WORLD SOLAR CHALLENGE 1993
TECHNICAL REPORT

DARWIN TO ADELAIDE
NOVEMBER 7 - NOVEMBER 16, 1993

PART I

CHAPTERS 1 - 6

Prepared by Energy Promotions
and Industrial Technology Development Organization
January 1994

Solar Racing Cars

The 1993 World Solar Challenge

by

J.W.V. Storey, A.E.T. Schinckel and C.R. Kyle.

Chapters

Appendices

The Authors.

- John W. V. Storey, PhD. Professor of Physics, University of New South Wales.
- Antony E. T. Schinckel, BSc. California Institute of Technology.
- Chester R. Kyle, PhD. Adjunct Professor of Mechanical Engineering, California State University, Long Beach.

Preface.

This book describes the 1993 World Solar Challenge and the technology that went into the cars that took part. However, the book is more than just a dry list of the technical features of each car. In the past six years, solar car racing has developed into an identifiable sub-discipline of engineering - one which extends across the boundaries of many existing fields. We have therefore brought together into a single work a review of each of these areas. In addition, we have tried to present enough of the background physics to enable readers to make their own assessment about the various new ideas which appeared in the 1993 cars.

Every effort has been made to ensure that all the information presented here is accurate. With such a huge volume of data summarised in this book, however, the occasional error is almost unavoidable. Each data sheet in Appendix A (150 pages of faxes) was sent to the relevant team for checking; all but a handful responded (7 rolls of fax paper). Thus, should any discrepancy exist between information in the text and that in the data sheet, the latter is more likely to be correct.

The 1993 World Solar Challenge was an outstanding success. The whole event ran very smoothly, and was a credit to the race organisers and the more than one hundred volunteers who assisted. Race speeds were much faster than in previous years, with the race record shattered and five cars completing the journey in under five days. The effort and dedication of the thousand or so people who made up the individual racing teams turned this event into a triumphant celebration of human ingenuity and technological excellence.

...JWVS, AETS, CRK.

Acknowledgements.

In putting this report together we have drawn on many sources. First and foremost has been the information generously supplied by the teams themselves, before, during and after the race. We thank the scrutineers for allowing us time to talk with team members; time which also gave us the opportunity to examine the cars in detail. Notes taken by the observers during the event were a rich source of information on the day-to-day progress of the race.

After the race, many individuals provided valuable input to and feedback on the report. We particularly would like to thank:

Mr. G.R. Allen, Solar Mobility Pty. Ltd.
Mr. J.R. Duncan, Solar Research Corporation
Professor M.A. Green, University of New South Wales
Dr. R. King, U.S. Department of Energy
Professor D. Patterson, Northern Territory University
Dr. D.A.J. Rand, CSIRO Division of Mineral Products
Dr. M.C. Storey, University of Sydney
Mr. Toshiaki Tsuchiya, Kyocera Corporation.

Many of the figures were drawn by Mrs Catherine Faust of the University of New South Wales. Dr. Peter Elliston, also of the University of New South Wales, assisted with some of the photographic production.

Finally, we gratefully acknowledge the assistance of:

Daido Hoxan Inc.
Hans Tholstrup and the staff of Energy Promotions
The Department of Primary Industry (Australia)
The Department of Energy (USA)
The New Energy Development Organisation (Japan).

Figures and Photographs.

All figures and photographs are by Joyce Kyle and the authors, with the exception of:

Figure 1.5, 1.7	Jason Allen
Figure 1.11	Graham Allen
Figure 2.8, 2.13, 2.15, 2.18, 2.25	Waseda University
Figure 4.7	René Jeanneret
Figure 6.11, 6.12, 6.17	SunPower
Figure 6.13, 6.14, 6.16	Martin Green
Figure 7.6, 7.7	Unique Mobility
Figure 7.13, 7.14	Northern Territory University
Figure 10.7	Tokai University
Figure 10.9	Waseda University
Figure 10.10, 10.11, 10.12 10.13, 10.14, 10.15	George Washington University and U.S. Satellite Laboratories
Figure 11.4	Paul Jarowski, University of Michigan
Figures in Appendix E	Toshiaki Tsuchiya

Chapter 1.

Introduction

On January 7 1983, Australian adventurer Hans Tholstrup arrived at the steps of the Sydney Opera House driving a type of car the world had never seen before - one powered solely and directly by sunlight. Twenty days earlier, he and engineer / racing driver Larry Perkins had set off from the west coast of Australia in the fragile *Quiet Achiever*. Their epic crossing of the Australian continent, at an average speed of just 23 km/hr, had made the solar car a reality.

Four years later, in 1987, Tholstrup's first World Solar Challenge was underway. Twenty-three solar-powered cars from seven countries set off from Darwin, heading down the newly paved Stuart Highway which crosses Australia from north to south. The first race was a spectacular success. General Motors' *Sunraycer* astounded the critics, and a new form of motor sport - one which captured the popular imagination in a way not seen for a generation - was born.

By 1990, when the World Solar Challenge was held for a second time, the 3,000 km competition was firmly established as the world's premier solar racing event. The field swelled, the cars were more sophisticated, the average race speeds significantly faster. Now, with the 1993 World Solar Challenge behind us, we can look back and review the extraordinary progress that has occurred over the last six years. Prior to the 1987 event, the solar car was a curiosity. In November 1993, the Honda *Dream* crossed an entire continent at an average speed of 85 km/hr (figure 1.1).

During the 1993 event, support crews were having great difficulty keeping up with the leading cars. It is easy to see why: in one single nine-hour stretch, for example, the Honda *Dream* travelled 802 km. Powered by sunlight, the *Dream* stopped only for driver changes. The support vehicles, however, had to be refuelled at least twice a day!

The World Solar Challenge is aptly named. More than a race it is a challenge - a challenge to the world's best engineers and scientists to build a car that is light and efficient, yet tough enough to cross one of the world's harshest continents (figure 1.2). It is a challenge to develop a solar array to generate the largest amount of electrical power, then to design a car to make most effective use of this power. Above all, it is a challenge to build a car which can travel fast - as fast as the permitted U.S. highway speeds - yet is powered only by the sun.

1.1 Regulations

Tholstrup's vision of the event is to set a clearly defined challenge: build a solar car which can get from Darwin to Adelaide in the shortest possible time. By keeping the rules as simple as possible, the human imagination is left free to grapple with the real technical issues, and to solve them in new and innovative ways. Rather than becoming a battle of wits between the rule makers and the bush lawyers, the event is to be the stimulus of new ideas; the genesis of technological development. As a result of this philosophy, there are effectively only three rules:

> **The box rule:** The car must fit in a box 6 metres long, 2 metres wide, and 1.6 metres high. These are the dimensions of a large family car. The solar cells and collectors must have a projected horizontal area of no more than 8 square meters.
>
> **The clock rule:** Cars may race only between 8 am and 5 pm. They may charge batteries, from the sun, for two hours before and after this time period (figure 1.3). This rule ensures that the solar cars are off the road during the hours of darkness, and everyone gets some sleep.
>
> **The fair-play rule:** Only solar power may be used. Competitors may not do anything which gives them an unfair advantage over other teams.

In addition, the rules attempt to ensure that vehicles are roadworthy, safe, and provide a suitable display for the sponsors. The rules are published by Energy Promotions [1], the organisers of the World Solar Challenge. Some interesting aspects of the rules are highlighted below.

Solar Array Dimensions.
While the maximum vehicle dimensions are specified as 6 m long x 2 m wide x 1.6 m high, the rule concerning the maximum solar array dimensions is more complicated:

Solar collectors may be constructed in any way provided that they lie, at all times, entirely within a single right rectangular parallelepiped of dimensions A x B x C, where A $\leq$ 4.44 m, B $\leq$ 2.00 m, C $\leq$ 1.60 m and A x B $\leq$ 8.00 m^2. When in motion, the parallelepiped must be oriented such that A, B and C are length (measured horizontally), width (measured horizontally) and height respectively; when stationary it may have any orientation.

This rule has evolved over the three events, and in its present form is intended to be helpful to competitors in the following ways:

1. By allowing the vehicle to be as narrow as 1.60 metres yet still carry an array 8 m^2 in plan area, cars can be built narrower and therefore be more readily fitted into a standard shipping container.

2. By allowing the solar array "box" to have any orientation when stationary, vehicles can be partially dismantled (thus allowing access for service crews) without the need for the observer to be armed with a plumb bob, spirit level, and theodolite.

Nevertheless, both rules are open to some interesting interpretations which imaginative teams can exploit and which are outlined in Chapter 6. These interpretations do not, however, extend to exceeding the maximum "box" dimensions set out in the rules (figure 1.4). The scrutineers were equipped with a highly inextensible steel tape-measure: regrettably, more than one car had to re-submit for scrutineering with portions of its panel blanked out.

Batteries.

Batteries (and by implication other forms of stored energy) may be carried in the car, but only to a maximum of 5 kWhrs (18 MJ). This is equivalent to the energy the solar panel can produce from about a half a day's sunlight. Battery replacement is only permitted in the case of a malfunction, and carries a stiff time penalty.

Heat Engines.

There is no requirement that vehicles be electrically powered, or that photovoltaic cells be used. In 1987, one entry (Harold Clisby's *Vapor 1* - figure 1.5) used a Rankine cycle engine ("steam engine"), while in 1990 another (Aisin Seiki's *Aisol* - figure 1.6) planned to generate part of its power with a Stirling engine heated via a parabolic mirror (concentrator). In neither case was the vehicle able to derive significant useful power from its heat engine. Without a concentrator, a heat engine is doomed to low efficiency by the small absolute temperature difference available to drive it. A concentrator, on the other hand, must track the sun, and this presents a severe technical challenge in a moving vehicle.

Wind.

Wind, although generated partly by temperature differences due to sunlight, is not often considered a form of solar energy. Nevertheless, any vehicle which has vertical airfoil sections (for example, in the form of wheel spats), is likely to experience forward thrust in the presence of a cross wind. The present regulations do not specifically forbid this. An interesting 1987 entry was the John Paul Mitchell Systems' *Mana La*, which sought to maximise its speed in a cross wind by means of an arched airfoil (figure 1.7). It was not particularly successful, and this approach has not been tried since.

Spare cars.

Teams are at liberty to bring along a complete spare car. The only component which has to both leave Darwin and arrive in Adelaide is the "chassis", which is curiously defined as being that part of the car that the battery is bolted to. While all serious competitors provided themselves with a comprehensive stock of spare parts, several teams, including Honda, Nissan and Aurora, had a complete spare vehicle. The idea of having a spare car dates right back to 1987, when the *Sunraycer* transporter which appeared big enough for only one car in fact contained two cars stacked one above the other. This was a well-kept secret until the *Sunraycer* appeared simultaneously at two motor shows separated by over a thousand kilometers!

Two-seater class.

Introduced in 1990, this category is covered by the same rules as the single-seat class - with two exceptions. A passenger must be carried at all times, and the solar cells may cover the entire surface of the vehicle. There is no minimum standard of accommodation specified for the passenger, leaving ingenious solutions such as the back-to back seating arrangement used by Cal. Poly. Pomona's *Intrepid* as valid interpretations of the rules.

1.2 Course.

Starting in Darwin, the course follows the full length of the Stuart highway across the red centre of the Australian outback to Adelaide (figure 1.8). The highway is named after the Scottish explorer John McDouall Stuart who, in 1862, first crossed the Australian continent from North to South. It was his sixth attempt, and he almost died on the return journey. The present highway, which was not fully sealed until after the first World Solar Challenge in 1987, closely follows Stuart's original route.

The highway is a smooth, two-lane road for most of its length, with short sections of four-lane divided road at each end. For the most part it is gently undulating, with grades of 2% and below (figure 1.9). Just 170 km out of Darwin, however, competitors strike the toughest climb of the course: the Hayes Creek Hill. For over 2 km the grade exceeds 3.9%, and the last 1.2 km is at a grade of 5.9%. Later on, between Alice Springs and Erldunda, an even steeper climb of 6% confronts the solar cars. This climb is short, however (200 metres), and is preceded by a down-hill stretch, so generally poses no difficulties. Course notes were written by Morphett Vale High School prior to the 1990 event and made available to all teams [2]. Since then, many other teams have visited the Australian outback to make their own course notes. Some have even pried up sections of the road surface and taken them back to their laboratories to help determine tyre suitability!

1.3 Previous Events

1987

The first World Solar Challenge started on the first of November, 1987 (figure 1.10). Twenty-three cars from seven countries began the race, but only seven vehicles were to finish within five days of the runaway winner, General Motors' *Sunraycer.* A brief technical report was prepared after the race [3], and there exist several valuable sources of reference material such as the wonderful "Sunraycer" book by Bill Tuckey [4]. C.R.Kyle's monograph [5] provides an excellent overview of the top six cars, and technical analyses of some individual cars were also prepared, including General Motors' *Sunraycer* [6] and Australian Geographic's *Team Marsupial* [7]. Several magazines also carried major articles on the race [8 - 14].

This first race was marked by a tremendous rain storm on the fourth day, which trapped most of the field north of Alice Springs. Water flooded across the road, forcing teams to wade alongside their vehicles as they crept along, fearful of being swept away at any moment. The normally arid Australian outback was drenched with over 100 mm of rain in 24 hours. Fragile solar panels were pelted with hail stones. At noon, under black skies, *Team Marsupial* recorded a solar panel output of just 40 watts from a panel capable of producing well over a kilowatt in full sun. Once racing stopped for the day, wet and exhausted crews struggled to dig drainage channels around their camp-sites, and to repair their battered vehicles as best they could.

Meanwhile, *Sunraycer* surged ahead of the clouds and into Adelaide to finish in a spectacular time of just over five days. The era of the solar car was born.

**** insert side-bar 1 here ****

1990

In 1990, thirty-six cars were to begin the race, including several veterans of the first event. Biel fielded a completely new vehicle, with a unified aerodynamic body and an almost flat solar panel behind a bubble canopy. Just 46 hours after the start they were to cross the finishing line in the Adelaide as clear winners, 11 hours ahead of second-placed Honda.

The race started an hour late, as race officials waited for the weather to abate. Just hours beforehand, a wild storm had ripped through Darwin, tearing roofs from buildings and sending a light pole crashing across the start line. Darwin City Council workers worked overnight to clear the light pole and other debris from the course. During the first day's racing, yet another storm lashed the field. Many cars were once again brought to halt as the solar flux dropped virtually to zero. Those that could ran on their batteries to escape the tempest. Rain poured into many of the cars, drenching the electronics and causing havoc. For the remainder of the race, teams enjoyed better but by no means perfect weather. Strong headwinds, particularly in the later stages of the race, frustrated many teams. Two cars were destroyed by willy-willys. The wreckage of one of these, *Grunfos,* arrived at the finish line on a flat-bed truck. A third car, *Ninja*, was run over by a Chrysler Valiant car on the second-last day. (Fortunately, in neither case was anyone injured.)

A detailed technical report was prepared by C.R. Kyle [16] and published by the SAE. Fuller technical analyses of the second-placed Honda *Dream* [17] and the eleventh placed California Polytechnic Pomona's *Solar Flair II* [18] are also available. Another very valuable source of information on this event is the monograph by Allen and Allen [19], published by the Australian Department of Minerals and Energy.

**** insert side-bar 2 here ****

Sidebar 1

First Six - 1987 Pentax World Solar Challenge 3004.76 km

Place	Entrant	Car	Country	Time (hrs)	Av. speed (km/hr)
1st	General Motors	Sunraycer	USA	44.900	66.904
2nd	Ford Australia	Model S	Australia	67.533	44.482
3rd	Ingenieurschule Biel	Spirit of Biel	Switzerland	69.967	42.935
4th	Aust. Geographic	Team Marsupial	Australia	81.433	36.889
5th	Darwin Inst. Tech.	Desert Rose	Australia	95.450	31.472
6th	Chisolm Inst. Tech.	Desert Cat	Australia	98.200	30.591

Sidebar 2

First Six - 1990 J. Ward Phillips World Solar Challenge 3007km

Place	Entrant	Car	Country	Time (hrs)	Av. speed (km/hr)
1st	Ingenieurschule Biel	Spirit of Biel II	Switzerland	46.131	65.184
2nd	Honda	Dream	Japan	54.997	54.676
3rd	Uni. of Michigan	Sunrunner	USA	57.247	52.527
4th	Hoxan	Phoebus III	Japan	57.347	52.435
5th	W. Washington Uni.	Viking XX	USA	58.497	51.404
6th	AERL	AERL	Australia	59.897	50.203

Sunrayce

The outstanding success of General Motors' *Sunraycer* in the inauguaral World Solar challenge led to the creation of the GM SUNRAYCE USA [20]. With the rules governing vehicle design based closely on the World Solar Challenge, SUNRAYCE offered US university and college teams the opportunity to compete against each other under well-controlled conditions. For the winning three teams, GM would provide funding to enable them to compete in the following World Solar Challenge.

In 1990, the first year SUNRAYCE was held, those winning three cars were Michigan's *Sunrunner,* Western Washington University's *Viking XX*, and Maryland's *Pride of Maryland.* All three were to perform well in the 1990 World Solar Challenge, Michigan in particular achieving an excellent third place after Biel and Honda. Several other SUNRAYCE competitors also entered the 1990 World Solar Challenge, and generally performed well. A special issue of the journal *Solar Cells* was devoted to an analysis of this event [21 - 24].

The second Sunrayce, *Sunrayce 93*, was held from 20 - 26 June, 1993 [25 - 26]. Once again the winning three cars (The University of Michigan's *Maize and Blue*, Cal. Poly. Pomona's *Intrepid,* and Cal. State Uni. L.A.'s *Solar Eagle II*), plus several of the other *Sunrayce 93* competitors, lined up for the World Solar Challenge as serious contenders for high outright placings. To keep costs contained, *Sunrayce 93* rules restricted cars to solar cells costing less than $10/watt, and also specified that these must be terrestrial grade. For the World Solar Challenge, many of the *Sunrayce 93* teams replaced the panels with the unrestricted, higher power panels allowed. Additionally *Sunrayce 93* required that entrants use only commercially available lead-acid batteries. For the World Solar Challenge, all but one of the *Sunrayce 93* competitors discarded these in favour of silver zinc cells. Yet another restriction placed on *Sunrayce 93* entrants was that all of the car's solar array had to be visible, and on the outside of the car, at all times.

Grand Solar Challenge

In August 1992 the first Grand Solar Challenge was held in Japan. A staggering total of 102 cars were entered, including the 1990 World Solar Challenge winner *Spirit of Biel II*, and new cars from Honda, Nissan, and Toyota (figure 1.11). The event was narrowly won by Toyota. Many of the Grand Solar Challenge entrants subsequently entered the 1993 World Solar Challenge.

Tour de Sol
The world's first solar car race, the Tour de Sol, was held in Switzerland in 1985 and won by Mercedes Benz [27]. This race, organised by Urs Muntweiler, continues to be held annually and attracts a field of over 100 competitors and provides fast, close racing. It is an exciting and highly successful event and, although the rules are very different to those of the World Solar Challenge, there is considerable overlap in the technologies used.

1.4 Design and testing

A striking feature of all of the front-running teams in the 1993 World Solar Challenge was the enormous effort they put into the testing and refinement of their entries. Honda, Biel and Kyocera all did extensive full scale wind-tunnel testing of their cars, and the effort clearly paid off. Both Biel and Honda had exceptionally detailed test data, and knew the performance of every component of their cars with great precision. In Biel's case, extensive testing of the completed car was carried out at Michelin test track. With the power input to the motor held constant, *Spirit of Biel III* was able to circulate around the 8 km circuit with lap times consistent to 0.1 seconds! When such incredibly precise data are available, the effect of even tiny improvements to the car's performance are readily discernible. The nett effect of many such tiny changes is of course a significantly faster car. Too much testing, however, carries other risks. The Spanish police, for example, apparently did not welcome the *Spirit of Biel's* 160 km/hr sprints down the local *autostrada*!

Another example of particularly thorough research is the extensive wind-tunnel testing carried out by Kyocera (figure 1.12). These tests are presented in Appendix E, and describe how the team systematically tested every plausible solar car shape before making an informed decision on which configuration to use.

Even for teams with more limited resources, the effort put into testing was handsomely repaid. For many, open-road testing of the solar car itself yielded all the data needed to measure and refine drag coefficients, tyre losses, and drive-line efficiencies. With permanent magnet motors, the output torque is closely proportional to drive current (once friction and other sources of drag within the motor are accounted for). Since motor current is easy to measure with high precision, the car thus forms its own dynamometer - the only remaining problem being the near impossibility of finding a completely flat, wind-free section of road! Together with wool-tuft testing and other time-honoured techniques, methods such as this allow even low-budget teams to refine their original prototype solar cars into highly efficient machines.

The top five cars were all designed by teams with previous experience in the World Solar Challenge - experience which was clearly valuable in helping to make the correct decisions at critical phases in the design process. Nevertheless, many teams entering the event for the first time also did exceptionally well. Overall, it is extraordinary just how different many of the top-performing cars were. There is clearly no consensus yet on the optimum shape for a solar car, nor on the suspension layout, motor design, type of cells or, for that matter, on any other aspect of the design. Until there is, the World Solar Challenge will continue to be the most technologically challenging and fascinating sporting event in the world.

...JWVS

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Figure Captions.

Figure 1.1 The Honda *Dream* won the event at a record speed of 84.96 km/hr.

Figure 1.2 Takahiro Iwata, Team Manager and chief designer of the Honda *Dream.*

Figure 1.3 The *Spirit of Biel III* performed superbly to finish the race in second place at an average speed of 78.27 km/hr. Here the Biel solar panel is tilted to face the morning sun on day 2, near Elliot. From left to right: Professor René Jeanneret, chief designer, Freddy Sidler, Team Manager, and Hans Gochermann of Deutsche Aerospace, designer of the solar panel.

Figure 1.4 Scrutineers measure the width and length of *Le Soleil* from Japan.

Figure 1.5 In the 1987 World Solar Challenge, Harold Clisby entered a steam-powered solar car.

Figure 1.6 Aisin Seiki's entry in the 1990 World Solar challenge included a Stirling engine heated via a solar concentrator mounted behind the driver.

Figure 1.7 Another interesting 1987 entry was the Hawaiin *Mana La*, which hoped to gain wind assistance from its arched airfoil.

Figure 1.8 The race runs the entire length of the Stuart Highway, crossing the Australian continent from Darwin in the north to Adelaide in the south, a distance of just over 3,000 km.

Figure 1.9 The twelth-placed Nissan *Sunfavor* passes a huge wind turbine generator after Coober Pedy.

Figure 1.10 The World Solar Challenge perpetual silver trophy, donated by the Broken Hill Associated Smelters Ltd. (BHAS).

Figure 1.11 Several of the World Solar Challenge entrants had competed in the Japanese Grand Solar Challenge, including the winner of that event, Toyota.

Figure 1.12 Extensive wind-tunnel testing and refinement paid off for Kyocera, earning them a well-deserved place in the top three.

1993 Entry List

Car Number	Entrant	Car Name
Australia:		
8	Dripstone High School	*Aquila*
12	Monash Uni. / Melbourne Uni.	*Solution*
13	Northern Territory Inst. of TAFE	*Trader*
15	Northern Territory University	*Desert Rose*
22	Team Alarus	*Alarus*
18	Annesley College	*EOS*
41	Mitcham Girls High School	*ISIS*
30	Aurora Vehicles Association	*Aurora Q1*
111	Morphett Vale High School	*Photon Flyer III*
888	Meadowbank TAFE	*Sunseeker*
Brazil:		
88	The Banana Enterprise	*The Banana Enterprise*
Canada:		
93	University of Western Ontario	*SunStang*
Denmark:		
32	Sonderborg Teknikum	*Solvogn Danmark*
England:		
20	Battery Vehicle Society	*Holy Cheat I*
29	Team Solar Flair	*Solar Flair*
50	Team T.R. 50	*TR-50*
Germany:		
21	Helio Det Team	*Helio Det II*
Japan:		
2	Honda R & D	*Dream*
3	Hokuriku Electric Power Co.	*Hokuden Phoenix* *
7	Panda-san	*Hosokawa-Go*

17	Team Doraemon	*Solaemon-Go*
23	Nissan Motor Co.	*Sun Favor*
24	JCJC Solar Car Club	*Φ Ω Σ Π*
36	Team Sofix	*Sofix*
38	Mino Family Team	*Mino Solar Special III*
39	Mabuchi Motor Co. Ltd.	*Let's Sunjoy*
40	Hokkaido Auto. Eng. College	*Sulis IV*
44	Le Soleil	*Le Soleil*
51	Tokai University	*Tokai-51 SR*
55	Waseda University	*Sky Blue Waseda*
56	Toyota Motor Corporation	*Toyota-56*
77	Kyocera Corporation	*KYOCERA SON OF SUN*
151	Zero to Darwin Project	*Be-Pal III*
320	Solar Japan	*Mainichi-Go*
555	Ashiya University	*Sky Ace*
599	Laughing Sun Racing	*Evolution 93/B*
0	Hama Yumeka Team	*Hama Yumeka*

Korea:

5	KIA Motors	*ConSole to the Future*

New Zealand:

6	Team Philips Solar Kiwi	*Philips Solar Kiwi*

Puerto Rico:

4	University of Puerto Rico	*Discovery 500*

Russia:

46	Team Moscow	*Moscow*

Switzerland:

1	Ingenieurschule Biel	*Spirit of Biel III*
16	Team Heliox	*Heliox*

USA:

9	San Diego State University	*SDSU Suntrakker*
19	California State University, L.A.	*Solar Eagle II*
25	California Polytechnic, Pomona	*Intrepid*

28	Team New England	*Team New England*
31	University of Oklahoma	*Spirit of Oklahoma II*
34	George Washington University	*Sunforce 1*
35	University of Michigan	*Maize and Blue*
101	Stanford University	*Sunburner*
150	Villanova University	*Solarcat III*

* Demonstration run.

Sidebar 1

First Six - 1987 Pentax World Solar Challenge 3004.76 km

Place	Entrant	Car	Country	Time (hrs)	Av. speed (km/hr)
1st	General Motors	Sunraycer	USA	44.900	66.904
2nd	Ford Australia	Model S	Australia	67.533	44.482
3rd	Ingenieurschule Biel	Spirit of Biel	Switzerland	69.967	42.935
4th	Aust. Geographic	Team Marsupial	Australia	81.433	36.889
5th	Darwin Inst. Tech.	Desert Rose	Australia	95.450	31.472
6th	Chisolm Inst. Tech.	Desert Cat	Australia	98.200	30.591

Sidebar 2

First Six - 1990 J. Ward Phillips World Solar Challenge 3007km

Place	Entrant	Car	Country	Time (hrs)	Av. speed (km/hr)
1st	Ingenieurschule Biel	Spirit of Biel II	Switzerland	46.131	65.184
2nd	Honda	Dream	Japan	54.997	54.676
3rd	Uni. of Michigan	Sunrunner	USA	57.247	52.527
4th	Hoxan	Phoebus III	Japan	57.347	52.435
5th	W. Washington Uni.	Viking XX	USA	58.497	51.404
6th	AERL	AERL	Australia	59.897	50.203

Chapter 2

The Race

Honda's *Dream* drove into Adelaide just 38 minutes into the fifth day of the race, shattering the course record which had stood for six years. They would not be the only car to finish in record time. Three hours later, the Spirit of Biel crossed the finish line to claim second place. Meanwhile, another three cars were locked in a tense battle. Before the end of the day, first Kyocera, then Waseda University, and finally Aurora would cross the finish line within 25 minutes of each other. All five cars had eclipsed the record set in 1987 by General Motors' *Sunraycer*. A major leap forward in solar car technology had clearly taken place since 1987.

The 1993 World Solar Challenge attracted a record field, with 52 entrants assembling at the starting line (Table 2.1). Of the 36 teams who had entered the 1990 race, a remarkable two-thirds (24 teams) returned for the 1993 race. Of these, 16 had brand new cars and 8 had modified versions of their 1990 cars. Two of the biggest improvements in this group were Waseda University, who went from 22nd in 1990 to 4th in 1993, and Team Philips Solar Kiwi, who went from 23rd in 1990 to 15th in 1993 - winning the Schools/Private class. Nine teams have now competed in - or can trace their pedigree back through - all three World Solar Challenge events: Biel, Aurora (formerly Ford and AERL), NTU (formerly Darwin Institute of Technology), Monash University (formerly Chisolm Institute of Technology), Hama Yumeka (formerly Hama Zero and Hajime Yamawaki), Morphett Vale High School, Alarus, Heliodet and Denmark.

Twelve countries were represented, with the largest number of entries (20) coming from Japan, ten each from Australia and the USA, three from Great Britain, two from Switzerland, and one each from Brazil, Canada, Denmark, Germany, Korea, New Zealand and Russia. Six of the ten US teams had competed in the 1993 Sunrayce, including the winner of that event - *Maize and Blue* from the University of Michigan.

As well as competing for outright positions, cars were divided into four classes. The top-performing cars were all using silicon solar cells and silver-zinc batteries, so this class also included the top outright positions. Additional classes were the Lead-Acid Class (for cars using only lead-acid batteries), a School and Private Entrant Class (for

Table 2.1 The 1993 World Solar Challenge results.

Place	Car #	Car name	Team	Country	Finish Date	Race Time (hrs:min)	Average Speed (km/hr)	Distance (km)
1	2	*Dream*	Honda R and D	Japan	Nov 11	35:28	84.96	3013
2	1	*Spirit of Biel/Bienne III*	Engineering College of Biel	Switzerland	Nov 11	38:30	78.27	3013
3	77	*Kyocera Son of Sun*	Kyocera Corporation	Japan	Nov 11	42:35	70.76	3013
4	55	*Sky Blue Waseda*	Waseda University	Japan	Nov 11	42:50	70.35	3013
5	30	*Aurora Q1*	Aurora Vehicles Association	Australia	Nov 11	43:00	70.08	3013
6	56	*Toyota-56*	Toyota Motor Corp	Japan	Nov 12	46:34	64.71	3013
7	15	*Desert Rose*	Northern Territory University	Australia	Nov 12	46:50	64.34	3013
8	25	*Intrepid*	Cal Poly Uni Pomona	USA	Nov 12	47:21	63.64	3013
9	34	*Sunforce I*	George Washington University	USA	Nov 12	47:46	63.08	3013
10	151	*Be-Pal III*	Zero to Darwin Project	Japan	Nov 12	48:38	61.96	3013
11	35	*Maize and Blue*	University Of Michigan	USA	Nov 12	49:07	61.35	3013
12	23	*Sun Favor*	Nissan Motor Co	Japan	Nov 12	50:21	59.85	3013
13	19	*Solar Eagle II*	Cal State Uni LA	USA	Nov 12	50:37	59.53	3013
14	101	*Sunburner*	Stanford University	USA	Nov 12	51:38	58.36	3013
15	6	*Philips Solar Kiwi*	Team Philips Solar Kiwi	New Zealand	Nov 13	60:36	49.72	3013
16	39	*Let's Sunjoy*	Mabuchi Motor Co	Japan	Nov 13	60:57	49.44	3013
17	36	*Sofix*	Team Sofix	Japan	Nov 14	64:56	46.41	3013
18	51	*Tokai-51SR*	Tokai University	Japan	Nov 15	74:22	40.52	3013
19	12	*SOLution*	Monash/Melbourne Universities	Australia	Nov 15	74:50	40.27	3013
20	599	*Evolution 93/B*	Laughing Sun Racing	Japan	Nov 15	75:48	39.75	3013

21	38	*Mino Solar Special III*	Mino Family Team	Japan	Nov 15	76:21	39.47	3013
22	31	*Spirit of Oklahoma II*	University of Oklahoma	USA	Nov 15	79:37	37.85	3013
23	32	*Solvogn Danmark*	Sonderborg Teknikum	Denmark	Nov 15	79:43	37.80	3013
24	555	*Sky-Ace*	Ashiya University	Japan	Nov 15	79:48	37.76	3013
25	8	*Aquilla*	Dripstone High School	Australia	Nov 16	81:17	37.07	3013
26	7	*Hosokawa-Go*	Panda-san	Japan	Nov 16	84:15	35.77	3013
27	29	*Solar Flair*	Team Solar Flair	Great Britain	Nov 16	84:57	35.47	3013
28	5	*ConSole to the Future*	KIA Motors	Korea	Nov 16	85:27	35.26	3013
29	22	*Alarus*	Team Alarus	Australia	Nov 16	86:42	34.76	3013
30	18	*EOS*	Annesley College	Australia	Nov 16	87:35	34.40	3013
31	3	*Hokuden Phoenix**	Hokuriku Electric Power Co	Japan	Nov 17	89:47	33.56	2953
32	40	*Sulis IV*	Hokkaido Auto Eng College	Japan	Retired	87:30	32.08	2636
33	17	*Solaemon-Go*	Team Doraemon	Japan	Retired	79:50	34.77	2687
34	320	*Mainichi-Go*	Solar Japan	Japan	Retired	80:10	31.73	2544
35	41	*ISIS*	Mitcham Girls High School	Australia	Retired	80:10	27.39	2196
36	111	*Photon Flyer III*	Morphett Vale High School	Australia	Retired	67:13	31.33	2106
37	4	*Discovery 500*	University of Puerto Rico	USA	Retired	62:36	30.08	1833
38	28	*Team New England*	Team New England	USA	Retired	53:02	28.13	1492
39	44	*Le Soleil*	Le Soleil	Japan	Retired	56:34	26.38	(1398)
40	93	*SunStang*	Uni of Western Ontario	Canada	Retired	63:51	23.37	1492
41	50	*T.R. 50*	Team T.R. 50	Great Britain	Retired	71:20	20.92	1490
42	9	*SDSU Suntrakker*	san Diego State Uni	USA	Retired	52:10	20.55	1072
43	13	*Trader*	NT Inst of TAFE	Australia	Retired	37:34	26.22	1035
44	888	*Sunseeker*	Meadowbank TAFE	Australia	Retired	26:17	24.05	628

45	150	*Solarcat III*	Villanova University	USA	Retired	20:50	15.07	422
46	24	ØΩΣΠ	JCJC Solar Car Club	Japan	Retired	21:55	14:33	396
47	88	*The Banana Enterprise*	The Banana Enterprise	Brazil	Retired	16:40	15.12	252
48	0	*Hama Yumeka*	Hama Yumeka Team	Japan	Retired	15:26	15.03	232
49	16	*Heliox*	Team Heliox	Switzerland	Retired	08:23	24.69	207
50	21	*Helio Det II*	Helio Det Team	Germany	Retired	09:00	21.46	193
51	46	*Moscow*	Team Moscow	Russia	Retired	03:35	09.77	35
52	20	*Holy Cheat I*	Team Holy Cheat I	Great Britain	Retired	00:00	0.00	0

cars using production lead-acid batteries and production, terrestrial grade solar panels) and a Two Seater Class.

