

**The Feasibility of  
A Human-powered Flight  
Between Crete and the Mainland of Greece**

Final Report of the Daedalus Project Working Group  
April, 1986



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Department of Aeronautics and Astronautics  
Massachusetts Institute of Technology

and the

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Smithsonian Institution

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## The Feasibility of a Human-powered Flight Between Crete and the Mainland of Greece

### Summary and Recommendations

History records many more poetic, romantic, and mythical references to flight than descriptions of vehicles capable of achieving it. Perhaps none is more famous than the Greek myth about Daedalus (Δαίδαλος), a master craftsman who flew to freedom from imprisonment on the island of Crete using wings he had fashioned himself. Until very recently, such a voyage remained purely in the realm of the imagination: from Crete to a major land mass is a distance of more than one hundred kilometers. Only in this century has man found the capability for true heavier-than-air flight, and the greatest achievement to date in *human*-powered flight is about thirty-five kilometers. Recent advances in aircraft structures, aerodynamics, and propulsion may now make it possible, however, for Daedalus' flight to be turned into a reality. The Massachusetts Institute of Technology and the Smithsonian Institution have together conducted a one-year study to evaluate the feasibility of such a flight. We have concluded that such a flight is technically, physiologically, meteorologically, and logistically feasible, and that it would have important benefits in terms of education, research, and increased cultural awareness.

Our judgement of feasibility is supported not only by detailed analyses and theoretical calculations, but also by an experimental research program designed to reduce uncertainty in key areas. These include: a) aerodynamics, where members of the study team have developed an airfoil with 30% less drag than that used on previous human-powered aircraft (HPA); b) structures and materials, where we have designed and built an advanced all-composite wing structure, and tested sections in the lab; c) human endurance, where, in cooperation with the Yale University School of Medicine, we have conducted investigations into the factors that limit human athletic endurance and successfully demonstrated a flight-power, full duration (4 hours) test on an ergometer; and d) meteorology, where we have reviewed detailed historical data in the region and concluded that flight opportunities do indeed exist. Coupled with our experience from two previous human-powered aircraft, the *Chrysalis* and the *Monarch*, we are confident that the chances for completing this historic flight are good.

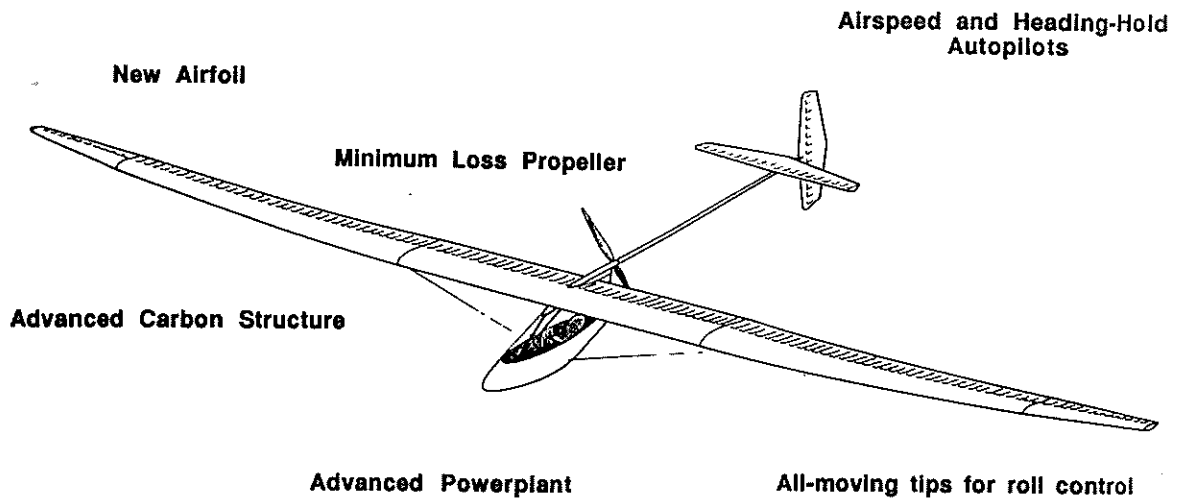
There are numerous reasons for undertaking such a venture. Perhaps the most important is education. Through MIT this project will provide a hands-on interdisciplinary design experience for undergraduate and graduate students. In addition to involving

students in aeronautical and mechanical engineering, the project will also draw together students and faculty from such diverse fields as Classical literature, archaeology and anthropology, meteorology, and the medical sciences. Through the Smithsonian, the project will reach an even larger audience. Museum displays, cultural exchange programs, and written or filmed documentaries will invite the vicarious participation of people around the world.

Another reason will be to conduct scientific research in aeronautics, physiology, and meteorology. The project will advance aeronautical technology by providing a stimulus for improvements in aircraft structures, aerodynamics, and energy-efficient vehicle design. The project will continue to advance our understanding of the limits of human performance, especially in tasks involving both physical and mental workloads. Micrometeorological data taken by the project using automatic weather stations deployed at the take-off and landing sites will expand the data base for the Mediterranean region.

A third reason will be to promote cultural awareness. In our experience, it is an extremely rare project that has the ability to excite specialists in the humanities, science, and engineering. We believe that, properly structured, the Daedalus project can help increase awareness of the long-standing relationships between art and science, and between the roots of technology and the origins of Western culture. Further, the project will promote international understanding and goodwill. We have received a warm and enthusiastic reception from both public and private citizens of Greece.

The study group thus recommends that the project go forward. We believe that the next logical step is construction of a prototype aircraft to be used for testing and pilot training. In parallel with this effort, we recommend moving forward with both a continued research program and an expanded cultural program. When the second phase culminates by breaking the existing world records for human-powered flight, the project will be prepared to move to the third and final phase of constructing the actual Daedalus aircraft and operating it in Greece. This two-tiered program is designed for maximum pilot safety while emphasizing the benefits discussed above. Together, the elements of technology, athletics, and culture follow in the spirit of the original Olympics. This adventure promises to capture the public imagination.



**Figure 1.** The proposed prototype for the Daedalus human-powered aircraft program. With a wingspan of 102 feet (31 meters) and a weight of 68 pounds (31 kilograms), it will have the lowest power requirement of any manned aircraft ever developed.

### Acknowledgements

Freed from the pressures and constraints of competition, which have dominated previous HPA efforts, the Daedalus project has been able both to conduct a broad-based research program and to explore the fascinating cultural linkages that this flight has to offer. In this effort we have been joined by a broad spectrum of individuals, from many different fields, all eager to help and to contribute. Many of these people are listed in the Appendix, and to all of them we extend our gratitude. We are especially indebted, however, to three groups. First are the people and companies who have supported the project with material donations, particularly the Aanderaa Instruments Company of Bergen, Norway, for its donation of three automatic weather stations for deployment in Greece; the Union Carbide Corporation of Danbury, Connecticut for its donation of graphite-epoxy material for the wing spar; and Paul A. Lagace of the Technology Laboratory for Advanced Composites (TELAC) at MIT, who provided laboratory facilities for the development of the wing spar. Second are scholars who have not only answered our questions but gone on to join us in our pursuit; in particular, Professors Ethan Nadel and Sarah Morris of Yale University. Finally, we wish to acknowledge the assistance of the Greek government (in particular Mr. Stavros Frangopoulos in the Washington embassy and Mr. Yannis Petsilas of the General Secretariat for Press and Information in Athens) and the many Greek-Americans who have become dauntless supporters and promoters of the project, particularly Mr. Nick Konidaris of the Teradyne Corporation.



## Table of Contents

Summary and Recommendations	1
Acknowledgements	3
Table of Contents	5
Introduction	7
Chapter 1: The Dream of Freedom Through Flight	
1.1 Daedalus: The Father of Human-Powered Flight	11
1.2 Interpreting the Myth	12
1.3 Selecting a Flight Route	13
Chapter 2: Weather and Geography	
2.1 Terrain	15
2.2 Analysis of Historical Weather Data	16
2.3 The Need for Detailed Local Data	17
Chapter 3: The Pilot and Engine	
3.1 Phase I Research Program	19
3.2 Human Power Production	19
3.3 Ergometer Testing	21
3.4 Pilot Cooling Requirements	22
3.5 Conclusions	23
Chapter 4: Technology for Human-powered Flight	
4.1 Notable Human-Powered Aircraft	25
4.2 Design Options and Goals	26
4.3 Advanced Airfoil	27
4.4 Carbon Spar	29
4.5 Flight Control System	31
4.6 Estimating Potential Performance	34
4.7 Proposed Prototype Design	38
Chapter 5: Making the Flight a Reality	
5.1 The MIT-Smithsonian Partnership	41
5.2 Need for a Film Documentary	42
5.3 Role of the Greek Government	42
5.4 Financial Sponsorship	43
5.5 Implementation Plan	44
Chapter 6: Conclusions	45
References	49
Appendix: The "Friends of Daedalus"	51





## Introduction

Almost every overview of flight inevitably refers to the legend of Daedalus and Icarus, the Greek craftsman and his son who supposedly escaped from imprisonment on the island of Crete, flying on their own power with wings they had built themselves. Such continued references have made Daedalus and Icarus the kind of cultural hallmarks that everyone recognizes.

Two years ago, members of this working group captured first prize in the Royal Aeronautical Society's Kremer World Speed Competition, the third in a series of contests promoting human-powered flight. In answer to the inevitable question "What next?" the idea emerged that it might be possible to retrace the route of Daedalus with a very long-range flight beginning in Crete. Although the distances involved were more than three times those of the 1979 flight across the English Channel by the *Gossamer Albatross*, initial calculations indicated that new technology might make such a flight possible.

Early in 1985, the MIT Department of Aeronautics and Astronautics and the Smithsonian Institution's National Air and Space Museum (NASM) agreed that the potential benefits of such a flight warranted a detailed examination of its feasibility. Together we assembled three-tiered volunteer study team consisting of 1) a senior-level Steering Committee, 2) a Working Group, and 3) an informal group of consultants known as "Friends of Daedalus". The Steering Committee represented the interests of the two sponsoring institutions; their primary operational roles were in setting broad policy and fundraising. The Working Group was made up of students, faculty, and recent alumni experienced with human-powered aircraft or the relevant technologies. They conducted the detailed analyses and research and prepared this report. The Friends supplemented the talents of the Working Group, but did not in general participate directly in the research. Members of the study team are listed in Table 1 and in the Appendix.

The study team's program is summarized in Figure 2. The first goal was to determine whether any insurmountable barriers existed that would outright prevent such a flight. Towards this end we identified four critical areas and established research programs in each. Individual members of the Working Group took responsibility for conducting or directing the research, with a particular emphasis on involving undergraduate students. When it became clear that no "show-stoppers" had been uncovered, the emphasis shifted towards concretely demonstrating feasibility and toward designing a prototype aircraft. Here, we have worked together as a design team. The design described in Chapter 5, while

not fully detailed, represents a significant advance in the state of the art and should be well suited to the Daedalus flight.

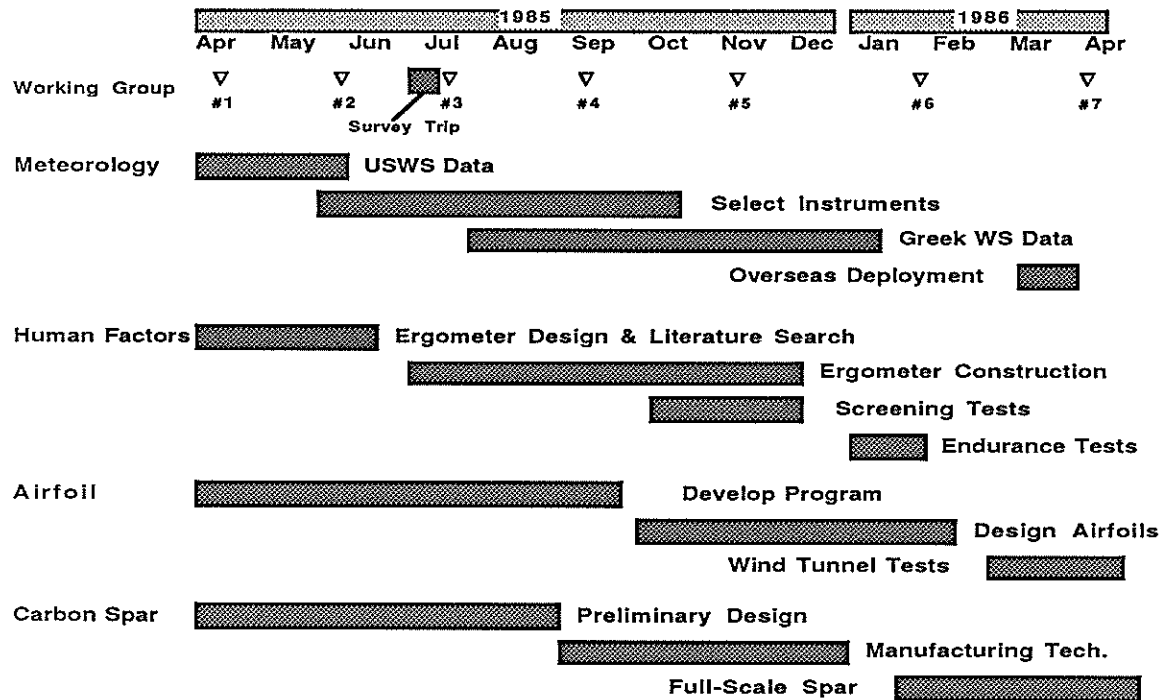


Figure 2. Timetable for the Phase 1 feasibility study.

