NASA/TM—2011-216815

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October 2011

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Summary

This report presents the conceptual design for a solar electric lighter-than-air, unmanned aerial vehicle, based on existing technology already reduced to practice, that could carry a 600-kg (1322-lbm) payload to altitudes up to 30 kft (9000 m), continuously maintain an airspeed up to 40 kt (21 m/sec), and remain in flight for up to 100 days. The design is based on modern nonrigid airship technology, high-strength polymer fabrics and barrier films, and previously demonstrated aerospace electrical power technology, including lightweight photovoltaics and hydrogen-air polymer electrolyte membrane (PEM) fuel cells. The vehicle concept exploits the inherent synergy between the use of hydrogen as a lifting gas and the use of hydrogen-air PEM fuel-cell technology for onboard solar energy storage. In this report, the air vehicle concept is physically characterized and its estimated performance envelope is defined.

Airship Description

The air vehicle's overall configuration is illustrated in Figure 1. This vehicle is of conventional nonrigid airship construction, with an outer envelope of semiellipsoidal/cylindrical shape and an external keel framework slung below the envelope. The hull has a 15-m diameter and a 110-m overall length. The external keel carries all of the onboard systems and hardware, including four swiveling electric-motor propeller-drive propulsion pods that are cantilevered outboard on each side fore and aft. Because of the directed differential thrust available from the propulsion pods, the hull has no empennage. The vehicle is stabilized by the control of its center of gravity and the controlled application of differential thrust to damp out oscillations (roll and pitch) as required. Yaw damping is achieved by an approximately 7.33 length to diameter ratio. The envelope is slightly pressurized over ambient according to conventional nonrigid airship practice, and there are seven internal air-filled ballonet chambers fore and aft that ballast the ship and control pitch attitude. The envelope is designed to accommodate the pressure rise associated with a maximum temperature change of 40 °F (±22 °C) within a 2-hr period plus 24-hr sustained operation at flank speed. The airship hull shape comprises three sections:

(1) Nose section—half of a prolate spheroid (ellipsoid of revolution) of 15-m minor diameter and 24-m major diameter, or 12-m leading length
(2) Midships—a right circular cylinder of 15-m diameter and 80-m axial length
(3) Tail cone—half of a prolate spheroid (ellipsoid of revolution) of 15-m minor diameter and 36-m major diameter, or 18-m trailing length

The nose and tail sections of the hull are fully exposed, but the center section is covered by a solar array blanket. Although slightly less aerodynamically efficient than a fully ellipsoidal shape, the right circular cylinder section amidships allows a multiple-series-string photovoltaic array blanket to be draped over its length such that all cells in each string (which is oriented lengthwise) will remain uniformly illuminated independent of the ship's orientation. The array blanket provides the ship's electrical power in daylight and also serves as an ultraviolet light barrier over much of the envelope surface, allowing some weight reduction in this section. The blanket also performs a structural function, serving as the catenary curtain that suspends the external gondola and keel.

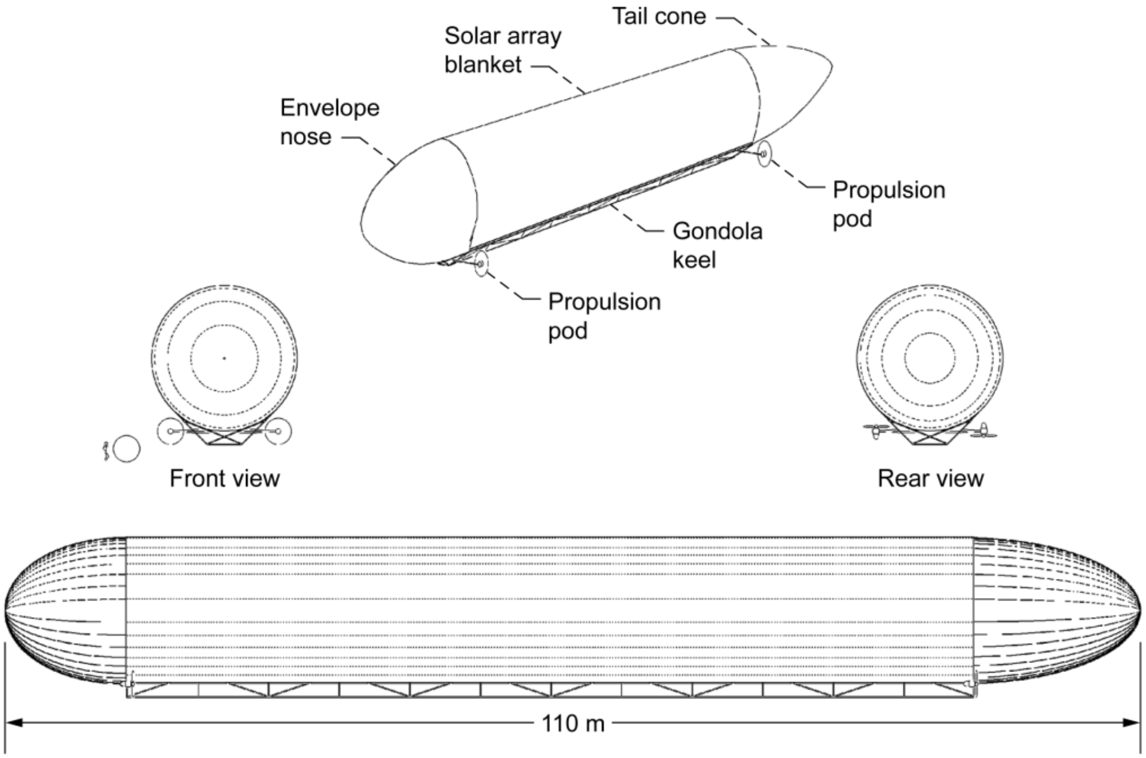

Figure 1.— Long-duration unmanned solar electric airship.

