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GaAs/Ge Solar Powered Aircraft

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ABSTRACT

Unmanned Aerial Vehicles (UAV) are being proposed for many applications including surveillance, mapping and atmospheric studies. These applications require a lightweight, low speed, medium to long duration aircraft. Due to the weight, speed, and altitude constraints imposed on such an aircraft, solar array generated electric power can be a viable alternative to air-breathing engines for certain missions. Development of such an aircraft is currently being funded under the Environmental Research Aircraft and Sensor Technology (ERAST) program. NASA Lewis Research Center (LeRC) has built a Solar Electric Airplane to demonstrate UAV technology. This aircraft utilizes high efficiency Applied Solar Energy Corporation (ASEC) GaAs/Ge space solar cells. The cells have been provided by the Air Force through the ManTech Office.

BACKGROUND

ERAST was started by the NASA office of Aeronautics to develop technologies which will enable safe and cost effective environmental research. The potential need for unmanned aerial vehicle's development is expected to grow over the next 10 years and expand into the private sector. Most of the current military applications view the UAV as a disposable vehicle for high risk missions. This effort is expected to enable the U.S. to get a competitive lead in the global market with miniaturized sensors and flight vehicle integration. Other projects being supported by ERAST include the Si solar cell powered RAPTOR / Pathfinder and three internal combustion engine powered aircraft: RAPTOR/Talon built by Scaled Composites, Perseus series of aircraft built by Aurora Flight Sciences and Altus series of aircraft built by General Atomics.

Possible applications of the UAV include a large number of military and classified surveillance flights where a small aircraft is difficult to detect by radar. Scientific applications include ozone monitoring, collection of data for weather and global warming studies, investigation of lightning-like flashes observed by shuttle astronauts, and studying the Aurora Borealis [1]. Commercial applications include aerial surveying, geological, and topographical mapping and communication links.

Solar cells can be a viable power source on UAVs for several reasons. Solar power density increases with altitude from 80 mW/cm² (AM 1.5) on the ground to 136.7 mW/cm² in space (AMO), this is shown in Figure 1. A rough calculation for light intensity in mW/cm² as a function of air mass is shown below [2].

