<u>A Short Explanation of the Effect of Low Fill Factor on Model Solar Car Performance.</u>
(And how it could be used to advantage.)

Before you read this be aware of the following:

I am not having a go at anyone, any school or any team.
I have not named anyone, any school or any team.
I have not accused anyone, any school or any team of cheating or anything else.
These are the views of the author alone and not necessarily the views of any other person whether they are a member of any state or national committee or not, and are not necessarily the views of any such state or national committee.
I am merely representing the facts as I (and some others) see them, and presenting the information as a public service to ensure the competition is as fair and equal as possible.
If anyone feels offended or unfairly singled out, tough. Get over it.

Everyone knows that solar panels produce an open circuit voltage and a short circuit current and that these are easy to measure with a multimeter. Also, most people have learnt by now that the maximum power produced by the solar panel is not equal to Voc times Isc but is something less than that figure. The ratio of the actual maximum power to Voc x Isc is called the Fill Factor. The laws of the universe limit the FF to a maximum of about 0.85 and the laws of commercial reality limit the minimum worthwhile figure to around 0.7. Most of this missing power is dissipated in the internal series and shunt resistances inherent in the manufacture of the cells themselves and there is little we can do about it except perhaps spend a lot more money for higher quality cells.

The type of cells that we can afford for our model solar cars are probably sourced from off-cuts and surplus stock but are still usually of normal commercial quality, with a FF of around 0.7. Occasionally though, a hobby cell will turn up that has been made from wafers that would normally have been rejected out of hand, perhaps due to a temporary shortage of normal quality stock.

In the many years of model solar car racing, this inferior quality of cell has only been observed on two cars, each from a different state, although the cells came from the same supplier. Initially both cars performed very badly, as would be expected. No-one really understood why, in both cases blaming faulty wiring or damaged cells. After all, there were cars fitted with very similar cells from the same supplier that behaved completely as expected.

Recently, however, one of these two cars, still equipped with some of these cells, performed way above expectations in the low light conditions experienced at the Nationals held in Adelaide in 2007. Subsequently a great deal of time and effort has been expended by three separate parties to analyse and fully understand the reason for this apparent superior performance and to undertake measures to ensure that the regulations are fair and equitable for all competitors.

In simple terms, it works like this. The cells produce a current that is proportional to the light that is falling on them and generate a voltage determined by the number of cells and the properties of the silicon atom, around 0.6 volts per cell open circuit. The internal parasitic resistances chew up some of this so the real world results are a little bit different.

The first question is this, what would be the effect on a model solar car if the panel used had a lower than normal Fill Factor? The second question then, is this. If there is some advantage in having a low FF panel, how can a panel with this normally unwanted characteristic be obtained? The answer to both questions is alarmingly easy to determine. Since the FF of solar cells is altered by the internal series resistance, what would happen if we just add some more series resistance external to the cells?

Imagine if you will, a large solar array comprising 48 cells each capable of (say) 500mA in full sun, connected in series/parallel to give 14.4 volts open circuit and 1 amp short circuit. By all normal reasoning, this panel should deliver around 10.5 watts when tested on a light box. This panel would therefore be required to weigh 1388 gm to satisfy the rules.

Now, consider what happens if we artificially lower the FF by simply placing 4 ohms in series with the output. The open circuit voltage will not change as there is no current flowing so no voltage is lost across the resistor. The short circuit current will not change since the cells generate current proportional to the light falling on them. (Actually they will both drop a little bit, but not enough to raise suspicion.) We can only detect that something is wrong when we measure the maximum power output of this large panel and we only get a figure of 6.5 watts! The missing 4 watts are going up in the resistor. ($P = I^2R$) Not only that but the maximum power voltage is not around the expected 11.5 volts but is several volts lower. No big deal, I hear you say, the panel only delivers 6.5 watts, let it only carry the 688 gm as required and all will be OK.

Wrong, wrong, wrong!!! Let's see what happens when the light level falls below 100%? At 50% the current will drop to 0.5 amps and the power from our panel will drop to 3.25 watts. No it won't!!! In a perfect world the power from the unmodified panel would drop to 50% or 5.25 watts but the power lost in the extra series resistor is not halved. The power in the resistor equals the resistance times the SQUARE of the current so the loss is now 0.5 x 0.5 x 4 or only 1 watt not 2 watts, meaning the resulting power output is 4.25 watts, a gain of 1 watt or 31% over a 'standard' panel. And it only gets worse at lower light levels.

At 25% the expected power would be 6.5/4 or 1.625 watts. However, our modified panel delivers 10.5/4 – 0.25 x 0.25 x 4 = 2.625 – 0.25 = 2.375 watts!!!! This is a theoretical gain of 46% and you can see that this can be a huge advantage. In fact, at all light levels below 100%, which is most of the time, a car equipped with such a panel will have a significant advantage over other cars.

At very low light levels it performs like a 10.5 watt panel but only carries the weight of a 6.5 watt panel. You don't need to be Einstein to work out which car will go better in low light.

To prove that this is not all fiction, a colleague in Melbourne, who shall remain nameless for his own protection, tested several different panels on a light box with the following results.