Envelope

The outer envelope is the major structural component of the hull, serving as a fixed-volume container (17 671 m^3) for the hydrogen lifting gas when it is inflated. The envelope is a laminated assembly of four layers: two plies of Kevlar 49 cloth with a 1-mil bonded layer of Kynar (Arkema Inc.) polyvinylidene difluoride (PVDF) film between the plies (which are oriented at 45° to each other) plus an additional 1-mil layer of Kynar film bonded to the interior ply. This produces a flexible laminate of approximately 230 g/m^2 that can withstand up to 1360-N/cm tensile stress. The envelope midsection, which is shielded by the array blanket, has no additional barrier coating; however, there is an outer layer of aluminized Mylar (DuPont biaxially-oriented polyethylene terephthalate) applied over the exposed nose and tail cone sections for ultraviolet light resistance. This adds 30 g/m^2 to these sections. Over its 15-m diameter, the envelope can withstand internal pressurization up to 300-mm Hg (40 kPa), which exceeds the maximum operating pressure differential of 90-mm Hg (12 kPa) by more than 3 times.

The interior ballonet is made of 1.4-oz (47.6-g/m^2) polyester fabric impregnated with 1-mil Kynar PVDF film on both sides. Because of the approximately 90 percent of interior volume that they will displace when the vehicle is at low altitude, the ballonet chambers cover the entire bottom of the hull. They take the form of a partitioned liner bonded to the inner wall of the envelope around its edges, conformal to the interior surface. It can best be thought of as an air/hydrogen separator membrane that lies rumpled against the bottom of the envelope when no ballast air is present, but that occupies up to 90 percent of the interior volume when puffed up with air. The ballonet is partitioned into seven chambers of roughly equal volume; these are filled and emptied independently to effect trim and balance. The total volume of all seven chambers, when fully inflated, is 15 900 m^3. The ballonet does not have to withstand pressure loads, but it must be flexible enough to withstand at least two inflation cycles per day over a 5- to 10-year lifetime while maintaining its effectiveness as a hydrogen-diffusion barrier. The ballonet material is much lighter than the Kevlar (DuPont) matrix-reinforced envelope, only 60 g/m^2.

The permeation, or diffusion, of hydrogen through both envelope components (outer envelope and ballonet) is less than 4.92 $cm^3/m^2/hr$ because of the excellent hydrogen-diffusion resistance of Kynar PVDF (Ref. 1). Nevertheless, a hydrogen diffusion loss rate of approximately 1 kg/day is expected from the envelope’s interior to the surrounding air and the air-filled ballonet chambers. This loss rate is mitigated by replacing the lost hydrogen with fresh hydrogen produced by onboard water electrolysis.

External Gondola and Keel

The gondola and keel is a semirigid truss structure that carries all the onboard systems (except for the solar array and hydrogen storage) and the payload. The truss is approximately 10 m wide, 2 m high, and 80 m long. It is the primary mounting location for all the system components (except for the solar array), including the propulsion and power. The keel is attached to rest of the airship by means of the solar array blanket, which is slung over the cylindrical portion of the hull envelope and clipped to attach points (electrical connections) at regular intervals along its length. By itself the keel is not stiff enough to remain straight over its entire length (although it is strong enough to support distributed loads from the various system components). Instead, the keel depends on the pressurized envelope’s stiffness to maintain alignment. Loading is limited to less than 500 kg over any 10-m section of the keel’s length, and no single point load attached to any frame member exceeds 100 kg. Lacking further mechanical detail, the gondola and keel is estimated to weigh no more than 10 percent of the subtotal of components supported, which are distributed along the keel to satisfy balance requirements.

Solar Power and Propulsion

The airship utilizes solar energy alone for its propulsion and onboard power. It is the inexhaustible solar power source that gives this airship the capability for extended-duration flight. Flight duration is extended, but not infinite, owing to the inevitable loss of lifting gas from the envelope due to permeation and diffusion. Consequently, the onboard electrolysis water supply has to be replenished periodically. The nine major components of the power and propulsion system are the

(1) Solar array
(2) Water electrolyzer and hydrogen generator
(3) Onboard hydrogen storage
(4) Hydrogen induction and pressurization system
(5) Air induction and pressurization system
(6) Hydrogen-air fuel-cell powerplant
(7) Electric motor drive propulsion system
(8) Thermal management system
(9) Water-recovery system

Note that the onboard hydrogen storage and the air induction and pressurization system are also used to provide buoyancy for the vehicle. The thermal management system includes payload cooling up to 1 kWt at 25 °C.

Solar Array

Primary electrical power generation comes from the photovoltaic array blanket that is draped around the airship’s midsection. The array blanket, similar to the solar array that powered the Aerovironment “Helios” fixed-wing solar aircraft under NASA’s Environmental Research Aircraft and Sensor Technology project several years ago (Ref. 2), is a laminated assembly of identical solar cells arranged in a matrix of series strings that are encapsulated and hermetically sealed between two layers of transparent polymer film (such as Kapton (DuPont)) to form a semiflexible flat sheet (blanket) that absorbs solar flux and that, when connected to an electrical load, delivers direct current at a voltage depending on the number of cells in the series strings and the load current being drawn.

