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# PHOTOVOLTAIC ELECTRIC POWER APPLIED TO UNMANNED AERIAL VEHICLES (UAV)

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## ABSTRACT

Photovoltaic Electric-Powered Flight is receiving a great deal of attention in the context of the United States' Unmanned Aerial Vehicle (UAV) program. This paper addresses some of the enabling technical areas, and their potential solutions. Of particular interest are the long-duration, high-altitude class of UAVs whose mission it is to achieve altitudes between 60, 000 and 100,000 feet, and to remain at those altitudes for prolonged periods performing various mapping and surveillance activities. Addressed herein are studies which reveal the need for extremely light-weight and efficient solar cells, high-efficiency electric motor-driven propeller modules, and power management and distribution control elements. Since the potential payloads vary dramatically in their power consumption and duty cycles, a typical load profile has been selected to provide commonality for the propulsion power comparisons. Also, since missions vary widely with respect to ground coverage requirements, from repeated orbiting over a localized target, to long-distance routes over irregular terrain, we have also averaged the power requirements for on-board G&C power, as well as ground control and communication link utilization.

In the context of the national technology reinvestment program, wherever possible we modeled components and materials which have been qualified for space and defense applications, yet are compatible with civilian UAV activities. These include, but are not limited to solar cell developments, electric storage technology for diurnal operation, local and ground communications, power management and distribution, and control servo design.

And finally, the results of tests conducted by Wright Laboratory on ultra-light, highly efficient MOCVD GaAs solar cells purchased from EPI Materials Ltd. (EML) of the UK are presented. These cells were also used for modeling the flight characteristics of UAV aircraft described in Section 3.0 and Table I.

**1.0 Solar-Electric UAV Background and History:** Solar powered human flight has been accomplished, and needs no elaborate historic overview. It evolved from the ultra-light technology of AeroVironment's human-powered aircraft, and evolved from retrofitting similar vehicles with single-crystal silicon solar cell arrays and electrically-driven propellers. They sustained low-level flight for limited periods, and remained airborne largely at the whim of prevailing weather conditions. In fact, as a class they can be described as propeller-augmented sail planes. Later, in the fall of 1991, Eric Raymond's Sun Seeker aircraft, using Sanyo amorphous silicon cells deposited on polymeric film, logged a cross-country flight of 2,467 miles during a series of hops which totalled 119 hours of electrically-augmented flight. But again, at the risk of under-emphasizing the significance of these remarkable accomplishments, this aircraft was controlled more by the weather than the pilot, and the aircraft electrical propulsion system.

