Use of a Thermophotovoltaic Generator in a Hybrid Electric Vehicle

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Abstract: Viking 29 is the World's first thermophotovoltaic (TPV) powered automobile. The prototype was funded by the Department of Energy and designed and built by students and faculty at the Vehicle Research Institute (VRI) at Western Washington University. Viking 29 is a series hybrid electric vehicle that utilizes TPV generators to charge its battery pack. Acceleration, speed, and handling compare to modern high performance sports cars, while emissions are cleaner than current internal combustion engine vehicles.

INTRODUCTION

The Vehicle Research Institute (VRI) at Western Washington University was founded in 1974 as a program of research in vehicle design, prototype construction and engineering. Funded by grants from the Department of Energy (DoE) and Department of Defense (DoD), the VRI and its industrial partner, JX Crystals Inc., have been involved with TPV research since 1993. This research has focused on low band gap gallium antimonide (GaSb) cells and broad band emitters. The VRI received a DoE grant to design and build a hybrid electric car that utilizes a TPV generator. This paper focuses on the design, fabrication, systems, and performance of Viking 29, the world's first TPV powered automobile (Figure 1).

FIGURE 1. Viking 29, the world's first TPV powered automobile.

Hybrid Vehicles

The performance limits of pure electric vehicles have curbed the public's acceptance of the electric vehicle as a replacement for internal combustion powered automobiles. Range is most commonly pointed out as the electric vehicle's greatest limitation. While the range of today's electric vehicles would be sufficient for a majority of commuters, families are not willing to give up the convenience of having an automobile that can make extended trips. Electric Vehicle supporters believed major advances in battery technology would extend the range of electric vehicles to be comparable with those of internal combustion powered automobiles. Despite substantial improvements, most notably in nickel cadmium and nickel/metal hydride research, battery technology has fallen short of expectations.

In the interim, industry has turned to hybrid electric vehicles (HEVs). Toyota is in the forefront with the Prius, the world's first production hybrid electric vehicle. The Prius utilizes an internal combustion engine to supplement the electric motor and charge the nickel/metal hydride battery pack. While the public has been very receptive of the Prius, production rates have doubled to meet demand (1), it has not eliminated reliance on the internal combustion engine. The hydrogen fuel cell and Thermophotovoltaic (TPV) generator are two less polluting options being researched for use in HEVs.

VEHICLE DESIGN

The initial proposal was to install the TPV generator into one of the existing Viking vehicles built by Western Washington University (2). Upon further study, it was determined that current Viking cars would not be able to accommodate the TPV generator and support systems necessary to power an automobile. It was decided that a new vehicle would be designed and constructed for the purpose of installing a TPV generator. The generator would charge a battery pack that in turn powers the vehicle's electric motor.

Design requirements were driven by the need for performance comparable to current internal combustion automobiles. The body and chassis of the vehicle was designed to minimize vehicle weight while maintaining sufficient rigidity. A body shape with low aerodynamic drag was important to maximize the range of the automobile. Wind tunnel tests with a 1/10 scale model were used to determine the optimum functional body shape.

Acceleration, speed, handling, and ergonomics were all major considerations. Acceleration needed to be sufficient for safe city driving. A Minimum top speed of 70 miles per hour was necessary to allow freeway driving. Handling requirements included full ackerman steering geometry, zero bump steer, and appropriate camber gain with roll. The ergonomics of Viking 29 would need to be similar to today's automobiles to ease the transition for users.

The TPV generator was to be made modular to allow the installation of other generator configurations in the future. An opening under the automobile would allow access to remove and install modular generators. All connections between the automobile and generator needed to be easily disconnected for quick generator removal and installation. Numerous components were required to support the multiple systems in the vehicle. The main components required for the TPV generator are a fuel source, power supply (12 and 50 volts), radiators, water pump, and peak power trackers.

Body/Chassis

Viking 29 is a unibody design, the body and chassis are a single structure. The monocoque design distributes loads throughout the chassis and body of the automobile. The force distribution allows for a lighter chassis and body design.

A full scale plug in the shape of the car was constructed. Female molds for the different components of the body were created from the plug. Additional molds had to be constructed for the internal components including the seats, battery boxes, and wheel wells. Each component was constructed in its respective mold, using a vacuum to remove excess resin and voids and increase laminar bonding. An E-glass and vinyl-ester resin composite was used to give the body and chassis the optimum combination of impact absorbing and load carrying properties. An additional advantage of using E-glass is the low conductivity of the material will help avoid electrical problems that can potentially occur in carbon fiber chassises. A carbon fiber composite was used for the doors and rear hatch for increased strength to weight ratio. The number of layers and fiber orientation varied depending on the component's function.