This report documents our study and its conclusions. It differs from most engineering analyses by beginning with a chapter devoted to myths and dreams. The three middle chapters examine the relevant aspects of nature, man, and technology. The fifth chapter explains how these elements might be integrated into a flight program that achieves the various goals of the project. The final chapter summarizes our conclusions and recommendations on how to proceed.

**Table 1. Members of the Daedalus Project Study Group**

A. Steering Committee:

Walter J. Boyne	Director, National Air and Space Museum
Eugene E. Covert	Head, MIT Dept. of Aero & Astro
Brian Duff	Associate Director, NASM
James Stark Draper	President, KTAADN, Inc.
Jack L. Kerrebrock	Associate Dean for School of Engineering, MIT
Robert C. Seamans	Senior Lecturer, MIT Aero Dept.

B. Working Group:

<u>Member:</u>	<u>Current Affiliation:</u>	<u>Primary Responsibility:</u>
Steven R. Bussolari	MIT (faculty)	Human factors
Juan R. Cruz	Beech Aircraft Corp.	Composite Structures
Deborah G. Douglas	NASM	Cultural coordination
Mark Drela	MIT (faculty)	Airfoil Design
Stephen L. Finberg	C.S. Draper Labs	Electronics
James H. Hilbing	MIT (undergraduate)	Ergometer construction
Theo P. Korakianitis	MIT (grad student)	Pilot Thermal Analysis
John S. Langford	MIT (grad student), IDA	Project Manager
Sarah P. Morris	Yale (faculty)	Classics
Ethan R. Nadel	Yale (faculty)	Physiology
Robert W. Parks	Lockheed Missiles & Space	Aircraft Sizing
R. Bryan Sullivan	C.S. Draper Labs	Flight Control System
John Tylko	General Computer Co.	Fundraising
James M. Wilkerson	MIT (undergraduate)	Ergometer construction
Jonathan Wyss	MIT (grad student)	Meteorology
Harold H. Youngren	Lockheed-California Co.	Aerodynamics

For additional study participants, see Appendix A.



## Chapter 1. The Dream of Freedom through Flight

Man's urge to fly seems a timeless aspiration. Yet for most of human history, the gap between nature's requirements and man's understanding was so large that many cultures resigned flight only to gods or those with divine assistance. From the Minoan and Mycenaean civilizations of 3500 years ago, however, came the story of a man who could fly using wings he had built himself. The concept and its implications were profound; the story has persisted to this day. We know the man as Daedalus.

### 1.1 Daedalus: The Father of Human-Powered Flight

The origins of the Daedalus story, like those of almost all myths, are lost in antiquity. Mycenaean Greek tablets dating from the 13th century B.C. attest to a shrine or sacred place near the palace at Knossos which is named after a figure known as "the Daidaleion". This is later corroborated by a specific reference to Daedalus in Homer's *Iliad* where his skillful design of a *choros* (a "dance" or "dancing floor") for Ariadne at Knossos is compared to the work of Hephaestus on the shield of Achilles. By the sixth century B.C. Daedalus appears in vase paintings and in plays of the classical period, most of which have been lost. These plays evidently were used as source material for later writers such as Ovid or Apollonius.<sup>1</sup>

The general picture that emerges from these various versions<sup>2</sup> is of an inventor and craftsman who is accused of killing his nephew in a fit of jealousy, and flees to Crete. In Crete he goes to work for King Minos as a builder and inventor, but gets into trouble with his employer by building a mechanical cow in which Minos' wife Pasiphaë can take her pleasure of a beautiful bull with whom she falls in love. The offspring of this union is the Minotaur, who Minos imprisons in the labyrinth which Daedalus constructs for him. Daedalus further upsets King Minos by helping Theseus (a fellow Athenian) slay the Minotaur and allowing him to find his way out of the labyrinth with the famous string that

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<sup>1</sup> Daedalus is mentioned, discussed, or otherwise noted by the following writers, historians, and poets: Homer (circa 8-7th Century B.C.), Apollodorus (c. 2 Century B.C.); Virgil (1st Century B.C.); Ovid; Pausanias (2nd Century B.C.); Diodorus Siculus (1st Century B.C.); Apollonius (2nd Century B.C.); Apollonius of Rhodes (3rd Century B.C.); Herodianus (2nd Century B.C.); Herodotus (5th Century B.C.); Plutarch (AD 1); Hyginus (AD 1); and Pliny.

<sup>2</sup> The authors wish to acknowledge the assistance of Prof. Arthur Steinberg of MIT in the preparation of this section.

he unwinds behind himself as he enters the maze.<sup>3</sup> Minos then imprisons Daedalus in the labyrinth and contemplates executing him, when Daedalus constructs his famous wings of wax and feathers and takes flight. Later versions of the myth have him accompanied by his exuberant son Icarus who ignores his father's warnings and flies too close to the sun. The sun melts his wings, sending Icarus crashing into the sea and drowning. Daedalus eventually ends up in Sicily, where King Cocalos takes him in as a court-inventor. The inventor-engineer then builds an intricate hot water bath system for the king. Minos pursues Daedalus, and brings a wonderful puzzle along with him, consisting of threading a string through a sea shell. Minos knows that only his former resident-engineer can figure the puzzle out, and true to form, Daedalus advises Cocalos on how to solve the puzzle. As Minos is about to do in poor Daedalus, who is too smart for his own good, Cocalos' daughters scald Minos to death in Daedalus' bath tub.

## 1.2 Interpreting the Myth

Man's urge to fly, the associations between flight and freedom, the conflicts between science and the state, and the dangers of hubris are all themes of the Daedalus myth that carry relevance today.

In its development over the centuries, each culture has interpreted the myth of Daedalus in light of its own mores and technology. Medieval Christians viewed the story as an important parable for the precept of honoring one's parents.<sup>4</sup> Many modern interpretations continue to focus on Icarus, citing him as an example of how "the human ego can be exalted to experience godlike attributes, but only at the cost of over-reaching itself and falling to disaster".<sup>5</sup> But as noted in Section 1.1, Icarus is a relatively recent addition to the Daedalus myth, so the myth's Minoan and Mycenaean originators need not have shared such modern interpretations.

We believe that Daedalus is an important figure precisely because he does not aspire to the province of the gods. The Classics are full of major and minor gods and of mortal descendants of gods, but Daedalus is patently human. In a culture that revered heroes like Theseus or Hercules, Daedalus was an intellectual -- an inventor, an artist, a craftsman. Indeed, he is the archetype engineer of western civilization. The myth shows that even

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<sup>3</sup> There are actually two separate mythological traditions surrounding this point -- one in which Pasiphae and the bull are cited as the source of Minos' anger with Daedalus, and one centered around Theseus and the sacrifice of Athenian youth. They are meshed together in this presentation.

<sup>4</sup> see Tom Crouch's unpublished work, "Where Dwells the Race of the Gods -- The Oldest Dream".

<sup>5</sup> Carl Jung, *Man and His Symbols*, p 121.

3500 years ago, people could envision flight as being within the province of human capability.

In a world where technology and the liberal arts are often regarded as distinct cultures, it is refreshing to be reminded that they share common roots and are, in fact, merely different manifestations of the same basic human urge to explore and to create. Through Daedalus, we follow the tradition of the original Olympics, which included both athletic and mental challenges. The purpose of our reexamination is not so much to produce an end that is useful in itself, but rather to stimulate imaginative thinking and to increase our awareness of the continuity and interdependence of our society and its different elements. It is the manner of thinking, more than anything else, that might make substantive contributions to modern society.

### 1.3 Selecting a Flight Route

When the Working Group first examined the story, one goal was to determine whether literary justifications existed for technological choices. We quickly discovered that there is no single, definitive version of the myth, so any attempt at a literal recreation would be futile. On the other hand, there are many guides for structuring a symbolic recreation. The ancient Greeks, for example, made no sharp distinction between sea and sky. In Greek poetry the imagery of the sea upon which a ship floats is repeatedly merged with that of the wind, which propels the ship. British historian Clive Hart suggests that "low, skimming, horizontal flight such as Daedalus commands is a form of motion which, although itself unnatural, is as far as possible in harmony with the natural order".<sup>6</sup>

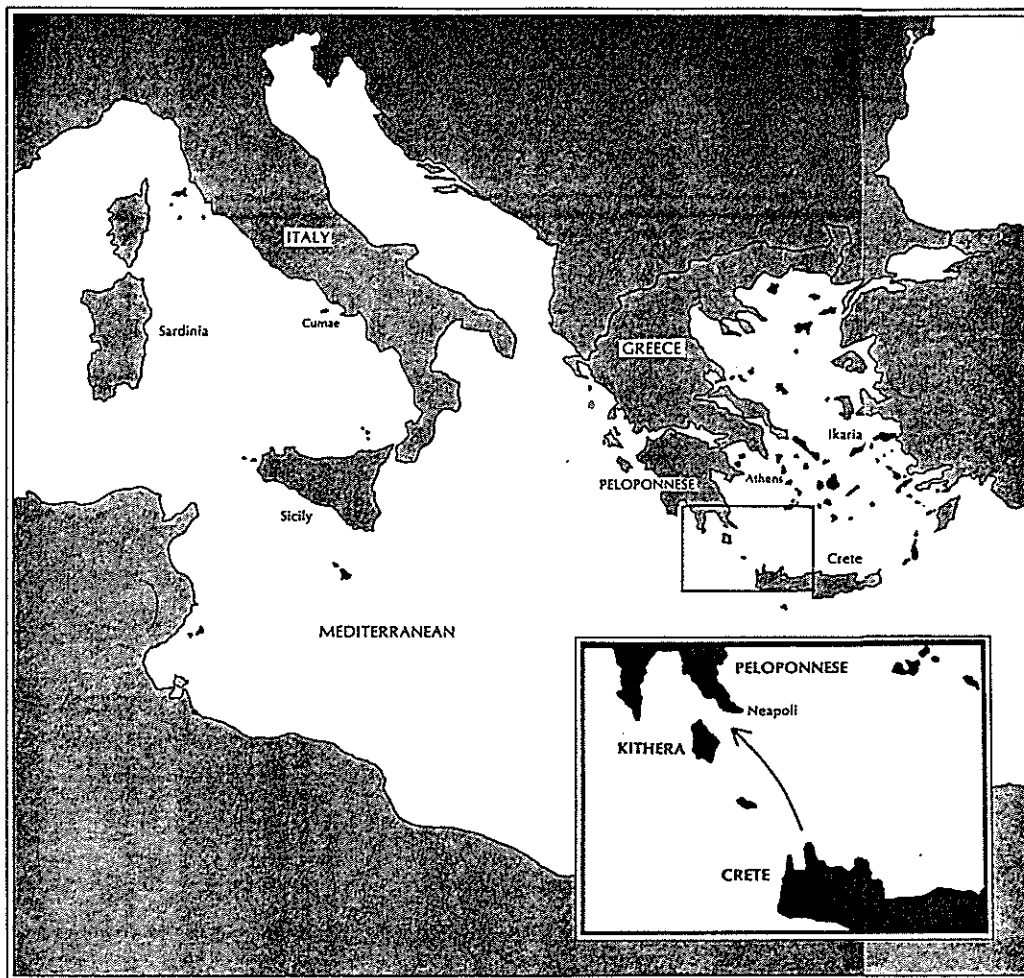
Among the destinations cited in various versions of the myth are the island of Icaria, Athens, Cumae (in Italy) or the island of Sicily. Whatever his ultimate destination, however, it seems logical to assume that Daedalus would plan his aeronautical voyage the same way he would have planned a voyage by ship. Lacking navigation tools, moving at slow speeds, and at the mercy of the elements, mariners of the day tended to make long voyages in short hops, staying within sight of land when possible and rarely spending a night at sea. Thus a journey to Icaria would be made through short hops from one island to the next, while a flight to Sicily would follow the coastline. In either case, Daedalus' first (and probably longest) hurdle would be to get from Crete to the mainland. As shown in Figure 3, this is a distance of some 110 kilometers (69 statute miles), or more than three

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<sup>6</sup> Clive Hart, "Low-Level Flight and the Greeks", unpublished material furnished to the Working Group from a forthcoming book.



times the distance of the current world record for human-powered aircraft. This follows a major Minoan trading route, and there was an early outpost on the island of Kithira. Although more suitable routes may emerge with continued study, we have used this route as a baseline for establishing aircraft design requirements.



**Figure 3.** General map of region, showing Daedalus' various destinations as mentioned in mythology and the proposed route of flight for our symbolic recreation..

## **Chapter 2. Weather and Geography**

### **2.1 Terrain**

The terrain in the region of the proposed flight is of volcanic origin and, as such, is quite mountainous and rugged. There appear to be three options for a takeoff site on Crete, each with its own particular advantages and limitations. The point on Crete that is closest to the Peloponnesian peninsula is Akra Spatha, at the tip of the Rodhopos peninsula. The site is on a fairly large plateau (roughly 500 x 500 meters) at an elevation approximately 300 meters above sea level. The surrounding terrain drops almost vertically to the sea. Access from the town of Rodhopos is by a very rough dirt road that ends approximately 1 km from the site (a 30 minute walk over rough ground). The second closest site to Peloponnesia is near the end of the Gramvousa peninsula, just west of the Rodhopos peninsula. There the terrain slopes gently to the sea, and ends in a large beach and sandbar that appear to be suitable for a sea-level takeoff, given the low amplitude of the tides in the area. This site is totally isolated from access by land transportation, but may be reached with relative ease by boat or helicopter. The third candidate launch site is located at the eastern base of the Rodhopos peninsula, in Maleme, at an airstrip that is very accessible by road. It appears to have little or no flight activity at the present time and has a paved runway that leads directly to the water's edge. This site is approximately 20 km farther from Peloponesia than the site at Akra Spatha. It is a very appropriate site for initial operations and flight testing if not for the actual flight to the mainland.

