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Regenerative Fuel Cells for High Altitude Long Endurance Solar Powered Vehicles

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Regenerative Fuel Cells for High Altitude Long Endurance Solar Powered Aircraft

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Abstract

High Altitude Long Endurance (HALE) unmanned missions appear to be feasible using a lightweight, high efficiency, span-loaded, Solar Powered Aircraft (SPA) which includes a Regenerative Fuel Cell (RFC) system and novel tankage for energy storage. An existing flightworthy electric powered flying wing design was modified to incorporate present and near-term technologies in energy storage, photovoltaics, aircraft structure, power electronics, aerodynamics, and guidance and control in order to substantiate feasibility. The design philosophy was to work with vendors to identify affordable near-term technological opportunities that could be applied to existing designs in order to reduce weight, increase reliability, and maintain adequate efficiency of components for delivery within 18 months. The energy storage subsystem for a HALE SPA is a key driver for the entire vehicle because it can represent up to half of the vehicle weight and most missions of interest require the specific energy (usable energy capacity/storage system weight) to be considerably higher than 200 W-hr/kg for many cycles. This stringent specific energy requirement precludes the use of rechargeable batteries or flywheels and suggests examination of various RFC designs. Although sufficient specific energy can be met by a properly designed large RFC system, such systems have inferior efficiency (usable energy out/gross energy in) compared with rechargeable batteries and do not scale well for the multiple smaller systems desired for ideal span-loading. An RFC system using lightweight tankage, a single fuel cell (FC) stack, and a single electrolyzer (EC) stack separated by the length of a spar segment (up to 39 ft), has specific energy of ~300 W-hr/kg with 45% efficiency, which is adequate for HALE SPA requirements. However, this design has complexity and weight penalties associated with thermal management, electrical wiring, plumbing, and structural weight (due to lack of span-loading). A more elegant solution is to use unitized RFC stacks (reversible stacks that act as both FCs and ECs) because these systems have superior specific energy, scale to smaller systems more favorably, and have intrinsically simpler thermal management.

The design, fabrication, and deployment of HALE SPA is an engineering feat that has strict weight, efficiency, and reliability requirements for all of the interrelated subsystems. Many of the design challenges in the areas of aircraft structure, power electronics, aerodynamics, and guidance and control, have already been addressed by AeroVironment, Inc. (AV) in their existing design of a flightworthy electric powered flying wing, completed in 1983, shown in flight in **Fig. 1** (Morgan, to be published). Improvements to this design that have been done in collaboration with LLNL, coupled with recent advances in lightweight, high efficiency silicon solar cells (Sinton, 1993) suggest that a virtually eternal SPA (that is capable of sustaining flight for a few months) is possible with the development of an energy storage subsystem with sufficiently high energy density.

Since the energy storage requirements are a strong function of aircraft and mission specifications, there will be brief sections entitled *Aircraft Description* and *Mission Description*, prior to the section detailing the *Energy Storage Requirements*. The minimum specific energy requirement for the baseline plane and mission is 230 W-hr/kg with 90% round-trip storage efficiency or 260 W-hr/kg with 45% efficiency. This criterion is used to eliminate all rechargeable battery systems, with the possible exception of an advanced custom-packaged Li-solid polymer electrolyte battery which is eliminated due to its lack of near-term availability, as described in the *Rechargeable Battery Survey* section. The remainder of the paper is devoted to the design of different *Regenerative Fuel Cells* for this application, with particular emphasis on lightweighting and integration of the *Fuel Storage* into the wingspar using a novel bladder technology. Results of recent American Society for Testing and Materials (ASTM) permeability tests for the

Fig. 1. Photograph of the 100 ft wingspan × 8 ft chord electric powered span-loaded flying wing in flight (designed and built by AeroVironment, Inc.).

bulk bladder material and its seams suggest hydrogen permeance through the entire bladder of less than 1/4% per year (~8 g/yr out of ~3.5 kg/plane). Using the bladder instead of aluminum liners saves >50 lb/plane, while integrating the tankage into the wingspar results in an additional weight saving of >40 lb/plane (for an RFC system weight of ~440 lb = 200 kg). The merits of using *Unitized Regenerative Fuel Cell Stacks* to reduce parasitic weight and system complexity are discussed qualitatively because results of the unitized RFC trade study with United Technologies Corporation (UTC), Hamilton Standard Division (HS) were not available when this paper went to press.