In principle, classes also existed for cars using amorphous solar cells and gallium arsenide solar cells. However, neither of these classes attracted the required minimum number of entrants (three), so no awards were made.

The cost of the entries varied widely. Given the difficulty of determining the value of the free time put in by students and dedicated volunteer groups, plus the sometimes inestimable value of donated materials, cost comparisons are fraught with difficulties. Vehicles in this event varied in acknowledged cost from $US 8,000 (Moscow) to well over $US 1,500,000 (Biel and Honda). It is likely that a top 10 competitive car could still be built for less than $US 200,000, if labour and logistics were not included.

Once the race was underway, every solar car would be under the watchful eye of an official observer. The observer would travel in a support vehicle behind the solar car, noting the car's progress and making sure the rules were obeyed. Each night, after the end of the day's racing, the observer would lock up or otherwise seal the car's battery pack to ensure no recharging could occur.

All competitors were required to present their vehicles for scrutineering over a two-day period just before the race. Here they were carefully examined to ensure they complied with the regulations. Of particular importance was the measurement of solar panel dimensions, as the solar array would be the sole source of power for the cars on their 3,000 km journey. Where discrepancies were found they were rectified on the spot, and carefully noted in the log book. This book, which travelled with each vehicle, enabled the observer to check that each vehicle's compliance with the rules was maintained. Checks of basic vehicle safety were also carried out by the Roads and Traffic Authority.

All teams had been required to submit either certified data sheets on their batteries, or a test cell, to the Battery Scrutineer, Dr. David Rand, by 1 August 1993. During scrutineering all batteries were checked to ensure they were of the same type as previously submitted, then sealed to prevent any replacement without the observer's knowledge.

2.1 Qualifying.

On the day before the race began, all vehicles had to pass a stability and braking test at the Hidden Valley motor sport complex, 10 km south-east of Darwin. The stability test (or speed trial) involved passing a Northern Territory Road Train, with three trailers totalling 50 meters or more in length, travelling at 80 km/hr in the opposite direction (figure 2.1). To ensure that drivers did not go unrealistically slowly (as the approach of 120 tonnes of metal on 62 wheels might otherwise suggest would be prudent), the speeds from this test were also used to determine the grid starting order. Whilst this may not appear important in a race of 3013 km, the heavy traffic at the start (due partly to the large numbers of support vehicles associated with each team) gives some advantage to cars at the front of the grid. Most teams therefore tried hard in the time trials to get the best possible grid placing.

The speed trial was over a very short run (~1 km), and so the results might not necessarily be expected to be a good indicator of the performance of the cars in the race. The speed achieved in the speed trial depended greatly on the maximum power the motor and its controller could deliver for a short burst, and on the gearing chosen by the team. While three out of the fastest four in the time trial finished in the top three of the race, there were some teams who started well down on the grid yet were highly placed at the finish. For example, *Aurora* qualified 17th at 83.0 km/hr, but finished 5th. NTU's *Desert Rose* qualified 24th at 78.1 km/hr, but finished 7th. It is clear that whilst top performance in the speed trials is not a prerequisite for final honours, there is some correlation between the speeds achieved here and the final race result.

In previous years, standard police radar has been used to measure the vehicle's speed. This has caused problems, as the "stealth" construction of solar cars often gives them a very low radar cross-section. For 1993 a laser timing system was used, eliminating errors and mis-timings. The solar cars were flagged off, one at a time, a short distance from a sweeping left-hand corner leading onto the main straight. Meanwhile, the road train was turning onto the other end of the straight and roaring toward the solar car at 80 km/hr, creating a scene strangely reminiscent of a grossly mis-matched jousting competition. The timing laser was set up at a point where the solar car would have had enough run-up to reach its maximum speed. Several of the photos in Appendix A were taken as the solar cars swung around the left-hander onto the straight during the speed trials.

The result of the speed trials was that the Engineering College of Biel's *Spirit of Biel III* won pole position with a speed of 129.9 km/hr. This was Biel's third appearance in the World Solar Challenge, having come third in 1987 and winning the 1990 event. This team has also had great success in previous Tour de Sol races, though with different vehicles. Second fastest was the Honda *Dream* at 125.0 km/hr. Honda first entered the World Solar Challenge in 1990, coming second that year. Next on the starting grid would be Toyota Motor Corporation's *Toyota-56*, with 107.0 km/hr. This was their first entry in the World Solar Challenge.

Kyocera Corporation's *Kyocera Son of Sun* was fourth fastest at 106.0 km/hr with the University of Michigan's *Maize and Blue* fifth at 105.1 km/hr. Both teams had competed in the 1990 event, and both had used that experience to build new and potentially much faster cars.

All cars completed the stability and braking test, though several had to make two attempts at the braking test. The slowest vehicle in the stability trial was clocked at only 19.8 km/hr. One vehicle did not register a speed at all, but was allowed to start the race at the back of the grid at the Race Director's discretion. Qualifying speeds were generally high - 29 teams managed to qualify at over 70 km/hr. This is very impressive, particularly as these solar cars are designed for a 3,000 km endurance race, not a sprint event. Figure 2.2 shows the qualifying speeds and the resulting grid positions.

2.2 The Race

Day 1: Race day, November 7th 1993, dawned relatively fine and sunny, with only some light stratus cloud - in marked contrast to 1990 when heavy rain caused the start to be delayed by one hour. Cars lined up in the darkness, awaiting final checks of the battery seals before responsibility for monitoring the car's progress was formally handed over to each observer by the chief scrutineer, Laurie Shaw.

The race started smoothly, competitors being flagged away by Marshall Perron, Chief Minister of the Northern Territory. (As an Australian "territory", the Northern Territory has a Chief Minister, rather than a premier as in other states.) Starting in front of the Hotel Darwin on The Esplanade, the cars ran over closed roads for several kilometres before mingling with ordinary traffic (figure 2.3). Only one car failed to move off - *Team New England* blew a 70 amp fuse right at the start line. Though the team thought at first that this would be a simple problem to fix, it was unfortunately a

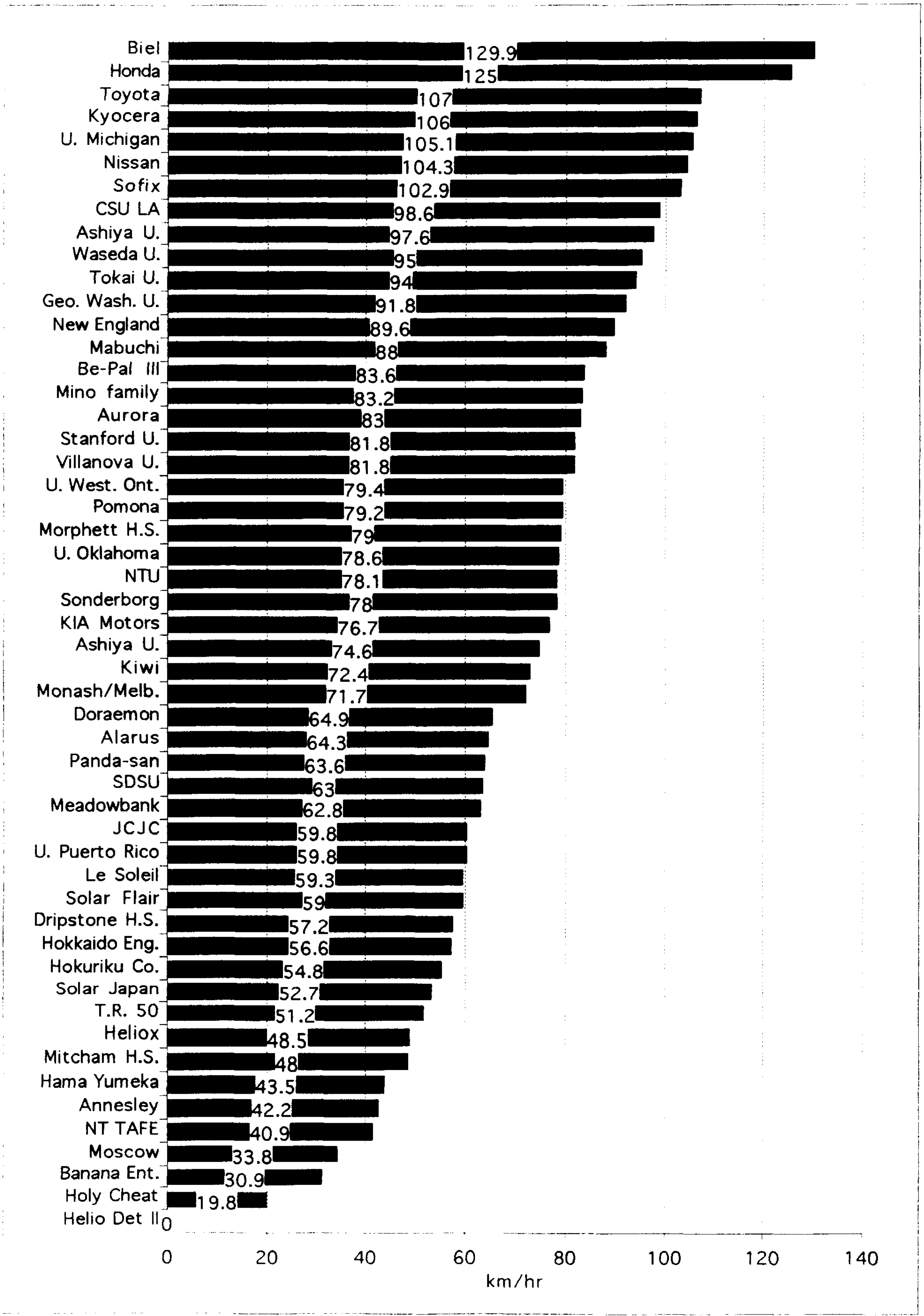

Figure 2.2 Speed trial results, by grid starting order.

symptom of a major electrical fault. They were not to leave Darwin until the following day.

At the 15 km point, on the edge of Darwin, the order was *Spirit of Biel III, Dream, Kyocera Son of Sun, Maize and Blue, Aurora Q1, Solar Eagle II, Toyota-56, Desert Rose, Sunforce I,* and *Intrepid*. Eight of these cars would still be in the top ten at the finish, 2998 km later. See figure 2.4.

Right from the start however, Honda's *Dream* was experiencing a problem - their motor or motor controller would not accept full power, but went into current limiting at 1300 W. The team could not easily diagnose the problem, so they stopped at 11:00 and changed both the motor (which was integral with the rear wheel) and controller, losing 7 minutes. Kyocera were able to overtake them whilst stopped, but Honda reclaimed second position a few minutes later at 11:18.

At Katherine, 314 km south of Darwin, *Spirit of Biel III* held a significant lead of about 15 minutes over *Dream*. Biel arrived at the Katherine media stop at 11:41, having set a cracking pace from Darwin. Their average speed over this first leg was 85.2 km/hr compared to *Dream's* 79.8 km/hr (figure 2.5). *Kyocera Son of Sun* averaged 77.8 km/hr (6 minutes behind Honda), *Sky Blue Waseda* 71.09 km/hr (a further 23 minutes behind), *Aurora* 70.82 km/hr (only 1 minute behind Waseda) and *Toyota-56* 68.76 km/hr (a further 8 minutes back). Table 2.2 gives a full list of all average speeds between media stops over the 8 legs of the race.

Unfortunately, *Spirit of Biel III* hit a deep gutter in Katherine, and unknowingly damaged their car. The motor was consuming 1300 W, but they were only able to achieve 74 km/hr, whereas they should have been running at 85 to 88 km/hr. It was not immediately obvious what the problem was, and some suspicion focused on the motor and the controller electronics. Hoping to diagnose the inefficient component by its temperature rise, the team monitored the telemetry data and continued running until 11:55. They then stopped and changed both front tires, together with the motor and motor controller as a precaution, all in 12 minutes. *Dream* overtook them while they were stopped. However the real reason for Biel's slower speed was not to be discovered until sometime later. A front wheel spat had been damaged by the gutter in Katherine and was rubbing on the tire, so that their speed dropped by about 14 km/hr. Frustratingly, when the car was lifted for inspection, the tire stopped rubbing, making it almost impossible to find the reason for the lower speed.

Table 2.2 Average speeds on the various "legs" of the race between the media stops. The locations of the media stops are shown in Figure 1.8

Place		CAR I.D.	Katherine	Dunmarra	Tennant Creek	Alice Springs	Cadney	Glendambo	Port Pirie	Adelaide
Distance from Darwin (km)			**314**	**632**	**985**	**1492**	**2030**	**2431**	**2808**	**3013**
1	Dream	2	79.83	90.86	84.72	88.17	92.76	83.54	79.64	73.76
2	Spirit of Biel	1	85.25	80.17	85.75	79.01	90.42	61.53	67.12	91.92
3	Kyocera Son of Sun	77	77.85	79.83	68.32	71.74	66.15	64.85	70.68	76.5
4	Sky Blue Waseda	55	71.09	60.96	70.6	69.93	69.72	72.25	76.42	74.65
5	Aurora Q1	30	70.83	70.93	74.84	74.37	64.69	70.14	66.72	71.62
6	Toyota-56	56	68.76	66.95	68.32	69.45	61.14	60	68.13	54.5
7	Desert Rose	15	62.59	60.76	54.03	66.13	68.39	65.78	68.29	70.79
8	Intrepid	25	54.61	79.83	61.93	64.72	61.72	65.2	61.3	66.94
9	Sunforce I	34	66.1	60.96	62.48	65.14	61.02	65.02	59.52	67.31
10	Be-Pal III	151	61.57	51.71	58.83	65.14	65.34	61.06	65.19	68.81
11	Maize and Blue	35	64.97	64.68	56.93	58.39	62.44	60.6	59.37	70.79
12	Sun Favor	23	59.81	60.76	61.75	58.5	61.72	56.21	58.91	63.49
13	Solar Eagle II	19	62.8	57.13	61.21	65	59.89	50.12	59.52	64.83
14	Sunburner	101	57.44	54.2	53.75	67.15	55.18	55.31	63.36	63.49
15	Philips Solar Kiwi	6	47.1	48.18	52.82	57.18	48.39	53.47	48.02	38.61
16	let's Sunjoy	39	53.37	49.56	43.4	52.9	50.59	51.52	46.64	46.3
17	Sofix	36	47.57	45.54	47.38	51.47	47.82	51.08	42.84	33.29
18	Tokai-51SR	51	40.43	39.34	44.68	42.13	39.46	43.67	35.57	39.73
19	Solution	12	46.29	40.51	46.65	36.38	36.23	39.25	38.53	53.32
20	Evolution 93/B	599	36.58	52.13	38.51	38.07	37.58	38.74	38.6	48.88
21	Mino Family Special	38	38.14	33.77	43.85	37.83	43.62	36.9	36.84	53.79
22	Spirit of Oklahoma II	31	44.02	42.59	45.06	34.41	34.6	35.23	36.72	39.1
23	Solvogn Danmark	32	40.6	37.63	44.87	34.49	38.2	37.71	36.37	34.89
24	Sky-Ace	555	50.78	38.08	38.79	35.83	36.27	34.37	36.13	40.38
25	Aquila	8	28.59	40.51	47.06	29.08	45.08	35.86	39.96	41.27
26	Hosokawa-Go	7	41.96	34.94	41.69	35.58	35.7	32.38	31.55	36.99
27	Solar Flair	29	36.23	32.78	44.87	28.19	41.97	26.73	39.34	61.59
28	ConSOle to the Future	5	39.17	33.89	31.85	31.78	39.03	34.52	33.66	46.48

29	Alarus	22	36.58	36.97	39.08	29.67	36.8	34.32	32.97	36.12
30	EOS	18	35.48	36	38.93	34.29	33.38	32.34	32.08	35.49
31	Hokuden Phoenix	3	36.16	30.92	37.03	29.85	35.59	31.08		
32	Sulis IV	40	41.96	33.01	31.66	26.85	37.4	29.92		
33	Solaemon-Go	17	37.08	23.27	37.35	27.78	40.45	34.67		
34	Mainichi-Go	320	36.37	34.63	36.77	26.73	31	31.12		
35	ISIS	41	28.72	24.62	24.34	30				
36	Photon Flyer III	111	34.89	27.57	37.09	27.91	35.09			
37	Discovery 500	4	29.21	25.27	22.36	26.04				
38	Team New England	28	18.56	33.47	37.88	29.31				
39	Le Soleil	44	28.85	27.1	27.19	24.18				
40	SunStang	93	27.62	35.46	16.87	22.43				
41	TR 50	50	22.06	20.06	20.66	21.08				
42	SDSU SunTrakker	9	29.16	15.07	19.83					
43	Trader	13	34.69	29.77	30.3					
44	Sunseeker	888	27.03	21.68						
45	Solarcat III	150	37.16							
46	JCJC	24	24.09							
47	The Banana Enterprise	88								
48	Hama Yumeka	1000								
49	Heliox	16								
50	HelioDet II	21								
51	Moscow	46								
52	Holy Cheat 1	20								

During the early afternoon, a thick layer of smoke blanketed much of the sky. Though it did not last long it had a dramatic effect on the solar flux - the current from the *Aurora* solar array jumped from 2.8 A to 5.1 A as they drove out from under the smoke. Figure 2.6.

By Dunmarra, the second compulsory 10 minute media stop, *Dream* was 13 minutes ahead of *Spirit of Biel III*. Both vehicles averaged over 90 km/hr from there till the end of the day! *Dream* had averaged 90.85 km/hr for the 318 km stretch between Katherine and Dunmarra, compared to *Spirit of Biel III* at 80.17 km/hr and *Kyocera Son of Sun* at 79.8 km/hr. *Intrepid* also averaged 79.8 km/hr for this leg, though as a result of their slow first leg they were now 8th on the road.

At the end of day one, *Dream* had established a 23 km lead over *Spirit of Biel III.* Both teams would start 2 minutes late the following day, as they had gone 2 minutes past the 5:00 pm nominal stopping time. *Dream* had travelled 746 km at an average of 86.08 km/hr. *Spirit of Biel III,* in second place, was at 723 km, followed by *Kyocera Son of Sun* at 674 km, then *Aurora* (632 km), *Toyota-56* (605 km) and *Sky Blue Waseda* (588 km). Biel spent Sunday evening carefully working on the front wheel spats which had caused their loss of time. Figure 2.7 shows the damaged tire from the front left wheel of *Spirit of Biel.*

Waseda University, like many teams, recorded detailed data on the incoming solar flux. Figure 2.8 shows their data for Day 1, measured with a horizontal cell on the roof of their support car.

Figure 2.9 shows the average speeds for the first day achieved by the cars which would eventually finish in the top ten.

Day 2: Overnight Biel thought they had fixed their wheel spat problem, but it was not to be. Though they averaged the highest speed (85.75 km/hr) over the 353 km between Dunmarra and Tennant Creek (a stage which included some of day 1 and 2 for Honda and Biel), they continued to experience problems. *Dream* continued to hum along at an average speed of 84.72 km/hr over this leg, with *Aurora* the next fastest at 74.84 km/hr. **Figure 2.10.**

Spirit of Biel III had gained slightly on *Dream* at this point - they arrived at the Tennant Creek media stop just as *Dream* were leaving, placing the two teams exactly 10 minutes apart. But *Spirit of Biel III* was plagued by further wheel spat problems. In last minute

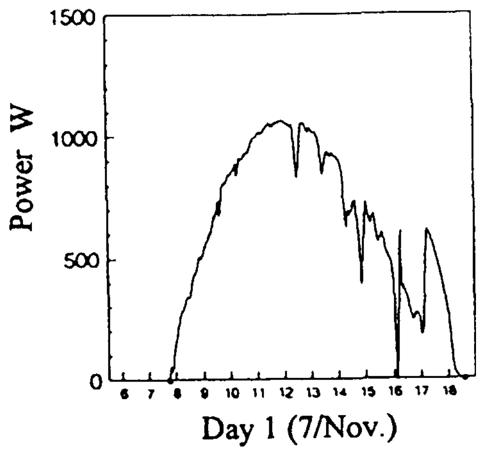

Figure 2.8 Waseda University measured the output of their solar panel every 5 minutes throughout the race. Shown here is a plot of this data for day 1. At 1700 hrs the car stops, as required by the rules. The solar panel output then jumps upward as the panel is tilted toward the setting sun.

pre-race testing, they had made modifications to the spats which slightly lowered the aerodynamic drag. Unfortunately they were not able to test these adequately, and the very fine clearance between spat and wheel was not being maintained under race conditions. **Figure 2.11.**

Biel made two additional stops after Tennant Creek in an attempt to fix the problem, losing a further 12 minutes. Eventually, they removed the left hand wheel spat altogether, finishing the last 3 hours of the day without it. Their average speed over the 441 km from Tennant Creek till the end of the day was only 76.92 km/hr - a significant reduction. They were now 66 km behind Honda, equivalent to about 50 minutes, and were unable to finally cure the wheel spat problem until the evening of the second day. By then, they had not only lost nearly one hour directly, but their energy management strategy was also badly affected. While *Dream* would run in relatively cloud-free skies on day 3 and 4 with some battery reserve, *Spirit of Biel III* would not have the surplus energy to break out of the slowly forming clouds. **Figure 2.12.**

Other teams were also experiencing problems. *Aurora* had fitted a smaller capacity motor controller at the end of day 1, as it was more efficient than the bigger and heavier controller which they had used for the traffic and hills of the first day. Unfortunately, the replacement controller could not deliver the full current required. They ran most of the day before changing the controller at the Tennant Creek media stop. From here till the end of the day they drove hard to average over 75 km/hr. It was important for *Aurora* to fully drain their batteries by the 5.00 pm finish of racing. With only 1.7 kWhr of rechargeable batteries, any charge left in them at day's end would be wasted if both the evening and following morning charging periods were cloud free.

Dream stayed overnight in Alice Springs, having arrived at the media stop on the road into Alice Springs at 16:51. The ten-minute compulsory media stop would then bring them to the end of the day. They had averaged 88.17 km/hr over the 507 km leg from Tennant Creek to Alice Springs, achieving exactly the same distance on day two as they had on day one - 746 km.

For day 2, *Dream* had averaged 82.88 km/hr. Already, after only two days they were in Alice Springs, and had travelled a total of 1492 km - almost half the race distance! Behind them, at 1426 km, lay *Spirit of Biel III*. *Kyocera Son of Sun* were next (1282 km), then *Aurora* (1278 km), *Sky Blue Waseda* (1166 km) and *Toyota-56* (1166 km). *Toyota-56* and *Sky Blue Waseda* were just 300 meters apart, and *Sky Blue Waseda* had run 1 minute past 5:00 pm to get in front of *Toyota-56*. Next day *Toyota-56* would start 1 minute before Waseda and regain their placing. The two teams would have an exciting day, with constant jockeying for position between the multinational firm and the small university team. These two teams would be close for many miles, and it wasn't until between Alice Springs and Cadney Homestead on day 4 that *Sky Blue Waseda* was finally able to break away from *Toyota-56.*

By the end of Day 2, the field was stretched over 1200 km. The top 6 spanned 326 km alone, and the top 10 were spread over 431 km. For officials, it was already extremely difficult to move around between even the leading 10 cars.

Figure 2.13 shows Waseda's solar flux data for day 2, while the average speeds for the top ten cars are shown in figure 2.14.

Day 3: For most of the teams, Day 3 started with good weather and sunshine, though there was still some thin, high cirrus affecting most teams. A few teams further back in the field, however, were starting to experience some heavier scattered cloud.

Spirit of Biel III reached the Alice Springs media stop at 08:41, 50 minutes behind *Dream*. They were followed by *Kyocera Son of Sun* at 10:45, *Aurora* at 10:58, *Sky Blue Waseda* at 12:13, *Toyota-56* at 12:17, *Intrepid* at 13:46, *Sunforce I* at 13:54, *Solar Eagle II* at 14:38, *Desert Rose* at 14:57, *Maize and Blue* at 15:08, *Sun Favor* at 15:22, *Be-Pal III* at 15:32 and *Sunburner* at 15:57. A number of teams missed the Stuart Highway turning on the southern outskirts of Alice Springs, losing several valuable minutes.

In 1990, only one car (*Spirit of Biel II*) had reached Alice Springs by the third day, with a further 8 cars coming in on day 4 [1]. The 1993 event was turning out to be a much faster race - thirteen cars made it to Alice Springs by the end of day 3 !

The afternoon of day 3 was when the first of the bad weather started to roll in. Increasing cloud cover began to have a serious effect on the vehicle speeds. As shown in figure 2.15, Waseda saw the solar illumination starting to drop dramatically at around 13:00, and by 15:00 were seeing only 40 to 50% of the power they saw on the previous day. Teams further north did not start to experience this cloud cover until the next day, day 4.

The 538 km leg from Alice Springs to Cadney Homestead was the fastest leg of the race, with *Dream* averaging an incredible 92.76 km/hr. *Spirit of Biel III* were also

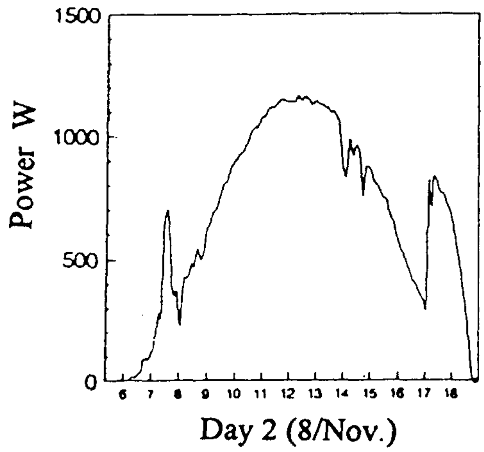

Figure 2.13 Waseda received this insolation for day 2.

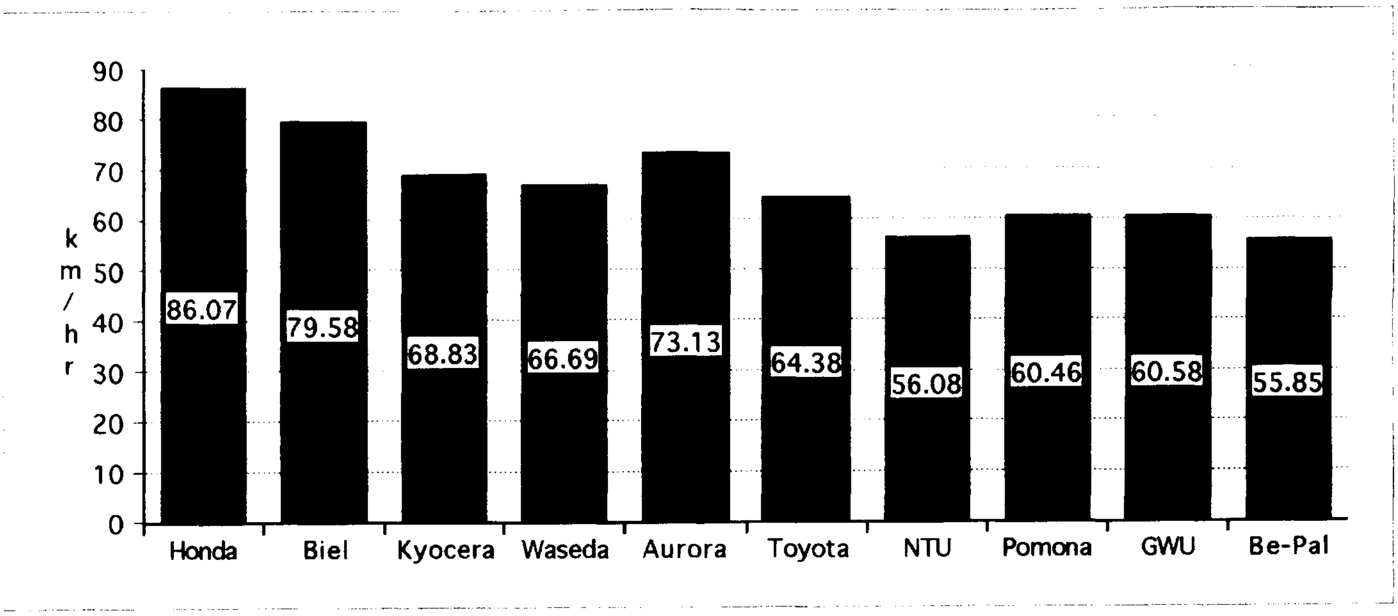

Figure 2.14 Average speeds for day 2 for the cars who would eventually finish in the top ten.

very fast, at an average speed of 90.42 km/hr. This six-hour stretch put a big gap between the two leaders and the rest of the field; the next fastest, *Sky Blue Waseda,* managing just 69.72 km/hr as it became caught in the ever-increasing cloud over Alice Springs.

Dream got through this section before the clouds moved in. *Spirit of Biel III* attempted to get in front of the gathering clouds, but did not quite succeed. *Kyocera Son of Sun* had to stop for 10 minutes late in the day to add some charge to their battery, which they had depleted trying to outrun the clouds. *Aurora* lost 19 minutes when the drive sprocket come loose from its shaft, and had to be hurriedly brazed back on. They were to lose a further 23 minutes on the following day when the drive shaft itself broke - possibly as a result of stresses introduced in the first repair. In a closely contested race, this problem alone was to cost *Aurora* two places.

Day 3 finished with *Dream* 2294 km from Darwin, having travelled 802 km during the day at an average speed of 90.79 km/hr. *Spirit of Biel III* were next at 2163 km, then *Kyocera Son of Sun* (1903 km), *Aurora* (1899 km), *Sky Blue Waseda* (1814 km), and *Toyota-56* (1763 km). The cumulative average speeds for the race to the end of day 3 were 87.67 km/hr for *Dream*, 82.66 km/hr (*Spirit of Biel III*), 72.26 km/hr (*Kyocera Son of Sun*), 72.11 km/hr (*Aurora*) and 68.89 km/hr (*Sky Blue Waseda*). *Dream's* new record for a single day of 802 km in 8 hours 50 minutes was a stunning achievement.

Further back in the field, *Toyota-56* was at 1763 km, followed by *Intrepid* at 1672 km, *Sunforce I* at 1654 km, *Solar Eagle II* at 1627 km, *Desert Rose* at 1620 km, *Maize and Blue* at 1591 km, *Be-Pal III* at 1580 km and *Sun Favor* at 1560 km.

Figure 2.15 shows the solar flux received by Waseda's reference cell, and figure 2.16 shows the average speeds of the top ten cars.

Day 4: On the fourth day strong winds started to batter the cars. With speeds from 15 to 50 km/hr, the winds varied from head-on to slightly trailing and made things especially difficult for cars with marginal cross-wind stability. The winds were to last for the rest of the race.

The winds (and two 10 minute compulsory media stops) slowed even *Dream,* which managed just 696 km for a day's average of 80.31 km/hr before stopping at the 2990 km point, on the northern edge of Adelaide in a small town called Upper Light. *Spirit*

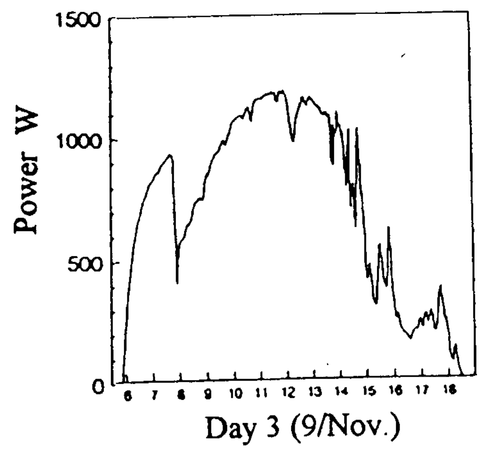

Figure 2.~~18~~ 15 Waseda's plot of the insolation for day 3 shows the bad weather starting to roll in at about 1300.