Standard 6 watt panel (9 DSE segments) Fill Factor 0.68

%Sun (Nominal)	Voc volts	Isc amps	Power @ watts	V	&	mA
100	15.85	580	6.3	12.1		524
80	15.55	452	4.9	12.3		403
50	15.1	282	3.06	12.0		255
20	14.25	113	1.17	11.77		100

Standard 9 watt panel (13 DSE segments) Fill Factor 0.69

%Sun (Nominal)	Voc volts	Isc amps	Power @ watts	V	&	mA
100	23.2	576	9.22	17.5		527
80	22.16	453	7.0	17.86		393
50	21.85	287	4.45	17.73		251
20	20.85	112	1.72	17.8		97

Modified 9 watt panel (13 DSE segments) Fill Factor 0.57
Series resistance added to reduce output power to 6.3 watts

%Sun (Nominal)	Voc volts	Isc amps	Power @ watts	V	&	mA
100	23.2	564	6.3	13.4		471
80	22.16	452	5.37	13.8		389
50	21.85	287	3.79	15.31		248
20	20.82	117	1.65	15.76		105

Power comparison of standard panel to modified panel

%Sun (Nominal)	Power Std panel watts	Power Mod panel watts	Power increase %
100	6.3	6.3	0
80	4.9	5.37	9.6
50	3.06	3.79	23.8
20	1.17	1.65	41.0

Notice how, allowing for experimental errors, the output current is only affected by the light level, and also notice that the performance of the two standard panels is in agreement with the number of cells in them. Notice that the maximum power voltage of the modified panel actually rises significantly at lower light as the resistor loss decreases. These actual test figures agree quite well with the simple first principles example given earlier.

My unnamed colleague then went a step further and fed the data into a simulator which is based on actual performance figures from a number of actual model solar cars.

Performance prediction summary.

Sun %	Race time seconds		Winning margin	
	Std panel	Mod panel	Seconds	Metres
100	No change, identical performance.			
80	18.95	18.45	0.5	3.6
50	21.9	20.45	1.45	9.1
20	32	27.6	4.4	20

Yes, you read correctly. At 50% light the modified car would be 9 metres in front and at 20% it would be a whole 20 metres in front!!! That's the full length of the straight!!! Even at 80% it was still 3.6 metres in front so at 90% or 95% it is reasonable to assume that it would still be measurably in front. What's more, I know this is true, I've seen it with my own two eyes. This is really scary stuff, and up until now it has probably been basically legal.

OK, how do you the competitor take advantage of this quirk of the rules? Well there is unfortunately an inherent difficulty purchasing cells to order with a low FF. There have only ever been two cars observed at the Nationals with such cells and the cells in question came from the same supplier. All other cells from this and other suppliers have had the expected FF and the performance to match. But all is not lost. Now that you know how this works you can make your own, it's easy.

First decide what type of cells you are going to use. Dick Smith, Scorpio, Tech Ed Centre, others, it doesn't matter, the method is the same. Make up as big a panel as you can that weighs just over 600gm to take full advantage of the power to weight formula. If you are fortunate enough to have access to a light box measure the power output, the open circuit voltage and the short circuit current. If you don't, work on Voc x Isc x 0.7 and you won't be far out. You may have to rearrange the panel to get the voltage and current that you want and more on this in a while. Make sure you keep below 25 volts and 2 amps.

Subtract 6 watts from the panel power and then use $P = I^2R$ to work out what value of extra resistance you need. You could just use normal resistors but this would probably raise the ire of the scrutineers as these are technically electronic components and must not be on the solar array. One possible much better idea would be to use resistance wire that you can get from Jaycar. This is 14 ohms per metre so for 4 ohms you only need about 280 mm. For my fore mentioned colleague's experimental panel he used 10.8 ohms which would need about 770 mm. This much wire is easy to hide by stripping out some normal cable and pulling in the resistance wire instead.

Then you fit several probably totally unnecessary multi-pole switches to the panel and wire the whole thing using your 'special' cable and more of the original unstripped cable. Go up and down several times to make it harder for the scrutineers to trace out and to use up all the cable. This is where you put the cells in the necessary series/parallel arrangement to get the desired voltage and current. Resistance wire is hard (but not impossible) to solder. Underfloor heating cable is another idea.

There you have it, an almost sure fire way to win at model solar car racing even if you have only built an otherwise pretty basic car. Oh, one more thing. Waste lots of time needlessly changing gears at the start of your races while waiting for clouds to cover the sun. After all, the cloudier the better.

Oh dear, one last thing. I forgot to mention that the scrutineers are awake up to this little ploy and the rules for 2008 have been re-written to prevent this being done. You cannot have any switches at all on your array. All wiring must be done with standard copper conductors. Individual sections of your array can be tested separately, bypassing the wiring, and then summed. The power may be measured at 50% sun level and then doubled. Supposed ‘faulty panels’ will be viewed with even more suspicion than in previous years. The concept of ‘Spirit of the Event’ will be more closely examined.

Such a shame, good while it lasted though, wasn’t it?