Along the route of flight are two large islands, Andikithira and Kithira, with some terrain that could permit a contingency landing. In general, access to the landing sites on these islands would require a significant deviation (approximately 15 km) from the direct route of flight.

The southeastern tip of the Peloponnesian peninsula (Akra Maleas) is very steep and totally unfeasible for landing. About 5 km to the west, however, are several level fields at Akra Zovollo that lie 3 to 5 meters above sea level along with a small beach. The access to Akra Zovollo is by dirt road that is easily negotiable by automobile.

Overall, there are several options available for takeoff and landing sites. Selection of the takeoff site should take place based upon the limitations of pilot and aircraft as they become better defined during Phase II. Selection of the specific landing site and contingency abort sites can be made early in Phase III.

## 2.2 Analysis of Historical Weather Data

The climate of Crete and southern Greece is generally benevolent: the summers are characteristically hot and dry, the winters mild and rainy. The precipitation in the winter months is linked to relatively warm sea surface temperatures, which are frequently 2° C warmer than the overlaying air. Cyclogenesis, with concomitant stormy winds and rain, results from this interaction of cold polar air from the European land mass with the sea over which it passes. In the summer, intruding air masses from higher latitudes are warmed during their passage over the continent, the instabilities producing cyclogenesis are suppressed, and weak but stable anticyclonic conditions of sunny, warm weather tend to persist over the entire Mediterranean region.

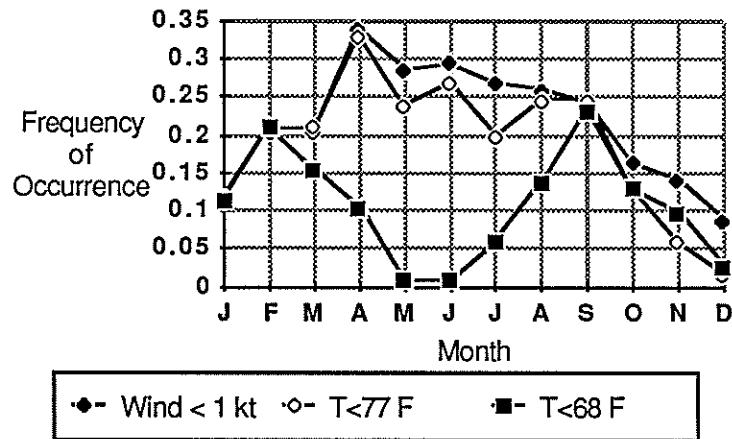
The transitions between these two regimes are often abrupt, and no seasons which correspond to our spring and fall can be accurately defined. Spring is an indecisive period extending from late March to early May, with several attempts by Summer at gaining supremacy. Autumn weather is similarly variable, with rainy periods in September-November appearing with increasing frequency after the isolated thunderstorms of August.

Yet, with respect to human-powered flight -- where the aircraft is inoperable in winds greater than a few knots and the efficiency of the pilot decreases dramatically in hot weather -- it is clear that we must consider spring and autumn most carefully, as it is during these transitional periods that we can expect the greatest percentage of calm, relatively cool days on which a flight would be feasible.

We began our investigation with weather provided by the U.S. Weather Service for three locations on Crete. This was supplemented by Greek data for two additional stations near the proposed route of flight. All the data was provided as monthly averages over a thirty year period. Typical results are shown in Figure 4, plotting 8 am wind readings for each month of the year. It is clear that although the greatest frequency of calm weather occurs during the summer, when a temperature constraint is added, a bimodal distribution appears, with spring and early fall appearing as the most suitable periods for a flight.

A more detailed investigation was then conducted, using actual day-to-day weather records for the period between 1979-1984 generously provided by the Hellenic National Meteorological Service for the locations of Kithira and Souda. Contour plots were constructed, showing the frequency of 3- and 6-hour "windows" during which acceptable flight conditions were present at both take-off and landing sites. Again, this data suggested that March, April, and September were the most suitable months, but also that much of the suitable weather occurred at night. Examination of the data on a year-by-year, rather than

averaged basis, suggests that there is a period of approximately two weeks during the spring when the weather is suitable much of the time, even in daylight. The exact date of the onset of this window varies from year to year, such that this feature is suppressed when the data are averaged. More details, including a discussion of the predictability of individual flight windows, is found in Reference 11.

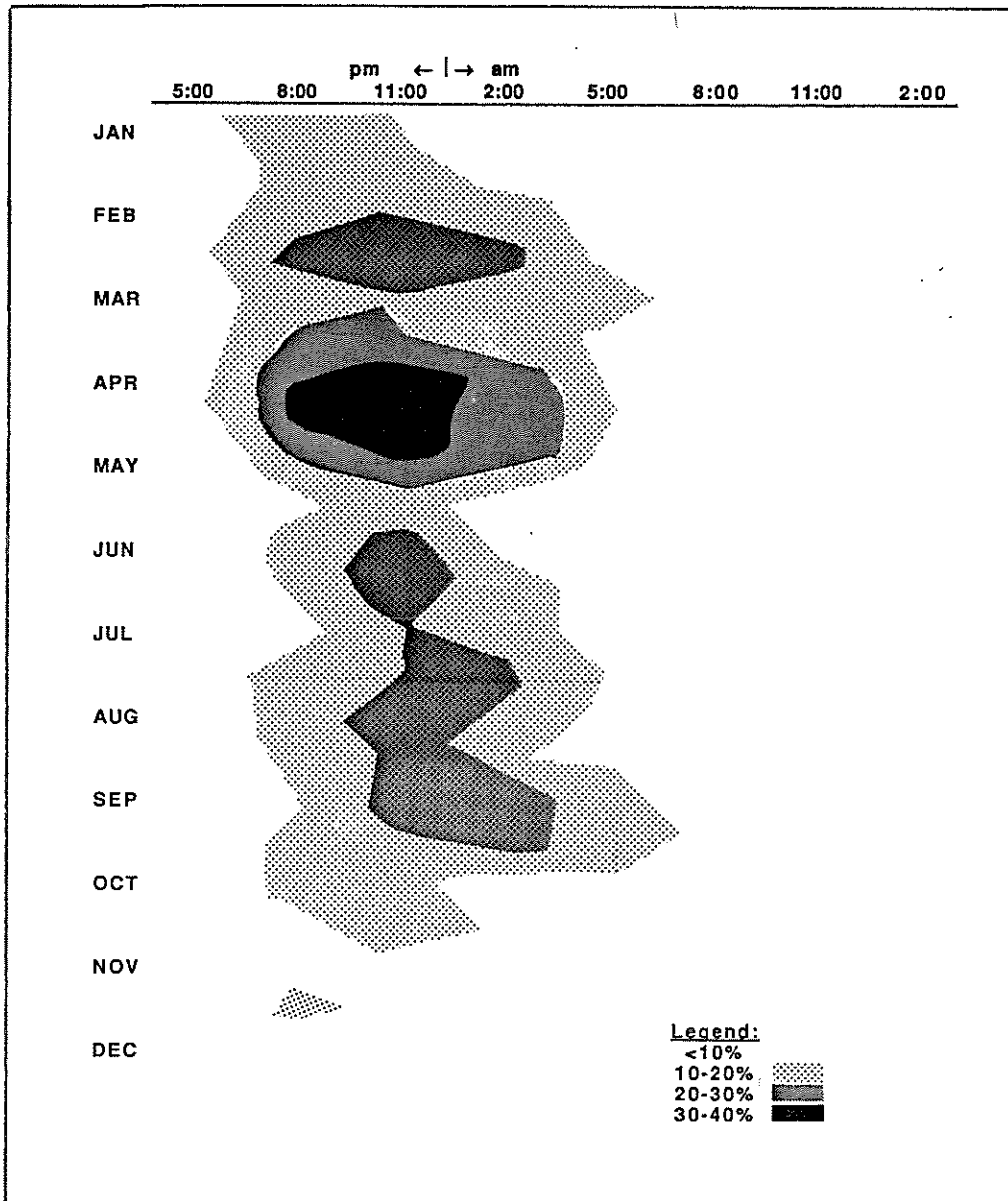


**Figure 4.** Summary of Weather Data from station on Kithira. Upper curve plots frequency of winds less than 1 knot with no temperatures constraints. Lower curves show frequency of winds less than 1 knot plus temperatures of less than 77° F (middle curve) and 68° F (lower curve). Data courtesy Hellenic National Weather Service.

### 2.3 The Need for Detailed Local Data

In order to determine precisely the micrometeorology along the route, we believe it is important to obtain detailed local data for both the take-off and landing site. The Aanderaa Instruments Company of Bergen, Norway has graciously donated a set of automatic weather stations for this purpose. With the cooperation of the Greek government and local officials, we have deployed these stations at proposed take-off and landing sites near Kastellion on Crete and Neapolis on the mainland. Data from these stations will allow us to more fully understand local conditions and assist in predicting suitable flight opportunities.

**Figure 5.** Probability of occurrence of six-hour window with winds under 1 knot and temperatures between 8° C (46° F) and 25° C (77° F). Window begins at time shown; all times are local time in Greece.



## **Chapter 3. Human Factors: The Pilot and Engine**

### **3.1 The Phase I Research Program**

The design configuration of any powered aircraft is strongly influenced by the characteristics of its propulsion system. The technological challenge of the Daedalus flight is a direct result of its use of the human pilot as the aircraft powerplant. The aeronautical engineer, who is unable to significantly alter the design of the human "engine" or depend on next year's model to be more powerful, is faced with the problem of matching the airframe to the human's capacity as a source of mechanical power as well as manual controller and decision-maker. In order to assess the feasibility of the Daedalus flight, the Working Group sought answers to four major questions:

- 1) What are the physiological mechanisms that limit the duration of human power production?
- 2) What power level (per unit of body weight) can be expected from a human pilot given a certain level of athletic ability and endurance training?
- 3) What countermeasures are available to insure that physiological limits are not encountered during the Daedalus flight?
- 4) How large is the population pool from which appropriate pilots may be selected?

In order to establish preliminary answers to these questions, the Working Group conducted a research program<sup>1</sup> with five components:

- 1) A review and analysis of existing literature;
- 2) Design and construction of a semi-recumbent research ergometer;
- 3) Development of screening tests to predict long-duration power capacity;
- 4) Validation of predictions via long-duration ergometer tests; and
- 5) Preliminary calculations of requirements for pilot cooling .

### **3.2 Human Power Production**

The production of mechanical power by humans has been the subject of many investigations. Much of the literature can be summarized in Figure 6, where the power produced by humans is plotted against sustainable duration. The methods employed in the investigations summarized in Figure 6 vary widely, as do the results; the data are uncorrected for such factors as body weight, level of training, and environmental

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<sup>1</sup>Much of this research was conducted at the John B. Pierce Foundation Laboratory at the Yale University School of Medicine. A more complete report on these tests may be found in Reference 1.

conditions and the accuracy of the calibration is unknown. Almost no scientific measurements exist beyond the one-hour duration point. Although the historical record is useful for establishing rough bounds to the problem, it is of little help in establishing the engineering feasibility of the Daedalus flight. For that, we must turn to first principles.

As with any engine, the human body combines fuel and oxygen to produce energy and waste byproducts. Small amounts of fuel and oxygen are stored in the muscle tissue and may be used for short-duration power production. These processes are anaerobic in the sense that they do not require the continuous supply of oxygen through the cardiovascular system. These anaerobic processes are inefficient and not sustainable for more than a few seconds. For prolonged exercise an integrated physiological response is required to provide the muscles with fuel and oxygen and carry away byproducts. The aerobic process can be roughly summarized as:

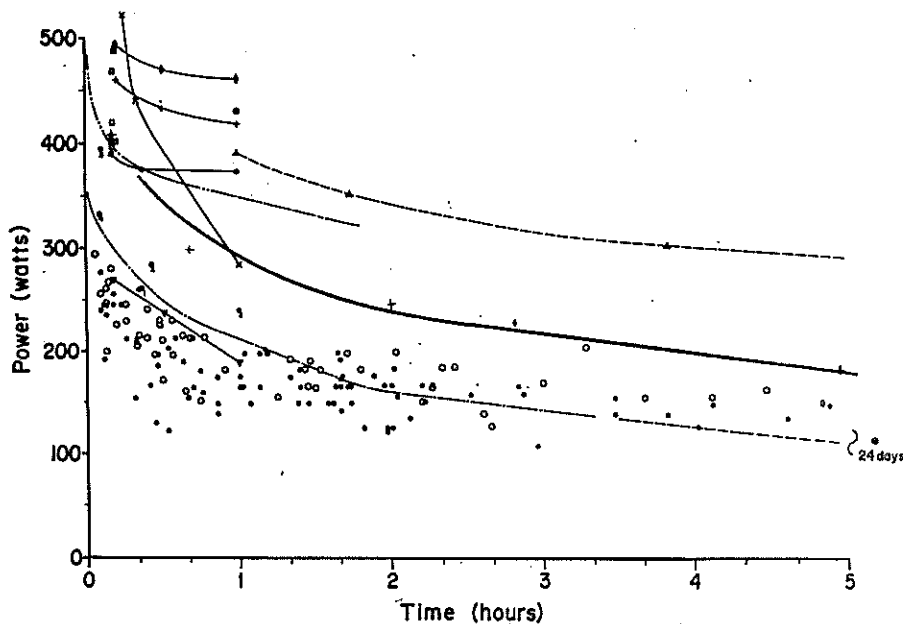


Figure 6. Human Power versus time as measured in previous studies (1937-1985). The bold line in the center represents the estimate used as input for the aircraft sizing algorithm described in Chapter 4.

