Sunraycer Odyssey

Winning the Solar-Powered Car Race Across Australia

by Paul B. MacCready

FOR DAYS WE HAD BEEN TRAVELING south on Australia's deserted Stuart Highway, but now crowds of spectators lined the road for the final few kilometers to watch the GM Sunraycer, powered by sunbeams, win the 3,005-kilometer (1,867-mile) race from Darwin to Adelaide. Sunraycer completed the Pentax World Solar Challenge course across the continent in 44.9 hours of running time during $5^1/_4$ days; the car's speed averaged 66.9 kilometers per hour (41.6 mph), 50 percent faster than the runner-up; the average electric power to the motor was just a bit over 1,000 watts ($1^1/_3$ horsepower). Of the 24 solar-powered vehicles that started out from Darwin on November 1, 1987 (nine from Australia, four from Japan, four from the United States, three from Germany, two from Switzerland, and one each from Denmark and Pakistan), 13 completed the course. The runner-up from Ford of Australia finished 23 hours behind Sunraycer, and only six had arrived by the time of the banquet and prize ceremony November 13. The last one finally reached Adelaide December 2.

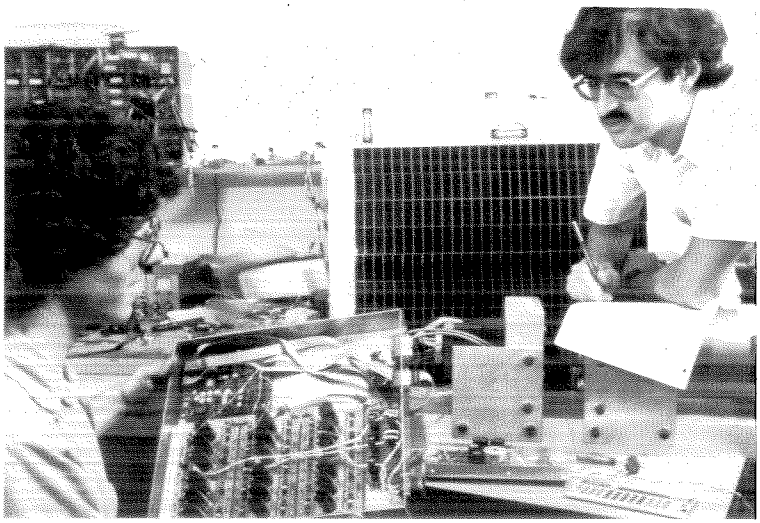
The story of the race began in 1982 when the Australian visionary and adventurer Hans Tholstrup drove a pioneering solar-powered car slowly from Perth to Sydney. Soon afterward he had the idea that a dramatic competition would stimulate global interest in this inexhaustible and nonpolluting energy resource, and he acted on the idea. In 1986 he sent out invitations to the 1987 World Solar Challenge. One of these invitations reached the desk of General Motors Chairman Roger Smith. Smith found the concept intriguing and sent the invitation on to GM's subsidiary, Hughes Aircraft, for consideration of the project's feasibility. From GM's standpoint, developing and racing such a vehicle would serve to focus technological developments within the whole company, would make GM's technological capabilities more evident to the public, would fit GM's racing philosophy, and would attract students to engineering as an exciting and rewarding career.

This article gives an overview of the GM-Sunraycer story and my personal view of some of the main issues. More detailed treatments of the technology and of the race are available elsewhere. Many people contributed significantly to the success of Sunraycer, although space allows me to cite only a few of them here.

My company's involvement began last February when Edmund Ellion of Hughes (whom I knew 35 years ago at Caltech) contacted me to explore whether AeroVironment (AV), with its reputation for developing unusual low-powered vehicles, could help. In early March Hughes and AV began an intense three-week program-planning effort.

The basic overall design had to be established during this three-week phase. Engineers always wish for adequate time to deliberate and explore alternatives before irrevocable decisions must be made, but the real world rarely grants that wish. We quickly considered the trade-offs involved in a dozen

Besides creating interesting photographic opportunities, the gold plating on Sunraycer's canopy (left) keeps out 98 percent of the infrared and 90 percent of the visible radiation. As a result of this shielding, plus a bit of ventilation, the driver remains comfortable even on the hottest days. From inside, the visibility is surprisingly good; sometimes a driver would even wear dark glasses. Such a windscreen wouldn't be suitable for night driving, but that's of small concern for a solar-powered car.



Alan Cocconi (left) and Alec Brooks check a power-electronics module prototype.

THE CALTECH CONNECTION

More than a dozen Caltech graduates participated in the Sunraycer programs. Four are full-time employees of AeroVironment: Paul MacCready (MS '48, PhD '52) was program director; Peter Lissaman (MS '55, PhD '66), who heads AV's Aerosciences Division, which handled the project, participated actively in the aerodynamic phases; Alec Brooks (MS '77, PhD '81) was Sunraycer project manager and also one of the six drivers in the race; and Bart Hibbs (BS '77) served as lead aerodynamicist.

Six Caltech alumni were consultants to AV. The most deeply involved was Alan Cocconi (BS '80), who was responsible for the power electronics system interconnecting the solar array, battery, and motor, plus the associated controls and instrumentation. John Gord (BS '75) built the telemetry system that continually conveyed Sunraycer's condition to the observer vehicle during the race; John Letcher, Jr. (BS '63, PhD '66) aided with the utilization of the VSAERO computer program used to refine the Sunraycer shape; Wally Rippel (BS '68) advised on electric drive systems; and Taras Kicenuik, Jr. (BS '78) contributed to the final stages of design and construction.

At Hughes Edmund Ellion (PhD '53), who initiated the Hughes/GM contact with AV, subsequently made sure the project stayed on course; Ervin Adler (BS '74) was responsible for the day-to-day participation of Hughes, particularly with regard to the solar array and battery; Max Schenkel (MS '71), an aerodynamicist at GM, helped with the Sunraycer wind-tunnel tests at Caltech.