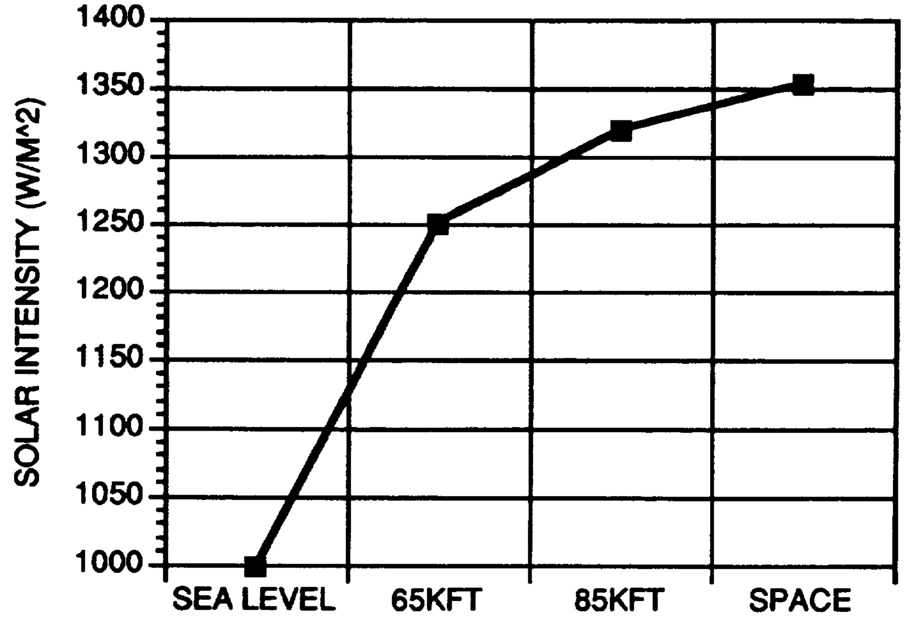

Figure 1: Relationship between altitude and solar intensity

**2.0 Insolation vs Altitude:** If the extended mission UAV must takeoff and achieve operational altitude as a conventional aircraft, it must operate through a wide spectrum of solar intensity which varies with altititude. On the ground, even though the batteries are fully charged, the array must be sized to operate the propulsion subsystem at Air Mass 1 (AM-1.0) However, as the vehicle climbs higher, and begins to rise above the near-ground atmosphere, it will eventually be receiving solar insolation which is 80-90% of AM-0.

Figure 1 depicts a general spectrum of solar intensity vs altitude, and shows an approximate gain of 25% in solar intensity at operating altitude. This prompts the designer to seek various means of hybrid or aircraft-assisted takeoff and climb-out augmentation, but in this paper, only electrical storage and solar power were modeled.

**3.0 Impact On Aircraft Performance of Solar Cell Efficiency and Weight:** As a general observation, until recently the efficiency of solar cells was inversely proprtional to their weight. Space-qualified single crystal silicon cells, which are moderately efficient (14-16%,) are comparatively heavy, and require large wing-surface mounting areas in order to achieve a given power level. In later developments, when engineers were enticed by amorphous silicon cells deposited on thin, flexible films, because they were dramatically lighter in weight, it was necessary to devote 60% more surface area because of their lower efficiency. The applicability of using standard GaAs-on-Ge technology for higher efficiency (18% @ 28°C, AM-0)) will not improve the aircraft weight due to the fact that the resulting array weighs even more than single-crystal silicon of a comparable thickness. It should be noted that certain U.S. companies are working on 3-mil GaAs-on-Ge technology, but this was considered too far term to use for a near-term comparison. However, in the present timeframe, a British company is demonstrating high-efficiency, thin-film GaAs solar cells which are comparable in weight with a-Silicon-on-Kapton blanket material, or conventional blanket consisting of GaAs deposited on germanium substrates, then bonded to a Kapton blanket. The relative merits of cost for per watt for the various options are not addressed in the paper.

It was considered useful in our analysis to review an existing UAV experimental aircraft (Pathfinder) and the associated weight and power algorithms that are derived from it, then calculate aircraft performance over a range of solar cell efficiencies and array mass densities. We then revised or updated aircraft component characteristics such as propulsion and storage conversion efficiencies, and solar cell/ wing area ratios, then compared the new over-all airplane performance using state-of-the-art solar cells with the new model using vastly improved solar cells.

For this purpose, the authors interfaced with EPI Materials Ltd (EML) of the UK and used their ultra thin, ultra-lightweight MOCVD GaAs solar cells modeled for application to the new "Pathfinder" baseline aircraft. The results of this modeling are presented in Table I.

