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Overview of Innovative Aircraft Power and Propulsion Systems and Their Applications for Planetary Exploration

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July 2003

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OVERVIEW OF INNOVATIVE AIRCRAFT POWER AND PROPULSION SYSTEMS AND THEIR APPLICATIONS FOR PLANETARY EXPLORATION

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ABSTRACT

Planetary exploration may be enhanced by the use of aircraft for mobility. This paper reviews the development of aircraft for planetary exploration missions at NASA and reviews the power and propulsion options for planetary aircraft. Several advanced concepts for aircraft exploration, including the use of in situ resources, the possibility of a flexible all-solid-state aircraft, the use of entomopters on Mars, and the possibility of aerostat exploration of Titan, are presented.

INTRODUCTION

Many technologies currently being developed for unpiloted atmospheric vehicles (UAVs) and high-altitude aircraft on Earth will be useful in the next century for exploring other planets and moons that have enough atmosphere to support flying vehicles. This paper gives an overview of some concepts for planetary exploration using advanced "rovers" that can fly and cover much greater territory than the current ground vehicles.

Although many planets and moons within our solar system have atmospheres capable of supporting winged flight, the majority of interest and analysis of the possibility of flight on other planets has been focused on flight Mars.

Mars has been a target of scientific exploration for more than 25 years. Most of this exploration has taken place using orbiting spacecraft or landers. Orbiters offer the ability to image large areas over an extended period of time, but are limited in their resolution. Landers can handle surface and atmospheric sampling, but are limited to the immediate landing site. Mobility is the key to expanding the scientific knowledge of Mars. The Pathfinder/Sojourner mission offered a new opportunity in that it was the first time that an autonomous mobile platform could be used for exploration. This allowed scientists the freedom to explore the surrounding terrain, maneuver to interesting sites, and perform an analysis of soil and rock composition over a broader area. In short, the scientific community has many more options. However, the surface rover is limited by the terrain it is traversing: large rocks and canyons are obstacles that are difficult for a surface rover to overcome.

Airborne platforms can achieve science objectives that are difficult to achieve from orbit or from surface rovers. They can cover much larger distances in a single mission than a rover and are not limited by the terrain, much more easily providing imaging of very rocky or steep terrain. Airborne platforms can return images of a magnitude higher resolution than state-of-the-art orbiting spacecraft. Near infrared spectrometry, which is crucial to analyzing mineralogy on the planet, and high-spatial-resolution magnetometry, which may provide clues as to the origin of high-crustal magnetism seen from orbit, require moving platforms. The resolution and sensitivity of these instruments is further increased by being close to the surface. Finally, atmospheric sampling can be accomplished over a far greater space, allowing scientists to study variations over a broad area.

HISTORY OF PLANETARY AIRCRAFT CONCEPTUAL DESIGN

The notion of flight on Mars has been a subject of NASA contemplation since Werner von Braun conceived a rocket plane as a means of Martian exploration in 1953. In the 1950s, Mars flight was purely fancy, but in the 1970s, it was revisited more seriously, being spurred on by the successes of the Viking Program.

One of the most studied airborne platforms for Mars is the airplane, with initial concepts dating back to the late 1970s. Flying an airplane on Mars represents a significant challenge, mainly because of the constraints posed by the Mars environment. The lift on a wing is proportional to the atmospheric density, velocity, and wing area. The Mars atmospheric density is extremely low, approximately 1/70 that at the Earth's surface. In order to compensate for this, the wing area and/or the velocity must be increased to generate sufficient lift. Wing area, however, is limited by packing, volume, and deployment constraints. Therefore, in order for flight to be feasible on Mars, the plane must travel at higher velocities to compensate for the lack of density and the constrained wing area. Furthermore, the speed of sound on Mars is approximately 20 percent less than on Earth. Both of these factors combine to put the plane in a low Reynolds number, high Mach number flight regime that is rarely encountered here on Earth. The high velocities limit imaging camera stability and resolution. Also, given the rocky Martian terrain, it is virtually impossible for a plane to land and take off again, thus limiting a mission to a single flight.

The NASA Dryden Research Center, Developmental Sciences, Inc., and the Jet Propulsion Laboratory (JPL) proposed unmanned aircraft designs for Mars exploration in 1977 and 1978 (ref. 1). Their concept was a propeller-driven fixed-wing aircraft fueled by hydrazine. This aircraft was based on the Mini-Sniffer high-altitude aircraft. A prototype of this aircraft was constructed and some testing was performed (fig. 1).

A decade later, JPL sponsored a Mars airplane study in which Aurora Flight Sciences proposed the electrically propelled "Jason" aircraft. About the same time, NASA Ames Research Center and Sandia National Labs conceived a high-speed aerospaceplane named AEROLUS. Unlike the earlier attempts to make a slow-speed aircraft that would be deployed from an aeroshell after touchdown on the Martian surface, AEROLUS would make a direct atmospheric entry and then fly through the Martian atmosphere at hypersonic speeds.

Throughout the 1980s and early 1990s, a number of studies were conducted to examine various approaches to flight on Mars. These studies were conducted by NASA and various universities. An example of some of this work was the long-endurance solar-powered Mars aircraft studied by NASA Glenn (ref. 2). An artist's concept of this airplane is shown in figure 2. As a technology demonstration for this project, a small model was successfully built and tested to fly in the Earth's atmosphere using only power produced by high-efficiency GaAs solar cells (refs. 3 to 5), as shown in figure 3.

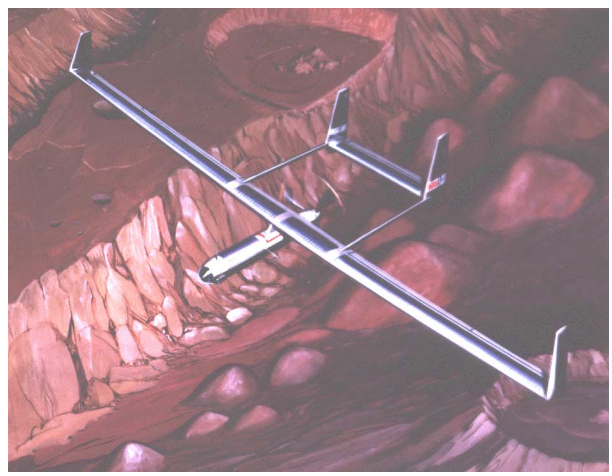

Figure 2.—Artist's concept of a proposed long-endurance solar-powered Mars aircraft (ref. 2).

Figure 1.—Mini-Sniffer Hydrazine Engine-Powered Mars Aircraft concept.

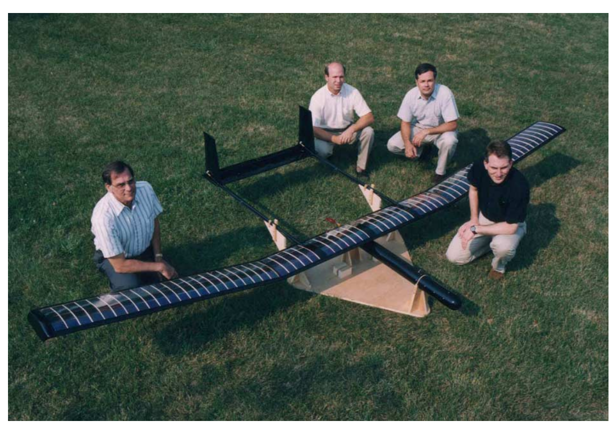

Figure 3.—NASA Glenn solar-powered aircraft demonstrator (ref. 3).

Successes with the Mars Pathfinder and Global Surveyor programs renewed interest in Mars flyers for exploration. In 1995, NASA Dryden and Ames Research Centers once again considered unmanned aerial vehicles to extend the reconnaissance range of Mars landers. The new concept was to launch a small unmanned aerial vehicle (UAV) from the lander after it had stabilized on the surface. The UAV would provide video of the immediate vicinity of the lander (within several thousand meters) to provide feedback as to the most interesting areas for investigation by ground-based rovers. The expendable, one-flight UAV would be electrically powered with rocket-assisted takeoff.