Maximum power is achieved when all the cells in a series string are at an identical angle of incidence, and when the incidence angle is near perpendicular. A series cell string's performance is always limited by the cell with the lowest incidence angle, so series strings in the airship array must be oriented axially, not circumferentially. Typical individual cell dimensions are 2 to 8 cm per side, with an output voltage of roughly one-half volt per cell. Depending on the dimensions available for the array blanket, the output voltages for each series string can be tailored from just a few volts to several hundreds of volts. The Helios array blankets, which covered an area of 186 m^2 and weighed 92 kg, delivered 214 We/m^2 blanket under 1-sun illumination (Ref. 2). The corresponding figures of merit were thus

- Area specific weight, 0.658 kg/m^2
- Area specific power, 214 W/m^2
- Mass specific power, 3.07 kg/delivered kW

Similarly, the airship array blanket, which if laid out horizontally would form a flat-plate collector 40 by 80 m, weighs approximately 2050 kg and delivers up to 684.8 kWe under 1-sun illumination. Draped over the airship hull, the blanket takes on the shape of a cylinder over the upper three-fourths of the envelope but forms tangential planar segments extending inward from the upper 270° of arc to the bottom edges where they attach to the keel. The illuminated active array area can thus be approximated by the projected shadow of the hull cylinder, which is a cross section 80 m long and never less than 15 m wide. If we neglect the Brewster angle cutoff and assume that the airship always maintains a flight path that keeps it within 30° of broadside to the Sun during the day, we could expect the array blanket to continuously deliver at least 200 kWe between sunrise and sunset.

The array blanket is also a structural component, performing double duty as catenary curtain to hold the gondola and keel closely underneath the hull envelope. To address this function, the blanket's sandwich encapsulation encloses aramid fiber tensile members laid vertically at regular intervals between the individual solar array strings. The tensile members may be directly connected to the gondola structure, perhaps in conjunction with the electrical power leads, which also extend from the edges of this blanket and connect to the gondola. An additional weight of 30 g/m^2 is attributed to the airship blanket's tensile member reinforcement. The array blanket is by far the heaviest and most expensive component of the propulsion and power system. Any improvements made in specific weight or collection and conversion efficiency during the last 7 years since "Helios" would directly translate to better payload and altitude capability for the airship than what is presented here.

Water Electrolyzer and Hydrogen Generator

A low-pressure polymer electrolyte membrane (PEM) water electrolysis unit, fed by onboard water supply, generates hydrogen gas for the airship. The electrolyzer makes hydrogen to replace lifting gas that is lost from the envelope through permeation and diffusion, and the hydrogen that is consumed by the fuel cell for onboard electric power generation. The low-pressure unit should weigh less than the PEM water electrolyzers used on submarines and regenerative fuel cells, since the outlet pressure that is required for the airship is only about 5 psig (34 kPa) versus the 200 to 400 psig (1.37 to 2.76 MPa) used in a regenerative fuel cell system or the 3000 psig (20 MPa) required for a submarine unit.

The electrolyzer characterization made here originates from the 15-kWe liquid-anode-feed balanced-pressure PEM water-electrolysis stack that Giner, Inc., delivered to NASA in the early spring of 2004 under the Low Emissions Aero Propulsion project, where the first fully closed loop hydrogen/oxygen regenerative fuel cell was successfully demonstrated (Refs. 3 and 4). This particular stack is highlighted because it was, despite its 400-psi (2.76-MPa) pressure requirement, designed for minimum weight. Capable of absorbing up to 15 kWe and delivering up to 17 g hydrogen/kWh at pressures up to 400 psi (2.76 MPa), the stack weighed 16 kg including the end plates, which accounted for 20 percent of its weight. For low-pressure operation, a weight reduction of at least 50 percent could be applied to the endplates; this would reduce the stack's specific weight to less than 1 kg/applied kWe with no other modifications.

If that figure of merit is used and the accepted rule of thumb that the ancillary weight of a water electrolysis unit roughly equals the stack's weight is applied, a preliminary weight estimate for the electrolyzer system excluding its water supply, yields 350 kg for an electrolyzer unit that can deliver up to 2.67 kg hydrogen/hr on a power draw of 157 kWe.

Because of the liquid anode feed, the hydrogen and oxygen exit streams from the electrolyzer stack are saturated with water. In the water-recovery system (described later), there are condenser heat exchangers (HXs) that drop each exit stream's dewpoint from the 140 °F (60 °C) electrolyzer operating temperature to approximately 45 °F (5 °C) and remove the bulk of this water from the streams. The remaining water vapor, up to 24 g/kg hydrogen produced and up to 3 g water vapor/kg oxygen, is further reduced by the water-recovery system until both streams have a dewpoint that is no higher than 18 °F (10 °C) above the ambient outside temperature. At typical flight altitudes, this amounts to a water release through each stream of less than 500 g/day.

At this point, the oxygen stream is vented overboard, but any remaining vapor in the hydrogen stream escapes to the envelope interior, where it preferentially condenses on the envelope inside walls (colder than the ballonet surfaces) and freezes overnight. During the day, however, the Sun's illumination reliably heats the envelope wall above freezing, causing the condensate to melt and run down to the bottom of the envelope, where it can be collected and returned to the water reservoir. In direct sunlight, heating of the envelope wall is almost instantaneous, even though that heat does not penetrate very quickly into the interior.