This equation suggests that among the factors that might limit long-term human energy production are: 1) exhaustion of appropriate fuel, 2) insufficient oxygen delivery, 3) dehydration, or 4) overheating. A full description of the physiological mechanisms behind each potential limitation is beyond the scope of this presentation, but interested readers are referred to References 1 & 9. It will suffice here to note that although fuel exhaustion might appear to be the most obvious (and ultimate) limit, the other factors (particularly those involving transport processes) are more likely.<sup>2</sup>

### 3.3 Ergometer Testing

The experimental program conducted in Phase I included two series of tests on a semi-recumbent cycle ergometer. The first tests were designed to measure maximum aerobic power, and serve as both a guide and as a screening test for the second series. The second test series involved cycling at 70% of maximum aerobic power for a duration of four hours, the expected length of the Daedalus flight.

**Maximum aerobic power ( $\text{VO}_2$  max) Tests.** Experience suggests that trained athletes are able to produce between 50% and 80% of their maximum aerobic power for relatively long durations (periods of several hours). Preliminary designs for the aircraft (see Chapter 4) suggested that the pilot would need to produce at least 3 Watts per kilogram of body weight during flight. Thus, if we select a value of 70% of maximum power as the design criteria, only athletes capable of producing a maximum aerobic power of at least 4.25 W/kg would be candidates for long-duration testing. Measuring maximum aerobic power is a relatively simple procedure that can be conducted in about 15 minutes per subject; it involves correlating the rate of power production with the rate of oxygen consumption under progressively higher physical loads during cycling. The power level at which oxygen consumption levels off is the maximum aerobic power. Since this is determined through measurements of oxygen consumption, the test is known as a " $\text{VO}_2$  Max" test.

To determine both the suitability of this criterion and to estimate the candidate pool size it would produce, five volunteers were recruited through an informal process. All were experienced athletes; our sample included a female national-class field hockey player, a male amateur tri-athlete, a female amateur tri-athlete, a male national class wrestler, and a male national class bicyclist. In October, 1985 we tested each volunteer for maximum aerobic power at the John B. Pierce Foundation Laboratory at Yale University. Two of the

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<sup>2</sup> An average person stores about 100,000 kilocalories of potential energy. The Daedalus flight will require about 4000 kilocalories, so the question is not whether a human has enough fuel, but how much of this fuel can be efficiently utilized for propulsion.



athletes were found to have  $\text{VO}_2$  max exceeding 4.25 Watts per kilogram of body weight, which suggested that they might be able to produce 3 W/kg for an extended period.

**Long-duration ergometer tests.** For the long duration tests, the two volunteers were asked to exercise on the cycle ergometer at 70% of their maximum aerobic power continuously for four hours (the estimated length of the Daedalus flight). For this initial feasibility test environmental conditions were carefully controlled and the subjects were allowed as much food and water as they desired. During the tests, heart rate and oxygen uptake were monitored continuously. Blood samples were withdrawn at regular intervals to measure: 1) glucose concentration (a measure of the body's fuel status), lactate concentration (to determine whether aerobic or anaerobic exercise was occurring), and osmolality and plasma volume (to assess the degree of dehydration).

Although both subjects found the test demanding, during the first two hours neither had great difficulty maintaining the required power level. Heart rates averaged between 150 and 160 beats per minute, and oxygen uptake was stable. After two hours the first subject found the test increasingly difficult and was forced to stop after 3.5 hours, complaining of soreness and cramping in his legs. The subject's blood osmolality had begun to climb at 2 hours, indicating progressive dehydration. His heart rate had also begun to climb, reaching 180 beats per minute at 3.5 hours. Both changes suggest an inability to maintain an appropriate distribution of blood flow to the muscle and skin.

The second test subject (a female triathlete) was able to complete the four hours easily and could, by her own estimate, have continued for another 30 to 60 minutes. The physiological data support this estimate; all variables were stable throughout the test. Of particular interest was the fact that the subject's blood osmolality was maintained, implying an adequate replacement of fluid lost. She drank more than three times the amount consumed by the first test subject, and her heart rate never exceeded 160 beats per minutes, implying steady cardiac filling and no pooling of blood in the periphery.

### 3.4 Pilot Cooling Requirements

With the basic feasibility established under ideal laboratory conditions, the question becomes how closely these conditions can be replicated in flight and what the effects of degradation are on pilot performance. Water, for example, is extremely heavy, while cooling air carries an inevitable penalty in terms of aerodynamic drag. *Gossamer Albatross* underestimated the requirements for both, with the result that the flight was very nearly lost due to pilot dehydration.

Since only 20-25% of the calories used by the human "engine" are converted into mechanical power, between 600 and 1000 Watts of energy will be produced by the Daedalus pilot in the form of heat. Without cooling, this is sufficient to raise the body core temperature 1° Celsius every 5-8 minutes. There may be additional heating of the cabin due to insolation (solar energy) during daylight hours. Cooling occurs primarily through evaporation of sweat and by convective cooling due to passing air. Although a precise analytical solution is extremely complicated, a first-order analysis has been conducted in order to bound the problem of how much cooling air will be required for the pilot.<sup>3</sup> For the best-case condition considered (ambient air at 14° C [57° F] and no insolation) the required diameter of the inlet air supply tube is about 80 mm (3 inches). Under adverse conditions (18° C [64° F] air and 700 W of insolation) the inlet diameter increases to about 130 mm (5 inches). Although these values are compatible with the overall aircraft design, they illustrate the rapid increase in cooling requirements due to increased ambient temperatures.

### 3.5 Conclusions

Based upon the research described above, we conclude that the Daedalus flight appears to be within the capabilities of a human pilot. More specific conclusions, presented in the context of the group's initial questions, include:

1) What are the physiological mechanisms that limit the duration of human power production? The physiological mechanisms that appear to limit the production of mechanical work in humans are related to the storage, transport, and metabolism of fuel and oxygen and the rejection of waste products and heat. Endurance-trained athletes have conditioned their bodies to maintain key physiological variables at stable levels during exercise at relatively high power outputs (approximately 70% of maximum aerobic power) for periods of several hours. The limits of endurance are characterized by departures from this steady state that result in the breakdown of transport and metabolic processes, with subsequent reduction of power output.

2) What power level (expressed per unit of body weight) can be expected from a human pilot given a certain level of athletic ability and endurance training? We have demonstrated that endurance-trained athletes exercising on a recumbent cycle ergometer are capable of producing power at 70% of maximum oxygen uptake (corresponding, in this case, to a specific power of 3 Watts per kilogram of body weight) for a period of four

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<sup>3</sup> see Reference 6. All cases assumed a flight speed of 15 knots and an ambient relative humidity of 70%, and a cabin outlet temperature of 21° C.

hours. These values of power and duration correspond to the requirements estimated for the Daedalus flight.

3) What countermeasures are available to ensure that physiological limits are not encountered during the Daedalus flight? At least four countermeasures are suggested from the test program to date: 1) endurance training under conditions similar to those expected in flight, 2) pre-loading the body with stores of glycogen; 3) control of cockpit environment to the extent possible; 4) generous intake of water (and some food) during the flight. Among the technical options suggested by these countermeasures are: 1) providing separate inlets for breathing and cooling air so that pilot does not breathe CO<sub>2</sub>-loaded air, 2) examination of possible cooling or humidity-control schemes, or, 3) supercooling the supply of drinking water for use as a heat sink.

4) How large is the population pool from which appropriate pilots may be selected? The population pool appears to be sufficiently large to ensure success in locating appropriate pilots. The specificity of muscle group training by endurance cyclists makes this group a likely source of pilots; regional or national class cyclists appear to have the level of fitness and training necessary to prepare for the Daedalus flight. No basis for preferring one gender over the other has been found. A high level of piloting skill may be required for the actual flight, but much of this experience will need to be developed through a training program in similar aircraft; thus, previous experience piloting conventional aircraft will be desirable but not required.

As the project moves forward with the selection and training of pilots, it will be important to continue the physiological research program. In particular, performance under degraded environmental conditions (temperature, humidity, cabin airflow) must be examined to determine more accurately the range of conditions physiologically acceptable to the pilot.

## Chapter 4: Technology for Human-powered Flight

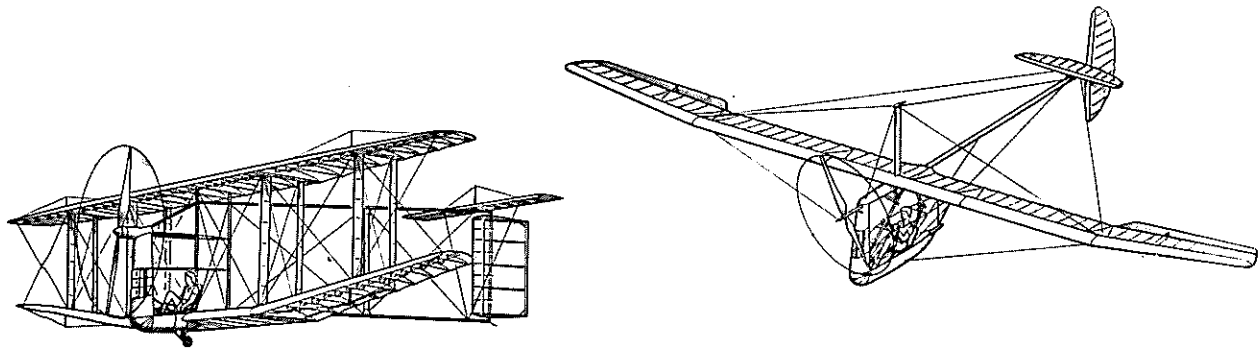
### 4.1 Notable Human-powered Aircraft

During all the centuries in which people dreamed of human flight it was supposed that the flier would supply the power. Yet only in the past 25 years -- after the development of the propeller-driven airplane and the jet engine as well as the achievement of supersonic flight and space flight -- has the human-powered aircraft come into its own.<sup>1</sup> This has occurred primarily because of the impetus provided by a series of competitions, the most famous of which have been sponsored by Henry Kremer, a British industrialist who in 1959 offered a prize £5000 to the first entrant who could fly an aircraft around a one-mile, figure-of-eight course under human power alone. Eighteen years passed and the prize money had increased tenfold before Bryan Allen successfully flew the *Gossamer Condor*, developed by a team under the direction of Paul MacCready, around the required course. Kremer subsequently offered the largest prize in the history of aviation, £100,000, for the first human-powered flight across the English Channel. Again the winner was Allen, who pedalled the MacCready team's *Gossamer Albatross* across the 21 mile strait between Folkestone and Cape Griz-Nez on June 12, 1979. Four years after the Channel prize, Kremer sponsored another competition, this one intended to make human-powered aircraft faster, and thereby smaller and more practical. First Prize in the Kremer World Speed Competition was won by Frank Scarabino, flying *Monarch B*, a craft designed and built at MIT by members of the current Working Group.

*Monarch* was actually the fourth human-powered aircraft to be built at MIT. Between 1969 and 1979, several generations of students had designed and built BURDs I and II and the *Chrysalis*. The BURDs had been built for the Kremer Figure-of-Eight competitions and, although neither ever flew, they made several contributions to HPA technology including wire bracing, composite construction, and efficient propellers. The 1979 *Chrysalis* was built as a technology demonstrator for the Cross-Channel Prize, and made more than 350 flights with 44 different pilots before being disassembled for lack of storage space. In addition to these aircraft, members of the Working Group also designed the propeller for the *Gossamer Albatross*.

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<sup>1</sup> For a more detailed overview of human powered aircraft, see M. Drela and J.S. Langford, "Human-powered Flight", in *Scientific American*, November, 1985. For more details on *Monarch*, see References 7 and 8.



**Figure 7.** Previous human-powered aircraft built at MIT include the 1979 *Chrysalis* (left) which made more than 350 flights with 45 different pilots, and the 1984 *Monarch B*, which won first prize in the Kremer World Speed Competition.

## 4.2 Design Options and Goals

In approaching the Daedalus flight the Working Group was unconstrained by any predetermined competitive rules. We have, however, attempted to stay within the definitions set by the Federation Aeronautique Internationale (FAI) for human-powered aircraft.<sup>2</sup> At our first meeting the Working Group considered a variety of concepts, four of which are summarized in Table 2. These included: 1) The "self-launching sailplane", a small, fast aircraft with a high load factor that would be launched on the island, climb in thermal or slope lift, and use human power to extend the glide for the flight to the mainland. We rejected this option because it would not qualify under the FAI definition of a human-powered aircraft. 2) The "medium altitude cruiser" which would attempt to use tailwinds, flying above the surface layer turbulence but below the altitude where thermals are well developed. This option was rejected when the weather data showed that tailwinds are essentially never present on the projected route. 3) The "sea skimmer" approach, which would have a size and power level comparable to *Gossamer Albatross* but use advances in technology to fly 50% faster. This was the option eventually selected. 4) the "low and slow" approach, which would essentially extend the *Albatross* concept by using extensive wire bracing to produce a wing with over 110 foot span. This option was rejected as being very inflexible in operation and not a very exciting technological challenge.

<sup>2</sup> The FAI is a Paris-based organization that certifies all aeronautical and astronautical world records. Under their definition, a human-powered aircraft must take off and be maintained solely by the muscular energy of one or more persons in the aircraft. No systems of static support (gas, hot air, etc) or devices to store or receive energy are allowed.