## TABLE I

EFFECT OF PHOTOVOLTAIC OPTIONS ON ELECTRIC AIRPLANE PERFORMANCE USING EPI MATERIAL LTD. (EML) THIN FILM GAAS CELLS

| FLIGHT CONDITIONS*<br>• 60 KFT<br>• Winter Solstice<br>• 24 Hr. Operation | NEW BASELINE PATHFINDER | EML STANDARD THIN-FILM GAAS | EML BIFACIAL THIN-FILM GAAS (ALBEDO=.24) |
|---|---|---|---|
| Cell Efficiency (%) | 21 | 21 | 24.6 |
| Cell Mass Density ($lbs/ft^2$) | .0457 | .0228 | .0228 |
| Payload Wt. (lbs) | 100 | 100 | 100 |
| Propulsion Wt. (lbs) | 233.9 | 179.6 | 153.1 |
| Misc. Wt. (lbs) | 117.4 | 89.5 | 76.3 |
| Solar Cell Wt. (lbs) | 132.5 | 51 | 43.5 |
| Energy Storage Wt. (lbs) | 1060.4 | 822 | 701.1 |
| Airframe Wt. (lbs) | 274.9 | 233.7 | 197.6 |
| Total Aircraft Wt. (lbs) | 1919.1 | 1465.8 | 1271.6 |
| Wing Area ($ft^2$) | 3636.3 | 2790.5 | 2339 |
| Wing Span (ft) | 208.9 | 183 | 169 |
| Storage Energy Density (Whrs/lb) | 126 | 126 | 126 |
| Payload Power (w) | 250 | 250 | 250 |
| Misc. Power (w) | 115.5 | 88 | 75 |
| Propulsion Power (w) | 8352.7 | 6413.8 | 5467.9 |
| Total Power (w) | 8718.2 | 6751.8 | 5792.9 |

* Wright Laboratory Spreadsheet Model

It should be noted that the UAV design challenge is not merely sustaining marginal near-ground flight conditions. It involves the optimization of an un-piloted aerodynamic vehicle and electrical propulsion system which will permit the UAV to operate completely under the control of the ground station, at extremely high altitude, for extended periods, bearing a payload, which for purposes of our comparison, weighs 100 pounds.

The aircraft, depending on mission requirements and design restrictions, may be capable of taking off conventionally on its own power and climbing out to design altitude, or if practical, it may be assisted by auxilliary propulsion, or carried aboard a larger mother aircraft where it is released at altitude. A computerized ground-control system will then "pilot" the aircraft robotically on a prescribed course over specified surface targets on a real-time basis. The electric propulsion and control systems would be capable of maneuvering the vehicle on an accurate, pre-specified flight plan during normal environmental conditions, thus requiring an adequate margin of power for all-weather aerodynamic stability.

It is clear from examining Table I that the use of EML ultra-lightweight, single-sided (high efficiency) solar cells reduces the present weight of a "Pathfinder" type aircraft significantly. Please note that Table I does not include performance for an aircraft with the type of solar cells currently used on the LLNL "Pathfinder" (mass density of 0.103 lbs./ft.$^2$.) For winter solstice flight conditions, this aircraft would weigh in excess of 6000 lbs., and have a wing area greater than 10,000 ft.$^2$, which is clearly an impractical design.

Column No.1 of the table is for a hypothetical baseline aircraft, similar to "Pathfinder," but with significant changes and/or improvements to aircraft component performance characteristics, as follows:

A. Propulsion efficiency is increased from 64% to 70%, which is considered feasible using available technology

B. Energy storage efficiency has been increased from 45% to 65%, which by today's space and aircraft technology standards is quite conservative

C. Solar cell/ wing area ratio has been upgraded from 0.55 to 0.799 by mounting solar cells on surfaces inside a transparent wing (see Fig.3)

D. Wing aspect ratio has been changed from 25 to 12

E. Cell performance has been increased from 19.5% to 21% efficiency, and cell density decreased from 0.103 to 0.0457 lbs./ft 2, which the authors note is presently unsurpassed by several potential domestic options other than the cells produced by EML

F. The lift coefficient has been reduced from 1.0 to 0.78 to assure that the airplane travels at 20 ft./sec above the theoretical stall speed

In addition, the analyses were made for planes flying at worst optical conditions (winter solstice,) rather than summertime conditions.

It should be noted that despite an arbitrary increase in "pathfinder" solar cell efficiency from 19.5 to 21%, and reducing the cell mass density by 55%, the weight of this model could be reduced even further if EML cell technology were employed. For example, if the present cells were replaced by the EML single-sided cells, another 453 pounds could be saved, and if EML bifacial cell technology were employed, almost 650 pounds could be saved. It is also shown that the power requirements can be reduced from 8.7 kW to 6.7 kW using the EML single-sided cells, and to 5.8 kW for the bifacial cells.