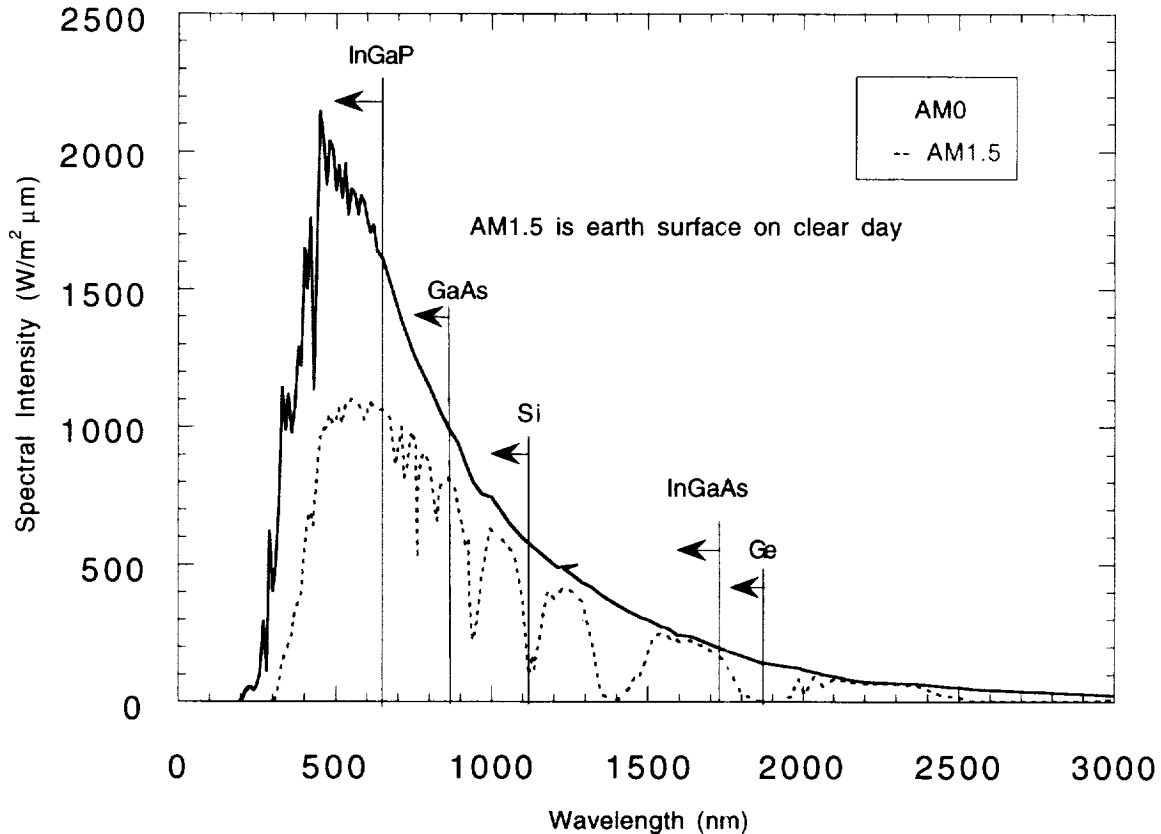


Figure 1: AM 1.5 and AM 0 Spectral Intensity

$$\text{Intensity} = 1.367 \times 0.7(\text{air mass})^{0.678} \text{ mW/cm}^2 \quad (1)$$

In contrast to an air breathing engine, a solar powered aircraft has no exhaust and therefore does not contaminate the atmosphere nor interfere with any delicate air measuring sensors on the aircraft. It also does not depend on the atmosphere for the production of power. Due to the low wing loadings necessary on a solar aircraft they are inherently slow which makes them well suited for atmospheric studies. One obvious disadvantage of using solar power is that it is not available throughout the whole day. However battery or fuel cell power could be used to extend flight times.

The ultimate goal for a solar powered aircraft is to be capable of continuous flight for months or even years. In order to accomplish this a rechargeable energy storage system would be needed. This energy storage system would need to be capable of supplying enough energy to sustain the aircraft at the desired altitude throughout a nighttime period. Also the solar array would need to be capable of recharging this energy storage system during the day time as well as maintain the aircraft power level for flight. Analysis of this type of continuously flying solar power aircraft is given in references 4 and 5. In order to examine the solar power generating aspects of this type of aircraft, a solar powered aircraft with minimal energy storage capabilities was constructed. This was done in order to further advance the development of a solar powered aircraft as well as to gain an understanding of the operational constraints and problems associated with the construction and flight of this type of aircraft. A GaAs/Ge solar array was used as the power source for the aircraft.

GaAs/Ge Cells

GaAs/Ge cells are now being produced for many space power applications and are readily available. GaAs/Ge cells have been shown to be as efficient as GaAs/GaAs cells and are considered a mature technology [2]. The GaAs/Ge cells to be used in this project were made by ASEC in 1993 as part of a pilot production run under a ManTech program for Wright Aeronautical Laboratory in Dayton, Ohio. These are Gallium Arsenide cells grown on an inactive Ge substrate by organometallic vapor phase epitaxy. The ManTech program was set up for a run of 500 cells. These cells are 6 cm. x 6 cm. in size and are either 3.5 or 4.5 mils thick. The thinness of the cells renders them extremely fragile so handling must be kept to a minimum, all aspects of plane construction are mindful of this.

The cells were measured by ASEC at AMO conditions and sorted by efficiency. Because this program is a developmental program all functional cells were shipped which included cells with mechanical defects, visual defects, and cascaded cells (active Ge). The AMO cell efficiencies ranged from 14% to 19%. The cells were measured at LeRC under AM1.5 illumination. This was chosen over AMO because the plane was designed for low altitude operation. The spectral response data shown in Figure 2 was performed on a 2 x 2 cm. cell, cut down from a larger cell. The AM1.5 short circuit current calibration was found by integrating the spectral response of the cell over the ASTM standard spectrum. Table I is a summary of the cell measurements, all cells were measured regardless of their apparent condition. Figure 3 shows a typical IV curve with close to nominal characteristics.