**Table 2.** Summary of Design Options Considered for Daedalus

<u>Design Option:</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Speed: (kts)	25	20	15	10
Cruise Altitude: (ft)	1000	500	15	15
Load factor: (g's)	6	4	3	2

Among the many other issues debated by the Working Group, three deserve mention here:

Single-versus multi-pilot crews, where we found no inherent advantage unless humans work better under cyclic loads. We rejected this configuration purely on size and complexity considerations.

Take-off from a cliff or mountainside, which may be required because of the terrain and lack of suitable beaches. The FAI rules require take-off and landing to be within 1:200 over the length of the course, which would allow up to 550 m altitude at take-off. Such an altitude could cut the energy requirements for the flight by 15-20% but much of this advantage would be lost due to the increased weight of safety devices, such as a parachute and a stronger structure. We feel that this option deserves careful study, including flight testing during Phase II.

Pilot cooling, which may well be the most critical problem on the flight. More sophisticated cooling systems add weight but allow a wider flight window. As discussed in Chapter 3, the problem is sufficiently complicated that a precise analytical solution is not possible, so experimental testing will be required during Phase II.

The design goals finally selected by the Working Group for inclusion in the prototype aircraft were: 1) Range: 60 nautical miles, enough to cover the shortest path between Crete and the mainland; 2) Speed: 15 knots, or as fast as possible; 3) Power requirement: 3 Watts per kilogram of pilot body weight, or about .27 HP for a 150 pound pilot; 4) Flight control system: capable of operation at night in light fog, when the horizon might be obscured, in order to take full advantage of calm air periods; 5) Strength: 3 times normal flight load (3 g's), to provide sufficient strength to allow take-off from the rugged, mountainous terrain found on western Crete.

#### **4.3 Advanced Airfoil**

The aerodynamic performance of a wing and the aircraft as a whole are strongly influenced by the wing airfoil, that is, its cross-sectional shape. Daedalus has three design

goals, including: 1) a large lift-to-drag ratio at design conditions; 2) a reasonably large lift-to-drag ratio at lower lift conditions, to allow the aircraft to fly faster into a headwind; and 3) a low pitching moment, to minimize loads (and hence weight) in the wing structure and to allow the use of smaller tail surfaces.

A series of airfoils have been designed for Daedalus using numerical design simulation procedures (Reference 2). Preliminary design was performed using a standard inviscid panel method extended to permit calculation of the airfoil shape from a specified pressure distribution. For viscous performance analysis, the flow around the airfoil was calculated using a novel, streamline-based computational technique (see Reference 3). The effect of the boundary layer on the pressure distribution was taken into account, and transition location on the airfoil surface was also properly determined. The overall aerodynamic prediction method is capable of simulating airfoil flows with limited separation regions, and is thus capable of predicting the onset of stall and the resultant loss of lift and rapid drag rise. The rapid performance degradation due to low Reynolds numbers can also be assessed properly. The calculation method has been verified by comparisons with wind tunnel data.

The aerodynamic design of the Daedalus wing is complicated by the fact that the spanwise variation in Reynolds number is very large (from 600,000 at the root to 200,000 at the tip). Thus a single airfoil cannot be used across the entire span. Three airfoils have been designed, designated the DAI 1335 (used across the center panel), DAI 1336 (used for the mid panels) and the DAI 1238, used for the tip section. Performance of the airfoils is shown in Figure 8. The airfoils differ primarily in the shape of their suction (upper) surface pressure distributions, to compensate for the lower Reynolds numbers towards the tips. The airfoils all have fully laminar bottom surfaces, extensive laminar flow on the top surfaces, and pressure recoveries designed to minimize the losses from laminar separation bubbles.

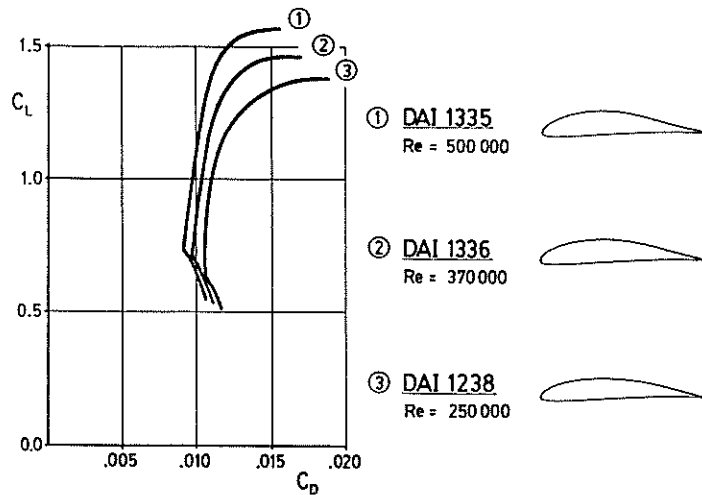


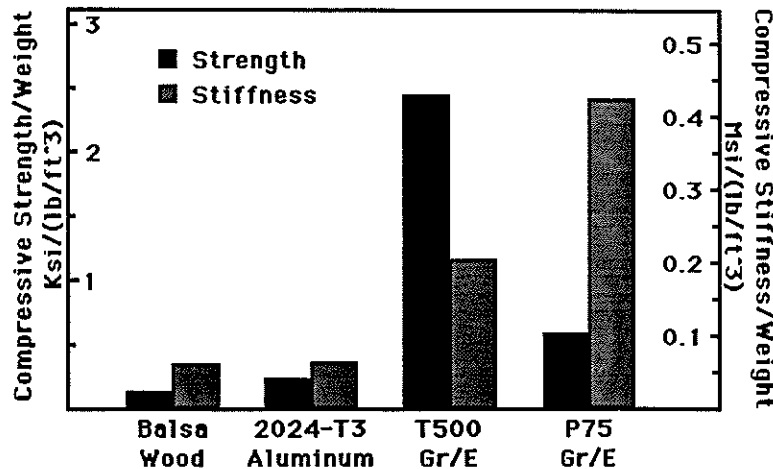
Figure 8. A series of three specially designed airfoils has been developed for Daedalus.

#### 4.4 Carbon Spar

Just as the wing is the dominant factor in the overall aircraft's aerodynamic performance, so it dominates the aircraft's structural weight. Thus in Phase I we have concentrated on developing an advanced wing structure. The design goals are high strength and stiffness in both bending and torsion, low weight, and low aerodynamic drag. These requirements inevitably conflict; for example, external wire bracing can make a very strong and stiff structure with low weight, but the exposed wire bracing incurs a penalty in terms of aerodynamic drag. The proper compromise cannot be made by considering only the spar alone; the characteristics of the entire aircraft must be included.

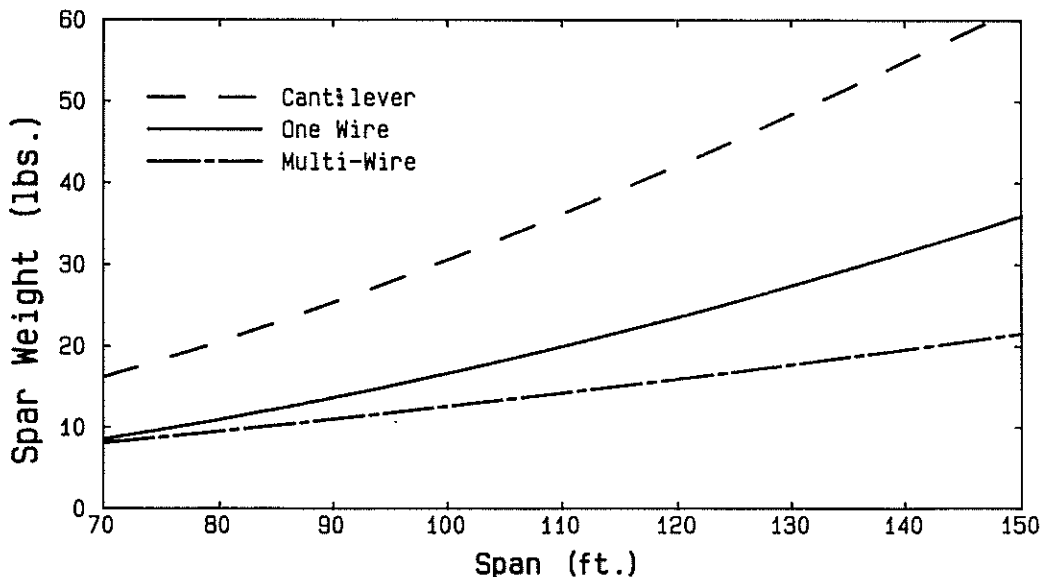
Materials play an important role in deciding which structural configurations are possible. The two most relevant measures are the ratios of strength-to-weight and stiffness-to-weight. As shown in Figure 9, modern materials such as graphite epoxy are far superior in these measures to conventional materials such as wood or aluminum. In recent years there has been steady progress in the development of materials that offer extremely high stiffness-to-weight ratios. Since stiffness is the limiting factor over much of the Daedalus wing, our aircraft will benefit significantly from using the latest high-stiffness materials. By carefully tailoring the design of the spar, including the exact type of material used at each location, an impressive advance over previous HPA structures can be achieved.





**Figure 9.** Graphite-epoxy is by far the best material for HPA structures. New types of graphite-epoxy material offer very high ratios of stiffness-to-weight. (Graphite-epoxy data courtesy of the Union Carbide Corporation.)

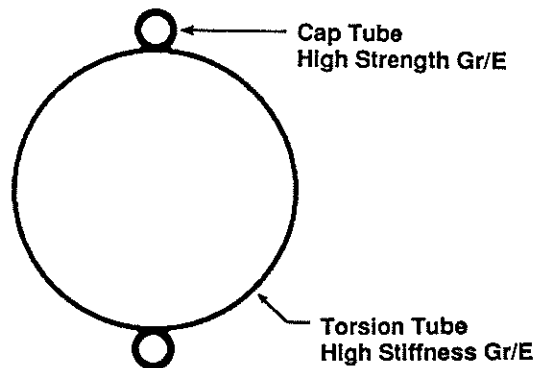
The three basic configurations considered for Daedalus involved using: 1) multiple bracing wires (to relieve both bending and torsion loads), 2) a single bracing wire (to reduce bending loads only), and 3) no bracing wires (cantilevered). The estimated weight of each configuration as a function of span is shown in Figure 10.



**Figure 10.** Variation of wing spar weight with span for different configurations. The spar shown is sized to carry 440 pounds (220 pounds at 2 g's) before failing.

When the data from Figure 10 is combined with other sizing considerations (see Section 4.6) the single-wire case appears to be optimum for the Daedalus design.

In order to fully utilize the advances in graphite-epoxy materials technology and to significantly reduce the exposed wire area, a new spar cross-section was developed. This design (shown in Figure 11) uses a tri-tube design to take all torsion, shear, and bending loads. By carefully tailoring the spar's design, including the exact type of material used at each location, an impressive advance over previous HPA structures can be achieved.



**Figure 11.** Daedalus wing spar cross section.

During the fall of 1985 several 4-foot long test section were built to develop manufacturing experience and to validate our design analyses. These were tested to failure in MIT's Technology Laboratory for Advanced Composites (TELAC). A 5-piece, full-scale (102') spar has been designed and is being fabricated (with materials donated by Union Carbide Corporation's Specialty Polymers and Composites Division) as part of Phase I. The spar will be tested early in Phase II.

#### **4.5 Flight Control System**

Since the ultimate flight of the Daedalus aircraft will require four to five hours to complete, it has been proposed that a flight control system be incorporated into the aircraft to reduce the pilot's mental workload. In addition, such an autopilot could potentially improve the system performance by maintaining flight near the aircraft's optimal cruising conditions, particularly at the speed that corresponds to minimum power. Finally, such an

autopilot will open the possibility of flight in reduced visibility, specifically at night, which might be required to take full advantage of calm air periods.

As part of the feasibility study, members of the working group designed and analyzed an autopilot system that can 1) hold desired airspeed 2) maintain a wings-level attitude, and 3) hold a desired heading (for a full discussion, see Reference 5). The airspeed-hold system maintains the selected speed by commanding the aircraft to gain altitude if the airspeed is higher than requested, thus converting kinetic energy into potential energy. Similarly, if the airspeed is too low, the autopilot causes the aircraft to descend and regain velocity (with checks to maintain a minimum acceptable altitude). The wing leveler and the heading hold system act together to keep the aircraft on the desired course. The wing leveler will maintain attitude despite atmospheric disturbances, while the heading hold system will observe drifts in the heading and remove them by commanding a slight roll angle until the correct heading is achieved.

During the study, working group members obtained data on various sensors, pilot displays, actuators, and batteries, and designed systems based on data from the MIT *Monarch B*. A six degree of freedom computer simulation was used to model autopilot performance. Typical results are shown in Figure 12 and 13. Based on this information, it appears that a control system can be built that will dramatically enhance the flight characteristics of the Daedalus aircraft without significant weight penalties.

In addition to designing and simulating the autopilots, the working group prepared preliminary designs for a 22 channel flight data recorder (for use in test flights) and a pilot radio system. Weights for these systems are included in Table 3.