Aircraft Description

There are three categories of SPA: direct solar power only (no energy storage), solar power with primary (non-rechargeable) energy storage, and solar power with secondary (rechargeable) energy storage (diurnal).

Solar electric flight without energy storage was first attempted by AstroFlight, Inc., in 1973, and AV flew the Solar Challenger from Paris to England in 1981. SPA, in general, require low wing loading (aircraft weight/wing area). Diurnal SPA require even lower wing loading. Solar Challenger was light, but its cantilevered wing construction cannot be scaled to the size required for diurnal flight. Therefore, a span-loaded (distributed weight) aircraft was designed, built, and initially flown by AV in 1983. More than 10 missions have been flown on this 100 ft wingspan plane using Ag/Zn batteries to supply the energy. The longest flight has been over an hour in duration. The maximum altitude attained has been greater than 10,000 ft above sea level (MSL). This 100 ft wingspan, 8 ft chord, ~400 lb span-loaded airframe is being refurbished to become the *Pathfinder* solar electric test platform whose purpose is to develop and test the critical technologies and mission operations necessary for continuous solar electric flight.

The design tools and methodology developed for the Pathfinder vehicle were used to define a larger wingspan version that could ultimately be capable of HALE solar powered level flight. One of the design tools is a static model (developed by AV) that is capable of sizing the various subsystems of a HALE SPA (based on their efficiencies and scaling laws) in order to balance the energy and power required to maintain level flight at a desired altitude through multiple diurnal cycles. This model is used in conjunction with a solar flux model to determine the usable solar energy available to the plane based on solar cell efficiency (as a function of temperature), fractional area covered, wing angle, time of year, latitude, altitude, average heading, and airspeed. The usable solar energy is balanced with the energy required for propulsion, all system loads, and charging the storage system sufficiently to assure ample useful capacity for nighttime flight.

After a conceptual design is validated by the static model, the design can be tested using a dynamic model (developed by AV). This model performs a similar power and energy balance, but on a time scale of seconds instead of days. Complex mission flight plans can be modeled more accurately instead of simply assuming a constant heading, altitude, and air speed.

Although the energy balance for HALE solar powered flight is easier for larger wingspan SPA, we have assumed a maximum feasible wingspan of ~200 ft (aspect ratio of ~25) until flight experience is gathered for larger wingspan aircraft.

The strength of this flying wing aircraft is given by a modular five segment graphite epoxy composite tubular spar that spans the wing. This modularity permits road or air shipment. The aircraft components are spread along the wing as uniformly as possible to approach a span-loaded situation. There is however, some divergence from span-loading caused by the discrete nature of several components. The preliminary maximum loadings in a mid semi-spar segment are shown in **Table 1**.

Loading Condition	Maximum Value
+5g flight shear	14500 lb*
+5g flight moment	29000 ft-lb
+5g flight torsion	240 ft-lb
-3g flight shear	8700 lb*
-3g flight moment	17400 ft-lb
-3g flight torsion	140 ft-lb
+1g flight shear	2900 lb*
+1g flight moment	5800 ft-lb
Control deflection torsion	760 ft-lb
Landing shear	10000 lb*
Landing moment	12200 ft-lb
Landing torsion	280 ft-lb
Gas storage pressure	300 psia†

*These shears result from carrying the moments present at the ends of the spar segment across the wing rods used to connect adjacent spar segments, and for asymmetric landing loads.

† The spar must carry flight or landing loads with or without pressure loads present.

Table 1. Preliminary maximum loading conditions for a mid semi-spar segment.