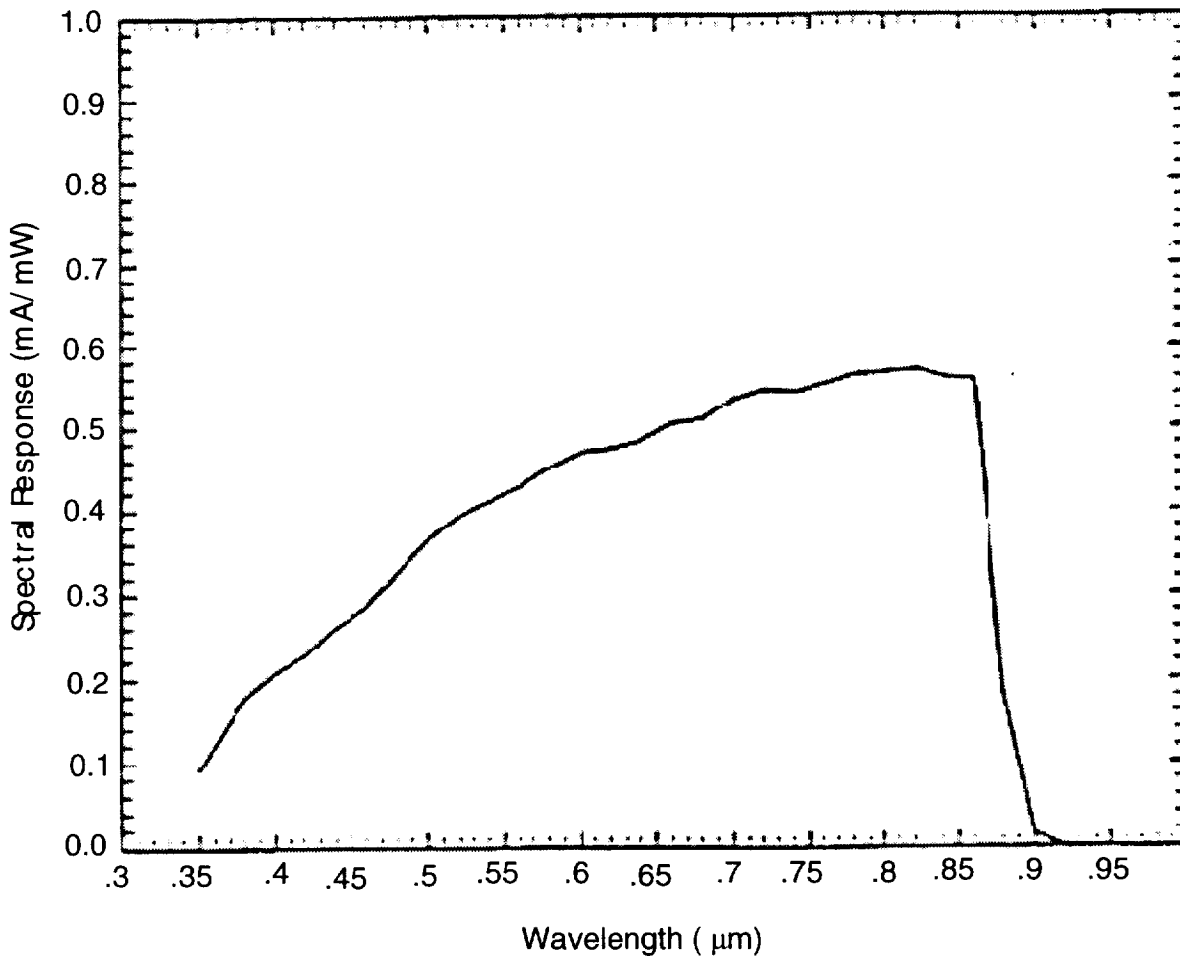


Figure 2: Spectral Response of GaAs/Ge Cell

	mean	sdev	# within 1 dev.
Isc	0.676 A	0.0136	292
Voc	0.997 V	0.0327	275
Pmax	0.492 W	0.0475	259
I _{max}	0.605 A	0.0318	294
V _{max}	0.811 V	0.0214	257
FF	72.9 %	5.454	250
Eff	17.77 %	1.719	258

Table I: GaAs/Ge Cell Data at AM1.5 (355 cells)