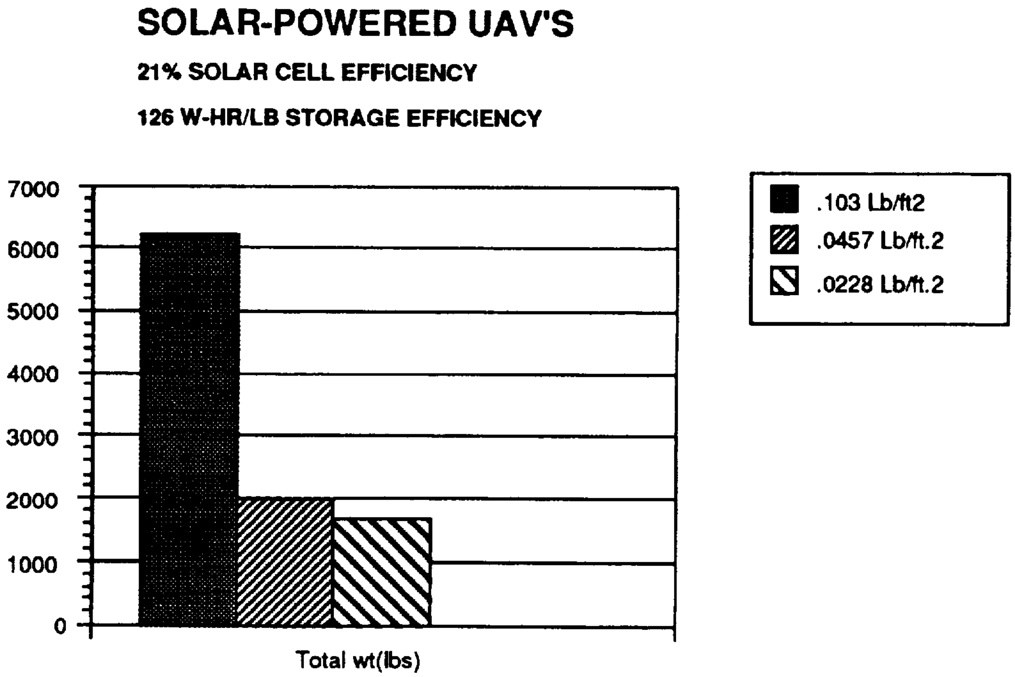

**Figure 2: Impact of improved solar cell weight densities on total aircraft weights**

Figure 2 illustrates graphically the effect of cell mass density on aircraft total weight for a 21% efficienct cell. It is also evident from Table I that significant gains in energy storage round-trip efficiency will dramatically reduce the overall aircraft weight. For example, present advances in space technology now yield upwards to 80% charge/discharge efficiency, which when coupled to improved storage capacity density in watt-hrs./lb, could make a profound impact on total aircraft weight. Clearly, each small improvement in aircraft component weight results in a cascade effect on total aircraft weight, and the end performance the aircraft can achieve.

A reduction in cell mass density means that the aircraft wing will weigh less, and the propulsion power (and weight) will be reduced to maintain the aircraft at nominal flying speed. Therefore, the aircraft can be proportionately downsized, including reduced wing area, resulting in still additional weight savings. For example, if the solar cell mass density is reduced by only1 %, the aircraft weight drops by over 9 lbs. Similarly, when the solar cell efficiency is raised by 1 %, the aircraft weight drops by almost 54 lbs.

**4.0 WRIGHT LAB TESTING OF EML SOLAR CELLS** : A 3.98 cm X 3.98 cm, 16-volt, high-efficiency, thin film GaAs solar cell substring was delivered to Wright Laboratory for performance verification. The general configuration of the cells are shown in Figure 3. The substring is produced by creating a single solar cell which is 4 cm square, and then photolithographically dividing it into sixteen 1 cm square solar cells which are interconnected in series to provide the 16-volt nominal output. Clearly, the device could be left as a single solar cell, with even higher efficiency, but in most UAV applications the higher voltage substring would provide a convenient electrical building block.