Onboard Hydrogen Storage

The outer envelope is the container for the hydrogen lifting gas and the fuel cell's hydrogen supply. For flight integrity, the envelope must always be pressurized to at least 4-mm Hg to prevent buckling (Ref. 5). The additional hydrogen to feed the fuel cell translates to extra hull pressurization and weight. This means that the envelope must be stronger and heavier than it would otherwise have to be, but the added envelope weight is less than the weight of dedicated pressure tanks, and the overpressurization provides additional hull stiffness. The envelope is overpressurized by about 30 mm Hg to provide for a minimum of 24 hr of flight at flank speed without solar power input. Since the fuel cell powerplant requires an inlet delivery pressure that is approximately 10 to 15 times higher than the available hydrogen supply pressure, there is a hydrogen induction compressor and ducting system that draws hydrogen from the envelope interior and directs it into the fuel cell powerplant.

Hydrogen Induction and Pressurization System

The hydrogen induction system consists of a sealed, electric-motor-driven compressor that draws hydrogen from the envelope interior, and a ducting system that directs it into the fuel cell powerplant, at rates up to 3 kg/hr at a delivery pressure of 15 psi (101 kPa) over sea level ambient, or approximately 30 psia. The system is schematically depicted in Figure 2 along with the air-induction system, which is described in the next section.

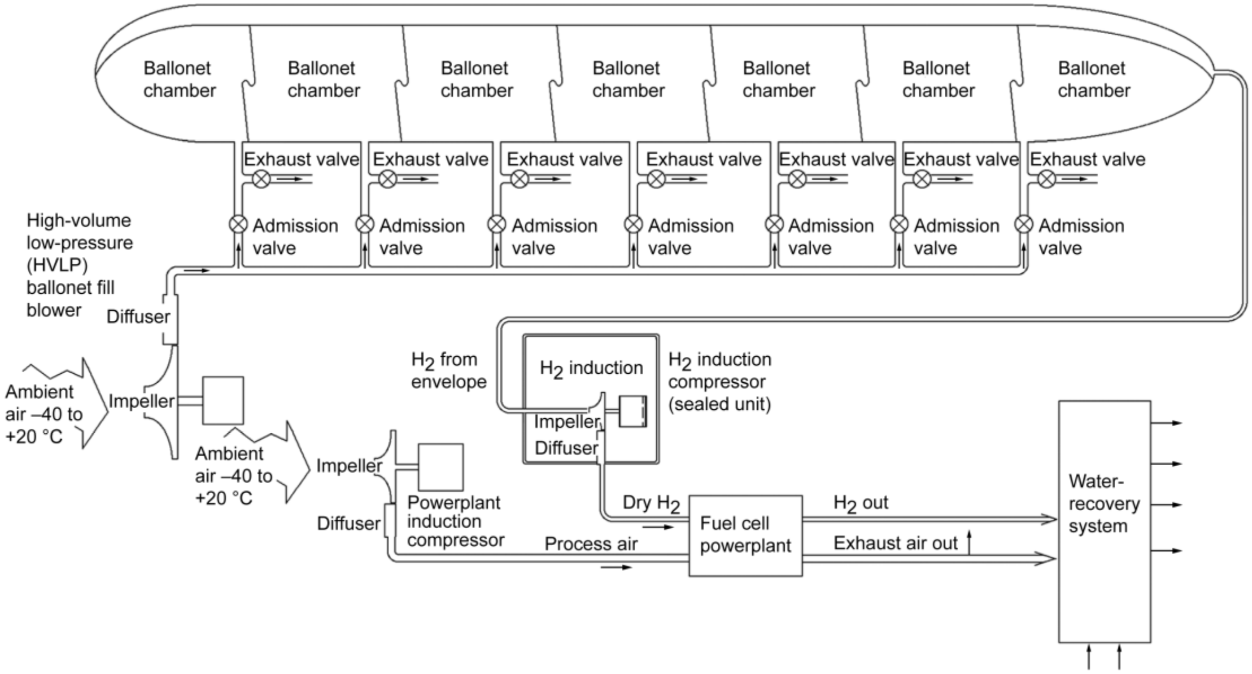

Figure 2.—Air and hydrogen (H_2) induction systems.

Air Induction and Pressurization System

The air induction and pressurization system is a network of ducting, electrically powered blowers, valves, and vents whose function is to ingest ambient air from outside, compress it slightly (to no more than 90-mm Hg (120 kPa)), direct the pressurized air into the individual ballonet chambers in a controlled fashion, and remove ballast air from the ballonet chambers as required. The system also provides induction air for the fuel cell powerplant, which requires up to 2.5 kg/min at a fairly constant delivery pressure of 20 psia (138 kPa absolute).

Two independently operated compressors are employed. The first unit is a high-volume, low-pressure electric-motor-driven blower that produces the 10- to 90-mm Hg overpressure needed to fill the ballonet chambers and stiffen the hull. The largest airmass flows, up to 3 kg/min, are associated with filling and emptying the ballonet chambers against pressure deltas that normally do not exceed 90-mm Hg (120 kPa). This compressor operates intermittently, in conjunction with the ballonet fill and drain valves. The second compressor unit, also electric motor driven, ingests ambient air and pressurizes the amount of airflow required to normalize the fuel cell powerplant to sea level, at flow rates up to 2.5 kg/min and pressures up to 20 psia (138 kPa absolute). This compressor operates more or less continuously at night. The 2.5-kg/min induction airmass flow ascribed to the fuel cell powerplant may be continuously sustained for up to 24 hr. Owing to the mass flows and pressure deltas that the induction system is required to work against, the adiabatic compressor power for the ballonet supply is 1.14 kW, whereas up to 5.15 kW is required to service the fuel cell powerplant. If a compressor efficiency of 65 percent is assumed, the power rating for the high-volume, low-pressure ballonet fill blower is 1.75 kW and that for the powerplant induction compressor is 7.9 kW.

