users will gain direct access by credit card similar to
that now being introduced at self-service filling stations. Some locations in
Switzerland already have public recharging hook-ups for EV's. PV-
generated power not used for EV recharging will power the building complex
and/or support the utility grid.

Within the next decade, PV will also begin to find its place on the roofs of
our homes and workplaces. These PV systems will be interfaced with the
utility grid and sell surplus electricity to the power company during the day
which nicely coincides with the utility grid's summer peak. The utility grid
thus provides "storage" for solar-generated kWh and, at night and during
bad weather, you can get these kilowatt-hours back through an arrangement
known to the utilities as net metering.
Many large-scale, utility-interactive PV demonstrations have already been fielded such as the 100-kilowatt PV program involving 39 buildings in Gardner, MA which my firm did for New England Electric. Many more are now in the planning stages. In Europe, thousands of buildings are now receiving PV systems. In Germany, Italy and Switzerland, government-sponsored programs are underwriting part of the PV system cost to create a "level playing field" against heavily-subsidized "conventional" energy sources.

Japan has also consistently supported the development of renewable energy and photovoltaics. In a cooperative effort between government and private industry the Japanese Ministry of International Trade and Industry (MITI) has recently joined with the Japanese Broadcasting System (NHK) to conduct a year-long, country-wide program to accelerate technology development and increase public awareness.

Sponsors say this program is "aimed at harmony between the earth environment and scientific technology to provide for the continued development of human society". What more can we learn from these people?

Scientists, engineers and environmentalists the world around agree, the next ten years will be the decisive decade of change. As we move toward a sustainable society, the future looks very bright for EV’s and PVs.

Solar Design Associates, Inc. is a group of Architects and Engineers dedicated to the design of environmentally-responsive, sustainable buildings, and the engineering and integration of renewable energy systems.
When confronted with the task of writing a four page summary addressing the state of the art in battery technology I am reminded of the proverbial long letter that got written because there was no time to write a short note! Although the battery concept has allegedly been with us since the Parthians constructed an Fe-Cu jar cell in 227 BC (Khiut Rabboua, Iraq), a useful and rugged rechargeable battery didn’t enter the picture until the late nineteenth century with Pb-acid. The lateness of this invention was intimately related to the absence of a means to charge a battery before the advent of the electromechanical dynamo in 1880.

In 1900, two scientists by the name of Jungner and Edison independently filed patents within weeks of each other for the first alkaline rechargeable cells, Ni-Cd, Ni-Fe, and Ni-Zn. At that point the stage was set for an unbearably slow incremental increase in battery technology for another 90 years. Intense pressure from the consumer electronics marketplace appears to be a harbinger of several new high energy density rechargeable battery technologies entering the marketplace ever so gingerly, which will be discussed below.

Bear in mind, that just as it was not the worry of dwindling oil reserves, but rather an intolerable level of air pollution in the LA basin that lead to a resurgence in interest in the EV, likewise it is the environmental movement that will force the battery manufacturers to take some risk and push better technologies into the marketplace that are more environmentally benign than the old reliables, Pb-acid and Ni-Cd. The greatest barrier in the last 50 years to developing improved battery systems has been the reliability and low cost of Pb-acid.

PITFALLS

General discussions on batteries are fraught with pitfalls, because individual battery systems are exceptionally applications oriented. The novice must be careful to specify all parameters before choosing a satisfactory solution to their power needs. Different chemistries may be limited to different size cells. Must the battery be completely sealed, or is a low-maintenance cell acceptable?
Rated ampere-hour (Ah) capacities will be a function of discharge rate. A 60 Ah Pb-acid battery rated at a discharge time of 20 hours will certainly not deliver 60 Ah in 3 hours. Likewise, energy densities (ED) are a function of a variable capacity and voltage per unit weight or volume. And caveat emptor, cycle life is a strong function of both the depth of discharge (DOD) and the somewhat arbitrary assignment of a nominal cell capacity.

Let’s consider these issues in more detail after a brief background report on rechargeable batteries. Remember that a battery is simply a group of series or parallel connected cells. Then we’ll examine how the tax payer’s dollars are being spent on EV batteries, and finally make some choices for the low volume low buck user. That’s you!

The History of Rechargeable Batteries Written on the Back of a Postage Stamp

The earliest rechargeable batteries were Pb-acid cells comprised of lead foil coils (Plante, 1860), which could only be charged from primary cells. With the advent of the electromechanical dynamo, Faure and Sellon developed the forerunner to today’s technology, pasted plates comprised of a lead sheet or grid (1881). The Pb-acid cells were characterized by good cycle life. ED was not an issue since there were no competitors. When Jungner and Edison paralleled development in the nickel alkaline rechargeable batteries (1900), great progress was made towards a higher performance battery in terms of cycle life, high rate capability, and low temperature performance. Interestingly, their motivation was for traction, as is ours.

The earliest nickel electrodes were made from rectangular and tubular pocket plates filled with active material, i.e., nickel oxyhydroxide, NiOOH. The Ni-Fe battery has traditionally been called the Edison cell, and enjoyed a long history (until ca 1970) in the US for applications such as train switching. The USSR is the only present day user of Ni-Fe as a result of cost. Ni-Cd proved much cheaper. Pfleiderer developed the forerunner to the modern day sintered (see below) nickel plate in Nazi Germany, where it was deployed in Ni-Cds for military aircraft and rockets. After the war, this technology was quickly disseminated.

Other rechargeable battery chemistries included Ni-Zn, which was first developed by Drumm (1920) and used commercially in train lighting and street cars. While Jungner made Ag-Zn cells as early as 1900, Andre exploited a semipermeable separator that enabled commercial production in 1941. These exceptionally high ED cells found wide application in military and aerospace applications in the 1960’s, despite having very poor cycle life. Likewise, Ag-Cd was used for
compromise situations where longer cycle life was needed, but lower ED could be tolerated. Obviously, the presence of silver renders these batteries prohibitively expensive for consumer or other large capacity applications.

Nickel Plate Dynamics

Consideration of some details of the sintered nickel plate is insightful, and has bearing on new plate technologies. An electrode is comprised of a plaque which serves two purposes: (1) to physically contain the active material, and (2) to aid in electrical conduction. Highly toxic nickel carbonyl, Ni(CO)₄, is reduced under high temperature and pressure, to "carbonyl nickel," Ni, a fine powder. This nickel powder is then compression sintered at high temperature in a hydrogen reducing atmosphere, to form a porous plaque (like a sponge). The void volume is in excess of 95%! The pore size is on the order of microns, small enough to enable conductivity. Plate thicknesses are generally between 30 and 50 mils. These parameters are painstakingly determined empirically.

The finished plaque is then loaded with active material. Traditionally, two methods have existed, a chemical technique (Fleischer method) and an electrochemical technique. The chemical technique is more common, but lacks precision. The electrochemical is a more recent approach, but is more costly. Typical loadings result in capacities of 5.5 - 6 Ah/cu. in of plate.

Recently, a slurry or pasting technique had been developed in Japan which makes use of a high density nickel hydroxide powder. This suspension impregnation technique is being used to manually load nickel foam metal. This technique shows great promise and has demonstrated nickel cathode plate capacities in excess of 9 Ah/cu in of plate. This translates into an overall cell ED increase of approx. 20%, since the large plate capacity increase is diluted by the weight of the anode, separators, electrolyte and cell case.

Sintered nickel plates are known to show a so-called "memory effect" after highly repetitive discharge programs. This results in an apparent reduction in capacity if the repetitive discharge is significantly less than full capacity. In fact, the cell forgets its full capacity value. Reportedly, new foam pasted electrodes do not suffer from such effects.

RECHARGEABLE BATTERY PARAMETERIZATION: WHAT YOU NEED TO KNOW

For EV applications, cycle life, ED (Wh/kg) and power density (W/kg) are all important. The cycle life determines how long your car can travel before the battery needs replacement, which is intimately related to the cost. When
the cycle life is specified with the cost, it is called a "life cycle cost." A $50 battery that runs 100 cycles is more expensive than a $100 battery that runs 250 cycles, assuming all other design parameters equal (ED, PD, etc.). Occasionally, cycle life and ED have a similar tradeoff. Aerobic Power Systems is presently developing a Zn-Air battery for portable computers that has a life of only 25-30 cycles, but has an extraordinary ED of 200 Wh/kg. Compared to 30-40 Wh/kg for Ni-Cds, it is as if the effective cycle life was 5-7X longer. This is a different kind of life cycle performance factor.

ED determines how far your vehicle can run before it needs to be recharged, which is the crux of the matter! Power density determines whether or not the battery can deliver that energy (Wh) at a specified rate (W/kg). This is important for hill climbing or acceleration, and can also play a role in regenerative braking, if the battery is unable to accept charge at a fast enough rate.

The conditions of a battery’s operating environment need to be fixed before performance can be properly ascertained. The Ah capacity of a battery is meaningless if the rate of discharge is not stated, e.g. "20 Ah at a 3h rate." Likewise, the cycle life of a battery is meaningless if not stated, e.g. "1000 cycles at an 80% DOD." Batteries are most fully described by their ED at a given discharge rate over a specified cycle life, although this is generally not revealed in sales brochures.

Gravimetric ED has traditionally been specified in Wh/#, although over the last several years the trend is finally shifting to Wh/kg. Volumetric ED in Wh/l have replaced Wh/cu in. For EV applications, both are important. The battery module must fit into the vehicle and the weight is a doubly important consideration because it adds to the payload. Often gravimetric ED is inconsequential, as in small batteries (wristwatch) and very large batteries (power plant load leveling, emergency lighting) for stationary applications where the footprint is all that matters.

ED is easily determined for a real battery by assessing the weight (or volume) of the module, estimating an average operating voltage, and determining the capacity at the desired rate. Let’s consider a specific battery that might be suitable for EVs. A 7200 Wh (5h rate) ATdS energy limit would constrain battery capacity at a 5h rate to 60 Ah for a 120V system. Trojan makes a conventional deep-cycle 12V Pb-acid golf cart battery with exceptionally high ED, the 22NF. It is rated at 55Ah at a 20h rate (written C/20), and therefore lies within the allowed capacity. It has dimensions (inches) of 9 1/2 X 5 1/2 X 8 3/4, and weighs 30 pounds.
A 3-hour rate capacity of 36.5 Ah was obtained by scaling (73%) to other Trojan batteries for which 3h and 20h capacity data was available. The value of 12V is a reasonable first estimate for the true average operating voltage of the battery. The product of 36.5 Ah and 12V yields 438 Wh. Dividing this by 30# provides an answer of 14.6 Wh/# (32.1 Wh/kg) at a C/3 rate. The volume is 457 cu. in., yielding a volumetric ED of 0.96 Wh/cu in (58.5 Wh/l) at a C/3 rate. The ED is excellent, but you must assure yourself that it can satisfy your power requirements, best done empirically.

**BATTERY BASHING**

Commercial availability of large capacity rechargeable batteries in excess of several Ah is still virtually limited to Pb-acid and Ni-Cd. This market is divided into two segments: **industrial** (motive and stationary power) and **aircraft**. Until recently, in the Ni-Cd marketplace, industrial was equated with the old pocket plate technology and aircraft was equated with the more modern sintered plate technology. That is now changing with the introduction of new lightweight nickel fiber and nickel foam substrates to create high capacity nickel cathodes. Besides these two well-known systems, as we’ve heard before, there are several other chemistries near ready to enter the marketplace, especially in smaller sizes. Note that as we enter the '90's there is a great emphasis on "Green" batteries. Let’s consider some chemistries, pros and cons.

**Pb-acid:** The more things change, the more they stay the same. So we are still with Pb-acid as the best option for your solar/EV. Trojan's golf cart batteries have excellent ED and they are very cheap. Low temperature performance is poor and cycle life is not exceptional. Modern SLI batteries have excellent rate capabilities, of course, but the deep cycle characteristics are very poor. The recent trend to use thinner plates in SLI batteries relinquishes cycle life to 20-50 cycles. It is easy to test this limitation. Since deep cycle capabilities have been designed out of SLI batteries, Pb-acid cells designed for deep cycle use are easily the best bet. As the pressures of the Green Movement become greater, there will be a slow shift from Pb-acid to other higher ED systems that are more environmentally benign, for the high production volume SLI car battery.

**Pb-acid aircraft batteries:** In the absence of any Wh limitation on an EV, it may be tempting to use a Pb-acid aircraft battery. Dimensions are standardized to 10.5" X 10.5" X 10.5". Conformation to aircraft specs sends prices stratospheric. They are manufactured by Concorde (W. Covina, CA) and Teledyne Battery Prods. (Redlands, CA). These type batteries were used by the GM SunRaycer at the GM...
Desert Proving Ground in Mesa, AZ, to establish land speed records. The 48 Ah Concorde 24-382 is 24 V and weighs 90#. Note that this battery does not have an ED greater than 13 Wh/#

Pb-acid gel cells: Johnson Controls makes a gel cell in large capacities. The U1-31B delivers 31 Ah at a 3h rate and weighs 24#, which for a 12V module yields an ED of only 24.2 Wh/kg (11.0 Wh/#). GM’s Impact EV may have used a gel cell. The folks at Delco-Remy are mum on the details. The 320V battery consisted of 32 10V modules (each containing 5 cells of 43 AH capacity at a 2h rate) in a 2x2x8 configuration, each module having a dimension of 10"x3.5"x6.6" (lxwxh). The total module weight of 850# translates into an ED of 35.6 Wh/kg (16.2 Wh/#) at a 2h rate! What’s the catch? The system was only good for 100 cycles at 30% DOD. Note that GM’s approach to an EV is very different than EPRI and DOE. GM was emphasizing power and speed in an EV that would closely resemble an ICE car. DOE is focusing on fleet vehicles where the customer is willing to accept low performance in exchange for longer life.

NiCd: Ni-Cd cells offer greater cycle life than any other rechargeable battery. In fact, 100,000 cycles have been exceeded for satellite applications involving a shallow depth of discharge. Alkaline cells in general (Ni-Cd, Ni-Fe, Ni-Zn) perform far better than Pb-acid cells at low temperature. The ED of conventional Ni-Cd cells are no better than Pb-acid batteries. They are generally considerably more expensive, but life cycle costs are apt to be cheaper if cycle life is considered. Cadmium is carcinogenic, recycling may become more problematic in the future.

Ni-Cd (cylindrical, sealed): Panasonic (Matsushita) and Sanyo have phased in a spirally wound cylindrical Ni-Cd battery that uses a foam metal Ni plate, and boosts ED substantially beyond the 12-15 Wh/# traditionally associated with Ni-Cd. As of now these are only available in cylindrical cells. The Panasonic SM60 cell is 2.3 Ah (C/5) and weighs 57g for an outstanding ED of 44.4 Wh/kg (20 Wh/#). The Sanyo E Series (KR-5000DE) is 5.4 Ah (C/5) and weighs 155g for an ED of 41.8 Wh/kg (19 Wh/#).

Ni-Cd (prismatic, vented): DAUG developed a lightweight fiber nickel plaque (as opposed to foam nickel) which serves as an excellent substrate for nickel plates. Hoppecke exploited this technology and now markets a 60 Ah (C/5 rate) cell (FNC203L) which weighs in at 2.75 kg, for an ED of 26.2 Wh/kg (11.9 Wh/#). While this is poor from an EV standpoint, it is appropriate for the photovoltaic market, especially in remote sites where the cycle life of 3000 (100% DOD) and excellent low temperature performance are big advantages
over Pb-acid. This cell is marketed by Rob Wills at Skyline Engineering (Temple, NH, 603-878-1600).

**Ni-Fe:** The Edison cell has slipped away into oblivion. Old designs used pocket plates for the cathode and found long cycle life service in railroad applications. Now the DOE is sinking money into modern Ni-Fe cells using sintered plates. However, hydrogen gassing is severe and a safety hazard, resulting in the need for high maintenance water additions. Fe electrodes are pyrophoric. EDs of 51 Wh/kg (23 Wh/#) have been achieved by Eagle Picher in 220 Ah cells designed for the Chrysler TEVan. But here’s the really bad news: at low temperatures they stop functioning.

**Ni-Zn:** This rechargeable battery system is severely maligned, as a result of the failure of considerable research during the Energy Crisis to make the system work with a satisfactory cycle life. In the last decade, Electrochimica Corp (Menlo Park, CA) has built cells to an advanced prototype stage, winning the 1976 Tour de Sol with 60AH cells. Cycle life using Japanese foam plates has reached nearly 1000 cycles at an 80% DOD. Excellent ED of 55-77 Wh/kg (25-35 Wh/#) has been achieved. The nontoxic Ni-Zn excels in ED, low temperature and high rate performance, low cost, and recyclability, but offers marginally acceptable cycle life. The author predicts that future world markets will dictate that for large capacity batteries in world production volumes, the combination of the above attributes will render Ni-Zn the only acceptable contender.

**Ni-MH:** Nickel Metal Hydride has burst on the scene in the last several years with a fury rarely seen in the battery world, and as a result has led to considerable skepticism. Ovonic Battery Co. has reported EDs of 65-70 Wh/kg (30-32 Wh/#) and a cycle life of over 1000 at a 100% DOD. Cells have been built as large as 200 Ah. They claim their metal alloy (V-Ti-Zr-Ni-Cr) powders are an order of magnitude below hazardous waste limits, and are capable of withstanding continuous overcharge. On the down side, when cycle life is expired, the capacity drop is precipitous. Given a low enough cost, this system could have the largest effect on the overall battery market of any technology in many years.

**YOUR SOLAR/EV RACE CAR**

While the EV market is forced to wait out a conservative battery industry for new high energy density systems, there remains little in the way of options for the grass roots hobbyist. While Ni-Cd offers superb cycle life capabilities and low temperature performance, the actual ED is not as good as the best that the venerable industrial grade Pb-acid
has to offer. The Trojan golf cart battery appears to be an excellent choice and is very cheap.

SELECTED BIBLIOGRAPHY


Making it Move:
From the Tracker to the Track

Gill Andrews Pratt
NESEA S/EV 91

1. Motors
2. Transmissions
3. Motor Controllers
4. AC Line Chargers
5. Maximum Power Point Trackers

Motors

1. DC Brushed
2. DC Brushless (AC Synchronous)
3. AC Induction (AC Asynchronous)

DC Brushed Motors

Advantages
- Inexpensive Motor
- Inexpensive Controller
- Low Torque Ripple

Disadvantages
- Narrow Efficiency Peak
- Poor Heat Dissipation
- Brush Friction
- Brush Arcing (esp. in regen)
- Brush Wear
- High Rotational Losses
DC Brushless Motors

Advantages
- Good Heat Dissipation
- No Brush Loss
- Low Resistance (Flat Efficiency Curve)
- High Reliability

Disadvantages
- High Motor Cost
- High Motor Controller Cost (only for 6-step controllers)
- High Torque Ripple
- Significant Rotational Losses

AC Induction Motors

Advantages
- Low Motor Cost (no Perm. Magnets)
- Good Heat Dissipation
- No Brushes
- Low Rotational Losses at light loads
- High Reliability

Disadvantages
- Complex Controller
- High Motor Controller Cost
- Less efficient than DC Brushless at low speeds
- Higher weight than DC brushless for moderate H.P.
Motor Losses

(DC Brushed + Brushless)

Torque Dependent
Resistive \( \Pr = \frac{J^2}{R} = (T/Km)^2 \)

Speed Dependent
For Strong Magnets
Eddy Currents \( Te = K1 \omega \) \( \Rightarrow \) \( Pe = K1 \omega^2 \)
Hysteresis \( Eh = K2 \) \( \Rightarrow \) \( Ph = K2 \omega^2 \)
Windage
Bearing

\( I = \) Motor Current \( \Pr = \) Resistive Power Loss
\( \Omega = \) Motor Speed \( Te = \) Eddy Current Torque Loss
\( R = \) Motor Winding Resistance \( Pe = \) Eddy Current Power Loss
\( T = \) Motor Torque \( Eh = \) Hysteresis Energy Loss (per rev.)
\( Km = \) Motor Constant \( Ph = \) Hysteresis Power Loss

Motor Constant

(DC Brushed + Brushless)

\( Km = Kt / \sqrt{R} \)

For constant winding area,
\( Km \) is independent of \# Turns!

Why?
If we double \# Turns,
we double \( Kt \)
but with double the length of
twice as thin wire,
we quadruple \( R \)!

Heat

(is your motor's enemy)

1. Increases Electrical Resistance
   Higher losses ... higher temp. ... higher losses ...

2. Lowers Lubrication Viscosity
   Eventual bearing failure

3. Reduces Permanent Magnet Strength
   Eventual demagnetization (at curie point)

4. Melts Insulation
   Eventual short circuits

Answer: Use a FAN !!!

Transmissions

1. Do you need one?
   ... depends on the motor type and driving schedule

2. Is an electronic transmission possible?
   ... motor controller already does some of this
   ... a series / parallel or delta / wye switch might do

3. Be realistic about mechanical losses
   ... 90% efficiency is extremely good

4. Be realistic about mechanical reliability

5. Don't be overly seduced by CVTs
   ... electric cars don't need clutches
   ... low tech CVTs have high losses

6. Don't forget the oil!
Electronic Transmissions

Most Motors and Controllers are limited by resistive loss

Series / Parallel

Delta / Wye

Switches

1. Changes Torque Constant of Motor (1:2 or 1:1.73)
2. Does NOT change motor efficiency at given $T$, $\omega$
3. Does NOT change controller efficiency at given $I$
4. DOES change controller efficiency at given $T$, $\omega$
### Motor Control

#### The Basics of Switch-Mode Control

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Back-EMF Matching</td>
<td>Lots of wires</td>
</tr>
<tr>
<td>Large (1:2) ratio</td>
<td></td>
</tr>
<tr>
<td>Controller needn't know</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fewer wires</td>
<td>Bad Back-EMF Matching</td>
</tr>
<tr>
<td>Smaller (1:1.73) ratio</td>
<td>30 degree phase shift</td>
</tr>
</tbody>
</table>

#### Motor Control

The Motor Model

\[
Torque = K_t I \\
EMF = Ke \omega
\]
Motor Control

Current Regulation is the goal,
NOT Voltage Regulation
(even w/ Current Limiting)

Why?
Because Motor Back-EMF
is not ours to chose !!!
(it depends on vehicle speed)

Current Mode
Control Methods

1. Hysteresis (Constant Ripple)
2. Cycle-by-cycle Threshold (Constant Frequency)
3. Average Current PWM

DC Motor Control

AC Motor Control
AC Motor Control

Phase / Frequency Feedback

1. Resolver – R/D
2. Encoder
3. Hall Sensors (3)
4. Sensorless

What to Look for in a Motor Controller

1. Current Mode (Torque) Control
2. Robust Design & Construction
3. At Least 2 Quadrant Operation
4. Undervoltage (low battery) lockout
5. Smooth Overvoltage cutback
6. Smooth Overtemp cutback
7. Smooth Battery current cutback
8. Adjustable pedal offset & gain
9. Galvanically isolated control signals
10. Brake light relay
11. High efficiency
12. Light weight (1/2 W/lb @ 40MPH !)

AC Line Charger
What to Look for
in an AC Line Charger

1. Current Mode Control
2. Very Low Power Factor (sine wave control)
3. High Precision Voltage Limit
4. Galvanically Isolated Case
5. Won’t Ever Discharge Battery
6. Overtemperature shut-down
7. Galvanically Isolated Output (if battery or motor leads exposed)

Maximum Power Tracking

What to Look for
in a MPPT

1. Won’t Ever Discharge Battery
2. Very High Efficiency (> 95%)
3. High Precision Voltage Limit
4. Fast Tracking (< 1/4 sec)
5. Tracks well in low light
6. Diagnostic display
Conclusions

Don't Compromise ...

OPTIMIZE!

1. Don't guess about losses
2. Understand loss tradeoffs
3. Be open to new ideas
4. Use your head, then a computer
5. Simulation costs less than lost races
6. Low Reliability is the highest loss of all
Basic Solar/Electric Vehicle Instrumentation

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The following is an introduction to solar/electric vehicle instrumentation. Starting with basic theory, we will progress to instrumentation with simple meters, and, finally, provide an introduction to some of the more advanced systems such as on-board computers.

Basic Measurements

Voltage: This is defined as the electrical potential between two points. It is measured with a voltmeter. The ideal voltmeter has infinite internal resistance so that it will have little or no effect on the performance of the circuit being measured. The basic unit of voltage (V) is Volts.

Current: This is the current flow through a wire and is measured by an ammeter. An ammeter must be inserted in the wire so that the current to be measured will flow through it. The ideal ammeter has zero resistance so that, like the voltmeter, it will have as little effect as possible on the circuit being measured. The basic unit of current flow (I) is Amps.

By convention, “positive” current flow is opposite the actual direction of electron flow.

Resistance: represents a circuit element that resists the flow of current. The basic unit of resistance (R) is the Ohm.

Ohms law: voltage, current and resistance are related by Ohm’s law; \( V = IR \).

Figure 1 shows a battery and a load (in the form of a resistor) with a voltmeter in place to measure the voltage produced by the battery, and ammeter placed to measure the current flow.

Figure 2

Power: The power (P) being consumed by a load is calculated by multiplying the Voltage across the load (V) by the current flowing through it (I), with the result being in Watts. \( P = IV \).

Energy: This is the power multiplied by time, with the result in Watt-Hours.

Measuring Instruments

Voltmeters: Voltage is perhaps the easiest measurement to make. Voltmeters are available in hundreds of varieties from conventional ‘moving needle’ type meters to the newer solid-state electronic versions with digital or bar-graph readouts. Distributors catalogs are an excellent reference source.

Ammeters: Small ammeters (less than 10 A full scale) are usually self-contained. Larger meters consist of an external shunt (usually calibrated in millivolts per Amp) with a voltmeter connected across it. The face of the voltmeter then is calibrated in units of current (Figure 2).

A current shunt is a special purpose resistor which produces a voltage drop proportional to the current flow through it.
Due to its resistive nature, a current shunt will dissipate power which can reduce the overall efficiency of the vehicle. A typical 50 mV per 100 A shunt would have a resistance of .0005 Ohms. At a current flow of 50 A, it would dissipate 1.25 Watts. This is relatively small, but could make a difference when seeking that last ounce of efficiency.

Another current measuring option is the Hall-effect current sensor. This senses the magnetic field around a wire and produces an output voltage proportional to the current flowing through the wire. The output is amplified and sent to a readout or meter.

The problems with Hall-effect current sensors are that they are affected by temperature more than current shunts and have zero offset drifts. The best accuracy you can expect from a Hall-effect sensor is about ±2%, and they are expensive ($50 to $200). If you are installing a simple current readout for your driver to observe, the accuracy and zero offset probably won't be a problem. However, if you are providing an output to a battery state-of-charge current integrator, a zero offset can be a major problem. There could be times when your car is actually at rest but the current integrator is registering a small but constant drain or charge. On the other hand, a current shunt has no zero offset (by definition) and ±1% accuracy are commonly available for about $20.00.

Amp-Hour Meters: Perhaps one of the most important instruments in the solar/electric vehicle is the battery amp-hour meter. This usually consists of an electronic circuit that integrates the current flow over time, continuously displaying the sum. This is the electrical equivalent of the fuel gauge in a gasoline powered car.

The Amp-Hour meter will require periodic calibration. It is normally set to zero with the battery discharged, or (preferably) set to the known capacity of the battery while it is fully charged.

A common question relates to why we don't use a Watt-Hour meter to keep track of battery charge instead of an Amp-Hour meter. The problem here is that the battery is at a higher voltage during charge than it is during discharge, so a Watt-Hour meter will assume that more energy has been put into the battery than you are going to be able to take out. Unless you correct for your batteries' charge/discharge efficiency, a Watt-Hour meter will provide erroneous information.

Temperature Sensors: The two most common types of temperature sensors are thermocouples and thermistors. Thermocouples are useful for measuring high temperatures (above 100° C). They produce relatively low output voltages, and because they respond only to temperature differentials, they require a conditioning circuit, or ice-bath reference. Users must also be careful that the thermocouple junction is electrically isolated from the vehicle and from other thermocouples.

Thermistors respond to changes in temperature by changing resistance. This is easily changed into a display of temperature for the driver by using a resistive divider or bridge, and a voltmeter. Thermistors are not usable at temperatures much above 100-150° C, so monitoring drive motor winding temperature is probably best left to a thermocouple.

Speedometers: A good solution to the problem of measuring road speed is an electronic bicycle speedometer. Many are available with odometers, and even trip computers. They utilize a 'reed switch' which detects the passage of a magnet mounted on the rim of a road wheel.

Motor RPM: If you are using a DC motor, its RPM can be determined by monitoring the voltage across the motor. AC and DC-brushless motors are not as simple. One solution is to mount a ferrous 60-tooth gear on the shaft, and sense the passage of the teeth with a magnetic pickup. The pulses from the pickup can be turned into an analog DC voltage by a 'frequency to voltage' converter. The 60-tooth gear makes calibration easier because the RPM will be numerically identical to the magnetic pickup's output in Hz.

The complete vehicle system

Figure 3 is a highly simplified schematic of a typical solar/electric vehicle, (S/EV) power system.

Voltmeters (V), ammeters (A), and temperature sensors (T) are shown.

Note that the ammeters are located as close as possible to the system ground point. The reason for this is to keep the voltage potentials on the wires to the gauges (or on-board computer if one is used) as close to ground potential as possible.

CAUTION! Connecting an ammeter or voltmeter installed in the driver's compartment to the solar array or main battery system can expose the driver to extremely hazardous voltages and currents.
The dotted line around the maximum power point tracker (MPPT) shown in the drawing represents a connection inside the device. Some MPPTs have the common connected across the positive side and this must be taken into account.

There are several temperature sensors shown in the drawing. The most important is Motor temperature. Motors are easily destroyed by overheating. Other temperature sensors can be located for reliability and/or efficiency measurements as desired.

The O.B.C. can monitor temperatures and compare them to preset values, notifying the driver if a temperature gets too high or is rising too fast.

Battery current flow can be integrated over time and can, when divided by distance travelled, provide the driver with a real-time display of miles per Watt-Hour, (the S/EV equivalent of miles per gallon).

The O.B.C. can also provide an analog voltage output that could be connected to the motor controller providing an intelligent "cruise control".

**O.B.C. Circuit description**

An O.B.C. need not be particularly sophisticated or fast. Computations can be done at a relaxed rate. The O.B.C. described in this paper is based on the Intel 80C31 microcontroller (Figure 4). It is clocked at 7 MHz even though the 80C31 is capable of over 12 MHz. It is a fairly straightforward "cookbook" circuit design with 32k bytes of ROM and (battery-backed) RAM.

**Analog inputs**

The O.B.C. needs to be able to convert analog DC voltages into binary digital form.

The analog to digital (A/D) conversion section is based on the Intersil ICL7109 integrating A/D converter. This is a 12-bit converter so its basic (quantization) accuracy is ±0.024%. The integrating type of A/D has the advantage of not requiring a sample and hold circuit, and it is immune to inaccuracies caused by high frequency noise.

The ICL7109 performs a maximum of 30 conversions/sec. This is not as fast as many other A/Ds but is fast enough for this type of application.
The A/D converter is fed by an Analog Devices AD524 programmable gain instrumentation amplifier. The gain is set by output lines from the 80C31 and can be set to a gain of from 1 to 1000. This provides a maximum system resolution of 0.5 $\mu$V. \((2.048V + 1000 \times 2^{12})\)

The A/D converter is calibrated to $\pm 2.048$ V full scale (as opposed to a round number like 2 V or 5 V) for ease of doing binary arithmetic. As a result each binary bit represents exactly 0.5 mV.

The instrumentation amplifier is fed by a pair of MUX16 16-in-to-1-out multiplexers. One multiplexer selects the 'high' side of an input signal while the other selects the 'low' side. The multiplexer channel select is controlled by output lines from the 80C31.

**Signal clamping**

The circuitry shown between the analog inputs and the multiplexer inputs are voltage clamps. This protects the O.B.C. circuitry from damage caused by excessive voltages at its inputs. If an input voltage goes a few tenths of a volt above +15 Volts or below -15 Volts, a diode will conduct, shorting the input to the power supply 'rails'. The resistor in series with the input protects the diodes from damage.

The resistor value is a trade-off. Too large and your system accuracy will be degraded, too small and the clamp might fail when most needed. The size can easily be determined empirically however, since the resistors (and the diodes too) are available in 'DIP' plug-in packages.

**Watchdog Timer**

The function of a watchdog timer is to reset the O.B.C. if it “goes into the ozone”. That is, if the O.B.C. somehow jumps into an unintended section of program memory, it may begin executing nonsensical instructions and become stuck in an infinite loop. This can happen as a result of an electrical spike or transient which can be a very common occurrence in an electrically powered vehicle. The watchdog timer will time-out and cause a reset of the microcontroller if it is not “tickled” periodically.

Most programs will have an interrupt driven background program running “concurrently” with the main

![Figure 4](image-url)
computational program. One of the tasks of the background program would be to keep setting the tickle line high, while the foreground program would keep setting it low. Therefore, as long as both continue running as intended the watchdog timer will not time out. A typical time-out for a watchdog timer might be a half second.

**Telemetry**

Information can be passed automatically from an O.B.C. to a chase vehicle for competition or development purposes through the use of telemetry. The chip used for this purpose is the AM7910 ‘World Chip’ from AMD. It is a ‘Bell 202’ compatible modem on a chip. Data can be sent in serial form from the microcontroller to the

A simple one-way radio system is usually adequate for this type of application provided the information is transmitted in character format, one line at a time. Errors in transmission become immediately apparent, and can be simply ignored.