The conversion efficiency was measured and recorded at the Air Force Institute of Technology by PhD candidate Kitt Reinhardt using a 1-kW Oriel Xenon solar simulator at AM-0 conditions, calibrated using a JPL balloon-flown standard GaAs cell. The I-V curve and the efficiency calculations are presented as Figure 4. As can be seen, the conversion efficiency of the planar solar cell was 20.3%. The Voc was 16.25 V, while the Isc was 31.85 mA, resulting in a fill factor of 0.84.

The general structure of the cell is shown in Firgure 5 The cell has a significant weight advantage over standard cells inasmuch as bonding the cell to a 1-mil coverglass will result in a cell mass density of less than .03 lbs/square foot, which represents a factor of 3.5 improvement when compared with the current "Pathfinder" cell.

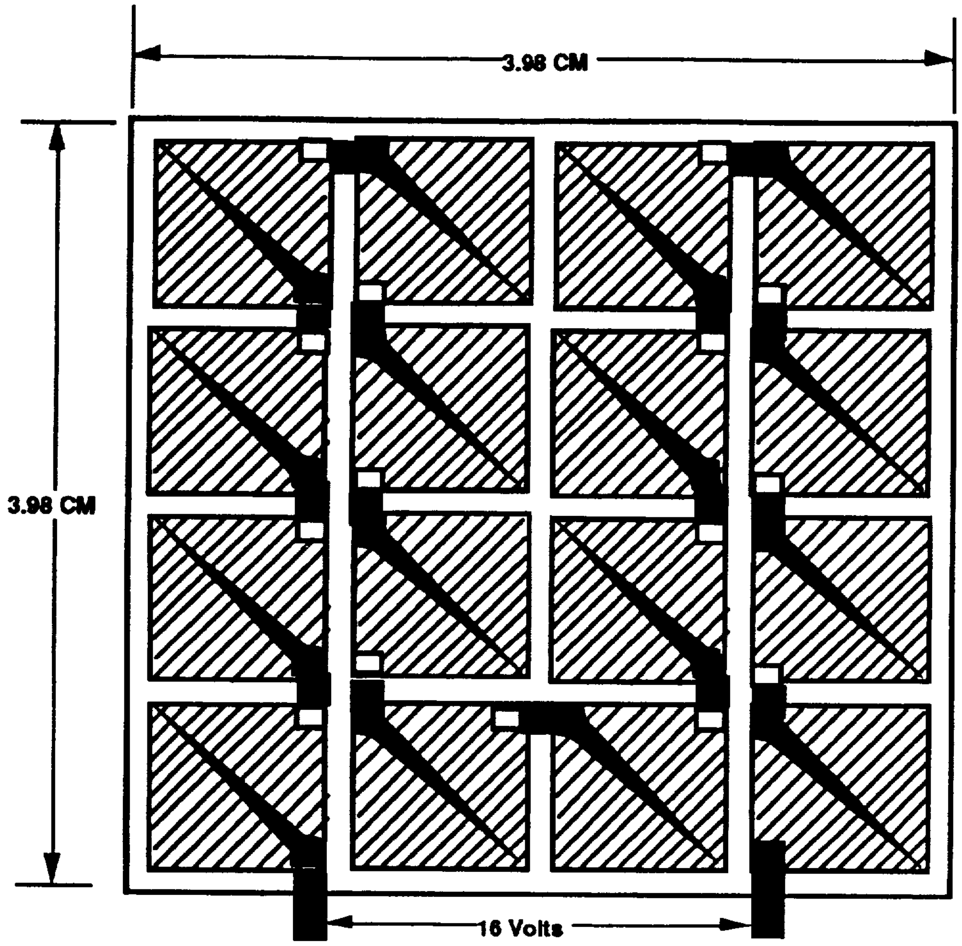

Figure 3: General Configuration of EML GaAs Solar Cell Substring

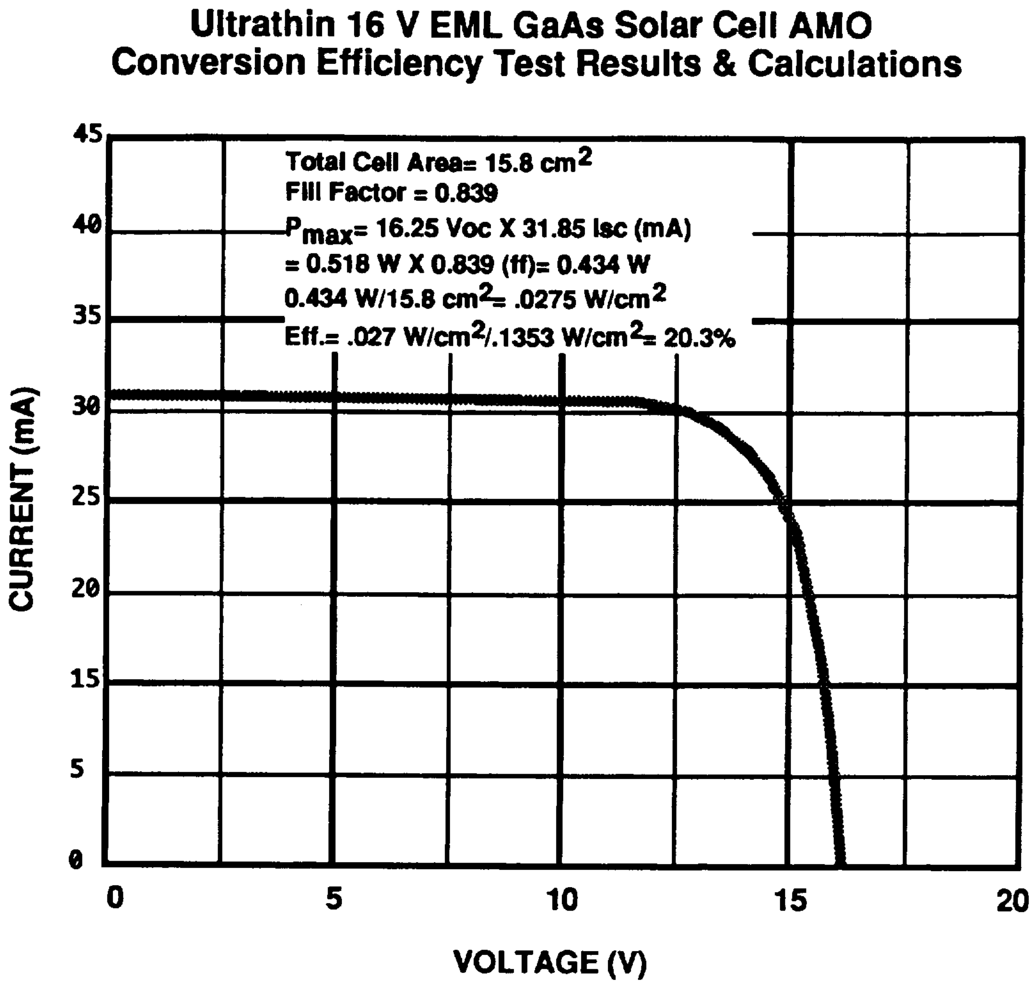

Figure 4: Current vs Voltage curve for EPI Ultrathin GaAs Cell

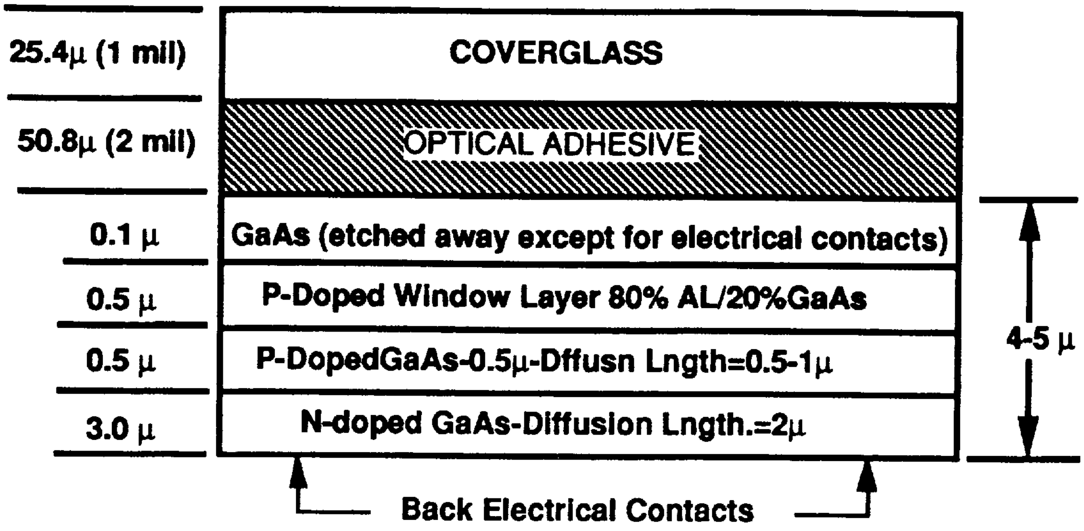

Figure 5: General structure of EML Ultrathin GaAs Solar Cell

**5.0 Bifacial Solar Cell Sunlight Conversion:** As previously described, bifacial solar cell performance is achieved when the solar cell is designed in such a way that it can receive and convert solar energy to electricity on either surface. In a UAV application, the wing-mounted solar arrays could be constructed in a manner that would allow the Earth's albedo, which is 20-30% of direct sunlight, to illuminate the lower surfaces of the solar cells, while the direct sunlight illuminates the upper surfaces.

The level of albedo intensity is a function of the Earth's local surface radiometric properties, but it is significant up to an altitude of 1000 miles, and intensified by snow and other highly reflective surface conditions. If employed, this "bifacial" feature could add about 20 to 30% to the conversion efficiency of the solar cell array, thus permitting it to be proportionately smaller and lighter in weight. Conversely, this makes the design of the wing structure more complex, thus requiring a trade study to determine the relative merits of bifacial power generation and its impact on construction complexities. Figure 8 illustrates how bifacial solar cell technology could be applied to a UAV wing construction.