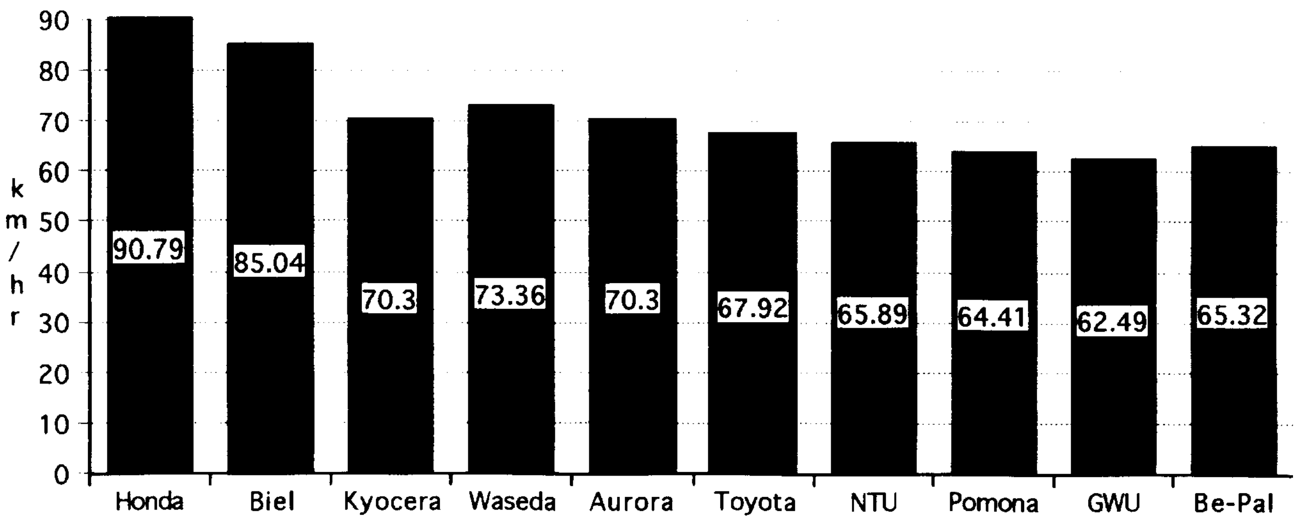

Figure 2.~~19~~ 16 Average speeds for day 3 for the cars who would eventually finish in the top ten.

of Biel III could only manage 540 km, and *Kyocera Son of Sun,* 543 km. *Sky Blue Waseda* picked up ground on the second and third place-getters with a day's distance of 619 km, as did *Aurora* with 563 km. *Spirit of Biel III* dropped back significantly behind Honda this day, as the cloud cover and early problems which had depleted their battery took their toll.

The order at the end of day 4 was *Dream* (2990 km), *Spirit of Biel III* (2703 km), *Aurora* (2462 km), *Kyocera Son of Sun* (2446 km), *Sky Blue Waseda* (2433 km), *Toyota-56* (2307 km), *Sunforce I* (2225 km), *Intrepid* (2223 km), *Desert Rose* (2194 km) and *Be-Pal III* (2159 km). The first 10 cars were now spread over 830 km.

From Cadney (late on day 3) to Glendambo, a distance of 401 km, *Dream* averaged 83.54 km/hr, while from Glendambo to Port Pirie (377 km) they averaged 79.64 km/hr to arrive at Port Pirie at 14:41 on day 4. *Spirit of Biel III* averaged 61.53 km/hr and 67.12 km/hr over the corresponding legs, arriving at Port Pirie at 09:16 on day 5. **Figure 2.17**

As Waseda's solar flux plot (figure 2.18) shows, day 4 also had extensive periods of cloud. To complicate matters further, the clouds were scattered and unpredictable, so determining a strategy for the day was extremely difficult. Telemetry data from the University of Michigan, Ashiya University and Tokai University for day 4 show that these clouds covered a significant portion of the track, especially in the second half of the day. The satellite photographs (figures 10.10 - 10:15) confirm this.

Several teams (University of Western Ontario, Hokuriku Co., Dripstone High School, Tokai University and Toyota) reported lightning storms during day 4 and 5, and a number where forced to stop to dry out their vehicles. Strong feelings of *deja vu* were occurring for many of the teams who had been in previous World Solar Challenge events or in the 1993 Sunrayce. These storms and general cloud cover were the bane of teams further back in the field - days 4 through 8 were affected by significant cloud cover, with some rain.

It is unlikely that Upper Light (Honda's camping ground for day 4) has ever seen anything to compare with the media attention it received that day. For the last hour of racing, *Dream* was dogged by a flotilla of helicopters, with up to four in the sky at the same time. Media cars, many of whose drivers appeared to have developed their driving styles by watching old Mad Max movies, pursued *Dream* along the highway. Fortunately, no accidents occurred. Honda camped in the back yard of the small pub in

Upper Light; the proprietress thrilled but somewhat overwhelmed at the influx of visitors. She even removed her car from her garage (a converted chicken coop) so that *Dream* could be under cover for the evening. **Figures 2.19**

At this point, Honda were very confident - they had just enough charge in the batteries to reach the finish line even if there were no sun at all the following day. They therefore elected not to charge during either the evening or the following morning charging periods, and in fact both charge periods turned out be affected by some scattered clouds.

Figure 2.20 shows the average speeds of the top ten cars during day 4.

Day 5: The final day brought sunshine once again to the lead team. *Dream* was only 23 km from the Bolivar Road timing finish, and only 45 km from Bonython Park, the official finish. An escort of police motorcycles and the usual media phalanx escorted *Dream* through streets lined with school children and office workers, all eager to see the car that had not merely shattered the record for the race, but had completed the route in a time comparable with that which a normal car would require.

Dream crossed the finish line at Bolivar Road at 08:38:40, and rolled into Bonython Park at 09:37, having successfully negotiated Adelaide's morning rush-hour traffic. Once again, a large contingent of media, and even larger quantities of champagne, were on hand to welcome the winners. **Figures 2.21, 2.22.**

Spirit of Biel III set an impressive pace on their final day. They had to travel 310 km to finish, and took a mere 3 hours 30 minutes to do so. This gave them an average speed of 88.57 km/hr for the final day, including city driving. In fact, for the last leg from Port Pirie to Bolivar Road, they averaged an astounding 91.92 km/hr! They finished the race in second place at 11:40, three hours two minutes behind *Dream*. **Figure 2.23**

Three more teams also finished on the fifth day. Kyocera's *Son of Sun* finished at 15:45, having covered 567 km during the day at an average speed of 74.77 km/hr, giving them an overall race average of 70.76 km/hr. *Sky Blue Waseda* were fourth at 16:00, having covered 580 km at 74.02 km/hr, for a race average of 70.35 km/hr. They were just ahead of *Aurora,* who had started the day in third position, 16 km ahead of *Kyocera Son of Sun*. *Aurora,* however, had made an error in configuring their electronics, and were temporarily down on power from their solar panel. They eventually finished 10 minutes behind *Sky Blue Waseda*, at 16:10, having completed 551 km that day at an average speed of 68.87 km/hr, achieving a race average of 70.08 km/hr. These three cars were extremely closely matched, separated by only 25 minutes after 3000 km of racing. **Figure 2.24**

Further back in the field, the weather was starting to degenerate even further. Winds were increasing and rain was again creating havoc for some teams. The cloud cover continued to keep the solar influx down, further spreading the already scattered field. When *Dream* crossed the line at 08:38, the last of the cars to officially finish, *EOS*, was only 1340 km south of Darwin - a full 1,673 km behind the winner.

Figure 2.25 shows Waseda's solar flux data for the day. In figure 2.26 are shown the average speeds of the top ten cars for day 5.

Day 6: This day was to see 9 teams finish. First was *Toyota-56* at 10:44, having completed 153 km at 55.97 km/hr for the day. Next was *Desert Rose* at 11:00, 204 km at 72.00 km/hr, followed by *Intrepid* at 11:31, 216 km at 64.48 km/hr, *Sunforce I* at 11:56, 250 km at 66.37 km/hr and *Be-Pal III* at 12:48, 313 km at 67.55 km/hr. *Toyota-56*, *Desert Rose*, *Intrepid* and *Sunforce I* had all been close throughout the race. At Glendambo (the sixth media stop), only 16 minutes separated the last three of these four cars, *Toyota-56* having broken away from *Intrepid* by 52 minutes. *Desert Rose* slowly but steadily worked its way through the group and finished a scant 16 minutes behind *Toyota-56* in 7th place. Toyota-56 had had a relatively trouble free race, but were disappointed with the performance of their solar array.

At 13:17, *Maize and Blue* crossed the finish line, having completed 320 km at an average of 62.54 km/hr for their last day. This was an excellent result, particularly as an error in their solar panel construction had led to highly resistive contacts and a reduction in power output. The team had also been decimated in the final days of the race with gastric problems, either due to illness or unfamiliarity with the local water and cuisine. (Truck stops along the Stuart Highway are not generally renowned for the quality of their food. One little cafe has a sign out the front which reads: "Sorry, we're open"!) This climaxed a difficult race for one of the pre-race USA favourites.

Following Michigan, *Sun Favor* finished at 14:31, having run 378 km at 59.68 km/hr on day 6. *Solar Eagle II* were next at 14:47, having come 418 km that day at 63.17 km/hr. *Be-Pal III, Maize and Blue, Sun Favor* and *Solar Eagle II* had also had a close race, *Be-Pal III* slowly working its way through this group. At Cadney Homestead on

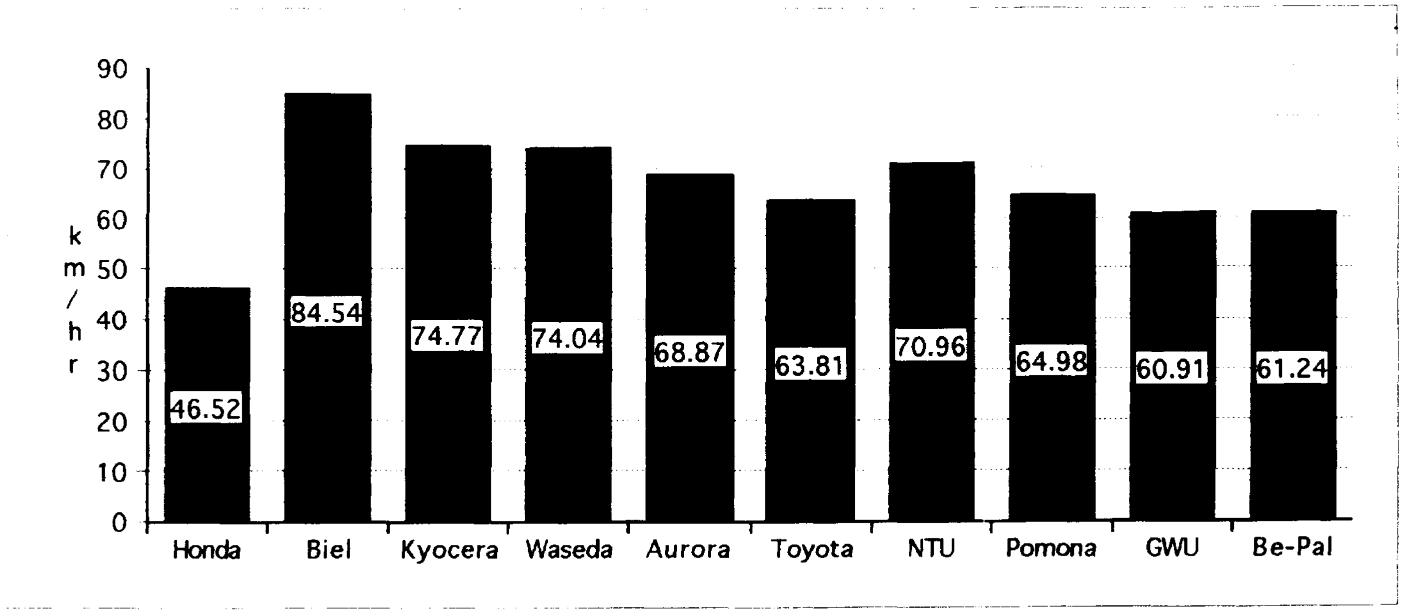

Figure 2.26[redacted] Average speeds for day 5 for the cars who would eventually finish in the top ten. Honda, Biel, Kyocera, Waseda and Aurora all finished this day, smashing the record held since 1987 by GM's *Sunraycer*. Honda had only 23 km to drive to reach the finish line: their low speed reflects the city driving conditions.

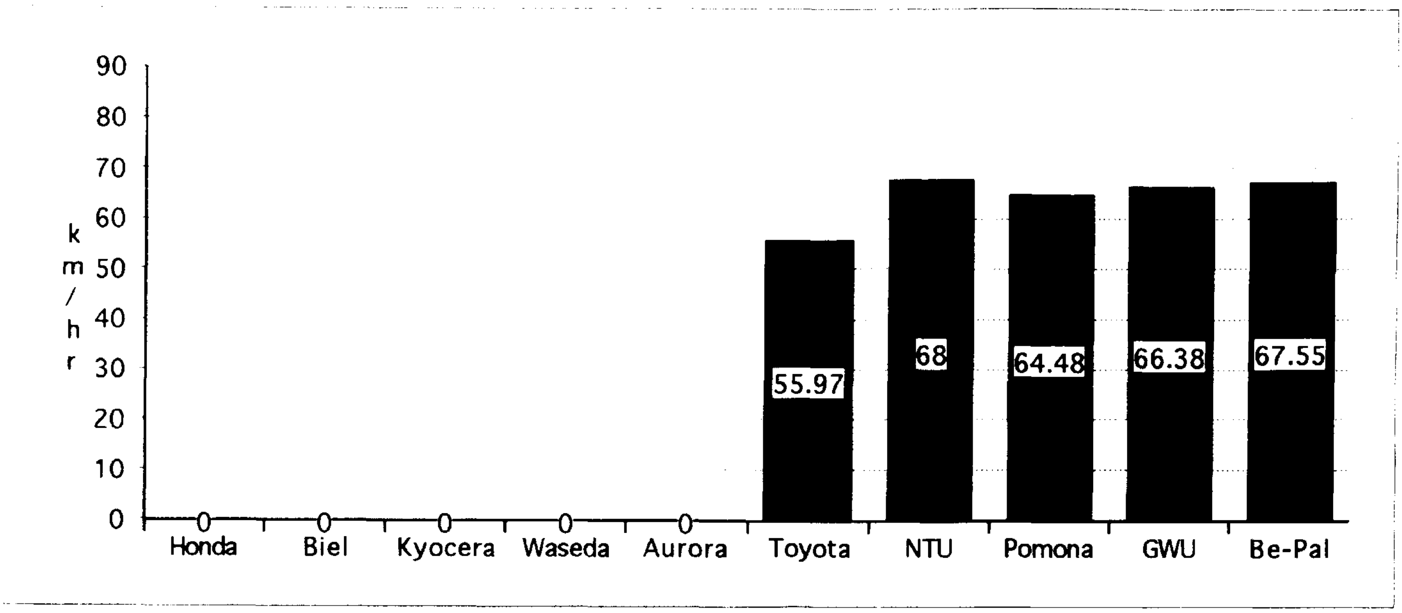

Figure 2.27 Average speeds for day 6 for the five cars that would finish that day.

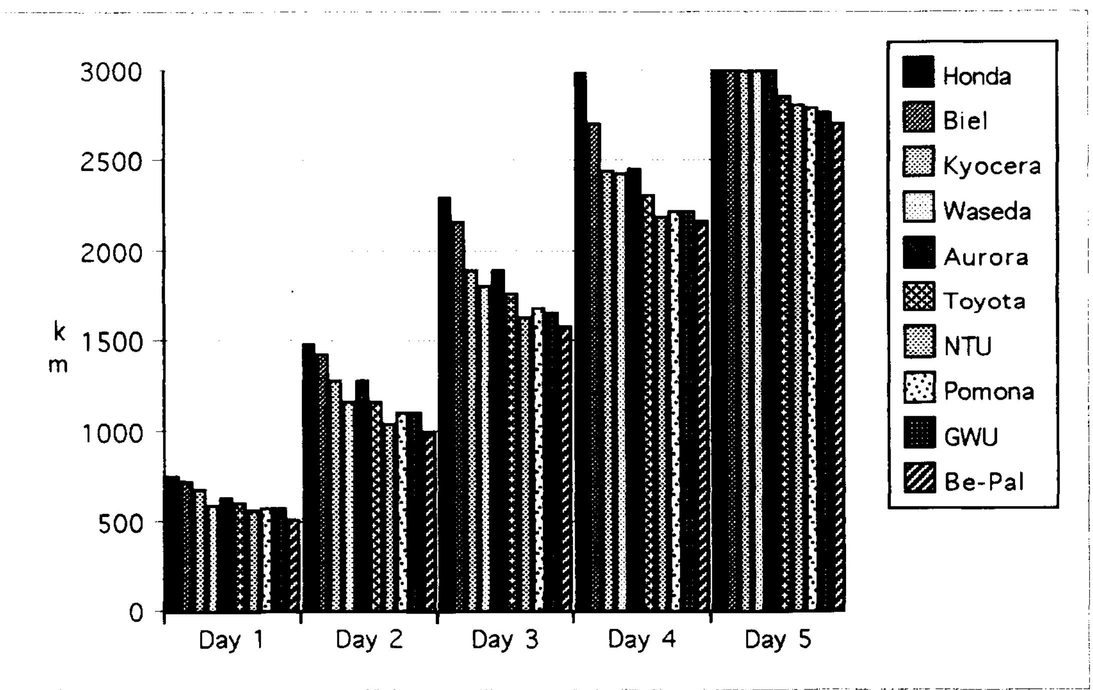

Figure 2.28 Cumulative distances travelled at the end of each day by the top ten cars.

the fourth day, these four cars were covered by only 28 minutes, with *Be-Pal III* and *Maize and Blue* only 1 minute apart !

Last in for the day was *Sunburner*, finishing at 15:48 after 501 km at 65.64 km/hr for the day. See figure 2.27 for average speeds of the top ten cars.

Remaining days: Further back in the field, the deteriorating weather extracted its price. Only two teams finished on November 13th, day 7. *Philips Solar Kiwi* finished at 15:46, having completed 293 km at 38.55 km/hr on their final day. Theirs was the first car in the Schools/Private class to finish. *Philips Solar Kiwi* also claimed the most dubious of honours this year, being picked up off the road by a willy-willy and flying some 20 meters through the air before coming to rest a good 80 meters from the road. Firmly wedged between two trees, and out of sight of the team, the car and driver (Mrs. Vivianne Lister) were in remarkably good shape - the car had a slightly bent front axle, but was otherwise drivable. Fearing the worst, the remaining team members rushed through the scrub to retrieve their vehicle. Most of the 39 minutes lost in this incident was taken up in getting the car back to the road, as it had flown over the scrub and there was no easy way back to the Stuart Highway! The official observer's log simply notes: "Damn tough Kiwis - driver change".

The only other finisher on day 7 was *Let's Sunjoy* from the Mabuchi Motor Company) who passed Bolivar Road at 16:07. On day 8, November 14th 1994, there was only a single finisher - *Sofix* (Team Sofix), winner of the Lead-Acid class.

Further back in the field there was still plenty of excitement, as teams from all over the world battled it out. *Spirit of Oklahoma II* (University of Oklahoma), *Solvogn Danmark* (Team Solvogn Danmark), and *Sky-Ace* (Ashiya University) ran a spirited race, a mere 11 minutes covering all 3 cars at the finish line. They were preceded by *Evolution 93/B* and *Mino Family Special* who had both worked their way through the field to take 20th and 21st position respectively.

Le Soleil took the view that they could not hope to compete with front running teams, and so elected to use relatively cheap amorphous silicon cells. These have a very low efficiency, typically around 6%. The team only ever saw a peak power output from their panel of 494 W, with more usual values around 390 W. Though they formally retired from the race, they did in fact finish the course, and crossed the Bolivar Road finish at 13:34 on the 20th November, 1994, fourteen days after setting out from Darwin.

Teams continued to arrive until the 16th November 1993, the tenth and final day of the race, with 6 cars arriving on each of the 15th and 16th. In total, 31 out of the 52 entrants were classified as finishers, including the *Hokuden Phoenix* which was not eligible to compete but was making a demonstration run.

The first five cars broke the race record, held by *GM Sunraycer* since 1987, of 44.90 hours at an average speed of 66.904 km/hr. *Dream* and *Spirit of Biel III* each averaged over 90 km/hr for 2 legs - *Dream* averaged 90.85 km/hr for the 318 km leg from Katherine to Dunmarra, and 92.76 km/hr for the 538 km leg from Alice Springs to Cadney; *Spirit of Biel III* averaged 90.42 km/hr for this leg and 91.92 km/hr for the 205 km leg from Port Pirie to Bolivar Road.

Several teams were very accurate at forecasting their race speeds: Honda estimated 86 km/hr, and averaged 84.96 km/hr, Pomona estimated 63 and averaged 63.64 km/hr. George Washington estimated 40 mph (62.76 km/hr) and averaged 63.08 km/hr - a mere 0.32 km/hr off! Be-Pal was also quite close with 60 and 61.96 km/hr, and Waseda estimated 70 and averaged 70.35 km/hr. But the record goes to Toyota, who estimated 65 km/hr and averaged 64.71 km/hr - a difference of just 0.4%!

The final race times and average speeds for all teams are presented in table 2.1, while table 2.3 lists the prizewinners in each category. The cumulative daily distances for the top ten cars are also shown in figure 2.28.

2.3 Disasters

For many teams the problems started well before the race did, with getting the car to Darwin in one piece a major challenge. While towing their solar car on an open trailer, Sonderborg Teknikum (*Solvogn Danmark*) were hit by a willy-willy which flipped it upside down. As it was dragged along the roadway the protruding nose of the solar car was ground away, condemning the team to many long hours in the workshop to get their car to the start line.

Mitcham High School (*ISIS*)had a similar experience, hitting a flock of kangaroos which jack-knifed and rolled their trailer. Several solar panels were damaged, but the car was repaired without too much difficulty.

Table 2.3 Prizes were awarded in several different categories.

AWARD	WINNER	PRIZE
First Outright	*Dream* Honda R & D	Solar Cup Pasminco
Second Outright	*Spirit of Biel / Bienne III* Engineering College of Biel	Framed photo of Solar Cup Pasminco
Third Outright	*Kyocera Son of Sun* Kyocera Corporation	Framed photo of Solar Cup
OMEGA Prize	*Dream* Honda R & D	Watches 4 each team - drivers
	Spirit of Biel / Bienne III Engineering College of Biel	Watches 4 each team - drivers
	Kyocera Son of Son Kyocera Corporation	Watches 4 each team - drivers
Special presentation by Howard Wilson	*Dream* Honda R & D	Framed Photo of Sunraycer
Special presentation by Howard Wilson	*Spirit of Biel / Bienne III* Engineering College of Biel	Framed Photo of Sunraycer
Special presentation by Howard Wilson	*Kyocera Son of Sun* Kyocera Corporation	Framed Photo of Sunraycer
Special presentation by Howard Wilson	*Sky Blue Waseda* Waseda Uni.	Framed Photo of Sunraycer
1ST Australian	*Aurora Q1* Aurora Vehicles Association	Crystal Trophy D.P.I.E.
Special presentation by Howard Wilson	*Aurora Q1* Aurora Vehicles Association	Framed Photo of Sunraycer
1ST Australian Secondary School	*Aquila* Dripstone High School	$12,000 D.P.I.E.
1ST Australian Tertiary Institution	*Desert Rose* Nthn. Terr. Uni.	$12,000 D.P.I.E.
1st Japanese School	*Sky Blue Waseda* Waseda Uni.	Framed boomerang Hokuriku Electric Power Co
1st American School	*Intrepid* Cal Poly Uni. Pomona	Framed boomerang
1st European School	*Spirit of Biel /Bienne III* Engineering College of Biel	Framed boomerang
1st Australian School	*Aquila* Dripstone High School	Trophy Commonwealth Bank

GM Sunraycer Award for Technical Innovation	*Desert Rose* Nthn. Territory Uni.	General Motors-Holden's Auton
1993 WSC Photographic Competition	Mr. Horst Lushington	Framed Participation Certificate $250
The Mal Trainer Battler Award	*T.R.50* Team T.R.50	Wooden Plaque N.T. Dept Transport & Works
First Place- Best Solar Array	*Dream* Honda R & D	Plaque US DOE
Second Place - Best Solar Array	*Spirit of Biel /Bienne III* Engineering College of Biel	Plaque US DOE

Classes:

Silicon/Silver Zinc Class		
Winner of Silicon/Silver Zinc Class	*Dream* Honda R & D	Framed photo of Solar Cup
2nd for Silicon/Silver Zinc Class	*Spirit of Biel / Bienne III* Engineering College of Biel	Framed photo of Solar Cup Pasminco
3rd for Silicon/Silver Zinc Class	*Kyocera Son of Sun* Kyocera Corporation	Framed photo of Solar Cup
School Private Class		
First, School - Private Class	*The Philips Solar Kiwi* Team Philips Solar Kiwi	Framed Photo of Solar Cup
Second, School - Private Class	*Solution* Monash/Melbourne Uni.	Framed Photo of Solar Cup
Third, School - Private Class	*Solvogn Danmark* Sonderborg Teknikum	Framed Photo of Solar Cup
Two Seater Class:		
First, Two Seater Class	*Intrepid* Cal. Poly Uni. Pomona	Framed Photo of Solar Cup
Second, Two Seater Class	*Sunburner* Stanford University	Framed Photo of Solar Cup
Third, Two Seater Class	n/a	Framed Photo of Solar Cup
Lead Acid Class:		
First, Lead Acid Class	*Sofix* Team Sofix	Framed Photo of Solar Cup
Second, Lead Acid Class	*Solar Flair* Team Solar Flair	Framed Photo of Solar Cup
Third, Lead Acid Class	*ConSole to the Future* KIA Motors	Framed Photo of Cup

J. Ward Phillips Awards:

Best Commuter Design	*Hokuden Phoenix* Hokuriku Electric Power Co.	Framed Photo of Cup
Fastest Four Wheeler	*Toyota 56* Toyota Motor Corporation	Framed Photo of Cup
Best Team Uniform	*Solar Eagle* Cal State Uni	Plaque
Best Sportsmanship	*Spirit of Biel/Bienne III* Engineering College of Biel	Plaque
Most Unique Car	*Solaemon Go* Team Doraemon	Plaque
Outstanding Team Spirit	Philips Solar Kiwi	Plaque
Last but not Least....	*EOS* Annesley College	Plaque

SunStang had their car shipped to Perth at the last minute, as the freighter taking it to Darwin had broken down. They had to quickly dispatch some team members to Perth to collect the car and drive the 5,000 km back to Darwin. In one week these young Canadians saw more of Australia than most Australians see in a lifetime.

During shipping from Melbourne to Darwin, the Stanford car developed a number of problems. Close inspection found that the lower wishbone forward pivot point had de-bonded from the composite sandwich chassis. Two team members, and a machinist kindly loaned by NTU, worked all through the night. The repair was finally completed at 6:00 am on the morning of the race.

George Washington University had perhaps the worst luck - whilst proudly watching their vehicle being unloaded by forklift from the plane in Melbourne, the team were horrified to see it teetering on the edge of the forks. The forklift driver, in a vain effort to save the situation, drove forward, neatly spearing the forks straight through the falling solar car. Amazingly, the damage was not as bad as it could have been, though a number of solar cells were destroyed and the chassis received significant damage. Much work was needed to get the car ready for the race, and the solar panel never produced the power it had before the accident. Once again, the Northern Territory University provided generous support, enabling George Washington to compete.

The Russian Team would not have got to Darwin at all were it not for the generosity of Biel, who paid for both their airfares and shipping costs. Operating on a non-existent budget, the Russian team immediately became a media favourite, and offers of support poured in. Free accommodation was provided by the Casino Hotel in Darwin, Territory Rent-a-Car provided free support vehicles, and a T-shirt printing company provided team T-shirts. With food generously provided by local shops, and a hitch-hiker volunteering her services as a co-driver, Team Moscow soon had everything they needed to participate.

If getting to Darwin was the first major challenge faced by teams, getting to Adelaide was the second. The problems which appeared most frequently on the debriefing sheets were: chain drive problems (either breaking or throwing chains), overheating electronics (frequently motor controllers), overheating batteries, and poor matching between the maximum voltage the MPPT could develop and that required to fully charge the batteries. Vehicle instability in cross-winds was another commonly-reported problem. Winds caused problems for a number of teams even when the car was stationary. Toyota nearly lost their solar panel and nose cone when a strong wind picked them up during an evening charge period - their nose cone's flight was only arrested by a conveniently placed fence. Waseda, too, had their solar panel picked up by a willy-willy and blown over.

Winds, however, were not the only source of vehicle instability. Some teams commented that they had experienced problems with their drivers falling asleep at the wheel. Another team, *Be-Pal III*, missed the 8:00 am start one morning as they had all slept in, becoming an excellent advertisement for the comfort of their sponsor's sleeping bags!

Aurora also had their fair share of problems - not just with the solar car but with support vehicles as well. On the last day of the race, one of their support vehicles which was towing their caravan lost control in the gusty winds. This resulted in both tow car and caravan gyrating together down the Stuart Highway until the caravan rolled. Fortunately nobody was injured, though the caravan was totally destroyed.

Some of the other problems reported by teams are listed below.

- *Hama Yumeka* had problems with their motors and retired on the second day.
- *Banana Enterprise* kept blowing MOSFETs in their motor controller and had to retire early.
- *Solar Eagle II* had thermal problems with the peak power trackers and were unable to develop the full charging voltage.
- *Solar Flair* kept breaking its front transverse leaf spring.
- *Solvogn Danmark* had 15 flat tires, plus many "preventative" tire changes. They also lost about half their battery cells, probably due to overheating, a problem also experienced by *Sky-Ace*.
- *ISIS* had a recurring problem with wheel spokes. They were breaking at the rate of 4-5 every one to two hours. In one particularly bad hour they broke 12. They had replaced 200 by the time they arrived in Alice Springs. After changing from 12 gauge spokes to 10 gauge they had no further problems.
- *SunStang* found that the sun was causing their solar panel to curl and crack. They were unable to successfully rectify the problem before the race, and were badly down on power - the peak power they saw was only 600 W. The controller for their low power, high efficiency "cruise mode" motor also burnt out, and they were left having to run their heavy duty, less efficient system. Their magnesium chassis cracked near one of the rear trailing arm mounting points as they traversed the second cattle grid of the race, possibly because they had not annealed it after

welding. The *Banana Enterprise* kindly gave them material to splint the damaged area. *SunStang* had one further problem: " the nose cone would tend to fly off".

- *Sunburner* finished the race well in 14th place, but their race was far from smooth. Their tribulations included a blown motor controller and progressively failing solar cells.

...AETS

References:

1. C.R. Kyle, "Racing with the Sun - The 1990 World Solar Challenge", Society of Automotive Engineers, Warrendale, (1991).

Tables:

Table 2.1 The 1993 World Solar Challenge results.

Table 2.2 Average speeds on the various "legs" of the race between the media stops. The locations of the media stops are shown in Figure 1.8

Table 2.3 Prizes were awarded in several different categories.

Figures:

Figure 2.1 These huge road trains are used in the Australian outback to transport large quantities of material over thousands of kilometres. Each has 62 wheels and weighs upwards of 120 tonnes.

Figure 2.2 Speed trial results, by grid starting order.

Figure 2.3 View across the start line just as the race begins. There are 28 cars in front of *Solaemon-Go*, the much admired pussy cat modelled after a well-known Japanese cartoon character, and 24 cars behind it.

Figure 2.4 *Alarus* and *Sulius IV* lead *SunStang* out of Darwin.

Figure 2.5 Honda's *Dream* and its support vehicles, including the support bus with telemetry antennas and weather sensors.

Figure 2.17 Takahiro Iwata, Honda's team manager, explains his strange car to the the publican at Upper Light. This tiny settlement, just 23 km from Adelaide, would be their camping ground for their last night (Day 4).

Figure 2.18 Waseda's insolation data for day 4 show the efffect of the intermittent cloud.

Figure 2.19 The converted chicken coop used to house *Dream* for its last night on the road.

Figure 2.20 Average speeds for day 4 for the cars who would eventually finish in the top ten.

Figure 2.21 Honda crosses the finish line to set a new race record. They had averaged 84.96 kph for the 3013 km.

Figure 2.22 Honda were justifably elated by their win.

Figure 2.23 *Spirit of Biel* crosses the line 3 hours and 2 minutes behind *Dream*. They had an uneventful final few days but had not been able to make up the time lost during the first 2 days. They averaged 78.27 km/hr for the race.

Figure 2.24 In outback Australia, the nearest phone box may be hundreds of kilometres away - unless you bring your own. This telecommunications dish, part of Biel's entourage, was powered entirely from batteries charged during the day from a solar array mounted on the roof of its support vehicle. It provided fax, phone lines, and even a pay-phone link to the outside world.

Figure 2.25 Waseda received this insolation for day 5.

Figure 2.26 Average speeds for day 5 for the cars who would eventually finish in the top ten. Honda, Biel, Kyocera, Waseda and Aurora all finished this day, smashing the record held since 1987 by GM's *Sunraycer*. Honda had only 23 km to drive to reach the finish line: their low speed reflects the city driving conditions.

Figure 2.27 Average speeds for day 6 for the five cars that would finish that day.

Figure 2.28 Cumulative distances travelled at the end of each day by the top ten cars.

Chapter 3.

Analysis

3.1 Introduction

It is always fascinating in auto racing to know why cars win, whether it is driver skill, equipment, teamwork, misfortune or other factors. In solar car racing speeds are relatively low, so driver skill is not as important as in other motor sports. The drivers are responsible however, for maintaining strategy, avoiding accidents and minimizing unnecessary energy expenditure. Equipment, teamwork and mishaps are of major importance. Primarily it is equipment that wins solar races. In theory, the car that converts radiation into propulsive force the most efficiently should be the fastest. Let's examine the factors that produce a fast solar car.

