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FEASIBILITY STUDY OF STATIONARY HIGH ALTITUDE RELAY PLATFORM (SHARP) CONCEPT

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SASKATOON CANADA

ADVANCED SYSTEMS ENGINEERING GROUP

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i EXECUTIVE SUMMARY

BACKGROUND

There is an increasing demand for improved communications in rural and remote regions of Canada. In these regions, the requirement for extended television services and improved fixed and mobile telephony is increasing as is the interest in a broad range of TV programming and as northern resource development takes place. For many of the regions, it is difficult to foresee how these needs could be fully and economically met with existing and proposed satellite and terrestrial networks. Using these networks only, it appears unlikely that a high fraction of the two million Canadian households in rural and remote regions could be economically offered more than a very few regionally-based basic and new TV programming services, including pay TV and off-air Telidon services. This appears also to be the case of regional telephony services in remote regions of many of the provinces.

The Stationary High Altitude Relay Platform (SHARP) concept appears to be a promising means to extend communications services at a regional level as a complement to satellite and terrestrial networks. From a proposed operating altitude of about 21 km, the radius of coverage of one relay platform would be about 520 km, (over an area of about 40 times greater than a 350 meter tower, or over about one half of a prairie province).

In 1977, as a result of mounting interest in the potential of civilian and military uses of near-earth, station-keeping, long duration relay platforms, NASA began a series of studies to determine the feasibility and application of such platforms. In the U.S., these platforms are described by the acronym HAPP (for High Altitude Powered Platforms). Table 1 lists the major studies to date.

TABLE 1 STUDIES PERFORMED FOR NASA(1)

STUDY	CONTRACTOR	DATE
HAPP Feasibility and Cost	Stanford Research Institute	10/77
HAPP Applications Study	Battelle Columbus Laboratory	10/77
User Def'n. Mission Reqt's.	" " "	12/79
Wind Study for Platform Design	Wallops Flight Center	12/79
Microwave Flight System Design	Raytheon	4/80
Wind Persistance	Wallops Flight Center	4/81
Vehicle Design	International Latex Corp., Dover	Current
Microwave Ground System Design	Raytheon	Current

From the table, it is apparent that interest in the United States is substantial and continuing.

- In 1981, in response to an unsolicited proposal by SED Systems Inc., a Canadian team was formed to study the feasibility of a Stationary High Altitude Relay Platform (SHARP) concept for application of Canadian latitudes. The team consisted of:

  . The Communications Research Centre, DOC, Ottawa, acting as team leader and conducting studies on the communications applications.

  . SED Systems Inc., Saskatoon, acting as prime contractor and contributing its expertise in System Analysis, radio and satellite communications and high altitude balloon payload design, operation, launch and recovery.

  . Prof. J. De Laurier, (University of Toronto Institute for Aerospace Studies), acting as aerodynamic and vehicle consultant, brought to the team expertise in vehicle flight analysis, development of hybrid lifting vehicles and experience on the TCOM tethered balloon, used for communications.

- The Flight Research Laboratory, National Research Council, Ottawa, while not a member of the team, participated informally by offering constructive criticism on the project.

The SHARP vehicle options selected for detailed study were based in part on the results of the early studies performed by NASA. The vehicle options considered in this study were: (i) a lighter-than-air vehicle (a neutrally-buoyant airship); (ii) a hybrid vehicle (a winged balloon); (iii) an aerodynamically shaped lighter-than-air vehicle; and (iv) a heavier than air-winged aircraft. Powering options considered were: (i) use of energy stored in the form of electro-chemical batteries; (ii) microwave power transmission from a ground station; and (iii) photo-voltaic cells. The propulsion options considered were propellers driven by electric motors or jet propulsion.

The major conclusion of this study is that a feasible vehicle for a communications mission is an ultra-light airplane flying at an altitude of approximately 21 km, and powered by microwave from the ground, as illustrated in Figure 1. None of the other vehicles investigated were assessed as capable of being successfully operated continuously during the most severe weather conditions at Canadian latitudes.