**Table 3. Weight Summary for Prototype Avionics Suite**

Sensors:	186 grams	Flight data recorder:	400 grams
Display:	100	Batteries:	85
CPU:	100	Radio:	200
Actuators:	254	Batteries:	68
Batteries:	210		
Autopilot Total:	850 grams	(1.9 lbs)	
Avionics total :	1603 grams	(3.5 lbs)	

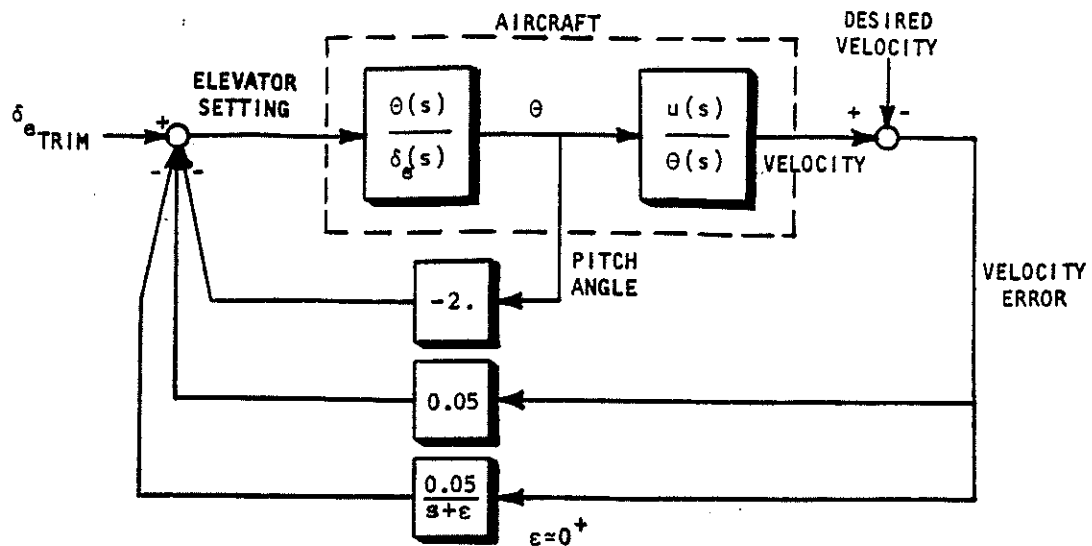


Figure 12. Block diagram for proposed airspeed hold system.

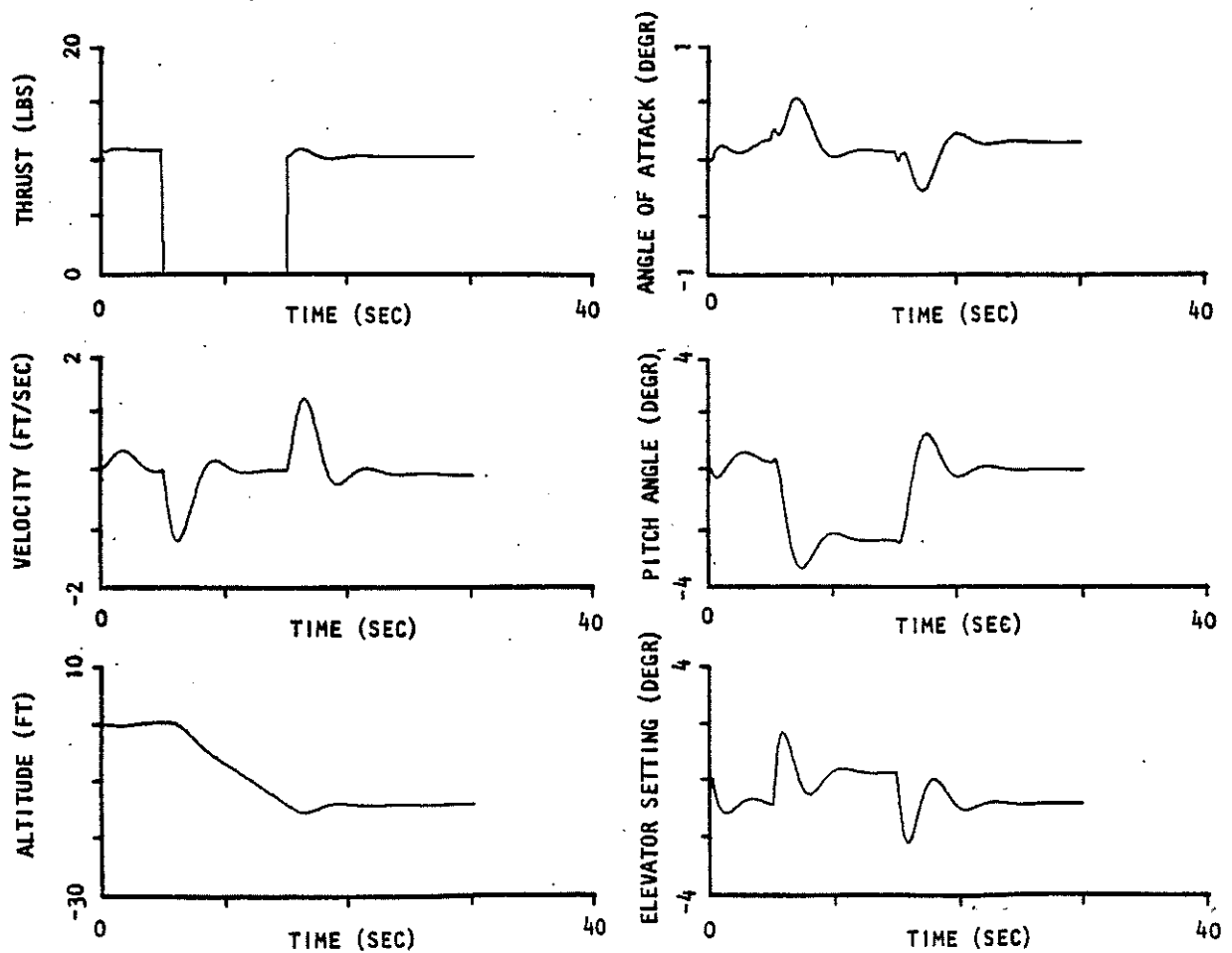
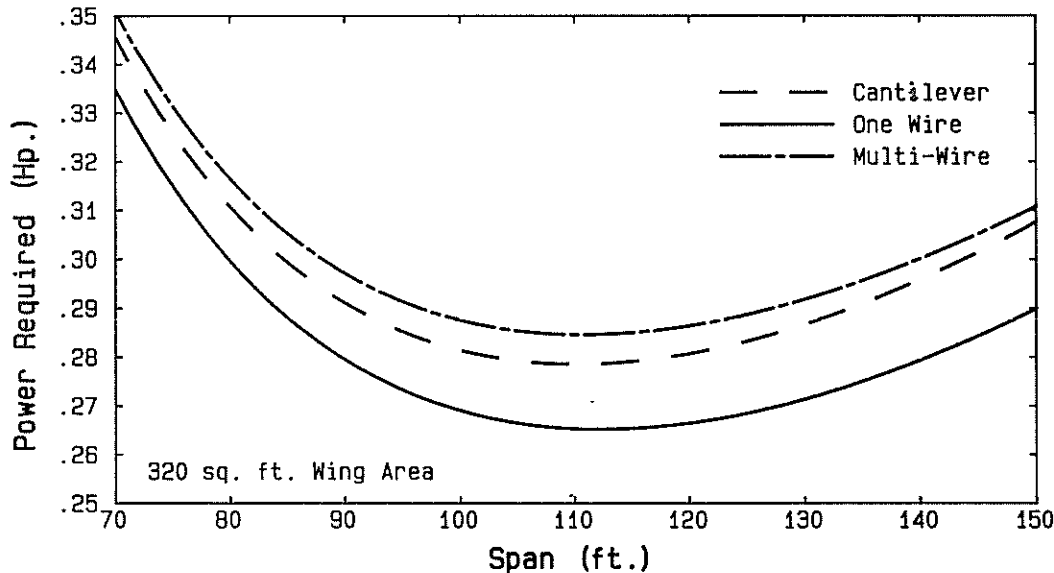


Figure 13. Demonstration of airspeed hold system (plots show perturbations about trim conditions).

## 4.6 Estimating Potential Performance

Following selection of the basic concept (Section 4.2), the Working Group undertook a detailed examination of design trade-offs. The general procedure was to develop parametric estimates for weights of various components and aerodynamic data, and then develop a computer program that sized the aircraft for minimum power given selected conditions.<sup>3</sup> Several configurations were examined, including a fully wire braced wing structure, a single wire, and a fully cantilevered. For each configuration we considered wing areas between 100 and 1000 square feet. For each wing area, the aspect ratio for minimum power was determined. Typical results are shown in Figure 14. The optimum aspect ratios tend to be very large, but the optimum is quite flat. Accepting a penalty of 3% in power often reduced aspect ratios by approximately 25%.

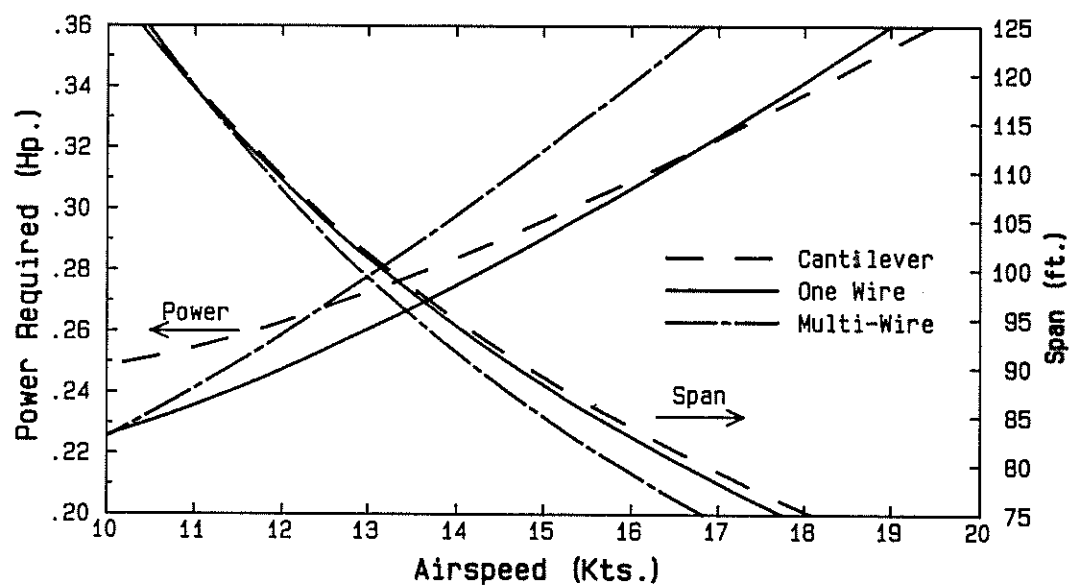


**Figure 14.** This is a typical span optimization plot. Power required from the pilot is plotted against wing span for a case with 320 square feet of wing area. The minimum power is required by a one-wire configuration with a 110 foot span. By accepting a small power penalty (under 3%) the span can be reduced almost 10%.

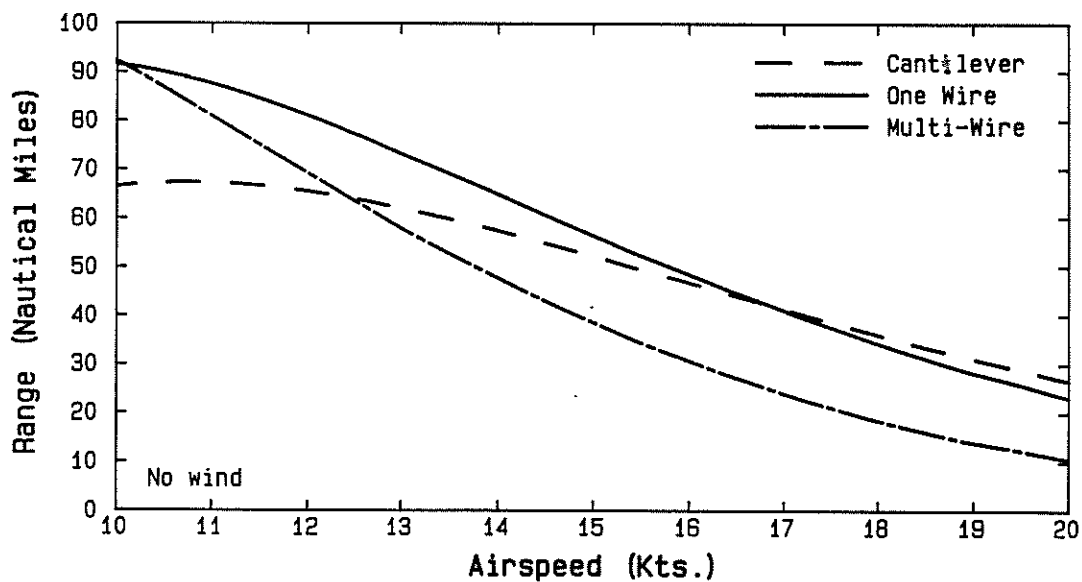
Once the full range of configurations and wing areas had been computed, cross-plots of power versus speed and wingspan versus speed could be determined. Typical results are shown in Figure 15. Finally, this data was combined with the performance of the human "engine" (Figure 6) to calculate range as a function of design speed. Results are shown in Figures 16 (for the no-wind case) and 17 (for a headwind of 4 kts). It should be

<sup>3</sup> Among the constants input were pilot weight, desired aircraft strength, and design lift coefficient.