In 1996, the Ames Research Center proposed an unmanned Mars aircraft in response to a NASA Announcement of Opportunity for Discovery Exploration Missions. Ames' approach was to use a propeller-driven, low-drag plane configuration that they called Airplane for Mars Exploration (AME). On the following NASA Announcement of Opportunity for Discovery Exploration Missions in 1998, JPL submitted a proposal for a multiple glider system (dubbed "Kitty Hawk") with which several areas could be investigated during a single mission. This concept is shown in figure 4. As gliders, the vehicles were obviously limited in endurance but benefited from the lack of weight and complexity associated with a propulsion system in return for redundancy of numbers. NASA Ames again proposed a motorized UAV, a concept named "MAGE" (fig. 5). This aircraft was based on a similar hydrazine propulsion system as the Mini-Sniffer concept. Both concepts deployed from an aeroshell once it had become subsonic, approximately 12 000 meters above the Martian surface. Again, neither concept was selected for the Discovery mission.

On February 1, 1999, NASA Director Daniel Goldin announced a "Mars Airplane Micromission," which would have been the first NASA micromission program to launch on an Ariane 5 rocket. The flight would have had the first Mars airplane arriving on the Red Planet around December of 2003, coincidentally close to the hundredth anniversary of the Wright Brothers' first flight. Although conceptual designs of the plane were completed, the project was cancelled without fanfare due to funding constraints.

The latest attempt at a Mars aircraft mission is the NASA Langley/JPL aerial regional-scale environmental survey (ARES) concept, being developed by NASA Ames Research Center, in collaboration with a number of other institutions including NASA Glenn and Aurora Flight Systems in Manassas, VA. This aircraft is rocket powered and is being proposed for the 2007 Mars SCOUT mission. This concept is shown in figure 6.

Figure 4.—JPL Kitty Hawk glider Mars aircraft concept.

Figure 5.—Artist's concept of the proposed Ames MAGE aircraft.

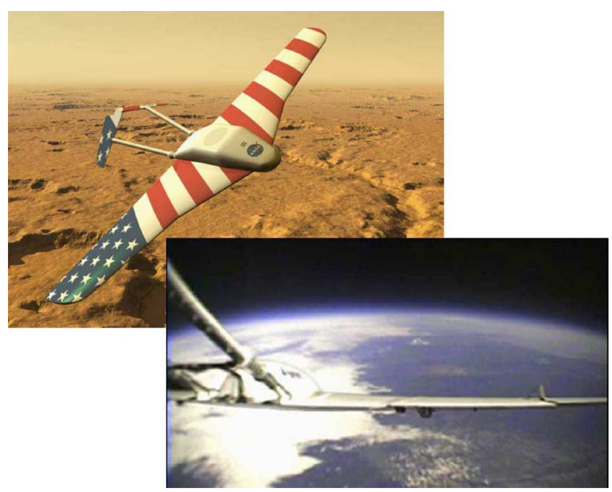

Figure 6.—The proposed ARES Scout mission Mars aircraft. Top: Artist's conception of ARES aircraft in rocket-powered flight. Bottom: Aurora Flight Sciences half-scale ARES aircraft test model in flight at 30 km altitude (frame from tail-camera video).

POWER AND PROPULSION SYSTEMS FOR PLANETARY AIRCRAFT

For all aircraft, the characteristics and capabilities of the propulsion system are key elements in establishing the aircraft's feasibility and flight envelope (refs. 6 and 7). This is especially true for an aircraft that is to fly on other planets. The planetary environment, as well as the launch from Earth and transit in deep space, produces additional obstacles to an aircraft's performance capabilities. Aircraft volume is critical since the aircraft must be stowed and fit into an aeroshell capsule for transit and entry into the planetary atmosphere. Therefore, propulsion system volume is also critical and any components (such as a propeller) that are large would also need to be stowed.

Because of the unique flight environments of the planetary environments, such as the thin atmosphere on Mars, where the surface atmospheric density is comparable to that at 30 km (110 kft) here on Earth, or the cold environments of the outer planets, the ability to generate lift and operate the aircraft may be difficult. To compensate for unusual flight conditions, winged aircraft may need to operate in ways different then on Earth in order to fly.

For example, on Mars the aircraft would need to fly fast and limit its mass as much as possible to compensate for the low atmospheric density; on Venus the aircraft would need to be sealed from the corrosive environment and (for low-altitude flight) constructed of materials tolerant of high temperatures; and for the outer planets, cold temperatures, low sunlight availability, and high gravity will drive the design. For all these environments and potential aircraft designs, the aircraft will be able to fly only as long as the propulsion system can operate.

Without the ability to refuel, mission duration will be limited to the amount of energy that can be stored and carried onboard the aircraft. Therefore, mission duration will depend on the efficiency of the propulsion system: the more efficient and lightweight the system is, the longer the mission and the more capable the aircraft.

There are four main types of conventional propulsion systems that can be considered for planetary flight. These main types of systems are

- Electrical propulsion systems
  - Fuel cell power propulsion system
  - Battery-powered propulsion system
  - Solar propulsion system
- Combustion engine propulsion systems
  - Piston expander combustion
  - Four-cycle internal combustion
  - Two-cycle internal combustion
- Rocket systems
  - Bipropellant rocket propulsion
  - Monopropellant rocket propulsion
- Unpowered systems (gliders)

Figures 7 and 8 show a basic concept and block-diagram for the electrical propulsion systems, using fuel cells or battery storage, respectively.

Figure 9 shows the block diagram for the piston expander propulsion cycle, while figure 10 summarizes the internal combustion conceptual design.

The electrical and combustion-engine propulsion systems both use propellers for propulsion, while the rocket system uses a rocket engine directly. The glider system uses the potential energy of the initial deployment altitude for propulsion; since planetary exploration systems typically start from orbit, in principle a large amount of energy is available.

For propeller systems, the propeller must be designed for operation in the planetary environment of interest. For Mars, the low atmospheric density requires a large propeller; the propeller operation is similar to the operation of aircraft at altitudes on Earth of about 30 to 40 km (ref. 8).

Each of these systems should be capable of operating within all of the known atmospheric environments within our solar system. The main drawback for these systems is their limited duration. Since all of these systems use consumable fuel or energy sources they will be limited in operational duration. However, the technology for these systems is well understood and in many cases would require very little development. Because of this, the first generation of aircraft for planetary exploration will most likely be based on one or more of these types of propulsion systems.

Another constraint on each of these systems is that there is no readily available source of oxygen within any known planetary atmosphere within our solar system (outside of Earth). Because of this, these types of propulsion systems will need to be modified to operate on a monopropellant fuel, like the Mini-Sniffer discussed previously, or carry along an oxidizer.