The spar sizing criterion is that only one of the flight or landing condition groups can occur at a given point in time. The cross section of the composite spar segment is 12.6 in. O.D. × 0.304 in. wall thickness with a weight of 1.37 lb/ft to satisfy these loading conditions including the necessary buckling resistance. The graphite fiber chosen is T-700. The wall construction is symmetrical with a surface layer of 0.005 in. (5 mil) thick ±45° fibers, followed inwardly by 10 mil thick 0° fibers over 100° sectors at the top and bottom, 6 mil thick ±10° fibers, 6 mil thick 90° fibers, and 125 mil thick honeycomb core. Another layer with the reverse of all of these covers the previous layer. **Fig. 2a** shows a portion of the spar segment and **Fig. 2b** shows the spar core material with reinforcement for a through hole in a portion of the spar segment. The spar design and prototype fabrication work was performed by EDO Corporation, Fiber Science Division (EDO).

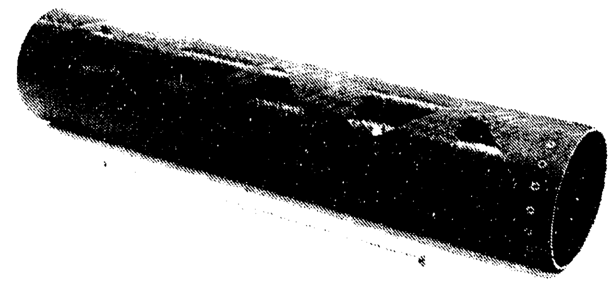

Fig. 2a. A portion of the prototype wingspar segment with a yardstick in the foreground.

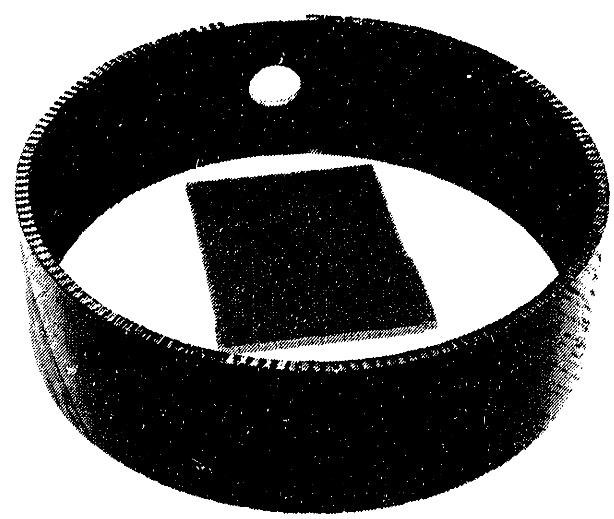

Fig. 2b. A reinforced hole in a short wingspar segment is shown with core material in center.

Mission Description

Three missions have been identified to prove the feasibility of HALE SPA:

(1) Use the existing 100 ft wingspan vehicle (Pathfinder) and populate it with solar cells using minimal energy storage in order to test the airframe, components, and electric propulsion system at high altitude.

(2) Use the Pathfinder populated with solar cells and sufficient rechargeable batteries (such as Ag/Zn) to break the diurnal cycle, possibly with the aid of gravitational energy storage (drop altitude at night). It is assumed that the maximum gross weight allowable for this plane is ~500 lb in order to use the existing airframe.

(3) Design and build a HALE SPA with the largest wingspan feasible (assumed to be 200 ft) and with an advanced energy storage system (such as RFCs) that is capable of maintaining level flight above local weather disturbances for multiple days.

The assumptions for mission (2) (diurnal) and mission (3) (HALE) are outlined in **Table 2**.

Parameter	Diurnal	HALE
Wingspan	100 ft	200 ft
Chord	8 ft	8 ft
Altitude (MSL)	10 kft, min.	60 kft, level
Solar cell efficiency	14%	20%
Solar cell areal wt	0.2 lb/ft^2	0.053 lb/ft^2
Solar cell coverage	33%	80%
Daylight duration	14 hr	12 - 14 hr
Time of year	6/21 ±30 da.	6/21 ±90 da.
Latitude	30 - 35° N	30 - 35° N
Maximum gross wt.	~500 lb	variable
Payload wt.	minimal	72 lb
Mission duration	>36 hr	>72 hr

Table 2. Baseline SPA parameters for diurnal and HALE missions.