**Crowbar protection**

Another useful circuit is the crowbar (Figure 5). It is designed to protect the O.B.C. circuitry from excessive or reversed voltages by blowing the fuse when the input voltage exceeds 18 V or goes below 0 V. This is particularly useful if your S/EV is assembled and/or worked on by committee.

**Isolation from electrical noise**

The greatest challenge in the design of an O.B.C. is making it as immune as possible to electrical noise. Wires carrying signals from the various sensors to the O.B.C. should be twisted pair (as a minimum) or, if possible, should be shielded twisted pair with the shield grounded only at one end.

All input signals should be ‘differential’. That is, the signal to be measured should be the voltage difference between two wires, as opposed to several signals all being referenced to a common point.

The O.B.C. design and construction should incorporate solid ground bussing, plenty of bypass capacitors, and noise filtering on its power input leads. This is beyond the scope of this paper but an excellent discussion of these techniques can be found in AP-125* Designing Microcontroller Systems for Electrically Noisy Environments* from Intel Corporation.

One last helpful technique is to keep one O.B.C. input channel shorted (i.e., at zero volts). This channel can be read regularly by the O.B.C. to detect any ‘zero drift’. This offset can then be subtracted from the other readings to maintain a higher level of accuracy.
Radio Communications
Carl Pietrzak, N9FNQ
Motorola, Inc.

I've compiled the following notes in an effort to help the developers of solar and electric vehicles to keep their attention focused on energy-saving technologies, rather than on the design of radio communications systems. As a result, I have dispensed with any lengthy discourse on the theory of radio communication in favor of result-oriented heuristics. References are provided for readers interested in learning more or investigating additional solutions.

Radio Equipment Recommendations

1) Power: 1-5 watts
In my experience, two 5 watt mobiles in moving cars will provide a reliable 1-2 mile range virtually irrespective of frequency in the 27MHz (CB) to 470MHz (UHF) band assuming typical trunk mounted antennas. 1 watt typically provides 1/4 to 1/2 mile range. Gain antennas (e.g. 5/8 wavelength) improve the 1 watt scenario. Much longer range is common in both of these cases, but I'm referring to the range with >90% probability of solid communication in a suburban landscape. Of course the ranges are probably shorter in downtown Manhattan and longer in open country.

2) Antenna Placement
Since all radio antennas are directional and are affected by surrounding objects, the placement of an antenna can have a profound impact on the operation of a radio system. A moving solar race car is a poor place to locate an antenna in general, but the following heuristics will help to make the best of a bad situation.

- Locate the antenna as high (relative to the earth) as possible.
The ground tends to reflect radiated energy upwards, reducing the amount of energy that is radiated horizontally.

- Orient the antenna vertically.
90° to the motion of the car is also acceptable. Aligning the antenna with the motion of the car will substantially decrease performance.

- Locate the antenna above the solar panel.
If this is not possible, locating the antenna half way between the panel and the ground, then to the side of the vehicle that is closest to the chase car (front or rear of car) is second best.

- This is an art, not a science!
Ultimately, try everything, including violating all of the above.

- Use the highest quality, impedance-matched coax available.
Teams locating antennas remotely from their portables should not attempt to save money on coax, especially at UHF frequencies. Poor coax can cause substantial
loss of energy and can actually receive interfering signals. In addition, be sure to verify that the impedance of the coax, radio, and antenna match. Radios and antennas are often designed to have 50 ohm impedance, but coax is available in many varieties. For example, cable TV coax is not acceptable.

3) **Chase Car Radio System**

Since the radio system in the prototype car is already heavily constrained, boosting the performance of the chase car radio system will boost the performance at both ends. Some suggestions:

- Use a 4-5 watt radio.
  This will compensate for the poor location of the antenna in the prototype vehicle.

- Use gain antennas.
  These work both ways: they are more sensitive receivers and stronger transmitters, again compensating for the situation in the prototype car.
  Examples are 5/8 wavelength and twin, diversity antennas.

- Locate the antenna(s) on the car roof.
  Looks ugly, but works much better than trunk or hood mounts.

4) **To Learn More**

I recommend the *Radio Amateurs Handbook*, available in most libraries. This is a practical guide to the design and construction of radio equipment.

**Licenses**

Title 47 of the *Code of Federal Regulations* is, in effect, the FCC (Federal Communications Commission) rule book. For those not familiar with the CFR, many federal agencies itemize their rules in this multi-volume set of books. For example, regulations established by the Department of Agriculture are listed in Title 7. Regulations governing the setting of import quotas and fees on food stuffs are described in Part 6 of Title 7. Federal banking regulations are listed in Title 12, etc. Those wishing to license a radio station are concerned with Title 47. After reviewing Title 47 (1990 revision), I've noted the following classes of licenses which are relevant to electric car development and race communication.

1) **Citizens Band**, Title 47 Part 95(c)

| Advantages: | You don’t need a license to operate CB equipment. Authorization to operate anywhere in the U.S. |
| Disadvantages: | Severe interference from others since anyone can use these frequencies in virtually any manner |

CB radio can be very frustrating to use in a major metropolitan area as the frequencies tend to become crowded and unruly. Having multi-channel capability is a must for use of this band (∼27MHz.) Crystal or channel-element radios
should be tuned to one of the more obscure channels (i.e. not 1, 9, 19, 13, 14, 19, 20, or 40.)

2) Experimental, Title 47 Part 5

Advantages: Customized license which can be established on virtually any frequency and physical location

Disadvantages: No guarantee of a clear frequency. You're the lowest priority user of your frequency. Authorization intended to be for only a limited period of time, but exceptions may be possible.

I've personally obtained an experimental license to support my college thesis, which was a radio data modem in the 450MHz band. However, I was only authorized to transmit in and around MIT, the license lasted for only six months (though I received a six month extension), and I had to find my own clear frequencies. To solve the last issue, I researched the FCC records to select a small set of frequencies, then scanned each potential frequency for one week using a scanner and a counter which tallied the number of times a carrier was detected.

3) General Mobile Radio Service (GMRS), Title 47, Part 95(a)

Advantages: Easy to obtain a license. Frequencies are specifically allocated for this purpose. Less interference than CB.

Disadvantages: Only a small set of frequencies are available (~8 around 462MHz.) Still have to contend with interference from others.

Also known as "Class A" CB, this is probably the best choice for solar and electric car development teams.

4) Itinerant Special Industrial Radio Service, Title 47, Part 90, Subpart 73

Advantages: Very easy to obtain a license. Less interference than CB.

Disadvantages: Smallest number of frequencies (4 around 464MHz; VHF frequency, 151MHz, is very crowded.) More crowded than GMRS, but less than CB.

Also known as "Dot frequencies" (Green Dot, Blue Dot, ...), these are the frequencies assigned to two-way, UHF radios that are commonly sold in mail-order electronics catalogs and specialty stores. While these frequencies are fairly quiet in rural areas, they are popular with construction companies, warehouse operators, and the like, and thus tend to be busy near cities. Nevertheless, this is also a good choice of license class.
5) **Amateur Radio**, Title 47, Part 97

**Advantages:**
- World-wide frequency allocations.
- License authorizes many, large bands of frequencies.
- "Primary" license on many bands.

**Disadvantages:**
- License comparatively difficult to obtain.
- Each radio operator must be individually licensed.

Also know as "Ham Radio," this is by far the most flexible type of license to obtain since virtually any type of transmission is authorized, the frequency bands are allocated for this purpose in almost every country in the world, and most countries have cross-licensing agreements with the U.S. In addition, unlike the above licenses, it is illegal for anyone else to interfere with your transmissions in the most useful bands, UHF and VHF.

6) **Cellular**

**Advantages:**
- No license.
- System allocates a clear channel for you.

**Disadvantages:**
- Expensive to operate.
- Poor coverage in rural areas and near many structures.

**Other Licensing Issues**

1) **International Operation**
   There is no such thing as a world-wide license which guarantees the holder a clear channel, although this is almost true with Amateur Radio. However, the following frequency bands have been allocated for the general use of land-mobile radio operators world-wide: 150-174, 406-430, and 450-470MHz. Thus purchasing equipment which operates in these bands maximizes your chance of obtaining a license in any particular country. For more information, refer to the CFR, Title 47, Part 2 in which the International Telecommunications Union agreements are described.

2) **Frequency Coordination**
   Assuming that many teams take my recommendation and obtain GMRS or Itinerant licenses, the fact remains that there are only about a dozen frequencies to choose from, creating a high probability of interference at a large event. Methods to mitigate this issue include:
   - coordination of team frequency selection by a central organization, such as NESEA,
   - teams assigned the same frequency can be assigned different PL frequencies (a sub-audible tone) or DPL codes (digital version), and
   - employ geographic frequency reuse when possible.
The American Tour de Sol is a showcase and proving ground for the emerging electric vehicle industry. Five years ago, major car companies said that electric vehicles were not viable. Now they say that they will be in production within five years. There are two reasons for this dramatic change:

* Legislation is providing guaranteed future markets, and
* Technological advances, many of which are outgrowths of solar/electric racing, are making electric vehicles more practical and cost competitive.

For the latter reason, it’s interesting to look at the development of technology, and its impact, in the 1991 American Tour de Sol.

**Notable Vehicles**

There were two basic types of commuter vehicles entered. Some were converted gasoline cars such as Solectria’s Force and Force GT (originally Chevy Geos) and New Hampshire Technical Institute’s Sungo (based on a Yugo). New England Institute of Technology’s Solar Tech is a converted BMW Izetta. Mattatuck Community College’s Sunbird is a beautifully converted 1952 vintage MG replica. Others are built from the ground up for lightness, aerodynamics and efficiency. The winning car, Solectria’s Flash has a fiberglass frame with a fiberglass/kevlar skin and weighs only 1000 pounds with driver.

In the racing categories, MIT’s winning entry, MIT V, is the epitome of lightness and aerodynamic design. Dartmouth’s new Sunvox IV featured an aluminum frame with a fiberglass body and composite front suspension members. Conval High School of Peterborough, NH, again entered their four-wheeled Sol Survivor with its kevlar monocoque body. In the cross-continental category, Rochester Institute of Technology’s Spirit, with an aluminum frame and foam/dacron skin, came in first.

The open category had many interesting cars ranging from Solar Car Corporation’s beautifully converted Ford Festivas, to the Rosebud team’s solar electric mountain bike. The winning car in the open category was the Electric Hilltopper from St. Johnsbury Academy, Vermont. Their converted 1979 VW Rabbit ran a perfect race and demonstrated a range of one hundred miles on the last day – a great performance by a high school team! The total cost of their vehicle was only $4,000.

**Technology Under the Hood**

Most commuter cars used 10 to 20 horsepower series wound electric motors made by Prestolite, Advanced DC motors or General Electric with Curtis PMC controllers. Exceptions were the Solectria cars, the Sungo and the Solar Tech which used 11 horsepower Solectria brushless dc motors. There is an interesting tradeoff between the simplicity of dc brush motors versus the efficiency and lightness of brushless motors, as the the brushless controllers are much more complicated and expensive. On the whole, the reliability of the electric drive systems was excellent.

Racing category cars, going all out for performance, generally used brushless dc motors from Solectria, Uniq Mobility or General Electric.

Most of the converted commuter vehicles kept a gear box in the drive train from motor to wheels. Notable exceptions were the Solectria cars and NHTI’s Sungo which has two Solectria motors connected via chain drives to each rear wheel. All of the racing vehicles used a direct drive, taking advantage of the wide torque range of their electric motors.

Batteries are well known as the limiting factor in electric vehicle performance. Most cars in the Tour de Sol used deep cycle lead acid batteries made by Trojan, Keystone or Sears. The winning commuter, Solectria’s Flash used SAFT nicad cells while NHTI’s Sungo had Hoppecke fiber nicas. The racing category cars either used lead acid cells, or if budgets allowed, super light-weight silver-zinc and silver-cadmium cells.

The use of silver based batteries is rather controversial in that they can not be used in large scale electric vehicle production because of their expense. For this reason, silver batteries may not be allowed in future Tour de Sol races.

Photovoltaic modules on cars ranged from the carefully integrated photocomm/Kyocera laminates on the Solar Car...
Results

Placings of the 26 entrants are shown in the table. Scoring for the American Tour de Sol uses "adjusted time." This is the route running time minus an allowance for each optional lap, plus any time penalties incurred for rule infractions or not completing a leg.

Motors

A significant change from last year was that 16 cars had brushless ac drive systems (62%) compared with only 4 out of 15 (27%) in 1990. Both brushless and conventional dc motor drive systems seemed reliable and performed well. The Solectria AC drive systems were popular—10 out of the 16 brushless drives used were Solectria units.

Batteries

Most cars used lead acid batteries in 1990, the exceptions being Solectria Lightspeed's SAFT nickel-cadmium cells and MIT V's Silver-Cadmium. In 1991, two commuter cars used Nicad systems: Solectria again used a bank of Saft pocket plate cells in their Flash, and New Hampshire Technical Institute's Sungo used Hoppecke Fibre-Nickel Cadmium cells.

The racing categories were more controversial. Solectria V ran with Silver-Zinc cells that the manufacturer claims are good for the 200 cycle life rule. Drexel's Sundragon also used silver-zinc, which are legal under the cross-continental rules. Dartmouth used silver-cadmium cells from Yardney.

Dr. Robert Wills is a consulting engineer and Co-Director of the American Tour de Sol.

Dr. Robert Wills is a consulting engineer and Co-Director of the American Tour de Sol.
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<td>84:20</td>
<td>N/A</td>
<td>100</td>
<td>70</td>
<td>1</td>
<td>600</td>
<td>1874</td>
<td>4</td>
<td>Emerson AC Induction</td>
<td>Lead Acid</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Title Results**

**First Place**
- SOLECTRIA V MT Solar EV Club | 302 | 7:19 | 55 | 175 | 85 | 0 | 350 | 3 | Selectria Brushless 5 kW | DC Motor 1.5 kW | 70 | 480 | 436 | Chrome-mapy frame, Birel glass body |

**Second Place**
- SOLARAY Virginia Technical Institute | 263 | 9:41 | 46 | 65 | 65 | 0 | 660 | 3 | Motion Controls 1.2 kW Brushless | 2045 Wh Lead Acid | 120 | 480 | 390 | Aluminum frame, Spectra body |

**Third Place**
- SUNTECH NJ Technical Institute | 258 | 9:43 | 56 | 100 | 55 | 0 | 150 | 540 | 3 | Selectria Brushless 9 kW | 7500 Wh Lead Acid | 72 | 479 | 439 | Steel-mapy wheel frame, FRP body & wiring |

**Fourth Place**
- SOL BORUVKA II Corvair High School | 247 | 11:07 | N/A | 70 | 40 | 0 | 300 | 600 | 4 | Selectria Brushless 9 kW | Lead Acid | 72 | 480 | 159 | Kevlar monocoque body |

**Fifth Place**
- SOLAR TOURism Dartmouth College | 220 | 20:59 | 90 | 200 | 65 | 0 | 365 | 3 | Selectria Brushless 9 kW | Varley Silver 5000 Wh | 120 | 480 | 360 | Aluminum frame, Birel glass body |

**Sixth Place**
- SOLAR ST AND University of Illinois, Chicago | 132 | 49:04 | 99 | 100 | 50 | 0 | 300 | 500 | 3 | Clark Series Wound 3 kW | 4,800 Whs, 4 x Seac0 9650 | 48 | 480 | 192 | Steel-mapy wheel frame Birel glass body |

**Seventh Place**
- INSPIRED PHOENIX Northwestern University | 45 | 73:15 | N/A | 70 | 50 | 0 | 135 | 475 | 3 | Emerson 1.5 kW | 4,800 Wh Lead Acid | 48 | 480 | 147 | Steel-mapy frame, carbon fiber-composite body |

**Cross Country**
- SPIRIT Rochester Institute of Technology | 243 | 15:10 | N/A | 100 | 60 | 0 | 178 | 400 | 4 | Gt Brushless 1.5 kW | Varley Silver Zinc 3,500 Wh | 150 | 900 | 904 | Aluminum frame, Kevlar body |

**WILD SOLARII Wild Solar IITI Vincennes University | 161 | 40:54 | 59 | N/A | 70 | 0 | 250 | 500 | 4 | Uni Brushless 15 kW | Lead Acid | 60 | 720 | 594 | Aluminum frame, Kevlar composites body |

**Eighth Place**
- SUNRAMON II DePaul University | 99 | 56:10 | N/A | 50 | 60 | 0 | 500 | 500 | 3 | Uni 1 kW Brushless | Eagle Revoir Silver Zinc 4000 Wh | 100 | 1630 | 263 | Carbon Fiber, fiberglass & Kevlar |

**Open**
- ELECTRIC HILLTOPPER St. Andrew Academy | 304 | 8:23 | 261 | 100 | 55 | 1 | 1800 | 4 | Pridestar 17kW Series Wound | 17,340 Wh, Trojan T-145 | 96 | 0 | 0 | Converted 1995 WV Rabbit |

**Second Place**
- FORCE OF Solectria Corporation | 269 | 14:58 | 123 | 120 | 60 | 1 | 2370 | 4 | Selectria Brushless 25 kW | 20,000 Wh Lead Acid | 120 | 0 | 0 | Converted Geo |

**Third Place**
- POETRY IN MOTION Albert Hutton | 244 | 19:04 | 206 | 50 | 45 | 1 | 900 | 3000 | 4 | Porter Series Wound | 40,000 Wh Lead Acid | 120 | 0 | 0 | Steel frame, Birel glass shell |

**Fourth Place**
- FESTIVA SOLAR Solar Car Corporation | 223 | 23:18 | 251 | 100 | 65 | 1 | 700 | 2500 | 4 | Advanced DC Series Wound, 12 kW | Trojan Lead Acid | 120 | 225 | N/A | Conversion - Ford Festiva |

**Fifth Place**
- FESTIVA ELECTRIC Solar Car Corporation | 170 | 33:28 | 283 | 100 | 65 | 1 | 700 | 2500 | 4 | Advanced DC Series Wound | Trojan Lead Acid | 120 | 0 | 0 | Conversion - Ford Festiva |

**Sixth Place**
- EV-A-EL 1 First Systems | 130 | 59:36 | 234 | 50 | 50 | 1 | 400 | 2200 | 4 | Advanced DC Series Wound, 12 kW | 12 x Trojan 110 (70,000 Wh) | 72 | 40 | 0 | Conversion - Ford Festiva |

**Seventh Place**
- SCF-2 Team Renaissance | 112 | 60:41 | N/A | 60 | 0 | 150 | 160 | 2 | Secco AC Brushless | 20kWh 22NF Lead Acid | 12 | 30 | N/A | Mountain Bike |

**Eighth Place**
- SUNPACER Carls Horizon High School | 10 | 82:05 | N/A | 60 | 40 | 0 | 180 | 760 | 3 | Advanced DC Series Wound | 1500 Wh, Extreme Deep Cycle Lead Acid | 36 | 240 | 193 | Sheet metal body |
Introduction To Some Basic Issues
Of Gas-To-Electric Conversions
by Michael P. Brown
Electro Automotive

My background and approach to electric car conversions are hands-on and practical, rather than theoretical or experimental. I have twenty-seven years of professional automotive experience and twelve years of professional electric conversion experience. From that background, I have developed a philosophy on conversions that is designed to minimize opportunities for error or failure:

1. Systems and designs should be simple.
2. Components and systems should be proven.
3. Components should be readily available.
4. Components and systems should be reliable.
5. Components and systems should be easy to use.
6. Designs should take advantage of as much of the original vehicle engineering as possible.
7. The finished conversion must be reliable and practical for the average person in normal daily use.

With this foundation in mind, I offer the following comments on some of the basic conversion components.

**Batteries.**

At the present time, lead acid batteries are still the best choice. There are many experimental batteries and fuel cells under development, but they are not commercially available now. Nickel cadmium batteries are available. However, they are expensive and bulky, and require too many connections between cells. There are also potential fire hazards if they charge unevenly and some cells overcharge. The batteries need to be deep discharge batteries intended for traction use. Standard batteries will not survive the repeated charge/discharge cycles. They should also be 6 volt batteries. Deep discharge 12 volt batteries are usable if space is limited, but vehicle range and battery lifespan are not as good. The type of batteries built for golf carts are the single most manufactured type of battery in the country, and are therefore the most highly developed, available, and affordable.

There are three possible type of terminals. The "automotive" style is a solid post for the cable connector to clamp around, and gives the best contact area. However, it is expensive to connect sixteen batteries with these. The "universal" post has a standard automotive post with a threaded stud extending up from the middle.
A lug and nut. This added height can be a packaging problem. More important, in time the process of "cold creep" will allow the steel stud to pull out of the lead and loosen the connection. After repeated tightening, the stud will eventually come out altogether.

The optimum choice is the "L" terminal. This is a flat upright post with a hole drilled through it. It provides better contact area than the universal post, and can maintain a tight connection very well if the lug is installed with a concave washer to maintain a constant tension against "cold creep".

The overall pack voltage determines speed and range. In order to be safe in traffic, a minimum of 72 volts is required. The optimum balance between energy vs. weight is 96 volts. For heavy cars or very hilly applications, 120 volts may be used. Beyond that, there is a scarcity of appropriate components.

Battery Placement and Housing.

Distribution of battery weight is important for handling. The weight should be distributed as evenly as possible from end to end of the car, with as much weight as possible between the axles. Keeping the batteries low improves handling, and reduces the danger to passengers in a collision.

Batteries should be in sturdy racks securely mounted to the frame. They should be firmly held in place, preferably in enclosed boxes with strong hinges and latches on the lids. Welded polystyrene makes excellent battery boxes. Plywood, while cheaper, is also thicker and heavier.

The batteries need to be held down against bouncing over bumps. Small blocks on the corners of the batteries that fit between the batteries and the lid can accomplish this. I know of a man who neglected to hold the batteries from bouncing up, and also made the mistake of doing away with the box lid to make room for taller batteries. The box was under a seat, which had a thin sheet of metal on its bottom. One day he loaded the family into the car, with Grandma on the battery seat, and hit a bump on the way to church. The batteries bounced up, the sheet metal "oilcanned" down, contact was made, and Grandma nearly went into orbit.

Leave 1/16" of space between batteries. They will swell as they age, and may become impossible to remove. One man I know had a car in which the batteries were packed tight when new. When it was time to replace the pack, he was forced to drain the center battery and destroy it in place in order to remove the rest of them.

Batteries do not gas much in proper use, but will gas a little, mostly during charging. Hydrogen is lighter than air, and very explosive. Boxes should be ventilated during charging with small anti-arc fans.

Suspension.

A conversion gains about 600 pounds and may need to have the suspension beefed up. Before disassembling the gas car, measure the ride height from the ground to the top of the fender wheel.
arch on all four corners. Measure it again after the conversion to determine how much ride height has been lost and must be regained.

The Plymouth Arrow I converted lost two inches in the rear, and gained two inches in the front. Once the rear was adjusted up to the proper height, the front corrected itself as well.

The simplest way to correct the suspension is to install air shocks. Another option is finding a heavier set of springs from a similar but heavier model of the same car that will interchange. The local dealership can determine if there are heavier interchangeable springs on another model. A third alternative is to have springs custom wound. The easiest way to do this is to send the spring winding company a sample of the old spring, and information on how much ride height was lost.

In addition to the springs, which actually bear the weight of the car, stronger shocks are recommended to dampen the oscillation of the added weight over bumps. I recommend something like a KYB gas-filled shock or strut insert. (Note: MacPherson strut inserts should only be replaced by professionals with the proper equipment. They can be very dangerous if disassembled improperly.)

**Tires.**

The lowest possible rolling resistance is recommended in the tires. Goodyear has developed some revolutionary tires for the GM Impact and plans to make them available on the market, but they aren't in production yet. For now, tires made by General seem to be the best, although they may be sold under other "house" brand names.

As a rule of thumb, low rolling resistance can be determined by three ratings on the side of the tire. The tread wear rating is a three-digit number, and should be 290 or higher. The traction and temperature ratings are letters. Traction should be an "A", and temperature should be an "A" or "B".

Use the largest size of tires and wheels that will fit in the wheel well without interference.

**Transmission.**

At this time, a direct drive system is not suitable for steel-body conversions with the motors that are commercially available. They require too much amperage to produce a reasonable road speed.

Automatic transmissions are still in the experimental stage. There are problems with getting sufficient power out of the automatic. Also, the automatic transmission depends on having a constantly idling motor to maintain fluid pressure. At this time, the automatic transmission requires compromises and added complexities. It is not economically justifiable except at a fleet or manufacturer level.

Although it is technically not necessary to use the clutch when shifting an electric, I prefer to use it to ease stress on the transmission. It is also a valuable safety feature. If something should lock up at speed, it allows the driver to instantly disconnect the motor from the wheels and retain control of the car.
Driving an electric does have a different "seat of the pants", including different use of the gears. In general, only second and third gears are needed most of the time.

**Heat and Air Conditioning.**
Heat is an area of electric that still needs development. Small resistance or gas heaters are available and can be incorporated into the design of the car. Another alternative is to cannibalize hair blow dryers and mount the components in the original defrost and head vents, running them from the battery pack.

Air conditioning is not practical in conversions at this time. It consumes enormous amounts of energy, complicates the system substantially, and severely affects performance.

**Motor Power.**
Gas engines and electric motors are rated differently for horsepower, and cannot be compared directly. Horsepower in an electric motor varies with volts and amps. To compare two electric motors, compare their manufacturers' continuous duty ratings at the same voltage.

In general, a motor with a continuous rating of 10 hp is sufficient for most conversions under 2,800 pounds. For a slightly heavier car, or one that needs to pull steep or extended grades, a 19 hp motor is recommended.

Only motors that are manufactured to be traction motors should be used. Generators and stationary motors are not designed to handle the specifics stresses of moving a vehicle at varying speeds.

**Conclusion.**
Certainly, there are other components and systems under development, and some of them will eventually prove out and become commercially available. The above recommendations are intended for building basic reliable affordable conversions with components and systems that are proven and readily available today.
MIKE BROWN'S PHILOSOPHY
ON ELECTRIC CARS

1. Systems & designs should be simple.
2. Components & systems should be proven.
3. Components should be readily available.
4. Components & systems should be reliable.
5. Components & systems should be easy to use.
6. Designs should take advantage of original engineering as much as possible.
7. The finished EV must be reliable and practical for the average person in normal daily use.

FORMULA FOR LOW ROLLING RESISTANCE TIRES

1. Manufacturer: General
2. Tread wear rating: 290 or higher
3. Traction rating: "A"
4. Temperature rating: "A" or "B"

BATTERY POST STYLES

"L"  AUTOMOTIVE  UNIVERSAL
STUDENT BENEFITS: EVENT DRIVEN CURRICULUM

1. AUTHENTIC LEARNING EXPERIENCE

2. OPPORTUNITY FOR COMMUNITY TO SEE LEARNING EXPERIENCE

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4. DIRECT RELATIONSHIP FROM TEXT BOOK TO APPLICATION

5. MEET OTHER PEOPLE WITH SIMILAR EXPERIENCES

6. TRAVEL

7. LEARN AND HAVE FUN AT THE SAME TIME

8. HANDS ON FIRST BOOK LEARNING SECOND

9. ABILITY TO SEE THE RESULTS OF A LARGE EFFORT
INFORMATION

1. ELECTRIC VEHICLES OF AMERICA
   P.O. BOX 59
   MAYNARD, MA. 01754
   508-897-9393

2. CONVERT IT
   MICHAEL P. BROWN
   P.O. BOX #1113
   FELTON, CA. 95018
   408-429-1989

3. NESEA
   23 AMES STREET
   GREENFIELD, MA. 01301
   413-774-6051
SAFETY ISSUES FOR CONVERSIONS

GARY A. CARR
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PO. BOX 1021
CAMBRIDGE, MA 02140

INTRODUCTION

In the process of converting a gasoline powered car to an electric car many decisions have to be made by the person doing the conversion. These decisions are at the same technical level required of the original vehicle designer and should be made only with the understanding of their safety consequences. Two safety issues of concern include the vehicle’s crash avoidance and its crash worthiness capabilities. These safety issues have been taken into account by the original designer which makes the job of the person doing the conversion somewhat easier. However, the process of removing significant components and adding others may change the crashworthiness and crash avoidance capabilities of the car intended by the designer. As an example, the engine system provides significant crush resistance during a frontal impact. If the engine is removed or relocated this will effect the vehicle’s expected crush response, possibly allowing some type of protrusion into the passenger compartment. This could induce passenger injury during a frontal impact. This presentation will focus on the major vehicle parameters likely to be modified by a conversion which will influence the vehicle’s stability on crash avoidance maneuvers and provide some insight to the design criteria used for crashworthiness.

CRASH AVOIDANCE

One of the issues to be presented under crash avoidance include vehicle stability under evasive maneuvers or heavy braking. The concern is that by modifying the location of the vehicle’s effective center of gravity (CG), the vehicle may have the tendency to spin during an evasive maneuver or heavy braking. This is related to a balance between the forces generated at the tires, the location of the geometric roll axis, and the location of the CG. Two terms are used to describe this balance condition: understeer and oversteer. The technical description of understeer is when the front tires have a greater drift angle than the rear tires and oversteer is when the rear tires have a greater drift angle than the front. The drift angle of the tire is defined as the angle between the plane of rotation of the tire and the path of the tire. An understeering car has the tendency
to push or plow while trying to negotiate a turn. Figure 1 shows a vehicle with an understeering path. As a car understeers, the radius of which the vehicle is turning increases. This increase in radius decreases the force level required of the tires to negotiate the turn allowing the vehicle to regain traction. Understeer is considered a stable reaction and in its worst case the vehicle will travel straight ahead. Vehicle manufacturers design an inherent understeer into their vehicles. An oversteering car has the tendency to have the rear of the vehicle swing out. As the vehicle oversteers, the radius of which the vehicle is traveling decreases. As the radius decreases, the forces required to negotiate the turn increase, but since the tires are already near their limit, the vehicle oversteers to a greater extent. Unless immediate corrective action is undertaken by the driver the vehicle will eventually spin out of control. Oversteer is considered an unstable reaction and difficult to control by the average driver.

Figure 1. Oversteer and Understeer Driving Conditions.

When converting a gasoline powered vehicle to electric power, major components are removed and other components are added. The one significant addition during the conversion is the weight of the battery pack. This battery pack increases the total vehicle
weight about 30%\(^1\). The addition of this weight would not be significant if it could be added at or near the CG. However, the location of the CG is usually in the middle of the passenger compartment, reserved for the passenger. For this reason the battery packs are usually placed in luggage compartments such as the trunk, rear hatchback, and in front of or on top of the electric motor. When the weight of the batteries are placed at these locations, the vehicle CG location is significantly effected. Moving the CG rearward increases the tendency of the vehicle to oversteer.

The static ride height is also effected by the CG shift. If the battery pack is placed in the rear of the vehicle the ride height at the rear will be lower than the front. Stiffening the rear springs is a usual method used to raise the rear ride height. Increasing the rear suspension stiffness also increases the tendency of the vehicle to oversteer. These two modifications alone can cause the vehicle to be difficult to handle under emergency maneuvers.

There are two practical methods that can be used to adjust the car so the tendency to oversteer will be reduced. The first method is to distribute the battery pack in a manner so that the CG location is not changed. This may be inconvenient to the wiring of the battery pack and may influence the overall efficiency of the power transfer. The second method requires modification to other vehicle parameters to increase the tendency to understeer. Table 1. lists some of the easier modifications that can be done and their overall effect. As shown in this table, by simply adding wider rear tires and increasing the tire pressures may be all that is needed to correct the balance of the car. In either case, the effects of converting the vehicle should be determined by testing. A typical testing procedure for determining oversteer and understeer would be to operate the vehicle on a skid pad. Procedures for setting up a skid pad in a parking lot or approved area is shown in many vehicle handling books currently available.

---

\(^1\) All numbers are based on the conversion of a 1992 GEO METRO Coupe, Vehicle Weight 1650 lbs + 150 lbs passenger = GVW 1800 lbs. Electrical componentry of 120 Volt system, (ie 10 batteries @ 60 lbs ea.), 100 lbs motor with mounts and controller.
TABLE 1. EFFECTS OF VEHICLE PARAMETERS ON OVERSTEER

<table>
<thead>
<tr>
<th>VEHICLE PARAMETER</th>
<th>INCREASE OVERSTEER</th>
<th>INCREASE UNDERSTEER</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT DISTRIBUTION</td>
<td>MOVE REARWARD</td>
<td>MOVE FORWARD</td>
</tr>
<tr>
<td>FRONT SPRING RATE</td>
<td>LIGHTER</td>
<td>HEAVIER</td>
</tr>
<tr>
<td>REAR SPRING RATE</td>
<td>HEAVIER</td>
<td>LIGHTER</td>
</tr>
<tr>
<td>FRONT SWAY BAR</td>
<td>LIGHTER</td>
<td>HEAVIER</td>
</tr>
<tr>
<td>REAR SWAY BAR</td>
<td>HEAVIER</td>
<td>LIGHTER</td>
</tr>
<tr>
<td>FRONT TIRE WIDTH</td>
<td>LARGER</td>
<td>SMALLER</td>
</tr>
<tr>
<td>REAR TIRE WIDTH</td>
<td>SMALLER</td>
<td>LARGER</td>
</tr>
<tr>
<td>FRONT TIRE PRESSURE</td>
<td>HIGHER</td>
<td>LOWER</td>
</tr>
<tr>
<td>REAR TIRE PRESSURE</td>
<td>LOWER</td>
<td>HIGHER</td>
</tr>
</tbody>
</table>

For distributing the battery pack, the location of the stock car CG can be measured. After the installation of the motor and controllers, the CG should be re-measured and the battery pack divided up in proper portions to prevent significant shift of the CG from the stock vehicle measurement. The CG can be measured by weighing all four corners of the car at the tire contact patch. All these weights added together equals the total vehicle weight. Summing up the weight supported by the front tires and dividing by the total vehicle weight gives the proportion of the total vehicle weight supported by the front tires. Keeping this proportion equal to the stock proportions will maintain the proper electric vehicle oversteer and understeer balance.