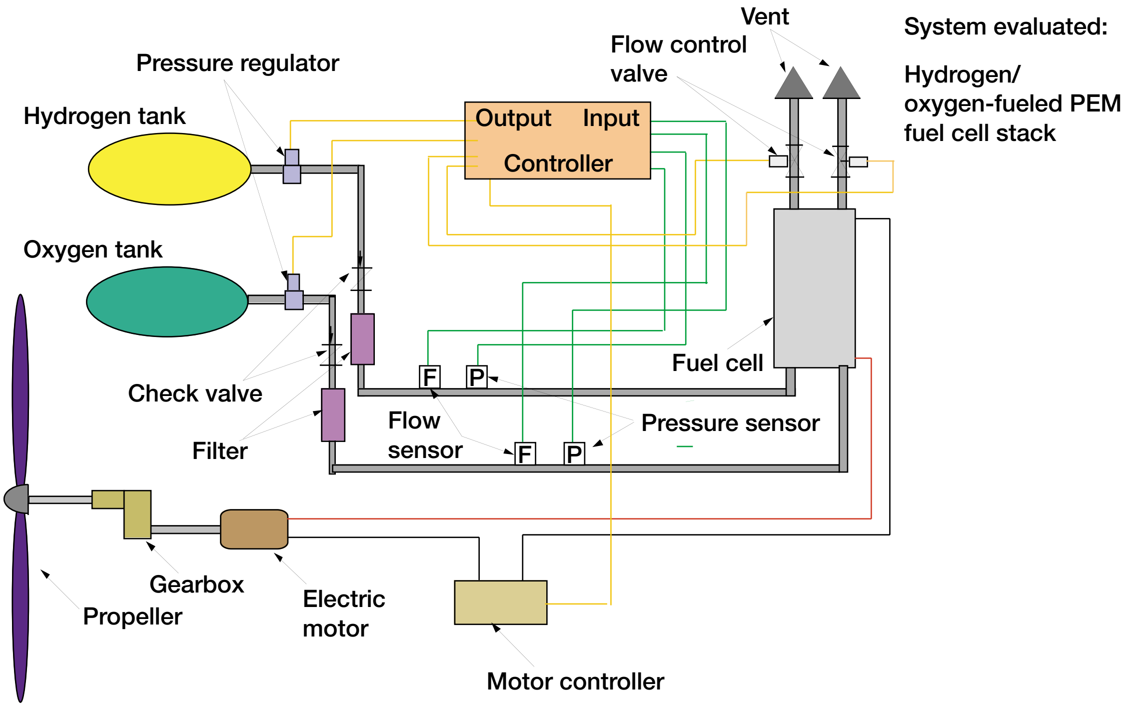

Figure 7.—Fuel cell propulsion system layout.

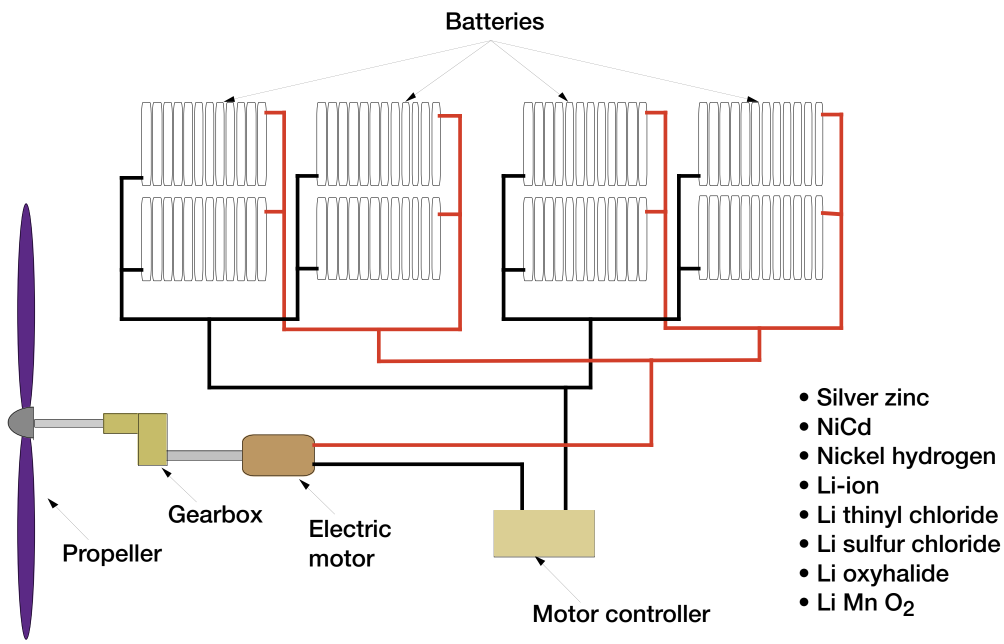

Figure 8.—Battery-powered system layout.

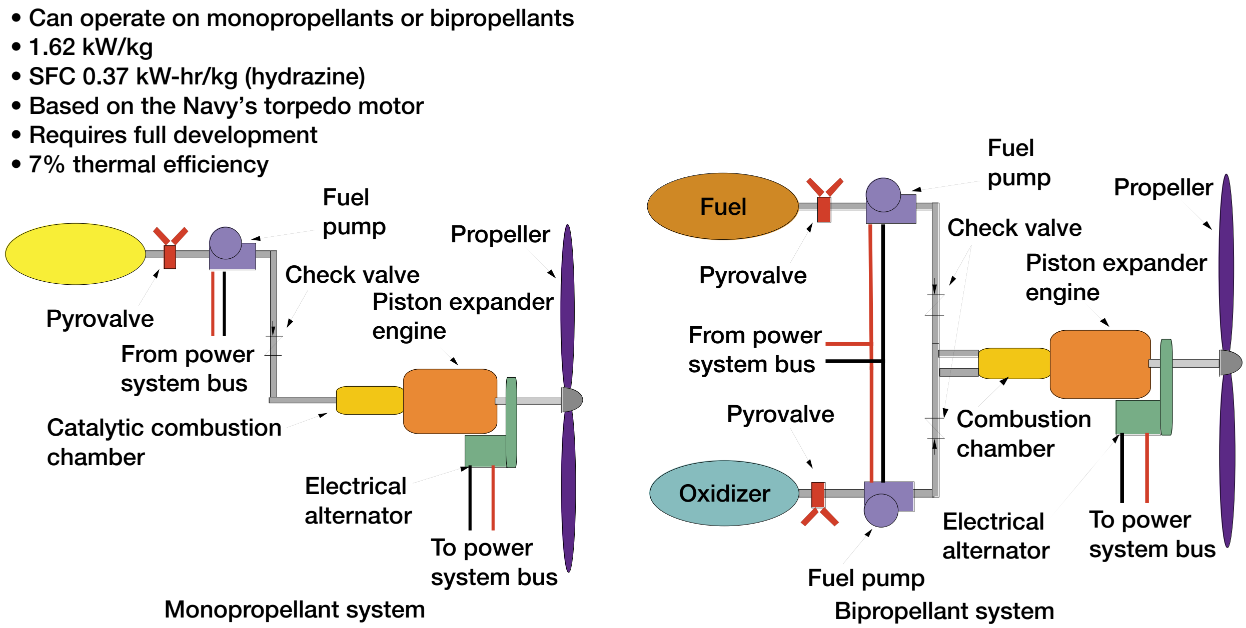

Figure 9.—Piston expander propulsion system layout.