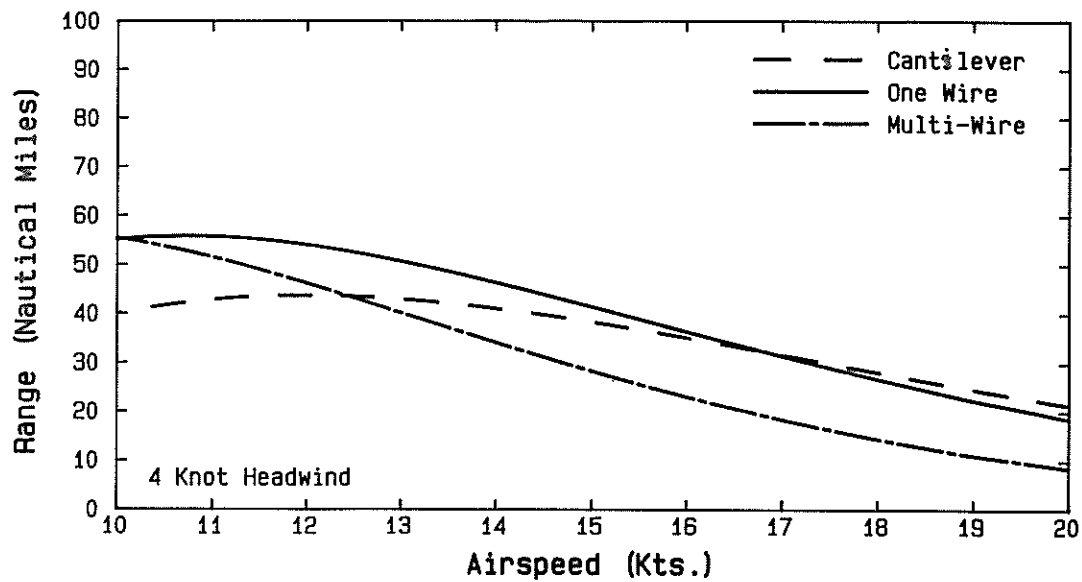
noted that these curves do not represent the performance of a single aircraft, rather, each point on these curves represents a totally different aircraft.



**Figure 15.** Example of output from aircraft sizing program, plotting power versus speed and wingspan versus speed. Pilot weight in this case is 140 pounds, design lift coefficient is 1.0.



**Figure 16.** Maximum still-air range as a function of design speed for three wing bracing configurations.

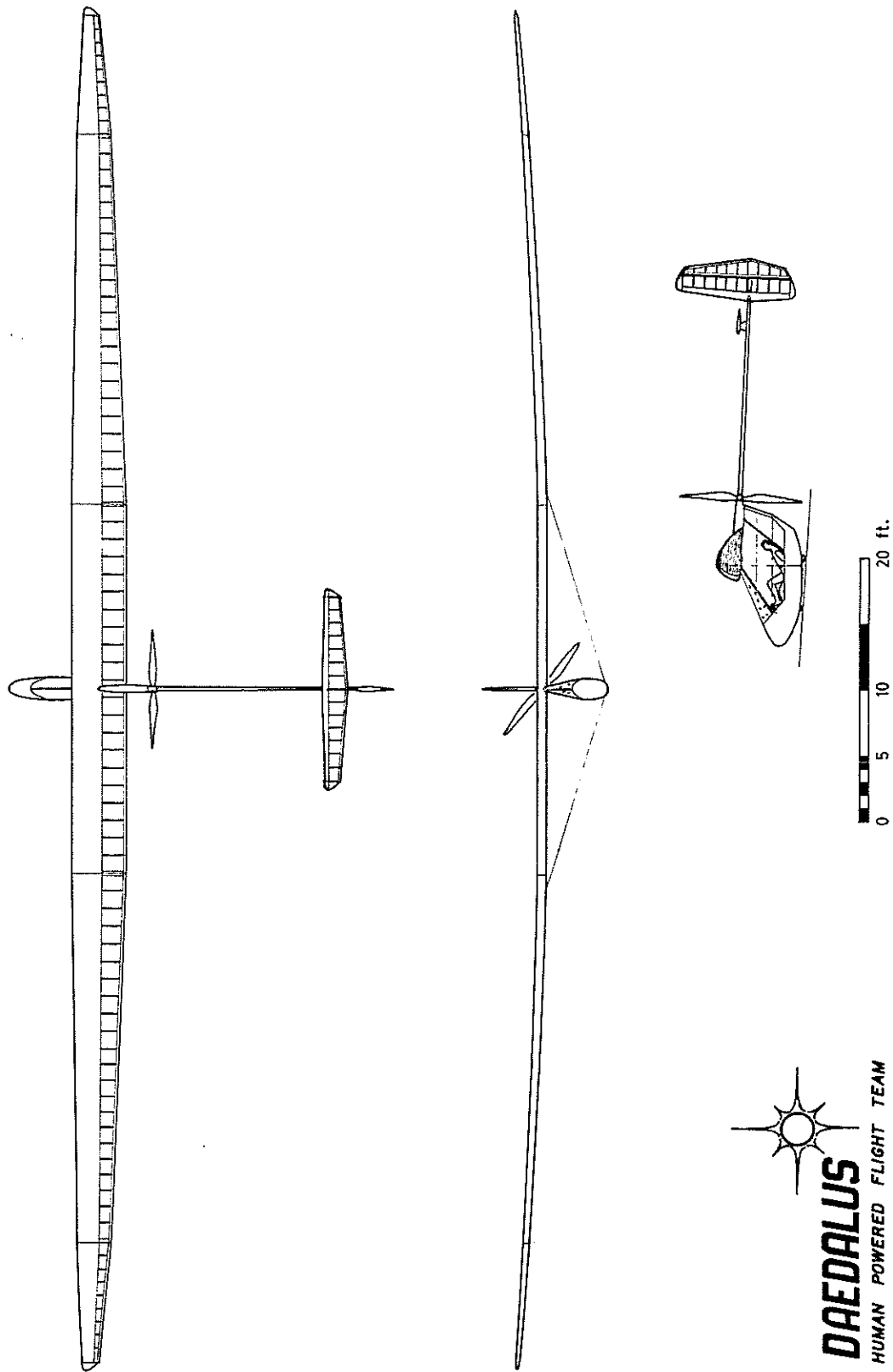


**Figure 17.** Maximum range with a 4-knot headwind, plotted as function of design speed and wing bracing configuration.

The entire procedure was then repeated for a variety of pilot weights, design lift coefficients, structural load factors, and aerodynamic assumptions. The general conclusions that emerge are:

1. Maximum still-air ranges on the order of 90 nm are theoretically possible;
2. The preferred configuration depends on the speed: for speeds of 10 knots or less the fully wire-braced structure is best, for speeds between 10 and 17 knots the single-wire configuration is more attractive, and for speeds above 17 knots a fully cantilevered design will have the longest range;
3. As wind increases, the optimum speed moves up but the range drops dramatically. Achieving 60 nm ranges will apparently require headwinds of 4 knots or less;
4. Range is insensitive to design pilot weight; what counts is the pilot's specific power (power divided by weight).

Figure 18. Proposed design for the Daedalus prototype.





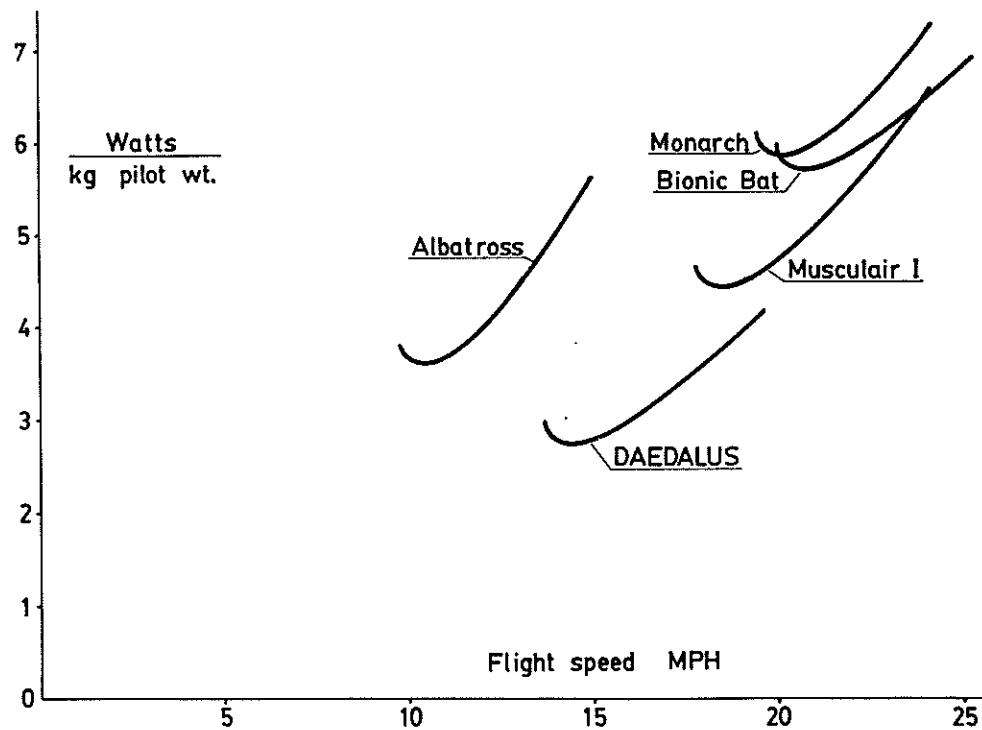
## 4.7 Proposed Prototype Design

Although we believe that an aircraft capable of making the Daedalus crossing could be built today, using the technology developed in Phase I, the Working Group strongly recommends that a prototype aircraft be constructed first. Night operations and cliff takeoff have never been attempted with a human-powered aircraft, and we feel it is essential to develop experience on an aircraft specially configured for such operations before attempting an "optimum" vehicle.<sup>4</sup> A second benefit of the prototype is that it could be specially instrumented to measure performance, and the resulting data used in optimizing the final design. Finally, such an aircraft would be a valuable aid in selecting and then training potential pilots.

The prototype need not be sized for theoretical maximum range; in fact, to challenge the state of the art we recommend a design with the highest speed consistent with the needed 60 nm still-air range. Selection of a 15 knot design speed goal is consistent with the estimated pilot power and range required, yet at the same time provides a much stronger challenge to the aircraft's aerodynamics than would a slower design speed. A proposed design is shown in Figure 18. The performance of this design is shown in Figure 19, along with a comparison to several previous aircraft. Finally, a comparison between the proposed prototype and the *Gossamer Albatross* is shown in Table 4. Daedalus will be 50% stronger, 30% faster, and still use 15% less power. The bottom line is that its potential range is increased more than 100%.

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<sup>4</sup> Although both night operations and cliff launching offer significant performance benefits, each imposes legitimate safety concerns. While both capabilities are proposed for the prototype, the Working Group believes it is unlikely that they would ever be used simultaneously.



**Figure 19.** Specific power required as a function of speed for the proposed Daedalus prototype. Data for the *Gossamer Albatross*, *Monarch B*, and *Musculair I* are included for comparison.

**TABLE 4.** Comparisons Between *Gossamer Albatross* and Daedalus Prototype

	<u>Gossamer Albatross</u>		<u>Daedalus Prototype</u>	
Wing Span (m,ft)	29	94	31	102
Wing area (m <sup>2</sup> , ft <sup>2</sup> )	44	472	30	320
Weight (kg,lbs)	33	72	31	68
Design Speed (m/s,kts)	5	10	7	13
Drag Area (m <sup>2</sup> , ft <sup>2</sup> )	2.5	26.9	1.0	10.4
Design Power (W, HP)	246	.33	210	.28
Still-Air Range (km, nm)	56	30	122	61
Load Factor (g's)	2.0		3.0	
Cliff-launch capable?	no		yes	
Night flyable?	no		yes	



## Chapter 5. Making the Flight A Reality

### 5.1 The MIT/Smithsonian Partnership

The Daedalus project brings together two institutions with long histories of involvement with aviation: the Smithsonian, which began a program of aeronautical research in the late nineteenth century; and MIT, which founded the nation's first university course in aeronautics in 1914. Cooperation between these two institutions dates from early in this century, when representatives of MIT and the Smithsonian worked together to establish the National Advisory Committee for Aeronautics, the predecessor to the National Aeronautics and Space Administration.

The National Air and Space Museum (NASM), currently the world's most-visited museum, originated in 1946. As part of the larger Smithsonian Institution, NASM is guided by James Smithson's original mandate to "increase and diffuse knowledge." Thus, in addition to conducting within the Museum an extensive and ambitious program of research, ranging from scholarly publications to satellite mapping, NASM is committed to pursuing joint programs with outside organizations. Ventures are designed as creative and stimulating contributions to a program of world-wide communication on aerospace topics; examples of current projects include the creation of a life-size flying replica of the pterosaur *Quetzalcoatlus northropi*, assistance to teams attempting the first round-the-world aircraft (nonstop, unrefueled) and balloon flights, and new large-format IMAX films such as The Dream Is Alive (1985) and On The Wing (1986).

The Department of Aeronautics and Astronautics of MIT brings to the Daedalus program an unparalleled combination of theoretical, computational, and experimental research capabilities. Of particular relevance for the Daedalus project are facilities such as the Man-Vehicle Laboratory, the Technology Laboratory for Advanced Composites, and the Center for Aerodynamic Studies. In addition, the Department has the accumulated experience of four previous human-powered aircraft (HPA), including the 1979 *Chrysalis*, which made over 350 flights with 44 different pilots, and the 1984 *Monarch B*, which was awarded first prize in the Royal Aeronautical Society's Kremer World Speed Competition for a record-setting speed flight on May 11, 1984.

The partnership of MIT and the Smithsonian, two organizations committed to the twin purposes of research and education, allows Daedalus to draw on a myriad of resources and to reach audiences within both the scientific community and the general public. Together, MIT and NASM have jointly funded and conducted the Phase I feasibility study for the Daedalus flight.

## 5.2 Need for a Film Documentary

The mutual goal for the two organizations is to stimulate thought about the challenges and excitement of extending technology, especially in the field of aeronautics. Both are particularly interested in illustrating for young people that engineering is an imaginative and creative force in our society. To achieve this it is apparent that some form of lasting documentary is required, both to record the project in detail, and to extend the record beyond the transitory coverage provided by news media.