Hydrogen-Air Fuel Cell Powerplant

The fuel cell powerplant characterization is adapted from a commercial hydrogen electric transit bus unit, in this case the Hydrogenics Corp. HyPM HD Mobility Power Module HD65 hydrogen/air fuel cell powerplant (Ref. 6). The hydrogen consumption of this powerplant varies from 30 g/hr/delivered kWe (at 66 percent of rated power) to 46 g/hr/delivered kWe (at 100 percent of rated power). The fuel cell plant accomplishes its internal humidification and exhausts its product water through the exit airstream; the product water is returned at the rate of approximately 9 g water/1 g hydrogen consumed. Both the air and hydrogen exit streams are routed to the water-recovery system to effect further water removal (lower dewpoints) from these streams before they are quit. This powerplant unit is rated to only 5000-ft altitude (1200 m) mean sea level (MSL), but at higher altitudes the air-induction system normalizes the unit to approximately sea level pressure.

Electric Motor Drive Propulsion System

The airship is propeller driven, with four propulsion electric drive motors of 16 kWe each that are housed in rotating mast-mounted pods cantilevered outward from the gondola keel at the four corners of the ship (shown in Fig. 1). The pods swivel on rotating masts such that propeller thrust can be independently directed over a nearly 360° arc in the vertical plane. The propellers are two-bladed fixed-pitch units of composite construction 8 ft (2.44 m) in diameter. The rotating masts allow thruster control of pitch attitude and, to a limited degree, lift. Differential thrust is used to control yaw and steer the ship. Because of the directed propeller thrust available, there is no need for hull empennage to control attitude. Each propulsion pod with its cantilevered rotating mast and associated mechanisms, electric drive motor, and propeller weighs approximately 215 lbm (97 kg).

Thermal Management System

The thermal management system removes low-grade waste heat from the fuel cell powerplant, water electrolyzer, and water-recovery systems and provides controlled temperatures to maintain their required internal process conditions. The waste heat is ultimately rejected to the ambient airstream. Depending on the operational phase, the thermal management system removes up to 50-kWt waste heat from the electrolyzer and up to 65-kWt waste heat from the fuel cell powerplant at temperatures not exceeding 140 °F (60 °C). The thermal control system also removes up to 200 W heat from the water electrolysis plant's output streams to maintain an exit dewpoint no greater than 18 °F (10 °C) above local ambient.

Thermal control is accomplished by an air-cooled two-stage pumped liquid loop system. Primary cooling is accomplished by a pumped liquid primary loop circulating coolant (antifreeze solution) through a liquid-to-air HX cooled by forced ambient air (electric fan). The primary loop connects to liquid-to-gas condenser HXs exchangers "ice catchers" to aftercool the hydrogen and oxygen and exit airstreams to their lowest possible temperatures (i.e., below freezing). Then it connects downstream to liquid-to-liquid HXs that service the four intermediate cooling loops:

(1) Liquid water removal from the fuel cell powerplant exit airstream, the electrolyzer hydrogen exit stream, and the electrolyzer oxygen exit stream at temperatures between 0 and 5 °C
(2) Payload cooling at temperatures between 25 and 40 °C
(3) Electrolyzer stack cooling via deionized water anode feed at temperatures between 40 and 60 °C.
(4) Fuel cell powerplant cooling at temperatures between 40 and 60 °C

The intermediate cooling loops circulate liquid coolant and deionized water at constant flow rates through intermediate temperature cold plates, the powerplant's fuel cell stack and the electrolyzer stack, then back to the liquid-to-liquid HXs that interface the primary loop. Although the primary loop temperature is not controlled (it tracks ambient air temperature), the intermediate loop temperatures are thermostatically controlled by means of bypass loops.