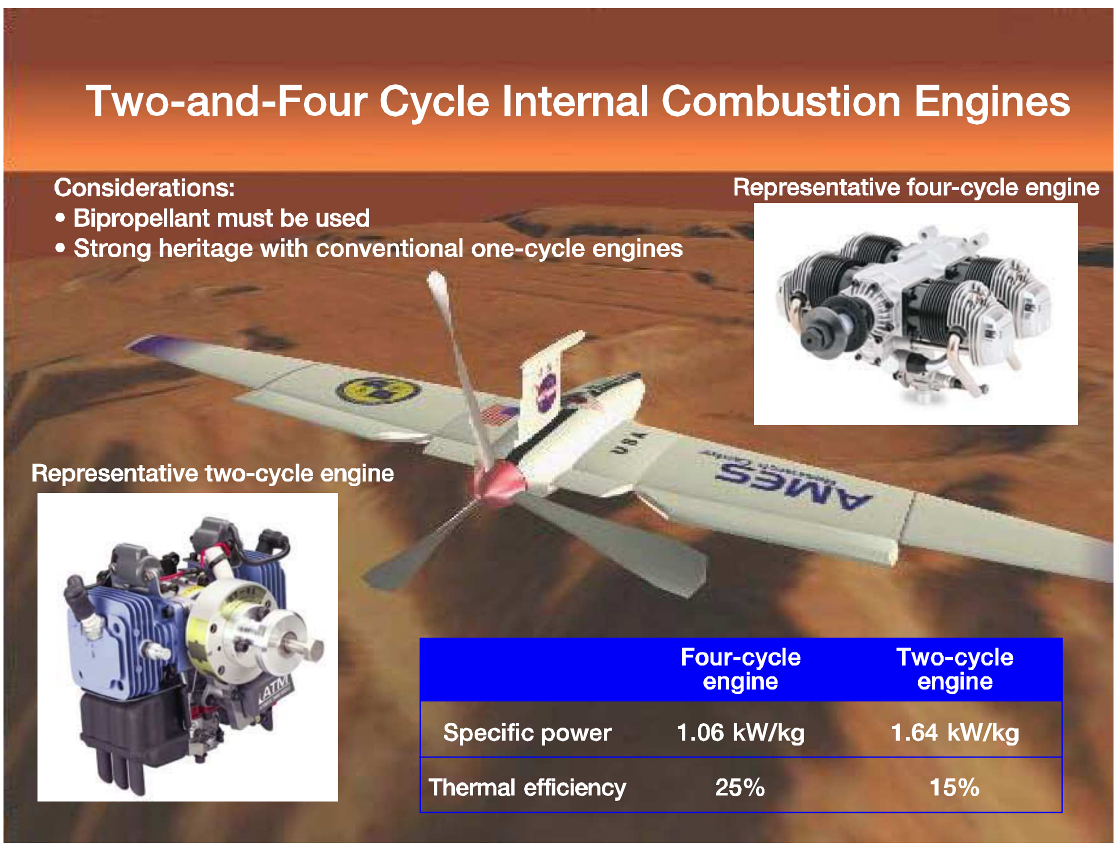

Figure 10.—Internal combustion aircraft characteristics.

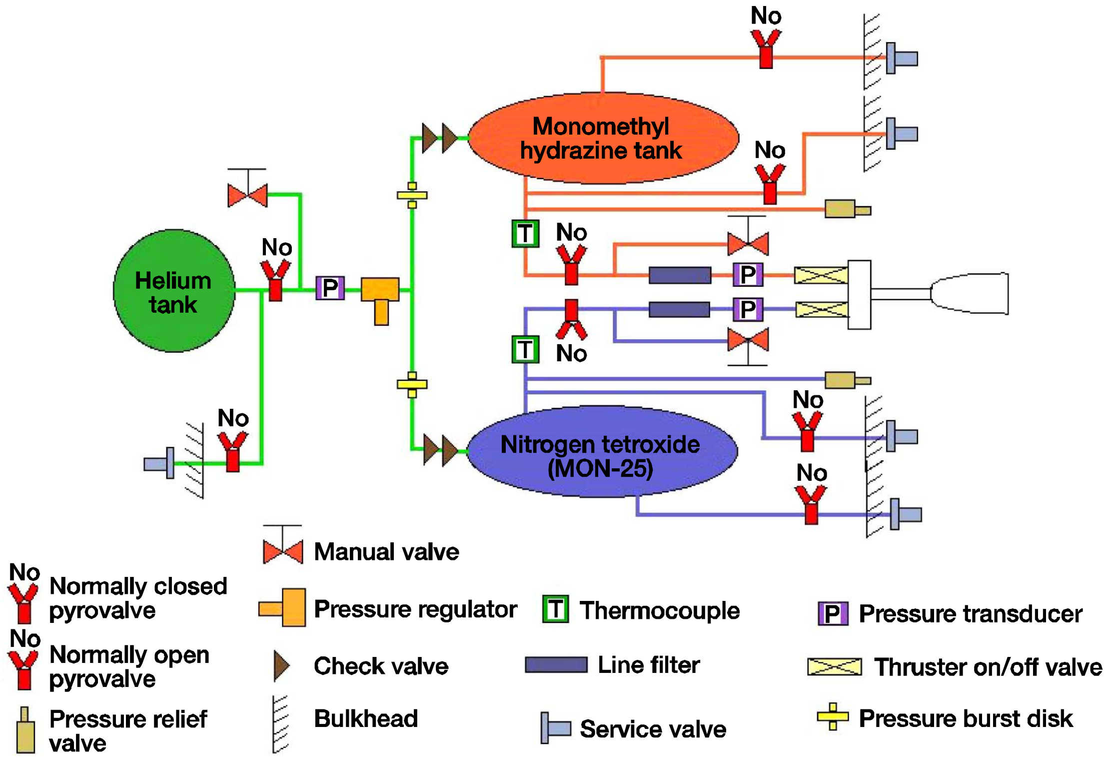

Figure 11.—Regulated rocket system layout.

SOLAR-POWERED AIRCRAFT FOR MARS AND SOLAR AIRCRAFT FOR MARS

One option for exploration of the atmosphere of Mars is a solar-powered airplane. Fleets of solar-powered aircraft could provide an architecture for efficient and low-cost comprehensive coverage for a variety of scientific missions. For long (multiple day) flight duration, solar aircraft (ref. 2) will require storage, such as a battery, to enable operation during the night. However, a short-duration flight, flying only during the daylight, could potentially be an extremely small and light airplane (ref. 9). A concept for such an aircraft is shown in figure 12.

Solar aircraft operate on Mars at an atmospheric density equivalent to the atmosphere of Earth at 30 to 35 km above the surface. Since in the terrestrial flight regime solar-powered aircraft have successfully operated at this altitude (fig. 13), even at relatively high sun-angles, and the gravity of Mars is less than that of Earth, it is clear that operation of a solar aircraft on Mars is physically plausible. Analyses of the solar energy availability for flight on Earth and Mars can be found in references 10 to 12.

Figure 12.—Mars solar airplane concept.

Figure 13.—Aerovironment Pathfinder solar-powered aircraft.

Solar Venus Aircraft

The atmosphere of Venus provides several advantages for flying a solar-powered aircraft (refs. 13 to 15). At the top of the cloud level, the solar intensity is comparable to or greater than terrestrial solar intensities. The atmospheric pressure makes flight much easier than on planets such as Mars. Also, the slow rotation of Venus allows an airplane to be designed for flight within continuous sunlight, eliminating the need for energy storage for nighttime flight. These factors make Venus a prime choice for long-duration solar-powered aircraft. Fleets of solar-powered aircraft could provide an architecture for efficient and low-cost comprehensive coverage for a variety of scientific missions.

Figure 14 shows a concept for a small solar-powered airplane deploying from an aeroshell and operating in the Venus atmosphere.

Inflatable Solar Aircraft for Polar Mars Exploration

Inflatable structures integrated with thin-film photovoltaic arrays could be used to produce an aircraft for planetary exploration. It could be used on Mars as well as other planetary bodies with atmospheres. The solar aircraft provides some significant benefits in that its flight duration would be much longer then any previously proposed aircraft, on the order of 7 days if the flight were to take place near one of the polar regions. Figure 15 shows a schematic diagram of such an inflatable-wing airplane in folded and unfolded form.

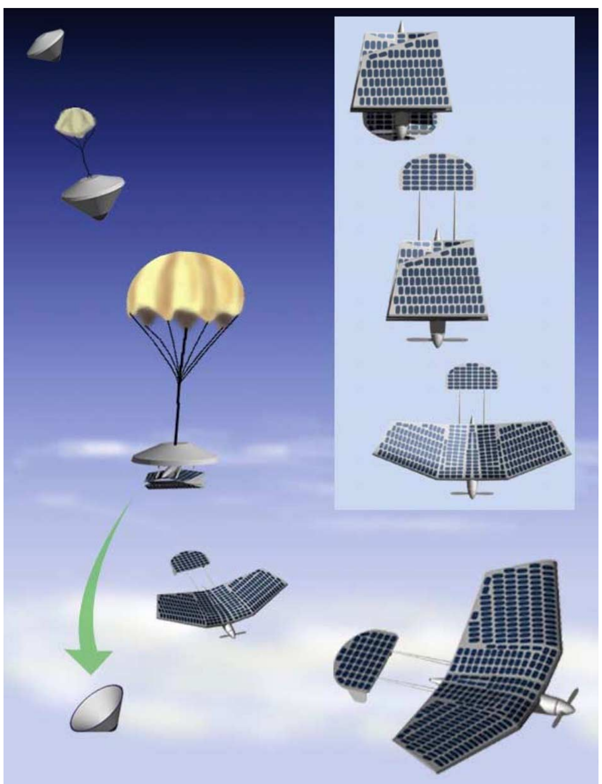

Figure 14.—Deployment of a folding solar-powered aircraft in the Venus atmosphere. The deployment of the flying surfaces is shown in the upper right: (top) folded configuration, (middle) tail unfold, (bottom) wing panels unfold.