Tests of various aerodynamic designs were performed over a two-week period at the GALCIT 10-foot wind tunnel, resulting in the selection of the final Sunraycer configuration.

different configurations: different shapes and orientations of solar panels, various body shapes, and the location and structural support of the wheels (and whether to have three or four of them). We explored virtually every vehicle configuration that finally showed up at Darwin. Our study supported the advantages of what was to become the Sunraycer concept, which emphasizes low aerodynamic drag and invulnerability to crosswinds even at the sacrifice of some solar power from additional or tilting panels. Almost all the other cars in the race had solar panels distinct from the car bodies. Although their frontal areas could be small, the vehicles suffered from the drag associated with large wetted areas, as well as the interference drag of separate wheels and connecting structures exposed to the wind. Such vehicles also had to cope with some structural complexities. Fortunately, our concept happened to result in a design that was not only efficient but also looked dramatically super-streamlined—like something James Bond might drive.

Essential to our design was the peak power tracker, a prototype of which was designed, built, and demonstrated during that three-week stage by AV's electronics consultant, Alan Cocconi. The peak power tracker continually adjusts the voltage of an array of solar cells so that the maximum power is extracted, and then it delivers this power with 98.5 percent efficiency to the battery or motor at the appropriate voltage. This prototype demonstrated the feasibility of the key concept of splitting the whole solar array into a dozen subarrays, each oriented differently on the vehicle's body and each operated optimally with its own peak power tracker despite exposure to different amounts of solar radiation. This made Sunraycer's curved panels practicable.

On March 26 we presented our plan in Detroit to Robert Stempel, soon to become GM's president, and Don Atwood, GM vice chairman. The presenters were Howard Wilson, the Hughes vice president who serves as the primary link between Hughes and GM; Bruce McCristal, whose public relations role for GM is also a part of the Hughes-GM link; and Alec Brooks and myself from AV. On April 1 GM accepted the plan and the project commenced officially with Howard Wilson in charge.

Although the basic Sunraycer shape was created in those first three weeks, now it had to be quantified by theory, validated and refined by wind-tunnel tests—and then built. The crosswind safety problem loomed large during the configuration-planning stage and subsequently during the refinement of the shape by computer, wind tunnel, and field tests. For a lightweight vehicle operating occasionally in the 70- to 100-km/h regime and encountering real-world winds, our preliminary calculations indicated that a tilted flat solar panel would be out of the question. A number of vehicles of such configuration did finish the Australian race without mishap, but they were slower and mostly heavier—and sometimes frightening to watch as they jittered along in a crosswind. Even a non-tilted flat panel above the body was considered dangerous because of the lift that could be generated at high speeds from momentary gusts (especially the up-gusts from the vortices in the wakes of the enormous trucks that ply Australia's outback region). Sunraycer's basic body shape is relatively impervious to crosswinds; but the four wheels, especially if covered with steamlined pants, tend to straighten the crossflow under the vehicle, creating a side force and also disturbing the balance between the vertical force on the upper and lower rear half.

The side force is associated with some beneficial thrust, as with a sailboat, but for the wind speeds expected in Australia and the anticipated vehicle speeds the net speed benefit would be insignificant. And there are drawbacks to consider. A side force adds a bit to tire drag and wear. Much more troublesome is the possibility that the side force will be enough to destabilize the vehicle and even blow it off the road.

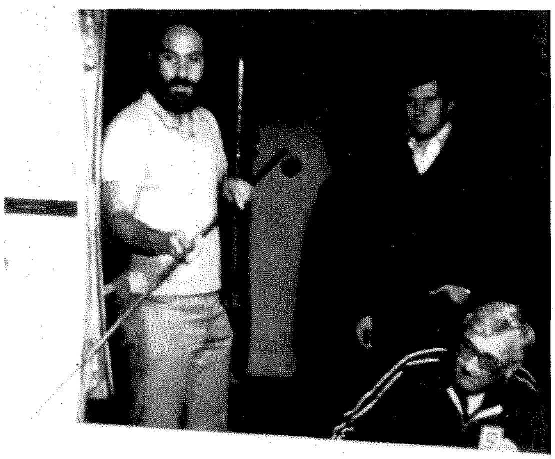
Also, at high vehicle speeds the vertical force from strong crosswinds could lighten the load on the rear tires enough to make the vehicle yaw. The two strakes, or fins, on Sunraycer's top are there to help solve this problem. They serve somewhat as flow straighteners for the top to balance partially the flow straightening produced by the wheels on the underside. They may also serve as vortex generators to modify boundary-layer separation. Tests in Caltech's 10-foot wind tunnel showed that the strakes yielded the desired result, while the many other configurations of add-on devices we tried—fins and spoilers that seemed more logical—did not do as well. There was no time to explore the matter more deeply; the empirical solution was adopted. Of course, like all engineers, we hope someday to be able to

SOLAR CHALLENGE RULES

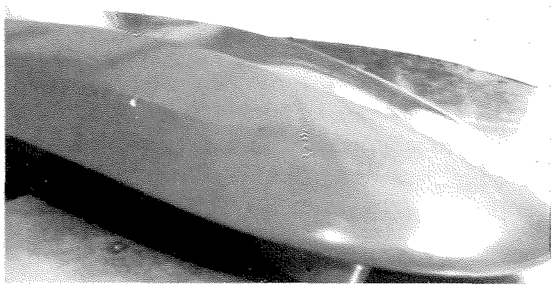
The vehicle can be as much as 6 m long, 2 m wide, and 2 m high, but the solar array panel cannot extend beyond an imaginary box 4 m by 2 m by 2 m (with the exception that the arrays can be hinged to exceed this height when the vehicle is charging while stopped). The vehicle must demonstrate adequate brakes, brake lights, and turn signals; it must show that it is stable when passed by large, fast trucks and that the driver can see surrounding traffic.