3.2 What Determines Solar Car Speed?

1. Reliability.

Obviously a car cannot win a race if it loses time in lengthy repairs. For the top cars, reliability was generally excellent. Down time didn't greatly disturb the finishing order. This can be easily illustrated by looking at the progress on the first day (Table 3.1). Of the first 10 cars to reach the outskirts of Darwin, 15 km from the start, 8 of them finished in the top 10 3000 km later and 17 of 20 finished in the top 20.

Even more remarkably, after passing Katherine at 317 km, the first six cars to finish in Adelaide at 3013 km, had identical positions as in Katherine. See Table 3.2 for the daily distances and standing at the end of each day. It was almost like a political survey that predicts the election winner fifteen minutes after the polls close: the race for the top six could have been called off 300 km from the start and the leaders could have gone sight seeing. It shows that fast solar cars can also be reliable solar cars. There were minor problems among the top 20, but nothing that completely disrupted performance. In general, reliability is the product of careful preparation, well organized teamwork and adequate pre-race practice. Even then, unexpected breakdowns can occur, but among the top 20 they were infrequent.

TABLE 3.1 - COMPARISON OF FIRST DAY PROGRESS AND FINAL WSC PLACE

Place at Start	Darwin City Limit 15 km	Hayes Creek 170 km	Katherine 314 km	Finish Adalaide 3036 km
1. Biel	Biel	Biel	Honda	Honda
2. Honda	Honda	Honda	Biel	Biel
3. Toyota	Kyocera	Kyocera	Kyocera	Kyocera
4. Kyocera	U. Michigan	Aurora	Waseda U.	Waseda U.
5. U. Michigan	Aurora	Toyota	Aurora	Aurora
6. Nissan	CSULA	Waseda U.	Toyota	Toyota
7. Sofix	Toyota	U. Michigan	Geo. Wash. U.	NTU
8. CSULA	NTU	U. Pomona	U. Pomona	U. Pomona
9. Ashiya U.	Geo. Wash. U.	Geo. Wash. U.	U. Michigan	Geo. Wash. U
10 Waseda U.	U. Pomona	NTU	CSULA	Be-Pal
11. Tokai U.	Waseda U.	CSULA	NTU	U. Michigan
12. George Washington U.	Ashiya U.	Nissan	Be-Pal	Nissan
13. Team New England	Nissan	Be-Pal	Nissan	CSULA
14. Mabuchi	Be-Pal	Stanford U.	Stanford U.	Stanford U.
15. Be-Pal	Sofix	Mabuchi	Mabuchi	Philips Kiwi
16. Mino Family	U. Oklahoma	Ashiya U.	Ashiya U.	Mabuchi
17. Aurora Q1	Mabuchi	Sofix	Sofix	Sofix
18. Stanford U.	Stanford U.	Philips Kiwi	Philips Kiwi	Tokai U.
19. Villanova U.	Monash U.	Monash U.	Monash U.	Monash U.
20. U.Western. Ontario	Villanova U.	Denmark Tech.	U. Oklahoma	Evolution
21. U. Pomona	Morphett Vale HS	Sulis IV	Hosokawa Go	Mino Family
22. Morphett Vale HS	Denmark Tech.	Tokai U.	Sulis IV	U. Oklahoma
23. U. Oklahoma U.	KIA Motors	Evolution	Evolution	Denmark Tech.
24. NTU	Evolution	Oklahoma U.	Denmark Tech.	Ashiya U.
25. Denmark Tech.	Philips Kiwi	Hosokawa Go	Tokai U.	Dripstone HS
26. KIA Motors	Mino Family	Mino Family	KIA	Hosokawa Go
27. Evolution	Tokai U.	KIA	Mino Family	Solar Flair
28. Philips Kiwi	Hama Yumeka	Phoenix	Villanova U.	KIA
29. Monash U.	Hosokawa	Morphett Vale HS	Solaemon Go	Alarus
30. Solaemon Go	SDSU	Mitcham Girls HS	Alarus	Annesley Coll.
31. Alarus	Meadowbank TAFE	Hama Yumeka	Mainichi Go	Phoenix
32. Hosokawa Go	Phoenix	Solaeman Go	Solar Flair	Sulis IV
33. SDSU	Sulis IV	Meadowbank TAFE	Phoenix	Solaemon Go
34. Meadowbank. TAFE	Alarus	Annesley College	Annesley College	Mainichi Go
35. Puerto Rico	U.W. Ontario	Puerto Rico	Morphett Vale HS	Mitcham HS
36. JCJC	Solaemon Go	NT TAFE	NT TAFE	Morphett Vale
37 Le Soleil	Mitcham Girls HS	Mainichi Go	Puerto Rico	Puerto Rico
38. Solar Flair	Puerto Rico	Solar Flair	SDSU	New England
39. Dripstone HS	Dripstone HS	JCJC	Le Soliel	Le Soleil
40. Sulis IV	Heliox	Villanova U.	Mitcham HS	U.W. Ontario
41. Phoenix	Annesley College	Heliox	Dripstone HS	TR 50
42. Mainichi Go	Solar Flair	Alarus	U.W. Ontario	SDSU
43. TR 50	JCJC	Le Soleil	Meadow. TAFE	NT TAFE
44. Heliox	NT TAFE	Heliodet	JCJC	Meadow. TAFE
45. Mitcham Girls HS	Mainichi	SDSU	TR50	Villanova U.
46. Hama Yumeka	Le Soleil	U.W. Ontario	New England	JCJC
47. Annesley College	Heliodet	Dripstone HS	—	Brazil
48. NT Inst. of TAFE	Moscow	Moscow	—	Hama Yumeka
49. Moscow	—	—	—	Heliox
50. Brazil	—	—	—	Helio Det
51. Holy Cheat	—	—	—	Moscow
52. Helio Det	—	—	—	Holy Cheat

TABLE 3.2 - CUMULATIVE DISTANCE AND PLACE VERSUS DAY

Final Place	Car	Qualifying (Place)	DISTANCE VERSUS DAY (PLACE) 1	2	3	4	5	6	7	8	9	10
1.	Honda	(2)	746 (1)	1492 (1)	2294 (1)	2990 (1)	3013 (1)					
2.	Biel	(1)	723 (2)	1426 (2)	2163 (2)	2703 (2)	3013 (2)					
3.	Kyocera	(4)	674 (3)	1282 (3)	1903 (3)	2446 (4)	3013 (3)					
4.	Waseda U.	(10)	588 (6)	1166 (5)	1814 (5)	2433 (5)	3013 (4)					
5.	Aurora	(17)	632 (4)	1278 (4)	1899 (4)	2462 (3)	3013 (5)					
6.	Toyota	(3)	605 (5)	1163 (6)	1763 (6)	2307 (6)	2860 (6)	3013 (6)				
7.	NTU	(5)	552 (10)	1038 (12)	1620 (10)	2194 (9)	2809 (7)	3013 (7)				
8.	U. Pomona	(12)	579 (8)	1103 (7)	1672 (7)	2223 (8)	2797 (8)	3013 (8)				
9.	Geo. Wash. U.	(12)	579 (9)	1102 (8)	1654 (8)	2225 (7)	2763 (9)	3013 (9)				
10.	Be-Pal	(15)	519 (13)	1003 (13)	1580 (12)	2159 (10)	2700 (10)	3013 (10)				
11.	U. Michigan	(5)	584 (7)	1076 (9)	1591 (11)	2150 (11)	2693 (11)	3013 (11)				
12.	Nissan	(6)	534 (11)	1049 (11)	1560 (13)	2122 (13)	2634 (12)	3013 (12)				
13.	CSULA	(8)	532 (12)	1061 (10)	1627 (9)	2141 (12	2595 (13)	3013 (13))				
14.	Stanford U.	(18)	517 (14)	976 (14)	1555 (14)	2030 (14)	2512 (14)	3013 (14))				
15.	Philips Kiwi	(28)	412 (17)	853 (15)	1345 (15)	1771 (15)	2288 (15)	2720 (15)	3013 (15)			
16.	Mabuchi	(14)	460 (15)	853 (16)	1299 (16)	1733 (16)	2206 (16)	2683 (16)	3013 (16)			
17	Sofix	(7)	420 (16)	813 (17)	1270 (17)	1681 (17)	2126 (17)	2579 (17)	2883 (17)	3013 (17)		
18.	Tokai U.	(11)	358 (23)	694 (22)	1099 (20)	1482 (18)	1790 (18)	2200 (18)	2492 (18)	2860 (18)	3013 (18)	
19.	Monash U.	(29)	403 (19)	753 (18)	1177 (18)	1471 (19)	1725 (19)	2118 (19)	2464 (19)	2808 (19)	3013 (19)	
20.	Evolution	(27)	370 (20)	730 (20)	1094 (22)	1440 (20)	1710 (21)	2100 (21)	2431 (20)	2797 (20)	3013 (20)	
21.	Mino Family	(16)	328 (28)	635 (26)	1027 (25)	1424 (23)	1715 (20)	2106 (20)	2431 (21)	2738 (21)	3013 (21)	
22.	Oklahoma U.	(23)	360 (22)	749 (19)	1150 (19)	1424 (24)	1705 (22)	2056 (22)	2361 (23)	2673 (23)	3013 (22)	
23.	Denmark Tech.	(25)	348 (24)	680 (23)	1084 (23)	1430 (22)	1657 (24)	2047 (24)	2379 (22)	2700 (22)	3013 (23)	
24.	Ashiya U.	(9)	404 (18)	710 (21)	1099 (21)	1433 (21)	1672 (23)	2052 (23)	2360 (24)	2656 (24)	3013 (24)	
25.	Dripstone HS	(39)	258 (41)	591 (33)	992 (27)	1306 (26)	1504 (27)	1912 (26)	2273 (26)	2534 (26)	2940 (25)	3013 (25)
26.	Hosokawa-Go	(32)	362 (21)	658 (24)	1044 (24)	1384 (25)	1602 (25)	1987 (25)	2288 (25)	2544 (25)	2819 (26)	3013 (26)
27	Solar Flair	(38)	320 (31)	613 (31)	1001 (26)	1213 (31)	1492 (28)	1858 (28)	2087 (30)	2405 (30)	2787 (27)	3013 (27)
28.	KIA Motors	(26)	347 (25)	632 (27)	980 (30)	1209 (32)	1492 (29)	1835 (30)	2154 (28)	2456 (27)	2772 (29)	3013 (28)
29.	Alarus	(31)	320 (32)	651 (25)	990 (28)	1273 (28)	1510 (26)	1883 (27)	2166 (27)	2455 (28)	2774 (28)	3013 (29)
30.	Annesley Col.	(47)	317 (33)	632 (28)	985 (29)	1300 (27)	1492 (30)	1852 (29)	2148 (29)	2431 (29)	2745 (30)	3013 (30)
31.	Phoenix	(41)	321 (30)	607 (32)	946 (32)	1229 (30)	1442 (31)	1767 (31)	2064 (31)	2332 (31)	2680 (31)	2953 (31)
32	Sulis IV	(40)	330 (27)	632 (29)	938 (33)	1209 (33)	1396 (33)	1720 (32)	2054 (32)	2269 (33)	2636 (33)	— (33)
33.	Solaemon-Go	(30)	333 (26)	533 (35)	836 (35)	1126 (34)	1279 (35)	1626 (35)	2007 (33)	2285 (32)	2677 (32)	2687 (32)
34.	Mainichi-Go	(42)	323 (29)	632 (30)	960 (31)	1230 (29)	1422 (32)	1717 (33)	1985 (35)	2217 (34)	2544 (34)	— (34)
35.	Mitchum HS	(45)	283 (38)	420 (44)	709 (39)	951 (39)	1136 (36)	1427 (37)	1683 (36)	1950 (36)	2196 (35)	— (35)
36.	Morphett Vale	(22)	314 (34)	533 (36)	844 (34)	1088 (35)	1349 (34)	1695 (34)	1990 (34)	2106 (35)	— (36)	— (36)
37	Puerto Rico	(35)	286 (37)	476 (39)	723 (38)	933 (40)	1107 (38)	1371 (40)	1580 (37)	1744 (37)	1833 (37)	— (37)
38.	New England	(13)	0 (51)	430 (40)	689 (40)	984 (38)	1099 (40)	1492 (36)	— (38)	— (38)	— (38)	— (38)
39.	Le Soleil	(37)	272 (39)	496 (38)	744 (37)	985 (37)	1104 (39)	1398 (39)	-- (40)	— (41)	— (41)	— (41)
40.	U.W. Ontario	(20)	217 (45)	532 (37)	659 (41)	826 (41)	1135 (37)	1203 (38)	1419 (39)	1492 (39)	— (39)	— (39)
41.	TR 50	(43)	162 (49)	381 (46)	628 (42)	759 (42)	915 (43)	1117 (41)	1300 (41)	1490 (40)	— (40)	— (40))
42	SDSU	(33)	272 (40)	425 (42)	493 (44)	751 (43)	960 (42)	1072 (42)	— (42)	— (42)	— (42)	— (42)
43.	NT TAFE	(48)	314 (35)	569 (34)	836 (36)	1015 (36)	1035 (41)	— (43)	— (43)	-- (43)	— (43)	— (43)

44.	Meadow. TAFE	(34)	236 (42)	430 (41)	628 (43)	— (44)	—	—	—	—	—	— (44)
45.	Villanova U.	(19)	314 (36)	422 (43)	— (45)	—	—	—	—	—	—	— (45)
46.	JCJC	(36)	229 (43)	396 (45)	— (46)	—	—	—	—	—	—	— (46)
47	Brazil	(50)	170 (48)	252 (47)	—	—	—	—	—	—	—	— (47)
48.	Hama Yumeka	(46)	224 (44)	232 (48)	—	—	—	—	—	—	—	— (48)
49.	Heliox	(44)	207 (46)	— (49	—	—	—	—	—	—	—	— (49)
50.	Helio Det II	(52)	193 (47)	— (50)	—	—	—	—	—	—	—	— (50)
51.	Moscow	(49)	35 (50)	— (51)	—	—	—	—	—	—	—	— (51)
52	Holy Cheat	(51)	— (52)	—	—	—	—	—	—	—	—	— (52)

2. Net Solar Radiation Received.

Like any other form of racing, available power ultimately determines speed. Part of the equation is the fuel supply, in this case solar energy. Dense clouds can cut solar radiation to a fraction of clear sky radiation. However, for the leaders the weather was generally clear except for day 4 when radiation was cut by about 40% due to scattered cloud cover. See Appendix B for the solar radiation following the leaders. The distances on day 4 were also less, averaging 7% lower than on the first three days (see Table 3.2). Since the power is approximately proportional to the cube of the speed, the speed reduction would be significantly less than the reduction in solar radiation. Also, battery reserves can be used to dampen out fluctuations in solar energy received.

The total radiation during the race for the winning cars was not remarkably different between 1993 and the two previous World Solar Challenges. Table 3.3 shows the total daily solar energy from 8 AM to 5 PM, for days one through five in 1987, 1990 and 1993 following the leading cars (the solar energy for cars further back in the field was often quite different). The average was 35,629 watt-hours per square meter with 1993 being high at 36,626, 1990 being low at 34,869 and 1987 intermediate at 35,394. The winning speeds in 1987 and 1990 were about the same considering the solar energy received (Sunraycer = 66.90 km/hr, and Biel = 65.18 km/hr respectively) . In comparison, Honda's 1993 performance of 84.96 km/hr, was a quantum jump in speed.

3. Electrical and Mechanical Power Conversion Efficiency.

The combined efficiency of the solar array and the electrical and mechanical systems determines the power that is available for propulsion. The greater the overall efficiency, the higher the available power and the higher the potential speed.

The solar cells used by the top 10 WSC competitors were monocrystalline silicon, (although Pomona used a small number of gallium arsenide cells). The rated solar panel conversion efficiency varied from about about 14% (Pomona) to 21% (Honda). Solar cell characteristics are reviewed in references [1] and [2] and in Chapter 6 of this book.

A small gain in solar cell efficiency can result in a large gain in available power. For example, Honda used cells manufactured by Dr. Richard Swanson of Sunpower, which produced a net panel efficiency of about 21%. The Honda solar array covered 94% of the panel area with active solar cells, giving an effective panel efficiency of 21 x 0.94 = 19.7%. Biel used overlapping solar cells in a panel designed by engineer Hans Gochermann of German

TABLE 3.3

SOLAR RADIATION ON A FLAT HORIZONTAL PANEL IN WATT-HRS/M^2

	Year		
Day	1987	1990	1993
1	6,265	5,664	7,125
2	6,537	7,224	8,931
3	7,003	8,565	8,284
4	7,561	4,994	4,912
5	8,028	8,472	7,374
Totals	35,394	34,869	36,626

See Appendix B for daily weather data

Aerospace. The array efficiency was 18.8% and the area coverage was 98.4% for an effective efficiency of 18.8 x 0.984 = 18.5%. The small increase in panel efficiency (19.7% versus 18.5%) gave Honda a 7% gain in available power over Biel, even though Honda's effective panel area was less.

Another important electrical component is the motor. Fourteen of the top fifteen cars used DC brushless motors (fifth place Aurora used a DC brush motor). One of the most creative innovations in the 1993 WSC was the use of direct drive wheel motors which eliminate transmission losses. Honda, Biel, and Northern Territories University, all used wheel motors which were unsprung, with the shaft directly driving the rear wheel. By doing this, the drive train losses of 3% to 4% were eliminated, giving a boost in available power.

For those cars not having direct drive motors, a chain drive or a tooth belt drive were the most commonly used transmissions. They were simple, reliable and quiet.

4. Aerodynamic Drag.

On a level road, the biggest force that retards motion is aerodynamic drag, (wind resistance), which can be 80% of the total drag (the other 20% is rolling resistance). The air drag forces are given by:

1. $\mathbf{D = 1/2 C_d A r (V)^2}$

where **D** is the air drag, $\mathbf{C_d}$ is the drag coefficient, (a geometric factor related to aerodynamic efficiency - see Chapter 4), **A** is the projected frontal area of the car, and **V** is the car velocity. Since air resistance goes up as the square of the velocity, at high speeds it becomes the single most important retarding force. In order to minimize aerodynamic drag, streamlined car bodies are used which have very low drag coefficients. Several methods of decreasing aerodynamic drag are discussed in Chapter 4.

5. Car Weight.

Added weight acts in several ways to slow a car. It retards acceleration because of added mass, it increases the rolling resistance because of greater tyre deformation and higher bearing loads, and it restrains climbing rate because of the need to lift the car uphill. Controlling weight is important, but not as critical as achieving high power output or low wind resistance [1]. In fact, many of the cars that have entered either two or three of the races had a heavier weight in 1993 than before, and yet achieved a higher speed. See Table 3.4 for a comparison of the weights of multiple year entries and the speeds. On a level road, adding 1 kg to the weight,

TABLE 3.4 - WEIGHT AND SPEED OF MULTIPLE YEAR ENTRIES*

1993 Place	Car	Weight Kilograms, No Rider: 1987	1990	1993	Average Speed kph (Place): 1987	1990	1993
1.	Honda	—	138	188	—	54.68(2)	84.96(1)
2.	Biel	203	183	158	42.94(3)	65.18(1)	78.27(2)
3.	Kyocera	—	154	155	—	42.13(14)	70.76(3)
4.	Waseda U.	—	156	190	—	30.10(22)	70.35(4)
5.	Aurora	189	160	240	44.48(2)	50.20(6)	70.08(5)
—	GM Sunraycer (Ref)	180	—	—	66.90(1)	—	—
7.	NTU	250	168	180	31.72(5)	43.20(12)	64.34(7)
8.	Pomona U.	—	207	254	—	44.20(11)	63.64(8)
11.	U. Michigan	—	229	216	—	52.53(3)	61.35(11)
13.	Los Angeles	—	205	238	—	44.38(10)	59.53(13)
15.	Philips Kiwi	—	256	180	—	29.35(23)	49.72(15)
17.	Sofix	—	187	250	—	30.34(21)	46.41(17)
19.	Monash U.	300	207	205	30.59(6)	43.07(13)	40.27(19)
22.	U. Oklahoma	—	268	134	—	00.00(36)	37.85(22)
23.	Denmark Tech	224	219	250	19.95(10)	39.93(28)	37.80(23)
25.	Dripstone H.S.	—	225	240	—	31.14(19)	37.07(25)
26.	Hosokawa-Go	—	132	150	—	4.48(34)	35.77(26)
27.	Solar Flair	—	208	?	—	12.39(33)	35.47(27)
29.	Alarus	237	142	265	20.51(11)	31.75(17)	34.76(29)
30.	Annesley College	—	280	?	—	30.71(20)	34.40(30)
33.	Simon Solaemon-Go	—	188	?	—	33.07(16)	34.77(33)
34.	Mainichi-Go	—	175	190	—	19.62(31)	31.73(34)
36.	Morphett Vale H.S.	289	220	220	15.89(13)	16.44(32)	31.33(36)
48.	Hama Yumeka	305	145	200	19.76(12)	21.79(26)	15.03(48)
50.	Heliodet	120	120	120	6.23(22)	20.25(30)	21.46(50)
	Average	230	191	201	26.54	34.39	47.80

*Teams may have had a somewhat changing membership each year and different names, however the same organization or group designed and built the car.

adds only about 1 watt to the required mechanical power at solar car racing speeds (70 - 80 km/hr).

6. Tyre Rolling Resistance.

In general, low friction tyres have low weight, thin walls, and thin smooth tread. They use high air pressure and are made of resilient elastic materials. Most of the WSC 93 entrants employed bicycle tyres. In spite of their light weight, bicycle tyres are rugged enough for solar car racing and they have about half the rolling resistance of standard motorcycle or automobile tyres. Also, because of their narrow profile they have less air drag, and they weigh less. The most common tyre in the WSC was a 20x1.75 inch with slick tread. Tyre pressures were from 90 to 140 psi. Also common were 26 inch wheels with slick mountain or city bike tyres. For more details on tyres, see the chapter on suspension, wheels and tyres.

The rolling resistance coefficient C_{rr}, when multiplied by the weight on the wheel, gives the retarding force due to tyre and wheel bearing friction.. Only two of the leading teams gave values for Crr. Biel reported a Crr of 0.0056 measured on a smooth asphalt road surface at 80 km/hr while Honda reported Crr values from 0.0040 to 0.0042 with the test conditions unknown. In other words, the rolling resistance of bicycle tyres is about 1/2% of the applied weight on the wheel.

An interesting field measurement was made by California State University at Los Angeles. They carefully observed the power consumption of their vehicle at a fixed speed (not specified) at various tyre pressures. By raising the tyre pressure from 90 psi to 110 psi, the power consumption dropped 5%. It is generally true that higher tyre pressures produce lower rolling resistance. Some teams used as high as 140 psi, although 100 psi was the average. Biel had an undetected low tyre, mentioned later, which raised the rolling resistance and caused a noticeable speed loss.

Two other interesting phenomena are worth mentioning. Worn tyres have a lower rolling resistance than a new tyre due to thinner tread [3]. It pays to leave tyres on the car as long as practical before changing them. Some teams kept tyres on the car for several hundred kilometres. Also as a tyre heats up, the rubber flexibility improves, thus hot tyres have a lower rolling resistance. Low temperatures in the Australian outback were not a problem.

7. Experience.

Like other technological sports, such as yacht racing or glider flying, experience has a major influence on performance. Of the 24 teams that entered both in 1990 and 1993, only three of them were slower in 1993 than in 1990. See Table 3.4 for comparative speeds. Nine teams entered all three races, 1987, 1990 and 1993. Six of the nine had their highest average speed in 1993. The other three were slightly faster in 1990.

The average speed of the multiple entry group increased from 26.5 km/hr in 1987, to 34.4 km/hr in 1990 and 47.8 km/hr in 1993. Northern Territory University went more than twice as fast in 1993 in placing 7th as they did in 1987 when they placed 5th. Obviously, the entrants have improved their overall car technology tremendously since the first race, and their previous race experience was an obvious help. The winner Honda went 30 km/hr faster in 1993 than in 1990 using basically the same car geometry. The reward for Honda car designer Takahiro Iwata was a record performance on the second try.

8. Budget

Unfortunately, cost is a big factor — efficient solar cells, special motors and other high-quality equipment, are normally more expensive. Consequently low budgets don't usually create winning cars. However, cost alone will not produce a winner. A solar car fits very well into the standard mission analysis concept used in the aerospace industry. All of the elements are there, budgets, PERT charts, schedules, logistics, strategy, teamwork, and tactics. It is a valuable real world experience for the entrants where their success or failure is immediately known when their car crosses the finish line. The sport is still new enough so that in the World Solar Challenge, Universities and private groups can compete successfully against major auto companies and other industrial giants.

9. Team Management

The influence of team leadership is sometimes underrated in producing a fast solar car. It doesn't matter whether the management style is loose or regimented, or the teams are large or small, what matters is the final result. The only criteria of real importance is whether the organization can handle the thousands of details efficiently, under stress, without making a major mistake. Albert Einstein considered this process so important that he said "God is in the details". Before a solar car is ready for the road, it is much like the take off of a passenger airliner. An elaborate check list must be followed to insure that everything is ready. Whether the check list is informal or formal is not important so long as the details are taken care of each time.

10. Technical Regulations

The technical regulations are covered elsewhere in this book, but one critical factor should be mentioned. It is sometimes possible to gain a significant advantage by interpreting the rules. An example is the regulation on solar panel dimensions and the size of the moving car. When in motion, a solar car must measure no more than 2 meters in width, 6 meters in length, or 1.6 meters in height. On the other hand, the solar panel must fit entirely within a rectangular box 4.44 meters long by 2 meters wide by 1.6 meters high, where the length times the width can't exceed 8 square meters. Three teams in the top 10, Aurora, Pomona, and George Washington University, used solar panel extensions which they deployed only for stationary charging. With the extension, the solar panel still fit in the box on the diagonal, giving 28% more area during the morning and evening charging periods, when the car was stationary. Carried on the inside of the car, the panel extension doesn't increase aerodynamic drag, and the added charging capacity more than compensates for the extra weight.

3.3 Common Mechanical and Electrical Problems

Electrical and mechanical failures are almost inevitable in such a long race. A survey of the top 15 cars after they had finished produced a list of problems that is typical of solar car races. Although some of these are covered in Chapter 2, a short list is included here to illustrate the importance of reliability in achieving the full speed potential of a car.

1. Electrical Component Failures.

Probably the most serious electrical failures were motor controllers. Honda, NTU, Pomona and Stanford all changed controllers after experiencing failure or power loss. Spare parts in the main power train are essential, and provision should be made for rapid exchange. Honda took only 7 minutes to change their motor and controller. Pomona had a broken wire in their motor and changed the motor along with the controller, losing 25 minutes.

Maximum power point trackers (MPPT) caused some problems. CSULA and Stanford experienced low output voltage from their trackers and had to replace them. On day 5, Aurora lost 1/2 of their panel power for 2 1/2 hours when their MPPT's were inadvertently not turned on. The car drifted back from 3rd to 5th place because of the power loss. Rapid detection of problems in the electrical system is essential. Real time monitors on critical components can detect problems before they cause unnecessary time loss. Teams mentioned that many of their electrical failures were due to overheating. Many electrical components require cooling.

Another common electrical problem was broken solar cells or connecting wires. Road vibration on the Stuart Highway often causes component failure, and solar cells must be supported by a rigid panel structure to prevent breakage. Both Aurora and Stanford had to bypass cells and Stanford ultimately lost about 1/6 of their panel area due to shorts. Pomona had a 20% power loss which was still unexplained at the end of the race.

Michigan had an another unfortunate electrical problem that could not be corrected during the race. The contacts on their solar cells were misaligned because of a manufacturing error, causing a high contact resistance which cost them about 200 watts of power. The panel was capable of over 1100 watts peak power output and it dropped to about 960 watts maximum. This unforeseen error cost them a few places in the final ranking.

Computer bugs and glitches were a factor for several teams. For example, Honda lost power on the hills due to a computer bug but they easily corrected the problem by resetting the program.

Battery Problems.

The usual solution to the measurement of battery charge for silver-zinc batteries is an ampere-hour meter (AH). Commercial AH meters were occasionally faulty. CSULA had one meter that burned out and the replacement was not accurate. Stanford also had a faulty AH meter. Managing the battery charge during the race is one of the most critical ingredients of success, so reliable and accurate meters are essential.

A lack of adequate ventilation on the CSULA battery box caused high battery temperatures and the battery pack lost at least 1 kilowatt-hour of capacity due to cell damage. Although CSULA was in 9th place on day 3, they lost ground after this due to low batteries and finished in 13th place.

2. Mechanical breakage.

Biel hit a bump on the first day near Katherine and damaged a front wheel fairing. The tyre rubbed the spat and the undetected braking force absorbed about two hundred watts of power.

Also on the first day, Biel had one tyre with a slow leak. The crew found the low tyre after the damaged wheel spat was repaired and they noticed another unexplained speed loss. Flat tyres are not ordinarily a serious problem. During the WSC, it was normal to have from two to five flats total during the race. A wheel and tyre could be changed in about two minutes. Often lighter tyres will have more flats, but their lower rolling resistance can more than make up the time lost in tyre changes. A team must perform a cost/benefits analysis on components of this type.

Structural breakage was an occasional problem. George Washington University had a series of mechanical failures which luckily did not cause a serious accident. Their most bazaar mishap was when the steering wheel came off in the drivers hands, the car swerved into a ditch and ruptured two tyres. The car was back on the road in a few minutes. George Washington also had two broken trailing arms and a broken brake mount. They were able to weld the parts at night without loss of time.

NTU had two rear wheels with spoke breakage, and a broken bracket on their tilt mechanism. Other teams had drive gears that failed. Waseda stripped teeth from a drive sprocket. The Aurora drive gear came loose twice within two hours.

Most of the mechanical problems in the top 15 were unpredictable which underscores the need for a completely mobile repair or replacement capability. All of the top teams were able to repair or replace broken parts rapidly, so time loss was a minimum. This was also true of electrical repairs.

3.4 Potential Versus Actual Performance

It would be interesting to compare the performance of solar cars on an equal basis. To do this, a simple mathematical model is useful [1].

$$(1)\quad D = W(\mathrm{Sin}(\mathrm{Arctan}G) + C_{rr1}\mathrm{Cos}(\mathrm{Arctan}\ G)) + NC_{rr2}V + 1/2C_dAr(V+V_w)^2$$

where **D** is the total drag at constant velocity, **W** is the total weight including driver, C_{rr1} is the low speed rolling resistance coefficient, **G** is the fractional slope (the rise divided by the horizontal distance), **N** is the number of wheels, C_{rr2} is a factor defining the variation of rolling resistance with velocity, **V** is the car velocity, C_d is the aerodynamic drag coefficient, **A** is the frontal area, **r** is the air density (a value of 1.2 kg per cubic meter was used in all calculations) and V_w is the velocity of a headwind or tailwind with the sign being positive for a head wind.

The net mechanical power **P,** in watts to the rear wheel, can be found by multiplying equation 1 by the velocity:

$$(2)\quad P = WV(\mathrm{Sin}(\mathrm{Arctan}G) + C_{rr1}\mathrm{Cos}(\mathrm{Arctan}\ G)) + NC_{rr2}V^2 + 1/2C_dArV(V+V_w)^2$$

Equation 2 will be used to compare the theoretical performance to the actual performance, of the first 15 WSC finishers. The first term in Equation 2 gives the power due to gravity in ascending or descending. The sign of **G** is positive uphill and negative downhill. The second term gives the power consumed by tyre rolling resistance. The value of C_{rr1} in the second term was estimated from previous measurements [1, 3, 4], except for Honda and Biel, where C_{rr1} was reported by the teams. The fourth term is the power to overcome the aerodynamic drag of the vehicle.

The third term in Equation 1 combines the drag due to wheel bearing and windage losses and also the velocity-dependent friction losses in the tyres [1]. A value of C_{rr2} = 0.0502 was determined for a Moulton bicycle tyre, in tests by General Motors in 1987 [3]. Apparently there have been no other measurements of this factor. The overall tyre rolling resistance reported by Biel (C_{rr1} = 0.00562) was measured at 80 km/hr and the resistance reported by Honda (C_{rr1} = 0.0040/42) may also have been measured at high speed. This would render C_{rr2} redundant. However, Honda and Biel may not have accounted for the rough asphalt pavement typical of the Stuart highway, which would raise the reported rolling resistance [1, 4]. In order to compare the first 15 cars on an equal basis, a value of $\mathbf{C_{rr2}}$ = 0.0502 will be used for all cars including Biel and Honda.

The factors in Equation 2 for the first 15 cars are listed in Table 3.5. Data for the 1987 winner, the GM Sunraycer, is also shown for comparison. The weight and drag area were provided by the competitors. The power train efficiency includes the combined motor and controller efficiency at operating load (given by the teams), plus an estimated 4% mechanical transmission loss for those teams using a gear reduction. For example, Kyocera had a 93% motor operating efficiency, a 97% controller efficiency and a 96% transmission efficiency giving a net power train efficiency of 0.93 x 0.97 x 0.96 x 100 = 86.6%. If 1000 watts of electrical power is fed into the motor, the net mechanical power delivered to the wheels would be 0.866 x 1000 = 866 watts. This would be the power **P** in Equation 2. Using the coefficients for Kyocera, 866 watts yields a speed of 68.7 km/hr. This is the computed speed on 1000 watts given in Table 3.5. Using Kyocera's average race speed of 70.76 km/hr, gives a power of 927 watts/0.866 = 1070 watts required at race speed. All calculations were done for a level road with no wind. Honda, Biel and NTU used wheel motors, so their net power train efficiency does not include the 4% transmission loss.