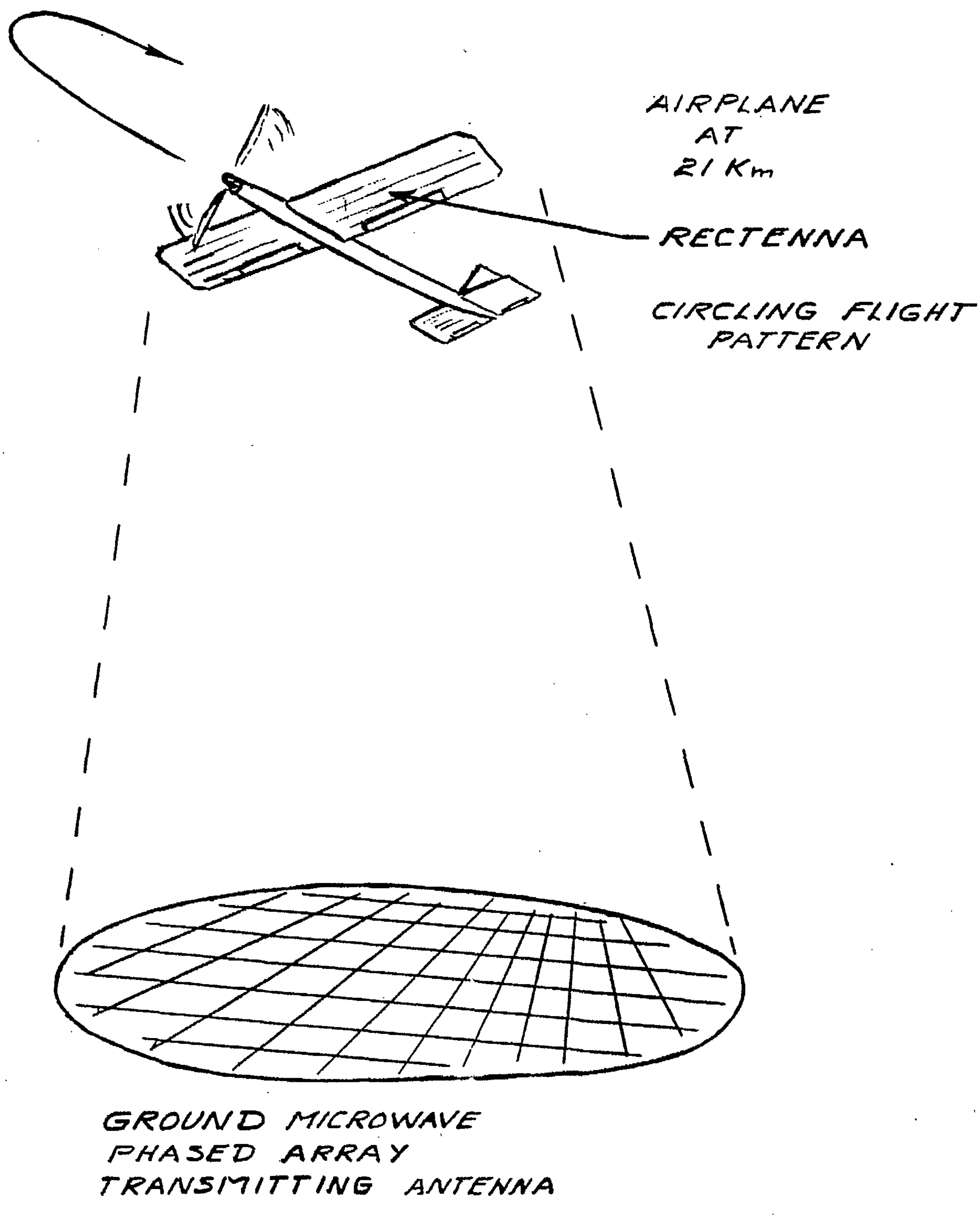
WINDS

Examination of winds over Alberta, Manitoba, and Western Ontario for several representative years established that:

- there is a relative minimum in average wind speeds at an altitude of approximately 21 km.

- at 21 km, the average wind speed varies seasonably, from 5 meters per second (m/s) in the summer to 25 m/s in the winter.

- at 21 km, peak wind speeds of 60 m/s must be expected at Canadian latitudes during the winter months (15 m/s in the summer).



STATIONARY HIGH ALTITUDE RELAY PLATFORM
CONCEPT

FIG. 1

The duration of the peak winds cannot be established from the data that exists. It is assumed that they are not short duration gusts, but are sustained for periods of hours. Results of Wind Persistance studies performed in the United States, reference 7, indicate that the persistance may be determined to the minimum time between radiosonde flights 6 or 12 hours. Accordingly, the SHARP vehicle and propulsion system must be capable of sustaining speeds of 60 m/s as an equilibrium condition.

VEHICLE CONFIGURATION AND PROPULSIVE POWER

Although the starting point for this study was lighter-than-air (LTA) vehicles, the results show that at wind speeds of about 30 m/s and greater, the propulsive power needed to maintain such vehicles on station is excessive. In fact, due to the flimsy nature of LTA vehicles, their inherent launch and recovery difficulties, and the need for on-board gas management system; they are not likely to be practical except at wind speeds much less than 30 m/s.

Also, investigation has failed to identify any potential advances in LTA technology which would make them feasible for the SHARP mission in the foreseeable future.

The calculated propulsive power required by various types of SHARP vehicles flying at 60 m/s is presented below:

TABLE 2

MAXIMUM PROPULSIVE POWER FOR SEVERAL SHARP VEHICLES

Wind Speed: 60 m/s

COMMUNICATIONS AND CONTROL PAYLOAD - 110 kgm

Vehicle	Volume (m^3)	Wing Area (m^2)	Propul. Power (kW)
Neutrally-Buoyant Airship	24075	-	315
Aerodyn. Lifting Airship	366	-	19
Wing-Balloon	29	-	23
Airplane (Solar Challenger Type)	-	39	10

The feasibility of the ultra-light airplane concept rests on three recent technically significant events:

- the successful flight of the solar powered Solar Challenger aircraft across the English Channel. (The aircraft has very high stiffness-to-weight and strength-to-weight ratios with a wing loading of about 5 Kg/m^2[3], and was designed to be flown to altitudes of 50,000 ft., or close to the proposed SHARP operational altitudes.)

- the efficient transmission of high levels of microwave power, over a 1.6 km distance (about 30 kw of dc power were received with efficiencies of over 80%)[2].

- the successful use of light weight and highly efficient Samarium-Cobalt brushless electric motors on the Solar Challenger.

THE SHARP AIRPLANE

An example SHARP airplane was identified which is a derivative of the Solar Challenger, specialized to the SHARP mission. Namely, it has a conventional configuration with a stabilizer and fin which are aft of the wing. The wing and stabilizer have rectangular planforms, where the wing's aspect ratio (span/chord) is 20. The stabilizer's aspect ratio is 3 and its area is 38% of the wing's area. The most important differences from the Solar Challenger are, first, that the fuselage is much more slender since there is no space requirement for a human pilot. Second, the airfoil is highly cambered (curved such that the underside is concave) since it isn't constrained to a flat-topped shape for solar-cell placement. This latter feature allows a significant performance improvement over the Solar Challenger, e.g. the SHARP airplane has a maximum lift/drag ratio of 31.9 compared with the Solar Challenger's value of 13.5.

It should be noted that the airplane's wing aspect ratio of 20 also contributes favourably to the performance, although it's a very high value which is at the limit of structural realization for this type of ultra-light airplane. The intention of this particular example has been to find out the ability to perform the SHARP mission of the most aerodynamically efficient SHARP airplane which could possibly be made. In fact, a reduction in aspect ratio to 10 would not greatly reduce the airplane's aerodynamic efficiency. If the aspect ratio 20 airplane is adequate for the SHARP mission, then the likelihood is high that the aspect ratio 10 version will also be adequate.

Figure 2 shows the predicted performance for the example airplane at an altitude of 21 km and with a propulsion system large enough to give a 60 m/s maximum speed. Also, it was assumed that the ratio of airframe mass (empty structural mass) to wing area is 2.5 kg/m^2, which is the same as the Solar Challenger's.

The variable parameters are wing area, S, and vehicle mean speed, U. It is assumed that for any combination of S and U, the airplane's angle of attack, α, is such as to give level flight. Since the maximum α is assumed to be 10^o, the lower speeds are limited by a "Stall Boundary", shown on the figure. When the ambient wind drops toward the "Stall Speed", the airplane must commence a circling flight pattern. In fact, this would be the most common mode of operation.