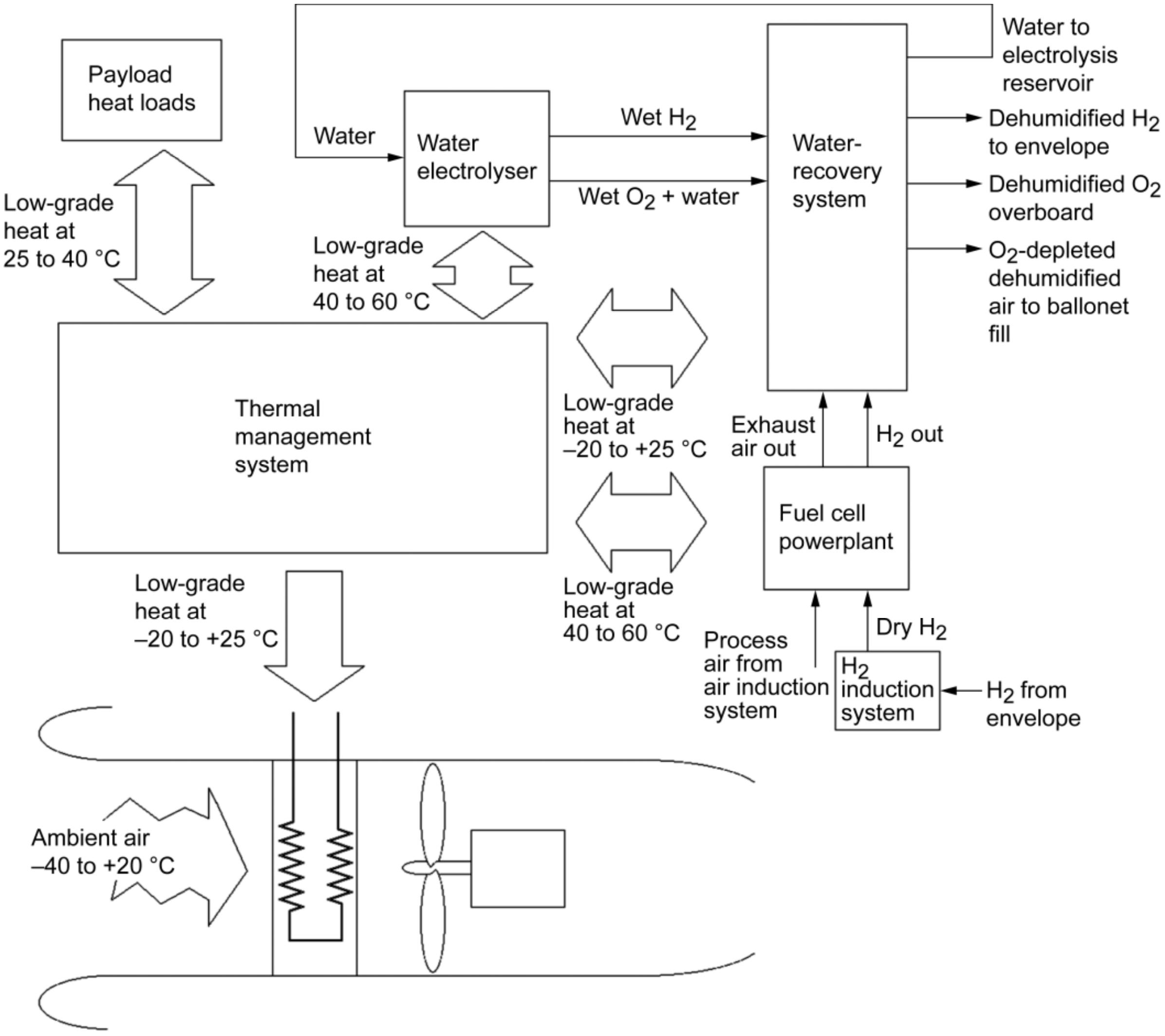

Figure 3.—Thermal management and water-recovery systems.

In addition to removing waste heat, the thermal management system heats the fuel cell and electrolyzer stacks when they are not active, keeping them at near operational temperatures to minimize startup times. Figure 3 is a block diagram depicting the thermal-management and water-recovery systems and the basic interrelationships with the other onboard systems.

Water-Recovery System

Ancillary to the thermal-control and air-induction systems, there is a water-circulation and water-storage system that accumulates product water from the fuel cell powerplant, collects electrolysis condensate that escaped to the interior hull and was subsequently melted, and provides an electrolyzer feedwater storage reservoir of at least 500 liters capacity (and not to exceed 4000 liters). Product water is removed from the powerplant via an exit airflow condenser HX (serviced by the thermal management system’s water-removal intermediate loop), which drops the local dewpoint to approximately 40 °F (4.88 °C), extracting roughly 140-g product water/kg exit air as liquid. The exit airstream is then dried further by means of an “ice catcher” low-temperature HX (serviced by the low-temperature primary loop), which drops the airstream’s dewpoint to approximately 10 °C above local ambient, thereby removing up to 14 g additional product water/kg air in the form of frost, before it is injected into the ballonet inlet. Meanwhile, the frost accumulates in the "ice catcher" HX until the next day when it is melted out by the application of the high-temperature intermediate loop during electrolysis and is returned to the reservoir as liquid. Water that remains in (i.e., is not recovered from) the exit airstream represents a loss of less than 3 kg/day.

The water-recovery system also removes and collects water directly from the electrolyzer hydrogen and oxygen output streams. The hydrogen gas is vented directly into the envelope after most of the water has been extracted. The oxygen gas is similarly dried but ultimately vented overboard, with a loss of less than 500 g/day. The system also delivers deionized feedwater to the electrolyzer, incorporating a once-through pass through a polishing bed that removes contaminants from the feedwater stream, ensuring sufficient water purity (better than 10 MΩ-cm) for continuous electrolyzer operation.

Weight and Balance

Table I summarizes the major components that compose the empty weight of the airship:

TABLE I.—WEIGHTS OF MAJOR AIRSHIP COMPONENTS

Component	Weight, kg
External envelope	
Nose section	128
Center section	848
Tail cone	180
Internal ballonet	220
Solar array blanket with tensile members	2147
Gondola and keel	
Truss structure	380
Water electrolysis units	350
Induction air pressurization	220
Induction air distribution	50
Hydrogen induction	150
Fuel cell powerplant	321
Electrical power distribution	65
Electric drive thrusters (four)	390
Thermal management	150
Water recovery	100
Water storage tanks	100
Command, communication, and control	20
Gondola keel subtotal	2295
Airship total (empty weight)	5820

Table I thus summarizes the "empty weight" of the entire airship sans payload, consumables, air ballast, and hydrogen lifting gas.