A battery may be used but can be charged only from the solar panel. A replacement battery may be installed but at the cost of such a severe time penalty that no serious contender would use one. Between 7:00 p.m. and 5:00 a.m. the panel is to be covered to preclude any charging from artificial light.

The race winner is the vehicle with the minimum running time to Gepps Cross at the edge of Adelaide, 3,005 kilometers from the start at Darwin. (The official, but not timed, end is at Seppeltsfield after a drive through Adelaide.) The daily running time lasts from 8:00 a.m. until 5:00 p.m. This may be extended as much as 10 minutes beyond 5:00 to facilitate camping-site selection, but the vehicle is then held an equivalent length of time beyond 8:00 the next morning. There are seven 10-minute media stops at specified locations, during which drivers can be changed but no maintenance work done.



This quarter-scale model of Sunraycer scored the lowest drag coefficient ever recorded for a land vehicle in Caltech's 10-foot wind tunnel. From left to right Bart Hibbs, Max Schenkel, and Kent Kelly view the tests.



treat the subject in a more fundamental way.

These strakes also offered several benefits beyond extending the envelope of safe speed in crosswinds. They added height, which allowed Sunraycer to meet the one-meter minimum height requirement while maintaining a slender silhouette for low drag and a low center of gravity for stability. They provided a convenient place for turn signals. And they helped solve the problem of giving the driver a rear view without the drag of an exterior rear-view mirror. Hughes concocted a fiber optics remote-viewing system whereby the driver could see on a tiny screen what was observed through a lens pointed rearward from the top of the right strake. And finally, we think the strakes look rather jazzy, and we would not be surprised to see their descendants sprouting on cars (and caps), whose owners appreciate Sunraycer's style.

Because of the tight schedule, many interrelated aspects of the design had to be pursued in parallel. While the shape was being refined, the chassis and suspension were under development, the electronic system was being designed, new tires were being researched, wheels and axles were being built, the solar cells were being ordered, and an expedition was mounted to Australia to gather meteorological data and to survey the entire Stuart Highway for road hazards and road-surface details.

A prototype vehicle was built containing 7,200 single-crystal silicon 6- by 1.8-cm cells. Manufactured by Hughes' subsidiary Spectrolab (the same brand that six years earlier powered our Solar Challenger on its 163-mile flight from Paris to England), these cells convert approximately 16.5 percent of the incident radiation to electricity. The final race vehicle had 20 percent of its panel area covered with these silicon cells, but the remaining 80 percent held 4- by 2-cm gallium arsenide cells. Half of these were obtained from Applied Solar Energy Corporation and the other half from Mitsubishi International Corporation. Use of these space-quality gallium arsenide cells resulted in a solar array having about 25 percent more power than the prototype array. In the best steady-sun conditions in Australia this 8-meter^2 array would deliver more than 1,550 watts. In comparison to silicon the gallium arsenide cells have higher output and a lower negative temperature coefficient of power, but they cost more, are smaller, more delicate, and heavier, and require more diodes to provide protection against back voltage when a portion of the array is shadowed. Both solar arrays were designed and built by Hughes.

The battery, also designed by Hughes, is silver zinc, has 68 cells, can store three kilowatt hours and weighs 27 kilograms (60 lbs). It is the electrical equivalent of a lead-acid battery weighing four times as much. A silver zinc battery tires rapidly as it is cycled a number of times, however, which lowers its capacity, but the effect was small for the few cycles of the Australian race.

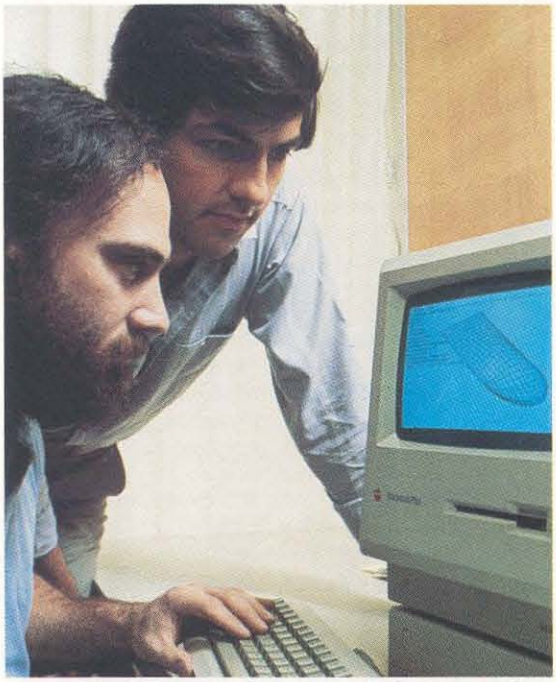
The motor, developed by GM's Research Laboratories, uses Magnequench magnets from GM's Delco Remy Division. It weighs 5 kg (11 lbs), reaches an efficiency of 92 percent, and can deliver 4 horsepower continuously and more than 10 horsepower briefly. A cogged belt conveys its output to the left rear wheel.

Twelve separate solar panel arrays are connected to the battery by peak power trackers. The battery drives the motor with a motor drive inverter that generates three-phase AC power. The drive inverter includes control based on constant current, constant speed (rpm), or constant torque; its efficiency is greater than 97 percent.

The human driver has instruments to monitor the operating conditions and temperatures of all the electronic devices, and there is a 90-channel telemetry system delivering all the information to the nearby observer vehicle.

Sunraycer weighs 175 kg and carries a driver ballasted up to 85 kg for a gross weight of 260 kg (573 lbs). The space-frame chassis, which weighs less than 7 kg, is constructed of aluminum tubing. The body's exterior is made of a Kevlar-Nomex-Kevlar sandwich. The portion supporting the solar cells is built with high-temperature epoxy to maintain structural integrity when heated strongly by the sun. To keep the driver cool, the canopy is gold plated. While every aspect of the Sunraycer development had its pressures, construction of the body was especially trying because of the need to let panel layers cure, sometimes for several days, before the next step could be undertaken.