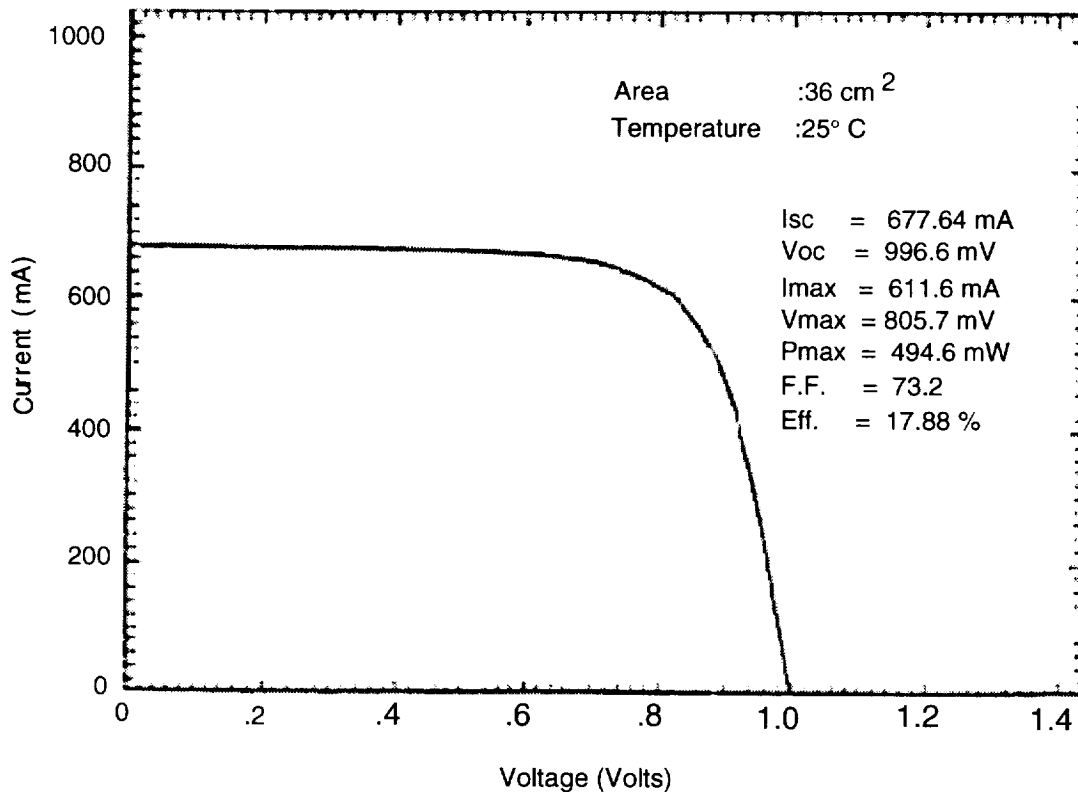


Figure 3 : I-V Curve of a Typical CaAs/Ge Cell

The highest cell efficiency measured was 20.43%. The data shows that the current is very consistent. Reverse breakdown characteristics of the cells have been studied by Iles et al. [5] and the results indicate that GaAs/Ge is more robust than GaAs/GaAs with respect to the amount of reverse current the cells can handle. These tests have shown that proper screening can eliminate this problem.

Aircraft Design

The Solar Electric Airplane was built at NASA LeRC it was assembled much like a model airplane. This is a second generation plane with many modifications for strength and stiffness. The first prototype aircraft was damaged due to radio interference and excessive wing flutter. The overall length of the plane is 2 meters with a total mass of approximately 9.2 kilograms. The wing has a span of 4.7 meters and a chord of 0.31 meters. It has a rectangular planform and is constructed of three equal sections, two outboard sections and one central section. The outboard sections are at a 12° dihedral to the center section. The fuselage is centrally located beneath the wing and the tail is attached to the central section of the wing in a dual boom configuration. The tail consists of a horizontal stabilizer and twin vertical rudders. The layout of the aircraft can be seen in figure 4.