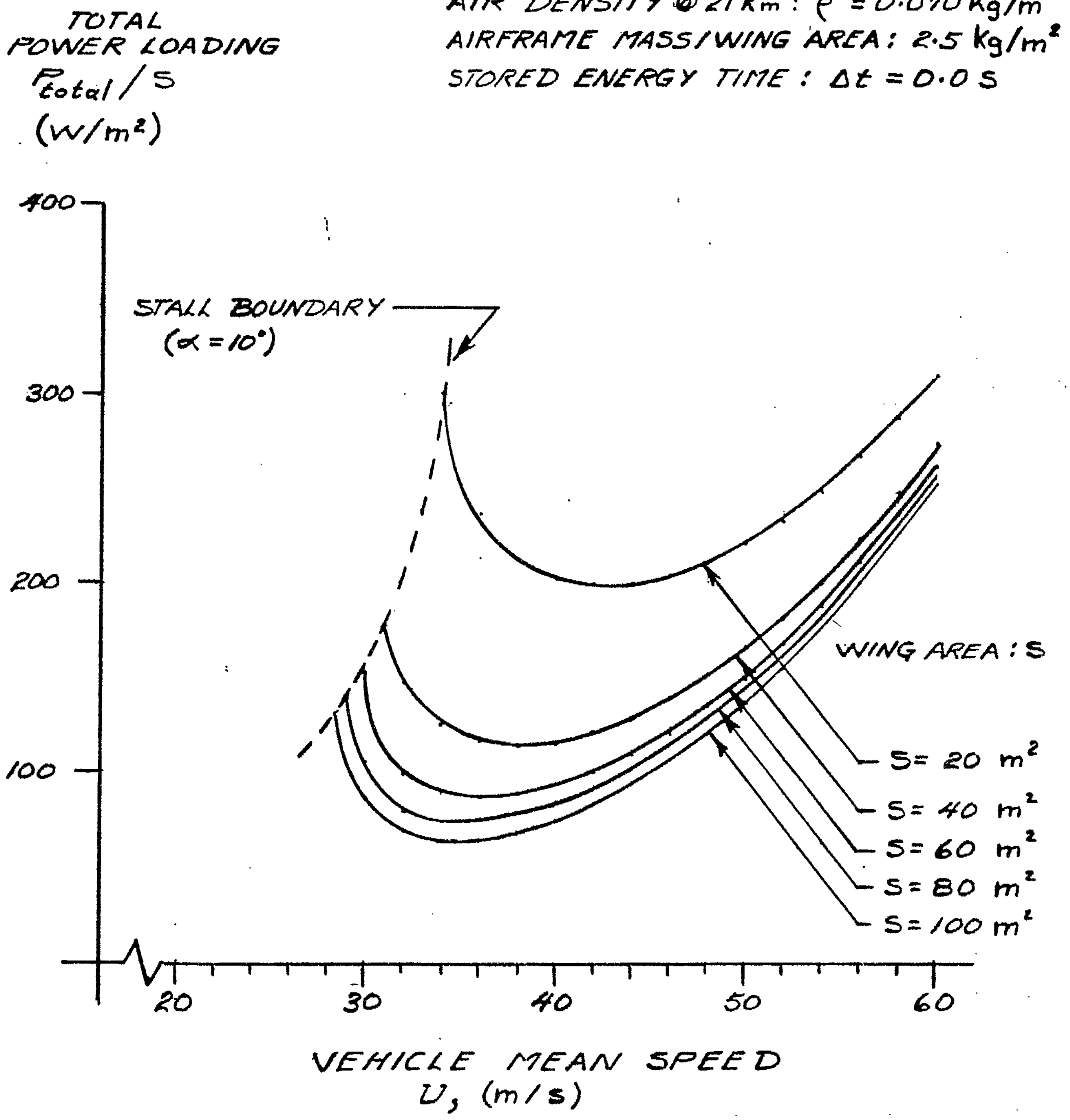
The result of interest is the "Total-Power Loading" which is the ratio of the airplane's total required power (propulsive power + 2.3 kW onboard power) to the wing area, P_{total}/S. This may be related to the "Power Flux Density" of microwave power relay if the rectenna area is equal to the wing area, and the transmission efficiency is 100%. The figure shows that for each S considered, there's a U for which P_{total}/S is minimized. These values, in fact, relate to the flight conditions for maximum lift/drag ratio. At speeds below these, α increases so rapidly, as does the drag which varies as α^2, that P_{total}/S increases. Also, at speeds above the minimal points, the drag begins to increase approximately as U^3, thus P_{total}/S increases to its maximum values at U = 60 m/s.