The oversteer and understeer balance of the vehicle becomes more and more important as tire friction is reduced. Driving on icy road conditions or using low friction tires for better efficiency will make a severely oversteering car hard to control and dangerous to drive. Following these simple suggestions on controlling oversteer will make a converted vehicle fun and safe to drive.

CONSIDERATIONS FOR ACCIDENT PROTECTION

When converting an automobile different safety issues become apparent besides the handling characteristics. Relevant safety issues include measures which are standard on conventional gasoline powered automobiles and new safety concerns which are specific to electrically powered vehicles. These issues include; prevention of electrocution of passengers or automotive
technicians, control of gaseous emissions to prevent explosion or fire, safety shutdown incase of controller failure or accident, increased energy absorption during impact due to larger weight, along with all the current safety regulations. Regulations are already being proposed to address these concerns which will center around vehicle safety.

Some of the prototype regulations being considered for electric vehicles are:

(1) The vehicle shall comply with all applicable Federal Motor Vehicle Safety Standards as set forth in 49 CFR Part 571, unless a temporary exemption is obtained by the manufacturer from the Department of Transportation.

(2) Until the Department of Transportation issues regulations which cover the same subjects, the vehicle shall also have the following performance characteristics:

   (i) The electric propulsion circuit shall be electrically isolated from other conductive portions of the vehicle sufficiently to prevent personal hazards due to contacting any portion of the propulsion circuit while in contact with other portions of the vehicle.

   (ii) The vehicle shall be capable of complying with their [sic] performance requirements of the Federal Motor Vehicle Safety Standards 208 and 301 with all battery materials remaining outside the passenger compartment.

   (iii) Vehicles with battery vents shall have a flame barrier provisions to inhibit battery explosions.

   (iv) Ventilation shall be adequate within the battery compartment to maintain the concentration of hydrogen below 4 percent by volume during vehicle operation (including charging and maintenance).
(v) The vehicle shall have a device which provides for the positive disconnection of the battery and which is operable from the normal operator position.

Each decision made during the conversion process will effect the safety of the vehicle. The prototype regulations, as shown above, demonstrates the subjects the government is concerned about. Anybody doing a conversion should also be concerned with these issues. Table 2, includes some safety questions to ask yourself while converting the car.

Table 2. Safety Questions to Ask During a Conversion

<table>
<thead>
<tr>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>How will the modifications effect the crush response during a; frontal impact, side impact, rear impact, and vehicle roll over?</td>
</tr>
<tr>
<td>Are the batteries securely mounted so that during vehicle roll over they don't contact any surface that would short circuit them and start a fire?</td>
</tr>
<tr>
<td>Will the battery box remain stationary during an impact? (Some vehicle accelerations during a 30 mph impact can reach 21 g’s)</td>
</tr>
<tr>
<td>Are the batteries contained and separated from the passenger compartment so that during crushing so no acid sprays onto passengers &amp; pedestrians?</td>
</tr>
<tr>
<td>Is there a fire wall or shield so that a fire or explosion will not penetrate the passenger compartment?</td>
</tr>
<tr>
<td>Is the battery box ventilated to prevent build-up of explosive gases during charging, maintenance and operation?</td>
</tr>
<tr>
<td>Are the electrical components properly insulated and shielded?</td>
</tr>
<tr>
<td>Does the original safety equipment still work (seatbelts, double hood latch,...)?</td>
</tr>
</tbody>
</table>

SUMMARY

These are only some of the questions that should be asked. It must be stressed that anyone contemplating the conversion of a gasoline powered car to an electric car becomes a vehicle designer. Two major safety issues of concern include the effects of the conversion on the crash avoidance and crashworthiness of the vehicle. These issues, which are similar in concern to the use of gasoline power, must be applied specifically to the electric powered vehicles. It is essential that very careful consideration of all safety issues be addressed in the mind of anyone proposing a conversion. This will insure progress in developing alternative energy forms for transportation.
Chassis Design and Construction Techniques for Prototype Vehicles

Erik Vaaler

October 17, 1991

1 Introduction

The primary focus of this paper is the design and construction of steel tube space frames. The relative advantages and disadvantages of other common frame types and joining techniques are also discussed. Although monocoque body/frames have replaced discrete element frames as the ultimate in high performance, there are many applications where the much higher performance to cost ratio of the tube frame strongly favors its use. Cars, airplanes, bicycles, wheel chairs, and even a few boats have been built with discrete element frames. Some of these applications are described in this paper. The presentation style is intentionally very qualitative. Quantitative information is available in large quantities in the books listed in the references. There are many other texts available on chassis and suspension design. Those listed in the references are considered by many chassis designers to be particularly useful.

2 Frame Design

The common discrete element frame types are rail, twin tube, multiple tube, and space frame. Examples of each type are shown in [1]. The history of the rail frame goes back several thousand years. Until recently, the rails were made of wood. In fact, wood was a common frame material for early automobiles. From 1910 to 1960 the rail frame was used on nearly all cars. Most passenger cars now use some form of unibody construction where the sheet metal floor pan has taken the place of the rails. Rail frames are still the most common frame for trucks. This continued popularity is due to the low cost of designing and building small production quantities (compared to passenger cars) of this type of frame and to the reduced emphasis on stiffness to weight ratio in truck design. Rail frames are also used by car companies to build test vehicles (often called “mules” which are used to develop new drivetrains or interiors. Having a vehicle that can be driven around, even if it handles like a truck, is crucial for studying the ergonomics of a new interior layout or the reliability or performance of a new engine or motor/controller.

Rail frames are usually made from two pieces of heavy (1/8 inch) steel sheet that are folded into a “c” section. The rails are often straight. A twin tube frame has, by definition, closed sections which are usually circular or rectangular. These closed sections have torsional stiffness to weight ratios hundreds or thousands of times higher than open sections. This
torsional stiffness allows a twin tube frame to be built with significant bends in the tubes. The frame tubes can be bent (or cut and welded) in such a way as to minimize the overall size of the vehicle. This type of frame is typically much wider at the passenger compartment than at the engine compartment.

The next step up in complexity and performance is the multi-tube frame. This type of frame generally uses 4 main frame tubes. The addition of the upper tubes offers convenient attachment points for suspension, steering, hoods, trunks, etc., while greatly increasing the bending strength and stiffness of the frame. Twin tube frames require brackets to reach these attachment locations. The brackets add considerable weight but very little stiffness or strength.

A space frame by definition has all of its elements loaded in pure tension and compression. Achieving this loading in a real frame is rarely practical. Reducing aerodynamic drag is accomplished in part by minimizing the size of a vehicle. Unfortunately, necessary evils such as drivers and motors are then required to occupy the same space as some of the tubes. The compromise is a frame that contains some elements that see torsional and bending loads and a driver that is somewhat uncomfortably constrained (but not skewered) by the frame tubes. Having the driver get into the car and then bolting in some more frame tubes has been outlawed in most forms of racing.

3 Materials

Welded, DOM (drawn over mandrel) 4130 alloy steel tubing is the nearly universal choice for high performance frame construction. Welded 1020 steel tubing is used when weight is less critical and cost is a concern. Aluminum frames can be slightly lighter, but aluminum has no endurance limit [5], so it will eventually fail, often catastrophically. Aluminum is also far more difficult to weld than steel. Titanium is a reasonable frame material if the vehicle is going to spend time submerged in salt water. Magnesium and graphite-epoxy has properties that make them suitable for derigibles and HPA (Human Powered Airplanes), applications where long spans are desirable and denting of the tubes is unlikely.

4 Joining Techniques

Welding, silver soldering, and brazing are the common methods used to join frame members together. The best method for a particular application is a function of many variables including tube material and thickness, number of frames to be made, operator skill, workshop facilities, and OSHA requirements.

TIG (Tungsten Inert Gas) is the most commonly used welding process for building high performance tube frames. TIG welding is used to make frames from steel, aluminum, titanium, and magnesium. The primary reasons for the wide applicability of TIG welding is that the source of heat is controllable during welding and independent of the introduction of filler metal into the weld. Lower performance applications such as lawn tractors and go-carts are often assembled with MIG (Metal Inert Gas) welding. MIG welding couples heat and filler metal flow, so welding the changing geometry of a tube joint (with varying requirements for heat and filler metal) is quite difficult. Successful MIG welding requires
some combination of more operator skill, better tube fit-up, and thicker tube walls than
is required for TIG welding. MIG welding is commonly used only on frames with simple
joints (one tube to another) and/or to frames using large tubes (2 inches or more). SMAW
(Shielded Metal Arc Welding, also known as “stick” welding) is used on heavier tubes and
rails (1/8 - 1/4 inch wall thickness). The big plus of SMAW is the low cost and portability
of the equipment ($200 - $1,000 vs. $2,000 - $10,000 for TIG and MIG). Truck frames are
often assembled with MIG welding or SMAW.

The joints formed by silver soldering are incredibly strong and fatigue resistant. In fact
they are often far superior to welded joints. Silver solder is not used extensively in industry
because of the high cost of the material (100 times as much as steel welding wire) and
the expense of close tolerances on the joint. The strength of the standard silver soldered
joint comes from a combination of good shear strength of the solder, close fitup, and large
surface area. Like many glues, the strength of a joint made with this process goes up as the
thickness of the solder joint is reduced, so fitup is critical. Silver soldering is by far the most
common method of assembling high performance bicycles. The desired large surface area is
achieved on bicycles through the use of lugs. The low surface tension and high wetability
of silver solder allow it to penetrate deeply into a gap only a few thousandths of an inch
wide. Since lugs are not made in the necessary shapes and sizes for most other frames,
there are very few applications for the use of silver solder in chassis construction. However,
silver solder is extremely useful in those few applications. Assembly of threaded inserts in
suspension rod ends, steering linkages, and spindle/flange assemblies are several important
uses.

Silver solder is also very useful for mix-and-match drivetrain assemblies. For example,
building a prototype may require grafting a transmission output shaft to a universal joint
to a gear sprocket, all from different manufacturers. Welding this type of assembly can be
very dangerous because the composition of the steel used for the parts is usually hardenable.
The resulting welds can therefore be very brittle and likely to fail without warning. Silver
soldering this type of assembly produces a more ductile joint, often with less warpage as
well.

Braze welding is a variant of brazing that has been used in this manner to build high
performance airplanes and racing cars. Joint fitup tolerances are so loose that frame tubes
are typically cut by hand using aircraft shears. Brass is then built up around the joint to 4
or 5 times the wall thickness of the tubes being joined. This guarantees that the brass has
a higher yield strength than the tubes. Brazing equipment is cheap ($300), portable, easy
to use, and very fast. Two people with one or two weeks experience can build a frame in
two or three days.
5 Suspension

Wishbone (A-arm) suspension has become the nearly universal choice of prototype and racing car chassis builder [1]. This type of suspension is used because it has very low unsprung weight, is easily adjustable, and is also one of the easiest suspensions to build. Springs and shocks are incorporated into the suspension in the form of direct acting coil-over-shocks (in full bodied cars) or as coil-over-shocks acting through pull rods or push rods (in open wheeled cars). The most common production vehicle suspension is the MacPherson strut [1,2,3]. This type of suspension is used because it is cheap to build in large quantities, not because it is particularly good mechanically. Building prototypes of this type of suspension is difficult, but cannibalizing parts from an existing car is often a viable option.

6 Steering

Rack and Pinion steering is positive, light, cheap, available in many sizes, easy to build (on the rare occasions when necessary), and easy to install [1,2,3]. There is really nothing else worth considering for a practical car. For impractical cars, e.g. high milage and land speed record, and also for other vehicles, steering using cables or tillers should be considered.

References


Wheels, tires, brakes and the drive train are the last links in the chain between the photons hitting the solar panels and the car moving along the road. Some may be tempted to put off wheel and brake related decisions until after the rest of the design has been finalized and then try to retro-fit a brake, steering and wheel system onto the car, but this will most often result in a compromised performance.

There are many tradeoffs to be considered when designing the wheels and brakes of a racing car. Most notably weight, aerodynamics, rolling resistance, manufacturing cost (including time, money and expertise), availability of parts, reliability, ease of maintenance, and ability to quickly replace a malfunctioning part under race conditions.

The choices made usually break down into:

1. Braking system(s)
2. Solid wheels vs. spoked wheels
3. Tire type
4. Drive type

The following comparisons of the advantages and disadvantages of different components is geared towards lightweight racing vehicles, but quite a bit of the information may also be useful when designing heavier commuter cars. I have attempted to make this list of options as complete as possible without bothering to include components obviously inappropriate for solar electric racing. Despite this, I have very likely left out some viable options, so your design should not be limited by the examples I have chosen. I have included a table at the end summarizing the comparisons.

1. Brakes:

Brakes are the most important safety feature of any vehicle. The most common types are disc/caliper brakes, drum brakes, regenerative brakes (using the motor as a generator to recharge the batteries), caliper brakes, and interference brakes. Most of these systems are usually actuated with a cable or hydraulically (a cable is much easier to install and maintain, but more prone to breakage). Since the safety rules in most races require more than one braking system, many will use combinations of these systems.

Regenerative brakes are the most efficient because they let you store some of the kinetic energy of your vehicle back in your batteries. 'Regen' is a feature offered on some motor controllers, and if available to you should probably be used for the initial braking of the car, but have a friction brake system for emergency stopping.

Disc brakes operate with a caliper or piston pushing on a disc. They are very reliable, have high stopping force and do not tend to 'fade' as overheated drum brakes can. Light weight disc brakes are made for bicycles by Phil Wood in California or for racing go carts by companies like DAP in Italy. If these special purpose disc brakes are too expensive, disc brakes may be bought at a motorcycle salvage shop and adapted for use on the car but you should keep in mind that these larger brakes will have enough stopping power to lock up your wheels as well as being heavy.

Drum brakes are cheaper and easier to use, but are not as powerful as disc brakes. Many different sizes have been made for two wheeled vehicles from small mopeds up to large older model motorcycles, and are readily available at used motorcycle parts dealers. If you use them, you will most likely want to build up your own wheel on the hub as the rims tend to be steel and very heavy.

The last two kinds of brakes should only be used as parking brakes, and never as a primary or backup braking system of the vehicle. Caliper brakes of the sort that are used in bicycles simply do not have the strength to stop a 400+ lb. vehicle under any circumstances. As a parking brake, they are a cheap,
easily installed system, but no driver should have to trust their safety to that kind of braking system. Interference brakes such as chocking the wheels or jamming a stick through the wheel and frame are useful as parking brakes but obviously impractical for slowing a vehicle down.

2. Wheels:

Spoked wheels are light, cheap, and easy to build on a variety of hubs. They do not require machining skills and local bike shops can lend their expertise when making them. Their downside is they are not quite as strong as a solid wheel and any steering arms, brake calipers or kingpins associated with the wheel is out in the wind causing drag.

The solid wheel alternative is much more expensive, requires many more manufacturing skills (machining, welding and composite work), but if properly done will yield a much stronger and more aerodynamic wheel with comparable weight. In the worst case, you will end up with a heavy, strong wheel without much aerodynamic advantage over the spoked wheel.

16-20" wheels are most often used for this kind of racing because of the variety of tires available. But be aware that a 16" motorcycle tire has a larger outer diameter than a 20" bicycle tire because of the different rating systems (motorcycles measure the rim diameter while bicycles rate the outer diameter of the wheel with the tire installed).

3. Tires:

Solar-electric racing vehicles are usually much lighter and operate at lower speeds than other classes of racing vehicle. Because of this, small, light, high pressure bicycle and motorcycle tires can be used instead of heavy car tires, letting you achieve greater efficiencies.

In general, the smaller the tire patch (the tire's area of contact with the road), and the higher the tire pressure, the lower the rolling resistance. The disadvantages of small tires is they tend to pinch tubes more easily when hitting pot holes (and go flat) as well as being more likely to roll off the rim under extreme cornering. The advantages are greater efficiency, better handling, quicker flat changes and cheaper tires.

The lowest rolling resistance tire I've come across yet is the Avocet Fasgrip 20x1.75" bicycle tire. It can be inflated to 100 psi, has Kevlar casing (puncture resistant) and has been used on both the GM Sunraycer and the MIT solectria 4 & 5 series cars. It is a slick (no tread), so there are some restrictions on its use in road racing, and the rules of the particular race you are entering should be consulted before deciding to use this tire. A treaded alternative to the Fasgrip is a 20x1.75" tire made by ACS. It has the same rated pressure and only a slightly higher rolling resistance. Both can be found in local bike stores.

If any wheels on your car are expected to carry a heavy load (more than 250lbs supported by that one wheel) or experience cornering at the limit of adhesion, heavier duty motorcycle tires are safer to use. Metzler Tires makes a 50cc racing class tire which is smaller and lighter than most motorcycle tires and has been used by the MIT team for their rear wheel in transcontinental racing. Performance scooter tires are another option. Both have the disadvantage that they must usually be special ordered, tend to be more expensive (can be as much as $100 per tire), are harder to change if they go flat, and have higher rolling resistance and aerodynamic drag than the bicycle tires. The advantages, however, are they very rarely get flats and are much more durable.

The puncture resistance of any tire can be increased by using puncture resistant inner tubes or liners which are available at bicycle stores.

I would NOT suggest that you use golf cart tires or low pressure moped tires, because the penalties you pay in decreased performance are too high. As a rule of thumb, if the rated pressure is lower than 50psi, it's probably too low for this kind of racing. In addition, any kind of knobby tread is a waste of power without giving you any increase in traction. For commuter cars, however, compact spare tire sizes are useful.
4. Drive type:

Chains are nice in that they cheap, can be cut and resized as you make design changes, and they are readily available in a large range of sizes and weights. Toothed belts are a more 'permanent' decision since they cannot be resized once bought, but kevlar reinforced versions will not stretch, and are much quieter and cleaner than chains. Direct drive gears are heavier, even more expensive and require that the motor be very accurately positioned w.r.t. the driven wheel, although they will last much longer than either chains or belts, it doesn’t seem to me that that is much of an advantage since are experimental cars and are not expected to driven 100,000 miles.

Suppliers:

Tires

Avocet USA (In bicycle shops)
Metzler (Motor cycle tires)
ACS Tires (In bicycle shops)
Compact spare tires (Car tire dealers) ** Commuter vehicles

Brakes

DAP (Italy)
Phil Wood, California
Motorcycle Dealers

Wheels/Rims

Araya Rims (In bicycle shops)
Aluminum Alloy Motorcycle rims (Motorcycle Dealers)

Hubs

Phil Wood, California
Make your own (for solid wheels)
The local moped junkyard

For further reading:

GM Sunrayce manuals
### A Brief Summary of Design Options

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Wind Drag</th>
<th>Roll. resist</th>
<th>cost</th>
<th>time</th>
<th>availability</th>
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Worse 1 2 3 4 5 Neutral 6 7 8 9 10 Better
The following comments are intended to clarify the "Scrutineering Checksheets" items 4/Construction & Safety, and 5/Cone test. The comments are titled following the areas of technical inspection listed in the Scrutineering Checksheet published for the Tour de Sol 91. The appropriate rules are cited using the numbering system set out in the 1991 American Tour de Sol Rules & Regulations Handbook.

6.27 Safety (4/Construction & Safety)

Note: All conversion vehicles which utilize unaltered Original Equipment Manufacturers (OEM) parts will be considered as having passed the Construction and Safety inspections and are only required to show that all parts are in good working order. Any alterations to the OEM steering, braking, suspension, or driver restraint systems must adhere to the following Standards. Conversion vehicles are, however, required to carry an appropriate fire extinguisher. See 6.27.10

6.27.1 Seat belts & Mounts

All vehicles with three or more wheels must be equipped with a two (2) strap (lap belt) restraint system. The belts must join with a single metal-to-metal quick release buckle, and be in good condition. Areas through which the belts pass must be grommetted to prevent chafing.

The belt attachment points must be designed in accordance with sound engineering practice. All attachments must be to the frame and not to the seat. (See Fasteners 6.27.6)

The belt must be worn in such a manner that it passes around the pelvic area at a point below the anterior superior iliac spines. Under NO circumstances may it be worn over the intestines and abdomen. The belt attachment points must be designed in accordance with Figure 1.

6.27.2 Sharp Edges

All sharp edges which might endanger the driver must be eliminated. All structural parts in the area around the drivers head (roll bar) must be padded with a resilient material. Recommended materials are Ethafoam or Ensolite.
6.27.3 Brake/Steering Controls

See 6.11
See Also Fasteners 6.27.6

6.27.4 Load Bearing Parts

All load bearing parts or areas which are part of the suspension, braking, steering, and driver or passenger seating areas, must be designed in accordance with sound engineering practice. All welds and/or other attachment methods must be checked for integrity. This is extremely important for older vehicles, and those constructed of materials which do not exhibit an endurance limit (i.e. aluminum).

6.27.5 Suspension/Steering Systems

Any vehicle using single shear connections for the upper and/or lower ball joint mounts (knuckle pivot points), the tie rod attachments, or suspension links, must incorporate a safety washer of sufficient diameter to prevent total separation in the event of bearing failure. Double shear connections are recommended. See Figure 2.

6.27.6 Fasteners

All fasteners in the steering, suspension, braking, and driver restraint systems must be captive. This is defined as requiring locknuts, cottered nuts, or safety wired bolts (in blind applications). Tread sealant does not meet this requirement. All bolts in these systems must meet SAE grade 5, or AN military specifications. See Figures 3, 4, & 5.

6.27.7 Driving Position

See 6.16

6.27.8 Driver's Visibility

See 6.17

6.27.9 Horn

See 6.15

6.27.10 Speedometer

See 6.18
6.27.11 Fire Extinguisher

A fire extinguisher with a minimum UL rating of 5 B-C must be mounted in the cockpit, and be easily accessible to the driver. Mountings must be designed to resist shaking loose while allowing the driver to remove it easily if necessary. Remote systems containing at least five (5) pounds of Halon 1211 or Halon 1301 are acceptable.

6.27.12 Brake, Turn Lights, & Reflectors

See 6.14

6.27.13 Head & Tail Lights

See 6.14

6.27.14 Stability Test (rocking test)

The technical inspector may ask to have the vehicle rocked to exercise the suspension system before proceeding to the Cone Test.

5/Cone Test

The "cone test" is a slalom course made up of a straight line of cones spaced at approximately twenty five (25) feet apart. This is not a speed event but rather a test of the vehicle's steering geometry. The technical inspector will view the vehicle as it makes it's way through the course, and comment on the vehicle's steering behavior through hard cornering.

Due to the limited space available in this publication, I have not attempted to include any of the illustrations cited above. I will however provide these at the presentation. I would also like to spend some time during the presentation sharing my views on several common errors in steering and suspension geometry that I noticed during the technical inspection of the vehicles for the 91 Tour de Sol. I will provide information and illustrations on this material as well.
Advanced Electric Vehicles, Parts I & II

Advanced Electric Vehicles, Part I
The finer points of solar and electric vehicle current technology and future prospects.

10:30-NOON
Session Chair: Gill Pratt, Research Scientist, MIT Cambridge, MA, Co-chair S/EV 91

Motors: Performance and Limitations
Bob King, Drive train designer, General Electric, Schenectady, NY

Motors of the Future
Steve Meyer, Manager of Motor and Drive Products, Unique Mobility, Englewood, CO

Power Electronics and Controller Design
Gill Pratt, Ph.D., Research Scientist, Massachusetts Institute of Technology, Cambridge, MA

1:45-3:15
Session Chair: Wayne Kirk, Composite Engineering, Concord, MA

Vehicle Construction From the Ground Up: Composite Basics
Andy Marshall, P.E. Marshall Consulting, Walnut Creek, CA

Advanced Composites: As Used in State of the Art Auto Racing
Jason Johnston, Advanced Composites, Owasso, OK
Richard Hewett

3:30-5:00
Session Chair: Steven Strong, Solar Design, Harvard, MA

Photovoltaics: Present and Future Prospects
Fritz Wald, Director of Research, Mobil Solar Energy Corp., Billerica MA

New Photovoltaic Techniques Coming to Market
Paul Maycock, Energy Systems Inc & PV News, Casanova VA

Advanced Electric Vehicles, Part II
The finer points of solar and electric vehicle current technology and future prospects.

10:30-NOON
Session Chair: David Reisner, Reisner Group, Bristol CT

Supercapacitors: Super Power Density Gives Improved Battery Performance
Andrew Burke, Idaho National Engineering Lab, Idaho Falls ID

Room Temperature Lithium Batteries
K.M. Abraham, Ph.D., Head of Research, EIC Laboratories, Norwood, MA

1:45-3:15
Session Chair: Dr. Robert Wills, Skyline Engineering, and Co-chair S/EV 91

Nickel Metal Hydride Batteries
Dr. S. Venkatesan, Ovonic Battery Company, Troy, MI

Sodium Sulfur Batteries: A Critical Look at the Hope of the Future
Andrew Burke, Idaho National Engineering Lab, Idaho Falls ID

3:30-5:00 Closing Plenary:
see plenary sessions

Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051
Advanced Drives for On-Road Electric Vehicles

R.D. King
General Electric Corporate Research and Development
Schenectady, New York, USA

Abstract

Electric vehicle research and development is increasing worldwide as a result of recent California legislation requiring that 2% of all vehicles sold in the state in 1998 have zero tailpipe emissions, and increasing to 10% by the year 2003. Widespread use of electric vehicles promise an improvement in air quality in urban areas as well as a reduction in foreign oil imports. An Electric vehicle produces less than 2% [1] of total amount of reactive organic gasses, (including emissions produced at the power plants) as produced by a conventional internal combustion engine vehicle.

Electric drive systems have made significant improvements during the past 12 years. These drives have increased efficiency, improved reliability, reduced size/weight and improved driveability through advanced controls and improved power electronics. Future electric vehicle drives will be ac. This paper compares electric drive systems for three advanced electric research vehicles developed at GE during a 12 year period.

Introduction

Most electric vehicle drives produced prior to 1975 utilized series dc motors and either a stepped resistor or Silicon Controller Rectifier (SCR) controllers. Series field DC motors have been used successfully for transit cars and locomotives that require large starting torques. Regenerative braking was not typical for these drives in electric vehicle applications. More recent DC drives for electric vehicle applications use shunt field machines that provide reasonable starting torque and can be designed to achieve constant power operation over a speed range of two or three to one with relatively low power transistor field choppers. Regenerative braking functions can easily be provided with the DC shunt machines and simple controls.

During the last 8 years, rapid development of power electronic technology, microprocessor-based controls, high speed/high power ac motors, and integrated transaxles have reduced the size, weight, and volume of electric vehicle drive system components. The following paragraphs provide a brief description of several experimental research electric vehicles developed by General Electric Company.

The Electric Test Vehicle (ETV-I) [2] was developed by General Electric Company and its subcontractors as part of the Near-Term Electric Vehicle Program. This contract number DE-AC03-76CS51294 was conducted for the U.S. Department of Energy from April 1977 through July 1979. ETV-I experimental vehicle incorporated technology improvements to achieve a level of performance substantially better than previous state-of-the-art electric vehicles.

In August 1985, the 50 Hp induction motor-based ETX-I Advanced Electric Vehicle Powertrain Program (Contract No. DE-AC08-82NV-10308) was completed. Testing performed under that contract [3,4] verified that the vehicle met its very aggressive targets for energy consumption, acceleration, gradeability, and automotive industry acceptable driveability. This highly successful contract, which 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 developed on the U.S. Department of Energy contract, Single-Shaft Electric Propulsion System Development Program (ETX-II). This contract commenced in March 1985 [5]. ETX-II research effort concentrated on development of highly efficient electric drive system components (96% maximum motor efficiency) [6,7], 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 concentrically mounted on 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 mini-van.

Performance goals for the ETV-I, ETX-I, and ETX-II propulsion system are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>ETV-I</th>
<th>ETX-I</th>
<th>ETX-II</th>
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<tr>
<td>Energy Consumption (FUDS), (kWhr/km)</td>
<td>NA</td>
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<tr>
<td>Maximum Speed, (km/hr)</td>
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<td>0-48 km/hr acceleration, (sec)</td>
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<td>Range on SAEJ227a schedule D</td>
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<td>Gradeability, (%)</td>
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**Drive System Description**

The ETV-I, designed in the late 1970's, was at that time, the world's most advanced electric vehicle. ETV-I drive system consisted of a 20 Hp continuous rated 2500/5000 rpm, 96 volt, 175 A separately excited DC shunt wound motor. Smooth control of the drive was provided by a transistorized armature chopper (400 A rated) and field chopper, both under microcomputer control. A single speed transmission with gear ratio of 5.48:1 was developed to couple the motor to the front wheel drive vehicle. The drive was powered from a nominal 108 V lead-acid battery.

ETX-I electric drive system consists of a high speed light weight 50-hp three phase ac induction 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 induction motor as adjustable frequency ac power. A unique compact 2-speed transaxle was developed with the induction motor mounted concentric to the drive axle. Motor cooling is provided by automatic transmission fluid, while the transistor inverter was liquid cooled with ethylene-glycol-water.

The advanced ETX-II ac electric drive system consists of a 70-hp interior permanent magnet (IPM) synchronous motor, a three-phase transistor inverter, and microprocessor-based field oriented vector 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.
Motor Design

Design and/or selection of the electric motor is vital to the success of the project. Analysis of the vehicle's acceleration, gradeability requirements and vehicle design, (including gear ratios, tire size, vehicle weight and drag coefficient), determine the maximum torque of the electric motor. If a single speed transmission is selected, then the motor needs a wide constant power range for adequate acceleration throughout the required vehicle speed range. Use of a multi-speed transmission allows the motor to have lower stall torque and a smaller constant power range, but not a lower power rating for similar vehicle performance. Reduction in the constant power range usually results in a motor design that is smaller and lighter weight. However multi-speed transmissions, compared to single-speed transmissions, are larger, less efficient, heavier and require increased control complexity for higher slew rates and/or synchronized speed matching.

Table 2 shows a comparison of the ETV-I, ETX-I, and ETX-II electric motor parameters selected for their respective vehicle designs.

<table>
<thead>
<tr>
<th></th>
<th>ETV-I</th>
<th>ETX-I</th>
<th>ETX-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power (HP)</td>
<td>42</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Design Speed (rpm)</td>
<td>0 - 5,000</td>
<td>0 - 9,000</td>
<td>0 - 11,000</td>
</tr>
<tr>
<td>Max Speed (rpm)</td>
<td>6,000</td>
<td>10,500</td>
<td>13,750</td>
</tr>
<tr>
<td>Rated Current (A)</td>
<td>400</td>
<td>225 A rms</td>
<td>325 A rms</td>
</tr>
<tr>
<td>Rated DC Link (V)</td>
<td>100</td>
<td>153</td>
<td>135</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>217</td>
<td>88 *</td>
<td>112 *</td>
</tr>
<tr>
<td>Transmission Speed</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air</td>
<td>Liquid (Oil)</td>
<td>Liquid (Oil)</td>
</tr>
</tbody>
</table>

Efficiency of the electric drive system is extremely important considering the limited energy density of today's batteries or solar arrays. Electric vehicle's range analysis requires detailed knowledge of the intended mission or driving cycle. Accurate models of the motor, battery, and power electronics' efficiency versus operating torque/speed points are necessary to predict vehicle range. In both the ETX-I and ETX-II programs, component (inverter and motor) and electric drive system efficiency was measured in the laboratory using a computer controlled data acquisition system. A matrix of these efficiencies, measured at specific torque/speed operating points, was input to a vehicle simulation program for predicting range over given driving cycles.

Motor efficiency can vary significantly over the range of torque/speed operating points. Also, motors that are very efficient on the maximum torque envelope are not necessarily efficient at other operating points. Examples motor efficiency for different torque/speed operating points will be included in the presentation.
Figure 1 shows the torque/speed curves for the ETV-I, ETX-I, and ETX-II motor designs.

Figure 1. Torque/Speed Curves for ETV-I, ETX-I, and ETX-II Motor Designs

References


INTRODUCTION

Electric motors consume more than half of all the electricity generated in the U.S. The most common type of motor, the constant speed ac motor, is widely acknowledged as the workhorse of industry. For decades, the brush commutated dc motor has filled the role of the adjustable speed system. Brush dc motors are relatively inexpensive and easy to control, but they require periodic maintenance due to the wear of metal to carbon contacts with the rotating armature.

Several years ago, advances in electronics led to the development of devices that could vary the frequency of ac current and thereby avoid the constraints of fixed 60 cycle line current as a power source. This meant that a constant speed ac motor could be made into an adjustable speed motor without the need for brushes. Some disadvantages, however, were the high cost of the power electronics and limitations in overall motor performance and efficiency.

More recently, similar control electronics have been applied to permanent magnet dc motors with the result that today's most advanced brushless dc motors can generally provide higher performance and efficiency than the variable frequency ac motor. Most of these improvements have been made possible by the increased sophistication in the electronics and controls field and not in the basic motor construction. Unique has closed this loop with a beyond-the-state-of-the-art motor design that represents a quantum leap in permanent magnet brushless dc motor performance.