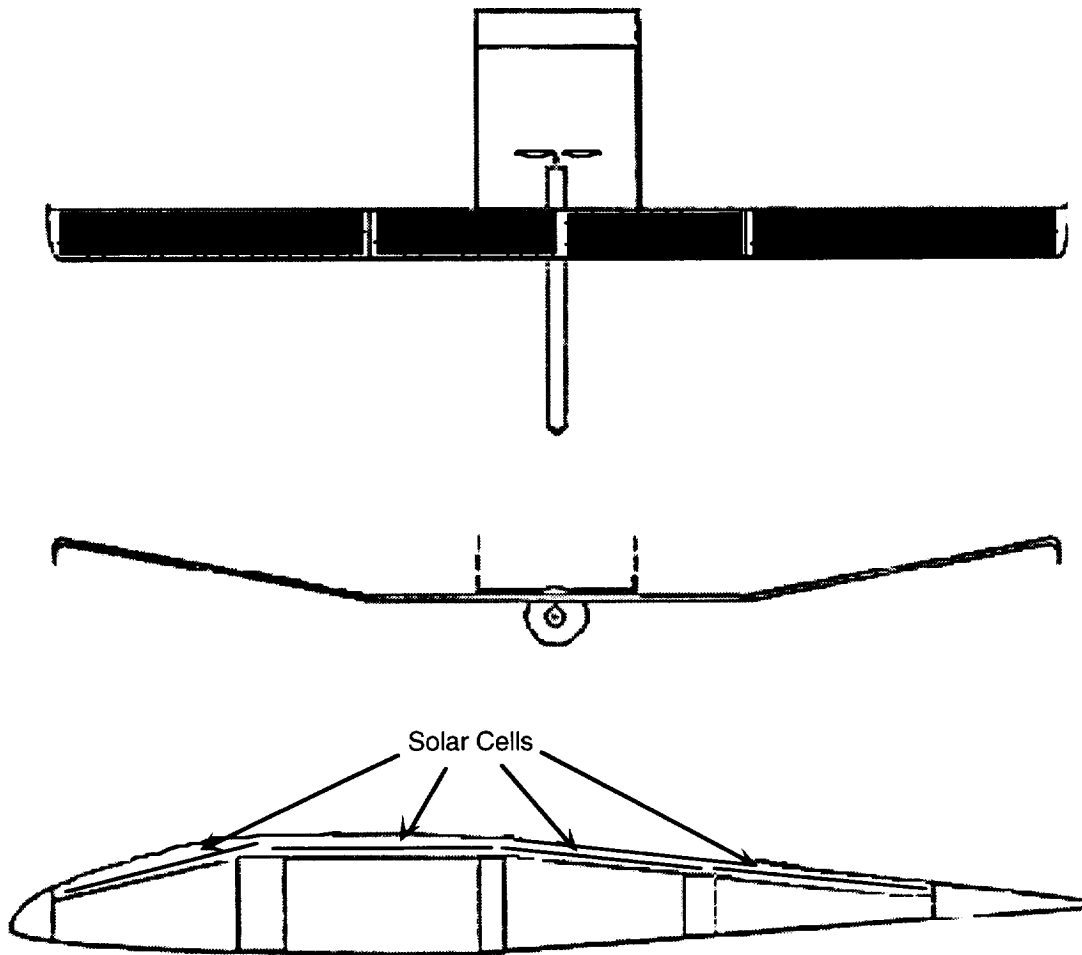


Figure 4: Solar Electric Airplane

The construction materials used for the wing and tail were balsa wood, spruce and carbon fiber. The wing is a frame construction consisting of ribs, spars, shear webs, leading edge and trailing edge. The ribs and spars are spaced 6.3 cm apart to accommodate the placement of the

solar cells. The first spar from the leading edge is the main structural member in the wing. This spar uses an I beam type of construction. This type of main structural member was chosen due to the brittleness of the GaAs/Ge solar cells which required the wing to be very rigid. The spar consists of two spruce strips each with a carbon fiber cap separated by a plywood shear web. The remaining two spars are constructed of balsa wood. The carbon fiber spar cap gives the wing the majority of its bending strength. The spruce spars were chosen over balsa due to the significantly greater hardness of the spruce. Tests were performed on a number of spar material combinations and it was determined that the balsa wood spar with a carbon fiber cap would compact under loading compromising the structural integrity of the wing. Balsa sheeting was used on the under side of the wing and also underneath the solar cells. This sheeting added torsional rigidity to the wing which was necessary to reduce the potential for wing flutter.

The wing is separated into three equally sized panels. This was primarily done to enable the aircraft to be easily stored and transported. In order to make the joint between the outer and inner panels structurally sound a 30 cm long titanium rod was used as the joining mechanism. The airfoil used for the main wing is the S4223. This airfoil was chosen due to its thickness and good low Reynolds number performance. Due to the length of the wingspan a thick airfoil was needed to achieve the required wing strength. There are no control surfaces on the main wing. All flight control is performed with the tail rudders and elevator. The servos for control of these surfaces are located within the wing.

The fuselage was constructed of fiberglass with plywood bulkheads. It has a removable hatch to access the wiring, control electronics and battery packs. All control electronics are mounted on a movable platform within the fuselage. The fuselage is attached below the wing in a pod fashion with a spruce faring between the wing and the fuselage. Two bolts are used to attach the wing to the fuselage. The wiring for the solar array passes through the faring and into the fuselage. The electric motor is mounted at the back end of the fuselage in a pusher configuration. The motor used is a modified Astro 40, samarium cobalt permanent magnet, electric motor. Modifications were made to the motor windings in order to match the operating voltage of the motor to the array / battery bus voltage.

The landing gear is constructed of aluminum struts with a carbon fiber axle and foam wheels. The landing gear is secured to the bottom of the fuselage by a retractable pin. The pin is controlled by a servo which if retracted allows the landing gear to be removed. This allows for the aircraft to takeoff under its own power and then have the ability to drop the landing gear once in flight. The elimination of the landing gear in flight significantly reduces the aircraft's drag profile. The ability to remove the landing gear also allows for easier transportation and storage of the aircraft. If the landing gear is dropped during flight the aircraft must land by sliding on the underside of the fuselage. This type of landing can take place only on a grass surface. Certain features have been incorporated into the aircraft to allow for this type of landing. These include the addition of an extra layer of fiber glass to the bottom side of the fuselage, the placement of a wire extending beneath each boom just aft of the wing to resist any rolling of the aircraft and the use of a folding propeller.

The tail is attached to the central wing section with two booms. The booms are hollow cylinders constructed of carbon fiber. The tail of the aircraft is constructed of balsa wood with a mylar covering. The span and cord of the tail section are 1.1 and 0.25 meters, respectively.

The plane is remotely controlled by a Futaba radio controller with six channels, four are used for servos, one is used for the motor and one is used to release the landing gear. The range of the controller is limited to line-of-sight up to approximately 1 mile.