The power required at the race speed listed in Table 3.5 seems high, but this is somewhat misleading. A car does not depend entirely upon the solar energy received while running, they can draw upon battery storage. Before the start, competitors are allowed to fully charge their batteries, giving an energy potential of 5 kw-hrs. The morning and evening charging periods together add perhaps 1.6 kw-hrs per day making 8 kw-hrs for 5 days. This means that during five days there would be a total of about 8 + 5 = 13 kw-hrs of energy available in addition to the solar energy received while the car is running. Assuming eight square meters of solar cells and a net panel efficiency of 18%, and using the solar energy listed in Table 3.3, the total energy available while running is approximately 8 x 36.6 x 0.18 = 52.7 kw-hrs. So, the initial battery storage adds about 10% to the total solar energy available during race hours and the stationary charging period adds another 15%. This means that a car can consume about 25% more power during the day than the energy directly available from the sun. This cushion allows cars to use extra power as needed on hills, or during cloudy periods.

3.5 Observations

The computations in Table 3.5, use information given to the authors by the competitors, along with indirect estimates of such factors as rolling resistance and power train efficiency. The

TABLE 3.5 - PERFORMANCE CHARACTERISTICS OF WSC LEADERS

Car	Weight Total kg	Cd	A m^2	CdA m^2	Tire Rolling R. Coeff.Crr1	Power Train Efficiency	Pre-Race Predicted Speed-kph	Actual Race Speed-kph	Computed Speed on 1000w-kph	Computed Power at Race Speed
1 Honda	268	0.10	1.14	0.114	0.0040	95.0%	86	84.96	76.6	1295w
2 Biel	238	0.10	1.10	0.110	0.0056	96.0%	81	78.27	75.9	1077w
3 Kyocera	235	0.127	1.07	0.136	0.0055	86.6%	75	70.76	68.7	1070w
4 Waseda U.	270	0.150	0.80	0.120	0.0055	86.4%	70	70.35	69.9	1018w
5 Aurora	320	0.133	0.75	0.100	0.0055	81.6%	75	70.08	69.3	1024w
Sunraycer (Ref.)	260	0.125	1.08	0.135	0.0066	86.6%	67	66.90	65.7	1042w
6 Toyota	240	0.140	1.00	0.140	0.0060	88.3%	65	64.71	67.3	913w
7 NTU	260	0.12	1.10	0.132	0.0055	94.0%	68	64.34	70.9	799w
8 *U. Pomona	414	0.15	1.30	0.195	0.0050	86.4%	63	63.64	58.3	1218w*
9 Geo Wash. U.	268	0.17	0.70	0.119	0.0060	87.4%	63	63.08	69.5	809w
10 Be-Pal	230	0.15	0.80	0.120	0.0050	84.5%	60	61.96	71.4	717w
11 U. Michigan	296	0.12	1.10	0.132	0.0060	89.3%	65	61.35	66.6	836w
12 Nissan	270	0.11	1.18	0.130	0.0055	88.3%	62	59.85	69.0	727w
13 CSULA	318	0.14	0.96	0.134	0.0055	88.3%	64	59.53	66.8	780w
14 *Stanford U.	392	0.15	1.40	0.210	0.0055	88.3%	50	58.36	57.3	1041w*
15 Philip's Kiwi	260	0.23	0.70	0.161	0.0050	88.3%	55	49.72	66.1	520w

*Two passenger cars. The regulations permit solar cells over the entire car surface, thus the higher panel power.

results are therefore only approximate. However, Table 3.5 can be used to make several pertinent observations:

1. The pre-race predictions by the competitors were very close to the actual race speed, indicating that they had a good prior knowledge of their cars' potential performance.

2. Based upon the computed speed for 1000 watts input to the motor, Biel and Honda were clearly superior to the other entrants.

3. Assuming that the basic performance properties are correct, Honda would still have won the race even if Biel's car had performed perfectly. Surprisingly, the biggest difference in the calculated performance was the reported lower tyre rolling resistance of Honda (C_{rr} = .0040 versus 0.0056). If Biel's tyres had the same tyre rolling resistance as Honda, (C_{rr} = .0040), Biel would have had a lower power requirement than Honda at the same speed. The comparative power at the winning race speed of 84.96 km/hr would be 1220 watts for Biel versus 1295 watts for Honda. Nevertheless, even with Biel's lower power requirement, Honda would still have the faster car. Honda had 7% more available solar power because of their greater solar cell efficiency. Another factor in Honda's favour was that their arch shaped panel intercepts more solar radiation at low sun angles than Biel's flat panel, thus giving a further advantage. The conclusion is that Biel's misfortune (a rubbing wheel skirt) did not decide the outcome, the fastest car still won.

4. The first five cars in the 1993 World Solar Challenge broke the old record of 66.90 km/hr set by the GM Sunraycer in 1987. Although the Sunraycer, for a pioneer solar car, was remarkably sophisticated, it did not establish the previous record solely because of its excellent aerodynamics, low weight or high power train efficiency. Although the Sunraycer had a superb overall car design, technology has progressed since then. In 1993, most of the cars in the top 15 cars were better than the Sunraycer in many ways, they had superior aerodynamics, a higher drive train efficiency and better tyre rolling resistance, while maintaining about the same weight and yet only five of them went faster. A major factor in the Sunraycer's record speed was the high power output of their gallium-arsenide solar panel. Until 1993, none of the entrants were able to match the 19% solar cell efficiency and the Sunraycer's 1100 watt average panel power (1500 watt peak at high noon). In 1993, both Honda and Biel succeeded in building more powerful arrays than the Sunraycer by using recently developed, highly efficient monocrystalline silicon solar cells.

The most important single factor in achieving high speeds is high power output [1]. With better solar cells, delivering 1100 watts of average panel power, probably nine more cars could also have broken the old Sunraycer record, i.e. places 6 through 13, Toyota, NTU, Cal Poly Pomona, George Washington University, Be-Pal, the University of Michigan, Nissan and Cal State Los Angeles. It is likely that in the 1996 WSC, the top 20 cars will exceed this speed.

There is no longer any mystery about how to do it, it is just a matter of whether 19% to 21% efficient solar cells are more affordable by 1996.

5. One innovative car, fifth place Aurora, deserves special comment. The body shape was pioneered by MIT and the University of Waterloo in the 1990 USA Sunrayce. It is basically a rectangular thin wing section with a gently curved solar panel that completely surrounds the cockpit canopy, placing the driver in the centre of the car. The body is short, compact and has a very low frontal area and wetted surface area. The Aurora team added several improvements to this tricycle design. They put the two outer wheels at about the midpoint of the car with the centre wheel forward. It was only necessary to steer the forward wheel, thus simplifying the steering linkage. The Aurora team mounted the wheels to a rigid sub-frame to preserve the orientation between the wheels. The upper chassis was isolated from the sub-frame with a complete suspension. Even though the car was heavy (320 kg including the driver), and the efficiency of the power train was low (81.6%), the Aurora had a higher speed potential than any other car in the race with the exception of Honda and Biel. If the power train efficiency had been equal to Kyocera for example (86.6% instead of 81.6%) the Aurora could have averaged about 3 km/hr faster and easily placed third. The team reported that as built, the car was unstable both in cornering and in unsteady winds. However, improvements in this body design will no doubt be popular in future solar car races.

...CRK

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Figure Captions.

Chapter 3, End Photo
The fifth place Aurora from Australia had several unique features. The wing shaped body placed the driver in the center of the car with the solar panel surrounding the canopy. This arrangement is compact, has a low frontal area and surface area and could be very light weight. The center tricycle wheel was forward. To maintain the orientation of the wheels, they were rigidly mounted to a triangular sub-frame. The car chassis was shock isolated from this frame with a full suspension. The batteries were a combination of lead-acid and non-rechargeable lithium. Variations of this body style should be more popular in future solar car races.

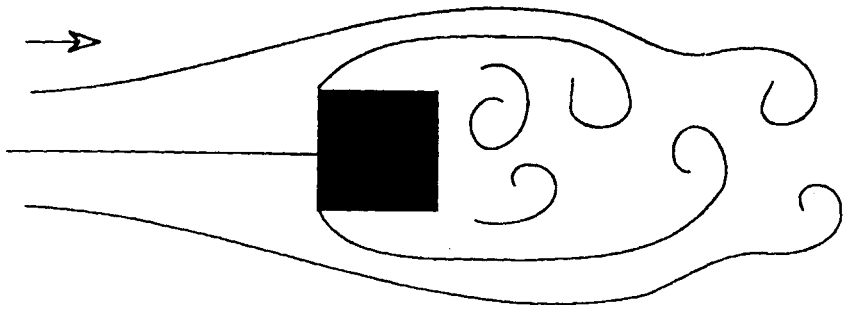
Chapter 4.

Aerodynamics

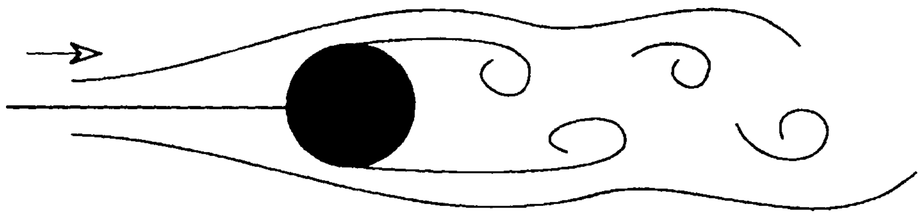
4.1 Introduction

Because internal combustion race cars have enormous power, sometimes more than 1000 horsepower (746 kw), low air drag is often a minor concern. Formula race cars almost always have poor aerodynamic shapes from a drag point of view. Aero-design in race cars is usually applied to other things such as traction, stability, and cooling. On the other hand, winning solar cars, must travel at 80 km/hr (50 mph) on about 1.3 horsepower (1 kw). This is less energy than consumed by a hair dryer, a motorized lawn mower or most microwave ovens. To attain such incredible efficiency, solar car designers, must refine all systems that consume energy, but above all, they must achieve extremely low aerodynamic drag.

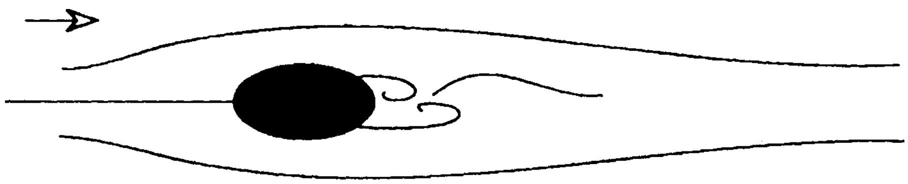
The 1993 World Solar Challenge (WSC) was unique in that some of the cars had the lowest operating aerodynamic drag coefficient of any land vehicle on record. The drag coefficient is a measure of the resistance that a body of a given frontal area experiences when moving through a fluid such as air or water; the lower the number, the lower the resistance (Equation 1 in Chapter 3). See Figure 4.1 for the drag coefficient of typical shapes. Cylinders have a drag coefficient of about 1.2, while wing shapes can have drag coefficients less than 0.1. For equal cross sections, it takes more than 10 times the energy to move a cylinder through the air than it does a wing. The best passenger cars to date have drag coefficients between 0.2 and 0.3. World record Bonneville streamliners have attained drag coefficients between 0.1 and 0.15. The top two competitors in the WSC, Honda and Biel, had drag coefficients of 0.1 or less as determined from actual road performance. Nevertheless, even with such efficient shapes, at 80 km/hr on level ground, aerodynamic drag is still 75% of the total retarding force (rolling resistance is the other 25%). Therefore, low aerodynamic drag will always remain a critical concern in racing solar car design.



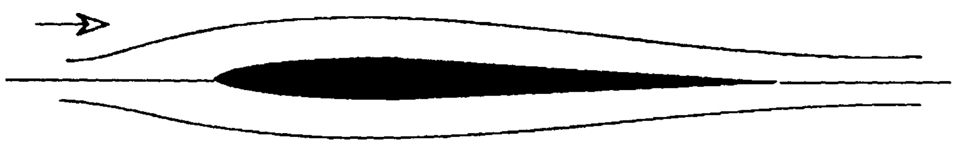
Shapes with sharp edges have a very high drag. Air separates at the corners, creating a larger effective profile area. All edges should be rounded to avoid unnecessary friction. By putting a radius about 0.2 times the height on the corners of this box shaped cylinder, the drag can be lowered from Cd = 2.0, to Cd = 1.3 [2]



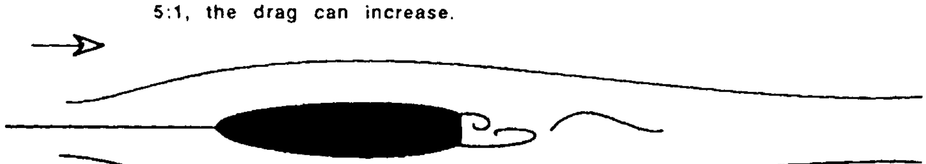
Cylinders are not much better than a box with rounded corners. Air separates from a circular cylinder and leaves a turbulent wake with a low pressure region in the rear of the cylinder. The pressure difference between the front and back creates a high drag. Cd = 1.2



A two to one ellipse (width to height ratio) has a lower drag than a cylinder, but not as low as a cut off airfoil section (below). Cd = 0.6. A 4/1 ellipse has a Cd = 0.35, and an 8/1 ellipse has a Cd = 0.25. For the drag of other shapes see S. Hoerner [2].



Air flows smoothly around a streamlined airfoil without turbulence. Cd = 0.1 or less. A wing shape takes less than one tenth the energy to move through the air as a cylinder and less than one twentieth that of a box shape. The width-to-thickness ratio of the airfoil should be between 3.5:1 and 5:1 (chord to thickness ratio). Beyond 5:1, the drag can increase.



When the rear of an airfoil is cut off, the drag increases because of the higher base drag due to turbulence at the rear. Cd = 0.3

FIGURE 4.1

4.2 How to Lower Aerodynamic Drag

The six most common ways of achieving low aerodynamic drag have been summarized previously [1]. A review of these methods, as applied to the 1993 WSC competitors, would be valuable.

1. Streamlining

Most of the shapes we are familiar with are not efficient aerodynamically. Cylinders, boxes and even ovals are examples of poor shapes (Figure 4.1). Bluff bodies, because of air separation, generate low pressure cavities on the trailing surfaces which create high drag. They waste energy in turbulent mixing. Streamlining allows air to flow smoothly over a body without separation, lowering the differential pressure between the leading and trailing surfaces and thus dramatically decreasing the drag. By simply rounding the corners of a box for example, the drag can be cut by more than 30%, or by turning the box into a 2/1 ellipse, the drag can be lowered by 70%. Streamlined shapes can cut the drag of a box by more than 95%.

Unfortunately, although they are efficient, streamlined forms are complicated and expensive to manufacture, whereas rectangular or cylindrical sections are quite simple. In building a solar car, it is tempting to use simple shapes that are exposed to airflow, but the result is invariably poor performance. Poor aero shapes were quite common in the lower 2/3 of the field in the World Solar Challenge Uncovered wheels, exposed mirrors, vertical antennas, sharp edges, flat surfaces facing the wind and unstreamlined supports were frequent offenders. Simple modifications (such as using a horizontal antenna or constructing a simple cardboard fairing to cover a box strut) would improve most of the obvious problems. However, a mixed combination of streamlined shapes would still have a relatively high drag. It requires a simple unified body shape to achieve low air drag.

All of the cars in the top 10 were superbly streamlined, with the occasional exception of the wheels. Wheels with exposed spokes have a very high drag. Adding disk wheel covers will smooth the airflow around the wheel and lower the drag by two thirds. However, wheels, even if covered by disks, are inferior airfoil sections. Lower air drag can be obtained by covering the wheel and the suspension parts with a streamlined fairing (wheel spat). By using spats, the drag of exposed disk wheels, brakes and suspension parts can be cut at least in half. See Figure 4.2 for photos of well designed wheel fairings. Even if the wheels are completely covered by a fairing, wheel disks are necessary to avoid rotational turbulence and pumping unwanted air into the wheel well.

Streamlined cockpit covers or canopies are probably the most difficult component to produce since they must be optically clear. They are usually thermally blown, drape formed or molded of acrylic, plexiglass or some other clear plastic. It takes extreme care to mold or vacuum form a canopy without destroying its visual clarity.

Because efficient aero canopies have long axial chord sections, they can encroach into the solar cell area. For this reason teams sometimes turn the airfoil teardrop around backwards (the pointed section becomes the leading edge) to permit more solar cell area. This is a poor strategy. The additional drag caused by separation on the rear of the canopy is seldom compensated for by the increase in solar cell output. A better tactic is to decrease the canopy size to a minimum and maintain the correct orientation with the rounded end forward (e.g. Biel).

2. Lowering the frontal area.

Given an identical shape and orientation, a lower frontal area will produce less wind resistance. It is better for example to position a license plate parallel to the wind like a wing rather than perpendicular to the wind like an oar, and obviously, a smaller plate will produce a lower drag. In a like manner, exposed radio antennas should be as small as practical and either oriented parallel to the wind or integrated into a surface or edge. A solar car can improve its WSC finish time by 1/2 hour by eliminating such a simple thing as a streamlined rear view mirror [1]. Fibre optic systems, a TV monitor or a canopy with an enclosed rear view mirror are some of the devices used to obtain rear vision without adding air drag due to an exposed mirror.

The frontal area of a solar car is determined by the shape of the body and chassis. The frontal area of typical solar cars can range between about 0.7 m^2 to 1.7 m^2. Of the top six cars in 1993, the frontal area varied from a low of 0.75 m^2 (8.1 ft^2) for Aurora, to a high of about 1.1 m^2 (11.8 ft^2) for Honda, Biel and Kyocera. The frontal area of the winning cars has not changed significantly since the World Solar Challenge began in 1987, it was 1.1 m^2 for the Sunraycer in 1987, 1.1 m^2 for Biel in 1990, and 1.1 m^2 for Honda in 1993. The drag coefficient of the leading cars, however, has continually improved.

The total wind resistance is determined by the product of the drag coefficient and frontal area C_dA (the drag area). Within a reasonable range, any combination of drag coefficient and frontal area can produce an identical wind resistance. Using the data reported by each team, Aurora (C_dA = 0.10 m^2) , Biel (0.110 m^2), and Honda (0.114 m^2) respectively had the lowest drag areas followed by Waseda (0.119 m^2), Kyocera (0.136 m^2), and Toyota (0.140 m^2). Considering their race performance and other factors, this ranking seems reasonable. The drag area of the GM Sunraycer in 1987 was 0.135 m^2.

3. Smoothing Surfaces

Several competitors reported that by polishing the surface of the car they improved the speed. Sometimes decals placed on the surface of a car, cause turbulence by tripping the boundary layer, destroying laminar flow and raising the drag. Any logos or decals should be painted on, feathered and polished. Any protrusions, uneven surfaces, cavities, bolts, rough edges, gaps or other breaks in the contour should be eliminated since they will disrupt the airflow. Transition fillets should be used where one shape such as a wheel spat joins another.

4. Simplifying Body Contours — Solar Car Shapes

It is remarkable that, after six years of solar car racing under the same rules, there is such a wild variety of solar car shapes competing in the World Solar Challenge. Apparently, many designers are not convinced that an optimum body design exists. One fact is clear however: since the World Solar Challenge began in 1987, complex shapes have not won races.

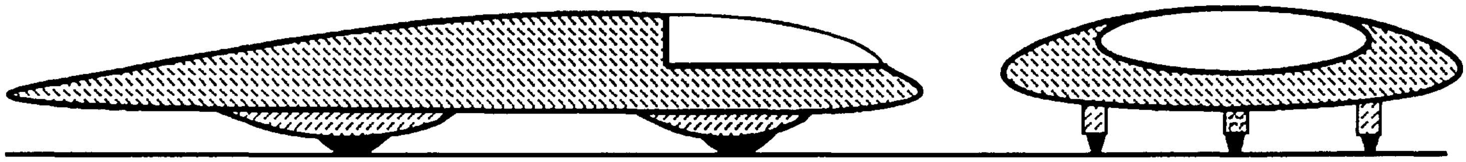
Figures 4.3, 4.4, 4.5, and 4.6 illustrate this point. Body styles fall into three general categories. A unified aero body with all of the components enclosed in a streamlined shell represented the most common type with 28 cars (Figure 4.3). Vehicles with separate cab and solar panels and outboard front wheels was the second most popular configuration with 17 cars (Figure 4.4). The third and least common general type were tunnel shaped catamaran cars with the wheels inside outriggers (4 cars - Figure 4.5). Three other cars which were difficult to classify are shown in Figure 4.6 The top 10 cars in 1993 all employed simple, unified aerodynamic bodies with the wheels and components enclosed within the body structure (Figure 4.3).

Complex multi-element surfaces have a higher wind resistance than smooth continuous curves. Complicated forms cause interference and parasitic drag since flow over one surface can adversely affect the flow over another [2]. The simplest aerodynamic shapes would be bodies of revolution such as torpedoes or tear drops and they have the lowest drag coefficients ever measured (about $C_d = 0.02$). However they are not practical for solar cars mainly because there is little surface area to install solar cells on. A solar car chassis must be a compromise which balances the influence of all of the performance factors such as solar cell exposure, safety, and stability as well as wind resistance.

FIGURE 4.3 - UNIFIED AERO BODY CARS - 28 VEHICLES

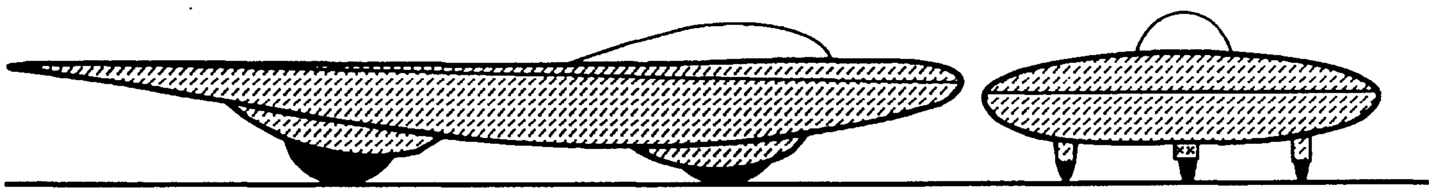
3A WING SHAPE - THREE AND FOUR WHEELS (3W, 4W)

Thirteen Cars: 1st **Honda** - 3W; 3rd **Kyocera** - 3W; 6th **Toyota** - 4W; 7th **NTU** - 3W; 17th **Sofix** - 3W; 18th **Tokai U.** - 4W; 27th **Solar Flair** - 3W; 29th **Alarus (Two Passenger, side panels)*** - 3W; 32nd **Sulis IV** - 3W; 42nd **SDSU** - 4W; 45th **Villanova U. (side panels)*** - 3W; 48th **Hama Yumeka** - 4W; 40th **UW Ontario** - 3W (Ontario has two small vertical side panels that tilt up and down for more solar exposure).



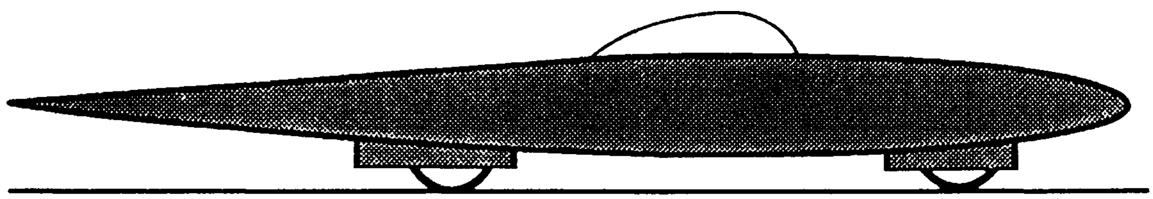
3B WING SHAPE WITH FORWARD CANOPY

Eleven Cars: 2nd **Biel**- 3W; 4th **Waseda U.** - 3W; 9th **George Wash. U.** - 3W**; 10th **Be-Pal** - 3W; 12th **Nissan** - 3W; 21st **Mino Family**- 3W; 23rd **Denmark Tech.** - 3W; 25th **Dripstone HS** - 4W; 26th **Hosokawa (side panels)*** - 3W; 28th **KIA** - 4W; 30th **Annesley College** - 3W



3C WING SHAPE WITH CENTRAL CANOPY- SOLAR ARRAY SURROUNDS CANOPY

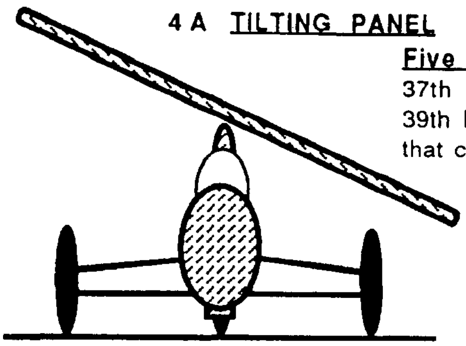
Four Cars: 5th **Aurora** - 3W (1 wheel forward)**; 8th **U. Pomona** (two passenger) - 3W**; 13th **Cal. State U. LA** (side Panels)* - 3W; 22nd **U of Oklahoma** (side Panels)* - 3W



* Side solar panels were used by some cars.
**Others employed one or two auxiliary solar panels underneath which could be deployed for stationary charging.

FIGURE 4.4 - SEPARATE CAB AND PANEL CARS - 17 VEHICLES

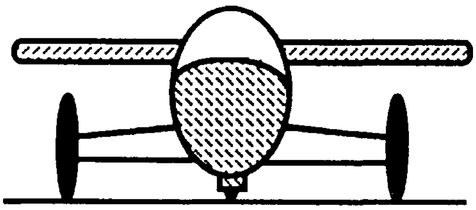
4 A TILTING PANEL



Five Cars: 15th **Philip's Kiwi - 3W**; 36th **Morphett Vale HS** - 4W; 37th **Puerto Rico** - **3W**; 43rd **Northern Territories TAFE** - **3W**; 39th **Le Soliel - 3W.** This car had a flat central panel with two small side panels that could be tipped vertically up or down to increase the solar exposure.

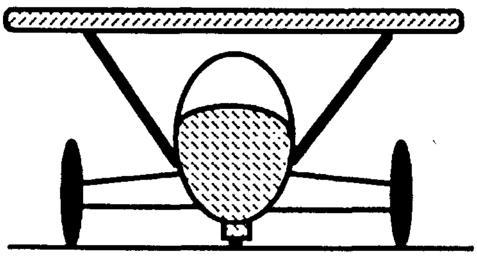
4 B FIXED PANEL

Eight Cars: 16th **Mabuchi (panel surrounds canopy)** - 3W; 20th **Evolution** - 4W; 24th **Ashiya** U. - 3W; 33rd **Solaemon-Go** - 4W; 41st **TR 50** - 3W; 49th **Heliox** - 3W; 50th **Heliodet** - **3W**; 51st **Team Moscow** - **3W**



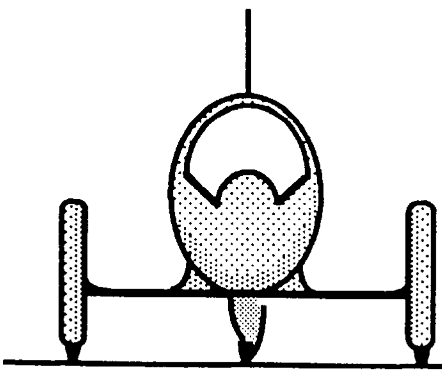
4 C FIXED PANEL OVER CAB

Three Cars: 44th **Meadowbank TAFE (two passenger) - 3W**; 46th **Japan Christian Junior College - 3W**; 52nd **Holy Cheat - 3W**



4 D TORPEDO SHAPED CAB, SMALL EXTERNAL SIDE PANELS

One Car: 38th **Team New England - 3W**
New England carried two rolled up solar arrays inside which could be deployed as required for stationary charging. The idea was to travel very fast, then stop periodically to charge the batteries. The tactic was not successful.



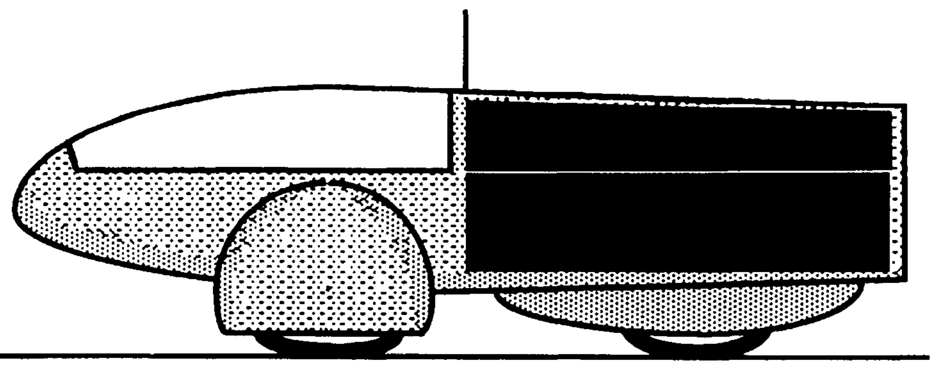
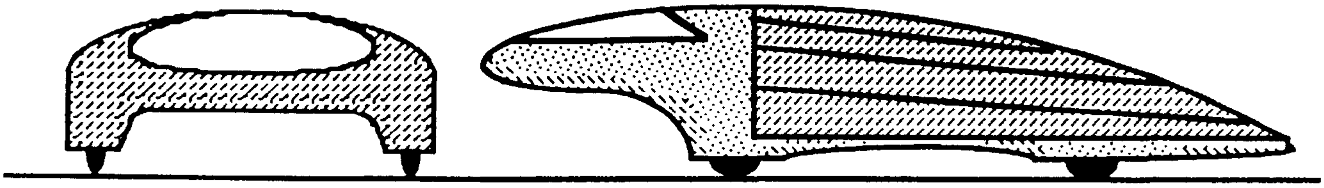
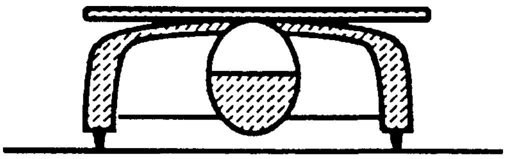


FIGURE 4.5 - CATAMARAN TYPE CARS - 4 VEHICLES



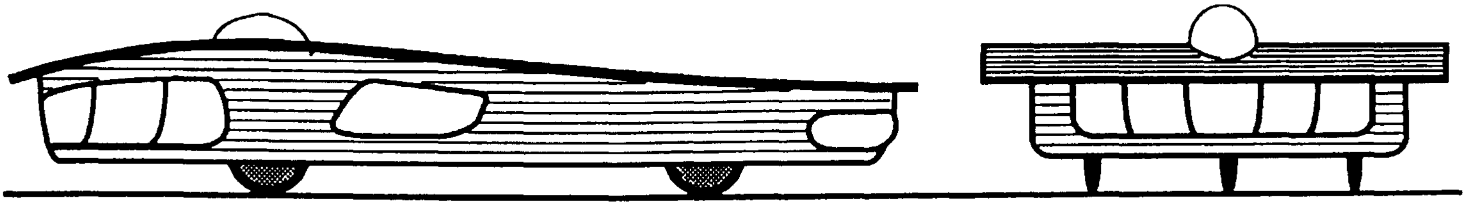
5A ARCH SHAPE WITH WRAP AROUND SOLAR PANEL
11th- **Univ. of Michigan - 4W**

5B Outrigger Type (Top and Side Panels)
19th- **Monash Univ. - 3W**
35th- **Mitchum HS - 3W**



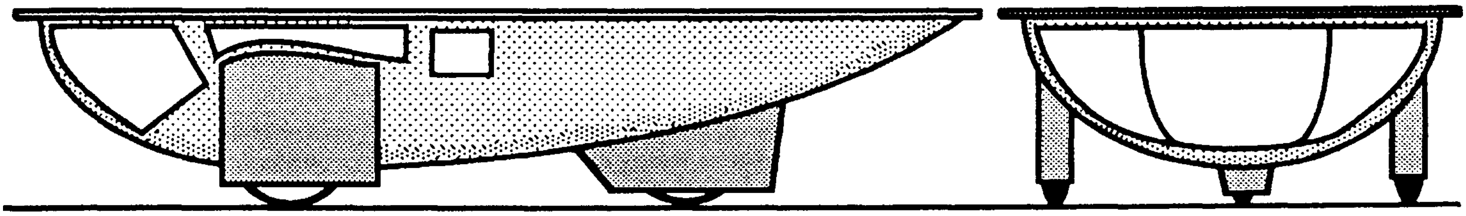
5C Central Pod, Top and Side Panels
34th- **Mainichi-Go - 4W**

FIGURE 4.6 - OTHER SHAPES



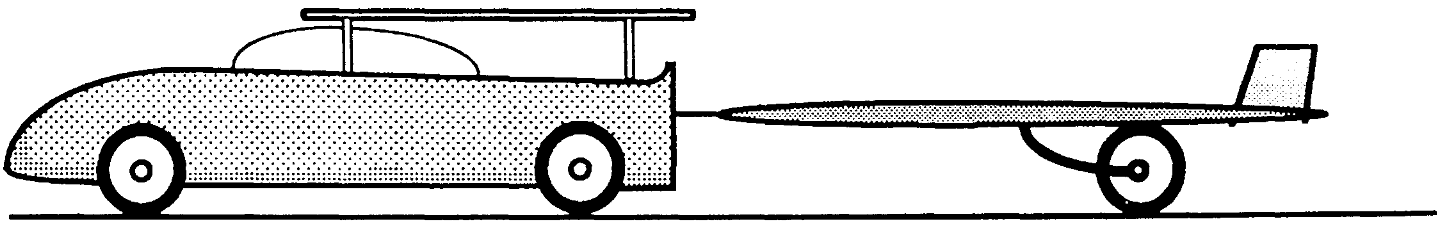
14th - **Stanford University (Two Passenger) - 3W**

The unusual wave shape of Stanford's solar panel was intended to minimize the drag of the body/panel combination. However, in cross winds, the shape proved to be a handicap. For two passenger cars WSC rules permit the whole vehicle length to be covered with solar cells, thus giving a higher potential power than for single passenger machines. Because of this rule, a properly designed two passenger solar car could probably win the World Solar Challenge. However, so far, two passenger cars have not seriously challenged single versions. The highest finish for a two passenger vehicle was 8th place for Crowder College in 1990 and 8th place for California Polytechnic University at Pomona in 1993.