DISCUSSION OF THE FUNDAMENTAL CATEGORIES

AC Single Phase versus Three Phase

The AC motor operates by rotating an electromagnetic field in the stator winding which produces torque by passive attraction of the rotor. The torque product of this design is limited since there is only one source of flux producing energy: the stator.
In an effort to create more mechanical power from this class of machine, the three phase design allows summing of three electrical power sources at 120 phase angle separation to produce torque. This permits power to weight performance of 13 lbs/HP in some of the better designs.

Application of inverter power electronics allows variable speed operation of this type of motor with very good power control. Starting currents and overcurrent conditions are severely limited by the solid state power electronics. Losses in the motor will still be governed by the magnetizing losses of the steel laminations and copper losses.

DC Single Phase versus DC Three Phase Brushless

The traditional choice for variable speed operation has been the brush commutated single phase dc motor. Cost of the power electronics has been low and efficiency has improved somewhat with the application of PWM type controls. The presence of brushes and the resulting maintenance requirement has always been considered a major disadvantage. Power to weight performance of 20-30 lb/HP is typical of this technology.

In an effort to eliminate brushes, a variety of motor structures has been developed, the most power-dense of which is the brushless dc motor. In this class of machine, the power electronics content is similar to that of the ac inverter and motor combination, but the motor has permanent magnets which produce greater flux density.

THE UNIQUE CONSTRUCTION

In this patented class of machine, a variety of design attributes has been combined to produce an extremely efficient, power-dense motor.

High Pole Count - Reduces magnetizing steel
Neodymium Magnets - Highest flux strength/weight
Slotless Stator Design - Reduces hysteresis and eddy current losses
The UNIQ® motor is of a tube or sleeve design in which radially positioned permanent magnets are mounted on a hollow rotor which is coaxial with a radially thin hollow stator (armature). Figure 1 shows an early embodiment of the technology in which the rotor element consists of two concentric magnet rings which rotate about the stator winding. This design is referred to as the double ring (DR) series and employs internal forced air cooling whereby the cooling air passes over both surfaces of the stator.

Figure 1
The magnet material used is a newly perfected "super magnet" formed from the rare-earth neodymium, alloyed with iron and boron (NdFeB). These magnets are stronger than the best samarium cobalt magnets and promise to cost much less as the demand for them increases. (See Figure 2).

![Developments of Permanent Magnet Materials](image)

Figure 2

A later (more practical) embodiment of the UNIQ® motor incorporates a single magnet ring (SR series). Heat transfer is improved because the stator winding is in direct thermal contact with an externally fin cooled motor housing as shown in Figure 3. Unlike the DR series, the magnetic return path is integral with the motor housing.
The essence of the technology in either the DR or SR series motors is related to the novel configuration of the stator winding. In conventional motors, the copper windings are placed in slots formed by the flux carrying "teeth" of a (heavy) pre-assembled stack of punched steel laminations. In the UNIQ® motor, bundles of fine copper wire are wound into a free standing cylindrical ring and (lightweight) flux carrying iron bars are then inserted longitudinally between the wire bundles. This structure is then cast in a thermally conductive fiber reinforced epoxy resin to form a monocoque shell which provides the rigidity required for mounting the stator to the motor backplate. Figure 4 depicts the stator winding in various stages of construction.
The geometry of the UNIQ\textsuperscript{®} stator construction such that the slots into which the copper is laid can be made much narrower than the slots between the teeth in a conventional lamination stack. This results in a wider dispersion of copper within the stator and permits tighter turns at the stator ends. Use of fine wire minimizes eddy current and hysteresis losses thereby improving efficiency. The tight end turns increase the utilization of copper. Moreover, the narrow slots enable the use of narrow magnets which, in turn, permits the use of a relatively thin mounting ring and a equally thin magnetic return path. Therefore, the overall iron content in a motor of this type is significantly less than in a conventional motor employing laminations. A graphic comparison of the iron content in a nominal 15 kW conventional motor versus a UNIQ\textsuperscript{®} motor of the same nominal rating is shown in Figure 5.
The net result of these features means that the UNIQ\textsuperscript{®} motor can operate at higher speeds with lower losses and thereby produce more power in a smaller, lighter-weight package than its conventional counterpart. Figure 6 depicts measured performance versus predicted performance for a 15 kW UNIQ\textsuperscript{®} motor weighing less then five kilograms, for a power density of 3 kW/kg (approximately 2 hp/lb).
The Unique motor offers:

1. High efficiency over a broad range of operation - Unlike other technologies, the Unique motor is 90+ percent efficient over 90% of its speed range. Most motors have a very narrow band of high efficiency operation which makes them relatively unsuitable for vehicle applications.

2. Reduced losses and heating - Given the overall package size, the amount of heat produced and its management becomes a limitation to motor operation. By reducing the required magnetizing steel, not only are losses reduced, but the net heating of the motor is reduced as well.

3. Highest power density available - Even a superconducting wire magnetizing a steel lamination will not produce the same high energy density as a UNIQ stator. The steel magnetizing losses will exceed the improvement from the wire losses. The only advantage will be reductions in heating from the copper.
ELECTRIC VEHICLE MOTOR CONSIDERATIONS

In order to properly build an electric car, the electric motor and drivetrain combination must be well matched to the vehicle power delivery requirements at several levels. In general, the profile for powering a vehicle follows a curve (See Figure 7) with high torque at low RPM and low torque at high RPM.

This profile can be achieved in a number of ways: 1) by using a winding switch in the motor to produce two different torque characteristics (See Figure 8), 2) by employing a two speed gearing arrangement (See Figure 9) or 3) by applying high technology power electronics schemes. Presently, Unique Mobility is developing technology for all three approaches.
Figure 8

PERMANENT MAGNET MOTOR CHARACTERISTICS

Figure 9
The electric vehicle motor of the future could be based on one or all of the emerging technical approaches depending on manufactured cost for a given type of vehicle performance. Due to the advantages of the Unique motor this technology should be a mainstream technology in future vehicle design.

Can the motor be designed into the wheel? Probably. The question involves two variables, the first of which is the ultimate weight of the drivetrain and the second of which is the impact on the suspension system as a result of weight. Since it has been demonstrated that in-wheel drive motors are very heavy and have a negative impact on the suspension, the objective will be to further push the weight constraints toward lightweight design. If the wheel rim can be reduced by using lighter weight alloys, and the tire design can be defined for this approach, the weight trade off to install the motor in the wheel could be feasible.
Appendix: Questions and Answers Relating to AC versus DC Motor Technology

Introduction

Most motor action is the result of at least one, but generally two magnetic fields interacting to convert electrical energy into mechanical energy.

In AC motors, the stationary portion of the motor creates a rotating electromagnetic field which induces rotation in the rotor by passive attraction of the moving field with iron poles in the rotor. Traditionally this approach results in constant speed rotation of the motor.

In a DC motor two opposing fields interact and this creates a mechanical torque over a narrow angle of rotation. Switching the current in the armature causes the interaction to be maintained and thus the armature rotates. This switching is referred to as commutation and is typically accomplished by connecting the windings to a segmented copper ring or disc and using spring loaded carbon brushes to effect current switching.

Recently, advances in power electronics have made variable speed AC possible as well as Brushless DC (BLDC) systems in which permanent magnets are used to create one of the two magnetic fields in the motor. Thus, in these systems commutation is accomplished electronically.

The superiority of one system over the other has been the subject of some controversy which we hope to address in this note. The two technologies considered specifically are variable speed AC and Brushless DC.

Some typical questions are:

1. What are the advantages of BLDC motors over AC?
   - The ability to generate power during braking and deceleration. (AC motors with standard rotors cannot generate any power.)
Higher efficiency which gives greater range to the vehicle particularly at lower speed ranges such as in urban stop-start driving.

With Unique’s construction, the motor is less than one-half the size and weight of the most advanced AC drives available.

Unique’s motor construction is BLDC so there is nothing to maintain.

2. What are the disadvantages of BLDC motors?

- Expensive controller electronics as compared to the electronics for brush commutated DC motors.

- Use of rare earth magnets. (Actually the forecast for Neodymium Iron Boron is a declining cost with increased capacity since it is not a strategic metal and is readily available.)

3. What are the advantages of AC motors over BLDC?

- More engineering history of AC motors and drive electronics.

- Greater manufacturing capacity for this technology, stamped laminations and automated winding machines already exist. Mature fabrication processes have produced low cost manufacturing capacity.
4. What are the disadvantages of AC technology?

- It is less efficient because the stator uses steel laminations with copper windings to produce a magnetic field. This results in losses magnetizing the steel.

- In order to reduce the weight from the usual 10-20 lbs/HP the motor speed is increased from 10-15,000 rpm. This requires very sophisticated materials and engineering and will prove costly to manufacture.

- Expensive and bulky electronics.

5. Is AC superior to BLDC in Electric Vehicle applications?

- No. It is generally conceded that BLDC motors are more efficient than AC motors.

6. Doesn’t BLDC motor technology cost more than variable speed AC?

- At the present, this is true for the motor. However, with the patented UNIQ structure and the elimination of laminated steel in either stator or rotor, the ultimate material costs are much lower. In addition, with volume manufacturing, the process costs should also be equal or less, since less material is being processed.

- The controller electronics cost is approximately equal since both systems are three phase electrically and the power electronics content is approximately the same.
The Subtle Aspects of Controller Design

Gill Andrews Pratt

Massachusetts Institute of Technology

NESEA S/EV 91

ABSTRACT

Electric vehicle motor controllers are often designed and selected without a clear understanding of the electric vehicle environment. A solar/electric vehicle is significantly different than a factory floor or an NC machine, but unfortunately most motor controllers are designed for these latter applications and "adapted" to electric vehicle use.

In this paper (and its accompanying talk), we will review what's important to look for in an electric vehicle motor controller. If time permits, we will then focus on a particular controller trade-off, the selection of 6-step or sine-wave drive for DC brushless motors.

1. What's Important

When selecting a motor controller for an electric vehicle, you should look for the following items, in decreasing order of importance:

1.1. Current Mode (Torque) Control

Velocity is not a directly controllable variable in an electric vehicle. Instead, it is determined by the speed of the car (and, of course, by the current transmission gear). Velocity changes slowly as the vehicle accelerates, and without extreme driver discomfort and great mechanical stress, velocity cannot be made to increase more quickly. Thus, velocity mode motor controllers, which are common in industrial applications, are ill-suited as electric vehicle controllers. Beware of speed controllers with over-current "safety" limits. The current limits in simple "open loop" PWM velocity controllers are usually not smooth enough to give acceptable ride quality in a car.

Unless a velocity controller with an inner current control loop and very weak feedback is used, torque should be the control variable, not velocity. This simply means that the driver's accelerator should control acceleration.

1.2. Robust Design and Construction

The engine compartment of an automobile, even without the engine, is not a very nice place. The ability of a motor controller to withstand vibration, temperature extremes, high humidity, and rain is of paramount importance. A controller built for educational purposes can be sloppy - but if you're expecting it to work in a racing or commuting car, don't be surprised if at least half your engineering time (and a good part of the cost) goes towards packaging.
1.3. At Least 2 Quadrant Operation

This means forward acceleration as well as regenerative braking. 4 Quadrant operation (the ability to go backwards) comes free in AC controllers, but is usually not justified in DC controllers, because the extra transistors of an "H" bridge generate extra loss. Motor reversal switches or transmission gears are the answer in these cases.

1.4. Undervoltage (low battery) Lockout

This is extremely important, and a test exists that every EV controller should pass: One should be able to attach a motor controller to a variable DC power supply and ramp the input voltage from 0 to its maximum value and back to 0, at any reasonable frequency, without damaging the controller or evoking "glitchy" behavior. This means the controller must have a hardware lockout circuit that works for ALL input voltages, regardless of rise-time. If this test is passed, you are assured that transients will not "get" you on some unexpected occasion.

1.5. Overvoltage Cutback

During regenerative braking, a motor controller may charge the battery completely (in a solar vehicle), or exceed the battery's maximum rate of charge. In such cases the battery voltage may come near a pre-set threshold, and the controller should gently reduce the commanded motor torque to reduce the power fed to the battery. This feedback is self-limiting, and should prevent the battery voltage from ever reaching the threshold. If the battery bus voltage rises rapidly (such as when a circuit breaker pops on a downhill brake), such feedback may be too slow and a very fast disable circuit should be called into play.

1.6. Overtemp Cutback

There is nothing worse than waiting for a hysteretic thermostat to reset. High temperature indicates something is wrong, either in operation, or in the original design - but this is no reason to strand the driver. As with over-voltage, high temperatures should invoke progressive cutbacks in operating current. A second, higher, temperature limit should invoke instantaneous (and perhaps latching) shutdown.

1.7. Battery Current Cutback

Battery life is directly related to rate of discharge and even more to rate of charge. Because every motor controller acts as an electronic transmission, it is possible, at high speeds, to run up against reasonable limits for battery current. Because batteries are, to first order, voltage sources, the easiest way to insure that battery current limits are not exceeded is to limit motor power. Feedback circuits based on battery current sensors tend to be unstable because the motor controller gain varies so wildly.

For slow speeds, the motor power limit does not come into play (motor current is limited instead), but as motor speed increases, the driver's pedal (torque) should be electronically pulled back, in feed forward fashion, in proportion to the motor speed. The motor power limits for acceleration and braking will typically be different.
1.8. Soft Connect

Motor controllers typically have large capacitors across the battery buss to act as local reservoirs of charge. As such, when any mechanical switch, be it a relay, circuit breaker, or power plug, first contacts the controller power terminals, a large spark is generated. This may excite the kids, but its bad for the capacitors and even worse for the contacts. Circuit breakers subject to this kind of abuse will fuse (closed!) after a short life, leaving the driver with no turn-off switch.

The answer consists of a slow charge-up resistor and an automatically activated contactor that bypasses the resistor once the capacitors are charged. When properly designed, this relay can consume less than 1/2 Watt of power.

1.9. Adjustable Pedal Offset and Gain

The importance of this depends on the type of pedal transducer you are using. Typically, the manufacturer of the controller doesn’t know your specific pedal mechanics. Thus, you’ll want to be able to adjust the controller to your set-up, rather than the other way around.

1.10. Galvanically Isolated Control Signals

It costs roughly an extra 100-dollars to completely isolate (to several thousand volts) a controller’s low level circuitry from its power stage. It’s worth every penny.

If every control circuit in an EV is isolated from the battery voltages, a non-isolated (transformerless) AC mains charger, with significantly better efficiency and lower cost, can be used. Isolated control means that ground loops aren’t formed when connecting instrumentation, or when ganging together two controllers in charge of separate wheel motors.

1.11. Brake Light Relay

Regenerative braking can be triggered by pressing the brake pedal, or in some controllers, by releasing the accelerator (a simulation of engine braking). The controller knows best when deceleration is occurring, and it makes lots of sense to have a relay closure output from the controller wired to the brake lights. An additional mechanical brake switch can be wired in parallel with this to make sure the brake light always go on, even if there is a controller failure.

1.12. High Efficiency

Motor controller efficiency IS important, but it is this far down on the list because the previously listed matters are more important. Good controller efficiency leads to longer range and longer controller life. As with motors, it usually (but not always) pays to force-air cool the controller. This is because FETs increase their resistance as temperature increases. To save power, a thermostat attached to the heat sink can be used to turn the fan on and off, but two thermostats should be wired in parallel for reliability’s sake.

1.13. Light Weight

This is an often heavily advertised feature, but is not really so important. At 40 MPH, the typical solar racing car pays a penalty of 1/2 Watt for every pound of extra weight. Thus, the advantage of lightening the controller by a few pounds is not very significant.
2. Sine-Wave vs. 6-Step

2.1. Introduction

In this month's (October '91) issue of the trade journal *Motion Control* there are two articles addressing the issue of sine-wave vs. 6-step control of DC brushless motors. Each article concludes with opposite statements - one promoting the benefits of sine-wave drive, the other of 6-step. Thus, one could correctly conclude that this issue is far from decided today.

2.2. Sine-Wave Control

Most sine-wave controllers use the technique of average current feedback to produce sine-waves (or more generally, arbitrary continuous waves) of current in a motor's windings. Each motor phase has a PWM circuit, and the signal from two phases of current sensors is low-pass filtered and then fed back to control two of the phases. Because the third phase current is the sum of the first and the second, the third PWM is usually driven by the (inverted) sum of the first two PWM control signals.

Most sine-wave controllers use a resolver for position feedback, which is an analog form of absolute encoder. In modern digital controllers, a R/D (resolver to digital) converter feeds a lookup table (ROM) which yields the desired phase currents.

2.3. 6-Step Control

Most 6-step controllers use PWM on only one motor phase at a time. Another phase is fixed by an always-on transistor at ground or the battery voltage, and the third phase is left floating. As the motor shaft revolves, the operation of only one phase is changed at a time, eliminating the possibility of "shoot through" and allowing for simple control circuitry.

3 hall effect sensors are usually used for one part in six absolute shaft position encoding, and simple digital logic can decode this signal into the appropriate drive configuration.

2.4. What kind of motor do you have?

DC brushless motors can be designed especially for 6-step or sine-wave drive.

If you have a brushless motor and want to find out what drive signals would be best, you can look at the back-EMF waveform as the motor is mechanically spun by an external source. If examining the phase-to-neutral leads, a six-step motor's back-EMF waveform should be very flat across 1/3 of a cycle, and each low/high or high/low transition should be limited to 1/6 of a cycle. If the phase-to-phase leads are being examined, the back-EMF of a 6-step motor should be very flat for 1/6 of a cycle.

Motors designed for sine-wave drive will have back-EMFs that look more like sine waves than 6-step waveforms. Because phase-to-phase waveforms are the sum of two offset phase-to-neutral waveforms, phase-to-phase waveforms tend to be more sine-like than phase-to-neutral, even if the motor is designed for 6-step (sum two ideal 6-step waveforms offset by 1/2 step and you'll see what happens).

2.5. Is There a "Natural" Motor Waveform?

It has been argued that a slotted DC brushless motor naturally has flat back-EMF peaks because of the width of the magnet poles and the narrowness of the winding slots. It is possible to make a brushless motor with sine-wave back-EMF by distributing the windings of each phase
across a wider area, but critics of this approach correctly point out that a more complex winding pattern is necessary, that adjacent wire voltages are high, and that the end-turns of the motor require more volume.

The trouble with this argument is that it ignores the fact that brushless motors with strong magnets and highly permeable laminations suffer from enormous reluctance cogging if the magnets are positioned without skew. To avoid this, manufacturers almost universally skew the rotor magnets, and this results in a smoother or more sine-wave like back-EMF. To achieve true 6-step compatibility, the magnets of a brushless motor would have to completely encompass the pole piece for 2/3 of a cycle, with only 1/3 of a cycle for the skew to completely traverse the pole piece. These limits can usually be imposed only at the expense of high cogging, and thus most brushless motors are not really designed for 6-step drive.

2.6. The Cost of Driving a Sine-Wave Motor with 6-Step

What if we drive the motor with 6-step anyway? First of all, the torque ripple will be worse. Let's take a hypothetical sine-wave motor with a back-EMF amplitude of 1 volt phase-to-neutral, or \( \sqrt{3} \) volts phase-to-phase. During one sixth of a revolution, centered on the peak of this phase-to-phase back EMF, a DC current is passed through the phase-to-phase winding. Centering the waveform around zero, the back-EMF is:

\[
\sqrt{3}\cos(\omega)
\]

as \( \omega \) varies from \(-\pi/6\) to \(\pi/6\). The fractional ripple is thus:

\[
1 - \cos(\pi/6) = .134
\]

Thus, one can expect about 13 percent of torque ripple in a perfectly aligned sine wave motor driven by 6-step current. As we will see later, this ripple can become much worse at higher speeds, or at lower speeds if static "timing advance" is used.

The average value of the phase-to-phase back-EMF during 1/6 of a revolution is:

\[
\frac{\int_{0}^{\pi/6} \sqrt{3}\cos(\omega) d\omega}{\pi/6} = \sqrt{3} \frac{\sin(\pi/6)}{\pi} = \frac{3/2}{\pi} = .95\sqrt{3} = P_{6\text{-step}}
\]

Because 1 ampere of phase-to-phase current flows through the motor during this period, this is also the average motor power \( P_{6\text{-step}} \). If the motor has a phase-to-neutral resistance of 1 ohm, the average resistive power loss (with 1 amp flowing) is \( \text{Loss}_{6\text{-step}} = 2 \) Watts.

Let's look at the same motor with the same average power and sine-wave drive. The average power is 3 times the product of the RMS leg voltages and currents:

\[
P_{\text{sine}} = 3 \frac{1}{\sqrt{2}} I_{\text{rms}}
\]

Setting this equal to \( P_{6\text{-step}} \), we derive that

\[
I_{\text{rms}} = .95\sqrt{3}/3
\]

The power loss for sine-wave drive with this RMS current is:

\[
\text{Loss}_{\text{sine}} = 3I_{\text{rms}}^2 = 3(0.95\sqrt{3}/3)^2 = 3(0.95)^2 = .91 P_{6\text{-step}}
\]
Thus, sine wave drive has the following advantages over 6-step when used with a sine-wave motor:

- Constant torque instead of 13% torque ripple
- 9% less loss

In practice even a sine wave motor controller has enough inaccuracy to yield about 3% to 5% torque ripple, but this is allot better than 13%!

2.7. Controller Efficiency

Six step controllers, other than being simpler and requiring less expensive shaft encoders, also have lower losses that sine-wave. This is because only one phase is being chopped at any given time, rather than 3. Thus, the switching loss will be somewhat lower than when all three phases are being chopped. Whether this offsets the extra 9% motor loss depends on the specifics of the controller power stage, and on the motor load.

2.8. The Cost of Torque Ripple

Torque Ripple can be a severe source of loss, driver discomfort, and poor reliability in electric vehicles. Typically, the drive coupling between motor and wheel has backlash and resonance, and the use of toothed belts or chains reduces the motor shaft inertia to low values. This means that even moderate motor torque ripple will cause high drive train losses and lead to mechanical failure - strong points in favor of sine wave drive.

2.9. The “Slushy” Zone

Every brushless motor has winding inductance and back-EMF. As the motor speeds up, the frequency of the current waveforms that must be driven into its coils increases, and the winding inductance makes this task more and more difficult (remember, the available battery voltage is fixed). The back-EMF also reduces the voltage margin that the controller has to place across the motor’s inductance, which further makes it difficult to generate the desired leg currents.

These two effects combine to establish a speed, lower than the unloaded motor speed, where the controller simply cannot deliver the desired current to the motor. Because this is a region of high power, battery limits may make this problem irrelevant, but in high-performance vehicles this “slushy zone” limit usually comes into play.

Because they request instantaneous changes in motor current, six-step controllers have a harder time with this problem than sine-wave controllers, and in many applications, this is a strong point in favor of sine-wave drive.

To compensate for this problem, motors driven with 6-step controllers often have their encoder vanes “advanced” statically so that the commanded current step changes will precede the motor’s back-EMF, hopefully resulting in approximately the desired current at high speed. This is an extremely crude and difficult to optimize process, and static tuning for good efficiency at high speeds often results in terrible torque ripple at low speeds. An approach to solving this problem involves fancy circuitry to dynamically advance the commutation points, but this pretty much negates the cost and simplicity advantages of 6-step drive.

Sine-wave driven motors also have a “slush” zone, but it is narrower than for 6-step drive and doesn’t require any sort of tuning (with accompanying low speed ripple).
2.10. The Shaft Encoder

The low cost of a 6-step hall sensor shaft encoder is an often cited advantage for 6-step drive. There are, however, alternatives for sine-wave drives that do not involve the cost of a resolver (and perhaps R/D converter).

An incremental encoder can be used, and the motor controller can be smart enough to rotate a weak magnetic field at startup to establish approximate position. Very little drive train backlash or spring is necessary to make this work. Once the index pulse of the incremental encoder goes by, absolute position is at hand.

Recently, “sensorless” techniques have been developed. Here, the motor is run in an open-loop synchronous mode at slow speeds (with high motor currents and the magnets essentially following the field), and readings of the back-EMF at higher speeds (as measured by phase PWM duty cycle) allow the controller to detect shaft position without a sensor.

Complexity can be Cheap

Without delving into details, it is proper to say that the cost of controller complexity has gone down significantly over the years, and this is no longer a very significant measure to use when deciding on control methodology. A typical EV controller has about 75% of its electronics cost in its power semi-conductors.

Conclusion

The debate is still raging in the industrial community, but it is this author’s opinion that, for the reasons outlined above, most EVs would benefit from the adoption of sine wave drive over 6-step.
October 26, 1991

COMPOSITE STRUCTURES

for

VERY LIGHT ELECTRIC AUTOMOBILES

by

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Summary

The growing interest in the use of battery power and solar power for propulsion of experimental automobiles has lead to the use of many composite structures, each aimed at the absolute minimum weight achievable. The practicality of such structures depends heavily upon the knowledge and judgment of the designer who chooses the materials and decides upon the processes. This paper reviews some of the practical choices which must be made, as well as the influence which the particular materials and processes chosen exert on the resulting strength, weight and reliability of the final automotive structure. No actual designs are considered, but rather, the effect of various specific choices upon the outcome is discussed.
PART ONE - THE MATERIALS

FIBERS

The materials used in our auto body may include low cost and commonly used fibers, such as E-Glass, or perhaps the more exotic candidates, up to the very light and very expensive high-performance fibers, such as Kevlar 49, Boron, or one of the high-strength graphite fibers. Each of these fibers has its own set of mechanical properties and physical characteristics, and the resulting structures are quite different. A few of them are listed below, with principal characteristics noted for each.

E-Glass
Low cost and very available in a broad choice of forms and weights. A little heavier than other fibers.

S-Glass
About 2% lighter than E-Glass, 25% stronger, 25% stiffer and noticeably tougher. Also more resistant to chemical attack. Although the above figures for fiber properties do not entirely translate into laminate properties, usually at least half the advantage appears in the final structure.

Kevlar 49
This du Pont fiber is 45% lighter than glass fiber, nearly twice as stiff, not much stronger in tensile strength, and not quite as strong in compressive strength. The major advantage is improved toughness at a given weight. This toughness advantage can be quite impressive in heavier laminates, but not quite as impressive in the very lightest laminates. Major differences are sometimes caused by a different resin system.

Carbon Fiber
This material is really a diverse family of materials, having only their black color and low density in common. Considering them as separate materials, we see:

Carbon Fiber - 33 mpsi, Old Generation
These materials have a modulus of about 33,000,000 psi, or double that of Kevlar and more than triple that of E-Glass. However, their strength, about 450,000 psi for the bare fiber, and lack of toughness limit their use in light weight structures where toughness or failure mode is a concern. Density is about 0.065 pounds per cubic inch; a little heavier than Kevlar and a little lighter than glass.

Carbon Fiber - 33 mpsi, New Generation
The same modulus and density as the old fibers, but much higher tensile and compressive strength, some of them double their predecessors. The end result is that the finished
laminates seem to behave in a much tougher way, provided the right resin system and cure process is chosen. Such materials as Hercules IM-6, or Celion 6000 are examples.

**Carbon Fiber - 50 to 100 mpsi, Old Generation**
Again, these were very unusual materials when first introduced, but are no longer used in new design due to their relatively low tensile strength. In addition to their low tensile strength, the common occurrence of surface defects on the individual fibers makes fracture behavior seem very brittle.

**Carbon Fiber - 70 to 120 mpsi, New Generation**
These materials are newly developed, most within the past five years, and appear to be about to become the standard structural of the Space Vehicle Industry. Although cost is comparatively high, from $200.00 to about $3,000.00 per pound of fiber, at least three companies are in current production. Most of these materials are based on pitch precursors, rather than PAN precursor, and the resulting graphite molecule seems to limit their compressive strength to a figure less than half their tensile strength. However tensile strength of the fibers approaches 600,000 psi.

At least 3 firms now produce these remarkable fibers, and at least one more is in the wings. The higher modulus members of this family have quite remarkable Thermal Conductivity (higher than copper) and Electrical Conductivity (also higher than copper). Also, the Thermal Coefficient of Expansion in the fiber direction (the amount that a part grows when the temperature rises) is nearly zero at modulus figures close to 60 mpsi, and becomes increasingly negative at the higher modulus figures. In other words, when a part becomes hotter, its dimension in the direction of the fiber grows shorter. By laminating the fibers in several directions in the various plies of the laminate, this figure can be adjusted to be essentially zero in all directions. This capability is very interesting to designers of optical equipment exposed to the temperature changes occurring in space. It is expected that other interesting applications will be found when the materials are better known to a broader spectrum of designers.

**Boron Fiber**
A very unusual material, but so difficult to work with that only a few examples of structures exist. The filaments are quite large—about 0.005" in diameter, and so stiff that handling is a problem.
RESINS

The usual manner of producing a composite structure is to wet out some structural fibers with a suitable resin. A great many choices of resin exist, but only a few are suitable for a project which does not possess ovens, autoclaves, and other such equipment. Some of those which should be considered are the following:

**Polyesters**
The workhorses of the low-tech composites industry. These materials are low in cost, about $1.25 per pound or thereabouts, and very easy to use, curing without the need for elevated temperature. Unfortunately they are rather low in strength, and completely unable to bring out the higher performance available in the more advanced fibers, such as Carbon Fiber and Kevlar. Normally these resins are used in amounts far larger than the optimum, and the structures are substantially heavier than those made from the more advanced materials.

**Vinyl Esters**
A clear cut above the polyesters, but still available in room temperature curing formulations for hand lamination of simple projects. Additives can extend the working life of the wet resin to as long as 8 hours, a big advantage in making large parts by hand lamination.

**Epoxies**
An extremely large family of materials, several thousand of them in current use, which are the current workhorses of the resin business. Many are available in room temperature curing formulations, both for laminating and for adhesive bonding of various adherends. A large part of this family is used as prepregs (pre-impregnated fabrics or strands, stored in a refrigerator and cured at elevated temperatures of 200 F up to 350 F. All of these materials are laid up as a complete part before cure, surrounded by a sealed bag which has a vacuum source connected to it, and then exposed to heat in an oven, or to both heat and added pressure in an autoclave.

The prepregs constitute nearly all of the materials used in the aerospace industry, as well as the more advanced members of the sporting goods industry. They are nearly always more costly to purchase, but save so much labor in assembly, that the end cost is actually lower. The one exception is the very new advanced versions of Resin Transfer Molding, in which wet resin is injected into a closed cavity which contains all of the reinforcing fibers already in place. This system can result in an even lower overall cost than can be achieved with prepregs.
Poly Cyanates
A relatively new family of resins which possess mechanical properties about the same as the better epoxies, but have easier handling properties and higher service temperatures. Because of their remarkable resistance to microcracking, a phenomenon observed in an outer or near space environment, they appear likely to become the new standard of that industry.

Other Resins
Many other families of resins are in current use, mostly in the aerospace area, for special purposes. Few are considered to be applicable to the structures considered in this paper.

CORE MATERIALS
Many composite structures are more efficient when designed as a structural sandwich, rather than as a simple laminate. A sandwich structure employs a relatively thick core material, with a relatively thin structural facing attached firmly to each side of the core. Typically, the facings are only some ten or twenty percent as thick as the core, but no firm figure applies. Designers sometimes find substantial advantage in sandwich structures which do not fall within these limits.

The main advantages of a sandwich are:

- higher stiffness-to-weight ratio,
- higher strength-to-weight ratio,
- higher compressive strengths in thin facings,
- no buckling at high compressive loads,
- aerodynamic smoothness with light structures,
- and many others, depending on the details of the design.

The main disadvantages of a sandwich are:

- Lower puncture resistance,
- Thicker structural elements,
- higher cost,
- increased fragility,
- lower abuse resistance,
- and many others, depending on the details of the design.

Some of the most-used core materials are:

Balsa Wood
This is just what the name says, the wood of the Balsa tree, usually from Ecuador, in Central America. The material is
used as an end-grain material, made up of blocks of selected wood, of reasonably uniform density glued together to make a piece several feet in each dimension, and cut to the exact thickness desired for the sandwich core. The material is quite stiff, unless cut into small blocks, and therefore is difficult to use where smooth rounded contours are desired. However, a formable grade, made up of small blocks attached to a scrim cloth backing, but not to each other, is available for use in contoured applications. Core densities below 8 pounds per cubic foot are difficult to find, and, where available, have a problem with uniformity of density unless their procurement is carefully controlled. The reasonably low cost of this material, however, leads to its use in a wide variety of applications.

**Styrofoam**
This family of materials is quite good in the range of 1 to 3 pcf, and also has the advantage of being able to be hot-wire cut. This carving method is used extensively on home-built aircraft projects. The material is soluble in Styrene, however, and so cannot be used with Polyester or Vinyl Ester resin systems.

**Urethane Foam**
This material is available in a broad range of densities, from 1 pcf in surfboards, to about 20 pcf in a few structural applications. For most structures, however, it is not used below 4 pcf, as it tends to be very frangible and has poor mechanical properties.

**Polyvinyl Chloride (PVC) Foams**
Several makers of this material family provide core materials in a broad range of densities. The material is reasonably resistant to Styrene, so can be used with Polyesters and Vinyl Esters, as well as epoxies. Both this and the Urethanes can be formed by heating to just below their softening point, and then forcing them to a specific contour with a vacuum bag. The trick is to choose the right temperature, and use a rather low pressure for the vacuum source. Holding for extended periods of time (8 to 24 hours) also helps.