Prior to installing the solar arrays in the aircraft some tests were performed on the airframe in order to determine its flight worthiness and ability to fly under solar power. These tests consisted of a structural loading test and a lift to drag test. The structural loading test was performed on the airframe in order to determine its structural integrity. The test was done by securing the aircraft to a platform on the back of a pickup truck. The platform was located

approximately 2 m above the cab of the truck to avoid any turbulence generated by the truck. The truck with the aircraft secured was driven up to speeds of 70 mph. This test was performed for a range of aircraft angles of attack. The flexing of the wing was observed as well as any tendency toward fludder. Little flexing occurred even under large wing loadings and no fludder was noticed over the complete speed range tested. Proceeding the structural testing was an in flight lift to drag test. This test was performed in order to verify that the calculated power required to fly the aircraft was capable of being produced by the solar cells. Since there was no down link communications capability on the aircraft the drag had to be inferred from observations from the ground. This was done by taking elevation measurements as the aircraft glided over a known distance. With the elevation change, time and distance known the lift to drag of the aircraft could be calculated. In order to reduce the error in the measurements this test was performed a number of times in opposite directions. From this test the lift to drag of the aircraft with the landing gear on was determined to be approximately 20. No tests were performed without the landing gear.

Solar Array

The solar array consists of 264 GaAs/Ge cells described previously. The array is divided into 12 strings of 22 cells, each string running a third the length of the wing. Each cell occupies a bay defined by the grid of the spars and ribs, covering the entire wing. A cross section of the wing through the spars is also shown in figure 4. The cells are interconnected using .040" x .002" silver ribbon fastened to the cells by a parallel gap welder which is used to solder the interconnects. Three sets of contacts are used for redundancy and to minimize series resistance. Any repairs to the array will be done using soldering. Each cell will be mounted on 9 6.4 mm diameter closed cell foam pads which in turn are glued to the thin balsa wood sheeting covering the wings. This is shown in figure 5. The 12 strings will be connected to a power management and distribution (PMAD) system and isolated using blocking diodes mounted on the underside of the wings between strings. Bypass diodes are not used because cells are arranged in single row strings.

The cells were interconnected using a silver ribbon which was soldered to the cell using a parallel gap welding machine. Attempts to weld the cell resulted in severe cell damage due to the shallow junction in the cells and thin metallization. The ribbon was tinned on one side and then soldered using the heat from a parallel gap welder to melt the solder, this provided a good compact connection without damaging the cell. Originally, gold ribbon was to be used for the interconnects however, the gold was not compatible with the hand soldering of the string ends. A silver plate invar was then selected and it was too stiff to allow routing of the interconnects around the ribs without cracking the cells. Finally, silver ribbon was selected for its compatibility with solder and flexibility.

The cells were soldered together in groups of eleven. Silver ribbon was soldered to the three front contacts of each cell. The cells with their ribbons were placed face down on a vacuum plate with proper spacing. The ribbons were then soldered to the backside of each adjacent cell making a complete 11 cell series string. With the vacuum on, the plate is held upside down over the wing section where the foam pads are already bonded in place and coated with DC93-500 adhesive. The vacuum is then released and the cells are lowered into place on the wing. At this time the cells are aligned and the adhesive is cured. The adjacent strings are connected using hand soldering. Then the Monocote is applied. Once the Monocote is stretched over the wing, a heat gun and adhesive is used to shrink it so that it conforms to the wing shape.

Based on ground tests conducted on a clear day in September on the full array installed in the aircraft, the maximum output was around 120 watts. The nominal operating temperature of the cells is difficult to predict but preliminary measurements indicate that it should not exceed 45°C The aircraft design indicates a stall speed of 15 mph and a cruise speed of approximately 25 mph requiring a minimum power of 83.4 watts. On a typical sunny summer day in Cleveland, Ohio, the plane should be able to fly for 8 hours.

A short wing section consisting of 5 ribs was constructed and is shown in figure 6. This was built to test and refine the assembly method and integrity between the cell and wing. The wing section was built using mechanical reject cells. Two rows of five cells in parallel were interconnected and mounted on the wing section by the techniques described previously. This array was measured using Spectrolab LAPSS100 FLASH test equipment both before and after a skin was applied to the wing. The performance of the wing section under AMO illumination is shown below.