Energy Storage Requirements

The energy storage requirements necessary to accomplish the missions described in **Table 2** were derived using the static and dynamic models described in the *Aircraft Description* section. The results are listed in **Table 3**.

Parameter	Diurnal	HALE
System voltage	80 - 120 V	40 - 120 V
Usable capacity	12 kW-hr	60 kW-hr
Capacity/cell	>500 W-hr	>500 W-hr
Efficiency	>80%	45 - 90%
Specific energy	>175 W-hr/kg	260-230 W-hr/kg
Cycle life	>3 cycles	>50 cycles
Charge time	13 hr	11 - 13 hr
Discharge time	12 - 6 hr	14 - 12 hr
DOD	>80%	>80%
Ambient temp.	-30° - +50°C	-30° - +50°C
Ambient press.	0.5 - 15 psia	0.5 - 15 psia
Acceleration	-3g - +5g	-3g - +5g
Recurring cost	<$15/W-hr	<$15/W-hr
NRE cost	<$100K	<$500K
Delivery time	<6 mo.	<18 mo.

Table 3. Energy storage system requirements for the Diurnal and HALE missions.

Of the requirements listed in **Table 3**, specific energy is the most difficult to meet. It should be noted that the voltage range for the diurnal plane was restricted to match Pathfinder's existing component voltages, whereas the lower limit voltage for the HALE mission was relaxed to allow more flexibility in the design of an RFC system. The cell sizing was targeted to reduce the mass of cell packaging and hardware.

A few battery and RFC point designs were examined in detail. For the specific point design, a typical mission would require an RFC system with 45% round-trip efficiency and specific energy of ~250 W-hr/kg. The same platform optimized for a rechargeable battery system with 90% round-trip efficiency would require specific energy >230 W-hr/kg. Although a 90% efficient energy storage system enables the use of fewer or less efficient solar cells to charge the storage system, it still requires a comparable amount of usable energy over the course of the night. This difference highlights the fact that the aircraft mission performance is limited more by its capacity to store energy than its efficiency or its ability to generate power.

Rechargeable Battery Survey

The specific energies of a variety of rechargeable battery candidates are listed in **Table 4**. This table shows that only three candidate systems could meet the minimum specific energy requirement of either mission.

Battery System	Theoretical Spec. Energy	Packaged Spec. Energy
Zn/O_2	1040	250
Custom Li-SPE	735	220
Ag/Zn	450	200
$Li/LiCoO_2$	735	150
Li/FeS_2	515	150
Na/S	1180	150
Li/TiS_2	470	130
Ni/Zn	305	90
Ni/H_2	470	60
Ni/Cd	240	60
Pb/acid	170	50

Table 4. Theoretical and packaged specific energies [W-hr/kg] of various rechargeable batteries (Barnett, 1993).

The Zn/O_2 system has severe cycle life and capacity fade limitations and is not available in high capacity cells. Development of custom Li-solid polymer electrolyte (Li-SPE) batteries will take >2 yr and an unknown NRE cost. High capacity Ag/Zn batteries which have very little excess Zn can have very high end of life specific energy (>175 W-hr/kg) after a few cycles (3 - 10). These batteries should enable a multi-day solar powered mission using the existing aircraft with minor modifications.

Regenerative Fuel Cells

A fuel cell is in some ways similar in function to an electrochemical battery. The main difference is that in most batteries, the chemical reactants are stored within the electrochemical cell and interact without a catalyst, whereas in a fuel cell, the reactants (fuel and oxidizer) are stored external to the catalytic electrodes. An FC becomes an RFC if the reactants (in this case H_2 and O_2) are regenerated from the reactant product(s) (in this case H_2O by electrolysis). The RFC system may either have a separate FC and EC in a closed loop, or a unitized FC/EC.