Table II summarizes the gross takeoff weight of the vehicle for five different missions starting with the airship empty weight depicted in Table I. For each mission, the following weights must be added to the empty weight:

- Consumables (water)
- Payload
- Hydrogen inventory
- Air ballast

TABLE II.—WEIGHT DISTRIBUTIONS FOR FIVE DIFFERENT MISSIONS

Mission altitude, m	3000	6000	7600	9000	10 000
Mission duration, day	1	109	26	26	1
Airship empty weight, kg	5820	5820	5820	5820	5820
Hydrogen inventory, kg	610	610	612	580	516
Air ballast, kg	7052	2885	1014	82	50
Consumables, kg	288	800	402	400	288
Payload, kg	1412	900	1297	900	212
Consumables plus payload, kg	1700	1700	1700	1300	500

Consumables and payload is the “useful load,” whereas the weight of ambient air displaced by the airship’s fixed volume is basically a function of altitude and temperature. Generally, the removal of air ballast before flight would buy more useful load (at the expense of flight altitude) until the point where structural limits prevail is reached. Within those limits, there is a payload/endurance tradeoff such that removal of water from the reservoir allows more payload to be carried, but at the expense of flight endurance. The minimum water inventory required to effect a day/night cycle is approximately 288 kg.

Operational Scenario

Two flight operations are illustrated: flight to service altitude and cruise flight at service altitude.

Flight to Service Altitude

Table III depicts the airship rising from a launch altitude of 1200 ft (366 m) to service altitudes of 10 kft MSL (3010 m), 20-kft MSL (6096 m), 25-kft MSL (7600 m), and 29-kft MSL (9000 m), respectively, in calm conditions at U.S. Standard Atmosphere. Table III shows how positive buoyancy is maintained within the fixed envelope volume by the uptake and discharge of air ballast as the ship rises. At liftoff, the onboard air ballast occupies roughly the same envelope volume as the hydrogen inventory. By the end of climb, however, the air ballast load is significantly reduced, its volume superceded by the expanding hydrogen charge. The 1700-kg useful load (restricted by gondola keel structural limits) that could be carried to a 7600-m altitude is diminished to only 500 kg at 10 000 m.

TABLE III.—SOLAR-POWERED HYDROGEN AIRSHIP, ASCENDING FLIGHT PROFILES
[At neutral buoyancy.]

Flight to service altitude from 366 m	Outside air temperature, K	Internal temperature, K	Envelope ΔP, mm Hg	Hydrogen mass, kg	Ballast airmass, kg	Consumables plus payload, kg	Displaced airmass, kg
Start at 366 m	286	286	8.3	610	11 639	7 520	19 769
Level off at 3000 m	270	284	38.7	610	7 052	7 520	15 183
Temp. eq. at 3000 m[a]	270	270	7.8	610	7 052	7 520	15 183
Start at 366 m	286	286	8.4	610	11 639	7 520	19 769
Level off at 3000 m	249	270	37	610	2 885	7 520	11 015
Temp. eq. at 3000 m[a]	249	249	7.3	610	2 885	7 520	11 015
Start at 366 m	286	286	9.5	612	11 645	7 520	19 769
Level off at 7600 m	239	268	43	612	1 019	7 520	9 152
Temp. eq. at 7600 m[a]	239	239	7.5	612	1 014	7 520	9 152
Start at 366 m	286	286	9.1	580	12 070	7 120	19 769
Level off at 9000 m	229	260	38.9	580	85	7 120	7 785
Temp. eq. at 9000 m[a]	229	229	7.2	580	82	7 120	7 785
Start at 366 m	286	286	8.6	516	12 933	6 320	19 769
Level off at 10 000 m	223	255	35.8	516	55	6 320	6 889
Temp. eq. at 10 000 m[a]	223	223	6.6	516	50	6 320	6 889

[a] Temp. eq. indicates temperature equilibrium.

Cruise Flight at Service Altitude, Through One Complete Day/Night Cycle and Associated Air Temperature Variations

Table IV depicts the airship cruising at a fixed altitude of 29.53 kft MSL (9000 m) while experiencing air-density changes associated with diurnal cycle temperature variations (Ref. 7, temperate latitude). In flight, ambient air temperature variations are the most stressful to the envelope and air-induction system, and require the most rapid ballast airflow rates to maintain neutral buoyancy.

TABLE IV.—SOLAR-POWERED HYDROGEN AIRSHIP, FIXED-ALTITUDE PROFILE
[Cruise at neutral buoyancy at an altitude of 9000 m.]

Day/night cycle	Outside air temperature, K	Internal temperature, K	Hydrogen mass, kg	Water mass, kg	Ballast airmass, kg	Airship gross weight, kg	Envelope ΔP, mm Hg
Mid-afternoon, 1st day	231.33	231.33	674.666	196	319.21	6735	54.612
Late afternoon, 1st day	231.33	231.33	680	147.9	361.68	6687	58.055
Just after sunset, 1st day	230.22	231.33	684	111.9	431.824	6651	61.777
Late evening, 1st day	229.67	230.78	674.666	195	375.38	6735	55.597
Midnight, begin 2nd day	228.56	229.67	669.332	242.6	369.9	6783	51.897
Early morning, 2nd day	228.56	228.56	661.332	313.8	306.88	6855	45.451
Predawn, 2nd day	228.56	228.56	654.666	373.2	253.45	6915	41.19
Just after sunrise, 2nd day	230.22	228.56	652	397	175.36	6939	37.816
Early morning, 2nd day	230.78	229.11	654.666	72.8	178.1	6914.9	39.626
Mid-morning, 2nd day	231.33	229.67	661.332	312.6	213.72	6854.7	44.036
Noon, 2nd day	231.33	230.78	666.666	264.3	255.916	6806.5	48.789
Midafternoon, 2nd day	231.33	231.33	674.666	192	320.58	6734.3	54.653
Late afternoon, 2nd day	231.33	231.33	680	143.8	363.05	6686.2	58.095

Flying into a cold front can change ambient temperatures by 30 to 40 °F (17 to 25 °C) in less than 1 hr, but the airship's thermal response (within the envelope interior) will take more than 4 hr to equalize. The fastest heating occurs immediately after sunrise when direct sunlight warms the envelope walls to temperatures well above freezing, inducing a temperature rise of 15 to 20 °F/hr (8 to 12 °C/hr) in the previously equalized predawn interior.