Isc	before Monocote:	1029.4 mA
Isc	after Monocote:	939.6 mA
	Transmission	91.2%

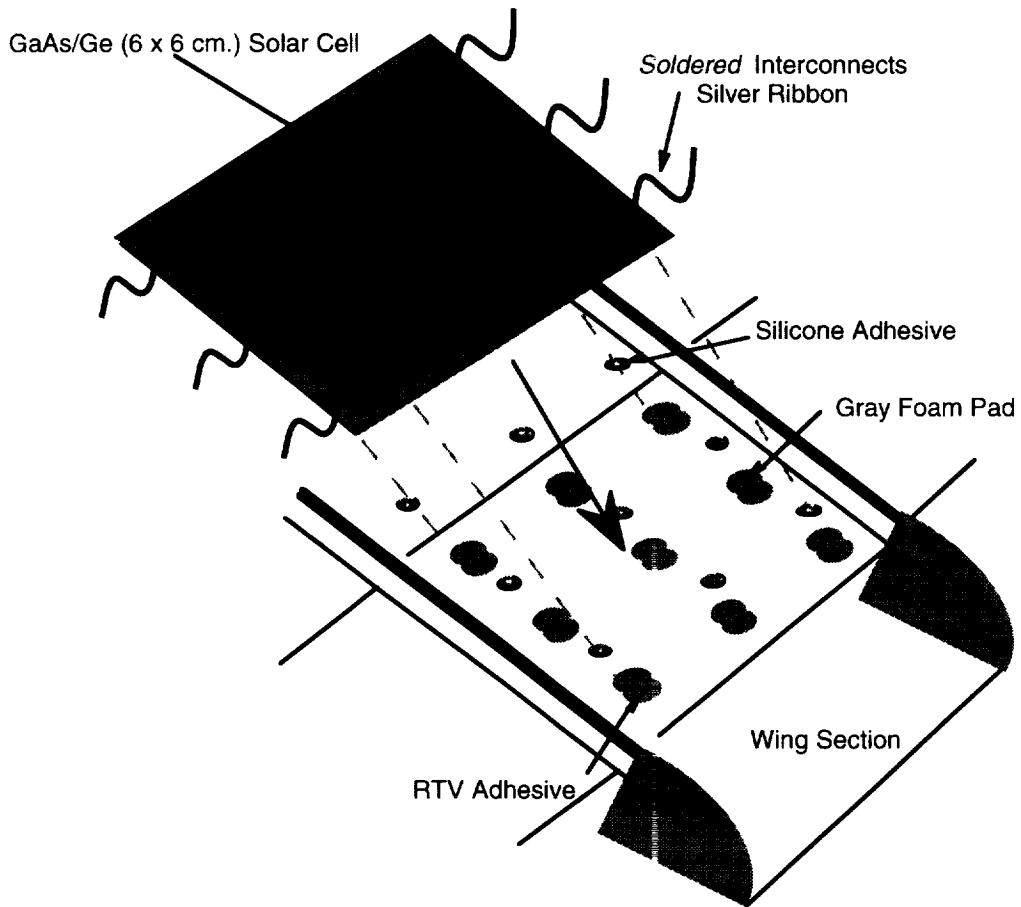


Figure 5: Cell to Wing Assembly

This wing section was also used to demonstrate repair techniques, several cells were removed from the wing and new cells were installed and reconnected by soldering. It will also be used for shock and durability tests.