Molded components were then assembled using overlapping joints (Figure 2). Honeycomb matrix was used for the firewall bulkhead to provide a rigid structure to attach components and to support the dash and windshield. Square steel tube frames were bonded in the front and rear to support the steering and suspension systems. A finish, matte, and veil is used on the exterior to provide a smooth contour. After applying multiple layers of primer, the vehicle was painted British racing green with acrylic urethane paint.

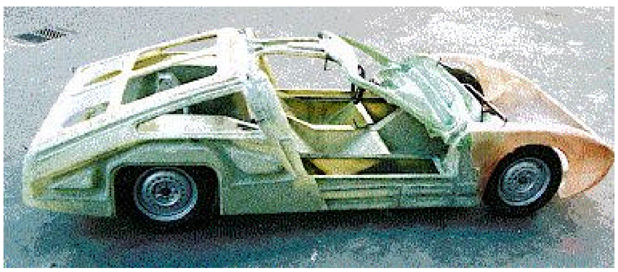

FIGURE 2. Fiberglass unibody chassis.

Semi-gullwing doors provide easier entry and exit over the battery boxes. A detented strut assembly holds the doors open. The front window is from a Dodge Neon while the other windows and headlight covers are thermoformed 3/16" from polycarbonate. Windows are bonded in place with a urethane adhesive. The dash is a clear coated carbon fiber layup. Custom leather seats surround the carbon fiber seat frames. The driver’s seat is adjustable forward and aft. Electric side mirrors provide for easy adjustment from the driver’s seat.

Vehicle Systems

Short and long arm wishbone suspension links are used in the front and rear of the vehicle. A-arms are mounted to the steel frames that are bonded into the chassis. Each corner uses direct acting coil-over shocks. The large 254 mm front and rear disc brakes provide ample braking without requiring power assist. An adjustable brake bias bar allows easy tuning of the front/rear braking ratio. Collapsible tilt steering turns the wheels through a 16:1 ratio rack and pinion. Low front end loading eliminates the need for power steering. EV1 tires mounted on custom machined rims provide a low drag power transfer to the road.

Power Plant

The main power plant is a Unique Mobility 100 hp 3 phase DC brushless motor. See Figure 3 for the location of major vehicle components. The motor’s operating efficiency is greater than 90%. A Unique Mobility processor and motor controller serves as the interface between the user, motor, and batteries. The motor and controller are water cooled. Plumbing the water through an off-the-shelf auxiliary heater box provides adequate cooling. Temperature and water flow gauges mounted in the instrument panel alert the driver of cooling problems.

Two hundred seventy-three Saft™ nickel cadmium aircraft batteries occupy the two battery boxes on either side of the passenger compartment combining for a total nominal voltage of 327.6 volts. Each battery is rated at 25 Amp hours per charge giving the battery pack a total power rating of 8.19 Kwhr (Equations 1 and 2). As weight is a major consideration in electric vehicles, specific energy is used to rate

$$P_{(per\ cell)} = I * V = 25 * 1.2 = 30 \text{ Whr.} \quad (1)$$

$$P_{(pack)} = P_{(per\ cell)} * \#\text{ of batteries} = 30 * 273 = 8.19 \text{ KWhr.} \quad (2)$$

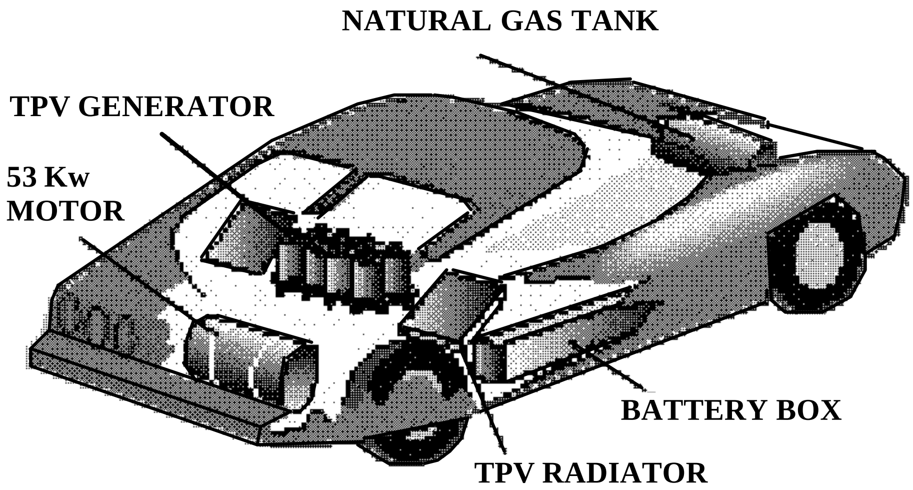

FIGURE 3. Viking 29 major components.