The technological phase of the Sunraycer program was essentially finished by mid-August—all the major engineering challenges were solved just four and a half months after the April 1 start. In the remaining two and a half months we placed a strong emphasis on reliability testing, somewhat to the neglect of

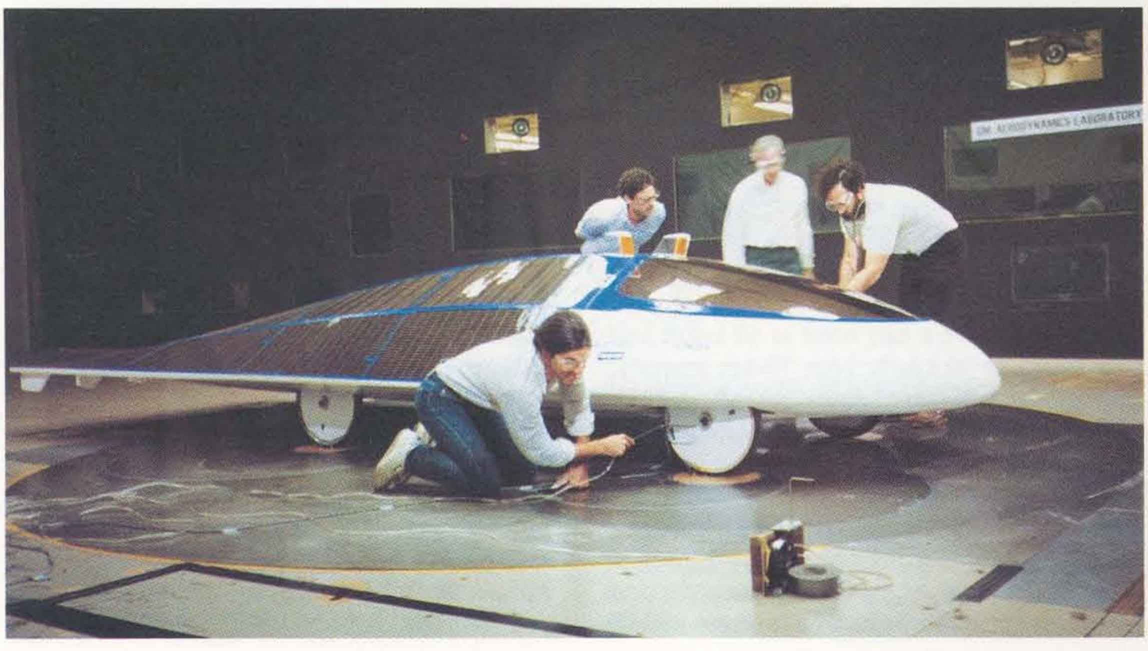


Bart Hibbs (left) and Graham Gyatt check the input data to the VSAERO program using a graphic depiction of the body shape.

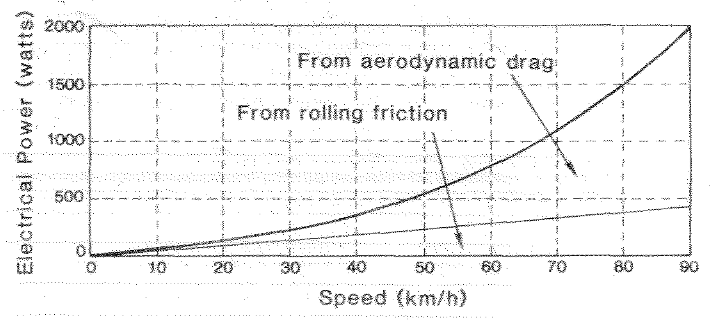
Above: Alec Brooks, who was one of the six drivers in the race, observes Paul MacCready through a fiber optics remote viewing system connected to the top of the strake at left. This served as Sunraycer's rear-view "mirror."

Above: Nomex honeycomb, the sandwich filling, is laid onto the Kevlar skin in the mold for the solar-array panel.

Left: the lightness of the chassis and emptiness of the interior are apparent when the canopy is removed and the solar-array panel tilted up.



An AeroVironment crew checks out the Sunraycer prototype during tests in the GM wind tunnel. There were no surprises, but the tests quantified the effects of many small cleanups, making it possible to decide which ones justified being incorporated into the race vehicle.



In constructing Sunraycer's idealized performance curve, the rolling-friction drag (tires, bearings) portion is assumed constant and so consumes power directly proportional to speed; the aerodynamic drag is proportional to speed squared and so consumes power proportional to speed cubed; and the conversion of electrical power to mechanical power of the drive wheel is taken as 88 percent efficient. For a smooth road surface and no wind or hills at the temperature and altitude typical of the Australia race course, the curve was consistent with observations in the 50-80 km/h range. Note that the graph can also be interpreted as energy (in watt hours) versus distance (in kilometers) for one hour of running.

some obvious improvements in aerodynamic details. We put the prototype vehicle through a rigorous 3,000-km field-test program while the actual race vehicle was built. Also time was spent planning the logistics of the race and developing race strategy. Then the race vehicle also received extensive field testing, much of it in Australia under the guidance of Ray Borrett (of GM's Holden subsidiary in Australia), who put the team through its practice for every conceivable contingency.

Race strategy would be simple if we didn't have batteries to store energy: except for speed limits imposed by safety or traffic laws, always go as fast as you can. The course is prescribed; you just follow the Stuart Highway (and drive on the left side). But a battery complicates the situation. It serves as a bank in which you can store your charge of energy "money" in sunny times for withdrawal at a time when you can make better use of it. This is a great convenience, but one for which you pay the price of having to use your brains without certain necessary inputs.