AR-20 AIRPLANE PARAMETERS -

AIR DENSITY @ 21 Km : ρ = 0.070 Kg/m³

AIRFRAME MASS/WING AREA : 2.5 Kg/m²

STORED ENERGY TIME : Δt = 0.0 S



TOTAL POWER LOADING

Vs

VEHICLE MEAN SPEED

FOR

THE AR-20 SHARP AIRPLANE

FIG. 2

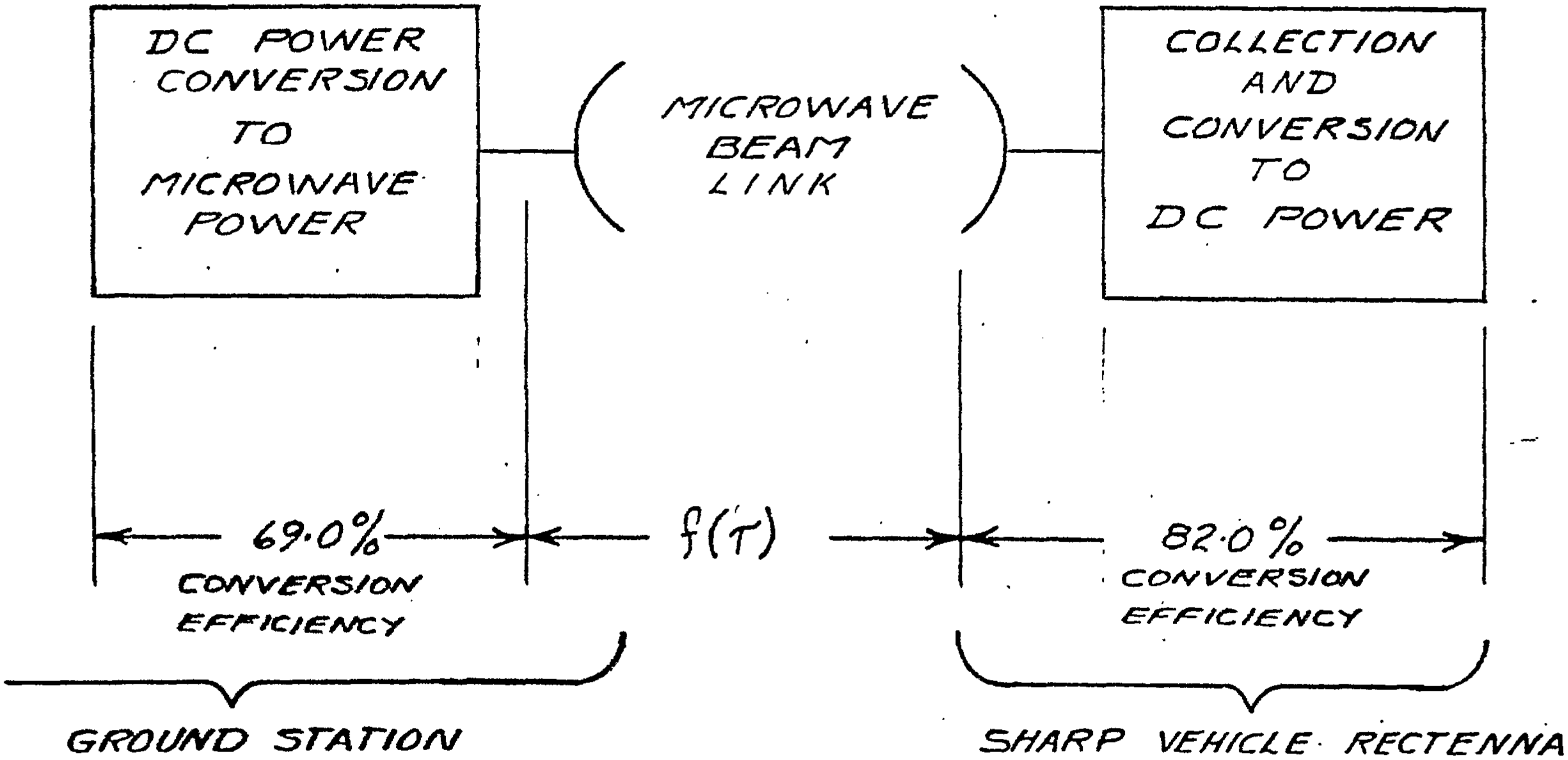
Also, note that the curves in Figure 2 seem to vary asymptotically with S. That is, the reduction in P_{total}/S in going from $S = 20\ m^2$ to $40\ m^2$ is much greater than in going from $40\ m^2$ to $60\ m^2$. This is because the required lift for level flight at a given U becomes proportional to S at the larger S values. That is, the fixed onboard mass becomes a smaller percentage of the airframe mass which is proportional to S. Thus, the drag and propulsive power, at a given U, also become proportional to S. Since $P_{total} \approx$ propulsive power for the larger S values, P_{total}/S approaches a constant value with increasing S.

Finally, note that the highest value of P_{total}/S is 300 W/m^2, which occurs when the $S = 20\ m^2$ airplane is flying at 60 m/s. As a relatively short-duration emergency situation, this appears to be comfortably within the latest capabilities of microwave power. Further, at U = 42 m/s, P_{total}/S drops to 200 W/m^2.

MICROWAVE POWERING SYSTEM

The microwave power transmission system consists of three major elements, as shown in Figure 3; The Ground Station which is comprised of the microwave power source and the ground transmission antenna, the Reception element which is mounted on a suitable surface of the SHARP vehicle. This element has been developed by Raytheon and is called a rectenna (receiving/rectifying antenna). Thin film printed wiring rectennas have been demonstrated with a power handling capability of 200 W/m^2. The Transmission element, which is the microwave beam link between the ground station and rectenna. Transmission tests performed by JPL at Goldstone (reference 4) demonstrated reception of microwave power densities of greater than 600 W/m^2.

The microwave transmission system frequency was 2.5 GHz, which is almost optimum for operation through heavy precipitation, and is the frequency at which all the microwave power transmission work including substantial systems testing and component development has been carried



MICROWAVE POWER
TRANSMISSION ELEMENTS
(4)

FIG. 3

out in the United States[2]. The transmission efficiency of the microwave link is usually given as a function of τ, illustrated in Figure 4. The parameter, τ, is related to the SHARP geometric parameters by the following relationship:

$$\tau = (A_t\ A_r)^{1/2}/\lambda D \qquad (1)$$

where A_t = Transmitting Antenna Area, m^2, part of the Ground Station

A_r = Receiving Antenna Area, m^2, part of the vehicle - the rectenna

λ = microwave length; 0.122 m @ 2.45 GHz

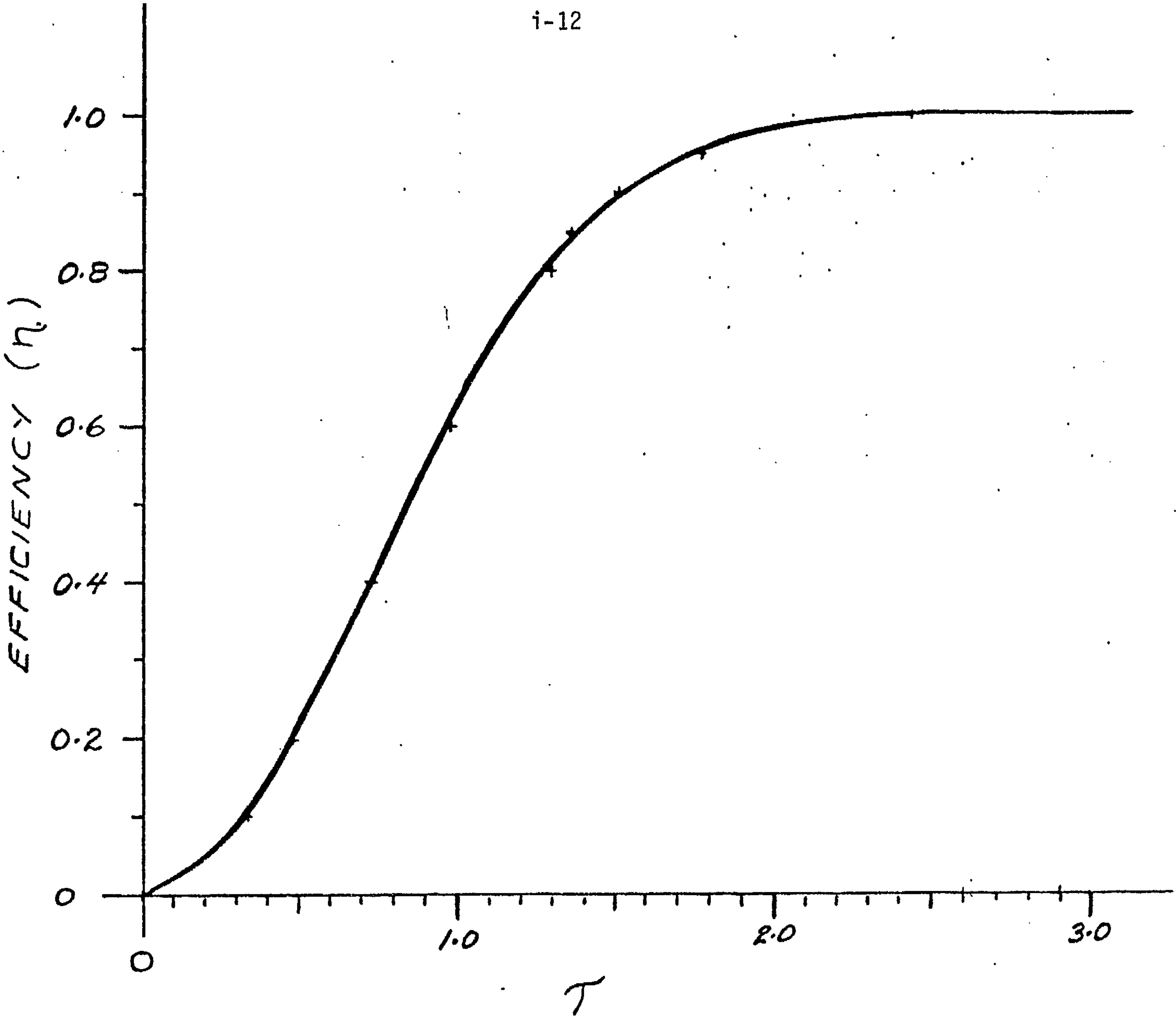
D = distance between A_t and A_r, m, the operational altitude

A relationship between the transmitting and receiving antenna size is seen if Equation (1) is rewritten in the form:

$$\frac{(\tau\ \lambda\ D)^2}{A_r} = A_t \qquad (2)$$

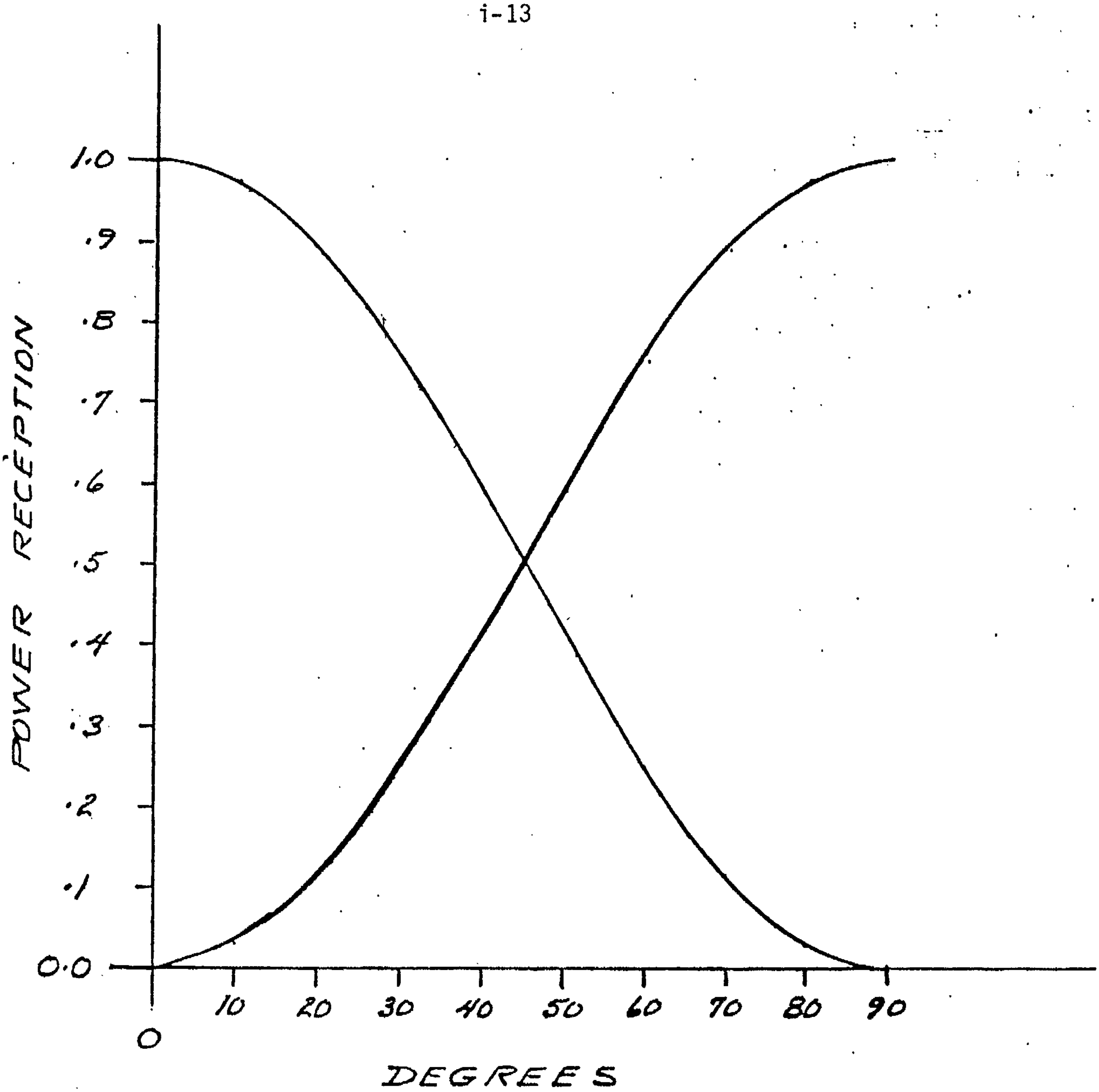
For a given vehicle configuration, the receiving antenna, the rectenna, size is determined. The transmission antenna, A_t, size is determined by the distance and the efficiency of transmission. A reasonable antenna size can be conceived if the efficiency is not required to be close to 1.0.