During the Phase I study we have consulted with two independent film production companies experienced in producing programs for PBS. From these conversations we are confident that a documentary on the project would be feasible and well received. The cost of such a film would be on the order of \$350,000-\$400,000.

## 5.3 Role of the Greek Government

One of the first questions addressed by the study was whether any legal, political, or institutional barriers existed that might prevent the Daedalus flight. In June, 1985 members of the project briefed representatives of the Greek government at their embassy in Washington, D.C., and in July Prof. Steven Bussolari traveled to Greece, where he spent a week meeting with representatives from various agencies.<sup>1</sup> In March 1986 a team of Working Group members traveled to Greece to perform a survey of potential takeoff and landing sites and to deploy two automated weather stations to gather meteorological data on the route of flight. From the discussions that took place during these two trips, we have concluded that the flight is not only feasible, but would be welcomed warmly and assisted by the Greek government and public.

During the study phase itself, we have been assisted both by members of the Greek government and by private citizens interested in the project. The General Secretariat of Press and Information was the coordinating body for the two survey trips conducted by Working Group members. The Hellenic National Weather Service provided historical climatological data for the region and is supporting the data gathering operations associated with the automated weather stations. The National Defense General Staff and the Hellenic

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<sup>1</sup> These included: The Ministry of Press and Information, the Ministry of Transportation, the National Defense General Staff, the Hellenic Air Force, the Hellenic National Meteorological Service, the Ministry of Science and Culture, the Hellenic National Aero Club, Olympic Airways, the Hellenic National Tourist Organization, the MIT Club of Greece, and the Hellenic National Police Force.

Air Force provided logistical support to aerial and ground surveys of potential takeoff and landing sites and the placement of the automated weather stations. Olympic Airways and the National Tourist Organization provided cost-free travel arrangements to members of the Working Group.

The Working Group has received numerous suggestions for possible cultural activities that might be coordinated with the flight operations in the Aegean. Prof. Bussolari has discussed with the Ministry of Science and Culture the possibility of a special archaeological exhibit at a museum on Crete and an international meeting of classicists, archaeologists, physiologists, and engineers who would exchange ideas reflecting the multi-disciplinary nature of the Daedalus Project. We intend to pursue the planning of these activities as part of Phases II and III.

It is the consensus of the Working Group that the Greek government and the people of Greece are essential partners and participants in the Daedalus Project. To this end, it is important to continue to establish and maintain close communication between the Working Group and Greece to ensure that the rich benefits of this cross-cultural endeavor are fully realized.

#### **5.4 Financial Sponsorship**

Phase I has benefited from generous donations of several private companies, most notably Aanderaa Instruments (donors of three automatic weather stations currently deployed in Greece), the Union Carbide Corporation (donors of the graphite-epoxy material used in the wing spar), and the Sikorsky Division of United Technologies Corporation (who provided use of their autoclave for curing the graphite wing structures). We greatly appreciate this sponsorship, and are encouraged that continued donations of materials and services can greatly reduce the required cash outlay for Phases II and III. Nonetheless, some financial sponsor must be found to supply a core of working capital for the second and third phases.

A multidisciplinary endeavor like Daedalus falls outside the bounds of most established sources for scientific or academic programs.<sup>2</sup> Likewise, although the project has strong cultural and artistic features, it cannot hope to pursue funding through foundation grants designed to support the arts. Thus we believe that the primary sponsors

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<sup>2</sup> For example, although portions of the project might be of interest to National Aeronautics and Space Administration, the National Science Foundation, the National Institutes of Health, or the National Foundation for the Humanities, it would be totally impractical to attempt to weave together a patchwork of grants for the relatively small amounts of funding needed here.

are likely to be organizations interested either in advertising exposure, in promoting Greek-American relations, or both. As an vehicle for gaining public exposure, Daedalus promises to be extremely effective. Discussions with official of the DuPont Company indicate that their \$180,000 investment in *Gossamer Albatross* produced media exposure that would have cost over \$400 million if purchased commercially. With its serious scientific and technical content, with its balance of athletic and intellectual challenge, and with its sense of adventure and enthusiasm, the project offers a unique opportunity for a suitably-matched sponsor.

## 5.5 Implementation Plan

As discussed in Section 4.3, there are important reasons for constructing and testing a prototype rather than proceeding directly to the final design. Combined with the weather windows discussed in Section 2.2, this poses definite restrictions to the planning schedule.

Overall, we believe that a period of approximately twelve weeks will be required to design and construct the prototype with an additional eight weeks for testing and modification. Assuming that 7,000 hours will be required for construction, we estimate total project will require about 15 people. Costs for Phase II are expected to range between \$195,000 and \$350,000, depending on the extent of material donations.

The third phase will require another twelve weeks for vehicle construction and eight weeks for final testing. We believe that at least two months should be budgeted for operations in Crete to allow for variability in the weather. This brings the total project to approximately 12 months from go-ahead and total costs of between \$500,000 and \$750,000. More detailed planning information is available upon request.

## Chapter 6. Conclusions

Based on our examination, the study group concludes that the proposed human-powered flight between Crete and the mainland of Greece is feasible. Specifically:

1) The myth has changed considerably during its 3500 year evolution. No single definitive version can be said to exist, therefore, the project should focus on a symbolic, rather than literal, recreation of the flight.

2) Greek literature often mixes metaphors between sailing and flying. The Daedalus flight should draw on this analogy, planning its flight in accordance with Greek nautical practices. In particular, this suggests than an island-hopping approach to cover long distances.

3) Whatever his ultimate destination, the first leg of Daedalus' journey would be the longest and most critical. We have therefore designed the aircraft to be capable of crossing the straits between Crete and the mainland, a distance of 110 km.

4) Analysis of historical weather data suggests that favorable winds and temperatures are most likely to coincide during the months of March, April, and September. During these periods approximately 20% of the days appear to be suitable for a flight.

5) Suitable flight conditions occur most often at night.

6) The terrain in the region is rugged and mountainous. Take-off and landing opportunities will be limited. The peninsula northeast of Kastellion has considerable area above 300 meters in altitude. Launching from this region could cut energy requirements for the flight by more than 15%, but would require increased structural margins and other pilot safety provisions.

7) The task of powering the aircraft appears to be within human athletic capabilities. Endurance of the pilot is more likely to be limited by overheating or dehydration than by fuel limitations. Specific powers exceeding 3 W/kg for four hours have been demonstrated during Phase I. It seems probable that higher levels can be obtained by highly trained and motivated individuals.

8) The program can find no inherent performance differences by gender; men or women are equally well suited to being the pilot given sufficient training.



9) The flight distances under discussion are triple those of the existing world distance record, and it seems clear that no existing human-powered aircraft would be capable of the proposed flight.

10) It is technically possible to build a human-powered aircraft capable of achieving these ranges under appropriate weather conditions. This conclusion is based not only on theoretical calculations but also on a series of demonstration milestones that include:

- Development of an airfoil with 30% less profile drag than on *Albatross*;
- Construction and proof-test of a full-scale graphite-epoxy wing spar;
- Design and simulation of an electronic flight control system;
- The Flight Team's experience from two previous HPAs, *Chrysalis* and *Monarch*.

11) The need to explore night and high-altitude operations, coupled with the need to recruit and train pilots, suggests that the proposed intermediate phase of building and testing a prototype is highly appropriate. A quantitative goal for such a vehicle would be to break the existing FAI world records. A detailed design for such an aircraft has been prepared.

12) Costs for the project will be small in comparison to other aircraft. The proposed Phase II (prototype construction and testing) can be accomplished for about \$350,000; donations in kind can reduce costs even further. The corporate response to requests for donations during Phase I has been most heartening. We believe that donations in kind of materials, services, or even loan of personnel can reduce actual cash requirements by up to 50%.

13) The primary benefits of the flight will be in terms of education. Through MIT, the project will provide an interdisciplinary, hands-on design experience to undergraduate and graduate students. The resources of the Smithsonian will enable the project to reach a much larger audience through museum displays, cultural exchange programs, and written or filmed documentaries.

14) The project will also create a base of advanced technology that may be applicable to other ultralightweight aircraft designs.

15) Scientific data concerning the factors that limit human endurance and the low-level micrometeorology of the Mediterranean will continue to be generated by the project.

16) Through worldwide public attention, the flight can help promote cultural awareness about the linkages between science and art or technology and culture. Towards

this end, it will be important to have a documentary film (or other communications annex) that could be used (for example) on the public broadcasting system.

17) International goodwill will be promoted by the effort. To date the project has been warmly received and greatly assisted by both private citizens and public officials of Greece. We expect that this base of goodwill can be built upon to strengthen understanding and friendship between the two countries.

In summary, the Working Group is aware of no fundamental obstacles that would prevent the proposed flight from being successful, and recommends that the project proceed.



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## Appendix A. The "Friends of Daedalus"

In addition to the direct participants listed in Table 1, the following people have contributed significantly to the work of the study team:

Ivar Aanderaa, President, Aanderaa Instruments Co. Dr. Aanderaa supplied the project with three automatic weather stations built by his company, which are now deployed in Greece.

Bryan Allen, pilot and engine, *Gossamer Albatross*. Mr. Allen attended the fifth meeting of the working group and provided valuable insight on the pilot's perspective of long-duration HPA flight.

Barbara Brennan, Exhibits Designer, NASM. Ms. Brennan provided graphic design work for the project.

Ed Brown, Estes Industries. Mr. Brown supplied information concerning possible construction techniques for the wing leading edges.

Ted Carter, Sikorsky Aircraft. Mr. Carter assisted in the use of the Sikorsky autoclave.

Stavros Frangopoulos, Press Counselor, Embassy of Greece. Mr. Frangopoulos assisted the project throughout Phase 1 establishing contacts in Greece and arranging transportation for the Spring 1986 survey trip.

Steve Hall, Assistant Prof. of Aeronautics & Astronautics, MIT. Prof. Hall assisted in the design of the flight control system and supervised undergraduate students working on the project.

Clive Hart, Professor of Literature, University of Essex. Prof. Hart is the author of several books on flight in antiquity, the most recent being The Prehistory of Flight. He met with Working Group members during a December, 1985 trip to London and provided several unpublished manuscripts relevant to the Daedalus myth.

Walter M. Hollister, Professor of Aeronautics & Astronautics, M.I.T. Prof. Hollister assisted with the flight control analysis and surveyed several prospective Phase II bases for the project.

Christos Kassapoglou and his father, Mr. George Kassapoglou. Assisted the project by obtaining initial weather data from Greece.

Nicholas Konidaris, Teradyne Corporation. Mr. Konidaris assisted with the coordination of Greek contacts during the July 1985 survey trip as well as communication with the Greek-American community.

Paul A. Lagace, Associate Professor of Aeronautics & Astronautics, MIT. Prof. Lagace provided the project with laboratory facilities for the preparation of composite wing spar sections.

Manousos Manousakis, Chania, Greece. Mr. Manousakis assisted with the logistics of the weather station deployment on Crete during the March 1986 survey team visit.

J. Wilson Myers, Boston University. Dr. Myers is the co-author of *The Aerial Atlas of Ancient Crete*, which he prepared by photographing archaeological sites from a gas balloon. He shared valuable insights with us concerning the winds on Crete.

David R. Nethero, Union Carbide Co. Mr. Nethero was instrumental in providing the project with graphite-epoxy materials for the wing structure.

Leslie Reinherz, Chedd-Angier Production Company. Ms. Reinherz acted as contact between the project and the Chedd-Angier Production Company.

Tim Severin, London, England. A maritime adventurer and author, Mr. Severin specializes in recreating mythical voyages. He discussed his experiences with representatives of the Working Group in February, 1986 and provided several valuable contacts in Greece.

Allan R. Shaw, Dept. of Aeronautics & Astronautics, MIT. The Working Group's most faithful supporter, Mr. Shaw provided laboratory facilities and materials for Daedalus, as he had for *Chrysalis* and *Monarch*.

Arthur Steinberg, Assistant Professor of Archaeology and Anthropology, MIT. Prof. Steinberg provided the Working Group with its initial background material on the early sources of the Daedalus myth.

Peter M. Warren, Department of Classics, University of Bristol. Prof. Warren has conducted extensive archaeological research into ancient Minoan civilization. He met with representatives of the Working Group in December 1985 and provided valuable suggestions on literature.

David Gordon Wilson, Professor of Mechanical Engineering, MIT. Prof. Wilson assisted the project in locating existing data on human cycling performance.

The five athletes who participated in the Phase I physiological testing conducted at the John B. Pierce Foundation Laboratory included:

Loretta DiPietro

Larry Gagnon

Lois McCallin

Rudy Sroka

Paul Widerman

The following Greek agencies and organizations have provided valuable assistance to the Working Group during two survey trips to Greece:

Ministry of Press and Information

Ministry of Transportation

National Defense General Staff

Hellenic Air Force

Hellenic National Meteorological Service

Ministry of Culture and Science

Hellenic National Aero Club

Olympic Airways

Hellenic National Tourist Organization

The MIT Club of Greece

Hellenic National Police Force

The following MIT Faculty members have provided assistance with contacts in the Greek and American government and scientific community:

Prof. Elias Gyftopoulos

Prof. Joesph Haritonidis

Prof. Michael Dertouzos

Prof. Amedeo Odoni

Prof. Lena Valavani

The following students assisted with the project:

Steve Allmaras

Ali Azar

Salvador Castillo

John Chandy

Joan Coyne

Farla Fleming

Richard Gueler

Steve Holzinger

Marc Lie

Stephane Monoloni

Kelvin Phoon

Peggy Scott

Richardo Zemella