battery packs by the amount of KWhr per Kg. Each battery weighs .915 Kg, giving the battery pack a specific energy of 32.8 Whr/Kg (Equation 3).

$$\text{Specific Energy} = \text{Whr} / \text{Kg} = 30/.915 = 32.8\ \text{Whr/Kg} \tag{3}$$

A machined adapter allows the motor to be mounted end on to a manual four speed Volkswagon transaxle. The dry plate clutch assembly runs on a ball bearing assembly hub that removes all thrust loading from the electric motor. The hydraulic clutch provides smooth shifting even at the motor's limit of 8000 rpm. Marine shifting cables were used to span the distance between the gearshift and transmission. A bell crank attached to the shifting cables allowed clearance of the generator compartment and reversed direction so a standard shifting pattern could be maintained. Driveshafts with inner and outer continuous velocity joints take the drive to the rear wheels.

The processor adjusts the motor's power usage to maintain a constant torque. A linear potentiometer mounted on the accelerator pedal provides the torque signal to the processor. The motor is also used as a generator that recaptures power from the car's momentum to charge the batteries. A potentiometer mounted on the brake pedal controls the regenerative braking signal.

Array Design

Infrared sensitive gallium antimonide (GaSb) cells manufactured by JX Crystals are used in the TPV arrays. Twenty circuit boards containing 19 cells each surround a black body emitter constructed of silicon carbide (see Figure 4). The emitter is heated by natural gas to a temperature of 1700C. A stainless steel recuperator preheats incoming air. A diffuser mixes the gas and air as they enter the combustion zone (3).

Photovoltaic circuit boards are bonded to aluminum receivers that conduct excess heat into the cooling water through fins. Two quartz crystal shields surrounding the emitter help to reduce convective losses and reduce exposure of cells to excess temperatures. Polished aluminum mirrors mounted in the gaps between cells reflect back photons that would other wise be lost as waste heat. An array output of 1 kW has been achieved on an electric powered test station. Past experiments indicate similar results are obtainable with a combustion powered system.

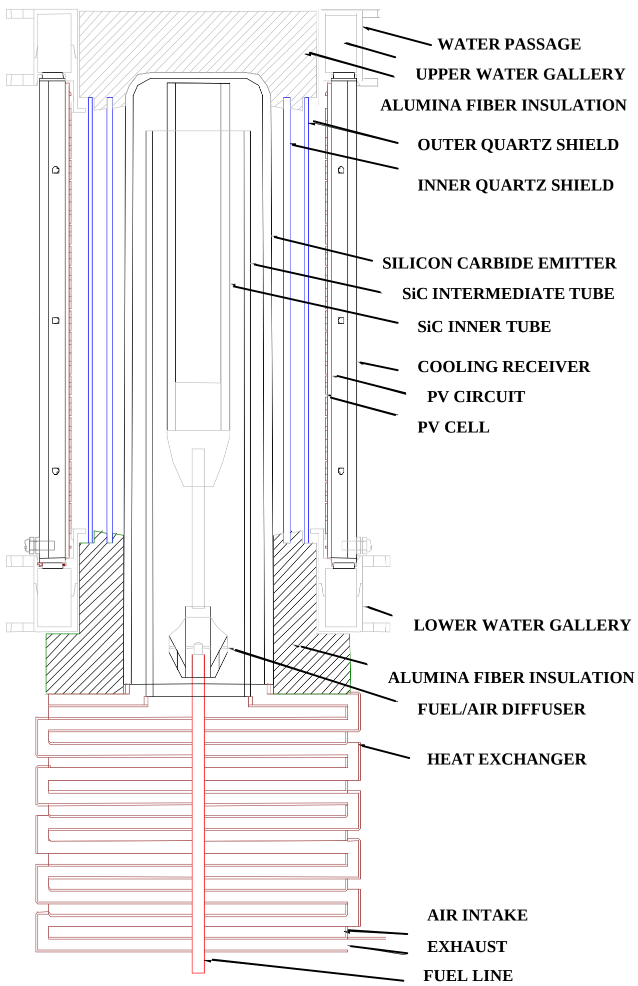

FIGURE 4. Diagram of TPV array components.

Generator

The goal of installing the TPV generator was to increase the range of Viking 29 to 200 miles to be comparable with gasoline powered automobiles (4). The battery pack has 8.19 kWhrs of energy and gives Viking 29 a range of 50 miles. The generator must provide 24.57 kWhrs of energy to make up the difference of 150 miles. With an output of eight kilowatts the generator will need to operate for 3.07 hours to increase Viking 29's range to 200 miles.