Various electrolytes can be used with H_2/O_2 FCs and ECs, including phosphoric acid, KOH, and proton exchange membrane (PEM, also known by the UTC trademark SPE). PEM is superior to phosphoric acid and KOH because of the ease of electrolyte management. PEM electrolyte is confined to a polymeric film and does not dilute as water is produced. PEM also tends to have longer cycle life than other electrolytes and is less likely to corrode due to migration of concentrated acids or bases. PEM FCs are only a few percent less efficient than comparable KOH FCs, while PEM ECs are a few percent more efficient than comparable KOH ECs. The engineering details required to build and successfully test an RFC system based on PEM electrolyte technology was proven in 1982 by GE. The PEM electrolyte system will be assumed because this RFC technology has been proven, has been shown to offer good cycle life, and is the simplest system to handle.

It is assumed that the O_2 will be handled in a closed loop, instead of trying to capture it from the rarefied flight environment. This is done to reduce system complexity and cost, while increasing system reliability. It is estimated that O_2 extracted from captured air would have 5-7% impurities at the design altitude (60 kft). These impurities would collect in the O_2 chamber of the FC and would diffuse through the PEM into the H_2 side. Therefore, both sides of the FC would have to be vented. The gases in the FC are at ~180 °F, 2-4 atm, and very high relative humidity during normal operation. The venting procedure would result in a loss of some moisture (and H_2), even if extremely efficient regenerative dryers are used. Therefore, additional fuel (hydrogen or water) would have to be carried on board to compensate.

While it is clear that reduced RFC efficiency can be traded for reduced weight (by decreasing the number of cells in the EC or the FC), it should also be clear that such a trade can only be done as long as the energy of the entire system is balanced as described in the *Aircraft Description* section. The maximum energy into the system during the minimum energy date/heading/latitude (equinox/270°/30°N) is ~ 141 kW-hr. The minimum energy required from storage is ~60 kW-hr over the course of that night. The minimum RFC system efficiency required for this design point is 45% with an additional 2% efficiency loss budgeted for the power electronics (resulting in a net efficiency of 43% = 60 kW-hr output/141 kW-hr input).

Results of an RFC point design which assumed a single EC with 1, 2, or 3 FCs, and commercially available ancillaries is shown in **Fig. 3** (McElroy, 1993). This study assumed that both the EC and FC(s) were designed to operate at 180°F with Ti hardware for lightweighting the cells. This figure shows that a single FC will be substantially lighter than two or three. Similar weight savings result from using a single EC. The minimum RFC weight is 225 lb.

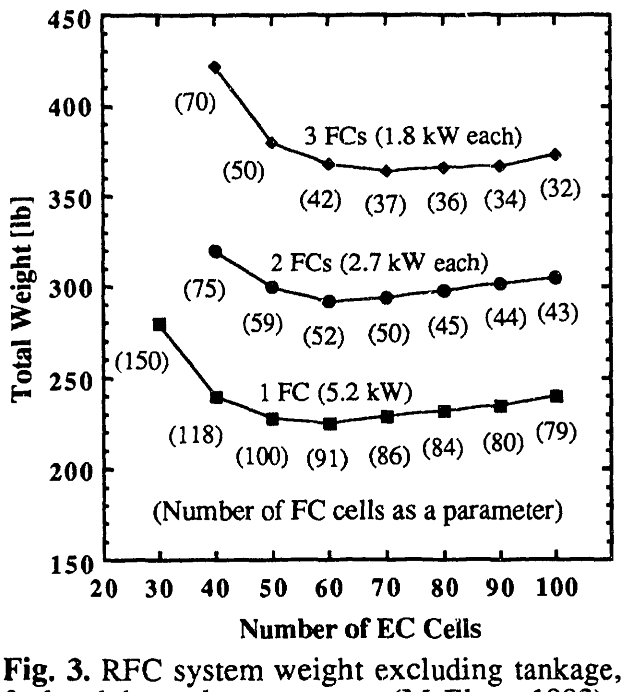

Fig. 3. RFC system weight excluding tankage, fuel and thermal management (McElroy, 1993).

The total system weight, including tankage, fuel, thermal management, and all weight penalties associated with a single FC/EC system is ~440 lb = 200 kg, resulting in specific energy of ~300 W-hr/kg.