Several inflatable-wing aircraft test models have been built and flown at NASA Dryden Research Center (ref. 16) as shown in figure 16. These models, with a wingspan of slightly under 2 meters, have demonstrated inflation and transition to level flight at Earth atmospheric conditions.

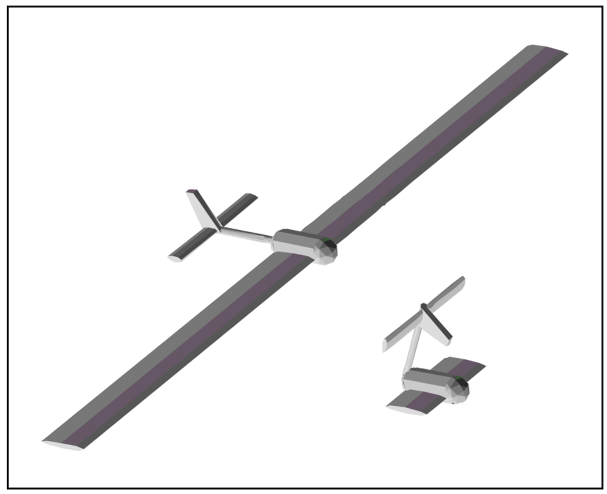

Figure 15.—Concept of an inflatable-wing Mars aircraft, shown in deployed and partially folded configuration.

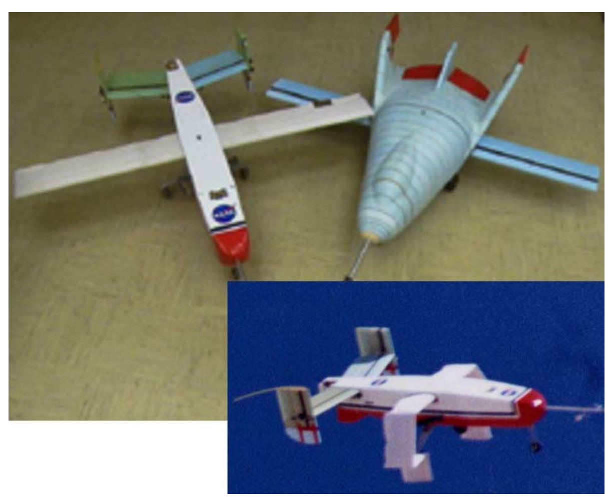

Figure 16.—Inflatable-wing aircraft tests at NASA Dryden Research Center (ref. 16). Top: two test models of inflatable-wing aircraft. Bottom: unfolding of inflatable wing in flight.

“SOLID-STATE” AIRCRAFT

Due to the recent advancements in photovoltaics, batteries, and polymer materials, a unique type of unmanned aircraft may be feasible. This aircraft is a “solid-state” aircraft with no moving parts (ref. 17). An artist rendering of the concept is shown in figure 17. The unique structure combines aerodynamic lift, propulsion, energy collection, energy storage, and control. Thin-film solar arrays are used to collect sunlight and produce power that is stored in a thin-film lithium battery. This power is used to fly the aircraft by setting up an electromagnetic field (EMF) along the wing of the vehicle. The wing, made with ionic polymeric-metal composite (IPMC) synthetic muscles, bends in the presence of this EMF producing the desired flapping motion. This layering of the various component materials is shown in figure 18.

This aircraft would fly in a similar fashion to a hawk or eagle. It would glide for long distances and flap infrequently to regain altitude. The solid-state nature of the aircraft allows it to be very robust, extremely lightweight, and capable of flight unlike any other present day air vehicle.

This type of air vehicle has a number of potential applications as a research platform on Venus or Mars. Because of its projected relatively small mass and flexibility, the aircraft is ideal for planetary exploration. These characteristics allow the aircraft to be easily stowed and launched at a minimal cost.

A fleet of these aircraft could be deployed within a planet’s atmosphere and used for comprehensive scientific data gathering/observation or as communications platforms. A whole planetary science gathering or communications/navigation architecture can be built around these lightweight, easily deployable, and robust aircraft.

The technology to produce this type of aircraft is presently available. There have been great advances in recent years in each of the three main components areas that make up the aircraft (thin-film photovoltaic arrays, thin-film batteries, and polymer composites). Because of these advances this type of aircraft may now be possible.

Vehicle Operation

The unique material composition of the aircraft enables flapping motion of the wing to be utilized as the main means of propulsion, thereby eliminating the need for a more conventional propulsion system. Figure 18 shows the layering of the “muscle” and “power” systems. The aircraft flight motion will consist of an intermittent flapping and periods of gliding. During the flapping portion of the flight, the aircraft will gain altitude. Then, during the gliding portion, will glide back down to the starting altitude. This cycle is shown in figure 19.

During gliding, the wing shape can be altered to enable steering and control of the aircraft. This control mechanism is similar to that of gliding birds, changing the angle of attack and/or wing shape to produce directional lift on a given wing. This variation in shape can be achieved through a grid of electrodes that are computer controlled. The voltage potential can be varied over the grid thereby tailoring the electric field generated to produce a nonuniform bending in the wing. This variation in lift can be used to steer and control the aircraft. The force vectors generated by the wing are shown in figure 20 for the upstroke and downstroke.

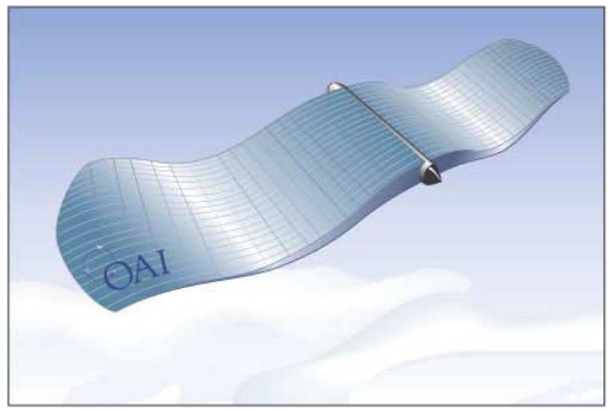

Figure 17.—Artist’s drawing of the solid-state aircraft concept.

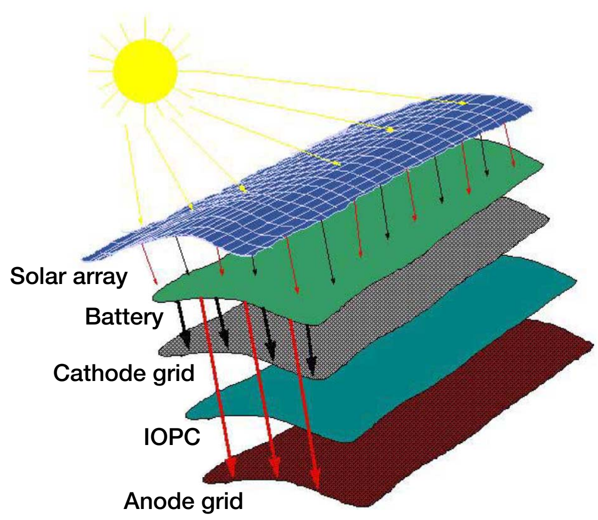

Figure 18.—Main components and layout for the solid-state aircraft.