In addition to the envelope pressure variations, notice how the vehicle's gross weight constantly varies over the day/night cycle as oxygen is taken from the water and thrown overboard during the day, but returned at night when the fuel cell ingests atmospheric oxygen, replacing water that was consumed the previous day. Because of the steady hydrogen leakage diffusion losses, plus the daily losses of water from the fuel cell powerplant air exit and the overboard oxygen stream, the weight of water left in the reservoir is slowly reduced until there is not enough left to make a full charge of hydrogen: this is where the flight must come to an end.

Performance

The airship's steady-state level flight performance is a balance between the propulsive thrust that can be indefinitely maintained from limited solar power, and the drag forces arising from its 4980-m^2 wetted area, which with its 7.33 length-to-diameter ratio, is reasonably well streamlined. For this vehicle in its anticipated flight regime of sea level to 30 kft, the (length-based) Reynolds number range is approximately 40 to 130 million, which results in wetted-area drag coefficients in the neighborhood of 0.003 to 0.004 for the ellipsoidal/cylindrical shape (Ref. 8). At 65-kWe maximum propulsive power, the top sea level speed achievable is 34 kt (17.5 m/sec), but this cannot be sustained for more than 24 hr. The highest sea level speed that can be continuously maintained (12 hr/12-hr day/night cycle) is 30 kt (15.5 m/sec).

Table V summarizes the steady-state level flight performance at a few different altitudes, including a payload versus endurance tradeoff. This summary assumes a 12 hr/12 hr day/night cycle with no clouds. Flight endurance is governed by the amount of onboard water and the rate at which it is consumed to replace lifting gas that was lost from the envelope and water that was not recovered from the overboard gas streams. The last two rows of Table V illustrate the limits of payload and endurance. The term "ten-day endurance payload capacity" refers to payload capacity when water sufficient for a 10-day flight is included in the useful load. "Zero payload cruise endurance" assumes that the entire available useful load was dedicated to onboard water inventory. Within limits, payload can be traded for endurance. For example, if a mission to 9000 m requires 100 days endurance, the payload would be 600 kg.

TABLE V.—SOLAR HYDROGEN AIRSHIP, STEADY-STATE FLIGHT PERFORMANCE SUMMARY

Cruise altitude, m MSL	3000	6000	7600	9000	10 000
Sustained true airspeed, m/sec	17	19	20	21.3	22.7
Flank speed, m/sec	19.3	21.4	22.6	24	25.5
Diurnal temperature variation,[a] °C	4.4	2.5	2.8	2.8	2.8
Diurnal envelope ΔP variation, mm Hg	33	26	24.2	23.7	23.2
Initial payload plus consumables, kg	1700	1700	1700	1300	500
Diurnal water consumption rate, liter/day	5.1	4.5	4.2	4.1	4.1
Ten-day endurance payload capacity, kg	1361	1367	1370	971	171
Zero payload cruise endurance, days	277	314	336	247	52

[a] U.S. Standard Atmosphere Supplement 1966.

Concluding Remarks

The vehicle concept for an unmanned solar-powered hydrogen airship was presented, with its physical characteristics and potential mission performance roughly estimated. The concept juxtaposes previously demonstrated aerospace electrical power technology, including lightweight photovoltaics and hydrogen/air polymer electrolyte membrane (PEM) fuel cells, with modern nonrigid airship technology, high-strength polymer fabrics, and barrier films.

On the basis of analysis and characterization estimates presented, the concept appears to be feasible, and the costs for its construction and operation can be estimated straightforwardly with a reasonably high degree of confidence. The major barrier to the implementation of this concept is cost of the photovoltaic array blanket, which is by far the most expensive component of the propulsion and power system. The Helios solar array blanket costs approximately $30 million; the acquisition cost for the airship array would be approximately $500 million.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01-10-2011	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Long-Duration Low- to Medium-Altitude Solar Electric Airship Concept

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bents, David, J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 038957.04.06.03.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17446

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-216815

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 05 and 07
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report presents the conceptual design for a solar electric lighter-than-air, unmanned aerial vehicle, based on existing technology already reduced to practice, that could carry a 600-kg (1322-lbm) payload to altitudes up to 30 kft (9000 m), continuously maintain an airspeed up to 40 kt (21 m/sec), and remain in flight for up to 100 days. The design is based on modern nonrigid airship technology, high-strength polymer fabrics and barrier films, and previously demonstrated aerospace electrical power technology, including lightweight photovoltaics and hydrogen-air polymer electrolyte membrane (PEM) fuel cells. The vehicle concept exploits the inherent synergy between the use of hydrogen as a lifting gas and the use of hydrogen-air PEM fuel-cell technology for onboard solar energy storage. In this report, the air vehicle concept is physically characterized and its estimated performance envelope is defined.

15. SUBJECT TERMS
Airships; Hydrogen; Photovoltaic conversion; Electrolysis; Fuel cell

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	19	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802