The second element, the collection and conversion of the microwave beam to DC power is accomplished by the rectenna. Presently, the rectenna has been developed to the state where it is suitable for use on a SHARP vehicle by the use of thin film rectennas. Design, analysis and testing has progressed to the point where highly efficient conversion to DC power is possible. It should be noted that rectenna orientation is critical to the efficient reception of power. In the case of linear polarized antennas, if the polarization angle between the rectenna and the ground station varies, the power received will decrease as the cosine squared of the angular difference, see Figure 5. Consequently, it may be desirable



FRACTION OF TRANSMITTED MICROWAVE POWER THAT IMPINGES ON RECTENNA AS A FUNCTION OF THE PARAMETER τ (5)

FIG. 4



RECTENNA POWER RECEPTION Vs
POLARIZATION EFFECT FOR TWO RECTENNAS
(1)

FIG. 5

to consider providing dual rectennas each aligned 90^0 apart on the vehicle or to transmit and receive circularily polarized waves. In this manner, full power may be provided at any orientation angle, in spite of the weight penalty.

The results of current research, particularly studies of the non-thermal and non-linear effects of low level radiation, appear to be leading not only toward enforceable safety standards for workers exposed to risks, but also to increased biological knowledge that may prove the basis for medical advances. In Canada, the present standard is 1 mW/cm^2 for the general public, averaged over one minute (reference 8). The exposure level that might be experienced by the passengers commercial aircraft passing through the beam would exceed this level outside the aircraft. However, the aircraft structure and duration of exposure would be within the recommended exposure levels.

If the present levels are found to be unsafe in the future, then additional measures would have to be taken to insure the well being of the general public.

RECOMMENDATIONS

Further study and preliminary demonstration of the feasibility of the selected Stationary High Altitude Relay Platform (SHARP) concept should proceed in stepwise fashion as follows:

1.0 Demonstrate, in Canada, the transmission of power via microwave by setting up ground based equipment uitlizing readily-available transmission equipment and a state-of-the-art rectenna (receiving antenna/rectifier) procured from Raytheon, U.S.A. This could be extended to the airborne case by using a remotely controlled dirigible.

2.0 Design, construct and flight test a scaled version of the ultra-light SHARP airplane using a conventional electric model airplane motor and remote control equipment. This would include a comprehensive engineering study of the full scale SHARP airplane structural configuration, weight, materials, etc.

3.0 Demonstrate microwave powered flight by utilizing the equipment assembled for recommendations 1.0 and 2.0. The rectenna would be mounted to the underside of the SHARP model.

4.0 Further investigate the characteristic wind speeds and duration at the altitude of interest (21 km). It is particularly important to obtain continuous statistical data on wind speed at those periods of the year (January) where the most severe conditions are expected. This could be obtained using a special weather radar which measures the back-scattered energy from air molecules at the altitude of interest; or perhaps, by the launch and tracking of balloon probes controlled to maintain a constant, 21 km, altitude.

5.0 Further engineering study of several issues is required:

- cost trade off analysis of the alternative microwave power transmission systems

- preliminary definition and cost estimates of the required strategies for the SHARP
  - ascent/descent aspects of the mission
  - altitude, attitude and geographic position control while on-station

Subject to favourable outcome of all of the above, a full scale flight demonstration will be required.

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1.0 INTRODUCTION

This report of the preliminary findings of the study of Stationary High Altitude Relay Platforms (SHARP) has been performed under contract to the Department of Communications, Communications Research Centre, Ottawa.

The report is preliminary from the standpoint that it is a concept feasibility study only. The analysis is based on the known environmental factors and an evaluation of the state of the art of relevant technologies. It will be readily appreciated that additional studies will be required to resolve technical problems of developing a SHARP in a cost effective manner.

In this report, the major factors affecting the feasibility of the concept of SHARP will be considered. These factors are: wind velocities at operating altitudes of 20-40 km, availability of power to maintain a SHARP in a wind regime of these altitudes in a quasi-stationary position relative to the earth, and the physical configuration of SHARP required to maximize the platform's endurance.

Each of these major factors and others shall be addressed separately in the following sections to an extent that will be concise, yet comprehensive.