**Polymethacrylimide Foam (Rohacell)**
This is probably the best of all the foams, having better strength-to-weight ratios than any of their competitors. It is immune to nearly all resins and solvents, and has sufficient heat resistance to be used in vacuum bag cures at 350 F. At 375 to 400 F it can be heat formed to quite severe contours. It is available in densities from about 2 pcf to 12 pcf.
Nomex Honeycomb

This is only one of a large family of honeycombs, which include various aluminum alloys, glass fiber/resin in several sub-families, stainless steel and refractory metal honeycombs, and many others. The material is available in many cell sizes and densities, and is uniquely suited to use in very light automotive structures.

The remarkable property which makes it notable however, is that it is quite sturdy and abuse resistant when used at densities as low as 2 pcf! Virtually no other core material can match it in this regard. Even at densities of less than 2 pcf, it has quite usable properties as a structural material. As a result of this, it is the most used core material for Human Powered Vehicles. The same attributes also make the slightly higher density members of this family the most-used core material for large commercial aircraft, such as the Boeing 767.

PART TWO - MANUFACTURE

Many methods of manufacture are used to produce composite structures. The choice of a method suitable for your project depends upon:

- Cost to be spent on tools and equipment,
- Nature of shop facilities available,
- Physical shape of the structure to be made,
and many other considerations.

Usually when the amount of money available to spend on production equipment is limited to a few hundred or a few thousand dollars, the decision is made to employ wet resins and hand layup methods. This avoids the need for an autoclave ($300,000.00), low temperature storage ($20,000.00), a curing oven (up to $50,000.00) and many other such expensive items. Even so, it still might be advisable to obtain a vacuum pump so that the parts can be cured at room temperature under a vacuum bag. Although more trouble than open layup, this method usually insures that the parts will be lighter and stronger than those made in an open layup. In any case, some of the following comments may apply:

Fiber Choice

The choice of a fiber is often dictated by what can be affordably purchased, or by what can be conveniently procured. Of all the choices, the most common is woven glass fiber, nearly always E-Glass, in a weight and thickness such that at least two plies can be used over most of the surface of the structure. Some structures are built with a single ply, but
the presence of pinholes is a constant problem, and abuse resistance is substantially improved by a second ply.

When absolutely minimum weight is desired, it is common to choose Kevlar or Carbon Fiber, rather than glass. Unless one of the new-generation carbon fiber fibers is used, the Kevlar will give a much tougher and slightly lighter structure. If the superior Carbon Fiber grades can be afforded, they will always result in the stiffest structure at a given weight, and will be about the same strength as the Kevlar. If the newer Kevlar 149, rather than the usual Kevlar 49, can be obtained in the light weave style needed, this is probably the best choice for the ultimate structure.

Resin choice
It is nonsense to choose a polyester resin system rather than a Vinyl Ester system. At least an extra ten to twenty percent strength will result from this single choice. A room temperature curing epoxy can add another five percent or so, but you must live with the added health hazards of the epoxies. Most of them will result in sensitization of 50% of those persons exposed, after the passage of a few years. If you use any of the wet resins, even those less hazardous, it is a very good idea to carefully observe all of the safety precautions cited by the resin manufacturer.

If a freezer and an oven can be made available, one of the epoxy prepregs is a very good choice. The weight will go down by perhaps ten percent, and the strength will go up about ten percent or so. Also, the health hazards are almost non-existent when using prepregs, as compared to wet resins of the same family. Although no shortcuts for a freezer are known, the entire Voyager airplane (the one that flew around the world non-stop, without re-fueling) was made in an oven consisting of a large plywood box, heated by a converted junk home heating unit, which employed natural gas as a fuel. Only the spar caps on that structure used an autoclave for cure.

Tooling
Most tooling which needs a compound curvature on the tooled surface can be made most expeditiously from composite materials. Glass fabric is the most common material. The same resin system as is to be used on the structure of the project can also be used to make the tooling. The exception is the case where an oven cure will be used, in which case the tool must be made using one of the high temperature tooling resins available. The Ren Plastics Division of Ciba-Geigy has an excellent brochure on the subject of making composite tools. Where simple curvature can be tolerated in the design, the tools may be made of flat sheet metal or plastic, curved to the shape desired, and held in place by wood ribs and stringers glued to the back side. Flat panels can be made using a
flat aluminum or Masonite plate as the tooling surface. Nearly any material can be used in tooling, as long as it is appropriate to the job to be performed.

**A Splash**

This is a standard method of reproducing any compound shape which needs a molding tool in order to be produced. If your friend has the shape you need, one simply coats the part with a mold release, such as hard wax, and then hand lays a wet resin part over the waxed surface. While the resin is wet, a back-up structure is added, using the same resin to bond plywood or Masonite ribs in place. When the resin has cured, the splash is gently separated from the master shape, and the resulting mold surface is then used to make the next part. If no existing shape is available, plaster, urethane foam, or any other such material can be sculptured to the precise shape desired, and the splash is taken from this surface.

**Adhesive Bonding**

Most composite structures are made up of several sub-structures which are adhesively bonded together in a final assembly operation. Several cautions should be noted.

Be sure that the adhesive you plan to use actually sticks to the composite material you have produced. Some of the very good adhesives do not bond well to cured laminates of some of the best resin systems. Even when this compatibility has been assured, it is wise to use a peel ply to prepare the surface to be bonded after cure, or at least to rough up the composite surface with some 200 to 300 grit sandpaper. Be certain, however, that you do not remove the structural fiber which is supposed to carry the load.

Be sure that the surfaces of the material to be bonded together are dry. Particularly in the case of Kevlar, the cured laminate picks up moisture while in normal dry storage, and must be oven dried before any secondary bonding is attempted.

Be sure to clean up the excess adhesive before it cures. Cured adhesive can be nearly impossible to remove without serious damage to the underlying composite structure.

Do not use solvents to clean off the cured surface of the composite structure. Most composites degrade slightly in the presence of some solvents. In particular, **do not use paint stripper on any composite structure!** The paint stripper will dissolve or seriously degrade the composite.

Be very careful when painting your finished composite vehicle. Removing fully cured paint can be as difficult as removing fully cured adhesive. Also, in the case of paint, an added coat of paint can result in a disastrous weight gain.
for your structure, negating all of the carefully calculated weight reduction sought.

Always use a light color when painting your vehicle. The normal exposure to sunlight can result in temperatures high enough to allow creep deformation in the structure, where such structures are painted a dark color. This is a particular problem in sandwich structures using a foam core. Also, the paint should be capable of shielding the underlying composite from ultra violet radiation normally found in sunlight. Unprotected composite structures will gradually become more brittle and lower in strength as a result of exposure to ultra violet radiation.

About the Author:

Mr. Marshall is a practicing Engineer who has spent his entire professional life as a Materials and Process Specialist. He is a graduate of the University of California-Berkeley, class of 1943, beginning his professional life in the Engineering Materials Laboratory there. He is also a Registered Professional Engineer, Mechanical, in the state of California. In 1950, he moved from United Airlines to the Hexcel Corporation, where he worked exclusively in the field of composites. In 1978 Mr. Marshall retired from Hexcel and formed his own Consulting company, which has remained in continuous operation to the present date.

Mr. Marshall has authored many technical papers in the field of composites, and is a Fellow of the Society for the Advancement of Materials and Process Engineering. He has authored chapters in the, "Handbook of Composites" (Van Nostrand Reinhold), "International Encyclopedia of Composites" (VCH Publishers), and has published his own book, "Composite Basics", now in its second edition.

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ABSTRACT:

There have been many race teams who have failed to score points at the race circuit for many reasons, including driver ability, engine performance, and, of course, chassis design. When these factors all come together you have a winning combination.

This paper is concerned with the design of master model, mold tool and structural components as used in the automotive racing industry, which over the years has seen constant change in direction including the introduction of composites in chassis design approximately ten years ago.

Today's cars are faster, stronger and lighter than their predecessors to the extent that composite chassis can now make the difference between winning and losing, life and death.
INTRODUCTION

The Advanced Composite Group, United Kingdom division, has been a major player in the field of component manufacture for the automotive racing market for many years and is now the largest sub-contract manufacturer of high performance chassis in the world.

In 1982, we produced our first composite chassis for the ALFA F1 race team, the success of that chassis was to carve the company’s future in race car design, support and prepreg material supply. To date The Advanced Composites Group has manufactured:

- 77 Formula 1 chassis,
- 247 Indy Car chassis,
- 58 Group "C" chassis (GTP),
- 39 F3000 chassis,
- 7 Experimental chassis,
- 40 Road Race cars and
- 31 Formula 3 chassis,

a total of 562 chassis. In addition to the chassis, there are a lot of composite parts the public do not see which play a critical roll in how the cars perform.

The experience gained by The Advanced Composites Group during it’s 15 year involvement is the equal of anyone in the automotive racing industry. We are unique in having an experienced technical staff extensive production facilities and the support of our own prepreg facilities, in both the United Kingdom and the USA where we produce a wide range of prepreg systems ranging from the LTM10, Low Temperature Tooling Series and LTM20 Low Temperature Structural Series to the MT6D Toughened Epoxy Prepregs for both automotive, aerospace industrial applications; this in itself is a highly technical field.

The marriage of these facilities make it possible to provide design, technical support, material and part production services for today’s race market.
TOOLING

There are three main groups of tools used for composite chassis manufacture:

1. The master model, pattern or buck.
2. The composite model tool.
3. Jigs and fixtures.

Let us consider each of these briefly.

MASTER MODEL SELECTION

The ideal model material choice would be an epoxy tooling block such as The Advanced Composites Group’s TB650 due to their inert nature, low CTE and high stability. As we don’t live in an ideal world, however, there are other cheaper materials to consider that could make the chassis model. In all choice’s of model material we must determine how our mold material will need to cure, for example, depending on the need for heat, vacuum or autoclave pressure, many materials may be eliminated as they will either expand excessively, distort or collapse during the molding operations.

MOLD MATERIAL CHOICE

To ensure the best dimensional accuracy in our parts it is important to match the thermal expansion of mold tool and component material thus, a carbon fiber mold will generally be used to manufacture a carbon part and a glass fiber mold used for a glass part. Not only can a poor mold material selection cause dimensional inaccuracies but may introduce bridging in female corners and in extremes cases can result in a part locking into its mold destroying the part or mold or possibly both.

This material selection becomes less critical in the unique case of LTM20 series structural prepregs where cure temperatures are very low.

JIGS AND FIXTURES

Jigs and fixtures take on two basic forms. The first are usually inexpensive composite tools used to mark out or route parts to size and drill holes in position. These tools are sometimes eliminated completely by scribing EOP (Edge of Part) lines and hole centers onto the mold face which then transfer to the part providing a trim guide. The other group of tools are the assembly fixtures. These can be very elaborate and complex and are usually built using an assortment of pins and locators which can be reworked and
reused year after year to avoid the expense of completely retooling. These are usually fabricated metal assemblies.

**STRUCTURAL DESIGN**

There are a great number of factors that need to be taken into account when a race chassis is designed, every team wants the lightest, stiffest chassis on the race track.

Briefly, engineers calculate the car to chassis weight ratio, stiffness and impact resistance required and the localized loading exhibited at mounting locations where inserts will be required. A finite element model is then prepared for analysis of the chassis performance before any prepreg is ever handled. This analysis enables the engineer to locate specialized materials, e.g. unidirectional high modulus carbon prepreg may be placed in the sills to increase stiffness.

As well as meeting the cars performance criteria, the designer must also meet the FISA envelope and safety criteria, especially crash survival.

In the following slides you will see a more detailed break down of the design criteria, plus a variety of chassis and related components both in construction and in action.
PHOTOVOLTAICS: A REVOLUTIONARY ELECTRICITY GENERATION OPTION

BY

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ABSTRACT: THE INTRINSIC ASPECTS OF PV ARE REVIEWED, THE STATUS OF THE 1990 MARKET WORLDWIDE IS PRESENTED. WORLD MARKETS TO 2010 ARE FORECAST UNDER TWO SCENARIOS: BUSINESS AS USUAL AND ACCELERATED. POLICY OPTIONS REQUIRED TO MOVE TO THE ACCELERATED SCENARIO ARE DEVELOPED. THE IMPACT OF THE ACCELERATED SCENARIO IS FORECAST.

PV CAN........

POWER BILLIONS OF CONSUMER SMALL POWER APPLICATIONS
POWER MOST REMOTE COMMERCIAL, INDUSTRIAL, AND GOVERNMENT APPLICATIONS
PROVIDE ECONOMIC POWER TO BILLIONS OF PEOPLE IN THE DEVELOPING WORLD
SERVE GRID CONNECTED RESIDENCES AND COMMERCIAL APPLICATIONS
RECHARGE ELECTRIC VEHICLES ON THE ROOF, HOME, PARKING, FILLING STATIONS
PROVIDE ECONOMIC CENTRAL ELECTRICITY GENERATION IN THE DESERTS OF THE WORLD
POWER ELECTROLYZERS TO MAKE HYDROGEN FUELS POSSIBLE
PHOTOVOLTAICS: A REVOLUTIONARY ELECTRICITY GENERATION OPTION

INTRODUCTION: Photovoltaics, commonly called "PV", is the direct conversion of sunlight to electricity using the semiconductor device—the solar cell. The solar cell, usually made of ultra-pure silicon, can convert ten to twenty percent of the sunlight energy into electricity. This electricity can power any electrical load from milliwatts for calculators, watches and battery chargers to kilowatts for residences, water pumping and purification, remote communications, area lighting, village power; and, finally, megawatts for utility-sized central power. We will cover the main aspects of the photovoltaic technology and the world markets for PV. We will attempt to forecast the impact of PV on the electricity supply on our remote electrical power needs, the developing world, powering our houses, powering the electric car, central power generation and the generation of hydrogen. We believe all of these applications for PV will be fully economic very early in the 21st century. Photovoltaic generation of electricity is not a "panacea" or a "cure-all" but we are convinced that PV can serve a significant portion of the world electricity needs reliably without pollution, toxic waste, noise, noxious gases, in most cases at the location where the electricity is needed. Before we explore the details and develop the future of PV, we will summarize the principal reasons why photovoltaic electricity generation should be seriously considered as a revolutionary product.

PHOTOVOLTAICS: A REVOLUTIONARY PRODUCT— SUNLIGHT TO ELECTRICITY IN ONE STEP

The conversion of sunlight to electricity using the solar cell is an incredibly, simple, elegant process. The solar cell absorbs sunlight, silently with no moving parts, no fuel, no noxious gases, no radiation, no odors and produces direct current electricity that can be used to power any electrical load. In the first chart, the attributes of PV that make it a revolutionary product for the twenty first century are listed. I will discuss the five key attributes so that you, too, may share my enthusiasm for PV.

1) PHOTOVOLTAICS IS RELIABLE AND ECONOMIC PROVIDING ELECTRICITY TO MILLIONS, NOW!

In 1991, fifty megawatts of photovoltaic modules will be sold throughout the world. In most cases, the PV systems are serving electrical needs that are fully economic. The list of reliable, economic applications for PV is virtually endless. The largest market for PV is the area of consumer products where a small amount of electricity performs a function normally served by a battery. Consumer applications of PV were over 35% of all applications in 1991. Over a billion hand held calculators get all their electrical power from PV. Most of you in the audience have several in your pocket, home, school, or office. The PV powered hand held calculator is primarily a Japanese product using one of the most advanced cell materials—amorphous silicon. In addition to calculators, PV is powering many other consumer products including: watches, TV remote controls, battery trickle chargers, portable lights, security lights, small ventilators, and power for remote cabins, boats, camping trailers, etc. etc... In the area of remote communication and signals PV is the preferred source of highly reliable electricity for microwave repeaters, fibre optic links, satellite receivers, environmental sensors, emergency communication, navigation aids... the list is endless. Over 30% of our PV products serve remote communication and signals. In the developing world PV is providing water pumping and purification, vaccine refrigeration, lighting, educational TV, and village power with costs now less than the total cost of owning, maintaining and fueling a small remote diesel electric generator. The message of this first factor is that PV is providing electricity to customers throughout the world, reliably and economically—NOW!
2) PV IS ENVIRONMENTALLY BENIGN IN USE

This attribute of PV is the most important motivation for my commitment to PV, personally and professionally. PV has zero impact on the environment when mounted on a roof and used to generate electricity. No gases are evolved. No noise is made. No fuel is consumed. No radiation is given off. No electromagnetic radiation is produced. When used to generate electricity, PV is considered to have no measurable environmental impact. The disposal of a PV module can be easily accomplished: move it to another site where the module is likely to be still working, recycle it for the glass and silicon content or dispose of it in a landfill. We see no adverse affects from disposal of the PV generator. We do have one small warning concerning the manufacture of PV cells. The manufacture of PV cells involves the same material and processes of the silicon based semiconductor industry. Normal semiconductor industry standards must be met in the manufacture of PV cells. Some new materials for PV cells involve elements and compounds other than silicon. We need to carefully consider their impact on the environment and humans in the production, use and decommissioning of some of the new materials. Of special interest are arsenic, cadmium, and tellurium.

3) PV IS ROOTED IN THE WORLD SEMICONDUCTOR TECHNOLOGY BASE

Photovoltaics has a technology base rooted in the 200 billion dollar electronics industry worldwide. PV uses the same pure silicon raw material, the same manufacturing processes, and is the simplest of semiconductor devices a one junction two layer device, similar to a diode. The physical theory of the solar cell is carefully developed. Research results in laboratories throughout the world have been remarkable. Laboratory efficiencies have doubled in all materials in the last ten years. The efficiency of solar cells produced the research labs of the world have increased from ten percent for crystal silicon to over 25 percent. The thin film area has increased efficiency from 4-6 percent in 1978 to over 14 percent in 1991. The concentrator cell efficiencies have increased to nearly 30% for silicon cells and nearly forty percent for a two layer gallium antimonide/ gallium arsenide cell. If the research results of the past ten years can be transferred to low cost manufacturing, the PV can be reliable, efficient, and cost effective electricity generator compared to generation from coal, oil, nuclear, and gas in most climates of the world. We predict that transition to economic viability will occur early in the twenty first century.

4) PV PROVIDES INDIVIDUAL CONTROL OF ONE'S ENERGY DESTINY.

Photovoltaic electricity can be generated at the location of the electrical load. In most cases there is enough sunlight to power an electrical load provide storage is provided. As we have discussed, millions of electrical loads are now being powered by PV systems where the PV module is mounted in or on the product, or in small arrays near the load. PV can provide all the electricity needed for remote applications where low cost land or roofs are available. In developed areas where land costs are very high, then the use of existing roofs permits the use of PV for homes, schools, and small commercial facilities. In many cases PV covering the south facing roof or building can provide a major portion of the electricity required by the building. In those cases where the roof cannot supply all the electricity we propose that the central utility be required to support the PV powered facility when the PV system cannot meet the load, in bad weather and at night. For the first time, an individual can generate electricity from the roof of his or her home, boat, and car and not be required to connect to the utility. Thousands of residences get all their electricity from the sun and pay no electric bills to a central utility. Some PV users justify the use of PV as fully "economic" because the cost of extending the distribution system exceeded the cost of the PV system. Others have installed PV because of concern for Acid Rain, Earth Warming, Nuclear safety and waste, Oil dependency or other economic/political reasons. These "early adopters" are the first wave in an unending transition to generating electricity on one's own roof to serve conservation-minded houses with a minimum of electricity - generated from the sun.

5) PV WILL BE FULLY ECONOMIC FOR ALL ENERGY NEEDS - FROM MILLIWATTS TO MEGAWATTS

We will discuss this later after we develop the policy options required to stimulate the full potential of photovoltaics. As you will see-- PHOTOVOLTAICS IS, INDEED, A REVOLUTIONARY PRODUCT!
OVER VIEW OF THE 1990 PV MODULE SHIPMENTS AND FORECAST TO 2010

WORLD PV MODULE SHIPMENTS 1990

Figure 2. shows the 1990 PV module shipments by country or region. (Reference 1) 1990 module shipments of 46.5MW increased 16% over the 40.2MW in 1989. U.S. shipments increased only 6% to 14.8MW. Japanese shipments increased 18% to 16.8MW while European module shipments exploded by 30% to 10.2MW. The Japanese shipments include about 13 MW of consumer electronic products normally used indoors-calculators, watches, etc. The Rest of the World shipments increased 17.5%. PV modules served all applications with many new products introduced in the remote power market. New pumping and water purification products were sold throughout the world. New outdoor lights, including high pressure sodium vapor lamps were introduced. The market is highly diffuse with the thirty three megawatts of outdoor products being shipped to over 50 countries.

1990 WORLD MODULE SHIPMENTS BY CELL TECHNOLOGY

Figure 3. shows the 1990 world module shipments by cell technology. The single crystal silicon option continued its dominant position in the market with rapid gains made by cast ingot polycrystalline silicon. Kyocera in Japan caused most of the growth in polycrystalline silicon with the tripling of its capacity. The amorphous silicon option lost ground for the third year in a row. Advanced Photovoltaic Systems, Newark, New Jersey acquired the Chronar 10 MW "Eureka" plant and it is now in production. New European amorphous silicon plants are planned to be operational in late 1991. When the sliced single crystal and the cast ingot polycrystal silicon products are combined, they account for 68% of the world PV product. Despite the intense R&D effort on thin films of all kinds, there is little evidence that the dominance of sliced silicon crystal product will be challenged in the next few years.

1990 WORLD MODULE SHIPMENTS BY COUNTRY OF USE.

Figure 4. shows where thirty three megawatts of outdoor PV product was installed. In order to locate the thirty five megawatts, we had to investigate nearly fifty countries. The fastest growing markets are in the developing world, especially South Africa and Mexico. Both have government subsidized programs to provide PV power to thousands of customers. Mexico has decided to provide village power systems rather than extend the utility grid. South Africa has decided to give low interest loans for PV systems on individual houses. The typical developing world market starts with successful installation of PV systems for communications leading to government interest which leads to "PV for the people". European markets will rapidly grow in the next few years with the "post Chernobyl, Green Energy" policy environment. Germany has a "2000 roofs" project and is building over a megawatt of central experiments. Switzerland has a "1000 roofs" project and is building nearly a megawatt of PV on highway sound barriers. Italy has a goal of 25 Megawatts to be installed by 1995.
FORECAST OF PHOTOVOLTAIC MARKETS TO 2010

Figures 5. and 6. show forecasts of PV module shipments (Reference 2). Time does not permit detail. A technology, manufacturing cost forecast was developed. The market was partitioned into the seven sectors shown. Market volume versus module price "elasticity" curves were generated. The forecast was then prepared using two scenarios - Business as Usual (BAU) and Accelerated. The BAU scenario involves continued low prices for oil and gas (less than 2% real growth); continued low priority for renewable energy in government funding (especially the United States); little internalization of the social costs of coal, oil, gas, or nuclear electricity generation; and a general malaise concerning energy. The Accelerated scenario assumes a 3% escalation of gas and oil prices; rapid expansion of government R&D funding for PV; internalization of social costs; real concern for energy and the environment; and emphasis on renewable energy by the international funding agencies for the developing world. The United States is clearly in the BAU mode, Germany is in the Accelerated mode, and Japan is mixed.

In the BAU scenario, the PV module shipments grow at about 12-15% per year. In the Accelerated scenario, the market grows at about 25% per year. The key issue confronting the PV industry is to grow with profit to recoup the enormous R&D investment to date (well over two Billion dollars, worldwide and to stimulate capital to build large, efficient manufacturing plants. At the moment, we feel confident that the "Business as Usual" market forecast has a high probability of occuring. If the policies that we propose later are adopted, then the Accelerated scenario can become reality. If the Accelerated scenario occurs, then PV will be fully economic early in the 21st Century for a wide range of applications.

CONCLUSION

The world PV markets are a complex array of applications, owner benefits, technology options covering product from milliwatts to megawatts. This diversity of application virtually assures a growing, vital industry. Government policy will dramatically shape the future. Environmental concerns, social costs of non-renewable options, and the cost of oil and gas will contribute to expanded markets. PV costs must be reduced by a factor of two, large automated plants constructed, and profits made before the Photovoltaics option can become a serious energy option. Presently the focus is on Europe as the post Chernobyl era couples with the "Green" politics to create an environment favorable for renewable, environmentally benign, fully economic PV. Japan with the largest production of PV modules in the world, and the worlds most effective semiconductor technology and manufacturing base, can lead the world to fully economic, environmentally benign Photovoltaics!

Reference 1. PV NEWS, VOL 10, NO 2, pp 1-6, Feb 1991. Published by PV ENERGY SYSTEMS, Inc. U.S.A.
Reference 2. "PHOTOVOLTAIC TECHNOLOGY, PERFORMANCE, COST AND MARKETS TO 2010", April 1991, 245 pps., published by PV ENERGY SYSTEMS , INC, PO BOX 290, CASANOVA, VA, USA, 22027. ($500.00)
In order for Photovoltaics to reach its full potential and have a significant impact on the world’s energy supply, we must implement the following key initiatives: (Figure 7)

- **CONTINUE AND EXPAND AGGRESSIVE R&D SUPPORT WITH EMPHASIS ON MOVING RESEARCH RESULTS INTO PRODUCTION**
  
  Present world support of PV research and development is about $200 million per year. This level needs to be expanded and emphasis placed on manufacturing of lower cost modules with adequate reliability. Special attention needs to be placed on the cost of pure silicon – the basic raw material of the industry. The DOE manufacturing initiative, if urgently managed and adequately funded can assist in moving the industry from the Business as Usual scenario to the Accelerated mode.

- **CREDIT PV AND OTHER RENEWABLE ENERGY OPTIONS TO BALANCE THE SOCIETAL IMPACT OF COAL, OIL, GAS, AND NUCLEAR GENERATION OF ELECTRICITY**
  
  Extensive analysis of the societal costs of electricity generation by coal, oil, gas, and nuclear energy indicate costs of five to ten cents per kilowatt-hour are reasonable. Germany is offering credits of five to eight cents for non-polluting renewable generation options. The New York State Utility Commission has proposed a 15% benefit (2.5 cents/kWh) for non-polluting options. Italy has initiated extensive tax credits for non-polluting generation options.

- **PERMIT FULL, TWO WAY GRID CONNECTION OF PV SYSTEMS WITH ONE-TO-ONE PAYBACK**
  
  The United States and Switzerland have laws which require the central utility to provide power to a customer with a PV generator when the sun does not shine and to purchase power from the customer’s PV generator when there is excess solar generated electricity. We propose that this option be accelerated and that U.S. States and other countries require that the excess PV power generated be credited at the same cost per kilowatt-hour as the cost of back-up peaking power.

- **USE A “SOCIAL” DISCOUNT RATE (2–3 PERCENT) FOR GOVERNMENT DECISIONS ON THE PURCHASE OF PV FOR GOVERNMENT USE**
  
  We propose that the governments of the world take the lead in identification and purchase of PV systems. Typical applications would include remote power for communication, signals, water purification, and for roof-mounted systems for all kinds of buildings. In order to increase the market and decrease the PV costs, we propose that governments use a “Social Cost of Money”, such as 2–3%, for those renewable options that use no imported fuel, and do no damage to the environment. This government “market pull” strategy could greatly accelerate the PV cost reduction. The United States has used the “social cost of money” to stimulate large expansions in its electrical supply. The Rural Electrification Administration, the Tennessee Valley Authority, and large hydro dams were federally supported and the cost of capital provided at costs from one to three percent. We envision that the capital cost of PV systems be treated in precisely the same way as the capital costs in the above projects. We call this “The Solar Dam” concept. This early, government use of PV would stimulate the investor decisions to built 50–100 MW/year manufacturing plants, which would accelerate the transfer of R&D results to manufacturing and demonstrate the economies of scale of large, automated plants.
CONVINCE INTERNATIONAL ASSISTANCE AGENCIES TO PROVIDE PHOTOVOLTAICS FOR VILLAGE POWER AND RURAL ELECTRIFICATION.

Presently the international assistance agencies (The World Bank, United Nations) invest billions of dollars for energy loans to extend the utility grid, build nuclear power plants, and provide millions of diesel generators in the developing world. Photovoltaic systems are now economic compared to grid extension and diesel generation for the billions of persons in the developing world without electricity. We must educate these agencies and demonstrate to them that PV systems are the optimum option to provide electricity to the remote populations of the world.

CONCLUSIONS: PHOTOVOLTAICS: A REVOLUTIONARY PRODUCT.

If the above policies are implemented, then PV can be a fully economic, non polluting electricity generation in most climates of the earth. Figure 8 shows our estimate of the possible impact of photovoltaics the world. Let us briefly discuss the PV POTENTIAL FOR THE 21ST CENTURY.
1) POWER BILLIONS OF CONSUMER ELECTRONIC, PORTABLE SMALL POWER APPLICATIONS

Consumer applications will proliferate as module prices drop. Hundreds of products will incorporate PV into the product, just as was done in the calculator. Portable products for our homes, boats, cars, motor homes, will become commonplace. PV will power lights, radios, TV, portable phones, portable computers, etc. We are just beginning to understand this exciting market.

2) PROVIDE ELECTRICITY TO THE BILLIONS OF PEOPLE IN DEVELOPING COUNTRIES

PV is the most reliable, economic option available now to provide electricity to the developing world. Several experiments in village power have been completed and some serious programs are under way. Tens of thousands of "residences" have one forty Watt PV panel that powers a few fluorescent lights, a black and white TV, and a radio. Even this small amount of electricity has dramatic impact on the people of the developing world. We must learn how to finance the high first cost PV. Local training and delivery systems is vital to the success of PV deployment. Ultimately we must transfer the manufacturing technology to the developing world so that they can make the electrical generators that serve the needs of their people.

3) POWER ALL REMOTE COMMERCIAL, INDUSTRIAL, GOVERNMENT NEEDS.

This sector is the second largest market now and can grow rapidly as costs decrease. The larger markets include: Communications, Signals, Area Lighting, Cathodic Protection, Water pumping and purification, Remote habitat, Navigation Aids, and Environmental Sensors. PV can grow at over 20% per year by serving only this sector and the consumer products sector.

4) SERVE GRID CONNECTED RESIDENCES AND COMMERCIAL BUILDINGS

If full grid interconnect and "$ for $" buy-back of excess PV electricity is permitted, then this application can be the most important for the developed nations. We estimate that up to 20% of a nation's electricity can be generated by the roofs of its houses, commercial, and government buildings. If a progressive connection and payment policy can be implemented for PV, then this sector can become the first real "large power" market for PV.

5) RECHARGE ELECTRIC VEHICLES FROM PV GENERATORS

It would be a tragedy if we develop the electric car and deploy it by the millions only to have it recharge from electricity made from coal, oil, or nuclear power. We must adopt a policy that the electric car should be recharged by renewable, non polluting generation options. PV can repower the car batteries at "PV FILLING STATIONS", from parking lots, from our homes. PV on the roof of the electric car can extend the range of the vehicle and extend battery life. It would be a serious mistake if we developed an effective electric car and did not consider the consequences of the electricity used to recharge the battery. PV is one option that should be seriously considered.

6) PROVIDE FULLY ECONOMIC CENTRAL POWER FOR THE UTILITY GRID

Even though PV is intrinsically a distributed option that provides the electricity directly where needed, in our cities where roof area and land cannot provide enough PV generated electricity to be of significance central generation of PV electricity may be a useful option. Clearly, if the deserts of the world were populated with 30% efficient, low cost concentrators, then PV could generate Gigawatts of electricity with no pollution or impact on society. We forecast that very early in the 21st Century PV will be fully economic for central power generation in the vast deserts of the world.

7) POWER ELECTROLYZERS TO MAKE HYDROGEN FUELS Viable

This exciting option follows from item six. If PV is economic on the deserts of the world for central power, then one of the most exciting uses of that electricity is the generation of Hydrogen (and Oxygen) from water thus providing an environmentally benign fuel for our industrial and transportation sectors.