Fuel Storage

The advent of high strength graphite fibers has led to a pressure vessel technology using these fibers in a composite epoxy matrix to provide high values for the pressure vessel performance factor (pressure*volume/weight), which can be 1 to 2 million in. Realizing a high performance factor is of particular interest for this ultralight aircraft. Adding a gas storage requirement leads to a tubular spar cross-section to meet the aircraft loading conditions, which in turn allows winding the composite on a mandrel. Reinforcements that are required in the tube for buckling resistance can be added as the final step while on the mandrel.

These composites do not show significant resistance to permeation by the stored gas, so some kind of a barrier must be provided. The usual means is to form a thin-walled aluminum vessel that can serve as the permeation barrier as well as a mandrel over which the graphite epoxy is wound. Typical metal-lined vessels for 3500 psi storage pressure have about a third of the weight in the liner (Kuhn, 1993). They operate at best with a specific storage weight of about 7 - 10% by weight H_2 gas and the balance vessel (Kuhn, 1993 and Appleby, 1992).

We are developing a sputtered metal coated laminated polymer bladder to lighten the aircraft (Mitlitsky, 1993). **Fig. 4** shows the details of the end of the bladder. The storage arrangement will be one or two bladders per spar segment (one for H_2 gas and the other half as long for O_2 gas). We expect to attain an effective specific storage weight of ~15% by weight H_2 gas.

The H_2 permeability of a number of materials and the characterization of the flow relation have been reported (Souers, 1985). That work suggests that a very thin layer of defect-free metal could reduce H_2 permeation to negligible levels.

As an example, for H_2 permeating through Ag:

$$\frac{dv}{dt} = \frac{kA}{L} P^{0.5}$$

where k (permeability) $=8 \times 10^{-19}$ mol/m-s-Pa$^{0.5}$ for Ag (Souers, 1985), dv/dt is the permeation in mol/s, A is the area in m^2, L is the thickness in m, and P is the pressure in Pa. Converting to g/yr and taking values of 1000Å Ag thickness, 39 m^2 for the H_2 portion of the total spar area, and 2.1 MPa (300 psia) maximum gas storage pressure results in a H_2 permeation loss of 14 g/yr (about 0.3%/year for the aircraft assuming 20 °C temperature). The reported value for the permeability of H_2 through Au is ~9 orders of magnitude lower than for Ag (Souers, 1985).

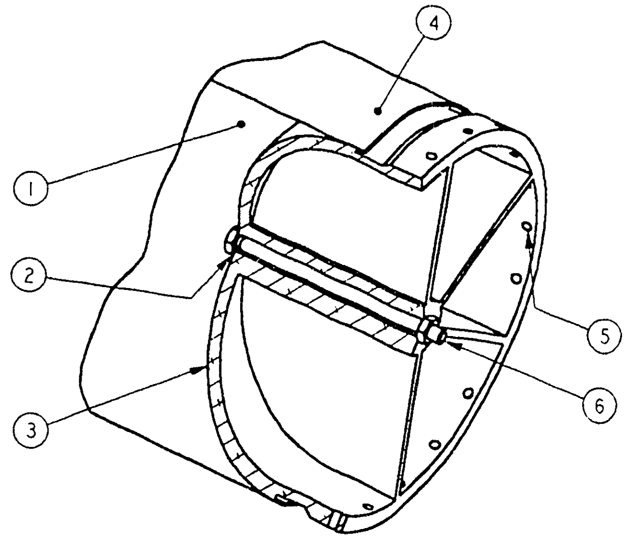

Fig. 4. Bladder endcap detail.
1–Laminated polyethylene (PE) and Ag-coated polyethylene terephthalate (PET) bladder, 2–O-ring seal, 3–Nylon bulkhead, 4–Heat seal, 5–Retaining pin hole, and 6–Gas connector.