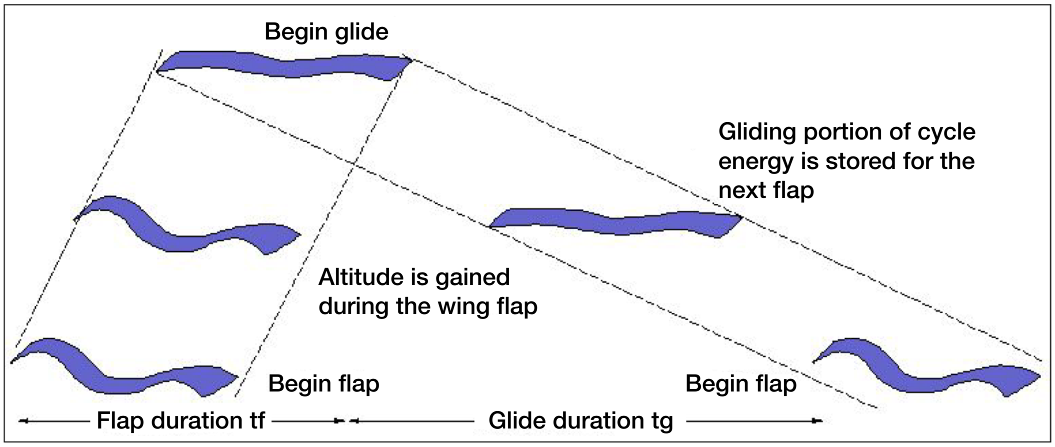

Figure 19.—Solid-state aircraft flap cycle.

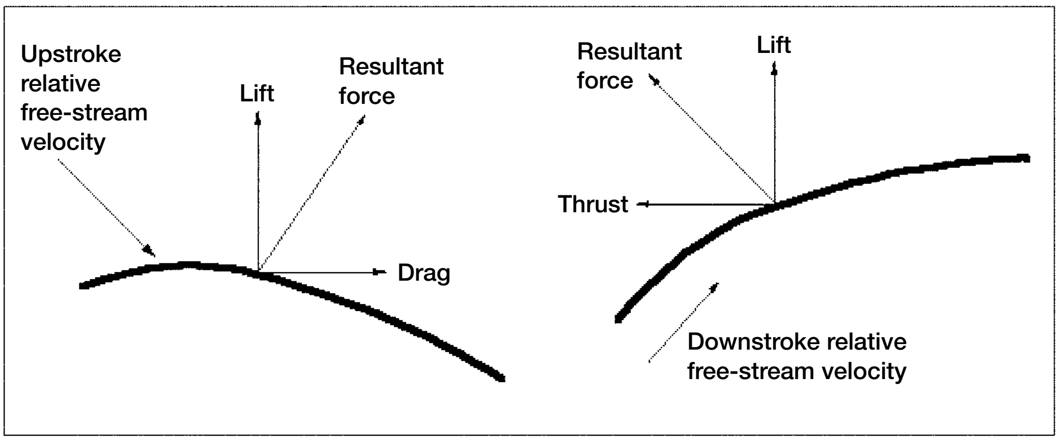

Figure 20.—Generation of thrust.

A control grid will be used to control the motion of the wing. This grid will enable various voltages to be sent to different sections of the wing, thereby causing varying degrees of motion along the wing surface. The amount of control on the wing will depend on the fineness of this control grid. A central processor will be used to control the potential of each of the sections to produce the correct motion of the wings to sustain biomimetic flight. Figure 21 shows this grid control concept and the material layers of the wing.

The most innovative aspect of this concept is the use of an ionic polymeric-metal composite (IPMC) as the source of control and propulsion. This material has the unique capability of deforming in an electric field like an artificial muscle, and returning to its original shape when the field is removed. Combining the IPMC with emerging thin-film batteries and thin-film photovoltaics provides both energy source and storage in the same structure.

Combining the unique characteristics of the materials enables flapping motion of the wing to be utilized to generate the main propulsive force. With a flight profile similar to a hawk or eagle, the solid-state aircraft will be able to soar for long periods of time and utilize flapping to regain lost altitude. By analyzing the glide duration, flap duration, wing length, and wing motion of travel, it has been determined that a number of design configurations can be produced to enable flight over a range of latitudes and times of the year on Earth, Venus, and Mars.

Recent discoveries and developments in these materials have indicated that this concept, on a preliminary level, may provide a robust advanced aeronautical architecture suitable for both terrestrial and planetary missions (ref. 17).

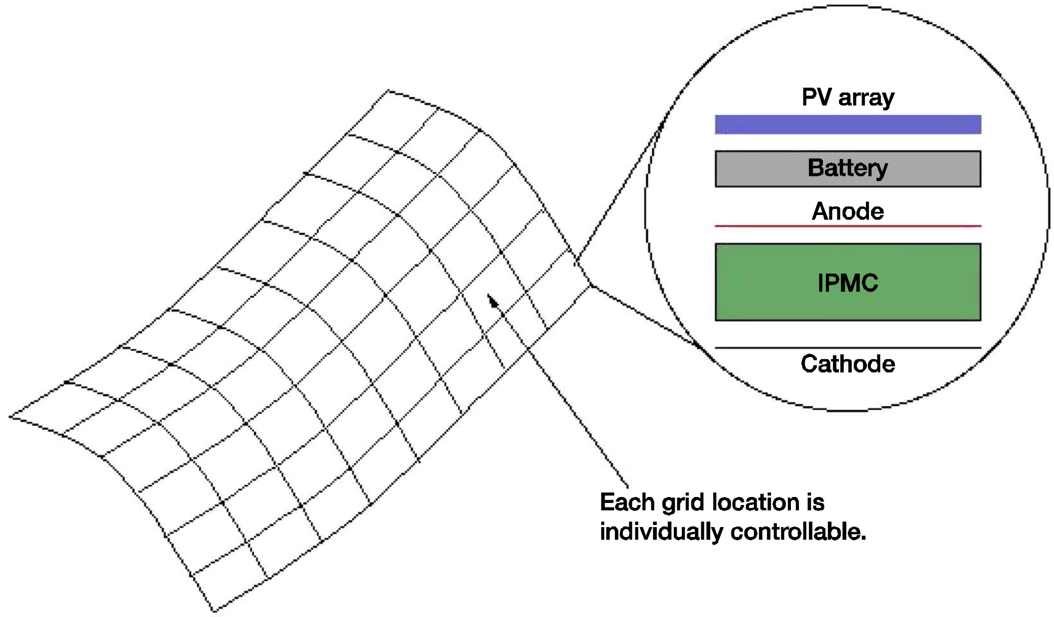

Figure 21.—Control grid for generating desired wing motion.

IN SITU RESOURCE UTILIZATION (ISRU) FOR MARS AIRCRAFT

For Mars flight systems that use consumable fuels for the propulsion system, resupply of the consumable must be accomplished for a repeat flight. For example, a combustion engine will require resupply of the fuel and of the oxidizer. Resupply can be done by manufacture of fuel from locally available materials, a process known as ISRU.

On Mars, a globally available resource for ISRU is the carbon dioxide atmosphere. Other resources include water in the form of atmospheric water vapor, permafrost, or water ice "snow" on the polar caps. Several processes have been proposed to chemically process Mars atmosphere into propellant. Possible propellants produced include carbon-monoxide/oxygen, a fuel combination that can be manufactured from Mars atmosphere with no external consumables required, and which can be burned in a rocket engine. Propellants such as methane/oxygen and higher hydrocarbons or alcohols are also possible fuels that can be produced from Mars resources, but either require a source of hydrogen or water, or else must use hydrogen brought from Earth as a consumable.

Use of in situ resources will require that the aircraft land on the surface for the duration of time required to manufacture propellant for the next flight. In essence, fuel production is a process of fixing energy into chemical form. The rate of propellant manufacture, therefore, is limited by the power available. Depending on the power supply available, this may require days to months.

For winged vehicles on Mars, landing presents a significant difficulty. For example, the aircraft proposed for the Mars Scout mission requires an airspeed of 130 m/sec (290 mph) for level flight. Achieving a successful landing without damage at 130 m/sec on an unprepared runway is a difficult problem. A refuelable aircraft needs to incorporate a low-speed, preferably vertical, landing.