47th - **Banana Enterprise, Brazil (Two Passenger) - 3W**

Similar in concept to Stanford, Eduardo Bomeisel's two passenger Banana Enterprise had electrical problems and was forced to abandon the race.



31st - **Phoenix, Hokuriku Electric Power Company - 4W**

The Phoenix participated unofficially as a demonstration vehicle with two solar panels, one over the cab and one on a trailer. The car included many of the features of a standard automobile and it crossed Australia successfully using only solar energy. The Phoenix was only 50 km short of the finish on the final day of competition, averaging 33.56 kph.

Many of the body types could be approaching the status of endangered species. For example, tilting panel cars finished in the top 10 in 1987 and 1990. Ford placed 2nd in 1987 and AERL was 6th in 1990. In 1993, Stewart Lister's Solar Kiwi achieved the same speed as AERL did in 1990 (50 km/hr), but the intense competition held Kiwi to 15th in 1993. Both the Solar Kiwi and AERL were superior in design and construction, but this type of vehicle is becoming less competitive. Admittedly the idea of a tilting panel is certainly attractive. A solar array that tracks the sun can generate at least 10% more power than a horizontal panel with the same area. However, the higher aerodynamic drag, plus an inherent instability in cross winds, are drawbacks that could phase this car out of existence. Stewart Lister commented that his car was so unstable at speeds exceeding 70km/hr (especially in cross winds) that they often had to reduce speed for safety.

However, there is an additional very important factor. Separate panel and cab cars such as those in Figures 4.4A, 4.4B and 4.4C are simple and economic to build. The primary objective of any race team should be to achieve the highest possible speed with the funds and resources available. In this regard, the Solar Kiwi was probably the most successful car in the race. Vehicles that finished ahead of the Kiwi cost from 5 to more than 100 times as much and the teams were larger and had greater resources. Because of economics and simplicity, teams with a limited budget may still choose the separate cab and panel concept.

One question is often asked: what sort of ground clearance is necessary in a solar car? The answer comes from observing functional streamlined race vehicles. Cars can be built with almost no ground clearance and still have a very low drag. Streamlined human powered vehicles have exceeded 100 km/hr with only one or two centimetres (0.5 inches) of ground clearance. The underbodies are perfectly flat and permit almost no air to flow underneath, (air velocity is with respect to the car as in a wind tunnel). Considering the road conditions in the World Solar Challenge (leaving or entering the road can be bumpy), some reasonable ground clearance, perhaps 15 cm, is absolutely necessary to avoid chassis damage. Once the body is raised off the ground, high speed air flows underneath, so it is necessary to carefully streamline the undercarriage to achieve minimum wind resistance. Bodies that allow air underneath can also have a very low drag.

Two devices used on passenger cars, air dams on the front and spoilers on the rear, are often suggested as methods of lowering air drag. These devices are only effective with poorly streamlined bodies and are not applicable to well designed solar cars. Since passenger automobiles are seldom streamlined underneath, air dams which block air flow from the underbody can often lower the drag. However, this is not the case with a solar car. An air dam would act like a drag brake and create havoc with smooth airflow.

Rear spoilers have another function. Typically, an automobile has a cut off flat tail section. A spoiler creates a trapped vortex in the rear which raises the base pressure thus lowering the drag. However, even with a spoiler, a cut off airfoil will have from 20 to 30% higher drag than an airfoil which tapers gradually to a sharp trailing edge. Aircraft technology applies to solar car body design more than does standard automobile technology.

Another common and closely related question is what kind of body shape will have the minimum drag in the presence of the ground? The answer is not clear and it does not become too much clearer with computer analysis. Expensive computer computational fluid dynamics can predict lift and drag on car bodies with a ground plane. The computations are extremely complex, and their accuracy on arbitrary body profiles can be poor without first calibrating the computer code with experimental wind tunnel data (using a family of similar profiles). Also, such programs, besides being costly, are available to only a few. What generally happens with computational methods is the designer selects a profile, analyses it, modifies the profile and analyses it again. It is an iterative process — computer programs do not do synthesis very well, this is still the province of the designer. In other words, there is still a lot of art in efficient body design.

In place of computer analysis, a more empirical method is used by most solar car designers. Teams can select known efficient airfoil shapes such as the NACA 66000 series and by using bodies of revolution, elliptical cross sections, radiuses and fillets, they can construct a smooth body shape that will have a very low air drag [3]. One design objective is to create a zero lift body for minimum drag. Lift deflects air and causes induced drag. Wind tunnel experimentation with models can be used to refine body shapes. Judging from the variety of wind tunnel tested body styles that were successful in the World Solar Challenge, an optimum profile remains to be found just as most designers suspected.

5. Controlling Ventilation

Outside air that enters the car causes an unavoidable retarding force. Any air mass taken into the car must be accelerated from zero to car speed, and the inertial reaction acts like a braking force. However, if the air is accelerated efficiently through a diffuser such as an NACA intake vent, and exhausted through an efficient nozzle, the drag from ventilation can be minimized.

Uncontrolled air circulation can cause huge power losses. Typical air flow rates for cockpit cooling would be 0.028 m^3 per second (1 ft^3/sec). If no energy were recovered from this air at 80 km/hr, 17 watts of power would be lost. Actually losses could be from 10 to 20 times higher if ventilation is uncontrolled. For example, open wheel wells, or a cockpit open to the air could cause high losses.

Biel realized a 5% to 7% air drag reduction by taping the seams of their body shell plus other improvements. See Figure 4.7. This represents a 50 watt power gain. Northern Territory University improved their speed on the final day by about 1 to 2 km/hr by taping over their air inlet, when cockpit ventilation was not so important in the cooler climate near Adelaide. This represented a 4% to 7% overall drag reduction.

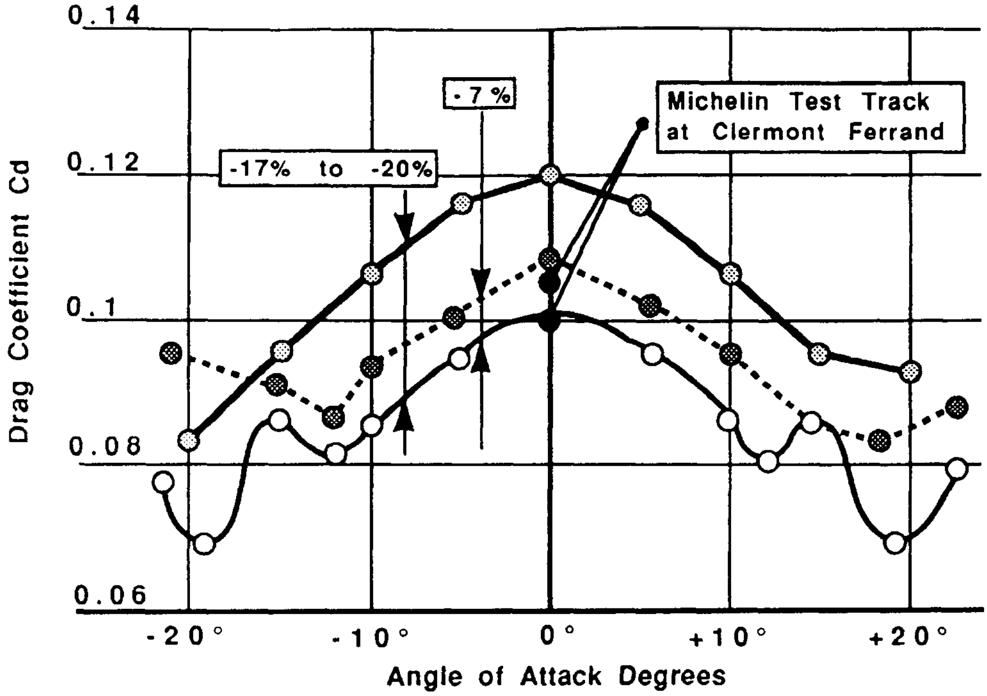
The best ventilation control was demonstrated by the top cars. They used carefully regulated cooling and exhaust air, and painstakingly sealed the wheel wells and seams. Wheel wells can be the biggest source of unplanned ventilation. Figure 4.8 shows photos of the wheel well construction of Honda, Biel and Kyocera. The wheels are completely covered and isolated from the rest of the car. To seal the front wheels, a circular rotating seal plate, with a slot for the wheel, allows turning without disturbing the body contour or exposing the interior to unwanted flow. It also permits a wheel spat with minimum frontal area.

6. Minimizing the Effect of Winds

Cross winds can actually decrease the drag of solar cars. Obviously, a design that benefits from side winds could have a real advantage over one that doesn't. This effect can be determined through wind tunnel tests. Figure 4.7 shows the results of full scale wind tunnel and field tests for three versions of the Biel car. As the effective wind angle increases (angle of attack), the drag decreases until about 20°. The wheel fairings, body and the canopy act like vertical wings or sails and develop a side force which has a forward thrust component. The result is that the drag declines until stall conditions occur (flow separates from the airfoils), then the drag will increase again. The curve for the Spirit of Biel III shows a strange peak around 15° angle of attack. This probably means that different aero components such as the canopy, the shark fin or the wheel fairings stall at different points, combining to produce the bump in the drag curve.

Winds can also produce vertical lift as well as lateral and longitudinal forces. As mentioned in Chapter 2, the solar Kiwi, a tilting panel car, was hit by a Willy Willy (a whirl wind), lifted off the ground and carried into the bush. Tear drop body shapes experience much lower side

FIGURE 4.7 - THE SPIRIT OF BIEL III, 1993,
WIND TUNNEL TESTS AND ROAD POWER TESTS



1990 Spirit of Biel II, Wind tunnel Test.

1993 Spirit of Biel III, Wind Tunnel Test, before Improvements.

1993 Spirit of Biel III, Wind Tunnel Test, after Improvements.
As the angle of attack increases, the wheel fairings and body develop horizontal lift. A forward component of lift causes the drag to decrease.

Track Tests, Spirit of Biel III, before and after improvements.

forces in cross winds than do cab and panel cars and although there were no reported accidents cause by wind among cars with the unified body style (Figure 4.3), this type of car still can swerve when a side gust hits it.

Honda reports that their 1990 car moved into the wind in a side wind and was more stable than the 1993 car which moves away from the wind. With the new wheel spats, the centre of pressure moves forward in a side wind, causing some instability. They reported that the rear of the car moved and the path followed could vary about 1 meter in a 10 meter/sec variable side wind. Honda said the worse case was a strong side wind from the right. A passing road train creates a wind shadow and the car tended to swerve toward the truck. Takahiro Iwata of Honda thinks that a 4 wheeled car may be necessary to assure stability under all wind conditions.

Approaching Adelaide, near Port Pirie, head winds often slowed Solar cars down due to added wind resistance. The effect of head winds can be minimized by having a car with low aerodynamic drag and one that can utilize cross winds for some added thrust.

4.3 Measuring Aerodynamic Drag

Biel used two ways of determining the aerodynamic drag of their car. In the first method, they performed full scale wind tunnel tests. Full scale tests using the actual car are preferable to scale model tests since the models cannot reproduce all of the details of the finished car. In the second method, Biel drove laps around a test track, at constant power, at the Michelin proving ground in Clermont Ferrand, France. The Michelin track is circular and 7.78 km in circumference. With 1200 watts of power, Biel achieved an average speed of 82.1 km/hr and with 800 watts their speed was 68 km/hr. Corrected for the rolling resistance, these track tests almost exactly duplicated the wind tunnel data (see Figure 4.7). On the track, Biel was able to test the effect of different tyres, tyre pressure, power versus speed, taping the seams etc.

Toshiaki Tsuchiya of the Kyocera Corporation tested several 1/5 scale models in the wind tunnel. See Appendix E. As a result of these tests they settled on their final design. In modifying models for wind tunnel tests, it is difficult to achieve accuracy and realistic surfaces, so some of the drag coefficients that Kyocera obtained are unreasonably high. However, the final version of the Kyocera car performed amazingly well. It was wind tunnel tested full scale and had a drag coefficient of 0.125 with a frontal area of 1.05 m^2.

A final method was used by some teams. Coasting a car on a level road with no wind, with the drive train disconnected, while recording the speed versus time, permits the calculation of deceleration. Knowing the car mass and the acceleration, the drag can then be determined from Newton's laws of motion. The problem is finding a level road without passing traffic and without wind. Carefully done, the accuracy of coast-down tests is about ±2% to ±5%. A variation of this option is to use hill coasting tests to measure the terminal velocity on a known slope. This method has the same problems as coast down tests with some added difficulties. Grades are seldom constant and any slight change in the initial speed, the wind or passing traffic will alter the point at which terminal velocity is reached thus producing questionable data. With either method it is hard to accomplish repeatable results that are accurate enough to isolate the effect of small changes in design. Wind tunnel tests are more accurate, but also more expensive.

...CRK

References:

1. Kyle, C.R., *Racing with the Sun*. Society of Automotive Engineers, 1991.

2. Hoerner, S.F., *Fluid Dynamic Drag*. Hoerner Fluid Dynamics, 7528 Straunton Place N.W., Albuquerque, NM 87120. 1965.

3. Abbott, I.H. & A.E. von Doenhoff, *The Theory of Wing Sections*. Dover Publications, 1959.

Photo Captions:

Chapter 4, Lead Photo
Honda (top) and Biel (bottom), recorded the lowest drag coefficients in history for streamlined land vehicles (Cd < 0.1). The best drag coefficients achieved to date by world record streamliners are between Cd = 0.1 and Cd = 0.15. Solar cars don't air for combustion or cooling and this gives them an aerodynamic advantage over internal combustion race cars. The streamlined fin on Biel's canopy is to satisfy the WSC one meter height requirement. Notice the smoothly streamlined undercarriage and wheel fairings of Honda and Biel. Solar car aerodynamics owes more to the technology of aircraft than to automobiles.

Figure 4.2 - The front wheel fairing of Honda (top) and the rear wheel fairing of Biel (bottom) smooth the airflow around the disk wheels, cutting the air drag of the wheel by about 50%. Both Honda's and Biel's front fairings swivel with the wheel and the top of the trailing edge seals against the bottom pan. When the total car weight is applied, the front wheel retracts deeper into the wheel fairing.

Figure 4.8 - The interior of the front wheel wells of Honda (top left) and Biel (top right). A slotted circular disk rotates with the wheel and is flush with the bottom pan. Biel encases the front wheel with a small cover which seals it from the car interior. Honda uses a larger cover which encloses the entire wheel well (bottom left) The rear wheel cover of Kyocera (bottom right) seals the rear wheel chamber. Isolating the wheel wells from the rest of the car, prevents unwanted air circulation which raises the drag.

Chapter 5

Body Architecture, Materials, Construction.

For many solar cars, the distinction between chassis and body is as blurred as it has become in a conventional passenger car. However, we can assume at least a conceptual separation of their functions. The tasks required of the chassis are entirely structural - the support of static and dynamic loads under stationary, moving and accident conditions. The body's role is less easily defined, as some functions may be performed by the body or chassis, but is generally to provide minor load-bearing capability, some safety functions, an environment for passenger(s) and to create whatever aerodynamic behaviour is required.

The static loads on the chassis are relatively simple, arising from the weight of the various items carried in or by the chassis. These include the driver, batteries, electronics, motor, solar array and body. In modeling the chassis, these weights are assumed to be fixed forces acting at specific node points.

The dynamic loads on the chassis derive from a number of different sources. The main ones arise from surface irregularities, acceleration and deceleration loads from the driving and braking wheels, and cornering forces. (For the 1987 GM *Sunraycer* [1], the designers assumed maximum values for these loads of 4.0 g bump, 2.0 g twist, 1.0 g cornering, and 1.0 g braking.) The careful springing and damping of the suspension is critical in keeping these loads to a minimum. Aerodynamic loads on the body (hopefully small, especially in a vehicle designed to have low drag) are also transferred to the chassis. Another possible source of dynamic loads - hopefully never to be experienced - is a crash. For the Sunrayce USA, teams are required to demonstrate either through modeling or crash testing that their vehicle has been adequately designed with the safety of the driver in mind. There are a number of papers [2 - 4] on vehicle construction for the 1990 Sunrayce USA which describe how some teams approached this issue. **Figure 5.1.**

The chassis needs to be as light as possible while having adequate levels of stiffness, strength and fatigue life, and providing the various practical features such as adequate interior space and access. It is essential that the wheels are always maintained in the correct relationship to each other. This requires both strength (to resist transient loads without breaking) and stiffness (to resist these same loads without allowing so much flexure as to deny the suspension its proper role). A four-wheel vehicle may need a chassis with significantly higher torsional stiffness than that for a three-wheel car. The chassis is also responsible at some level for keeping the body in its correct shape, so that the optimum airflow can be maintained. Finally, the chassis must survive many thousands of kilometres of varied road conditions, usually with somewhat stiff spring and damper rates (which are required to ensure that the vehicle maintains its correct angle of attack and relationship to the ground), and so fatigue life is also important.

The chassis/body unit must not only be able to carry the predictable loads, but it must also be able to exist in the real world, where people grab it, fall on it, spill things on it, etc. During the race, there a is need to access components quickly for service; being able to do so without risking damage to the vehicle is a very important requirement. In a space-frame chassis, for example, the ultimate level of performance is achieved when the tube diameter is a maximum and the wall thickness is a minimum. In extreme cases this could result in 50 mm diameter tubes with walls less than 250 microns thick [1]. Not only is such a structure very difficult to weld (though it could be bonded) but it is also extremely vulnerable to being crushed by a careless hand.

There are a variety of chassis philosophies, and virtually all of these were represented in one form or another in the 1993 World Solar Challenge. They range from the minimalist, open frame chassis approach, through simple, space-frame construction with totally separate and largely non load-bearing body panels, through the ladder frame chassis and the "tub" style, to the totally integrated monocoque philosophy. By far the three most popular methods of construction were the space-frame chassis of tubular alloy members with a separate, usually composite body, the composite "tub" style (again with separate body), and the monocoque.

A number of vehicles which looked very similar from the outside had actually taken totally different structural approaches. For example, *Solvogn Danmark* was a stainless steel space frame construction, but appeared similar to *Sunforce I*, a tub/monocoque design utilizing carbon/honeycomb sandwich construction. The decision on whether to use a space-frame, tub or full monocoque depends in part on the relative emphasis placed by the team on the different areas such as cost, repairability, crash worthiness, stiffness, accessibility, construction feasibility etc., and in part on the previous experience of the team with the different construction styles and materials.

5.1 Space-Frame Structures

The alloy space-frame chassis has the advantage of being well understood and easy to model mathematically. It is also fairly fast and simple to construct, can be quickly modified, and can similarly be speedily repaired (though this is dependent on exact choice of alloy). Structural failures, or impending failures, are often easy to recognize - manifesting themselves as obvious cracks or bends. Failures in sandwich and composite structures, on the other hand, are usually much harder to detect, as they are not always visible.

One major advantage of the space frame (and also some "tub" type structures) is that the vehicle can be tested in various stages of completion - as a raw chassis and suspension towed behind a support vehicle, for example, then in stages as the various sub-assemblies are added. The development of the chassis and related components can also progress even when only a vague idea of what the eventual body shape will be is known. **Figure 5.2.**

A true space-frame uses materials efficiently by placing very thin, light members purely in tension and compression. To take full advantage of this, great care is required in the early planning stages of a vehicle to ensure that all load inputs are carefully taken into account, and fed into appropriate nodes. Where this is not possible, and a load has to act at a point not at a node, that member experiences an additional bending stress. This immediately compromises the space-frame, and the member has to be "beefed up" to support the additional weight in its centre.

Where structural members are placed in compression, it is possible for them to fail in two ways: either by straight compressive failure of the material, or by buckling. The tendency of a tube to buckle is minimized by giving it a large diameter. Such a tube then requires only a very thin wall to cope with the expected stress. In general, practical considerations will dictate the minimum wall thickness that can be used. Table 5.1 lists the characteristics of a number of materials used in the chassis of solar cars. **Table 5.1**

5.2 Space-Frame Materials

Well over half the field - 29 entries - adopted the space-frame approach. A wide range of materials was used, and the weight of the final chassis varied greatly from car to car. Chassis weights should not be directly compared, however, since the chassis also

Table 5.1
Properties of some commonly-used materials.

Material	Tensile Strength (MPa)	Young's Modulus (GPa)	Density g/cm^3
Alloys			
Mild steel	400	210	7.8
Magnesium (AZ31b)	250	45	1.77
Aluminium 6061 T0	124	70	2.72
Aluminium 6061 T6	310	70	2.72
Titanium B120VLA	1379	110	4.85
Chromoly 4130	2068	205	7.9
Fibres			
E-glass	3448	73	2.54
S-glass	4482	86	2.49
AS-4 Carbon	4000	228	1.80
IM-7 Carbon	5413	276	1.77
P-100 Carbon	2241	690	2.16
Kevlar 49 Aramid	3792	131	1.47
Boron	3516	400	2.49
Wood	100	8 - 13	0.4 - 0.8

Note: The properties listed are for the fibres themselves, not for a composite material incorporating fibres.

varied greatly in overall size and complexity: some were for three-wheeled vehicles while others were for four, some were for two-seater cars, and so on.

Choice of materials was also based on a variety of factors. Some of the characteristics considered by the teams include strength, Young's modulus, weight, ease of construction, ease of repair, availability and cost. (Young's modulus is the ratio of applied stress to deformation - a high Young's modulus means the material is stiff and does not deform much under load). Stress relieving of welds is very important in magnesium structures, but less so for those made from aluminium or stainless steel structures. When working with a frame that may be 2 meters wide and over 4 meters long, being able to avoid heat treatment and/or quenching processes can be a significant factor in making the choice of material. Similarly, the relative ease with which field repairs can be made should not be discounted.

Aluminium. The most popular material was 6061T6 aluminium alloy, used by twenty-one teams. This alloy is strong yet light, and is easy to weld. The welds typically will "cure" or age to a T4 temper, whose characteristics are close enough to T6 temper that there should not be any excess embrittlement at load-bearing nodes. A chassis made this way may weigh as little as 7 kg (e.g. GM's 1987 *Sunraycer* [1]), including all major attachment points for suspension etc.

Chrome-molybdenum steel. Two teams - *TR-50* and *Holy Cheat* - elected to use this material, often called "chrome-moly" or simply "chromoly". This is a common, though expensive steel alloy which is used extensively in racing cars and bicycles. One advantage of chromoly (for example Reynolds 531) is that it has a significantly higher Young's modulus than 6061 aluminium. Another is that, if necessary, it can be brazed. This can provide a serviceable and road-worthy emergency repair, as a gas welder is somewhat easier to cart around than a TIG welder. Ideally it is necessary to stress relieve the welds in chromoly if they are to attain the full strength of the native material. Annesley College's *EOS* made a space-frame from a manganese molybdenum steel alloy.

Stainless steel. One vehicle, *Solvogn Danmark*, used stainless steel for its space-frame. This was a special alloy made by Sandviken, and was used as 19 mm diameter tubes of 1 mm wall thickness to produce a space frame that weighed 10 kg.

Titanium. This is an exceptionally light and extremely strong (though not particularly stiff) material, well suited to space frame construction. It is, unfortunately, rather difficult to weld, and is thus not ideally suited to roadside repairs. Only one team, Tokai University, used a titanium space frame. They used TTW35W titanium tubes of 22.2 mm diameter and either 0.7 mm or 1.0 mm wall thickness. Their car was one of the lightest in the event, weighing a mere 150 kg, while the bare chassis with all attachment points fitted weighed only 8.0 kg.

Magnesium. *SunStang* from the University of Western Ontario had a space-frame chassis made of very large diameter (44.5 mm), thin wall, AZ31B magnesium tube. Their chassis was fairly heavy at 18.3 kg, but they still experienced some problems with the brittleness of the alloy - especially at the welds, which were not annealed.

Carbon fibre. One vehicle, *Helio Det II* used commercially available carbon fiber tubes. These were epoxied together to form a lightweight space frame structure. *Photon Flyer III* from Morphett Vale High School also used some carbon fiber tubes in its chassis.

5.3 Composite "Tub" Structures.

One of the most common chassis styles amongst the Japanese entries was that of a multiple "tub" type chassis, a semi-monocoque arrangement with longitudinal and rib members, usually made of a sandwich material. The tub is essentially a hybrid of the space-frame and monocoque approaches. This layout was used by Honda, Kyocera, Waseda, Toyota, Nissan, and Laughing Sun Racing. Such a design can also result in a very lightweight, extremely rigid structure, with weights of well under 15 kg, including bonded-in pickup points for suspension components. ** Figure 5.3.**

In a number of cases it was not clear whether a vehicle's load-bearing structure should be considered a space-frame with some composite panels added for shear strength or a composite tub chassis with space-frame subframes, or a composite tub with some semi-structural skin surfaces. In fact, it can be seen that an excellent compromise can be achieved by using this hybrid approach - for example, the bottom skin of the tub can also form the lower surface of the vehicle, saving the weight of an extra skin. These tubs provide a good compromise between the sometimes conflicting requirements of torsional stiffness, strength, low weight and component accessibility. There were twelve entries with tub style chassis.

5.4 Monocoque structures.

Eleven cars had monocoque structures. Monocoque construction makes very efficient use of materials. Its advantage is that it utilizes a single component (the skin) to perform two tasks - provide the outer surface of the car, and act as a structural member - and thereby saves weight. It also allows good, uncluttered internal space.

The monocoque approach also has its disadvantages. First, it requires that the whole vehicle be very much designed and built as a package - the aerodynamic design must be finalized before any part of the body can be built. Also, it is not as easy to do the stage-by-stage testing and evaluation which is an attraction of the space-frame and tub approaches. Access to the interior components is frequently more difficult, as the skin is an integral structural component and it is therefore difficult to design with large removable panels which can still act as structural components. Finally, it is more difficult to repair if damaged than a space-frame chassis.

One potential disadvantage for solar cars is that in a true monocoque, the skin is the important stressed member. In a solar car, the top skin consists largely of solar cells, which are not exactly renowned for their structural characteristics. Nor does the usual set of shapes for a solar car closely match the ideal requirements for a monocoque structure. This limits the degree to which a car can be a full monocoque if the solar cells form the top surface. *Team New England* and *Philips Solar Kiwi* had bodies which were largely devoid of solar cells, and so could use the monocoque approach to full advantage. (Team New England rolled their solar array up and carried it in the car, while and Solar Kiwi had a separate tilting solar panel mounted above the car.)
Figure 5.4

Most of the monocoque designs were not "pure" monocoques, but included additional stiffening. The majority used two relatively deep longitudinal members, plus a number of ribs, with the skins bonded to these. The usual design was to use a sandwich material of either an Aramid fiber or a carbon fiber in an omnidirectional weave on either side of a foam or honeycomb material, frequently Nomex, though sometimes aluminium honeycomb was used. These pre-formed sheets of material are readily obtainable, and can be cut, shaped and bonded fairly easily.

5.5 Composite materials.

Composites are those materials consisting of two or more components, where the separation between the components occurs at a macroscopic level, rather than a microscopic level [5]. In the present context, the term refers to the combination of a fiber material (such as carbon) and a bulk bonding material (such as epoxy). The advantage of fibres is that some materials have significantly better strength and stiffness properties when in fiber form than they do in bulk form. Why this should be so is a fascinating story, elegantly told by J.E. Gordon in his two popular books [6,7].

The most commonly used fibres are glass, carbon based, and Kevlar (or aramid). Different fibres have different characteristics. S-glass has a very high tensile strength, but a poor tensile modulus, similar to that of aluminium. Carbon fibres have similar tensile strength to S-glass, but may have a dramatically higher Young's modulus - up to three times that of steel, for example. Unfortunately a structure made from carbon fiber is very brittle - the fibres tend to break or shatter (depending on the matrix they are in) under a severe impact. The aramid fibres (best known under the trade names of Kevlar and Nomex) also have high tensile strength, but a medium modulus. They are, however, tough and ductile. A structure made from aramids thus has very good impact resistance, and will not shatter like carbon or glass fibres. As a woven material, Kevlar is much prized in yacht racing for its ability to cope with the extremely high tensile loads placed on sails.

These fibres are usually bonded into a matrix, typically polyester or epoxy, whose job is to tie the fibres into a structural unit, transfer and distribute the loads into fibres themselves, and provide some level of protection for the fiber. The bond between the fiber and the matrix material is clearly crucial, so the selection of matrix material is of prime importance.

Sandwich construction is a common way of using composite materials. It consists of a high strength composite layer bonded to both sides of a lightweight foam or honeycomb core. The skin material carries the longitudinal loads, so its characteristics determine the tensile stiffness and strength of the sandwich. The core is usually a lightweight foam or honeycomb, and must be strong enough to handle the distributed shear and compression loads. Structures made this way has an extremely high flexural stiffness to weight ratio - they may easily be a factor of five to ten stiffer for a given weight than one made from steel [9]. Nevertheless, when high point loads (for example, from suspension points) have to be fed into the structure, the material must usually go through a gradual variation in its dimensions to take these loads and distribute them via the skins correctly. The difficulty of inserting highly localized load points into composite structures is one of the problems to be faced in designing structures with them.

The main materials used for the skin of the sandwich were carbon fiber (in its various forms), E-glass and Kevlar (or its equivalent). Nomex honeycomb was the most common core material. Reinforcing to local joints was often performed with glass tape or unidirectional carbon fiber tape impregnated with epoxy resin (pre-preg). The *Alarus* team used aluminium honeycomb with aluminium skins to create its chassis. A number of teams also used aluminium honeycomb as the core material in their sandwich construction. For example, both Nissan and Laughing Sun Racing's *Evolution 93/B,* used carbon fiber laminated to thin aluminium honeycomb.

While composite structures have a number of advantages, they also have some major drawbacks. It is much harder to model a distributed structure accurately than it is to model a space-frame - indeed the computer modeling programs such as NASTRAN treat a slab of composite material essentially as a space-frame with a very large number of members and nodes. In addition, the anisotropic nature of the materials needs to be accommodated. The orientation of the fibres plays a crucial part in determining the end product's strength and stiffness properties in different directions. Continuous fiber (unidirectional placement) materials often have excellent longitudinal strength, but very poor transverse characteristics which may be more dependent on the characteristics of the matrix media . Choice of matrix material and adhesive for bonding is an important part of the design process, and can significantly affect the strength, stiffness and durability of the finished product. **Figure 5.5.**

It is also more difficult to construct a lightweight structure. Ideally, autoclaving and/or vacuum bagging techniques should be used to ensure the resins have cured correctly, have penetrated, and that there is no excess resin in the final product. These techniques are time consuming, labour intensive, and frequently require specialized equipment. Additionally, it is quite difficult to get the consistently high quality and uniformity of bonding that is required, especially when joining prefabricated panels. Unless properly cured, bodies can deform in the hot central Australian sun - several cars had a significantly different shape on arrival in Adelaide than the one they left Darwin with.

Structural failures in components made from composite materials, particularly when sandwich construction is employed, can be much harder to detect than those in metal structures. Laminates (and therefore sandwich materials, too) are susceptible to various forms of delamination which may only be detectable using various non-destructive imaging systems, often acoustically based. These defects can be caused by construction imperfections, such as failure of the bulk bonding material to uniformly fill a volume. This allows compressive loads to cause buckling, which severely reduces the strength of the section. A sharp impact may also cause an internal delamination, as could a poorly inserted load point which placed too high an interlaminar tensile load on the laminate and caused an internal crack to develop.

GH Craft in Japan provided expertise in composite design and construction to a number of Japanese teams, mainly for some chassis components. They designed and built the carbon fiber trailing arm used by Kyocera and Waseda, which weighed only 1.324 kg (bare). They also designed and built the wheels for Kyocera, which weighed only 1.020 kg (without tire). Many other entrants used their own facilities to construct their vehicles.

There are two other characteristics of composites which are important. Some, such as carbon fiber, are electrically conductive. This can easily cause short circuiting problems, which will either be almost impossible to trace (as in the case of shorted individual solar cells) or all too readily apparent (as in the case of shorted battery terminals). Secondly, whilst some materials (such as Nomex) are flame retardants, others burn quite well and produce toxic fumes.