We have been measuring the permeation of 1000Å thick Ag films deposited by sputtering onto 1 mil thick PET and latex-bonded on both sides with 1 mil of 5% by weight ethylene vinyl acetate (EVA), 95% by weight low density polyethylene (LDPE) copolymer. We supplied hydrogen at 35.8–38.4 psia and 22–25°C in a Dow permeability cell (ASTM, 1982). The resultant permeance ranged from $1.7 - 3.6 \times 10^{-12}$ mol/m^2-s-Pa$^{0.5}$ for 5 runs with an average value of 2.5×10^{-12} mol/m^2-s-Pa$^{0.5}$. This result leads to the permeation of hydrogen through the 39 m^2 Ag-coated PET bladder system in the aircraft of 8.8 g/yr, which is in good agreement with the previously reported data.

There will be permeation through the polymer paths in the bladder seams. Permeabilities of hydrogen and oxygen through PE and PET are shown in Table 5.

A typical seam will involve 2 mil of PE and 2 mil of PET between the Ag layers on each side. The fusion width of the seam will be ~1 cm. The airplane will have ≤260 ft of 2 longitudinal bladder seams and ≤10 end seams of 12 in. diameter. These measurements result in a maximum total seam permeation area of 0.0045 m^2 each for the PE and PET. The resultant maximum permeation of hydrogen through the seams is 0.2 g/yr. The data in **Table 5** indicate a 2 order of magnitude lower permeation for the oxygen. The oxygen/hydrogen weight ratio of 8 in the airplane leads to an oxygen weight loss of 15 mg/yr.

Polymer	Gas	k × 10[16] [mol/m-s-Pa]	Reference
PE	H_2	34	Mercea, 1983
PE	H_2	31	Pye, 1976
PE	H_2	6.7	Othmer, 1955
PE	H_2	10	Brubaker, 1953
PE	T_2	30	Maienschein, 1993
PET	H_2	2.0	Tuwiner, 1962
PET	H_2	2.7	Mercea, 1983
PET	H_2	0.8	Othmer, 1955
PET	T_2	2.0	Maienschein, 1993
PET	H_2	5.6	this paper
PET	O_2	0.06	this paper

Table 5. Permeabilities for polyethylene (PE) and polyethylene terephthalate (PET).

An indication of the low rate of gas loss through the seam is given by the permeation data for the patched specimens sized for the Dow cell, as shown in **Fig. 5**. Two patched specimens were tested with the following results: 4.2×10^{-12} mol/m^2-s-Pa at 35.9 psia/25°C, and 3.2×10^{-12} mol/m^2-s-Pa at 36.7 psia/25°C. These data compare closely with the unpatched specimen data. The specimens were constructed of the same laminated 1000Å thick Ag/PET material with a 4.5 cm diameter hole cut in the bottom piece and a patch fused on a 7.2 cm O.D. and a 4.7 cm I.D. The patch was placed with a Ag/copolymer/PET interface.

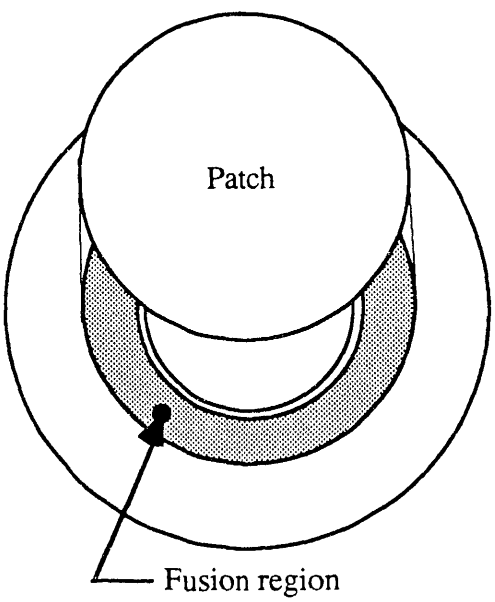

Fig. 5. Patched Dow permeability cell specimen.

Individual bladders will be inserted into spar segments to their proper positions and pinned at each end as shown in **Fig. 2a** and **Fig. 4** to take the axial pressure forces. Removal of the pins will allow easy replacement of a bladder.