On a windless day in nonhilly terrain, a reasonable initial strategy is to maintain constant speed independent of the sun situation —the speed that just consumes the total energy available from sun and/or battery in the available time. Referring to the performance curve above, if in one hour you go 70 km/h you will "spend" 1,080 watt hours. If instead you drive a half hour at 50 km/h and a half hour at 90 km/h, your 70-km journey in one hour will "cost" more, namely 1,250 watt hours, because of the nonlinearity of the performance curve.

Selection of the proper constant speed requires that you assume how much energy will be available for the time interval in question. Unfortunately, this assumption depends on future events that can't be forecast with certainty. If the last day of the race is going to be cloudy instead of sunny, you should go more slowly during the early days so as to have more energy in the bank to spend on maintaining speed at the end. If all forecasts through the end of the race could be counted on to be perfect, there would be a specific optimal speed for any moment, and it can be calculated. The complete calculations depend on many factors besides the amount of cloudiness. For example, a headwind or a rougher road surface in the future will then affect the Sunraycer performance curve (watts vs. speed), and this affects the present optimal speed. The solar array power depends on Sunraycer's heading relative to the sun's position, a function of the highway orientation where the vehicle will be at a particular time. Motor efficiency varies with both the power and the rpm (vehicle speed). Battery

SOLAR CELLS AND YOUR BATTERY "BANK"

Solar cells (photovoltaic cells) generate power when the sun shines on them. If the energy is not consumed immediately, it can be stored in a battery "bank account" for later withdrawal. If you think of energy as dollars (not an unreasonable concept nowadays), the strategy for managing the energy is analogous to the way you budget your money. You know how much energy you are starting with in the battery (your bank balance), how much you want to finish the period with so as to be prepared for the future, and, if the weather forecast is accurate, you know the rate at which energy will be provided to you by radiation during the day (your salary).

Your race strategy is to spend your energy in a way that avoids overdrawing your energy account while achieving the maximum distance by day's end, just as you budget spending to maximize life's rewards without causing distress to your bank.

The analogy holds if you explore some aspects more deeply. The energy available from solar cells or battery has a "sales tax," say 15 percent, by motor and transmission inefficiency before the power is converted to driving power (the product of your speed and the force pushing you along the road). The energy from the sun is taxed heavily, some 80 percent, before the solar cell electrical output is available for your use. And the battery bank charges a service charge of 20 percent on each withdrawal. These inefficiencies may seem large in comparison to real taxes and service charges, but at least the sun's radiation is free.

efficiency, the charge you get out compared to what you put in, varies with the charge/discharge rate, the total charge in the battery, and the battery's prior history of charge/discharge cycles. Because of the motor and battery inefficiencies, you don't save as much energy going down 100 m of altitude as you spend going up.

A further complication is that the battery storage is not infinite. The charge is just three kilowatt hours at most, and only the region between 20 percent and 80 percent of full charge should be used for best efficiency and cell longevity. This 1.8 kilowatt hours of preferred battery range is only about a fifth of the total energy available to Sunraycer on a sunny day. The right speed at one moment depends on events throughout subsequent days, but only insofar as these narrow battery limits are not exceeded each day. In practice, the battery operating limits for race strategy solution are even more restrictive. The target discharge condition for the end of a day had to be pre-selected within a narrow range of only 0.5 kilowatt hours, a conservative target for preserving "fuel" to get through a cloud cover the next morning. The target would be revised as the end of the day neared, and the forecast of evening and morning radiation became more certain.

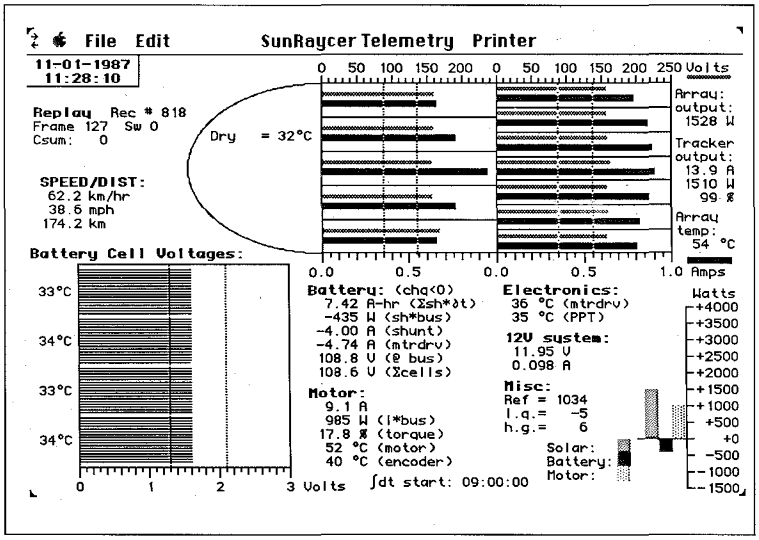
The complete race strategy was modeled by Mike Cassidy and Joe Gurley of Hughes Aircraft Co. Their program was used to explore various scenarios and thereby develop guidelines or rules-of-thumb to guide decisions during the race. For the race itself the program was exercised before each day began, using the weather forecast, to yield optimal speeds and battery charge conditions throughout that day. As the day progressed, if forecast conditions changed significantly, new speed and charge scenarios would be prepared for the remainder of the day.

Graham Gyatt at AV had also modeled strategy factors and worked on rules-of-thumb with the Hughes group. One rule was to avoid mechanical braking at all costs consistent with safety; such braking represents an unproductive withdrawal from your energy bank. Regenerative braking is more desirable. It converts your kinetic or potential energy into battery energy for subsequent withdrawal, but because of various losses you can recover only about half. So, until your speed is considerably greater than the average speed for the day, it's best to avoid regenerative braking while descending a hill.