One composite material has been used in structures since the dawn of time, and has played a major role in the development of modern civilization - wood. (Another such material is bone, though this has yet to be incorporated successfully into a solar car.) Like artificial composites, wood is strongly anisotropic - plywood is any early attempt at achieving better uniformity in the directional properties. The only vehicle which used wood extensively in the body was *Aquila* from Dripstone High School, which used plywood to construct a ribbed, monocoque-style body. Holy Cheat also created an elaborate wooden lattice to support the solar cells. Many other cars, however, used small pieces of wood in various places, especially to create transitions from a sandwich monocoque to, say, a suspension hard point. **Figure 5.6.**

5.6 Individual Cars.

Honda used a version of the carbon tub approach. While many of the other teams made tubs from slabs of pre-formed carbon/honeycomb/carbon sandwich material which they cut and epoxied together, Honda molded their vehicle. The basic tub had three open-topped sections: one for driver, one for the battery and electronics, and one at the back for the rear suspension. The body was effectively a single piece with the array, nose and much of the underpan a single unit which used "Dzus" fasteners to mount tightly to the tub around its lower edge. The windscreen was removable as a single unit to allow easy driver access. The basic tub was autoclaved using various sandwiching techniques with resin-impregnated (pre-preg) carbon fiber and an Aramid honeycomb. The body was similarly constructed but with the addition of carbon/honeycomb ribs epoxied into place. **Figures 5.7.**

The Biel car (*Spirit of Biel III*) also used a carbon/honeycomb approach. It had longitudinal members and ribs, with some open box members (which were vaguely tub-like) triangulated with diagonal tension members. The body was made by Bücher of carbon fiber/Nomex honeycomb sandwich which was hand laid up and vacuum bagged. The body was basically the same as the 1990 vehicle, and in fact was made in the same mold. There were, however, some minor - but very important - modifications: specifically a depression under the car to allow the driver to sit lower, and a smaller canopy, which significantly lowered the C_D (see Chapter 4). The complete body/chassis unit without suspension or solar cells weighed 30 kg. Driver access was through a small and elegantly hinged canopy. **Figure 5.8.**

The Honda and Biel cars were typical of two of the main schools of thought of vehicle architecture. Ignoring the nose, the Biel car could basically be seen as two pieces - a top and a bottom half, which were split approximately around the middle. The solar panel and top "half" of the body hinged up to gain access to the internals, somewhat like a clamshell. The Honda vehicle had a more marked separation between body and chassis. The body included the top and bottom skins and nose. When it was removed, the tub chassis and ancillaries were left very accessible. One area the two cars had in common was exquisite attention to aerodynamic detail. The surface finish on both cars was superb, the Biel team actually incorporating the event and sponsor logos into the paintwork so that the outer surface of the car was as smooth as glass. Panel fits were extremely precise on both vehicles, as required if the ultimate aerodynamic performance is to be achieved.

Both Biel and Honda used small, snug-fitting wheel spats. These spats needed to rotate to allow for steering motion. Honda had a separate set of cables from the steering mechanism which rotated a "turntable-like" plate to which the spat was attached - Biel used a similar turntable mechanism. **Figure 5.9.**

Kyocera and Waseda shared a number of their components. Kyocera's *Son of Sun* used one mold for the lower half of the car and another for the upper. *Sky Blue Waseda* used the same lower mold as Kyocera for both the upper and lower skins, creating a body with a very low frontal area and drag coefficient ($A = 0.796$ m^2; $C_D = 0.150$). Waseda's chassis was of carbon/honeycomb slabs which were epoxied to form a tub/monocoque hybrid, while the body was made of carbon, Kevlar and Nomex sandwich ribs with a Kevlar skin. Figure 5.13 shows the way the body, which was composed of the upper skin, screen and 50% of the lower skin, could easily be removed. Kyocera's construction was similar, except that they incorporated more of the lower skin into the chassis unit, which was supported by ribs. **Figures 5.10, 5.11, 5.12.**

The *Aurora Q1* vehicle had a very unusual chassis. Driven by the desire to achieve minimum wetted surface area and the best possible aerodynamic performance, the team faced a difficult challenge to achieve a viable packaging. The end product was the separation of the suspension subframe and body in a novel way. The subframe was a triangular structure (one front wheel and two rear wheels) which rigidly located the three wheels with respect to each other, thus minimizing scrub due to geometry variations. This subframe was then sprung fairly softly with respect to the body, which supported all the ancillaries. The body itself was similar to the modified monocoque approach described above, and was split into two (as was common), with the lower half made from carbon fiber/Nomex honeycomb sandwich material by racing boat specialist Jeff Sykes. Again, a variety of rib and longitudinal members were made from sheets of this material. The top half (including array support) was mainly cut from pre-fabricated slabs of fibreglass and Divynicell sandwich, glued together and reinforced with fibreglass tape. Viv Baddeley of the Aurora team describes this technique as being like "...cutting out a model from the back of a breakfast cereal packet, except you can get in it and drive it away". **Figures 5.13 and 5.14. **

The *Solar Kiwi* was a good example of a true monocoque design. The shell was a skin of carbon fiber, Kevlar and Nomex, with some longitudinal stiffening provided by molded-in rails of carbon/foam-sandwich construction. Despite being a small vehicle (0.70 m^2 frontal area) it featured a relatively large and uncluttered interior space because of the monocoque layout. The car was built by first creating a foam body plug, laying up the body to the outside of this, then digging the foam out from inside. Despite this very simple technique, the result was a beautifully finished car.

Intrepid from Cal. Poly. Pomona used a monocoque derived body, incorporating relatively large box members (100 mm by 100 mm) made from a carbon/Kevlar/honeycomb sandwich material to locate the tops of the motorbike forks which were used for each front wheel. This allowed a relatively thin body cross section at the extreme edges of the vehicle, whilst still maintaining a stiff suspension mount and keeping the body away from the road surface where undesirable venturi affects could occur. The *Intrepid* team had special difficulties in post-curing their mold when the propane-fired burners used to heat the mold set fire to a wooden support. Despite the best efforts of the Pomona fire brigade, the warehouse in which the car was being built burnt to the ground. Recovering well from this setback, *Intrepid* was the top performing US entry, finishing in eighth place overall (and with the Pomona fire brigade as sponsors!). **Figure 5.15.**

The University of Michigan's *Maize and Blue* was a classic space-frame with separate body. Aluminium 6061 T6 tubes were used for the space-frame, while the body was a carbon fiber/Kevlar/Nomex structure. An earlier Michigan vehicle of similar construction is described in [2].

The Monash/ Melbourne *SOLution* was an unusual catamaran design which, because of its shape, required a carefully designed structure to achieve the required stiffness. The structure used a combination of fibreglass-faced aluminium honeycomb and Nomex honeycomb with glass and fibreglass faces [8]. **Figure 5.16.**

There were a number of rather unusual body architectures. Doraemon's *Solaemon-Go* was one of the most interesting, modelled after a well-known Japanese cartoon character. It performed extremely well, particularly in view of the somewhat dubious aerodynamics. At the opposite extreme was the minimalist approach of *Team Moscow, Heliodet* and *Holy Cheat*, who all used the simplest chassis/body that would support all the required items - driver, solar array and batteries. Another interesting body shape was that of *Alarus*, which resembled a gigantic trilobite.

5.7 Driver Accommodation.

Designing a solar car would be a whole lot easier if there were no need to accommodate the driver. (In fact, one team did write to the event organizers to ask if the driver could ride in the support vehicle, and drive the solar car by remote control!) The driver is a large, heavy and relatively fragile component which, unlike the electronics, cannot be broken up into separate functional modules and distributed around the car (though this is not explicitly forbidden by the rules). Furthermore, the driver must be placed with an eye-height of at least 70 cm, and must have a good view of the road. Achieving this in a clean aerodynamic design requires a transparent canopy or windshield with compound curves.

To minimize the heat load on the driver, some teams used coated their canopies with a partially reflective layer, or simply tinted them to minimize the amount of light and heat transmitted. The University of Michigan's approach was typical - they simply drape-molded a polycarbonate sheet over their master plug, and then applied a commercial automobile window tinting film to the top half to reflect some of the incident sunlight. California State University LA also stretch-molded an acrylic Plexiglas sheet over a male former. Teams have tried a variety of different materials for minimizing the heat load on the cockpit - more exotic solutions have included sputtered gold (GM *Sunraycer* in 1987) and titanium nitride (University of Michigan *Sunrunner* for the 1990 Sunrayce USA). Most teams used simpler automotive type reflective films, or simply coated part of the canopy with a suitably reflective paint. One team painted the top of the canopy black - it subsequently melted. Nissan had 2 canopies - one which had a gold tinting and a second which had a "smoked" gray finish.

Solar cars which consist of a "wing" with a small bubble canopy have some important aerodynamic advantages, and potentially have excellent all-round visibility (e.g., *Spirit of Oklahoma III, Intrepid, Spirit of Biel, Aurora Q1*). Unfortunately, the driver's head may be surrounded by only a relatively small volume of air and achieving sufficient ventilation may be difficult. A well designed roll bar must also be an integral part of any such design. **Figure 5.17.**

A number of different approaches were taken to the regulation which requires "car-type rear vision". While most teams elected to use conventional rear view mirrors, a number used small CCD-based camera systems (e.g. *Toyota-56, SDSU Suntrakker, Solar Flair).* These were usually used in conjunction with compact LCD displays, though one team (*Solar Flair)* used a complete 6-inch tube TV. These displays do not always produce the left-right reversed image that a driver used to a conventional rear-view mirror would expect (see Chapter 11).

The drivers of *Hama Yumeka* were well catered for. Integrated into the driver's headset was an LCD display and half-silvered mirror, giving a "heads-up" rear vision display. This whole system was made by Yazaki. A number of teams (for example, the University of Michigan) used a fiber optics bundle for rear vision. **Figures 5.18, 5.19.**

Driver comfort received mixed attention from the teams. It was clearly a high priority with the Mino Family - the Momo steering wheel, woodgrain dashboard, compact disc player and stereo speakers were no doubt much appreciated by their drivers on the 3013 km journey to Adelaide.

Seats also varied greatly. Some teams used bare composite shells to which 10 mm of sponge had been glued. Others had carefully profiled seats which clearly provided good support. Many teams used some version of a hammock type seat. These seats were usually made of a synthetic material in a coarse mesh, though some were woven from relatively wide webbing akin to seat belt material. The advantage of this style of seat is that it is extremely light, fairly comfortable, and exposes some additional surface area of the body to air circulation, thus increasing cooling. The University of Michigan has performed a range of studies on factors that influence driver comfort and efficiency [2].

Most cars had some kind of cooling available for the driver - usually ducted air (see Chapter 4). In some cases, cooling fans were provided, though in not every case were the blades placed out of reach of the driver's fingers. The University of Western Ontario's *SunStang* provided an adiabatic cooler for the driver. Another team, however, took the opposite approach to the question of driver cooling - they painted the entire front of the car matt black!

Seat belts were required by the race rules. They ranged from mountain climbing harnesses through simple lap belts to full racing harnesses. It should be emphasized that seat belts are only as effective as their mounting points. They should also be designed to be comfortable for extended periods, and to be easy to get out of in an emergency (see Chapter 11).

Cockpit ergonomics is an area that has received extensive research over the years, in both automotive and aeronautical areas. Some teams had elegant, carefully thought-out panels (such as *Spirit of Biel* , *Dream* , *Maize and Blue* and *Mino Family Special*), whilst others had a more haphazard look about them. Instrumentation ranged from a minimalist set of two meters (*Philips Solar Kiwi*) through a collection of commercial multimeters (*Aquila* and *Console to the Future*) to PC-based monitoring systems (*Tokai-51SR* and *Sofix*) which included a whole laptop computer.

While some cars used conventional steering wheels, many fabricated their own, usually of very small diameter. Several cars used aircraft type joysticks, push-pull levers, tillers or motorbike type handle bars, as appropriate to the steering mechanism. In a number of cases either the steering wheel was removable or the steering column had a flexible joint to allow for driver entrance and exit.

5.8 Weight budget.

Waseda University were one team who kept very close track of the weight of every component that went into their car. The total weight of their vehicle, *Sky Blue Waseda,* was 189.5 kg, of which batteries accounted for 83.8 kg. The total chassis, body, suspension, electronics, solar array thus weighed only 105.7 kg. In fact, the bare chassis weighed only 14.5 kg, the body (without cells) weighed 23.7 kg. A complete breakdown of the component weights is given in Table 5.2.

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Table 5.2 Weight Budget for Sky Blue Waseda.

Item	Weight (kg)	Qty	Total (kg)			
Driver:	80 (ballasted)	1	80.000			
Total for Driver					**80.000**	**(A)**
Battery	1.337	60	80.220			
Battery Box	0.432	4	1.728			
Fasteners etc			1.888			
Total for Battery Module:					**83.836**	**(B)**
Solar Panel:						
Photovoltaic cells	0.0085	1144	9.724			
Bonding	0.700	4	2.800			
Corting			1.664			
Wire, solder diodes			3.995			
Subtotal for solar panel:				18.183		
Cowl Structure:						
Upper cowl			9.860			
Lower cowl			7.410			
Reinforcement etc			4.290			
Subtotal for cowl:				21.560		
Lamp, fasteners, film			0.320			
Hatch:						
Canopy			1.210			
Fame			0.512			
Subtotal for hatch:				1.722		
Total for Solar Cowl:					**41.785**	**(C)**
Monocoque:						
Under panel			6.306			
Side panel	1.747	2	3.494			
Bulkhead, etc			4.756			
Subtotal for monocoque:				14.556		
Bonded-in parts:						
Cowl fasteners (Dzus)	0.0088	16	0.141			
Rear trail arm bracket			0.993			
Front wish brackets			0.195			
Subtotal for bonded-in parts:				1.329		
Bolted parts:						
Seat			1.062			
Seat belt			0.604			
Cover, fasteners etc			0.342			
Subtotal for bolted parts:				2.008		
Front suspension:						
Wheel hub assy	0.486	2	0.972			
Upper wishbone assy	0.371	2	0.742			
Lower wishbone assy	0.741	2	1.482			
Upright/brake assy	2.072	2	4.144			
Coil/shock	1.802	2	3.604			
Subtotal for Front suspension:				10.944		

Brake linkage:					
Brake lever			0.230		
Brake wires			0.970		
Subtotal for brake linkage:				1.200	
Steering:					
Handle bar			0.751		
Tie rods			0.919		
Pulleys, wire, bolts			0.729		
Subtotal for steering:				2.399	
Rear suspension:					
Trailing arm			1.324		
Bracket, flange etc			0.713		
Hub, shaft, boss			1.502		
Coil/shock			1.770		
Primary chain			0.112		
Secondary chain			0.249		
Sprocket 1			0.068		
Sprocket 2/3			0.210		
Sprocket 4			0.224		
Bearing, collar etc			0.054		
Subtotal for rear suspension:				6.226	
Motor unit:					
Motor			4.018		
Frame, plate, bolts			0.791		
Subtotal for motor unit:				4.809	
Wheel:					
Disk wheel	0.890	3	2.670		
Tire	0.420	3	1.260		
Tube	0.150	3	0.450		
Subtotal for wheel unit:				4.380	
Aero parts:					
wheel shutter, spats, strake			1.012		
Wheel house			1.320		
Subtotal for aero parts:				2.332	
Electrics:					
Switch board			3.148		
Motor controller			7.080		
MPPT	0.280	4	1.120		
Power supply, switch			0.810		
Fan, meters etc			1.568		
Subtotal for electrics:				13.726	
Total for Chassis:					**63.908 (D)**

Total weight of car (B + C + D): 189.53 kg

Total weight of car plus driver (A + B + C + D): 269.53 kg

Figures:

Figure 5.1 The chassis and body of a solar car have to perform several functions. Shown here is *Sunforce I* from George Washington University.

Figure 5.2 University of Michigan used a classic space frame for *Maize and Blue* .

Figure 5.3 The Honda *Dream's* chassis was a carbon "tub" structure. The structural support of the front wheel spats is beautifully integrated with the main chassis - essential if tight clearances are to be maintained between wheel and spat.

Figure 5.4 *Philips Solar Kiwi* - a good example of a monocoque construction, with a clear, uncluttered interior.

Figure 5.5 Carbon/honeycomb ribs form the structure of the *Spirit of Biels III* solar panel, which is effectively the top half of the car. The main chassis structure has two longitudinal members and a number of ribs which form box-like sections.

Figure 5.6 *Aquila* (Dripstone High School) made extensive use of wood. Its entire chassis was a plywood tub/monocoque structure.

Figure 5.7 Honda's body shell was designed to be built as a single piece, giving both excellent aerodynamics and good accessibility. It fits tightly over the chassis. The windscreen also removes for driver entry and exit.

Figure 5.8 The *Spirit of Biel III* canopy was very small and was well sealed to the body when closed, minimising its impact on the aerodynamics. The instrument panel is mounted in the lower edge of the canopy, which also carries a reflective coating and a surface-mounted antenna.

Figure 5.9 The lower half of *Spirit of Biel III*s front wheel fairing is removed to change the wheel.

Figure 5.10 *Sky Blue Waseda* used the same upper and lower body profiles and achieved a very low frontal area.

Figure 5.11 Waseda University used the tub/monocoque approach for *Sky Blue Waseda*. They sealed the wheel wells (the covers have been removed in this photo), as did all the top teams.

Figure 5.12 *Sky Blue Waseda*'s body/solar panel on its charging stand. The spoon-shaped cutout where it tightly connects to the chassis can be seen. This interface is sealed when driving to minimise undesirable airflow through the body.

Figure 5.13 *Aurora Q1*. The small frontal area, supine driving position, and carbon/honeycomb construction can be seen. The triangular subframe allowed the designers to optimise the suspension geometry and suspension rates.

Figure 5.14 *Aurora Q1*. With all the weight toward the front of the car, the rear chassis sections could be made relatively small and light.

Figure 5.15 *Intrepid* used a carbon/honeycomb sandwich to create box sections which were extremely stiff and strong to locate the front suspension forks.

Figure 5.16 *Toyota-56*, like many other teams, had a separate frame to hold their solar array during the morning and evening charge periods.

Figure 5.17 The *Spirit of Biel* canopy. Small frontal area is a key ingredient in minimising aerodynamic drag. Biel made their canopy significantly smaller this year than in 1990 - note the "shark's fin" to bring the car up to the minimum legal height of 1.0 m.

Figure 5.18 *Toyota-56* had a simple, well laid-out cockpit with the instruments mounted in the traditional position.

Figure 5.19 Honda's *Dream* had instruments mounted in a small module attached to the steering handlebars.

Chapter 6.

Solar Cells

6.1 The Solar Spectrum.

The sun generates energy via nuclear reactions in its core (principally the conversion of hydrogen to helium) at temperatures in excess of ten million degrees. This energy is transported to the sun's surface, which then radiates approximately as a blackbody at a temperature of 5,800 K.

The flux received from the sun at the top of the earth's atmosphere is known as the **solar constant.** Traditionally this has been taken to be 1353 watts/square metre, although more recently the World Meteorological Organisation has adopted a figure of 1367 watts/m^2, while NASA uses 1372 watts/m^2. However the earth's orbit is in any case slightly elliptical, and so the amount of sunlight per square metre incident on the earth (known as the **solar flux**) actually varies throughout the year. The earth is closest to the sun in January - southern hemisphere summers are in fact sunnier (by about 7%) than northern hemisphere ones!

In passing through the earth's atmosphere, the spectral distribution of the sun's radiation is modified both by scattering and by absorption. At the ultraviolet end, the earth's ozone layer removes a significant fraction of the flux, while water vapour accounts for the absorption of large parts of the near infrared spectrum. Our eyes have evolved over hundreds of millions of years to operate in that part of the spectrum where the highest solar flux is available. What we call "visible" light, however, accounts for only a part of the sun's spectrum - solar cells can make use of the energy at both shorter and longer wavelengths than we can see (figure 6.1).

At the earth's surface the solar flux is reduced to approximately 1000 watts/m^2 (when the sun is directly overhead), and has a "redder" spectrum than it does at the top of the atmosphere. If the sun is directly overhead, its light has to pass through one "thickness" of atmosphere, or airmass, in order to reach the earth's surface. Under the simplest assumption that the atmosphere is in the form of a plane-parallel slab, the airmass through which the light must pass varies as the secant of the sun's zenith angle. Solar cells intended for terrestrial use are usually specified at standard ("**one-sun**") conditions of 1000 watts/m^2 , 25 ^{o}C, 1.5 airmass spectrum.

Because the spectrum received at the top of the atmosphere is substantially different to that which strikes the earth's surface, solar cells designed for terrestrial use are optimised in a different way to those intended for use in satellites. Furthermore, the flux of high energy particles in space places more stringent requirements on the radiation hardness of "space" cells; requirements which are not so relevant at ground level. "Space" cells are therefore not usually the best choice for a solar car.

6.2 Efficiency

In the past, claimed cell efficiencies were difficult to interpret due to the different procedures and standards used in different laboratories. The situation is now greatly improved, and a high degree of consistency exists world wide. An "honour roll" of top-performing cells is listed periodically in *Progress in Photovoltaics: Research and Applications.* A few examples of cells tested at standard (one-sun) conditions from the January 1994 issue [1] are shown below:

Table 6.1

Cell type	Efficiency (%)	Laboratory
Silicon (single crystal)	23.1	UNSW
Silicon (polycrystalline)	17.7	Georgia Tech.
Silicon (amorphous)	12.7	Sanyo
GaAs	25.1	Kopin
Multijunction	29.5	NREL

In the following discussion, a working knowledge of semiconductor physics is assumed. Much can be understood, however, by simply appreciating that the most important characteristic of the solar cell is the **bandgap** of the material it is made from. The bandgap is an intrinsic property of the material and, loosely speaking, is the amount of energy that an electron in it must acquire in order to be able move about freely and participate in an electrical current. In a solar cell, this energy is acquired by individual electrons from individual incoming photons of light.

A solar cell consists of a p-n junction fabricated from a slice of semiconductor material of appropriate bandgap (see, for example, Green [2]). Photons of energy greater than the bandgap energy are absorbed, and in the process create an electron-hole pair. The electron and hole move apart under the influence of an internal electric field, thus creating an emf across the cell. When connected to an external circuit, the solar cell has a characteristic I-V curve similar to that of a diode, but displaced along the vertical (current) axis, as shown in figure 6.2. Since the output power is the product of the voltage and the current, the actual power delivered by the solar cell to the load is critically dependent on the load resistance. Maximum power output is obtained when the load resistance is such that the cell is operating at its **maximum power point**, as shown in figure 6.3.

It is interesting to try to estimate the fundamental limits to solar cell efficiency. Such a procedure is fraught with danger, however: present day laboratory cells are already exceeding what a few years ago were considered in some theories to be "fundamental" limits!

The maximum power output of the cell is equal to the product of the open-circuit voltage, the short-circuit current, and the "fill-factor" - a term describing how rectangular (or otherwise) the plot of I versus V appears for the particular cell. The fill-factor, in turn, is determined by several factors including the series resistance of the cell contacts and the internal shunt resistance of the device. Simple thermodynamic arguments [3] can be used to derive a limiting efficiency of about 29% for a silicon solar cell under standard one-sun illumination.

In one simplified model of a solar cell, every photon with energy greater than the bandgap is absorbed and creates one electron, while every photon below the bandgap is ignored. The number of electrons created is then calculated by integrating the number of photons in the solar spectrum from the bandgap to the UV atmospheric cutoff. From this, a reasonably accurate estimate can be made of the maximum possible short-circuit current, I_{sc}, of a cell. Calculation of the open-circuit voltage, V_{oc}, is more uncertain. Placed in sunlight, a solar cell becomes forward biased and an internal current begins to flow. This "bucking" current is an exponential function of the forward voltage. The open circuit voltage, then, is the voltage at which the bucking current is exactly equal to the photocurrent generated by the solar flux. Different models are available to describe the bucking current, leading to a variety of different estimates of the open-circuit voltage and hence of the maximum possible cell efficiency.

Clearly, there is an optimum value for the bandgap of the solar cell material. If the bandgap is too high, then too many of the incident photons will be ignored. If, on the

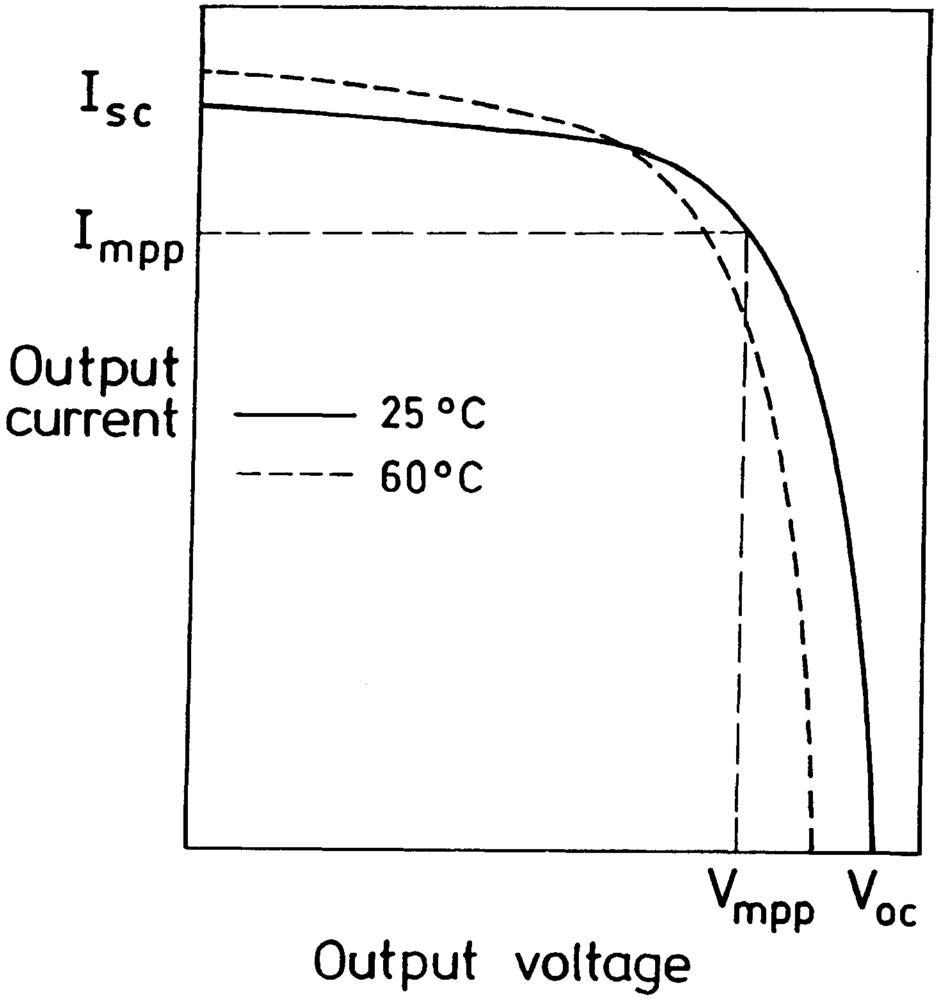

Figure 6.2 Current versus voltage (I-V curve) of solar cell at 25 °C (solid curve), and 60 °C (dotted curve). I_{sc} and V_{oc} are the short-circuit current and open-circuit voltage respectively. MPP signifies the **maximum power point**, the point on the curve corresponding to maximum output power from the cell.

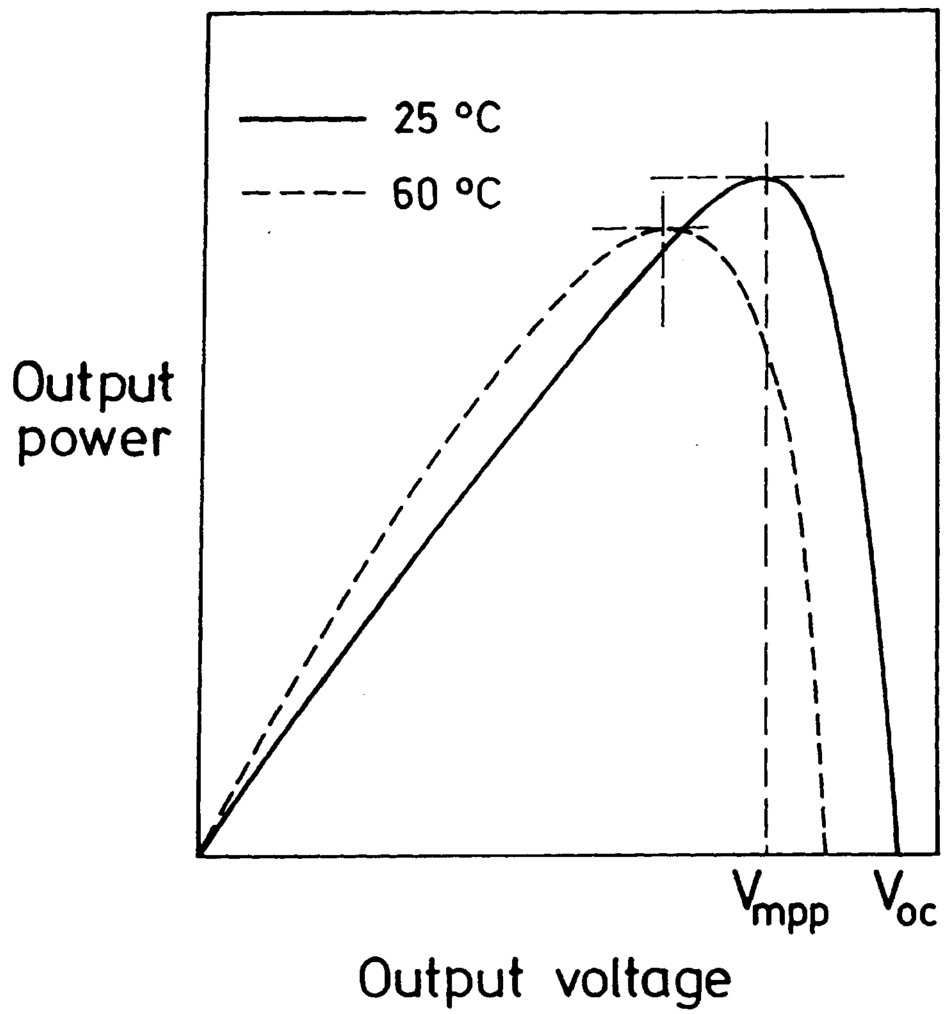

Figure 6.3 **J**. Power output versus output voltage for a typical solar cell. Note the shift in maximum power point as the temperature is increased to 60 °C (dotted curve).

other hand, it is too low, then the energy that can be extracted from each photon is correspondingly low. These simple arguments would suggest that the optimum band gap for a terrestrial solar cell is approximately 1.4 eV. However more detailed calculations [4], which take into account the actual solar spectrum, show there are two peaks in the efficiency curve - one at 1.15 eV and one at 1.38 eV. Silicon's bandgap is very close to the first of these, while gallium arsenide's lies very close to the second. Both silicon and gallium arsenide can thus be used to make cells of very high efficiency. The advantages of silicon - low toxicity, generous natural abundance, and generally well understood chemistry - have led to its present dominant position.

The efficiency of a solar cell is a function of many things, including the operating temperature. As the temperature of a silicon solar cell increases, its bandgap decreases. The short-circuit current thus increases, while the open-circuit voltage decreases (refer again to figure 6.2). This decrease in voltage amounts to some 2 mV/^{o}C per cell. In addition, the fill factor decreases, as the competing processes internal to the cell generate an increased "bucking" current. The nett result is a shift in the maximum-power point, and an overall decrease in efficiency, as shown in figure 6.3.

The efficiency of a solar cell also increases with the level of illumination. This can be understood as follows. As the flux increases, the current increases almost in direct proportion (since one electron is produced for each photon of energy greater than the bandgap). However, since the I-V characteristic of the cell is that of a diode (figure 6.2), the increased current leads also to an increase in the operating voltage. The output power therefore increases faster than linearly with flux.

A flat panel is therefore more efficient near mid-day than a steeply angled one, simply because the "concentration" of the sunlight is greater in the former case. In this instance the effect is almost negligible. If, however, lenses or mirrors are used to concentrate the sun's rays a hundredfold or even more, significant improvements in efficiency can be gained. The record for a solar cell with a factor of one hundred solar concentration is held by Boeing, and currently stands at 32.6% efficiency [1]. These values cannot be compared directly to non-concentrator efficiencies, however, since they relate only to the direct beam illumination whereas non-concentrator cells can also make use of the diffuse radiation. In the 1993 event, no cars attempted to use concentrators, either while stationary or in motion.

Although obviously of crucial importance, the efficiency of the bare solar cell is not the only factor in determining the power output of the panel. Some of the other factors are listed below.

Cell cooling. Because the efficiency of solar cells decreases with temperature, maximum output will be obtained when the cells are kept as cool as possible. While the car is in motion, airflow over the panel is the main cooling mechanism. When laminar flow can be achieved, aerodynamic drag will be greatly reduced but, perversely, cell cooling will be least effective. Some teams designed the car in such a way that air flowed under the cells as well; however it is difficult to do this without seriously compromising the drag coefficient. Other teams attempted to maximise the radiative cooling from the underside of the cells. NTU, for example, painted the underneath of their cells black and exposed as much cell area as possible by cutting away the support structure behind each cell.