Unitized Regenerative Fuel Cell Stacks

Prior to considering unitized RFCs, an RFC system consisting of a single separate FC stack coupled with a single separate EC stack appeared to be the least expensive, lightest weight, and highest efficiency option for meeting the energy storage requirements of a HALE SPA. This is true even when assessing moderate penalties caused by the inherent divergence from span-loading associated with such a system. Weight and complexity penalties of such a lumped design result from additional plumbing, thermal management, electrical wiring, and structural reinforcement of the spars near each lumped mass. If the penalties are even more severe than the moderate estimates assumed, then multiple FCs and/or ECs would be required. This would make the system even heavier because of the redundant parasitic masses that do not scale well.

Unitized RFCs would reduce the large mass penalties associated with multiple small RFCs and would reduce the mass and complexity penalties caused by the large physical separation required when using a single FC/single EC system for a HALE SPA. Unitized stacks would also simplify the thermal management of the energy storage system because the stacks would operate almost continuously (instead of using an EC stack during daytime and a separate FC stack during the night) and would not have to be kept warm during long dormant periods. A thermal management analysis trade study is being performed.

Endplates, cells, and some of the ancillaries would be used for both FC and EC operation, which suggests a potential for significant weight savings. However, since the optimal catalysts for FCs and ECs are different, each individual cell of a unitized stack generally has reduced performance (lower efficiency at a given operating point and possibly reduced cycle life). Unitized stacks will probably require additional development time and cost, and system efficiency may be inadequate for this application. A trade study with Hamilton Standard (HS) has commenced to determine the viability of unitized RFCs for HALE SPA. A unitized RFC schematic is shown in **Fig. 6**.

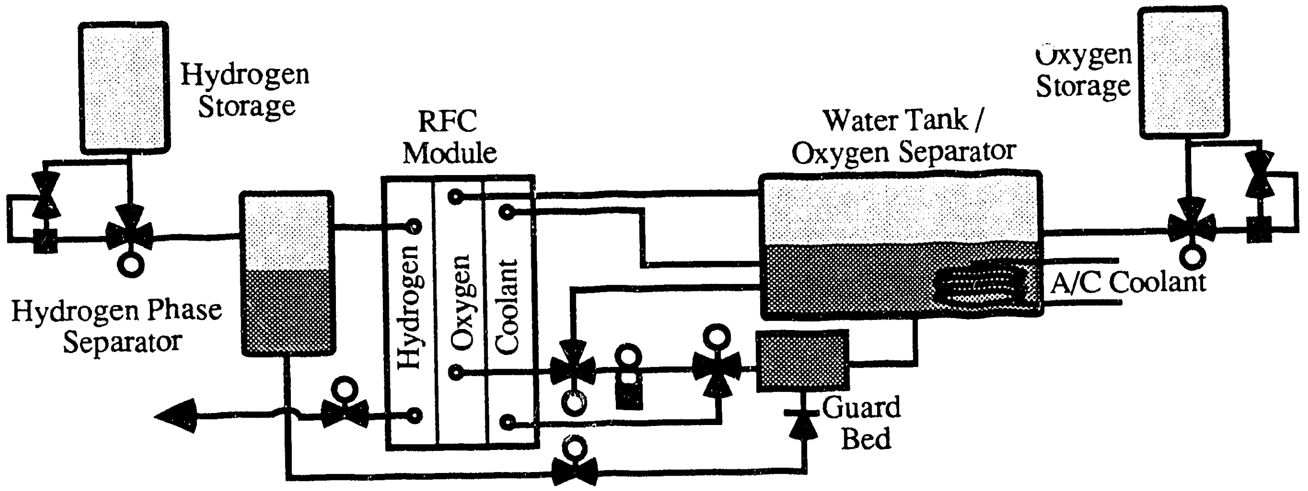

Fig. 6. Unitized regenerative fuel cell schematic (McElroy, 1993).

Conclusion

We have shown that HALE SPA are feasible using an existing plane design with increased wingspan, existing solar cells, and an RFC system for energy storage. Only modest performance improvements are required to existing FC and EC designs if the novel lightweight bladder-lined fiber composite fuel tanks described above are used to integrate fuel storage into the wingspar. Prototype bladder-lined wingspar segments have been fabricated and are currently under test. An RFC system using unitized stacks is expected to have even higher specific energy and reliability, but will require additional development.

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