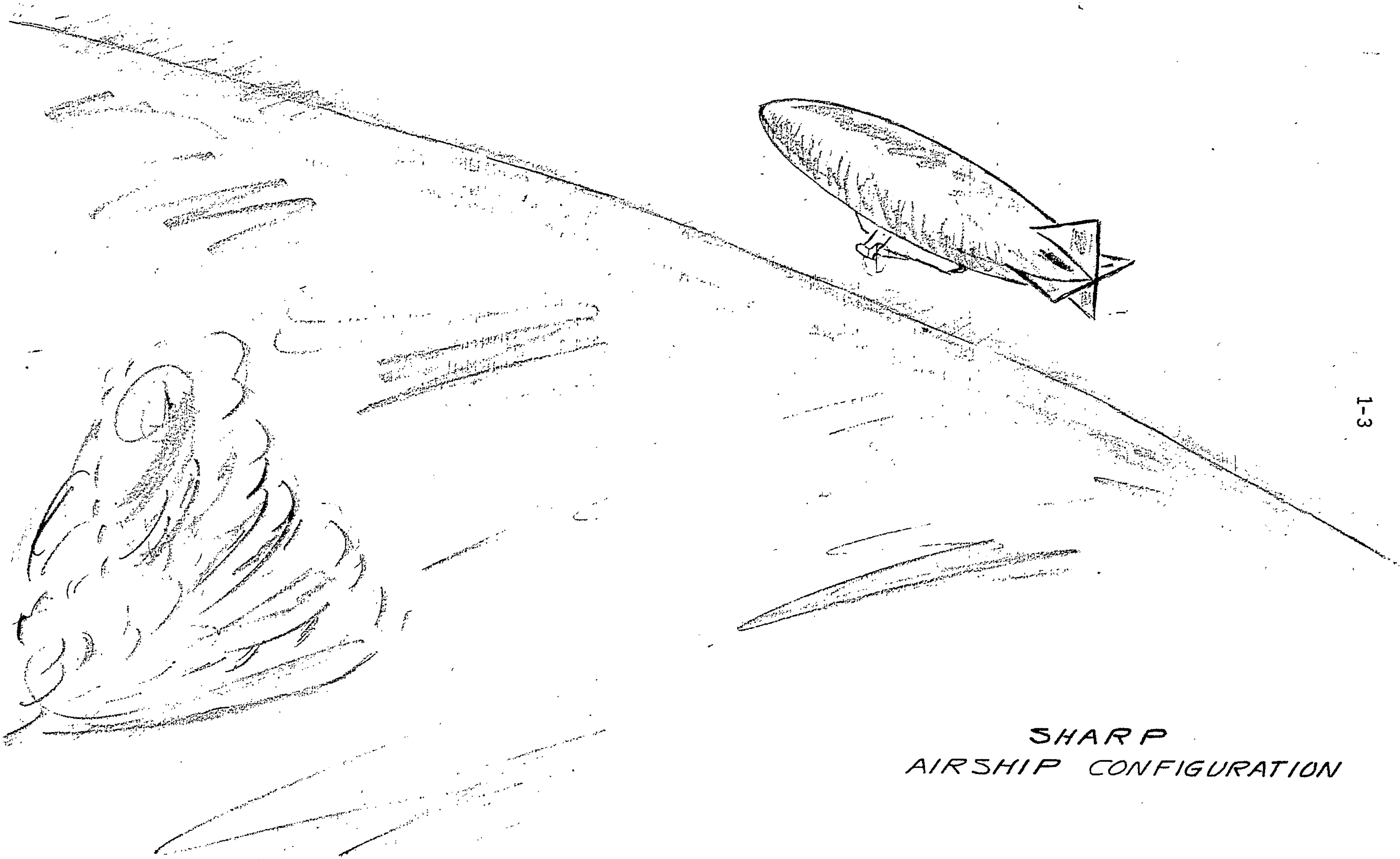
During the initial investigation into the feasibility of a SHARP, it was apparent that much effort has been done and is continuing in the United States on similar platforms.

The literature search indicated that, for a Canadian platform development and application program, two areas would have to be addressed anew. The first was the upper atmospheric winds analysis for Canadian latitudes and the second was the most appropriate platform configuration for these latitudes and possible communications applications. The availability of appropriate materials, power transmission and reception by microwave, photo voltaic cell availability, and characteristics would be largely dependent on state of the art from the United States technological development in these areas.

The concentraion on the Canadian atmospheric conditions is self evident. The Canadian climate is especially severe in winter which has a dramatic influence on launch techniques and materials from which the platform may be constructed. Further, early investigation revealed that although upper atmospheric data is available, it is not in a form that may be readily usable for this project. Data on upper atmospheric conditions such as wind velocity, duration of wind velocities, rate of change of velocity, and direction are not available. The existing data was compiled such that an insight into the conditions of the Canadian upper atmosphere was obtained.

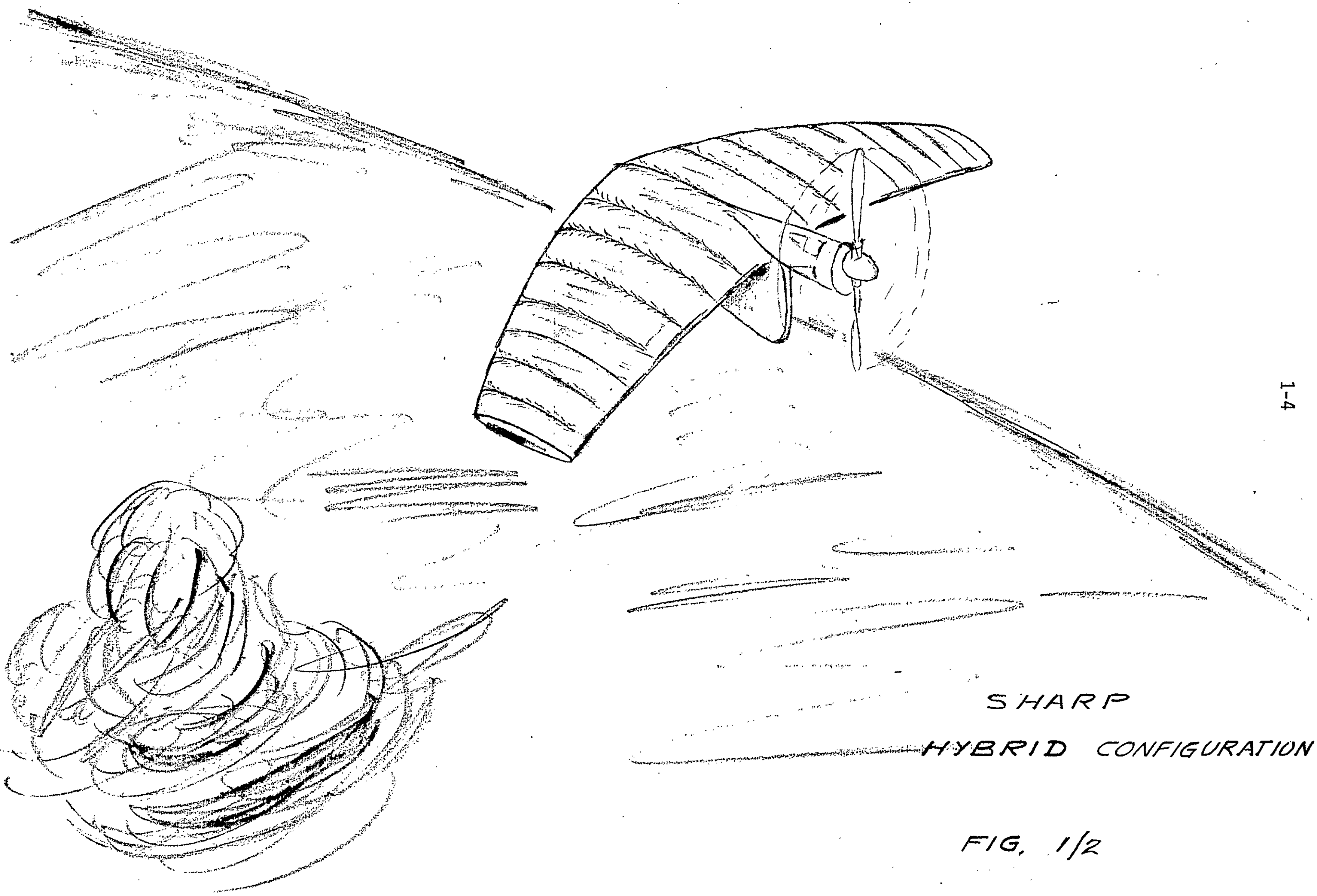
The vehicle configuration and analysis was performed by Dr. J. De Laurier of the University of Toronto, Institute for Aerospace Studies. Early discussions resolved that the configurations should be limited to types of vehicles that are well within the technological capability of Canada to develop and operate in the near future. The configurations chosen are the traditional lighter-than-air ship (reference Figure 1/1), a non-conventional hybrid lighter-than-air ship that combines attributes of the lighter-than-air ship with an aerodynamic lifting body (reference Figure 1/2), and a conventional aircraft shape (reference Figure 1/3).

