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Solar-Electric Generation Considerations for the Solar Plane

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Solar Array Description

A total of 32 solar cells are mounted in the aircraft wing. The cells in each half of the wing are wired in series. Then, the two strings are paralleled. This has the advantage that if the cells in one tip section suffer a poor Sun-cell angle (perhaps because of a banked turn, or if the flight path favors one wingtip over the other) the other side of the wing will be favorably angled toward the Sun.

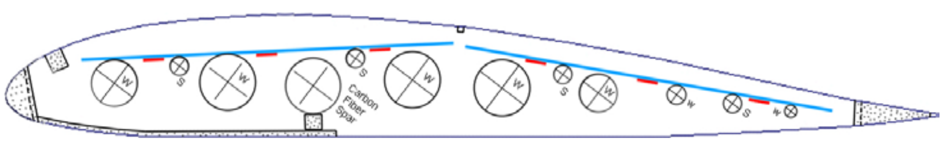
I'm using Sunpower Maxeon C60 cells because they have these excellent properties for use in the plane:

- High efficiency (22.4%)
- High output power (3.38W/cell at standard test conditions)
- Lightweight (6.25 grams/cell)
- Convenient size (5 x 5 x 0.006")
- Flexible
- Cheap! (under $2.00 each, on eBay)

Cell Mounting

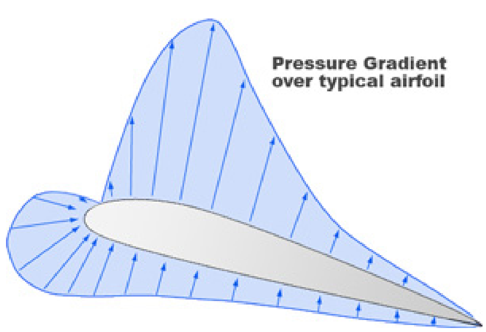
The cells are mounted internally in the wing's three panels, sitting in free air below the clear shrink-film covering. The center section of the wing is flat, but each wingtip section is tilted upwards with 11.3 degrees of dihedral (slope=0.2). Within the wing, the forward row of cells tilt nose-down at 3 degrees, and the rear row tilts nose-up at 9 degrees. Shadowing of cell edges by neighboring ribs is minimized by leaving 1/2" gaps between cells and ribs.

This drawing shows the location of the cells (shown in blue) within the wing:



Cell Cooling

By design, solar cells have very low albedo. Much of the solar energy striking the cells remains as heat. Hot cells produce less voltage, so elevated temperatures are the enemy. Even a 25C (45F) temperature rise costs 8% in output voltage. The wing will be designed with inlet and exhaust ports to allow an in-flight internal flow of cooling air to lower cell temperatures. The cooling ports will be positioned to maximize pressure differences and airflow.



Drawbacks of Series-Connected Solar Cells and the Impact of the Cosine Law

In a series connected string of solar cells, the output current delivered by the string is limited by the cell of lowest output current. That's *really* important, because a single cell (or group of cells) that's performing poorly will drastically limit the output current of the entire array! For example a 250W, 60-cell rooftop solar panel that's 3' x 5' can be completely shut down by the shadow of one Maple leaf or by the shadow of a rooftop vent pipe casting a small shadow on the panel.

It becomes necessary to evaluate the performance of the array based on the lowest-performing cell in the string. Consider these examples:

1. While flying away from the sun, the nose-up cells in the rear of the wing have favorable pointing toward the sun, potentially yielding more output from the array. Unfortunately, the nose-down cells at the front of the wing are disadvantaged by this geometry. It's the output current of the weaker cells at the front of the wing that sets the performance.

2. Consider level flight with the Sun directly off one wingtip. Not only do we need to account for the nose-up & nose-down tilts of the cells, but now one tip section favors the sun (because of dihedral), and the other tip is disadvantaged by its poor sun-cell pointing angle. The wing that's farthest from the sun gets a boost, while the tip closer to the sun takes a hit.

The "Cosine Law" lets us calculate the projected area of each cell (and hence, the solar energy it receives) as seen by the sun. The cell's output is maximum when the sunlight arrives normal to the cell's surface. If the angle is less than 90°, the received solar energy varies with the cosine of the pointing error.

For example, if the light strikes a cell off-axis by 30°, the cell captures 86.6% as much sunlight, and produces 86.6% as much current, as it would with perfect pointing. At a 45° error, the cell's projected area is down to 70.7%. When the error gets to 90° the illumination is from the side of the cell and the output drops to nearly zero current.

Note: Cell illumination from diffuse skylight accounts for less than 15% of the full-sun output current.

Estimating the available electrical power from the plane's solar array is very complicated, given that there are six groups of cells in the wing all pointing in slightly-different directions. In flight the airplane undergoes changes in pitch, bank, and roll. The direction of flight varies with respect to the sun's azimuth angle. The sun's elevation angle varies by season and by time of day. I can only guess what temperature rise the cells will experience inside the wing during flight. Also, air temperatures vary. A cool day at 60F OAT will give 10% more voltage (and power) to propel the airplane versus a hot summer day at 105F.