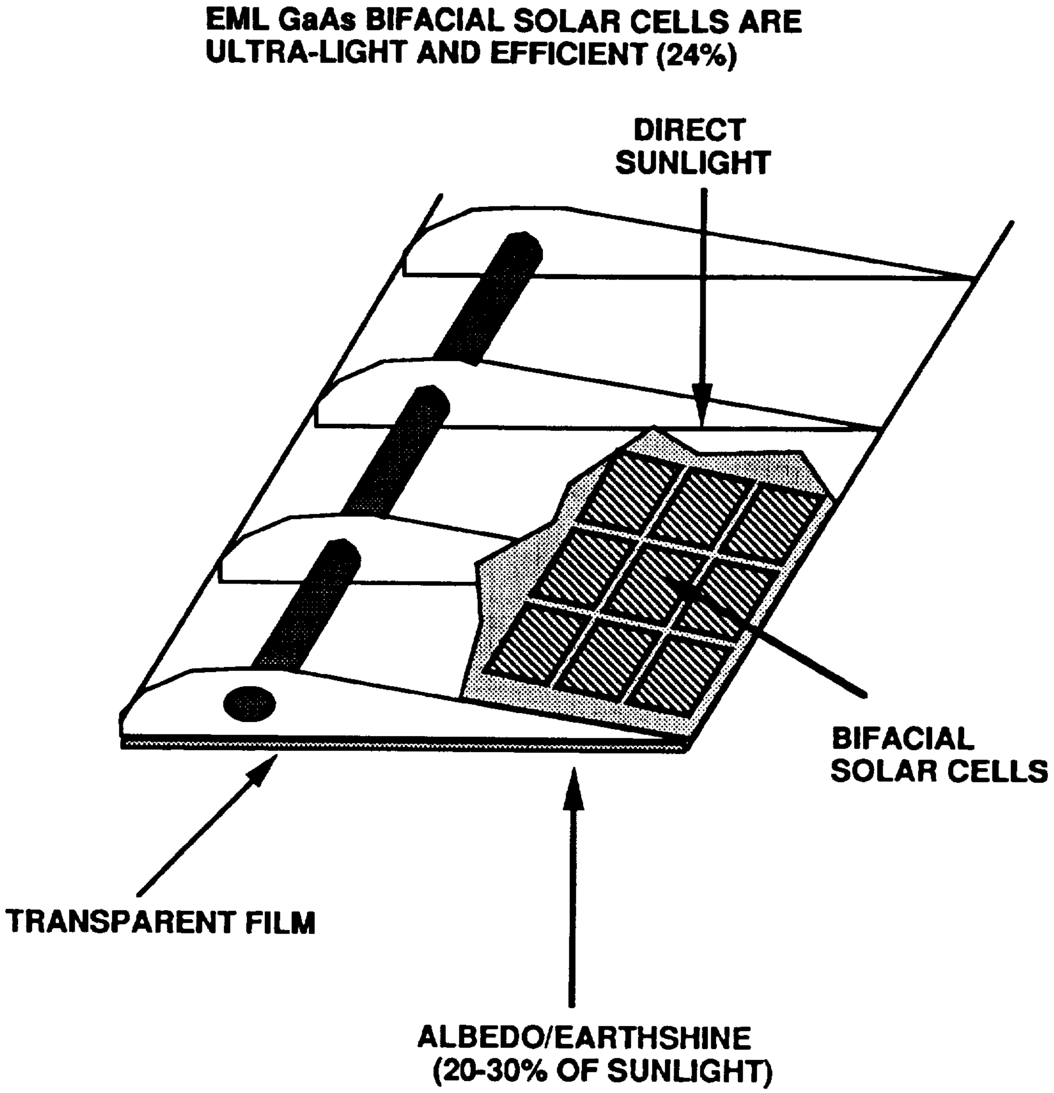

**Fig. 6: UAV Wing Construction Can Support Bifacial Solar Cell Insolation**

**6.0 Advanced Control and Sensing System:** An advanced solid state control and sensing system would monitor the sunlight and maneuver the aircraft, when permitted, to maximize the solar-electric conversion process. Another feature of the automatic sensing/control system will monitor current loading and tachometer rotational speeds of the propeller motor drives. When the motors are developing higher torque than necessary to maintain the prescribed flight characteristics, more of the power delivered by the solar arrays will be switched to the battery recharging system for night operation. Under these conditions, when the battery reaches a fully charged state, portions of the solar arrays can either be automatically switched off the load buses, or shunted to a thermal rejection radiator.. In this manner, during favorable weather conditions, the propeller motor life will be extended by minimizing over-current and voltage conditions. In summary, the solar power/control system will (1) drive the propeller motors during daylight hours; (2) replenish the battery to a fully charged capacity; (3) provide required power to the housekeeping and payload buses, and (4) optimize the torque of the propeller drive motors to conform to the conditions of maintaining the flight plan under variable weather conditions.

**7.0 Summary:** In summary, the use of extremely light-weight, highly-efficient, MOCVD GaAs solar cells, as described herein, represents an enabling technology which, in fact, allows solar-electric UAV aircraft to perform their mission, bearing reasonably heavy payloads, and of taking off in a conventional manner, climbing to high-altitude, and remaining aloft for long durations, whereas when they previously employed standard Si or GaAs cells they could not achieve these goals.

**8.0 Conclusions and Recommendation:** Although the adaptation and retrofitting of existing ultra-light aircraft to unmanned solar-electric flight is perhaps the most economic and expeditious method of near-term demonstrations, it will not bring the UAV community nearer to achieving the goals of high-altitude, long duration, stable and reliable flight. What seems to be required to realize these goals is designing an aircraft from scratch, using existing 1994 aerostructure, control, and propulsion technology transferred from the space and advanced aircraft industry, that can takeoff from the ground, climb to high altitude, and remain there in stable and reliable flight for extended periods. This, of course, requires the enthusiastic support and dedication of a strategic government/industrial alliance in which key national Superlabs and industrial firms not only identify desirable mission architectures, but fully collaborate in these efforts in a comprehensive national, and perhaps international, UAV solar-electric initiative.