ALTHOUGH NOT A PANACEA, PROTOVOLTAICS - THE DIRECT CONVERSION OF SUNLIGHT TO ELECTRICITY IS, INDEED, A REVOLUTIONARY PRODUCT THAT CAN POWER OUR REMOTE POWER NEEDS, ELECTRIFY THE DEVELOPING WORLD, AND ULTIMATELY POWER OUR HOMES AND COMMERCIAL ELECTRICAL LOADS WITH NO NOXIOUS GASES: NUCLEAR WASTE, ACID RAIN, EARTH WARMING, NOISE... AT A FULLY ECONOMIC COST.
PHOTOVOLTAICS: A REVOLUTIONARY PRODUCT
SUNLIGHT TO ELECTRICITY IN ONE STEP

- PV IS RELIABLE, ECONOMIC PROVIDING ELECTRICITY TO MILLIONS
- PV IS ENVIRONMENTALLY BENIGN IN USE
- PV IS ROOTED IN THE WORLD SEMICONDUCTOR TECHNOLOGY BASE
- PV PROVIDES INDIVIDUAL CONTROL OF ENERGY DESTINY
- PV WILL BE FULLY ECONOMIC FOR ALL ENERGY NEEDS—FROM MILLIWATTS TO MEGAWATTS WHEN RESEARCH RESULTS ARE TRANSFERRED TO MANUFACTURING TECHNOLOGY

WORLD PV MODULE SHIPMENTS
(CONSUMER & COMMERCIAL) (MW)

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<tr>
<td>UNITED STATES</td>
<td>7.7</td>
<td>7.1</td>
<td>8.7</td>
<td>11.3</td>
<td>14.1</td>
<td>14.8</td>
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<tr>
<td>JAPAN</td>
<td>10.3</td>
<td>12.6</td>
<td>13.2</td>
<td>12.8</td>
<td>14.2</td>
<td>16.8</td>
</tr>
<tr>
<td>EUROPE</td>
<td>3.4</td>
<td>4.0</td>
<td>4.5</td>
<td>6.7</td>
<td>7.9</td>
<td>10.2</td>
</tr>
<tr>
<td>REST OF WORLD</td>
<td>1.4</td>
<td>2.3</td>
<td>2.8</td>
<td>3.0</td>
<td>4.0</td>
<td>4.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22.8</td>
<td>26.0</td>
<td>29.2</td>
<td>33.8</td>
<td>40.2</td>
<td>46.5</td>
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### 1990 WORLD MODULE SHIPMENTS
**BY CELL TECHNOLOGY (MW)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>U.S.</th>
<th>Japan</th>
<th>Europe</th>
<th>R.O.W.</th>
<th>Total</th>
<th>Percent</th>
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<tbody>
<tr>
<td>Single Crystal Flat Plate</td>
<td>7.2</td>
<td>2.5</td>
<td>3.1</td>
<td>3.6</td>
<td>16.4</td>
<td>35.3</td>
</tr>
<tr>
<td>Polycrystal Silicon</td>
<td>5.4</td>
<td>3.5</td>
<td>5.9</td>
<td>0.5</td>
<td>15.3</td>
<td>32.9</td>
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<tr>
<td>Amorphous Silicon</td>
<td>2.1</td>
<td>10.8</td>
<td>1.2</td>
<td>0.6</td>
<td>14.7</td>
<td>31.6</td>
</tr>
<tr>
<td>Crystal Silicon Concentrators</td>
<td>0.03</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Ribbon (Silicon)</td>
<td>0.06</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>14.8</td>
<td>16.8</td>
<td>10.2</td>
<td>4.7</td>
<td>46.5</td>
<td>100</td>
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### PV WORLD MARKET FORECAST
**BUSINESS AS USUAL (MWp)**

<table>
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<tr>
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<tr>
<td>Consumer Products</td>
<td>16</td>
<td>50</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>US Off Grid Res</td>
<td>3</td>
<td>10</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>World Off Grid Rural</td>
<td>8</td>
<td>8</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Communication</td>
<td>14</td>
<td>30</td>
<td>40</td>
<td>160</td>
</tr>
<tr>
<td>PV/Diesel Commcl</td>
<td>7</td>
<td>20</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>Grid Conn Res,Commcl</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>Central Station</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td><strong>Total MW/Year</strong></td>
<td>48</td>
<td>124</td>
<td>195</td>
<td>800</td>
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*2010 Forecast: 80%/Year 2000-2010*
PV WORLD MARKET FORECAST
ACCELERATED SCENARIO

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<tr>
<th>MARKET SECTOR</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2010</th>
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<tbody>
<tr>
<td>CONSUMER PRODUCTS</td>
<td>16</td>
<td>70</td>
<td>80</td>
<td>500</td>
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<tr>
<td>US OFF GRID RES</td>
<td>3</td>
<td>20</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>WORLD OFF GRID</td>
<td>6</td>
<td>15</td>
<td>40</td>
<td>600</td>
</tr>
<tr>
<td>COMMUNICATION, SIGNAL</td>
<td>14</td>
<td>40</td>
<td>60</td>
<td>200</td>
</tr>
<tr>
<td>PV/DIESEL COMMCL</td>
<td>7</td>
<td>50</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>GRID CONN RES, COMMCL</td>
<td>5</td>
<td>20</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>CENTRAL STATION</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td><strong>TOTAL (MW)</strong></td>
<td>48</td>
<td>210</td>
<td>440</td>
<td>4000</td>
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</tbody>
</table>

2010 FORECAST: 25%/YEAR 2000 TO 2010

POLICY TOWARDS THE 21st CENTURY
ACCELERATION OF PHOTOVOLTAICS

- AGGRESSIVE R&D SUPPORT—MOVE RESEARCH RESULTS INTO PRODUCTION—ACCELERATE MANUFACTURING INITIATIVE
- CREDIT PHOTOVOLTAICS AND OTHER RENEWABLE OPTIONS WITH "SOCIAL VALUE" CREDITS
- PERMIT TWO WAY GRID CONNECTION WITH PEAKING $ FOR $ PAYBACK
- IMPLEMENT A "SOCIAL DISCOUNT RATE" FOR GOVERNMENT PURCHASES OF PHOTOVOLTAICS, RENEWABLE ENERGY OPTIONS—"SOLAR DAM" PROJECT
- INTERNATIONAL ASSISTANCE AGENCIES TO PROVIDE PV VILLAGE POWER INSTEAD OF GRID CONNECTION AND CENTRAL GENERATION
PHOTOVOLTAICS: A REVOLUTIONARY PRODUCT
PHOTOVOLTAICS CAN...

- POWER BILLIONS OF CONSUMER SMALL POWER APPLICATIONS
- POWER MOST REMOTE COMMERCIAL, INDUSTRIAL, AND GOVERNMENT APPLICATIONS
- PROVIDE ECONOMIC POWER TO BILLIONS OF PEOPLE IN THE DEVELOPING WORLD
- SERVE GRID CONNECTED RESIDENCES AND COMMERCIAL APPLICATIONS
- RECHARGE ELECTRIC VEHICLES-ON THE ROOF, HOME, PARKING, FILLING STATIONS
- PROVIDE ECONOMIC CENTRAL ELECTRICITY GENERATION IN THE DESERTS OF THE WORLD
- POWER ELECTROLYZERS TO MAKE HYDROGEN FUELS POSSIBLE
SUMMARY

Laboratory tests of advanced, high energy density capacitors in the Battery Test Laboratory of the Idaho National Engineering Laboratory have been performed to investigate their suitability for load-leveling the battery in an electric vehicle. Two types of devices were tested- 3 V, 70 Farad, spiral wound, carbon-based, single cell devices obtained from Japan and 20 V, 3.5 Farad, mixed-oxide, multi-cell bipolar devices purchased from Pinnacle Research Institute, Cupertino, California. The energy density of the devices, based on energy stored during charge to the rated voltage, was found to be 1-2 Wh/kg, which agreed well with that claimed by the manufacturers. Constant power discharge tests were performed at power densities up to 1500 W/kg. Discharges at higher power densities could have been performed had equipment been available to maintain constant power during discharges of less than one second. It was found that the capacitance of the devices was rate dependent with the rate dependency of the carbon-based devices being higher than that of the mixed-oxide devices. The resistances of both types of devices were relatively low being 20-30 millions.

Testing done in the study showed that the advanced high energy density capacitors can be charged and discharged over cycles (PSFUDS) which approximate the duty cycle that would be encountered if the devices are used to load-level the battery in an electric vehicle. The test data indicate that the useful energy from the device when it is operated between rated and one-half rated voltage is about one-half that stored in the capacitor when it is charged from 0.0 V to the rated voltage. This is less than would be expected because the capacitance of the device is rate dependent and round-trip efficiencies of the present devices are 75-85%. Thermal tests of the advanced capacitors in an insulated environment using the PSFUDS cycle showed the devices do not overheat with their temperatures increasing only 4-5°C for tests that lasted 5-7 hours. Life cycle tests of the Japanese capacitors showed a cycle life in excess of one hundred thousand charge/discharge cycles. Tests of the PRI capacitors indicated a shorter cycle life of about thirty thousand cycles.

The performance characteristics of the advanced capacitors tested in the present study were compared with those of commercially available supercapacitors.
from NEC Electronics and with the minimum requirements for electric vehicle applications (see the Summary Table). It was found that the energy densities of advanced capacitors are a factor of 3-10 higher than that of the NEC Supercap and that the resistances of the advanced capacitors are much lower (several orders of magnitude) than that of the Supercap devices. The energy density of the NEC Supercaps is 1-2 orders of magnitude higher than that of low voltage, electrolytic capacitors, so that the energy density of the advanced capacitors represents a very large increase over that expected of capacitors in the past. A further increase in energy density of at least a factor four (4) is required to meet the goal of 5 Wh/kg needed for electric vehicle applications. The challenge of future capacitor development will be to achieve at least 5 Wh/kg and at the same time maintain an acceptably low resistance. Projections of future development given in the literature for mixed-oxide ultracapacitors indicate that the performance goals can be met and surpassed in a few years. Meeting the 5 Wh/kg goal for carbon-based capacitors is expected to be more difficult, but the cost of carbon-based devices is at the present time projected to be much less (at least a factor of ten) than that of the mixed-oxide capacitors, which presently utilize ruthenium and tantalum oxides as key materials. If substitution of lower cost materials in the mixed-oxide devices proves feasible, then those devices would seem to offer the best prospects for high energy density capacitors to load-level the battery in electric vehicles.

Summary Table. Summary of the characteristics of the advanced and commercially available high energy density capacitors compared with electric vehicle requirements.

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Rated Voltage/Cell Voltage</th>
<th>Rated Capacitance (F)</th>
<th>Wh kg</th>
<th>Wh l</th>
<th>Resistance ohm - cm²/1v cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEC Supercap</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FS</td>
<td>5.0/1.0</td>
<td>1</td>
<td>0.19</td>
<td>0.39</td>
<td>9</td>
</tr>
<tr>
<td>FY</td>
<td>5.0/1.0</td>
<td>2.2</td>
<td>0.33</td>
<td>0.55</td>
<td>45</td>
</tr>
<tr>
<td>FR</td>
<td>5.0/1.0</td>
<td>1</td>
<td>0.26</td>
<td>0.43</td>
<td>43</td>
</tr>
<tr>
<td>FE</td>
<td>5.0/1.0</td>
<td>1.5</td>
<td>0.007</td>
<td>0.18</td>
<td>1.9</td>
</tr>
<tr>
<td>Japanese Cap*</td>
<td>3.5/3.5</td>
<td>70</td>
<td>1.8</td>
<td>2.8</td>
<td>0.025 ohm/3v cell</td>
</tr>
<tr>
<td>Pinnacle Research Institute</td>
<td>20/1.0</td>
<td>3.4</td>
<td>0.8</td>
<td>2.5</td>
<td>.08</td>
</tr>
<tr>
<td>Development Goals</td>
<td>&gt;100 V, bipolar stack</td>
<td>&gt;1.5 F/cm² 1 V cell</td>
<td>&gt;5.0</td>
<td>&gt;11.0</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

* Spiral wound construction. All other capacitors in the table are planar in design.
APPLICATION OF CAPACITORS FOR BATTERY LOAD LEVELING IN ELECTRIC VEHICLES

The average power that must be supplied by the battery in an electric vehicle is relatively low (10-30 W/kg) depending on the driving mode and grade. The peak power pulses of relatively short duration are much higher (80-100 W/kg). The battery must be designed to supply both the required energy (kWh) and the peak power (kW) if the vehicle is to meet its range and acceleration goals. The battery energy density and peak power density requirements can be decoupled if the battery is load leveled using a peak power device (see Figure 1 for a driveline schematic), which can meet the peak power demands.

Various aspects of battery load leveling in electric vehicles are discussed in detail in References 1-3. The effect of battery load leveling on the battery power profile for a minivan on the FUDS cycle is shown in Figure 2. It is clear from the figure that the high power transients can be transferred to the capacitor with the battery supplying nearly constant power over the driving cycle. Since capacitors have very high power capability and long cycle life for rapid, deep discharges, the primary limitation on their use in this electric vehicle application is their low energy density, which limits the energy that can be stored in a weight and volume that is practical for a vehicle. Computer simulations (Reference 3) of vehicles utilizing the hybrid electric driveline shown in Figure 1 indicate that a capacitor energy storage of 300-500 Wh is needed to load level the battery on the FUDS cycle. This results in the capacitor performance specifications shown in Table 1. There are no capacitor devices available at the present time that have an energy density as high as 5 Wh/kg. The two devices procured for testing in this study have the highest energy density of any known to be available at the present time. The capacitors operate between rated voltage and one-half rated voltage, and the power in and out of the capacitors is controlled by interface electronics to maintain a near-constant battery power (See figures 1 and 2). Capacitors are capable of providing short power pulses at very high power density (2 to 3 W/kg), but the simulation results indicate that for electric vehicle applications, operation at power densities above 500 W/kg is not required. These devices are representative of the state-of-the-art of the carbon-based and mixed oxide (Ruthenium)-based technologies. Their construction is very different, with the Pinnacle devices being bipolar in configuration and the Japanese devices being spiral wound. For high voltage applications such as electric vehicles, the bipolar design is preferred, because of the ease of packaging long series strings of the devices. The energy density of the Japanese device is about twice that of the Pinnacle device with both devices having an energy density significantly less than the specification of 5 Wh/kg and 11 Wh/l. The power capability of the bipolar Pinnacle device is higher than that of the spiral wound Japanese device indicating there are energy-power trade-offs in capacitor design as there are in battery design. The difference in the power capability of the two devices will be discussed later in the report.
Figure 1: Schematic of an electric vehicle propulsion system, including battery load leveling.

Figure 2: The effect of the ultracapacitor on the battery power profile on the FUDS cycle.
Electric Vehicle (EV) propulsion has been a principal objective behind the development of ambient temperature secondary lithium batteries (1,2). Requirements of an EV battery include a specific energy of \( \geq 100 \text{ Wh/kg} \), an energy density of \( \geq 135 \text{ Wh/l} \), a sustaining specific power of \( \geq 20 \text{ W/kg} \), a peak specific power of \( \geq 150 \text{ W/kg} \), a power density of \( 250 \text{ W/l} \), and a cycle life of \( \geq 1000 \) full depth-of-discharge cycles. The battery must be safe under all use and most abuse conditions, and be inexpensive. A comparison of the energy density and specific energy of Li and several aqueous battery systems presented in Figure 1 illustrates the desirability of Li batteries for EV propulsion.

Conventional secondary lithium batteries consist of a Li metal anode, an intercalation cathode and a non-aqueous organic liquid electrolyte, Figure 2. Prominent systems include Li/TiS\(_2\) (3-5), Li/V\(_6\)O\(_5\) (6), Li/Cr\(_{0.3}\)V\(_{0.7}\)S\(_2\) (7), Li/MoS\(_2\) (8), Li/MoS\(_2\) (9), Li/NbSe\(_2\) (10), Li/MnO\(_2\) (11), Li/Li\(_2\)CoO\(_2\) (12) and Li/organic redox polymers (13). They are characterized by specific energies in the range of 80-150 Wh/kg, volumetric energy densities of 150-300 Wh/l, and 200-300 full depth-of-discharge cycles. Li batteries presently available fulfill the energy and power density demands; their cycle-life and safety characteristics fall short of EV needs (3); Table 1.

Recent efforts to develop EV batteries have emphasized all-solid-state systems utilizing polymer electrolytes (14,15). All of the above chemical couples can be used for fabricating solid-state batteries. Their promise lies in higher energy densities, longer cycle life and the ability to provide high power through the "bipolar" design (Fig. 3). It is to be noted that the United States Advanced Battery Consortium, a partnership between the big three automakers and the Federal Government, has embarked on the development of a polymer battery by the year 2000 for EV propulsion. Nonetheless, as long as the anode is metallic Li, safety concerns may remain an issue with polymer electrolyte batteries also.

The ultimate solution to the safety hazards in ambient temperature secondary Li batteries may lie with "Li ion" batteries which utilize a Li intercalation anode such as WO\(_3\), Fe\(_2\)O\(_3\) or C (16). Prominent examples from the EV perspective are the C/Li\(_2\)CoO\(_2\) (17), C/Li\(_x\)NiO\(_2\) (18) and C/Li\(_x\)MnO\(_2\) systems. For the solid-state versions of these cells, the highly conductive polymer electrolytes we have recently developed are useful due to their exceptionally high anodic stability (19). "Li ion" batteries are still in their infancy. Their energy density, power density and cycle life capabilities have yet to be demonstrated in practical cells. Nevertheless, it is believed that a "Li ion"-polymer electrolyte system may be the ultimate EV propulsion battery.

Li batteries for EV propulsion must also provide satisfactory solutions to overdischarge and overcharge problems of organic electrolytes (20,21) and incorporate efficient thermal management (22). Ultimately, they must be cost effective.
REFERENCES


11. MoLi Energy, Vancouver, Canada, Product Bulletin, see also J. R. Stiles, in Ref. 3.


### TABLE 1

**PRESENT LITHIUM BATTERY CHARACTERISTICS VERSUS EV REQUIREMENTS**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Present Li Battery</th>
<th>EV Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power Density, W/l</td>
<td>Mid-Term</td>
</tr>
<tr>
<td></td>
<td>400-500 W/l</td>
<td>250</td>
</tr>
<tr>
<td>Specific Power, W/kg (80% DOD/20 sec)</td>
<td>200-250 W/kg</td>
<td>200</td>
</tr>
<tr>
<td>Energy Density, Wh/l C/3 Discharge Rate</td>
<td>250-300</td>
<td>135</td>
</tr>
<tr>
<td>Specific Energy, Wh/kg C/3 Discharge Rate</td>
<td>120-150</td>
<td>100</td>
</tr>
<tr>
<td>Cycle Life (80% DOD Cycles)</td>
<td>250</td>
<td>600</td>
</tr>
<tr>
<td>Operating Environment</td>
<td>-20 to 50°C</td>
<td>-30 to 65°C</td>
</tr>
<tr>
<td>Recharge Time, hr</td>
<td>5-10.</td>
<td>&gt;150</td>
</tr>
<tr>
<td>Price ($/Kwh)</td>
<td>250*</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Safety</td>
<td>Hazardous under some conditions</td>
<td>Must be safe under all use and abuse conditions.</td>
</tr>
</tbody>
</table>

*Estimated.
Fig. 1. Comparison of the Energy Density (Wh/l) and specific energy (Wh/kg) of lithium and aqueous battery systems.

Fig. 2. Schematic representation of a lithium battery.

Fig. 3. Schematic representation of a 3 cell, bipolar, solid polymer electrolyte battery.
After years of investigation and enormous expenditure, batteries are still considered the major obstacle to commercial viability of electric vehicles. As in the seventies, today there are a multitude of systems offered as the "best electric vehicle battery". However on careful examination one finds that these are the same systems that have been evaluated for over the last 15 years.

If forced to decide, today, an electric vehicle design engineer would reluctantly choose lead-acid batteries for electric vehicles. Nonetheless, for all but short commuter applications, vehicle range is inadequate with lead acid power sources. The achieved energy densities for Na-S batteries have proven to be significantly less in practical modules than theoretical projections and concerns remain over the practically attainable cycle life under aggressive conditions, reliability under freeze/thaw cycling, and high temperature operation. The conventional nickel based systems such as nickel zinc, nickel cadmium, and nickel iron, do provide near term higher energy density with acceptable performance but fail to address the need for maintenance free operation, environmental acceptability, low cost, and high performance.

The following critical issues have prevented large scale introduction of electric vehicles:

a. low energy density of the batteries
b. high cost
c. safety

Ovonic nickel metal hydride (Ni-MH) batteries are ideal candidates for Electric Vehicle applications due to high energy density, high discharge rate capability, nontoxic materials, long cycle life, relatively low cost, tolerance to abuse, and ability to be sealed for totally maintenance free operation. Although the Ovonic metal hydride technology was initially applied to consumer type cells, it has also been applied to large size batteries, achieving the same energy density and general performance as the small sealed cells in sizes ranging up to 200Ah capacity, appropriate for E.V.'s. These batteries are presently providing significantly longer device run times versus comparable Ni-Cd cells and have eliminated the manufacturing and disposal issues related to cadmium. Even with the present high level of performance there is still potential for significant increase in energy density. Test results on consumer cells, including simulated SFUDS tests done by an independent national laboratory, have been presented in various conferences. Test results from 150 to 200Ah prototypes have also been included in some of these presentations.
The Ovonic Ni-Metal hydride battery technology has been licensed to several major battery manufacturers including Varta Batteries (Germany), Hitachi Maxell (Japan), Gates Energy Products (Gainesville, Florida), GoldPeak Industries (Hong Kong), Sovlux (U.S.S.R) and Samsung (Korea).

Ovonic Battery Company has been working to improve the energy density of these cells. Prototype C cells demonstrating up to 70 Wh/Kg have been made in the lab and are undergoing testing in house and at an independent national lab.

Figure 1. Cycle life under C/2 to Temperature cutout charge, C/2 to 100% DOD Discharge
## OVONIC BATTERY COMPANY

### 25 AH CELLS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL WT</td>
<td>600 g</td>
</tr>
<tr>
<td>AVG. CAPACITY</td>
<td>29.8 AH</td>
</tr>
<tr>
<td>OPERATING VOLTAGE (VOLTS)</td>
<td>1.23</td>
</tr>
<tr>
<td>IMPEDANCE (1kHz)</td>
<td>1 mΩ</td>
</tr>
<tr>
<td>INT. RESISTANCE (ANSI method)</td>
<td>2.33 mΩ</td>
</tr>
<tr>
<td>ENERGY DENSITY</td>
<td>61 WH/Kg</td>
</tr>
<tr>
<td>VOLUMETRIC ENERGY DENSITY</td>
<td>180 WH/L</td>
</tr>
</tbody>
</table>

**Figure 3:** Cycle life comparison—various systems
OVONIC BATTERY COMPANY
VARIOUS DISCHARGE TESTS ON 25 Ahr CELLS
ALL TESTS TO 1.0 VOLT CUT-OFF

CELL NUMBER

5 AMPERES
50 AMPERE DISCHARGE
100 AMPERE DISCHARGE
+40C 5 AMP DISCHARGE
-20C 5 AMP DISCHARGE

OVONIC BATTERY COMPANY
Performance at various discharge rates

Michael A. Fetcenko, Director of Technology, OBC: B.S. Chemical Engineering Wayne State University (1982). Joined ECD in 1980 and has been engages in research and development of metal hydrides and their applications.

Subhash K. Dhar, President OBC. B.S. Chemistry (1971) and M.S. Process Engineering (1974). Has held several engineering and project management positions for various chemical process engineering and manufacturing companies prior to joining ECD an 1981.

Stanford R. Ovshinsky, President and Chief Executive Officer of ECD and Chief Executive Officer of OBC. As the founder and Chief Executive Officer ECD, Mr. Ovshinsky has been associated with ECD as an executive officer since its inception and is the principal inventor of ECD's Ovonic technology. Mr. Ovshinsky is Chairman of the Board of Directors and Chief Executive Officer of OSMC, Co-chairman of Sovlux and also serves on the Board of Directors of USSC.
Policy, the Environment and Economics Driving the Market

Policy, the Environment and Economics Driving the Market,
Policy makers will be key players in bringing EV's to market.

10:30-NOON
Session Chair: Larry Alexander, Editor, Electric Vehicle Progress, New York, NY (212)-228-0246

US DOE: Current and Future Plans
Ken Barber, Director Electric/Hybrid Propulsion Div., US Department of Energy, Washington DC

EV Options: Current and Future Designs
Paul Brown, Director, Electric Vehicle Association of the Americas

EV's and the Environment: Driving the Green Revolution
Deborah Gordon, Union of Concerned Scientists, Berkely CA

EV's: Entrepreneurs Leading the Way
Doug Marsh, Sebago Technologies, Batavia, IL

1:45-3:15
Session Chair: Molly Magoon, Environmental Protection Agency, Boston, MA

Environmental Protection Agency: The Clean Air Act
Linda Murphy, Director of Air Management Division, Environmental Protection Agency, Region #1, Boston MA

Kateri Callahan, Assoc Dir, Electric Transportation Coalition, Washington DC

3:30-5:00
Session Chair: Warren Leon, Education director, Union of Concerned Scientist, Cambridge, MA

California Legislation: Paving the Way for the Nation
John Dunlap, South Coast Air Quality Management District, Del Monte, CA

NESCAUM: Global Issues, Regional Solutions
Michael Bradley, Executive Director, Northeast States for Coordinated Air Use Management, Boston, MA

Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051
Introduction

I appreciate the opportunity to discuss the current status and future designs of electric and hybrid vehicles in your S/EV 91 Solar and Electric Vehicle Symposium. The recent mandate by the California Air Resources Board for zero-emission vehicles beginning in 1998 has resulted in major electric and hybrid vehicle programs by the auto industry both in our country and abroad.

1. Benefits of Electric Vehicles in Reducing Air Pollution

For those of us living in and around our major cities, traffic congestion and the slowing down of traffic in the rush hours are raising the level of air pollution. This is particularly true of two of the most difficult to control pollutants: ozone and carbon monoxide. Electric vehicles emit virtually no air pollutants. When substituted for petroleum-based vehicles, the use of electric vehicles clearly reduces the air pollution of hydrocarbons, carbon monoxide, and nitrides of oxygen emitted by automobiles. However, there could be a potential increase in sulfur oxides by power plants providing the electricity for recharging electric vehicles. However, flue-gas desulfurization technology is available today for utility boilers to reduce sulfur-oxide emissions by over 90 percent. Improved emission control technology for power plants will probably be installed in the time frame of electric vehicle market penetration due to the Clean Air Act recently signed into law. In those areas of the country where the base load of electric utilities is not high sulfur coal the emission benefits of electric vehicles would be substantial.

2. Benefits of Electric Vehicles in Reducing Petroleum Consumption

Let us not forget the issue of our dependence on imported petroleum. After peaking at 18.8 million barrels after the first oil crisis occasioned by the Iran boycott, we began to lower our level of consumption through fuel switching by industry and utilities, some conservation measures, and more fuel-efficient automobiles. However, beginning in 1983, our rate of petroleum consumption continued to rise to a level of 17.1 million barrels of oil per day in 1988 and the rate of consumption continues to grow. Our production of petroleum has been declining since 1985 due to the low world prices of petroleum. In 1988, our domestic crude oil production was only 8.13 million barrels per day or slightly less than one half of our consumption. The transportation sector is by far the largest petroleum consumer in the United States. Since 1982, the transportation sector total consumption has been rising so that by 1988 it accounts for 62.6% of our total consumption. We consume more petroleum in the transportation sector alone than we produce in the United States. Clearly, if we want to reduce our
dependence on imported petroleum as a nation we must focus on the transportation sector and consider the use of alternative fuels such as electricity.

The potential benefits of electric vehicles in reducing petroleum consumption can be seen from these factors. The transportation sector consumes 10 million barrels of oil per day of which 74% is consumed by the highway mode. Only 5% of the electricity in the United States is generated from petroleum. Thus, the substitution of electric vehicles for conventional vehicles results in direct savings of petroleum and switches to other domestic sources of energy. A market penetration of electric vehicles of 10% of the automobiles and 15% of light trucks and vans would save 292 million barrels of petroleum per year or 800,000 barrels per day. The total size of the vehicle fleet in the United States includes 119 million automobiles and 47 million trucks. The total new sales per year are on the order of 10 million automobiles and 4.9 million trucks and vans. With that large a market, and the mandate of Zero Emission Vehicles by California and a number of other states, the potential for the substitution of a substantial number of electric vehicles clearly exists.

3. Current State-of-the-Art of Electric and Hybrid Vehicle Technology

Having discussed the potential benefits of electric vehicles, let us now turn our attention to the current status of electric and hybrid vehicle technology in the United States, Europe and Japan. All three of the major automotive companies in the United States--General Motors, Ford, and Chrysler--have active electric vehicle programs.

A. Electric Vehicle Programs in the United States

The General Motors Corporation Truck Division is providing "gliders" of their Vandura full size van for the electric conversion to the G-Van by the VEHMA Corporation (a Division of Magna International, Canada). Limited production to orders from electric utility companies of some 150 G-Vans was initiated in the last three months of 1990. The G Van has been crash tested and meets all of the Federal Motor Vehicle Safety Standards. It has an urban driving range of around 60 miles, an acceptable acceleration, and a top speed of 53 mph. The GMC Truck Division views the G-Van program as a controlled field test program to develop dealers, salespeople, and service personnel in the unique sales and service requirements to support electric vehicles in the marketplace. Early in 1990, General Motors introduced their Impact electric passenger car designed from the ground up. It accelerates from 0 to 60 mph in eight seconds with a top speed of 75 mph. In tests at their Proving Grounds, the Impact demonstrated a 124 mile range on the Federal Urban Drive Cycle. The energy storage system is based on a high power Delco Remy sealed lead-acid battery, thirty-two 10 volt batteries, arranged for installation in a central tunnel. The vehicle is powered by two AC induction motors at each
front wheel. The motor is a permanent magnet motor developed by Delco Remy. For competitive reasons, GM has not announced when the Impact will be in production or its selling price.

On January 4, 1991, the Chrysler Corporation announced that it has signed a 28-month agreement with the Electric Power Research Institute (EPRI) to engineer and develop an electric-powered Chrysler minivan for possible commercial production. The performance with nickel-iron batteries of the TE Van are impressive with a range of 120 miles, acceleration of 8 seconds from 0 to 30 mph, and a top speed of 65 mph. The TE Van concept vehicle ("T" for Chrysler's minivan code name T-115 and "E" for electric) uses a nickel-iron battery, DC-powered motor, and an electronic system controller. The battery pack weighs approximately 1800 pounds. The nickel-iron battery supplied by Eagle-Picher Industries of Joplin, Missouri is an 180 volt, 200 ampere hour pack with an Integrated Support System that includes an Automatic Watering System with a three week refill schedule.

The Ford Motor Company has developed an advance AC propulsion system for installation into their Aerostar minivan that is called the ETX-II. In addition to the Ford/DOE Modular Electric Program, the Ford Motor Company is producing 70 to 100 Ecostars, an electric version of their European Escort Van. The electric version of the Ecostar was on display at the Frankfurt Auto Show in September of this year. The vehicles will be leased for 18 months to fleet operators in the United States and Europe for field test operations in 1992.

B. International Electric and Hybrid Vehicle Programs

Let us turn our attention to International EV Developments. Asea Brown Boveri continues to develop and provide sodium sulfur batteries for installation into experimental vehicles for road testing and evaluation. Working with Volkswagen, ABB supplied sodium sulfur battery systems for installation in the VW Jetta CitySTROMers. In March 1990 RWE AG of Germany and Chloride PLC of England announced the formation of a Joint Anglo-German Venture to exploit sodium-sulfur batteries. A pilot plant is scheduled to come on stream in 1991 and will have a capacity of 200 batteries per year. Each battery will have a capacity of 25 kWh, large enough for a car or small van.

VW is in the process of a 20 car build of the Golf Diesel/Electric-Hybrid drive vehicle for Zurich, Switzerland. The first vehicle was delivered in May 1991. VW is using a small fuel injected diesel in combination with a battery in their hybrid vehicle. The concept is to drive in the electric battery powered mode in the city and the diesel outside of the city.

The Fiat Panda is a very popular passenger car and small van in Italy and in Europe. Due to the increasing air pollution problems in Milan and Turin, Fiat has developed an electric
conversion which they have named the "Elettra". Fiat is building some 500 Panda Eletra on a trial basis for companies in Italy at a selling price of $20,000. The lead acid battery in the Elettra provides a cruising range of 75 miles and a top speed of 70 mph. Optional nickel-cadmium batteries boost the range to over 110 miles.

At the Frankfurt Auto Show in September 1991, BMW displayed their BMW E1, and electric vehicle designed from the ground up with sodium sulfur batteries and motor and controls by Unique Mobility, a U.S. company. VW showed for the first time, their "Chico" a 2+2 electric hybrid passenger car. The Swedish CleanAir company displayed their LA 301 hybrid being built for the Los Angeles Initiative. Daimler-Benz, Renault, Fiat, and Peugeot also displayed their latest versions of electric and hybrid passenger cars.

The Japanese conducted an intensive national "Large Scale Project for Electric Vehicles" for six years, from 1971 to 1976. Experimental vehicles were developed including passenger cars, vans, trucks, and buses such as the Mazda Familia, Mitsubishi Minica, Daihatsu Charmant, etc.

New electric vehicle concept cars are being developed and shown in auto shows in Japan such as the NAV or Next Generation Advanced Electric Vehicle, with electric motors in each wheel. The NAV was developed in 1990 by Nippon Steel and Tokyo R&D. Toyota has announced that they are making three electric vans based on their "Town Ace" vehicle by the end of 1990. Nissan has announced the conversion of 14 of their luxury Gloria sedans for leasing to city governments in 1992. Recently Nissan announced their plans for this Future Electric Vehicle of the "FEV". Both the Gloria conversions and the FEV are based on the new Super Quick Charge Battery Systems developed by Nissan and Japan Storage Battery Company. In this battery system the electric vehicle using nickel cadmium batteries would drive 100 miles and then be recharged to restore 40% of its energy in 6 minutes and be on its way for another 80 to 90 miles.

4. Summary and Conclusions

In summary, it is in our national interest to introduce electric vehicles into the nation's transportation fleet and thereby reduce our dependence on imported petroleum and reduce air pollution in our urban centers. All three of our major automotive companies have active electric vehicle development programs. A resurgence of electric and hybrid vehicle development programs is occurring in Europe and Japan. In order to meet air quality objectives the California Air Resources Board (CARB) adopted stringent air pollution controls, mandating the production and sale of ultra-clean" low-emitting cars beginning in the mid-1990's. Only electric vehicles will meet the "zero-emission vehicles" (ZEV) mandated for 1998 in California. Electric vehicles are definitely on the horizon.
EVs AND THE ENVIRONMENT:
THE DRIVE FOR ZERO EMISSION VEHICLES

Deborah Gordon
Union of Concerned Scientists

Presented to:
Solar and Electric Vehicle Symposium
Northeast Sustainable Energy Association

October 1991
SUMMARY

Zero emission vehicles--vehicles running on electricity, fuel-cells, or hydrogen--are an environmentally promising form of transportation for several reasons. First, as their name suggests, zero emission vehicles emit virtually no air pollutants from their tailpipes and therefore do not deteriorate urban air quality. Electric vehicles (EVs) and vehicles powered by fuel cells have the added benefit of using a variety of domestic energy sources in their operation, thereby helping to reduce U.S. dependence on imported oil. In addition, since the electricity supply for electric vehicles could be generated from renewable energy sources such as solar, wind, and biomass fuels or natural gas, the greenhouse impact of electric vehicles is potentially negligible.