The Computational Challenge

I'm not a genius. I'm not a wizard at math. I'm no good at spherical trig. So, I've tried to answer some basic questions about how the sun moves across the sky and I've tried to estimate the performance of the plane's two solar strings during flight. I've run experiments to evaluate the effects of placing clear Solite covering film over the solar cells. I've estimated the cells' performance at elevated temperatures.

To perform the calculations below, I've made some assumptions:

- Cell temperature during flight = 50C (122F)
- Solite wing covering film causes 8% output current reduction (established by direct measurement)
- The first set of calculations is for a Sun-zenith angle of 20°
- The first set of calculations is for a Sun-zenith angle of 30°
- Each series-connected string will operate at (16)(Vmp) = 8.0V
- At 50C cell temp and 1-Sun normal to the cell's surface: Vmp = 0.50V, Imp = 5.70A (from the Sunpower C60 datasheet)

Case-1 Level flight with Sun off one wingtip:

For the *adverse* wingtip, Imp = (5.70A)(.92SoliteTransmission)(Cos(20ZenithError+11.3dihedral)) = 4.48A

For the *advantaged* wingtip, Imp = (5.70A)(.92SoliteTransmission)(Cos(20ZenithError-11.3dihedral)) = 5.19A

These two strings are paralleled, so the total power is 8.0V @ 9.67A = 77.4W With sun off either wingtip

Case-2 Level flight toward the Sun:

Rear cells tilt away from the Sun and dihedral reduces projected wingtip area.

Imp = (5.7A) (.92SoliteTransmission) (Cos(20ZenithAngle+9RearCellTilt))(Cos(11.3Dihedral)) = 4.50A from each wing half

These two strings are paralleled, so the total power is 8.0V @ 9.00A = 72.0W   Flying toward Sun

Case-3 Level flight away from the Sun:

Front cells tilt away from the Sun and dihedral reduces projected wingtip area.

Imp = (5.7A)(.92SoliteTransmission) (Cos(20ZenithAngle+3ForwardCellTilt))(Cos(11.3Dihedral)) = 4.73A from each wing half

These two strings are paralleled, so the total power is 8.0V @ 9.46A =75.7W   Flying away from Sun

A similar set of calculations were performed allowing for a zenith-Sun error of up to 30 degrees. Results are summarized in the table below.

Solar Power Generated vs. Flight Path and Sun-Zenith Angle

Flight Path	**20° Sun-Zenith Angle(1)**	**30° Sun-Zenith Angle(1)**
Sun is off either wingtip	Imp= 9.67A, P= 77.4W	Imp= 8.91A, P= 71.3W
Flying toward Sun	Imp= 9.00A, P= 72.0W	Imp= 8.00A, P= 64.0W
Flying away from Sun	Imp= 9.46A, P= 75.7W	Imp= 8.62A, P= 69.0W
Random or circling path	Imp= 9.45A, P= 75.6W (avg)	Imp= 8.61A, P= 68.88W (avg)

Notes
1. Dates and times for these Zenith-Sun angles are available from the chart of "Solar Altitude by Month and Hour".
2. String voltage is set by Vmp=0.50V/cell at 50C, so operating voltage is 8.0V.

Solar Altitude by Month and Hour, Plus Relative Projected Area of Horizontal Collector

(Los Angeles, CA)

Gary Stevens 7/5/16

	9AM	10AM	11AM	Noon	1PM	2PM	3PM	Time Standard
21-Jan	20	28	34	36	34	29	22	PST
	0.34	0.47	0.56	0.59	0.56	0.48	0.37	
21-Feb	27	36	43	45	44	38	29	PST
	0.45	0.59	0.68	0.71	0.69	0.62	0.48	
21-Mar	25	36	46	54	57	54	46	PST
	0.42	0.59	0.72	0.81	0.84	0.81	0.72	
21-Apr	33	45	56	65	68	63	54	PDT
	0.54	0.71	0.83	0.91	0.93	0.89	0.81	
21-May	38	50	62	72	76	69	58	PDT
	0.62	0.77	0.88	0.95	0.97	0.93	0.85	
21-Jun	38	50	63	74	79	72	61	PDT
	0.62	0.77	0.89	0.96	0.98	0.95	0.87	
21-Jul	36	48	60	71	76	71	60	PDT
	0.59	0.74	0.87	0.95	0.97	0.95	0.87	
21-Aug	32	44	55	64	68	63	54	PDT
	0.53	0.69	0.82	0.90	0.93	0.89	0.81	
21-Sep	27	39	48	54	56	52	44	PDT
	0.45	0.63	0.74	0.81	0.83	0.79	0.69	
21-Oct	21	31	39	44	45	41	34	PDT
	0.36	0.52	0.63	0.69	0.71	0.66	0.56	
21-Nov	24	31	35	36	32	26	17	PST
	0.41	0.52	0.57	0.59	0.53	0.44	0.29	
21-Dec	19	27	31	32	30	25	17	PST
	0.33	0.45	0.52	0.53	0.50	0.42	0.29	

KEY:
- Altitude (degrees above horizon)
- Projected area of horizontal surface %

Sun is above 60 degrees

Sun is above 70 degrees