One possible system for such landing is the Mars entomopter concept, discussed in the next section. Another approach to flight of a refuelable vehicle is the Mars hopper concept proposed by Landis and Linne (ref. 18). In this flight concept, a vertical-takeoff, vertical-landing rocket-powered vehicle is used. The rocket fuel is generated between hops by production of carbon-monoxide/oxygen propellant by use of a solid-oxide electrolysis process on the carbon dioxide atmosphere. Such a vehicle could hop over rugged terrain and land at a number of interesting scientific sites. A rocket-powered landing could also be used for a winged airplane, allowing a low-velocity controlled vertical landing under rocket power. The vehicle could then use either a vertical or horizontal takeoff, again under rocket power, to achieve airspeed for either powered or gliding flight.

ENTOMOPTER CONCEPT

The very low atmospheric density on Mars poses a significant problem for conventional aircraft designs. In order to generate sufficient lift, the aircraft must fly fast. That fact and the rough rock strewn surface of Mars makes it almost impossible to produce a conventional aircraft that can safely land and take off again. Therefore, all previously proposed aircraft missions have been limited in duration to the amount of fuel the aircraft could carry for one flight.

The entomopter (insect-wing) concept is a potential way around this problem of having to fly very fast within the atmosphere of Mars (refs. 19 and 20) by using the low Reynolds number as an ally, rather than as an enemy. The entomopter does not generate lift in the same fashion as a conventional aircraft. The entomopter concept uses the same lift-generating means that insects do here on Earth to generate lift within the Mars environment. Unlike aircraft or birds, insects generate lift by the continuous formation and shedding of vortices on their wings. This vortex formation and shedding produces very high wing lift coefficients on the order of 5 compared to maximum lift coefficients of 1 to 1.2 for conventional airfoils. This very high lift generating capability is what allows insects to fly, hover, and maneuver as they do.

The investigation of the aerodynamics of insect flight is still a new science and the mechanisms for how they fly are not completely understood. However, it is believed that their ability to generate these large amounts of lift is a Reynolds-number-based phenomena. As Reynolds number increases, the ability is diminished.

This high lift-generating capability under low Reynolds number flight conditions poses an interesting solution to flight on Mars. Because of the low atmospheric density on Mars, a vehicle with a wing-span on the order of 1 m would be in the same flight Reynolds number regime as most insects are here on Earth. Because of this, it is conceivable to construct a vehicle that can fly near the surface of Mars (up to 100 s of m in altitude) and generate sufficient lift to allow it to fly slow, maneuver easily, and land. This realization is the genesis for the entomopter concept for Mars.

The entomopter consists of a central fuselage that houses the propulsion system, fuel, and all instrumentation. On top of the tubular fuselage are two sets of wings that oscillate 180° out of phase. These wings provide the flapping motion that generates the lift for the vehicle. Beneath the vehicle are spring-loaded legs that absorb energy during landing, assist in takeoffs, and stabilize the vehicle while on the ground.

For the entomopter to fly, it will need to flap its wings at a specified rate, thereby producing and shedding the vortices that will generate the lift. The motion of the wings is a fairly power intensive process so a given flight mission for the entomopter will be short (on the order of 10 to 15 minutes). These short flight times are due to the amount of fuel it is estimated the entomopter can carry. Because of these short flight times, the entomopter would need to be operated as part of a system. It is envisioned that this system would consist of one or more entomopter vehicles that operate in conjunction with a base vehicle such as a lander or rover. This base vehicle would provide refueling capability to the entomopters as well as act as a data relay for the science data and samples the entomopters collect.

The most promising scenario is to utilize the entomopter in conjunction with a rover. The rover would be capable of slowly moving over the Martian surface, while the entomopters fly off to investigate areas inaccessible to the rover. The entomopters could also be used to guide the rover from the air, indicating the best path to traverse to scope out interesting terrain or objects for the rover to further investigate.

In addition to acting as a scout for the rover, the entomopter could perform a number of science data-gathering tasks on its own. These tasks could include surface imaging in the visible, infrared, or other wavelengths; magnetic field mapping; atmospheric science; and surface sample collection and searching for the chemical signs for life.

For the entomopter to work within the Mars environment it will need to be as lightweight and efficient as possible. This means that systems and devices on the vehicle will need to perform more the one task if possible. This multiple-use philosophy has been integral to the design effort. It begins with the propulsion system. The engine will decompose hydrazine (a monopropellant) to provide the power to move the wings.

Hydrazine was chosen as the candidate fuel because of its high energy density and the fact that it was a monopropellant. Utilizing a monopropellant simplifies the fuel delivery and refueling systems by requiring one tank and filling nozzle. Also, hydrazine decomposes when passed over a catalyst, allowing for a low-risk combustion scheme. The gas produced during the decomposition of hydrazine will be used to produce the wing motion through the reciprocating chemical muscle engine.

Once the exhaust leaves the engine, it is then passed through the wing and blown out the trailing edge of the wings. This gas entrainment into the flow field over the wing enables vortex stabilization and greatly enhances the lifting capacity of the wing. It is estimated that with the trailing edge blowing, wing lift coefficients of 10 or greater would be achievable. In addition to lift enhancement, the trailing edge blowing will be used as a means of control for the entomopter. The gas flow to each of the individual wings will be controlled to enable differential lift to be generated between the wings. To steer the entomopter, lift variation through control of the trailing edge blowing will be utilized to provide banking and pitching moments.

The communications system is another example of the implementation of the multiple-use philosophy. The communications system will utilize an ultrawide band (UWB) signal for sending signals to and receiving signals from the base vehicle. The type of signal provides large data transfer rates with very low power consumption. In addition to communications, the UWB signal can also be used for obstacle detection, establishing positioning between the entomopters and the base vehicle and altimetry. In addition to utilizing the communications system, a passive navigation and obstacle avoidance scheme has been devised that utilizes signals sent from the base vehicle to the entomopter.

To power the communication system as well as all of the electronics and payload will be supplied by a photovoltaic array and small rechargeable battery. The system provides adequate power for running all of the systems as well as keep alive power for extended periods of time if the entomopter is away from the base vehicle overnight.

In addition to optimizing the operation of the various systems and components of the entomopter, the wing motion itself has to be optimized to produce adequate lift while minimizing power consumption. To determine the wing motion characteristics, a design of the wing structure had to be performed. The weight of the wing itself is a critical aspect to the vehicle optimization. The wing has to be rigid enough to withstand the rapid acceleration/deceleration associated with the flapping motion. However, the wing mass must be minimized in order to limit the power consumption and reduce wing structural loading.

For flight on Mars, an estimated vehicle size of 1.2-m wingspan and operational configuration of 6-Hz flapping frequency and 75° maximum flap angle would be necessary. This would produce a total lifting capacity of 2.5 kg and a cruse velocity of 14 m/s. A sequence of images visualizing the entomopter concept on a mission flight are shown in figure 22.

AIRSHIP FOR PLANETARY EXPLORATION

In addition to the aircraft concepts discussed, airships may also be useful for planetary exploration. Balloons (unpowered aerostats) have been proposed for Mars exploration, and have been successfully used by the Russian Vega mission for Venus atmospheric exploration. Airships (powered lighter than air vehicles) can be used for exploration for a number of interesting scientific missions.

For the outer gas giant planets, with primarily hydrogen atmospheres, airships will require heated gas for the lifting envelope. For a number of targets including Venus (primarily carbon dioxide composition of the atmosphere) and Titan (primarily nitrogen), airships can be made that use conventional lifting gas such as hydrogen or helium.

Saturn's moon Titan is considered as one of the prime candidates for detection of extraterrestrial life. A unique combination of dense atmosphere (more than four times that of the Earth), low gravity (six times less than on the Earth), and small temperature variations makes Titan almost ideal for studies with aerobots.