Electric vehicle's affects on water and solid waste pollution are more difficult to project. Depending on the chemicals used to charge the battery and the types of fuels used to generate electricity, water quality and solid-waste streams could be adversely affected.

It is very important to consider the fuel-cycle (i.e., means of power generation) with EVs and fuel cells in order to achieve the desired environmental goals. If EVs are powered by new coal and nuclear plants, or fuel cells are run on methanol made from coal, the environment does not stand to gain much over today's oil-powered transportation system. Nevertheless, zero emission vehicles each have a role to play in the transportation sector of tomorrow.

BACKGROUND

POLLUTION FROM TODAY'S MOTOR VEHICLE FLEET

Our cars and light trucks are the largest single source of air pollution in the United States and a major contributor to global warming. They emit carbon monoxide, nitrogen oxides, reactive hydrocarbons (forming smog), and the principal greenhouse gas, carbon dioxide. Despite continuing gains in pollution control and efficiency improvements, overall emissions of pollutants are projected to increase by almost 40 percent by 2010 because Americans are driving more and under more congested conditions.¹

Motor vehicles pollute not only the air but also our water and land. Oil spills contaminate our waterways, as evidenced by the Valdez catastrophe. And motor vehicles require large amounts of irreplaceable land; in cities, upwards of one-third of the land is taken up by cars, trucks, roads, and parking lots.

Today's gasoline-powered cars and light trucks are responsible for nearly one-half of hydrocarbon and nitrogen oxide emissions in urban areas which are in turn transformed into smog by a complex set of photochemical reactions. Moreover, 85 percent of the carbon monoxide in U.S. cities are a direct result of motor vehicles. From a global warming perspective, our vehicles emit more carbon dioxide than any other single pollutant--20 pounds for every gallon of gasoline burned--accounting for 20 percent of total U.S. CO$_2$ emissions. (See figure below).

**EMISSIONS FROM HIGHWAY VEHICLES, 1987**

![Emissions from Highway Vehicles, 1987](image)


**WEANING OUR TRANSPORTATION SECTOR OFF OIL**

The U.S. transportation sector has relied on petroleum for virtually all (97 percent) of its energy needs for decades. Clearly, energy sources other than conventional gasoline can fuel this nation. There are many alternatives derived from a wide array of natural resources. Switching to one or more of these alternative fuels can do more than reduce our oil consumption--it can also reduce greenhouse gas and other air emissions and ameliorate a host of other environmental problems.

Deciding which is the right alternative fuel to replace gasoline is as much a policy question as it is a technical one. The answer depends on the objectives we wish to achieve. Each fuel has trade-offs associated with its production, distribution, and use. It is vital to determine these trade-offs before we give up our gasoline habit altogether and become dependent on another (potentially worse) fuel.
Although this paper focuses on the single objective of minimizing the environment impacts associated with the fuel burned in our cars, several other criteria are worthy of consideration. Briefly, these include whether the fuels in question are: cost competitive; available from secure sources in ample quantities; safe to transport, store, and use; technologically and financially compatible with vehicle and infrastructure hardware; and subject to existing regulatory barriers. There can be no definitive answer as to whether EVs (or any other alternative-fueled vehicle) are superior to gasoline-powered vehicles without addressing each of these issues objectively.

ENVIRONMENTAL IMPACTS OF ELECTRIC VEHICLES\(^2\)

GREENHOUSE-GAS AND OTHER AIR EMISSIONS
EVs shift emissions away from vehicles themselves to electrical-generating facilities. Since most U.S. cities obtain their power from relatively distant generating facilities, urban air quality stands to benefit from the use of electricity as a fuel. Trading locally, low-level, multiple, small-pollution sources (i.e., gasoline-powered vehicles) for centralized, tall-stack, large pollution sources (i.e., power plants), however, will have a different set of environmental consequences. Merely transferring pollution can have negative side-effects. Therefore, the benefits of EVs will require location-specific examinations which address powerplant location in relation to population centers, powerplant fuel mix and control effectiveness, urban meteorologic conditions and pollution mix, and regional long-range transport characteristics.\(^3\)

Most directly, greenhouse-gas and other air emissions depend on the type of fuel used to generate electricity. Today, most U.S. electricity is generated from a primary energy input of coal, nuclear fuel, natural gas, and hydroelectric sources, which results in some form of air pollution and greenhouse gases. Specifically, electric utilities in the U.S. generated their power using 55 percent coal, 10 percent natural gas, 4 percent oil, 10 percent hydroelectric, and 21 percent nuclear power in 1990.\(^4\) Less than one percent of

\(^2\) Author's Note: Although this paper focuses on the environmental impacts of EVs and finds those to be less problematic than gasoline-powered vehicles, it is not the author's intent that other zero-emission vehicles such as fuel cells, hydrogen, solar-equipped vehicles be omitted from the discussion on the future of transportation fuels. In fact, given the fact that hybrid EVs are probably necessary to extend the vehicle's driving range (an important component of consumer acceptance), it is plausible that fuel cell and hydrogen vehicles could operate even cleaner than hybrid EVs.


total power generation is from renewable resources such as wind, photovoltaic, solar thermal, and biomass.

Emissions per-mile of hydrocarbon and carbon monoxide emissions could be reduced by over 90 percent, because utility electric generators emit few of these pollutants. However, older coal and gas-fired baseload plants produce high levels of NOx emissions, and the net effect on NOx emissions regionally could be largely negative. Nevertheless, newer plants (powered by natural gas and renewables) could decrease NOx emissions. There would be no substantial change (and possibly a slight increase nationwide) in sulfur oxide and particulate emission levels.\(^5\)

The greenhouse impact of a significant shift to EVs depends on the nationwide power generation mix, the efficiency of the EVs themselves, and the efficiency of the conventional vehicles they replace. Since in the near-term, EV power generation is likely to come from coal-fueled power plants, CO\(_2\) emissions are projected to increase 3-10 percent, even with more efficient vehicles. If in the future natural gas were substituted for coal-based power generation, greenhouse gases would decrease by a projected 30 percent, and combined cycle gas plants would bring that reduction to an estimated 50 percent. Powering EVs with renewable energy sources such as solar, wind, and biomass would reduce greenhouse gases from these motor vehicles entirely, as would nuclear sources.\(^6\)

![PROJECTED REDUCTION IN CO2 EMISSIONS FROM SELECTED EV POWER SOURCES](image)


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WATER AND SOLID WASTE EMISSIONS

Depending on the chemicals used to charge the battery and the types of fuels used to generate electricity, water quality and solid-waste streams could be adversely affected. Two major studies have found that EVs could worsen water quality and solid-waste problems at the local level. The studies that cited the worst environmental impacts of EVs considered only the manufacturing and disposal of lead/acid, zinc/nickel, and nickel/iron batteries, and the production and use of nuclear and coal fuels to generate electricity.7 Neither study considered sodium/sulfur batteries and renewable energy sources to generate electricity, both of which are more environmentally benign.

CONCLUSION

The pollution and consequent damage to health and agriculture caused by our dependence on gasoline-powered motor vehicles are just a few of the hidden costs of our transportation system. These costs are not paid by drivers directly. The price we pay for transportation is artificially low because gasoline remains relatively inexpensive and nearly all roads are free of charge. But this should not obscure the fact that as a society we are paying these hidden costs—projected at upward of $100 billion annually for air pollution alone.8 And as the costs continue to mount, we will pay them increasingly with our health and welfare. Transportation policy must steer a new course; we cannot afford to wait. Replacing our gas-guzzlers with electric, fuel cell, hydrogen, and solar-equipped vehicles is a good place to begin.

Inc. magazine reported that 80% of the inventions and innovations of today come from small companies. The electric vehicle industry is no exception. Of the 7 manufacturers of electric vehicles in this country, all are small start ups and all are making major technological contributions to the field. This does not include the consultants, parts suppliers, or research & development firms that are also involved. Outlined here are those six companies that are making such contributions and are producing vehicles for sale today.

**Solectria Corporation** was incorporated in 1989, selling primarily electric vehicle components, however its mainline goal is to produce state of the art, practical solar-assisted electric cars. Several prototype vehicles have been developed from the ground up that demonstrate Solectria's engineering ability to create EVs with great performance characteristics. While this ground up design is a constant at Solectria, the current production models are a 2 and 4 seater vehicle dubbed "The Force". These models are based on the Geo Metro glider, using brushless DC motors, lead-acid or NiCd battery packs, and roof mounted solar panels with maximum power point tracking. Solectria achieves a higher degree of performance over other converted vehicles by mounting their DC motors directly to the differential rather than the transmission. This eliminates the energy loss that occurs in a transmission.

**Solar Car Corporation** offers a number of models, all of which are based on the frame of an internal combustion production vehicle. The Ford Festiva conversion uses lead-acid battery technology, an Advanced DC motor, and a solar panel option that covers the hood and roof of the vehicle. A hybrid option is also available, which consists of an 8 horsepower single cylinder engine that can burn gasoline, methanol, or propane. This option boosts the range to over 100 miles. In their new 14,000 square foot facility they are gearing up to be able to produce over 5000 vehicles a year.

Solar Car is not just gearing up for production of vehicles, but is offering standard kits, custom retrofitting services and EV components as well. A large business is planned in component and sub-assembly sales. The component list includes high efficiency DC electric motors, a 1/2 hp, non CFC based air conditioning unit, their patented, light weight charging unit, controllers and more.

**Clean Air Transport**, a Swedish based company made up of engineers from Saab, Volvo, Siemens, and Enfield Automotive, is planning production of its model, the LA301. Production is to begin in England by 1993 with plans to move production to California in the future.

The 4-seater, front wheel drive automatic sedan has a body constructed of light weight reinforced plastic to achieve maximum efficiency. A combined city and highway driving range of over 150 miles is possible when using Auxiliary Power Unit (APU). The APU is an advanced technology, clean and quiet four cylinder engine fueled by "reformulated gasoline". The gasoline, through an electronic fuel injection system and an electrically heated catalytic converter, achieves absolute minimum emissions, with a reduction of 95 percent over conventional automobiles.
The Power Train Management System (PTMS) is a computer controlled system that blends the power of the electric motor and the APU to the wheels. The PTMS makes decisions based on the state of the batteries, the driving conditions, acceleration, regenerative braking, and the driver's trip schedule to maximize performance. This system also continually informs the driver about the current state of the vehicle functions, as well as storing information for diagnostic purposes. Top speed is regulated at 70 mph, with an acceleration of 0-30 in under 9 seconds. Non-CFC, energy efficient electric air conditioning and heating units are also available for the LA301.

In 1990, C.A.T. was selected under the international competition known as the "LA EV Initiative" to produce the first 10,000 EVs for sale in the Los Angeles basin by 1995.

Sebring Auto-Cycle, Inc. of Sebring Florida, is currently producing the Zipper. A light weight, inexpensive, three wheel EV that is highway legal with a base price of under $9,000. The frame is constructed of an aluminum chassis and tubular aluminum body support, surrounded by a body constructed of high impact Royalite plastic, for a total vehicle weight of just 1490 lbs. Both the chassis and body are covered against structural failure for five years. The vehicle has a 44 X 12 inch cargo area or enough room for about 5 bags of groceries. For the RV traveler, the rear wheel retracts into the car for towing, to eliminate drive train wear.

Solar Electric, a California based company produces a number of vehicles based on various gasoline production vehicles. Their high performance model, the "Destiny 2000", is a modified Pontiac Fiero. The body panels have been replaced with light weight plastic and contain integrated solar panels. The "Electron Two", a Ford Aerostar van with solar panels, will carry 5 to 7 people for a maximum range of 60 miles and top speed of 60 mph. Solar Electric has produced and sold over 50 vehicles to date.

B.A.T. Technology, is the latest start up company. The vehicles are currently produced on a Volkswagen Beetle frame and use a kit car body for style. Two body styles are available, the Porche 959 and the Bradley. However, one of the most interesting aspects of B.A.T.'s technology is in their batteries. The batteries use a special electrolyte that achieves a battery life of 75,000 miles guaranteed. This is 3 times the life expectancy of conventional lead-acid batteries. The electrolyte retards sulfation of battery plates and has a much lower impedance. This allows the batteries to be charged in half the time, eliminate corrosion of battery terminals, and eliminate water consumption. The price of the batteries is currently only slightly more than conventional lead-acid batteries.

How are these smaller companies going to survive in the highly competitive, big dollar automotive world, with the likes of GM, Ford, Nissan, etc.? Each companies view on this is as different as their products. Most are not pretending to compete, but are intending to fill a niche market. Each obstacle of distribution, service, sales, etc is addressed by each company, providing as complete a package to the customer as possible.
WHAT WE'RE DOING ABOUT SMOG IN THE L.A. BASIN

John Dunlap
Public Advisor
South Coast Air Quality Management District

Last year our air in the Los Angeles Basin was the cleanest on record since we began measuring pollution in the fifties--no small achievement when you consider the rise in population--from 5 million people to over 13 million today.

Unfortunately, our region is known for its smog which has been a problem here for forty years. But, my agency is working very hard to reduce air pollution, and we're headed in the right direction. A little background on the District:

The Los Angeles Basin in Southern California is a metropolitan area that encompasses four counties, over 13,000 square miles and 184 cities. The District is home to 13 million people and 9 million vehicles.

The Los Angeles area is the second most populous in the country and the hub of Southern California. It also has the most polluted air in the United States. But, we have managed to cut this pollution in half despite a 160% increase in population since 1950. Despite this progress, our District’s air pollution is 2.5 times the federal standard.

Smog reduces our visibility, and it seriously affects our health. A study we commissioned estimated the benefits of achieving clean air in our Basin at 9.4 billion dollars a year.

What about the future of the Los Angeles Basin? Without regulation, emissions would rise over the next 20 years along with a 37% increase in population and an even greater increase in vehicle usage. That’s without regulation. But, the South Coast Air Quality Management District is committed to changing that dismal picture.

Our District is responsible for analyzing air quality as well as developing and implementing an effective plan of action for the Los Angeles Basin. After eight years of research, the Air Quality Management Plan was adopted in March 1989 and updated in July of this year.

The District’s 20 year goal is quite simply to attain all federal air quality standards. To accomplish this goal, we are making major changes in the way we live and work. The Plan’s control measures will regulate industry, on-road mobile vehicles, consumer products and indirect sources such as shopping malls.
The Plan affects everything from large power plants to house paint and floor polish.

My remarks here will focus on our District’s commitment to new mobile technology and, in particular, on our support for the development of the electric vehicle. I will also comment on the District’s public education efforts.

Gasoline emissions are a significant problem: cars, trucks and buses cause roughly two-thirds of the air pollution in the Los Angeles Basin. District controls regulating gasoline emissions include:

--A vapor recovery system requirement for gasoline transfer and dispensing operations. Ninety-five percent of lead emissions from this source are recovered since this regulation was enacted.

--A commuter program, Regulation XV, designed to reduce tailpipe emissions. Regulation XV requires companies of 100 or more employees at a single worksite to submit a rideshare program. Companies whose employees commute in low emission vehicles are eligible for credits. The credit for electric vehicles is 5:1, the equivalent of a 5-person carpool.

Three years ago a Technology Advancement Office was opened at the District to help identify clean fuels and low emissions technologies. The office was charged with shepherding the development and commercialization of new technology through public-private partnerships. The office funds development and demonstrates new vehicles. The District has a fleet of more than 100 flexible fuel vehicles which run on both gas and methanol as well as propane-powered cars.

Last year the California Air Resources Board set a new precedent: the agency was the first in the world to establish requirements for mass production of the electric vehicle. Requirements include: Beginning in 1994, auto manufacturers must phase in new cars and trucks that pollute at least 50% less than new 1993 models. Also starting in 1994, Southern California’s service stations must begin phasing in cleaner-burning alternative fuels, such as methanol, natural gas, propane, ethanol and reformulated gasoline.

In support of CARB’s mandate, the city of Los Angeles sponsored an international competition in May 1988. The goal was to bring 10,000 electric vehicles to the L.A. area by 1995. The winner, Clean-Air Transport, a Swedish company is now building a prototype vehicle which will be exhibited at the Los Angeles Auto Show this January.

The District’s 20-year plan is looking at other strategies to help reduce vehicle emissions.
The District is interested in sponsoring battery development: sodium sulphur and nickel iron show promise. At present, we have a contract with San Diego Gas and Electric to develop new, higher charge batteries.

Local government has been responsive to the development of the electric vehicle in several ways.

A task force in the city of Los Angeles created a resolution to promote the use of electric vehicles.

The Southern California Regional Rail Authority plans to construct 8 lines over the next 10 years covering 400 miles. Naturally, the District hopes these rail lines will be electric.

Mass transit planners are celebrating some proposed changes in federal programs which would allow cities more flexibility where mass transit is concerned. As a result, funds could be used to develop carpool lanes, rail lines or buses as needed. The transportation bill is expected to receive congressional support by the end of the month.

Our agency is responsible for supporting California Environmental Quality Act (CEQA) standards. We do this by setting regional goals, guidelines and thresholds that relate to air quality. District planners are creating a handbook which will list thresholds for key pollutants and mitigating measures to enable project developers to meet CEQA requirements.

Our local utilities are currently seeking a way to make electricity more affordable. Gas companies have already been permitted to offer subsidies for conversion to CNG at work sites. Now the Department of Water and Power and Southern California Edison are asking the Public Utilities Commission to approve a rate increase which will subsidize electric van purchases.

Earlier on, I spoke of the importance of attracting community support for clean air goals. The District’s Clean Air Plan was created with the contributions of the general public in addition to government agencies, business groups and environmentalists. And, public participation continues to occupy a prominent spot on our agenda.

Like many government agencies, we have built-in structures to allow the public and the regulated community input on proposed rules. We request public input at an early stage immediately after control concepts are formulated, before the rule is actually written.

Our public awareness campaign over the past couple of years has been extensive. The District produced a series of public service announcements. One popular brochure, "25 Ways You Can Clean the Air," explains in everyday language how to take personal action. The brochure has been translated into four languages. The
District's Speakers' Bureau reaches over 10,000 people each year.

Each year the Public Affairs division sponsors a Clean Air Awards program to celebrate the contributions of business and industry, environmentalists, government, media and individuals who promote clean air goals. Past winners include ARCO for reformulated gasoline, Santa Monica for its rideshare program, and Southern California Edison for educating the public on energy saving materials and appliances for both commercial and residential applications.

Our agency's recent move to a Los Angeles suburb, Diamond Bar, has given us an opportunity to demonstrate clean air practices first hand. The location reduces long commutes for most employees. And the facility is environmentally-friendly. There are energy saving features and smart cabling which provides for voice and data transmission reduce transportation needs. And there's a child care facility on the grounds. And for those times employees have to be on the road, there are a number of low emission fuels available at the worksite.

Much remains to be done. The setting of our new facility makes that fact apparent. The gentle rolling hills just outside are still encased in smog. So the struggle for clean air continues. And, of course, it is a fight without end. But, we are moving in the right direction and increasingly it seems that the public is on our side.
The Northeast states are very interested in promoting the use of the cleanest vehicles available, including electric vehicles, as a means of reducing exposure to unhealthy air quality. Summertime ozone pollution (smog) is a serious and pervasive public health and environmental problem in the northeastern United States. Despite more than two decades of emissions controls, attainment of the ozone health standard in the region remains elusive. The highest concentrations of ozone occur during the summer when meteorology and ambient concentrations of ozone precursors favor rapid ozone formation. Exceedances of the ozone health standard occur in urban areas, such as New York City and Boston, as well as in rural areas such as Cape Cod and Acadia National Park as a result of interstate pollution transport. Other air quality concerns include exposure to high levels of carbon monoxide, fine particulates, and toxic air pollutants.

Motor vehicles contribute approximately 50% of smog-producing hydrocarbons (HC) and nitrogen oxides (NOx) emitted in the NESCAUM region during the ozone season. Motor vehicles are also the source of approximately 75% of all carbon monoxide (CO) emissions and, according to the US EPA, up to 50% of toxic air pollutants. A number of motor vehicle emission control strategies will have to be implemented as part of the overall program to bring all areas of the Northeast into attainment with the ozone and carbon monoxide health standards and to reduce exposures to air toxics.

Several states in the northeast are proceeding to propose the adoption of the most stringent motor vehicle emission controls available, the California Low Emission Vehicle (LEV) program. The LEV program requires the phase-in of significantly more stringent new vehicle exhaust emission standards for HC, NOx, and CO than the future federal standards mandated by the Clean Air Act Amendments of 1990. The LEV program represents one of the most promising long term emission reduction strategies available to the Northeast states. The program will result in the introduction of four new categories of motor vehicles between 1995 and 1998: (1) transitional low-emission vehicles (TLEVs); (2) low-emission vehicles (LEVs); (3) ultra low-emission vehicles (ULEVs); and (4) zero-emission vehicles (ZEVs). The hydrocarbon certification standards from the California vehicles will be lower than those from the future federal standards by 50% for TLEVs, 70% for LEVs, and 85% for ULEVs. Vehicles certified to ZEV standards will emit no pollutants directly. Beginning in the mid-1990s, vehicle manufacturers will be required to certify sufficient portions of their sales fleet to the California vehicle categories in order to comply with an increasingly stringent annual fleetwide average standard for new vehicles. Manufacturers will be allowed to meet the fleetwide hydrocarbon average using any combination of the LEV vehicles. Only the ZEVs, or electric vehicles, will have a mandated sales requirement of 2% in 1998, increasing to 10% by the year 2003.

Governors in Massachusetts, New York, New Jersey, and Maine have all announced their intention to proceed with adoption of the CA LEV program. In fact, regulatory hearings on adoption of the LEV program in Massachusetts are scheduled for October 30 and 31. Several states outside the Northeast are also interested in the California LEV program. The Governors of Maryland and Pennsylvania support adoption of the LEV program. Texas, Illinois, Nevada, Utah, Oregon and Washington, are also considering the adoption of the California LEV program. In addition, the LEV program is currently being considered by all of the states in the Ozone Transport Commission (Virginia to Maine) as a regional ozone control strategy.
NESCAUM is currently evaluating the potential impacts on utility emissions that will result from shifting the source of air pollutants from vehicles to power plants. Preliminary results indicate that, based on the current Northeast power grid, switching to electric vehicles will significantly reduce total VOC and CO emissions in the Northeast. Assuming a future electric vehicle fleet efficiency of 0.2 to 0.4 kilowatt hours per mile, the future electric fleet will also deliver substantial NOx and CO2 reductions.

If all eight states in the NESCAUM region opt into the LEV program with the ZEV mandate, the electric vehicle fleet could range in size as follows.

<table>
<thead>
<tr>
<th>Years</th>
<th>No. of Electric Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001-2004</td>
<td>50,000 - 100,000</td>
</tr>
<tr>
<td>2005-2009</td>
<td>180,000 - 200,000</td>
</tr>
<tr>
<td>2010+</td>
<td>200,000 - 250,000</td>
</tr>
</tbody>
</table>

These estimates are based on annual sales of 2% in 1998, 5% in 2001, and 10% in 2003. The range in fleet size will depend on the growth in overall vehicle sales, the actual size of the electric vehicle sales area, and consumer demand.

Northeast states that adopt the LEV program will conduct a electric vehicle technology review in the 1994 to 1995 timeframe to determine if the electric vehicle technology and production is adequate to meet the 1998 sales mandate. The electric vehicle component of the California LEV program is viewed as an essential element of the program, one which will produce substantial air quality benefits.

The NESCAUM states are encouraged by the electric vehicle advancements which have been achieved by Ford, General Motors, Chrysler, and other U.S. electric vehicle manufacturers as well as by foreign automakers during the past few years. There is a growing sense that enlarging the future electric vehicle market will create substantial additional incentives for increasing research and development investments to produce advancements in vehicle range, battery performance, recharge timing, and other technical areas. NESCAUM believes that broadening the market demand for electric vehicles will result in lowering electric vehicle costs nationally.

NESCAUM is in the process of completing two reports related to low emission vehicles and electric vehicles. The first report, which was recently completed, compares the potential emission reductions associated with the California LEV program to reductions associated with the future federal motor vehicle control program administered by the U.S. Environmental Protection Agency. The report predicts that by 2015, VOC emissions from light-duty vehicles in the NESCAUM region will be 23 to 61 percent lower, NOx emissions will be 26 to 41 percent lower, and winter time CO emissions will be 10 to 33 percent lower under the LEV program than under the federal program. By 2015, 1,3-butadiene emissions are projected to decrease by 23 to 66 percent, benzene emissions by 23 to 64 percent, and formaldehyde emissions by 22 to 65 percent under the LEV program. The emission control costs for the LEV program were calculated at $180 to $500 per ton.

The second report is an analysis of the impacts of electric vehicles on power demand and utility emissions in the Northeast. This report should be completed within the next month and will be available through NESCAUM.

In addition to these reports, during the next year, NESCAUM will be involved in promoting electric vehicle demonstration projects in the Northeast in cooperation with utilities, evaluating LEV/ electric vehicle incentive programs to encourage the purchase of these vehicles by fleets and private customers, developing potential state legislative incentive proposals, evaluating the need to expand battery recycling programs within state
waste programs, continuing to work with northeast utilities on power demand and air quality impact issues, and beginning to assess electric vehicle infrastructure needs in urban areas.

In conclusion, NESCAUM believes that electric vehicles have a tremendous potential to deliver significant air quality benefits in addition to the energy dependency and economic related benefits. The NESCAUM states are interested in working with other organizations, vehicle manufacturers, and utilities to evaluate electric vehicle technical issues, promote the early introduction of electric vehicles into the market, and develop economic incentives for the purchase and use of electric vehicles.
# TABLE 1
CARBON DIOXIDE REDUCTION FROM VARIOUS MODES OF ELECTRIFIED TRANSPORTATION

<table>
<thead>
<tr>
<th>Transportation Mode</th>
<th>BTU per Measure Requirement</th>
<th>Carbon Dioxide Produced per Unit (lbs)</th>
<th>Carbon Dioxide Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passenger Vehicles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Automobile</td>
<td>6624/vehicle mile</td>
<td>1.141</td>
<td></td>
</tr>
<tr>
<td>- Electric Vehicles</td>
<td>1264/vehicle mile</td>
<td>0.556</td>
<td></td>
</tr>
<tr>
<td><strong>Trains (Passenger and Freight)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Diesel</td>
<td>3.23 (1/efficiency)</td>
<td>5.64 x 10^-4</td>
<td></td>
</tr>
<tr>
<td>- Electric</td>
<td>1.18 (1/efficiency)</td>
<td>4.80 x 10^-4</td>
<td></td>
</tr>
<tr>
<td><strong>Buses</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Gasoline Bus</td>
<td>1138/passenger mile</td>
<td>0.199</td>
<td></td>
</tr>
<tr>
<td>- Trackless Trolley</td>
<td>137/passenger mile</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>- Diesel Bus</td>
<td>711/passenger mile</td>
<td>0.135</td>
<td></td>
</tr>
<tr>
<td>- Trackless Trolley</td>
<td>137/passenger mile</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td><strong>Trucks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Large Semi-Trailer Truck</td>
<td>1110/ton mile</td>
<td>0.194</td>
<td></td>
</tr>
<tr>
<td>- Electric Train</td>
<td>255/ton mile</td>
<td>0.104</td>
<td></td>
</tr>
</tbody>
</table>

* Cross-Substitution analysis.

## References:

Greenhouse Gas Impact of Alternative Fuels -- (light duty vehicles)

Fleet Opportunities

Fleet Opportunities
Fleet owners and operators will be key players in bringing EV's to market.

10:30-NOON
Session Chair: Geraldine Zipser, Senior Attorney, New England Electric System, Westborough, MA

Fleets, the Clean Air Act, and NES
Ben Yamagata, Executive Director, Electric Transportation Coalition, Washington, DC

Electric Vehicles: Past and Present
Cliff Hayden, CMA Ltd, Everett, WA

EV's for Fleets: Taxis to Garbage Collectors
Paul Brown, Director, Electric Vehicle Association of the Americas, Washington, DC

EV's: Entrepreneurs Leading the Way
Doug Marsh, Sebago Technologies, Batavia, IL

1:45-3:15
Session Chair: Bob Batson, New England Electric Auto Association, Maynard MA

Electric Vehicle Fleets of the Future
Cliff Hayden, CMA Ltd, Everett, WA

Infrastructure for EV Fleets, Including the EV Center in Queens.
Dr. Edward F. Duffy, VP of Development, York Technical College, Rock Hill, SC

3:30-5:00
Session Chair: Charles Vidich, US Postal Service facilities Service Center, Windsor, CT

EV's: Market Niches and Utility Benefits
Mark W. Goldsmith, President, Energy Research Group, Waltham, MA

The Impact: a Vision of the Future
John Dables, Dir. Marketing Development, General Motors Corp, Detroit, MI

Northeast Sustainable Energy Association, 23 Ames Street, Greenfield, MA 01301, (413) 774-6051
EV FLEET HISTORY
Cliff Hayden, Chairman
Continental Management Associates Ltd.

INTRODUCTION

Today I would like to take this opportunity to revisit the past 14 years in the development of the modern electric vehicle. Many of you have probably heard much of what I have to say but I believe it bears repeating. This is especially true for those new to the field, those starting projects on their own, and lastly to gauge how far we have come.

In order to provide a complete assessment of the development of the electric vehicle in the United States it is first necessary to review what has transpired since EV site operator participants first began to look at this method of propulsion for transportation in 1976.

The Congress of the United States passed public law 94-413 in September 1976. This law is known as the “Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976.” The law provided for research in battery technology, propulsion systems, the development of a complete state-of-the-art vehicle, and a demonstration of commercially available electric vehicle technology in both public and private fleets. It is to the demonstration that I will be addressing my remarks.

The original program called for an increasing number of vehicles, beginning with 200 units in 1977-78 and increasing to a total of 10,000 vehicles. In actuality, around 1,100 vehicles were introduced through the program at over 90 site locations in the continental U.S. and Hawaii.

There were a number of reasons why the original goals were not reached. These reasons are as follows:

1. No major manufacturer entered the market with a fully integrated vehicle — or with appropriate chassis equipment.
2. Most EV manufacturers who did begin production were under capitalized — and had reached total production capacity by 1979.
3. No manufacturer did more than assemble a group of “off the shelf” equipment.
4. No major battery improvements were accomplished prior to vehicle purchases so as to be integrated into the demonstration.
5. The lessening of pressure on energy price removed much of the impetus to continued manufacture and marketing.
6. Those vehicles which did enter the program had major deficiencies — production deficiencies which were construed as technology deficiencies.
7. Governmental funds did not maintain the pace.

With all of the above, the program faced major survival challenges — a number of major and seriously committed demonstration site operators stepped up to meet the challenge.

The most active demonstration site operators met as a group to see what could be done to salvage the program by addressing technology and other problems affecting site operators. This group carefully articulated the problems it faced and presented these, along with suggested solutions, to the United States Department of Energy. The group proposed to try to find available and nearer term technology that could solve or mitigate the problems, and to systematically test them by integrating them into their fleets. This approach fit well with evolving Reagan administration policy, and formed the basis for a new “test and evaluation project.”

As a result — and with the endorsement of DOE — the Electric Vehicle Users Task Force, including DOE site operators and others (including EPRI and the Tennessee Valley
Authority), was formed in late 1981. One of its first meetings brought together most of the government laboratories to listen to and comment on the problems uncovered and the preliminary research of the group on measures that could be taken to address technology problems and knowledge gaps. There was consensus that some solutions were workable and some not. With this information, we, the EV Users Task Force, next met with leading electric vehicle component manufacturers. We sought their proposals to correct the problems and to use any acceptable retrofits to keep the fleet on the road. The response was very good.

The problems which we saw facing us were:

1. **Battery Watering/Maintenance**
   In many cases the labor costs expended in monitoring and watering batteries annually exceeded the cost of the batteries themselves. The problem of hydrogen gassing due to low water levels had resulted in a number of battery explosions in the fleet.

2. **Thermal Management**
   No attention had been paid to the thermal management within a battery pack. Temperature differences between batteries exceeding 40°F were not uncommon. Operation in cold weather climates found that EV ranges were restricted due to temperature induced degradation.

3. **Battery Charging Regimes**
   The integration of batteries and charging had not been accomplished. The result was uncontrolled under-over-charging of battery packs — resulting in severe degradation and/or increased risks of overcharging.

4. **Controllers**
   We felt that the controllers we were using were inefficient. They were reliable, but there was evidence that the inefficiency probably limited range by as much as 20%.

5. **Battery Module Matching/Performance Monitoring**
   No progress had been made in matching battery voltage and current characteristics within the pack and in controlling factors that resulted in mismatches during charge and discharge cycles.

6. **Fuel Gauge**
   No adequate instrumentation was available to reliably monitor and report remaining range to the operator during operation.

7. **Battery Charging and Hazardous Gas Protection**
   Provisions for removing hazardous gases left much to be desired. No failsafe and consistently effective system existed.

8. **Battery Cable Connections**
   Little or no attention had been paid to this aspect of the battery pack, which resulted in numerous problems and high maintenance costs.