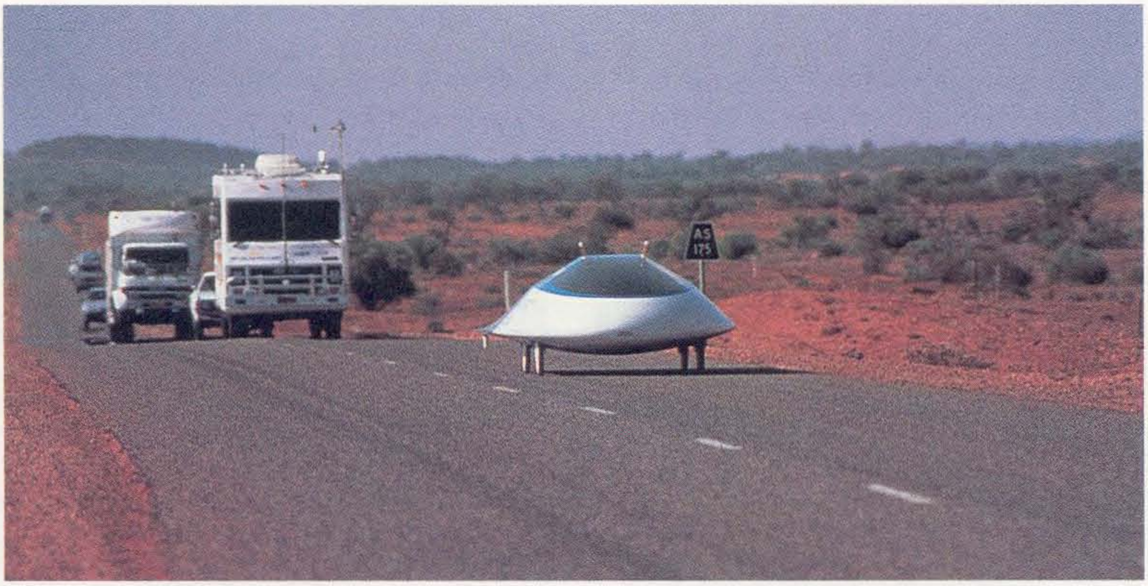
Another rule-of-thumb was to maintain constant speed during cumulus cloud conditions when small cloud shadows alternated with sunny spots. But when cloud shadow areas were large (say, five kilometers or more), the driver should speed up when in shadow. It may seem counterintuitive to go faster when nature is giving you less power, but since you get through the shadow more quickly you actually benefit. In a headwind (or tailwind), you should slow down (or speed up) from the zero-wind optimum by an amount of about half of the wind speed. A constant battery current mode is convenient for handling varying winds as long as the terrain is rather flat.

Fortunately, operating a bit off optimum does not hurt much. If you operate 10 percent faster or slower than the optimum speed for 100 seconds, you lose only about 1 second; for a 20-percent difference the net loss is under 4 seconds. Going too slowly costs you distance in a given time but consumes less energy, and so the battery ends up containing more energy. This excess can then be spent efficiently over a long period of time to increase your subsequent speed. The net consequence on time lost is surprisingly small.

Sunraycer managed to maintain a rather steady average pace from Darwin to Adelaide.

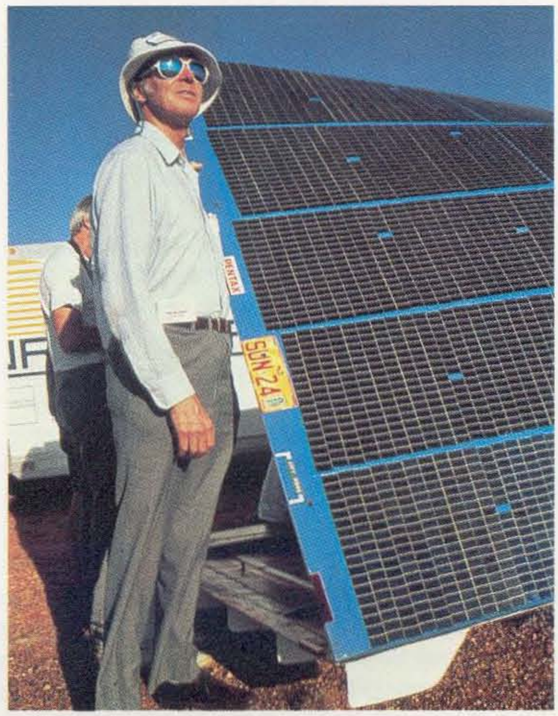


The telemetry display above shows Sunraycer's health. Graham Gyatt developed the display that updates 90 items of Sunraycer's condition every six seconds. On this first day of the race the battery cell temperatures in the lower left are a comfortable 33- 34°C, and voltages are 1.60, well within the 1.25 and 2.05 volt limits. The top of the screen depicts Sunraycer from above, with bars showing the output of each of the dozen subpanels that make up the solar array. The total array output is a healthy 1,528 watts (upper right). The bar graph in the lower right shows at a glance that the motor is drawing only about 1 kilowatt, and the rest of the power is going into the battery. The surrounding numerical information quantifies the situation.



Sunraycer leads its entourage of observer vehicle (the motor home immediately behind), supply truck, and various cars containing helpers and media. The entourage also included a lead car 100 meters ahead, a scout car that roved sometimes many miles ahead, a communications car, a satellite-system vehicle, trucks carrying the camping gear, and a media bus. Sunraycer may save global fuel in the long run but definitely did not do so during the race.

The crew changes one of three flat tires during the race. Stopping, changing the wheel, and reaccelerating took only about two minutes.



Paul MacCready checks out sky conditions as Mother Nature recharges the battery.

Sunraycer's solar panel is tilted for recharging at 5 p.m.

At 7 p.m. of the third day Sunraycer is snuggled under its blanket for the night.

For the first five days the daily average speeds ranged from 62.8 to 69.5 km/h. The difference arose mostly from headwinds and tailwinds and only secondarily from altitude changes, sections of unpaved road, or the amount of battery charge consumed or replaced. We traveled 521 km on the shorter (8-hour) initial day and on the subsequent four days, 605, 564, 563, and 600 km. For the last 152 km on the sixth day, since there was no need to preserve battery charge for later, Sunraycer's average speed increased dramatically but was held down to 77.1 km/h by the heavier traffic.