Remoteness from the Sun, as well as the opaque atmosphere of Titan, makes nuclear energy the only practical source of power. Remoteness from the Earth (~10 AU (astronomical unit) and two-way light-time ~160 min) imposes restrictions on the data rates and makes impractical any meaningful real-time control. The super-pressure-powered aerobot (airship) and inflatable rover (aerover) concepts are prime lighter-than-air (LTA) platforms. The aerobots can be used for in situ studies of the surface while landing (aerover) or winching down an instrumented surface platform (powered aerobot) (refs. 20 and 21).

The power system is one of the key components for the successful operation of the Titan airship. This power will be used for the propulsion system, onboard electronics, and payload. The power system selected for the airship must be capable of meeting the power demands of the various systems as well as being able to operate within Titan's environmental conditions. Because of the distance of Titan from the Sun, approximately 10 AU, the incident solar intensity is only 14.87 W-m^2. A thick atmospheric haze in the Titan atmosphere reduces this value even further to the point that solar energy is not at all feasible for the airship. For long-duration missions, the conventional power systems discussed previously would not be feasible.

This leaves a nuclear dynamic isotope system based on the standard space-qualified radioisotope thermal generators (RTGs) as a particularly attractive

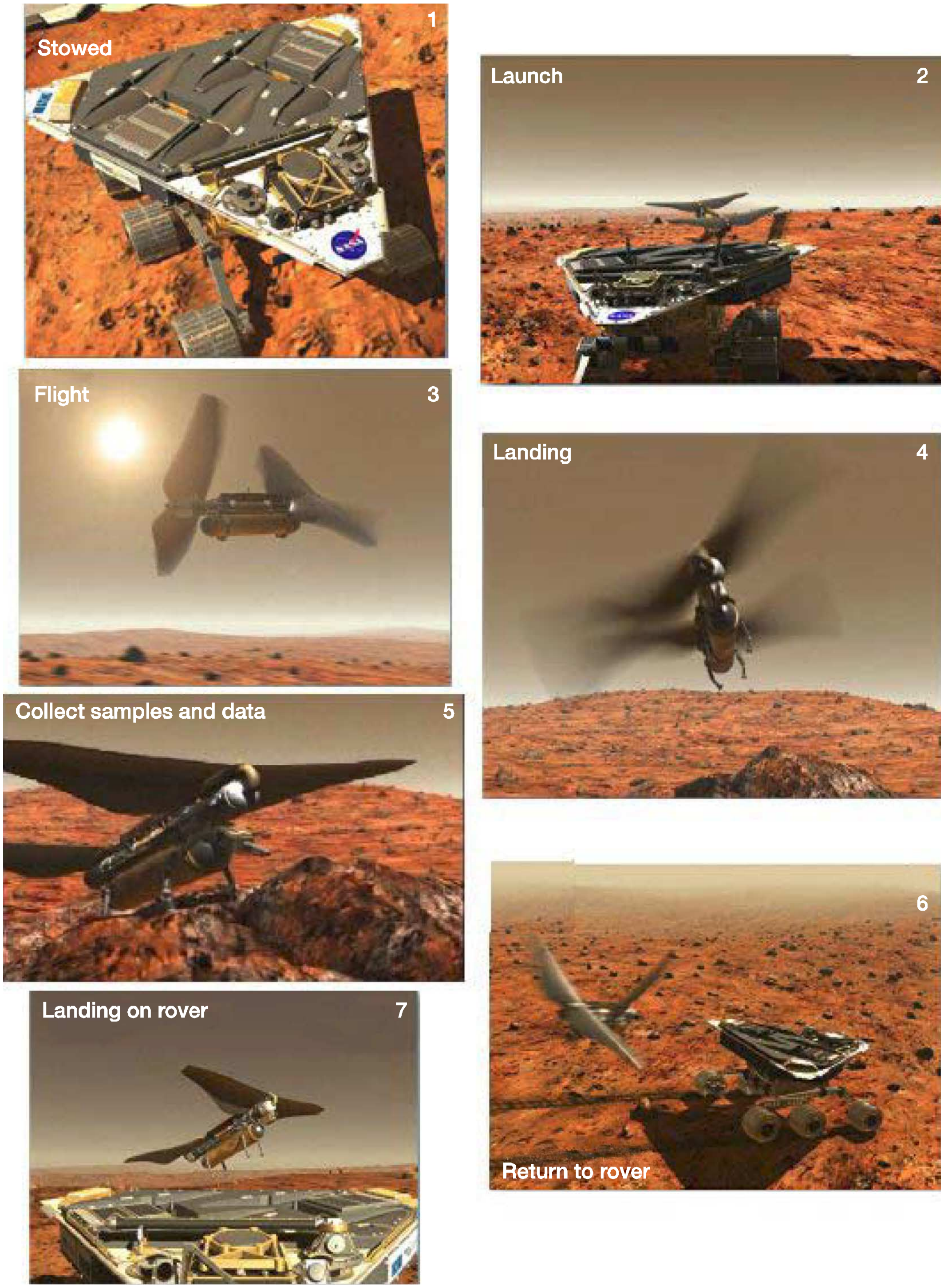

Figure 22.—Graphics visualization of Mars entomopter concept (refs. 19 and 20).

option. This system does not require any fuel, and the waste heat provides a heat source for the other airship's systems. Also, the dense atmosphere and low temperature are favorable for minimizing the radiator size for rejecting any waste heat from the system. A Stirling isotope system would be a good choice for this application due to the relatively low power levels needed.

A 55-W Stirling conversion system has been under development at the NASA Glenn Research Center. A layout of two 55-W converters is shown in figure 23. Operating at a 570 °C temperature difference between a 650 °C heat source and an 80 °C heat sink, each engine would be capable of producing 65 W of power with a direct thermal-to-electrical conversion efficiency of 27 percent (ref. 22). Presently, the Stirling power system (including the converter and isotope heat source) has a specific power of greater then 4 W/kg. It is estimated that this specific power can be increased to 6 W/kg through proposed near term development work. A 130 W system would produce approximately 350 W of waste heat that can be utilized to warm the electronics or other vehicle components. This will require some kind of heat distribution system in the form of conduction paths or heat pipes.

There are several advantages to Venus exploration using airships. A Venus airship could stationkeep over a given surface location in the comparatively cool middle atmosphere. Such an airship could in principle serve as the "brains" for a relatively simple surface-exploration robot, which would use high-temperature electronics and sensors to explore the hot (460 °C) surface environment. This is shown conceptually in figure 24.

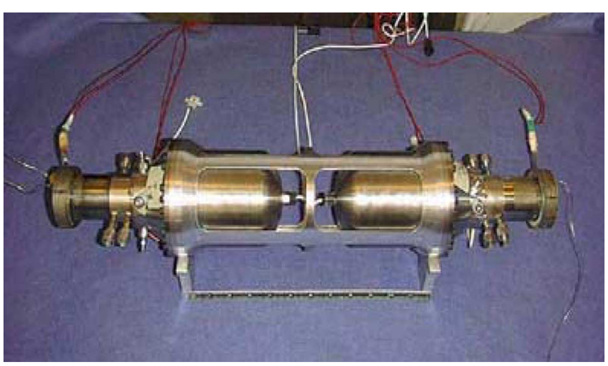

Figure 23.—A 55-W free-piston Stirling engine for planetary aircraft power (ref. 23).

Figure 24.—An aircraft or airship in the cool middle atmosphere of Venus could be used as the command and control element to operate a dumb robot on the hot Venus surface.

CONCLUSIONS

Aircraft could expand the range and mobility of planetary probes, and give a new aerial perspective for planetary mapping. There are a large number of concepts for power and propulsion of such winged planetary explorers, and new technologies may allow the possibility of advanced concepts, such as all-solid-state aircraft and entomopters, that could greatly expand the applicability of flight to new worlds.

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Planetary exploration may be enhanced by the use of aircraft for mobility. This paper reviews the development of aircraft for planetary exploration missions at NASA and reviews the power and propulsion options for planetary aircraft. Several advanced concepts for aircraft exploration, including the use of in situ resources, the possibility of a flexible all-solid-state aircraft, the use of entomopters on Mars, and the possibility of aerostat exploration of Titan are presented.

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