The eight arrays are arranged in groups of four (see Figure 5). Each array has a stainless steel recuperator that sits in the generators main frame. Alumina insulation is wrapped around the recuperators to decrease heat loss. Each of the variable speed fans supplies combustion air for two arrays. Exhaust, containing mostly water and carbon dioxide, exits the recuperator under the generator.

A compressed natural gas tank in the front of the vehicle fuels the TPV generators. The carbon fiber wound tank has a maximum pressure of 3500 psi. The tank is filled through a quick connect fitting under a hatch on the hood of the vehicle. A two stage regulator brings the pressure down to 28 psi. Flow control valves on each gas line regulate the amount of fuel entering the individual arrays. A manifold mounted on the generator allows for easy disconnect of the fuel lines.

The efficiency of the photovoltaic cells decreases as their temperature increases. The water cooling system minimizes the operating temperature of the cells while maximizing their efficiency and decreasing their exposure to thermal shock. Each group of four arrays has its own cooling system consisting of a pump, radiator, fan, and fill cap. Large radiators (28" X 18") are used to keep the cooling water temperature as low as possible. The radiators are mounted below slats in the rear hatch. Fans circulate air from under the car, through the radiator, and out the slats.

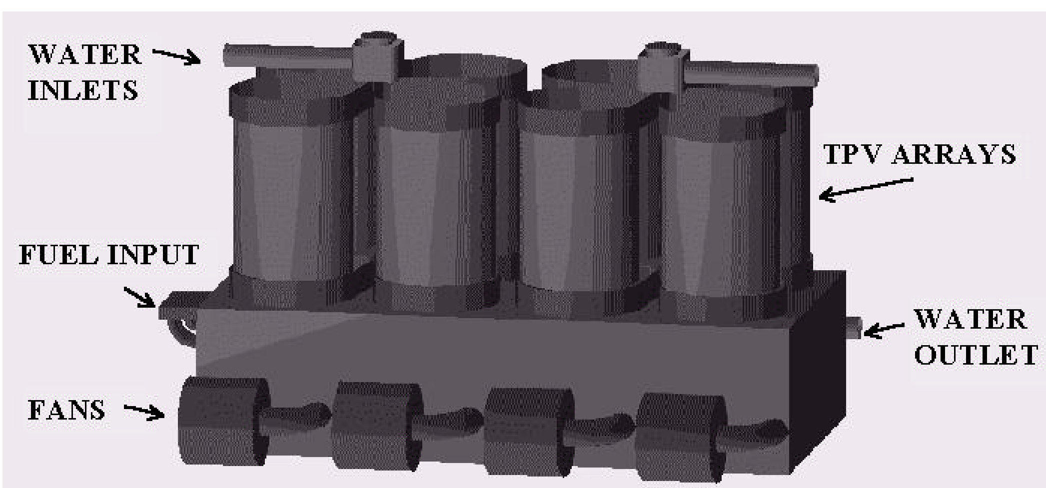

FIGURE 5. The TPV generator is capable of supplying 8kW to Viking 29's battery pack.

The arrays have an average output of 35 volts. Peak Power Trackers (PPT's) adjust the load to maximize array power and output a higher voltage suitable to charge Viking 29's battery pack.

Performance

Viking 29 performs very well as an electric vehicle. With a top speed of more than 100 miles per hour, it can easily maintain freeway speeds. Viking 29's 0-60 time of ten seconds is more than sufficient acceleration for safe city driving. The battery pack alone provides a range of 50 miles, well above the average commute. A coefficient of drag of .335 was calculated from coast down test data. Viking 29's aerodynamic body and weight of 2330 pounds contributes to the low coefficient of drag.

While the generators have been operated in the vehicle, their performance has not yet been tested. Research is currently under way to automate the operation of the generator. Automation requires the air/fuel mixture be ramped up slowly to avoid thermal shock to the components. In addition, the circuit will monitor buss voltage and turn on the appropriate number of arrays when necessary.

CONCLUSION

The goal of demonstrating the use of a TPV generator in an automobile has been accomplished. However, substantial improvements need to be made for the application to be a feasible alternative to other methods of transportation. The two main focuses of improvement are the automation of the generator and increased efficiency of both the arrays and their supporting components, both of which are being researched at Western. The robustness of the ceramic components inside the arrays is another concern being addressed.

With the success of Viking 29 and other hybrid electric vehicles, it appears a feasible alternative to relying on fossil fuels is on the horizon. Continued research will improve current technologies and explore future possibilities.

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