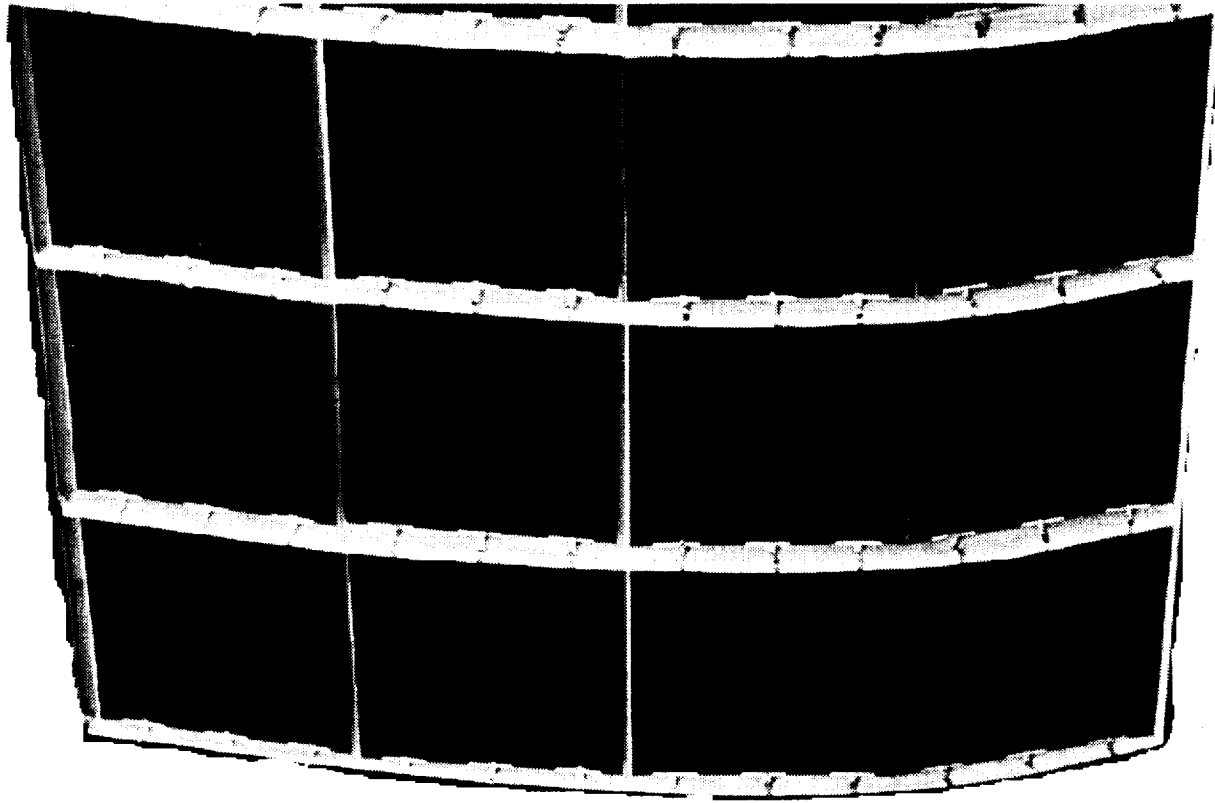


Figure 6: Prototype Wing Section

Power System

The power system for the aircraft consists of an 11 cell NiCad battery pack and the solar array. Presently there is no control electronics between the battery pack, motor controller and the array. Operation of the system is obtained by matching the voltage of the array, battery and motor. Both the battery pack and array are connected in parallel to the motor controller. The battery pack regulates the bus voltage and maintains it at approximately 15 volts during normal flight. As the current draw from the motor increases the bus voltage will decrease and current will flow from both the array and battery to the controller. If the current draw of the motor is less than that available from the array then the bus voltage will increase and the excess current will go to charging the battery. The system voltage floats over a range of values from approximately 10 volts when the motor is at full power to around 15 volts when it is at cruise power. The complete power system was tested on the ground under sunlight conditions in order to verify its proper operation. Measurements were made of voltage and current at the battery, array, motor controller and motor locations. It was determined from these measurements that the power system was functioning as designed and that the array was capable of producing upwards of 120W. However, it was noted that there was a 10% power loss due to resistance in the power transmission lines and the various power system connection points. This fairly high power loss is due mainly to the low system voltage the aircraft is operating at. This system voltage, however, was set by the desire to connect the arrays in each of the three wing panels in parallel. The reason for this is that each of the panels is at a different angle with respect to the sun. If the panels were connected in series the lowest current level of the three panels would become the total array output current. Due to the angle difference between the panels, the loss in output power which would occur by connecting the panels in series can fluctuate from 10% to 100% depending on the sun orientation.

Conclusion and Future Plans

The airplane has been completed and has now flown for 15 flights under battery power and one flight with the full array installed (see figure 7). Based on the data collected during the ground tests of the power system it was determined that it is possible to overcharge the battery during long duration flights at low power levels. A battery charge controller suitable for regulating the current going to the battery has been purchased and is planned to be installed in the aircraft. This charge controller will eliminate the possibility of overcharging the battery pack.

During the flight test of the aircraft with the full GaAs/Ge solar array installed insufficient power was produced by the array to sustain flight. Since the ground testing of the array output power and the drag testing of the aircraft indicated that there should be sufficient power to fly the aircraft an alternate explanation for the insufficient power production had to be found. It was noted that a significant amount of condensation formed on the inner surface of the wing covering. It was presumed that this condensation was caused by the air within the wing heating due to the energy absorption and reradiation of the solar cells and the cooler air passing over the outer surface of the wing. This could have been the cause of the reduced power output of the solar array. In order to eliminate this problem a steady stream of low pressure nitrogen gas has been pumped into the wing panels while the aircraft is being stored. We believe that this gas will dry out the wing and eliminate the condensation problem and hopefully the power production problem.

All the flights to date have taken place with the landing gear attached to the aircraft for the duration of the flight. However in future flights the landing gear will be dropped in order to minimize the drag of the aircraft and therefore maximize its endurance.

This plane was built primarily for technology demonstration using high efficiency GaAs/Ge cells. Future plans also include using this plane as a testbed for rechargeable lithium batteries. When all testing is completed, the aircraft will be turned over to the Air Force ManTech Office.



Figure 7: Completed Aircraft Under Test

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