It was not as easy as it may have looked. The steady pace belies the stress on the weather forecasters and strategists for the first several days, until improving weather and the lack of any close competition took some of the pressure off. At the very start of the race we wanted to drive fast and escape the traffic problems associated with all the other solar vehicles and their large entourages. This required borrowing heavily from the battery bank to cope with low sun angle, clouds, and hills. Operating Sunraycer in a constant-speed mode was appropriate for the hilly topography and cumulus-cloud weather, but this mode makes the prediction of battery charge difficult. Our anxiety was compounded by the fact that we were unsure of the battery charge condition; this could only be determined from an amp-hour meter, and the accuracy of ours was uncertain. Only when the battery was recharged back up to the effective top at the official end of the race at Seppeltsfield were we able to ascertain that the amp-hour meter had been right all along.

The strategy discussions continued throughout the first day, as we watched the battery condition and modified our view of the weather forecast. Watching the weather unfold in our region seduced us into upgrading the forecast that had been provided by the Australian Meteorological Service (and interpreted for our purposes by AV's George Ettenheim). When we saw that the clouds were developing unexpectedly slowly, we could not help but presume that radiation would be better than predicted for late in the day. But Nature disdained our revised expectations. As the 5:00 p.m. stopping time neared that first day, the radiation was weak because of cloud shadows, and the forecasts of the charging potential for the evening and morning grew pessimistic. We drove slowly to conserve battery charge and leave enough in the bank to handle possible poor sunlight conditions in the evening and next morning. The evening charging period indeed yielded almost no charge, but on the morning of November 2 the sun filled the battery even above the top of its efficient range.

On the second day I decided to maintain speed late in the afternoon because I was optimistic about the upcoming evening-morning radiation situation. But Nature was again uncooperative during the final running period of the day (perversely agreeing well with the official forecast). The battery was reduced to 25 percent of full charge by the 5:00 p.m. stopping time, and large storms made the evening charge negligible. If the next morning were overcast, we might have a serious problem. I spent a sleepless night, promising Nature I would be more respectful in the future if she would just give us a fair shake. Nature didn't listen. It rained that night, and clouds kept the morning charge small. At 8:00 a.m. the battery was recharged to only 30 percent, but we started out courageously and spent charge rapidly to maintain a fair speed under the overcast to try to reach the sunny area far to the south. We did reach sunshine as planned, and hindsight showed that we had used almost exactly the proper strategy for the previous 24 hours. It is sometimes better to be lucky (or to have a special relationship with Nature) than to be skillful.

On subsequent days we were usually a bit more cautious, but the weather was improving and the last half of the course proved to be almost a slam dunk, with only a bit of high cloud. Still, every day the strategy decision process was dicey after 4:00 p.m., as solar radiation diminished and Sunraycer

TIRES

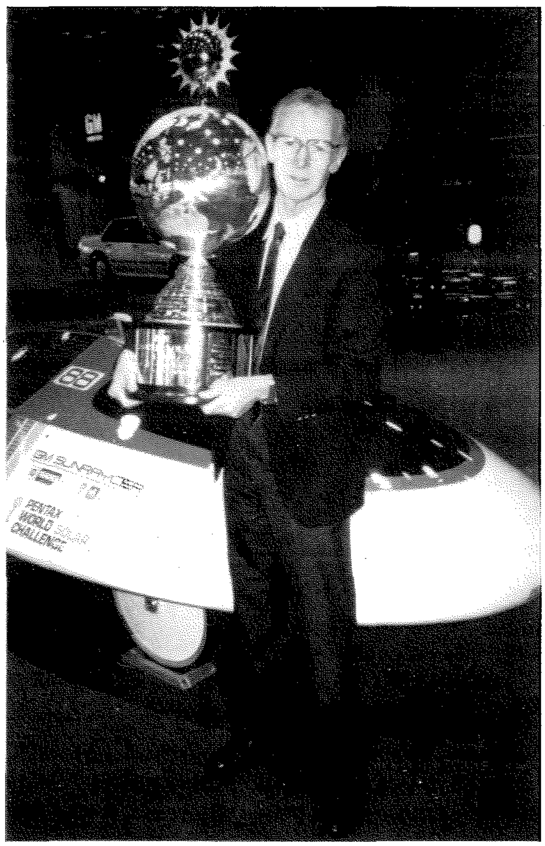
The race did demonstrate one system design "flaw" in Sunraycer. We had only three flat tires during the race; we should have had more. If we had used tires with thinner tread, the lessened rolling friction would have saved a good hour over the 45-hour race, more than compensating for the extra 15 minutes or so that would have been lost handling another dozen flats. Stopping, changing a wheel, and reaccelerating took about two minutes (after many practice sessions), while the extra charge accumulating from the sun during the interval could later be used to make up some of the time lost.

began feeding hungrily on an emptying battery, while we hunted for a stopping location in the 5:00-5:10 p.m. time slot that would afford both a comfortable camping spot and a chance for a good evening charge unhindered by shadows of trees or clouds. The scout vehicle would be probing ahead for likely spots, and we would be coordinating by radio and trying to locate ourselves on featureless terrain while using uncoordinated odometers. The scout car always requested that we use constant speed the last half hour so as to make the coordinated selection of a roosting location somewhat easier. We always agreed, but then worries about the battery would cause us to change speed anyway. After making bum decisions about our stopping point for several days, I was delighted to leave it to others thereafter.

Sunraycer cruised to the finish line on the sixth day with a huge margin of victory. Most of this was due to Sunraycer's basic speed, but other factors helped. There were some jokes about GM's influence extending to very high levels, and we did indeed have some luck with the weather. Our early speed helped us escape the meteorological misery that moved in on those farther back in the race, including gully-washing precipitation that flooded roads and a storm with 1-inch hailstones in a spot where reportedly no rain had been recorded in three years.