To keep their cells as cool as possible, Biel exploited another effect. By designing the cells with a reflective rear surface, infrared light which would otherwise be absorbed is reflected back into space, and the heat load on the cell thereby reduced. The success of this approach can be judged by the fact that, under standard illumination conditions and with a power output of 1250 watts, their panel temperature rose by only 6 or 7 ^{o}C above ambient when driving.

During media stops and the charging periods, active cooling of the panel is not permitted (unless the power to achieve the cooling is derived from the battery pack). Washing and cleaning of the panel is, however, permitted (figure 6.4). It is surprising how many team managers appeared to suffer from the misconception that ice-cold water is the best possible cleaning agent, and sprayed it diligently over the entire panel during stops...

Diffuse radiation. Not all of the sunlight falling on the cells has arrived along a direct line-of-sight from the sun. Even on a perfectly clear day, some 10% of the radiation is diffuse, i.e. arriving from the entire hemisphere. Under cloudy conditions the figure rises to 100%. (The presence of clouds is not necessarily bad news for a solar car - peak power will actually be obtained when bright, white clouds lie either side of an unobscured sun, adding their scattered light to the sun's direct radiation. Flux levels of up to 1400 watts/m^2 have been observed under these conditions.) Provided it can be done without undue weight or aerodynamic penalty, it may therefore be worthwhile adding cells to the side - or even the underneath - of a car. *Toyota-56* and *SDSU Suntrakker* were two cars which placed cells under the car to take advantage of scattered light (figure 6.5). Other cars, such as Michigan's *Maize and Blue*, used a highly arched body which was very effective in diffuse radiation and at low sun angles.

Add-on panels. The rules state that all solar cells (and other collectors) must fit within a "box" of specified maximum dimensions. When in motion, this box must be oriented with its length and width parallel to the ground. When stationary, however, the box may have any orientation. During the morning and evening charging periods it is therefore permissible to tilt the car. In some cases it is possible to do this in such a way that it lies across the diagonal of the box; additional panels can then be added along the edge of the car to completely fill this diagonal. For example, a team whose car used a flat panel of dimensions 2 m x 4 m could, when stopped, add a panel along the edge of the car to give an overall width of $(2^2 + 1.6^2)^{1/2} = 2.56$ m. (Note, however, that the additional panels must be carried in the car at all times.) Some teams took advantage of this rule, while others did not (figure 6.6).

Cell matching. To obtain maximum power from an array it is essential that all cells which are connected directly together (i.e., are in the same "**string**") are closely matched. For a series string the most important parameter is I_{mpp}, the cell output current at its maximum power point. To achieve good matching of the cells once they are assembled into an array, it is necessary to ensure that the sun illuminates the same projected area of each cell. There are several ways this can be accomplished:

1. Use of an almost flat panel. This was the approach adopted by Biel. Each cell obviously has the same projected area regardless of its position in the panel and, in Biel's case, only three Maximum Power Point Trackers (MPPTs; see section 6.7) were required.

2. Where a more complex panel shape is desired, good matching can still be obtained by grouping the cells into small sub-arrays, each with its own MPPT. Each sub-array is approximately flat; every cell within this sub-array therefore has the same projected area. Honda adopted this approach, using 10 MPPTs. The minimum number of cells in a sub-array is constrained by the requirement that the series string must generate sufficient voltage to enable the electronics it feeds to operate efficiently. By using small cells, the area of the sub-array can thus be made smaller. Michigan used 9,267 special-made mini-Green cells, and 11 MPPTs.

3. By overlapping ("**shingling**") the cells in such a way that the degree of overlap varies from cell to cell in an appropriate way, a curved array can be made up of identical cells yet still have each cell project the same area towards the sun - at least for one position of the sun. *Aurora Q1* arranged the overlap of the cells to give best matching for the sun directly overhead, thus maximising the panel efficiency to coincide with the condition of maximum incident sunlight.

Bypass and Blocking Diodes. If a single cell in a series string becomes shaded, the internal resistance of that cell will become very high and the entire string will cease to operate. At best, the string will simply stop supplying any useful output power; at worst it will continue to generate almost full power which it dumps into the unfortunate cell which is in the shade, causing it to overheat and blister its laminate. Which of these outcomes occurs depends on the quality of the cells used, but both can be prevented by including a diode (which is reverse-biased under normal conditions) in parallel with every few cells. Such a diode is called a **bypass**, or **shunt,** or **shading** diode.

Where two or more strings are placed in parallel, shading of one string will result not only in loss of power from that string, but also a draining of current from the unshaded string. This can be prevented by placing a **blocking**, or **series** diode in series with each individual string. Such a diode also prevents discharge of the batteries through the panel overnight (although this will often be prevented anyway by the battery charging electronics).

Some teams consider both types of diode to be essential. Other teams leave them out altogether, citing the inevitable loss of efficiency caused by the blocking diode and the inconvenience and potential unreliability of the bypass diodes, together with the fact that, under normal conditions, the diodes are doing absolutely nothing.

Tilting Panels. While tilting panels have been popular with top teams in previous events (in 1987, three of the top six vehicles had moveable panels), their popularity has greatly declined. In 1993 none of the top finishers had a tilting panel - the first such vehicle to finish was the *Solar Kiwi*, which finished in a creditable fifteenth place. An interesting variation on the tilting panel theme is the tilting car concept, as used by *Desert Rose*. This vehicle, which was an improved version of the 1990 car, could tilt up to 15 degrees to either side to maximise the sunlight intercepted. It performed well, finishing the race in seventh place.

6.3 Materials

Silicon solar cells can exist in three variations: single-crystal (or monocrystalline), polycrystalline, and amorphous - in decreasing order both of efficiency and cost per cell. In the 1993 event almost all cars used single-crystal cells.

Polycrystalline cells (figure 6.7) were used by just three cars. *Solar Kiwi* and *Aquila* used Solarex cells with an efficiency of around 13%, while *ΦΩΣΠ* used Kyocera cells of about 11% efficiency. Of these vehicles, *Solar Kiwi* was easily the most successful.

Only one entry, *Le Soleil*, used amorphous silicon cells (figure 6.8). These cells were manufactured by Kaneka Corporation, and had an efficiency of 6%. *Le Soleil* finished in 38th place, officially retiring after travelling 1,486 km at an average speed of 26.38 km/hr. They continued driving and completed the course in 14 days. This represents a significant improvement over previous amorphous-powered cars - 1990's S.E.L. managing only 21 km/hr and the 1987 car requiring a full month to complete the course!

Almost all cars used silicon solar cells exclusively. Only one car, Cal. Poly. Pomona's *Intrepid* used Gallium Arsenide (GaAs) cells, and even then covering only a small fraction of the car (figure 6.9). In 1987, General Motors' *Sunraycer* owed much of its exceptional performance to its use of GaAs cells which easily outperformed the silicon cells of other competitors. By 1990, however, silicon solar cell technology had significantly improved, with the result that the advantage of GaAs was greatly eroded. Only one vehicle was to use GaAs in that race - Cal. Poly. Pomona's *Solar Flair II* [5]. Nevertheless, GaAs cells still enjoy a small but significant efficiency advantage over silicon cells (see table 6.1), and their efficiency falls less steeply with increasing cell temperature. Their very high cost, however, is a serious impediment to more general use.

While several other materials such as copper indium diselenide and cadmium telluride are being studied in the laboratory as being potentially useful for solar cells, none has so far made it onto a World Solar Challenge solar car.

6.4 Cell Construction.

The cells used by the Honda *Dream* (figure 6.10) were manufactured by SunPower Corporation, and were based on the rear point-contact design developed by Stanford University. Known as Backside Contact (BSC) cells (figure 6.11), they have the

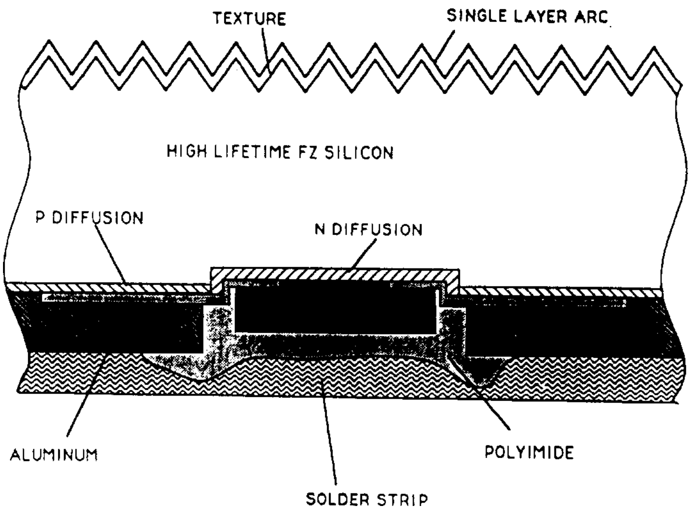

Figure 6.11 **J.** SunPower's Backside Contact (BSC) cell, as used on the winning Honda *Dream.*

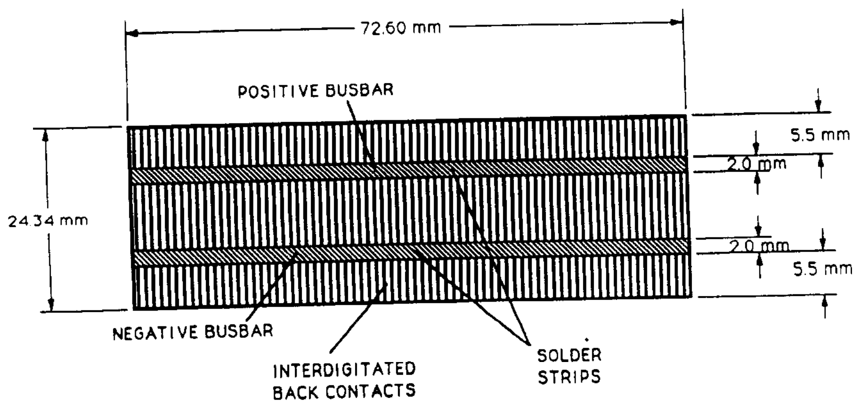

Figure 6.12 **J.** Rear surface of the SunPower BSC cell, showing the complete electrode coverage which contributes to the low series resistance of the cell.

obvious advantage of having no electrodes on the front surface, 100% of which is therefore available for the collection of light. In addition, the complete decoupling between the optical (front) side and the electrical (back) side enables each surface to be separately optimised for the function it must perform. Consequently, the front surface can be textured and antireflection coated to maximise light absorption and minimise carrier recombination, while the rear surface can be totally covered with the two polarities of metal electrode (figure 6.12). The cells thus have very low series resistance. Additionally, the metallic rear surface acts as an excellent light reflector, and also assists with side-by-side cell interconnection - leading to very high packing densities. A description of the technology used to fabricate the BSC cells is given by Verlinden, Swanson and Crane [6]. The *Dream* cells were 2.43 cm x 7.26 cm x 160 μm thick, with an average cell efficiency of 21.3%. The overall efficiency of the 8 m^2 panel was 20.3%.

The Deutsche Aerospace cells on the *Spirit of Biel III* were remarkable not only for their very high efficiency, but also for the fact that they were fabricated on Czochralski-grown silicon. This type of material is less expensive to produce than float-zone silicon, but generally produces cells of poorer performance. The achievement of a tightly-controlled cell efficiency of 19.0% on this material is therefore all the more noteworthy, and suggests the potential for significantly lower solar cell prices in future. The cells are apparently similar to the University of New South Wales PERT cell, which in turn is similar to the UNSW PERL (Passivated Emitter, Rear Locally-diffused) cell (figure 6.13) - a technology which currently holds the world record for efficiency (23.5%) for a silicon cell under one-sun illumination conditions [7].

Kyocera solar cells, as used by both Kyocera and Toyota, were fabricated using a photolithographic process to define the electrical contacts. These cells were made as a special fabrication on the R&D line of Kyocera's space cell production line. The cells are described [8] as being similar to the University of New South Wales PESC (Passivated Emitter Solar Cell) device (figure 6.14), but with random texturing of the front surface. Nissan's *SunFavor*, also used photolithographically produced cells. Supplied by Sharp from their space cell production line, these cells had a nominal efficiency of 18% and probably achieved around 17% under terrestrial (airmass 1.5) conditions.

Most commercially available solar cells are fabricated by depositing the top-surface electrodes with a screen printing process. This process is inexpensive, but somewhat limited in the efficiencies that can be achieved. Waseda University's *Sky Blue Waseda* achieved a remarkable fourth place with screen-printed cells hand picked from the Sharp production line (figure 6.15). Sharp cells were in fact the most popular choice in the

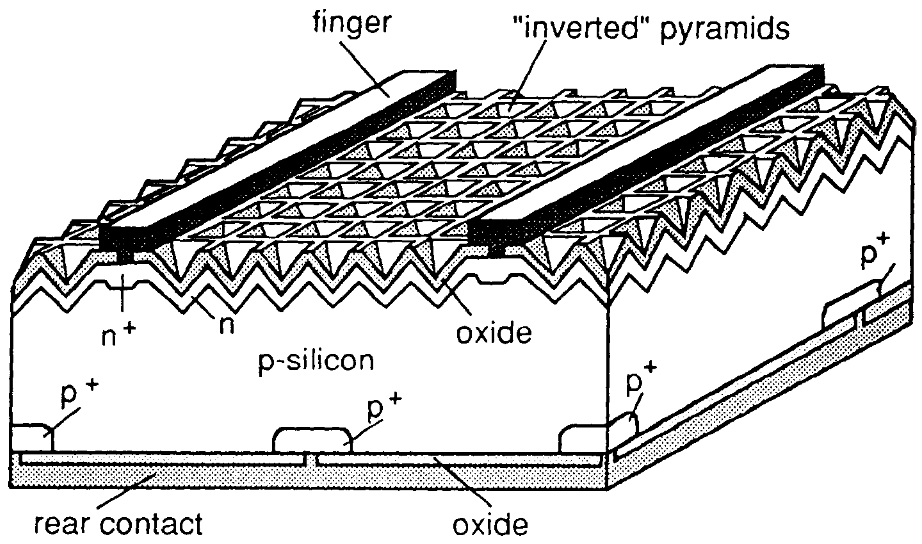

Figure 6.13 **J.** The University of New South Wales PERL (Passivated Emitter, Rear Locally-diffused) cell.

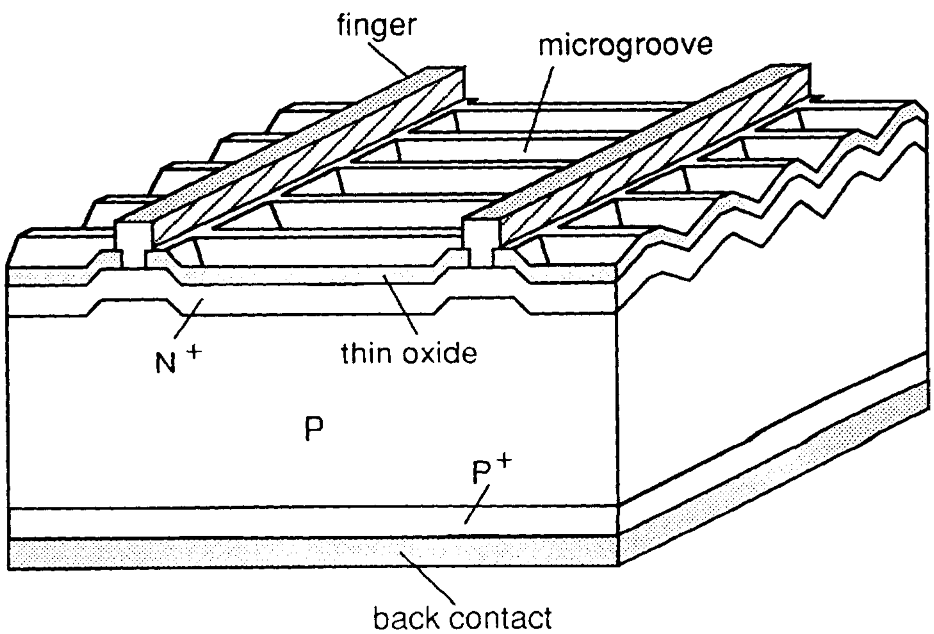

Figure 6.14 **J.** The University of New South Wales PESC (Passivated Emitter Solar Cell) cell.

race, being used by eleven of the 52 entrants. *Be-Pal III* was another top performing car to use screen-printed cells, this time from Showa Shell.

Laser-grooved cells [9] were used by fifth placed *Aurora Q1*. These cells (figure 6.16), called Green cells after their co-inventor, were fabricated on a pilot production line established in collaboration with Unisearch at the University of New South Wales. Other top-performing cars to use UNSW Green cells were NTU's *Desert Rose*, and the University of Michigan's *Maize and Blue*. The Aurora car also had a small number of UNSW PERL cells with efficiencies as high as 21%.

BP Solar have taken out a licence to produce the UNSW-developed laser-grooved cells, which they sell under the designation "Saturn". The adaption of the fabrication process to a production line is described by Mason and Jordan [10]. Cells produced on this line were made available at a modest price to the *Sunrayce 93* entrants, and were in fact used by nine of the top ten finishers in that race. In the 1993 World Solar Challenge, several of the top cars used these cells including the winner of the two-seater class, California Polytechnic Pomona, who used a mixture of BP Solar laser-grooved silicon cells, Spectrolab silicon cells, Applied Solar Energy silicon cells, and Mitsubishi GaAs cells! Other well-placed cars which used BP Solar laser-grooved cells were George Washington University's *Sunforce 1* and California State University, L.A.'s *Solar Eagle II*, which finished ninth and thirteenth respectively. In total, seven of the first fourteen finishers used laser-grooved cells.

A wide variety of other solar cell manufacturers were also represented, including Arco, Hoxan, Siemens, Solel, Astro Power, and Factory Pravda.

6.5 Panel Construction

Although cells can be used "bare", and simply glued to the surface of a supporting frame, there are significant advantages to be gained in encapsulating the cells. These include:

- Protection from water, which can corrode contacts.
- An aerodynamically smooth surface.
- Better refractive index matching.

A standard "commercial" solar panel uses a superstrate of toughened glass, typically about 3 mm thick, to which the cells are laminated with Tedlar (polyvinyl fluoride) and EVA encapsulant. Some teams (e.g. Mitcham High School - *ISIS*) used these standard panels, although they are very heavy. Other teams, such as Biel and Aurora, potted the cells in a clear resin. Such a resin, however, will reflect a few percent of the incident light from its top surface at normal incidence - and even more at oblique angles. (The same effect occurs with other superstrates such as glass; the magnitude of the reflection depending on the refractive index of the material.) This energy is lost even before it has the chance to reach the solar cell.

Honda sought to overcome this loss by using a specially developed moduling technique with a sawtooth-grooved surface on the upper surface of the acrylic cover, as shown in figure 6.17. The effect of these grooves was to give only a slight increase in the peak power at noon, but to give significantly increased power in the early morning and late afternoon. The nett gain (over a smooth acrylic surface) appears to have been about 2%. Honda were later to report that dust accumulation in the fine grooves caused concern during the race, but clearly the problem was not too serious.

After the race a small module consisting of 48 BSC cells was fabricated with the same techniques used for fabricating the *Dream* panel [11]. The efficiency of this module was independently measured by Sandia National Laboratories at 21.6%, setting a new world record for a flat-plate module.

Another clever feature of the Honda panel was that it was only 1.8 m wide, while the car itself was 2.0 m wide. The car could thus be built with curved sides and hence the best possible aerodynamics. (The full 8 m^2 projected panel area was still achieved, as the panel was 4.4 m long.) Many teams build their panels out to the full width of the car, with the inevitable result that an aerodynamically unfortunate bluff edge runs along the length of the car.

Except for one small section, the Biel panel had no anti-reflection coating. An experimental panel was fabricated, however, with a textured upper surface carrying 5 to 10 micron features. This produced up to 4% more power in Switzerland, and as much as 6% more power under Australian conditions, than did the standard sections. Unfortunately, a full panel with this textured surface was not ready in time for the race.

Figure 6.18 shows the "brickwork" shingling used by Biel to achieve the highest possible cell packing density. Not only were the gaps between the cells reduced to microscopic values, but the overlapping cells were placed so as to cover the contact pads of the cells below them. The active area of the array was thus increased to an astonishing 99%. Biel's modules were built by Deutsche Aerospace to exacting standards. Each module was 1 m x 0.5 m, and was machined to 0.01 mm accuracy on a numerically controlled milling machine. Only 1 mm thick, the entire panel weighed just 13 kg.

Both *Be-Pal III* and *Sky Blue Waseda* also use cell encapsulation with a textured upper surface. In Waseda's case this was created by impressing a cloth into the resin while it was still soft. Both teams performed extremely well, despite the modest efficiency of their screen-printed cells.

One of the more unusual panels was the "Space Umbrella" carried by Team New England. Made by SpectroLab for space use, the panel was light weight and flexible, allowing it to be folded up and carried inside their tiny, low-drag vehicle (figure 6.19, 6.20).

** insert table 6.2 here **

6.6 DC-DC Conversion.

In an efficient solar car it is important to be able to convert the voltage from one value to another with a minimum of loss. This is carried out by a DC-to-DC converter (figure 6.21). The input can be converted to a higher voltage by means of a boost-, or up-converter, to a lower voltage with a buck-, or down- converter, or to a voltage of opposite polarity and any desired voltage with a buck-boost converter. In each case the basic components are an electronic switch, such as a MOSFET (Metal/Oxide/Semiconductor Field-Effect Transistor), an inductor to store energy, and a steering (or "flywheel") diode which carries the current during that part of the cycle when the MOSFET is nonconducting.

Downconverter.

The MOSFET can be thought of simply as a switch (shown as S in figure 6.21), which turns on (typically with an "on" resistance of just a few milliohms) when a positive voltage is applied to its gate, and off (with an "off" resistance of many megohms) when the gate voltage is reduced to zero. During positive half-cycles of the gate waveform, the MOSFET is on and the current through it (and hence through the inductor and the load) increases as:

$$dI/dt = (V_{out} - V_{in})/L$$

When the MOSFET is switched off, the current that was passing through it now passes through the diode. The current decreases as:

Table 6.2 Solar cell and array performance of the top ten finishers.

Place	Car no.	Car name	Team	η_{cell} (%)	η_{panel} (%)	Peak power (W)	Average daily max. (W)
1	2	Dream	Honda	21.3	20.3	1800	1520
2	1	Spirit of Biel III	Biel	19.0	18.8	1750	1391
3	77	Son of Sun	Kyocera	18.5	-	1400	1200
4	55	Sky Blue Waseda	Waseda Uni.	15 - 17	16	1500	1100
5	30	Aurora Q1	Aurora Vehicles	18.8	-	1400	1130
6	56	Toyota 56	Toyota	18.5	-	1324	1092
7	15	Desert Rose	N.T.U.	18	17.5	1780	1250
8	25	Intrepid	Pomona	various	14	2000	1600
9	34	Sunforce 1	G.W.U.	14.5	-	950	910
10	151	Be-Pal III	Zero to Darwin	16	15.2	1100	900

Notes:

1. Cell and panel efficiencies are the values supplied by the teams prior to the race.

2. Peak and average maximum powers are the actual values recorded by the teams during the race.

3. Car # 25, Cal. Poly. Pomona's *Intrepid,* was a two-seater car and hence had a larger panel area than the other vehicles listed.

4. During unloading, G.W.U.'s *Sunforce 1* (car # 34) was severely damaged by a fork lift truck. This caused a reduction of at least 150 watts in the panel output.

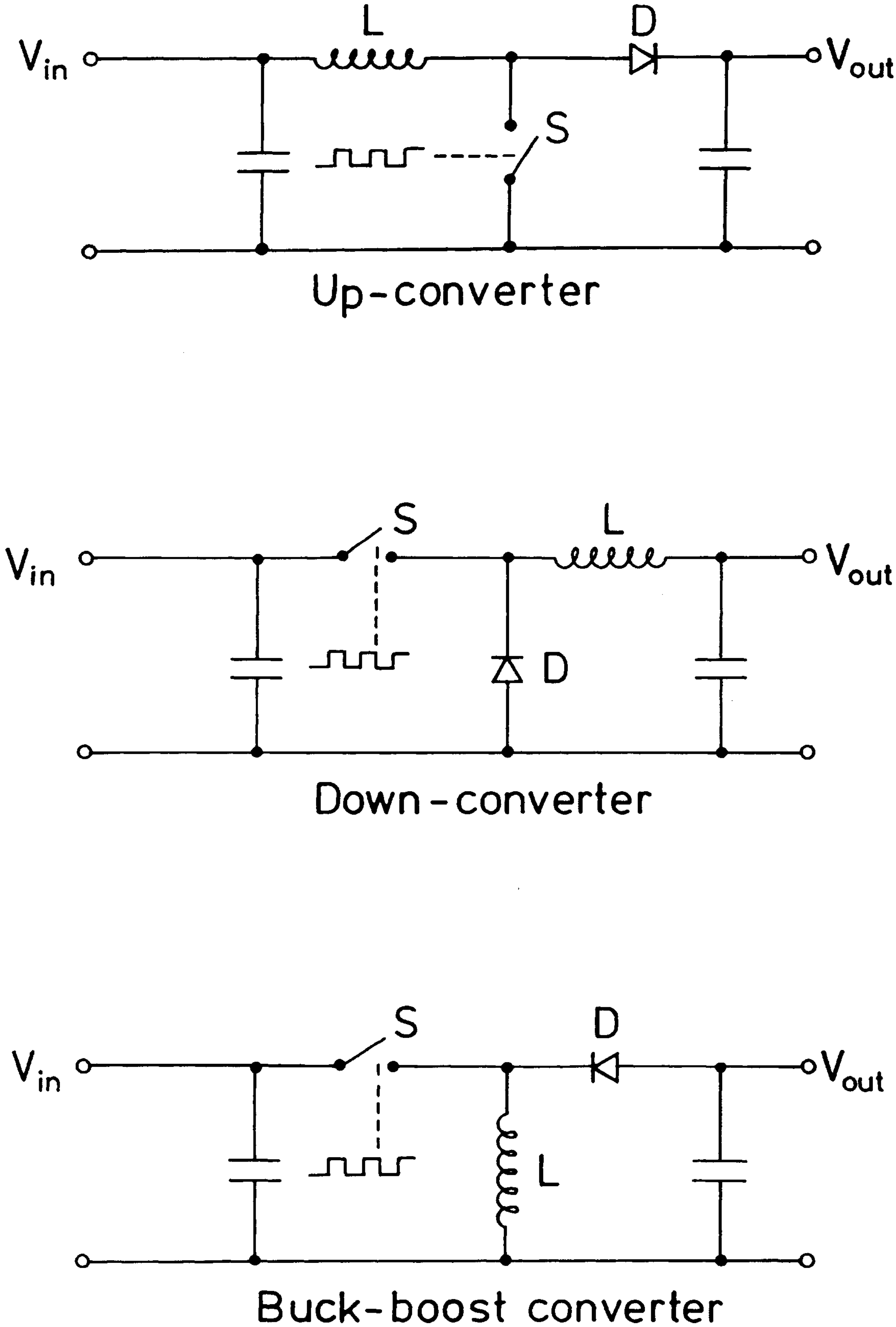

Figure 6.21 **J.** Simplified schematic of the three main topologies of DC - DC converter, used to match the output voltage of the solar panel to that of the load it is driving.

$$dI/dt = -V_{out}/L$$

until the MOSFET is switched back on again. The frequency of the switching waveform is made high enough that the changes in current are in fact very small; input and output capacitors reduce them even further. Under steady-state conditions it is straightforward to show that the duty cycle of the MOSFET gate drive waveform is just equal to the ratio of V_{in} to V_{out}.

Upconverter.

During positive half cycles of the gate waveform, the MOSFET is on and the current through the inductor increases:

$$dI/dt = V_{in}/L.$$

When the MOSFET is switched off, the current that was passing through it must now flow through the load via the diode, D. The current decreases as

$$dI/dt = (V_{out} - V_{in})/L$$

until the MOSFET switches back on again.

Relative to a down-converter, an up-converter suffers from two disadvantages:

1. The diode is always in series with the load current. Losses are therefore likely to be slightly higher.

2. In the absence of a load, the output voltage will rise without limit. Special protection circuitry is thus required to prevent the converter from destroying itself.

On the other hand, an up-converter is always able to supply current to the load, no matter how low the array voltage has fallen as a result of clouds, shading etc.

Buck-boost converter.

In this configuration the output voltage has the opposite polarity to the input voltage, and can be either greater or less than it in magnitude depending on the switch duty cycle.

A few general observations can be made. The higher the switching frequency, the smaller and lighter the inductor can be. However, switching losses in the MOSFET increase with frequency, as do both the losses in the inductor core and those due to the skin effect. An optimum operating frequency of a few tens of kHz is usually found. The on-resistance of the MOSFETS can be very low. During the part of the cycle that the MOSFET is off, the load current is carried via the diode. For this reason (and also because they are very fast), Schottky diodes with the lowest possible forward voltage drop are normally used.

6.7 Maximum Power Point Trackers.

In order to extract the maximum electrical power from a solar panel, it is essential that it be operated at close to its maximum power point, P, as shown in Figure 6.3. The maximum power-point voltage, V_{mpp}, is a function of cell temperature and illumination, and also varies from array to array even for cells manufactured under identical conditions. Furthermore, the load into which the panel is delivering its power, whether a battery or drive motor, will have its own characteristic I - V curve. It is therefore highly desirable to have a DC - DC converter which matches the solar panel to its load in such a way that maximum power is transferred. Such a device is known as a **Maximum Power Point Tracker** (MPPT).

An MPPT consists of a highly efficient DC-DC converter together with appropriate control circuitry which varies the mark-space ratio of the drive waveform to the switch in such a way as to maintain the input voltage to the tracker at the peak power point of the panel. Two ways of achieving this are in common use. The first, described by Schoeman and van Wyk [12], is based on the assumption that the maximum power point will be some fixed fraction of the open-circuit panel voltage. By periodically switching the panel to open circuit, this voltage can be monitored and the appropriate value for V_{mpp} obtained with a simple voltage divider. This was the technique used by NTU's *Desert Rose*, which employed 26 such trackers to give the highest possible output from all cells on its curved panel.

The second method used is to "dither" the input voltage around the optimum value by alternately giving it a small increment or decrement. The effect on the output power is then assessed (often it is sufficient to monitor just the output current and assume the output voltage remains constant), and a further small correction made to the input voltage in the correct direction. In Biel's realisation of this method, the dither frequency was 40 Hz, and the overall conversion efficiency was 99% at 500 watts.

Ten teams, including Honda, Biel, and NTU, built their own MPPTs. MPPTs are also available from a variety of commercial manufacturers, including the Australian Energy Research Laboratories (AERL), AES, Brusa, Kyocera and Solectria. All units are extremely efficient, with efficiencies often exceeding 99%. Some, such as that manufactured by AERL, are down-converters, while others, such as the Brusa/Solectria device, upconvert.

The AERL MPPT, sold under the name "Maximizer" uses a patented technology to maintain its input at the maximum power point to very high accuracy. This particular MPPT was used by 24 cars, or almost half the field. In fact, a total of 111 AERL trackers were installed in various cars, making it probably the single most-generally used component in the race! Many teams used multiple AERL trackers, with two cars, *Maize and Blue* and *Solarcat III* each using eleven. Most of the vehicles used the latest model from AERL, the "Mini-maximizer", which can deliver up to 600 watts and weighs just 0.35 kg. Losses are typically 3 to 6 watts, allowing efficiencies in the range 98.3 to 99.3% to be achieved.

Almost all teams used one or more MPPTs. Of the eight vehicles which did not, only one (Dripstone High School's *Aquila*) finished the race (figure 6.22).

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Figure Captions.

Figure 6.1 Honda's solar panel was one of the most efficient solar modules ever made for any purpose.

Figure 6.2 Current versus voltage (I-V curve) of solar cell at 25 ^oC (solid curve), and 60 ^oC (dotted curve). I_{sc} and V_{oc} are the short-circuit current and open-circuit voltage respectively. MPP signifies the **maximum power point**, the point on the curve corresponding to maximum output power from the cell.

Figure 6.3 Power output versus output voltage for a typical solar cell. Note the shift in maximum power point as the temperature is increased to 60 ^oC (dotted curve).

Figure 6.4 Cleanliness is next to godliness - it doesn't hurt the efficiency, either. Many teams sprayed their cells with water to lower their temperature and hence increase the efficiency. Kyocera, shown here, was the only solar cell manufacturer to enter their own car.

Figure 6.5 San Diego State University's *Suntrakker* carried cells on the underside of the car to take advantage of diffuse radiation.

Figure 6.6 Aurora carried extra panels inside the car so that they could be deployed in the morning and evening for additional solar generating capacity. With the extensions, the stationary panel still fits within the regulation dimensions.

Figure 6.7 Polycrystalline silicon solar cells have a characteristic mottled rainbow appearance.

Figure 6.8 *Le Soleil* was the only car in the race with inexpensive but low efficiency amorphous silicon solar cells. *Le Soleil's* cells had an efficiency of about 6%, while other types of silicon cells had triple this efficiency or more.

Figure 6.9 As a two-seater car California Polytechnic Pomona's Intrepid was allowed to carry 12 square metres of cells. The team filled this vast panel with three different types of silicon cell, plus some gallium arsenide devices.

Figure 6.21 Simplified schematic of the three main topologies of DC - DC converter, used to match the output voltage of the solar panel to that of the load it is driving.

Figure 6.22 Dripstone High School's *Aquila* was the only car to finish the event without the benefit of maximum power-point trackers.