It should be pointed out that these problems had been frequently misconstrued as peripheral to future EV success, with the basic problem being the battery. Everyone assumed that the battery was the overriding problem; therefore, all research had been devoted to this area. In reality, the battery worked well from an electro-chemical standpoint, delivering the predicted limited ranges. True, there were production related problems, particularly from a quality control standpoint. Clearly, battery R & D to further
improve vehicle range and performance and to reduce battery life cycle costs is needed. However, it is also critical that research, outside of the battery, needs to be ongoing, including in-use vehicle testing, particularly new state-of-the-art units, since the demonstration clearly showed that problems, other than batteries, do exist.

Today, as far as batteries go, we have improved and continue to improve lead acid batteries, both flat and tubular plate. Our nickel iron batteries can provide over 100 miles between charges. Work is going forward on nickel zinc, zinc bromide, sodium sulphur, improved tubular lead acid and gel cell lead acid and other systems. With the problems we have identified and corrected out of the way, these can now be carefully and fully evaluated when ready.

Each of the problems identified by the Task Force was addressed with retrofits where applicable. Our results to date are as follows:

1. **Battery Watering/Maintenance**
   A reasonable approach to the watering of flooded lead acid batteries was developed. While this was not a single point watering system it did have the effect of significantly reducing the time required to water a battery pack. With the advent of gel cell batteries and single point watering systems, the use of this device is limited only to the older vehicles still in service.

2. **Thermal Management**
   The problem of thermal management was brought home very clearly by tests conducted at a number of locations. In those vehicles having no battery thermal management systems, temperature variations between batteries often exceed 40°F. Several passive approaches were tested and found to be effective in controlling temperatures within 2°F. This appeared to be more than adequate. All newer systems are designed to provide for some thermal management.

3. **Controllers**
   The early vehicles were all equipped with General Electric controllers. While these were dependable, they were noisy and highly inefficient. The testing of new solid state transistor controllers which were quieter and more efficient than the older SCR type showed an improvement of 15 to 20% range. All new vehicles incorporate the new solid state transistorized controllers.

4. **Battery Charging**
   As in the case of several other components, the early chargers left much to be desired. They significantly overcharged and/or undercharged the batteries and were not integrated with the battery so as to provide optimum charging rates. Several approaches to battery charging were tested and have resulted in new smart charger technology. Many of the early chargers have been modified and all new chargers are of the smart charger type.

5. **Fuel Gauge**
   One of the early problems uncovered was the lack of an adequate fuel gauge. Several different technologies were applied to this problem, but I must say that at this time I know of no good accurate fuel gauge. This, I feel, is a problem which must be addressed prior to the widespread introduction of electric vehicles.

6. **Battery Gassing Protection**
   The early vehicles had little attention paid to the problems of gassing. The result was several unfortunate explosions. This pointed up the need for maintenance of the systems, which has resulted in gassing becoming a manageable problem. Care must still be taken, but to my knowledge, no recent incidents have occurred.
7. **Battery Cable Connectors**
   Our early experience resulted in severe problems connected with the battery cabling and connectors. Poor contact, loss of power, and in several instances, battery post "melt down" were experienced. Today, most if not all cable connectors are welded. This results in a maintenance-free situation without the earlier power losses.

8. **Batteries**
   Several different types and manufacturers' batteries are tested under this program. The most reliable flooded lead acid battery is of the tubular plate design. The most maintenance-free battery is of the gel cell type. Experience with the nickel iron battery has been good from a standpoint of reliability and range. However, its gassing problems and high cost continue to prevent its wide spread introduction.

   We are proud of the progress made by the Users Task Force, but none of the remaining program participants is fully satisfied that all of the problems have been resolved. However, many of the original vehicles are still operational and providing good daily service. These vehicles continue to demonstrate that the electric vehicle has a place, even though they are by no means state-of-the-art.

   On a going forward basis, the Task Force now feels that it's time to test and evaluate several of the newer technology vehicles presently being presented that are under development. These include both AC and DC drive, as well as several vehicles with new propulsion systems. Currently, Ford Motor Company has under development two vehicles, General Motors is producing the G Van (ready for initial commercialization), Chrysler Corporation is developing a mini van, which it hopes to introduce in late 1989, and Eaton has an advanced Gesep vehicle under development.

   The Users Task Force would like to test several of these vehicles for evaluation, as well as to introduce several G vans for public demonstration. In addition to testing complete new vehicles, we expect to continue with testing and evaluation of several batteries. These include, but by no means are limited to, various gel cell batteries, tubular plate lead acid batteries and eventually some sodium sulphur batteries.

   The Task Force is planning to continue testing and evaluation of many evolving technologies. This "pull" from both the public and private sectors in the U.S. and worldwide R & D toward commercial application will continue until an economically viable, universally acceptable and commercially marketable vehicle has been demonstrated. We hope to provide the economic viability using advanced, but near term batteries in this decade.

   In addition to all of the tests and evaluation activities, there is significant renewed interest in commercialization of electric vehicles in the U.S. and abroad. This year in the U.S. the Electric Vehicle Development Corporation, in conjunction with General Motors, has developed the first prototype of the commercial van. This company, comprised of major electric power utilities throughout the U.S. and Canada, has as its mission the future development and marketing of commercial electric vehicles within this decade. While this is an ambitious project, we feel it is possible to make substantial progress and, given continued petroleum supply inconsistencies, it is necessary.

   An additional pull to the commercialization of this vehicle is the growing concern for the environment. At present there are 82 cities within the U.S. in non-compliance with air quality standards. The electric vehicle could do much to alleviate this situation. Legislation is presently passing through the Congress to provide incentives for alternative fueled vehicles. In each bill the electric vehicle is included among the options.

   Within the state of California there is great interest in electric vehicles. Tests are being conducted by Southern California Edison, the Los Angeles Water and Power Commission and GTE. Recently, legislation was introduced to facilitate the introduction of large numbers of electric vehicles into the area.
In summary, we have overcome most of the early problems. Today the world's major automobile manufacturers are working on sophisticated electric vehicles free of any of the aforementioned problems. The only obstacle now facing the industry is in the area of power storage systems. The recent formation of a battery consortium with major auto manufacturers, battery companies, the U.S. Department of Energy and other interested parties should go a long way to overcome this item.

I cannot close without recognizing the tremendous support provided over many years to this endeavor by the United States Department of Energy and its staff. Their contribution cannot be overstated. The industry owes them a vote of thanks.
Introduction

In your consideration of electric vehicles, you should be aware of some of the unique applications and demonstrations that are being tried worldwide. The electric vehicle fleet options include taxicabs, trash collectors, rental and leasing cars, street cleaners, and conventional commercial fleet operations. This paper will describe some of these electric vehicle fleet options and suggest some future applications.

1. Electric Taxis

Journey with me to the beautiful resort village of Zermatt, Switzerland in the Swiss Alps. As we leave the train station we are able to hail an electric taxi. There is room at the back for our skis and luggage. As we take our quiet electric taxi to our chalet hotel, we notice that all the vehicles in Zermatt are electric vehicles. Gasoline and diesel vehicles are not permitted. The Society of Automobile Free Swiss Tourism Villages or GAST has established eight vacation villages such as Zermatt where conventional cars are not permitted. Their appeal and advertising feature: COME TO BE A GUEST AT GAST! Eight villages in the Swiss mountains which know car traffic only from hearsay and where kids don't need white pedestrian stripes on the road are part of this program. Vacation without cars, instead with horse buggies and electric vehicles means leisurely and quiet vacations. They provide vacations without exhaust gasses, without noise and without having to worry about a parking spot.

2. Renting and Leasing of Electric Cars

While in Zermatt, we may wish to rent an electric car to tour around the area. The charging stations at the rental office ensure a fully "fueled" battery before taking off.

In Amsterdam some years ago, a leasing system of some ten vehicles called Whitcar or "White Car" was set up in which you had a metal credit card that unlocked and operated the first charged electric vehicle at a station A. You drove to Station B and parked in another charging area. When you left the area you took the first car in line at the station. The vehicles were two passenger special vehicles in cylindrical shape with lots of visibility due to the glass enclosure. Through the computer system, the subscriber logged in and logged out at the station where he picked up or deposited the vehicle. Subscribers were charged on the basis of the number of kilometers driven by the user on a monthly basis. The operation of such vehicles in Amsterdam was acceptable.
The Japanese conducted a similar eight month experiment of a car leasing system designated PREET for Public Rent and Electric Towncar between April and December 1979. The Citicar System involved the use of five EV passenger cars developed by Daihatsu, five computer-operated charging stations and 150 member drivers. Vehicles were operated daily by the associated members using their special credit cards to log in and log out of the computer vehicle stations that handled the operating logistics, billing and vehicle status.

3. Electric Refuse and Garbage Collectors

The City of Yokohama, together with Fuji Heavy Industries, Nissan Motor Co., Hitachi, Japan Storage Battery Co., and Calsonic Corporation jointly developed the first electric refuse collection truck in 1985. Later, air conditioning and other improvements were added to the second and third vehicles. All three are presently being used and have been subsidized by the government. In the overall concept of the system, power is generated from the burning of the refuse to operate the plant, recharge the batteries on the vehicle and sold to the utility company. The operational efficiency of the electric version is comparable to the gasoline version. The overall reaction of the drivers is favorable and the residents are very pleased with the quiet and clean operation of the electric version.

For many years, two French manufacturers of garbage trucks, SITA and SEMAT, have offered their customers a choice between conventional and electric models. Both companies are now bringing out the latest generation of vehicles with electric drive and compacting. SITA has sold 75 garbage trucks: 25 to Paris, 25 to Bordeaux, and the remainder to local authorities around Paris.

4. Electric Pavement and Street Cleaners

The French manufacturer SITA has also produced two electric street-cleaning vehicles which are undergoing trials: one is a road cleaner, the "Lama L", and the other is a smaller pavement clean the "Lady L". The Paris city authorities have a goal of environmental protection against both noise and atmospheric pollution. The electric garbage trucks and street cleaners meet both of these goals.

5. Battery Powered Buses

Six electric buses were built by Mitsubishi and put into operation in Rakusai Newtown, a residential suburb of Kyoto from 1979 to 1986. In this demonstration project, the buses ran two routes for a total of 30 kilometers before returning to the terminal for a battery exchange. At the bus terminal the battery pack is removed with automated transfer equipment and moved to the charging bay. 14 charging bays were used to provide for the charging of the batteries. The turn around time for the buses was approximately 8 minutes.
6. Commercial Fleet Operation of Electric Vans

In the Site Operator Program between the U.S. Department of Energy and fleet operators throughout the country, electric vehicles were placed in actual work missions to test and evaluate new and existing technologies. Any vehicle deficiencies were identified and corrected. Experimental models of advanced batteries were also tested. Detroit Edison set up an electric vehicle maintenance facility and leased electric vehicles to customers in their geographical area.

In the United States and Canada, individual electric power utilities have been evaluating some 25 prototype G-Vans. The G-Van is currently in limited production by the VEHMA Corporation and is an electric conversion of the GM Vandura full sized van.

Southern California Edison have been using the prototype vans in their own fleet in typical work situations. SCE has also been loaning vans to interested customers. As the production G-Vans become available SCE is considering a leasing program to customers in their area. Pacific Gas and Electric Company is also demonstrating its G-Van at key events in their area. In addition they are evaluating the performance of an advanced air conditioning system for electric vehicles. North Carolina Alternative Energy Corporation (NCAEC) representing five utilities is putting a G-Van into the moving of people and goods between public housing sites in Raleigh, North Carolina.

7. Opportunity Charging

Another fleet option is suggested by the recent announcement by Nissan of their intention to develop the Future Electric Vehicle or FEV shown in the slide on your screen. The FEV will utilize the Super Quick Charge Battery System developed by Nissan and others. In the Super Quick Charge concept the vehicle would run for about 100 miles and then be recharged in 6 minutes to restore 40% of its capacity. If this intermediate opportunity charging is feasible, the range of in town missions of commercial fleet operations is no longer limited to the single charge capability of a work van. With charging stations strategically placed around the service area of the company, there would be no range limitations of existing electric vehicle technology.

Nissan has also announced the conversion of 14 of their luxury Gloria sedans for leasing to city governments in 1992. The fleet options for these vehicles are to familiarize city officials with the operation of electric vehicles in consideration of measures to control air pollution in their jurisdictions.

Summary and Conclusions

In this presentation, I have attempted to give a brief survey of different electric vehicle options that are being utilized today worldwide--from "taxis to garbage collectors." The issue of urban
air pollution caused by the tailpipes of automobiles, trucks and buses is resulting in the demonstration of electric and hybrid vehicles in many different applications. It appears that the first market niche for electric vehicles will be the commercial fleet operation where the company's vehicle fleet is centrally garaged and returns to the home base after the day's operation. With the continued development of electric vehicles by the major automakers the introduction of electric cars for the motoring public is certain to occur in the near future.
It is always difficult to predict, with any degree of accuracy, the future. This is especially true where there is no history to provide a road map. However, it is important to attempt a forecast to provide some basis for forward planning. While future events will change any forecast, as periodic review of your plan can accommodate changes to keep it correct.

Having given you my excuse for future changes, I can now give you my best guess as to what lies ahead. My prognostications are based on fourteen (14) years of working with electric vehicles, seeing the tremendous progress made to date, being aware of what is occurring worldwide, and my belief in the concept.

So that I don’t confuse you with time frames, let me first provide you with what I will be using as a frame of reference. Nearterm is the next five years; midterm is five to ten years; longterm is into the next century.

As I see the introduction of commercial vehicles, it will occur as follows:

The first units will be primarily work vehicles seeing service in fleets. The reason for this is the availability of service facilities, the lack of infrastructure and the high first cost. Also driving this will be the laws and regulations being promulgated across the nation.

I should point out that the mix will include vans, pickups, some medium duty vehicles, as well as some automobiles. The first pure electric vehicles will have somewhat limited range and therefore will fit fleet requirements having predictable daily routes. In order to accommodate longer missions some hybrid vehicles will be introduced. These are already being produced utilizing a small CNQ engine as a generator and/or a range extender. This provides an ultra-low emission unit meeting most, if not all, nearterm air quality standards.

Once an infrastructure is in place, significant units are being produced to begin bringing the price down and a reliable battery is being mass-produced, I believe the public will begin to see the benefits of electrics and will begin to purchase them. This will probably require some form of incentive. These could include tax relief, either from sales tax and/or use tax. I also feel that we must change our thinking concerning our use of autos.

In most two-car families, I believe the process of acquiring and maintaining cars is as follows:

One car is the “family car” and the second is the commuter and/or about town car. When the time comes to replace a car, it is the second car that goes and the “family car” becomes the second car. The new car becomes the commuter car. The second, or commuter car, is not usually called upon for long trips. Rather it has fairly short trips, well within the capability of an electric vehicle. Since the annual mileage is low, the life could well be much longer than currently viewed as appropriate. By viewing these as two distinct vehicles, we could easily accommodate one ICV and EV.

I feel that one other change in our thinking needs to occur, even within fleets. Today, we tend to think almost exclusively in cost per mile. With an electric vehicle, traveling limited miles per annum, this leads to a high cost figure. Rather than this cost per mile, we
must look at “life cycle cost.” While the original cost may be high, the maintenance and operating cost is much lower than an ICV. This is true since there are so few moving parts, no belts, pulleys, cooling system, etc. to wear out and cause problems. With the new batteries there is no watering, gas management and associated labor requirements. Again, since the vehicle can be kept for a much longer time, the original cost can be amortized over many more years.

Now let’s begin to look at the evolution of the electric vehicle into the next century.

For the next five years, I believe we must rely on one of the batteries presently or about to be available. These include lead acid and/or sodium sulphur. In order to obtain reasonable range from lead acid, should ranges in excess of 100 miles be required, we must look to hybrids. A well-designed hybrid can provide very significant range. The range basically can be anything you need. With a sodium sulphur battery ranges of up to 200 miles will probably be achieved on battery power alone.

A hybrid may take many forms. In most cases, a small engine would be utilized to power a generator feeding power to the batteries. This may be constant or on demand. The engine may burn any fuel, but to be classified as a ULEV (ultra low emission vehicle) it would very probably have to be fueled with natural gas.

There is the possibility of a breakthrough in some other technology, but introduction would probably take a number of years to occur. I personally do not view nickel iron as being a major factor. This is based on its huge appetite for water and its gas management requirement. That, coupled with its high cost, weighs heavily against it.

Beyond the next five years there is the possibility for the introduction of several new batteries. These include Lithium, Iron Monosulphide, and Lithium disulphide batteries, as well as lithium polymer batteries. The range envisioned for lithium polymer batteries would be 300 miles plus. It would operate in the 250 F range.

Assuming any of these have fairly long and predictable life, there is the possibility of some battery leasing to occur. This could well be done by either the battery manufacturer or the electric utility. This would address the problem of high first cost and possible midlife battery replacement. Were this to occur, the electric vehicle could well rival the first cost of an internal combustion vehicle. These vehicles could then see us into the 21st century and what I see as the ultimate EV.

Ultimately, I would expect a hybrid vehicle utilizing a fuel cell as power generation for some form of storage battery to be a major contributor to our transportation sector. Such a vehicle would be silent, relatively maintenance-free, non-polluting, and have virtually unlimited range subject only to replenishment of the fuel and water the fuel cell. This would be accomplished at a service station much as we do today for gasoline and diesel fuel. I believe this must occur both for the environment as well as to replace a diminishing supply of petroleum.

One last item. Someone recently suggested that solar power could supply the recharge capability for present day batteries, particularly if an economical photovoltaic process is developed. This may well be within reach.
DEVELOPMENT OF A NATIONAL ELECTRIC VEHICLE SUBSTRUCTURE

YORK TECHNICAL COLLEGE

by Dr. Edward F. Duffy, Ph.D.

Introduction

The history of electric vehicles in the United States is an interesting one. If we go back to 1900, we would find that there were more electric vehicles than conventional vehicles using internal combustion engines. However, as time went on, the internal combustion engine was further refined. The consumer found that the number of BTU's in a gallon of gasoline significantly exceeded efficiency of the per-unit-weight of the battery. In the early 1930's the electric vehicles started to phase out and were almost non-existent by the late 1960's.

In the 1970's there was a renewed interest in E.V.'s because of OPEC and the resulting increase in gasoline and diesel fuel cost in this country. As a result, the U.S. Department of Energy and several private inventors got together and developed an electric vehicle program. Many vehicles were built during the late 70's and early 80's are presently on the York Tech campus. At the present time, there is a resurgence of interest in electric vehicles throughout the country. York Technical College is committed to being a major partner in ensuring the success of this effort. The College clearly saw the demand for a cleaner environment and the availability of an alternate energy source vehicle for transportation. Electric vehicles should become a major viable alternative for transportation as we approach the year 2000.

Introduction to the College

York Technical College is a two-year public institution located in Rock Hill, South Carolina. It is one of the 16 technical colleges in the South Carolina Technical Education system. York Technical College is fully accredited through the Southern Association of Colleges and Schools. It was first organized and established in 1964 to serve Chester, Lancaster, and York counties in the northcentral section of South Carolina. York Technical College enrolls more than 3,000 full-time credit students and serves more than 11,000 students through continuing education. The College was first accredited in 1968 and the reaffirmation of the accreditation occurred in the summer of 1984. The College is 10 miles from Charlotte, North Carolina and serves as a major technical college in the Charlotte, Metrolina area. The College provides 58 different program areas including technical, engineering, health sciences, and college transfer. The College has always been committed to economic development and fostering technical
education. The College has gained a reputation for providing quality education and training for its students as well as the business and industry in the area.

Why The College Got Involved With The E.V. Program

Throughout its 27 year history, York Technical College has remained committed to its position of promoting technical education. The College has a long history of working with industry as well as with government grants. The College was recognized by the U.S. Department of Energy's Electric Hybrid Vehicle Program as a Site Operator in 1989. As a result of this designation, the College has been able to pull together its technical faculty from automotive technology, machine tool technology, computer technology, micro-electronics, industrial electronics, and other areas to work on this single project. The Site Operator Program was started in the 1970's and provides utilities, universities, and colleges throughout the country with information on the use and maintenance of electric vehicles. York Technical College is the only community college in the country with such designation.

The project creates a great deal of interest in technology. Over the last five years, technical and community colleges have seen a decreasing interest in technical fields. Electric vehicles create a major area of interest among traditional high school graduates in principles of physics, mathematics application, computer programming, micro-electronics, and industrial electricity. The College program has been very helpful in creating interest among potential students in the many technical programs at York Technical College.

Overview of the Electric Vehicle Program at York Technical College

York Technical College has a fleet of 18 electric vehicles. These include four (4) nickel-iron battery powered Volkswagens and seven (7) conventional E.V.'s powered by lead acid deep cycle batteries. The College also has five (5) Griffon Vans from England that use chloride batteries. Finally, the College has two (2) Unique Mobility Vehicles that use conventional batteries but have a unique design.

The College is also maintaining a G-Van for Department of Energy, Washington, D.C. This vehicle will be used to promote E.V.'s in the District.

The College is presently looking to expand the fleet of vehicles.

York Technical College has made a major commitment to developing technical training substructure for E.V.'s in North America. The College felt that the more than 1,800 two-year colleges in the country can play a major role in bringing together training
opportunities for E.V. technicians in this country. York Technical College has played a major role in developing curriculum that relates to changing technologies. The College has over 58 programs that addresses various electronics, engineering, computer programming, and automotive technology. The College is committed to develop the outline of a major curriculum dealing with electric vehicle operation and maintenance. Over the last three years, the College has been able to develop an operating fleet for utilities and municipal power authorities. York Technical College has gained a reputation of having well trained technical faculty that can respond to the technical needs of electric vehicles.

Goals of the York Technical College Electric Vehicle Program

York Technical College has established the following as major long range goals of its Electric Vehicle Program:

1. To maintain an Electric Vehicle Program at York Technical College that will reflect the current technology.

2. To establish and maintain an Electric Vehicle Consortium of interested corporations, municipalities and Electric Cooperatives to foster the performance and acceptability of these vehicles.

3. To develop with Duke Power and other interested parties a method of collecting and analyzing the performance of electric vehicles over a five year period.

4. To establish an electric vehicle repair library.

5. To develop a curriculum and curriculum outline related to electric vehicle repair.

6. To provide data through field testing electric vehicles powered by advanced battery technology.

7. To host a meeting of senior electric vehicle technicians to gather data on repair of electric vehicles.

8. To integrate advanced electric vehicles into the York Tech and Duke Power fleets.

9. To establish an awareness of electric vehicle technology by developing curriculum and modules for the K-12 environment.

10. To examine the feasibility of working with a rural electric cooperative in testing electric vehicles.

11. To build an Electric Vehicle Building.
The Site Operator Program

The College works directly with the Department of Energy. Through the program, the College buys vehicles that are used by their partners. These partners include the City of Rock Hill and Duke Power. Several other companies have also shown interest in the program.

The College also uses E.V.'s in their fleet of vehicles. By using these vehicles the program gathers a picture of the vehicles efficiency and use. The lab technicians have looked at some of the following areas:

1. Batteries
2. Charging Systems
3. Watering Systems
4. Controllers
5. Motors
6. Vehicle Subsystems
7. Range Extenders

The College technicians have maintained records on the findings that relate to each of the technical aspects of the electric vehicles. The collected data is shared with the nine other Site Operators. The data is also reviewed by the Idaho National Engineering Lab (INEL) and the U.S. Department of Energy.

Based on this analysis, recommendations are made to manufacturers and used to improve the use and manufacture of electric vehicles. The program represents a major process to foster the development of E.V.'s.

Summary

The College has worked over the last three years to establish a well respected E.V. program and the structure to support the program. The partnership with Department of Energy utilities, municipalities, and corporations has been very helpful in ensuring the success of the effort.

The College plans to expand its fleet and respond to the changes in E.V. technology. Many breakthroughs are taking place related to this technology. These changes will be integrated into the College and the Site Operator Program.

The future potential of the program is limitless. The resources available to the College should enable the College to respond to this opportunity.
Abstract

This paper addresses the advantages of using electric and solar assisted vehicles in a number of fleet applications to provide transportation services in a cleaner, more efficient and environmentally sound manner. The opportunities for increased use of these vehicles will occur through regulations emanating from the Clean Air Act Amendments of 1990. Under these new draft regulations, fleet owners (those with greater than 10 centrally-fueled vehicles) will have to begin to equip their fleets with low-emitting, ultra-low-emitting and zero-emitting vehicles. The zero emissions vehicles will most probably be electric, as opposed to natural gas or other vehicle types.

Opportunities currently exist for increasing electric and solar-assisted fleet vehicle usage in applications involving airports and electric and telephone company fleets, as well as for other short distance vehicle applications. The advantages of using these vehicles include a significant decrease in carbon dioxide emissions as well as the elimination of tail pipe emissions. However, additional research and development and commercialization of electric vehicles will be necessary to support the introduction of increasing percentages of EV's in clean alternative fuel fleet vehicles by the proposed introduction dates of the late 1990s.

I. Introduction

Electric vehicles, including automobiles and trains, have literally been around for decades. Efforts are now underway to re-commercialize these vehicles to obtain significant advantages in pollution reduction and energy efficiency. These advantages would be particularly beneficial in not only reducing urban pollution but also in reducing global warming gases.

The high efficiency electric traction motor offers significant reductions in global carbon dioxide over its internal combustion gasoline or diesel equivalent. There are significant opportunities beginning with fleet introductions to achieve a new market and enhance clean air. These new market opportunities range basically from airports to zoos. They not only can take the form of the traditional electric/solar recharge car, currently the topic of much discussion in today's conference and exposition, but also in the form of the more mundane materials handling vehicles, postal vehicles and vans. In addition, re-electrifying many existing rail and bus lines will provide additional significant environmental advantages in 1992 and beyond.

II. The Marketplace

In 1992, approximately 13.9 million new cars will be purchased in the United States, most of which will be traditional commuter/consumer automobiles. However, a significant number, totaling about four million automobiles, will be purchased for fleet use. In many cases, there is an excellent match between the requirements of the fleet automobile and the performance attributes of the electric car. In addition, the
development of more advanced batteries and electric vehicle designs will significantly improve the application ranges of electric vehicles through improved power performance and range.

The marketplace for EV's will initially be forced by the regulatory environment brought about by the Clean Air Act Amendments of 1990. The proposed regulations will require that fleet purchases conform to the clean fuel emissions standards at the rate of 30 percent of light duty vehicles in 1998, 50 percent in 1999 and 70 percent in 2000. Heavy duty vehicle requirements will have a separate rate of 50 percent in 1998, 50 percent in 1999 and 50 percent in 2000.

Expansion of the marketplace beyond this will be dependent on improved performance of the battery and electric vehicle and/or rising costs of the use of foreign oil imported for gasoline. As a result, the electric vehicle marketplace will attract not only the big three automobile manufacturers in the United States, but numerous international car makers. There will also be significant encouragement from governments internationally to create and improve both the basic vehicle and the battery.

III. POTENTIAL FOR EMISSIONS REDUCTIONS THROUGH THE USE OF EV'S

There is a large potential for carbon dioxide reduction through the use of EV's and electric trains. These reductions are the result of greater efficiency in the conversion efficiencies to electricity and motive power over the internal combustion engine. The savings can be exceptional as shown in Table 1.

IV. THE CURRENT STATE OF ELECTRIC VEHICLES

Electric vehicles are re-entering a commercialization phase consistent with today's commuter and fleet needs. While around for a long time, the electric vehicle design has fallen behind the internal combustion design in terms of performance. Today's new electric vehicles with solid state control, significant improvements in motor efficiency and better battery performance have made these vehicles a marketplace reality. Significant research and development is underway by the major car manufacturers, Electric Power Research Institute (EPRI) and numerous entrepreneurs. Improvements are occurring on a daily basis in controllers, motors, batteries, chargers and other key aspects such as solar assist for battery charging.

Significant improvement in battery performance is still necessary to make the vehicles more competitive with internal combustion engines and, in particular, the compressed natural gas engine. Strides are also being made in battery charging in order to be competitive with the short fueling periods related to the other vehicles. Announcements of breakthroughs are occurring weekly in both the battery and the charging areas. For example, a Japanese manufacturer recently announced a battery that can accept an almost instantaneous charge. Considerable effort will be necessary in order to make these laboratory pilot scale breakthroughs commercial reality.

There is a major area of electric vehicle commercialization that is receiving little attention and will be critical to the marketing success of electric vehicles. This area is in the infrastructure and pricing design for new electric vehicles. It is necessary to have publicly available charging stations as well as reasonable charging rates in order to make electric vehicles competitive with the alternatives. It will be insufficient to argue environmental improvement through electric vehicles without having the marketing necessities of comfort, convenience, speed and choice with respect to electric vehicles. It will be clearly impossible to market electric vehicles based on "we have a better widget." The buying patterns, attitudes and influences on the American car buyer are fairly well established. Changing these patterns will be difficult to say the least and any marketing effort should try and appeal to existing attitudes and the environmental and efficiency concerns.
Entrepreneurs and electric vehicle manufacturers need to have electric vehicles with the features and comforts expected in the standard commuting automobile. Since I believe the initial market interest will be for fleet vehicles, due to environmental regulations, it would behoove the entrepreneur to design the vehicle to be attractive to fleet managers from the viewpoints of standardization, ease of maintenance, low maintenance and operating costs. In addition, it would make sense if the electric utilities provided off-peak charging rates and incentives that encourage the use of off-peak electric charging. These rates will significantly enhance the operating costs of the vehicles and could improve utility system efficiency. In addition, electric utilities are a prime market for EV’s. Electric utilities could also provide prime locations for battery charging stations, possibly providing credit cards as well.

V. NECESSARY RESEARCH AND DEVELOPMENT FOR COMMERCIALIZATION

In order to make the electric vehicle more attractive both to fleet owners and to individual car owners, some significant additional R&D and infrastructure development is necessary. Efforts are required to improve battery performance, which leads to greater range and higher power levels.

Improved acceleration, range, life and quick recharge are a few of the major characteristics being targeted for new batteries under development. A major consortium has been put together to enhance the next generation battery for electric vehicle use. Significant improvements have already occurred in battery monitoring and test equipment as a result of computerization and solid state monitoring. These improvements will lead to better quality control of batteries and significantly enhanced lifetimes and performances of the current battery mix.

In addition to improving battery performance and lifetime, it is necessary to provide attractive locations and effective recharging stations for electric vehicle use. Infrastructure development has significantly lagged that of the compressed natural gas automobile fuel market, which has over 2,000 public fuelling stations in place today. It will be necessary to provide electric refueling stations with a standardized set of batteries or voltages in order to provide publicly accessible electric charging stations possibly akin to parking meters. On-board charging control will be a plus.

Electric utilities are in a unique position to provide the infrastructure research and support necessary for advanced electric vehicles. This infrastructure development can consist of public charging stations and electric charging billable directly through an electric customers bill (charge cards) and a variety of other support services such as the definition and standardization requirements for enhanced outlets for in-home charging areas would be helpful. Lastly, electric utilities could expedite rate structure modifications to provide the appropriate incentives for off-peak use of electricity in charging vehicles. This will enhance utility load factor and profitability and reduce environmental impacts. The EV offers a win/win situation for the consumer, the environment and the utility.
In order for the electrons to travel from the anode to the cathode side of the cell, they must flow through an external load. In the case of the fuel cell vehicle, they pass through the electric motor providing the source of propulsion power.

In the LaserCell prototype, the fuel cell consists of two stacks of cells inside of a single enclosure. The small stack consists of 16 cells, and produces 12 volts to power the vehicle's accessories. The large stack, consisting of 135 cells, outputs 100 volts to power the drive motor. It is not necessary to balance the output of the two stacks because they are electrically isolated.

The cell operates at a current density of about 0.5 amps per square centimeter at 0.75 volts per cell. The cell voltage as a function of load is presented in Figure 3. The dimensions and mass of the LaserCell fuel cell shown in Figure 4 are:

<table>
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<th>Dimension</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Height</td>
<td>0.23 meters</td>
</tr>
<tr>
<td>Length</td>
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</tr>
<tr>
<td>Width</td>
<td>0.16 meters</td>
</tr>
<tr>
<td>Mass</td>
<td>34.0 kilograms</td>
</tr>
</tbody>
</table>

In order to achieve adequate cell performance, reaction kinetics dictate that hydrogen flow through the cell must be 0.5 times greater than actual cell consumption. Surplus hydrogen is captured upon exiting the cell and is recirculated. Oxygen is supplied to the cell at a rate of 2.5 stoichiometry, and at a pressure of 1.15 atmospheres (absolute).

![FIGURE 4. HYDROGEN FUEL CELL AND COMPRESSOR](image)
A recharge "quick" connect is installed on the left side of the vehicle. To recharge the hydride, hydrogen is supplied at a pressure of 17 to 20 atmospheres. Heat must be removed from the hydride bed to achieve a quick recharge. This is accomplished by connecting an external heat exchanger to the vehicle through the twin "quick" connects installed on the rear of the vehicle to the right of the hydride storage vessel. The external heat exchanger consists of a finned tubing coil through which cooling fluid is pumped as air is forced over the fins to dissipate the heat. The design of the external heat exchanger is shown in Figure 10.

**Accelerator Battery**

To minimize the fuel cell capacity required for the prototype, an accelerator battery was installed in the vehicle. The accelerator battery is utilized to provide part of the power during periods of high acceleration, and then is recharged during cruise. The vehicle accelerator battery is lead-acid, and has a total capacity of 25 horsepower-hours. The 13, 6-volt batteries were provided for the project by the Exide Corporation.

A safety analysis of the prototype design and construction was performed by Air Products of Allentown, Pennsylvania. The Pennsylvania State Energy Office provided part of the funding.
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