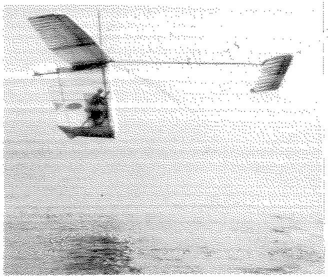
Was Sunraycer's edge due to the solar array, power electronics, motor, battery, aerodynamics, tires, race strategy, reliability, or luck? Every factor helped, with the effectiveness of the total power system from the solar cells to the motor output representing a substantial advantage. Sunraycer was 50 percent faster than the runner-up and would probably still have been 30 percent faster if the runner-up had had our weather. Comparisons become less clear as we explore "ifs" further. The 30-percent figure would probably have been below 20 percent if we had used the all-silicon solar array and the prototype Sunraycer, but we would have won even with a total power system equivalent to those of the next two finishers. But if we had opted for a less advanced power system, we would have saved development time, which could have been invested in aerodynamic cleanup. And with a slower vehicle we would have been less concerned with vehicle dynamics and could have used our alternate tires, which featured substantially lower drag but less comfortable stability and control. Sunraycer's superiority and value lay not in one single advantage but in pushing the frontiers in all the technological areas encountered. The race was the design focus; technological advancement on a broad front was the goal.

This success and the fact that the whole project was conceived and accomplished in so short a time were partly the result of a remarkably effective organizational setup, which harnessed diverse talents. General Motors had the resources— GM's Magnequench motor and car-suspension design;

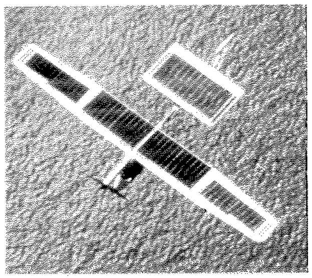


At right Paul MacCready holds the World Solar Challenge Perpetual Trophy, which was donated by Broken Hill Associated Smelters Pty. Ltd. It will reside in Detroit until (and after?) the next race in 1990.

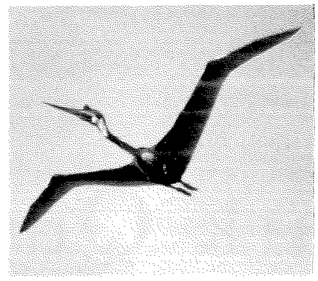
Below: GM's President Bob Stempel talks design with Sunraycer driver Molly Brennan (also from GM) at Seppeltsfield, the ultimate finish of the race. The car behind was the first to cross Australia from south to north, a feat it accomplished in 1908.



Gossamer Albatross



Solar Challenger



Quetzalcoatlus northropi

Flying Fish hydrofoil

Some of the previous projects of AeroVironment's staff are shown above.

Hughes' unique abilities in solar arrays, silver zinc batteries, electromechanical testing, and strategy theory; the GM-Holden strengths in race management in Australia; and the abilities of another 10 GM groups that were involved more peripherally. GM also had the vision and daring to enter the competition and, with priority commitment from the top levels, to take it seriously.

AeroVironment, which was given the charter to play a substantial role in both program management and technological areas, had resources of another sort to contribute. The company's background has included a number of vehicle developments featuring the emphasis on low power and efficiency that is the essence of a solar-powered race car. Members of AV's staff or teams at the company itself had created human-powered aircraft (the Gossamer Condor and Gossamer Albatross, and the battery-assisted Bionic Bat), the solar-powered Gossamer Penguin and Solar Challenger, a flying replica of a giant pterodactyl (*E&S*, November 1985), and various human-powered land and water vehicles, such as the Flying Fish hydrofoil. All of these projects had to operate with power in the 0.25- to 2-horsepower range. These projects, in addition to a number of specialized aircraft developments AV has conducted for government customers, made it uniquely qualified to take on Sunraycer. Also, AV, 10^{-4} the size of GM, with its short chain of command and versatile staff, has the capacity for quick response to a problem and rapid development of solutions. Together—the huge company and the tiny one—we formed a team of unusual strength—one especially appropriate for this challenge.

Can this sort of organizational system and the excitement of a race situation (which demands absolute deadlines and produces an unequivocal winner) be applied to handle other developments as quickly and effectively? The answer is probably "yes" in principle, but perhaps only in rather special circumstances. One should recognize the uniqueness of the confluence of challenge, interest, resources, and capability that this project represented.

The second most frequently asked question (after "How much did it cost?") has been, "What good is it?" or, phrased differently, "Will solar-powered cars ever be practical?" The answer seems clear. Cars powered solely by sunlight are unlikely to be practical enough to justify wide usage. The maximum solar power intercepted by a car-sized object is small in comparison to the power required by our present safe and comfortable automobiles, and, in any case, sunlight is not always available. But Sunraycer and the World Solar Challenge are valuable when viewed more broadly. The attention that a solar car race focuses on doing big jobs with little power expands our insights into, expectations of, and demands for getting better fuel economy with gasoline and edging battery-powered and hybrid cars toward practicality. The project moves us toward handling the transportation needs of the future while making fewer demands on the earth's resources and environment. And, as a special bonus, as Sunraycer goes on an extended tour, it can serve as a stimulus to students to appreciate that engineering is fun and that nonpolluting transportation is achievable. □

Stories about Sunraycer and the World Solar Challenge are also currently appearing in the February issues of Smithsonian *magazine and* Popular Science. *A book on Sunraycer is expected out by the middle of 1988, and a* National Geographic *television documentary on the race is scheduled for the summer. A series of papers is in preparation for technical symposia. Sunraycer will also be touring museums and schools as well as auto shows and will be demonstrated in action on the highways of many states.*