The main thrust of this report will concern itself with the analysis of the Canadian upper atmospheric environment, the winds and solar radiation, the platform vehicle characteristics and the power required for station-keeping.



SHARP
AIRSHIP CONFIGURATION

FIG. 1/1



SHARP

HYBRID CONFIGURATION

FIG. 1/2

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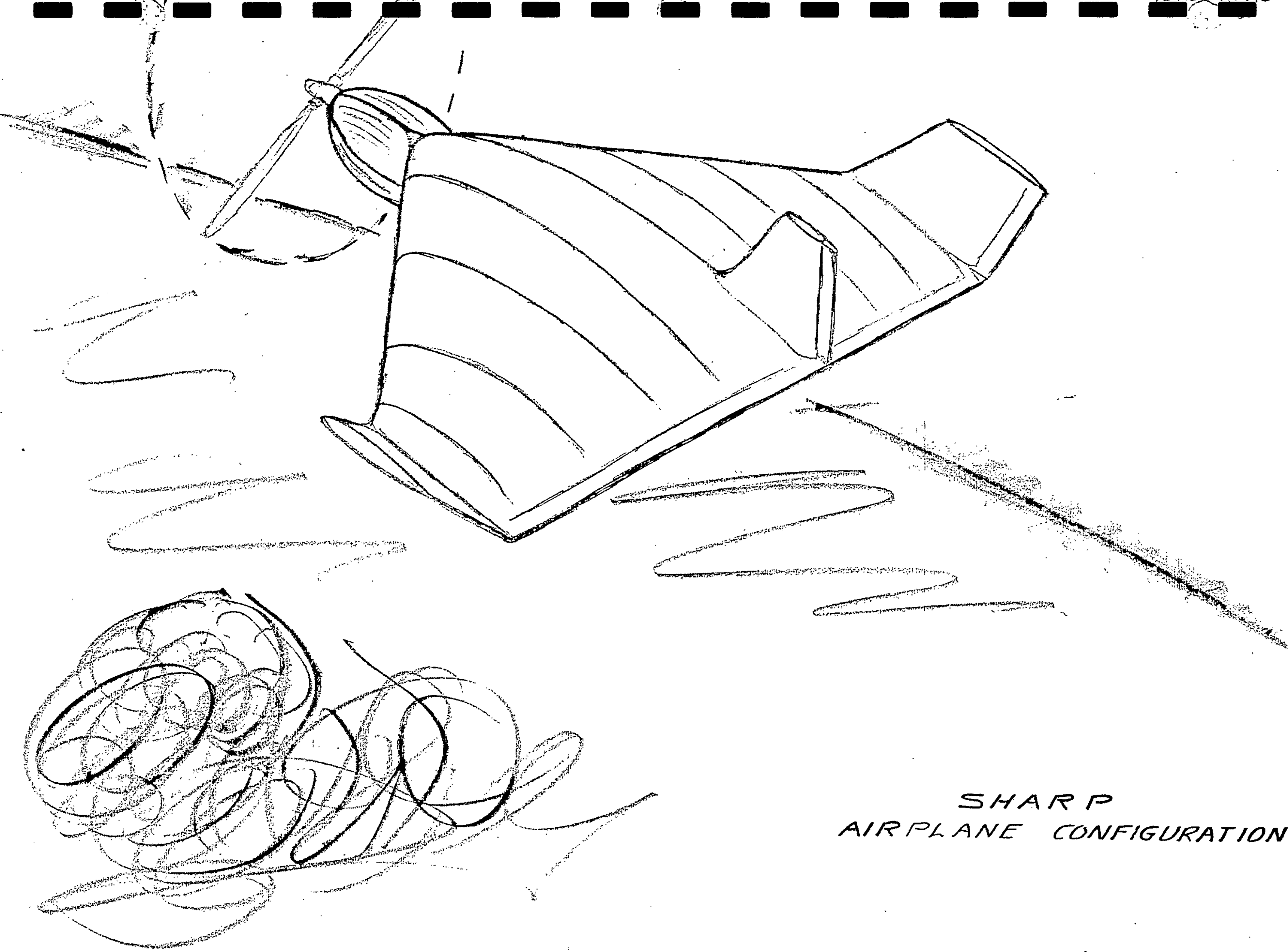


SHARP
AIRPLANE CONFIGURATION

FIG. 1/3

2.0 SUMMARY OF RESULTS

A summary of the principle results from this study which significantly influence the feasibility of the SHARP concept are presented below.

2.1 Aerophysics Environment - Winds

(i) A preliminary examination of wind data for the years 1963, 1969, 1970, and 1975 at two southern and two northern locations has revealed that wind speeds are, on average lower at 21 km than at alternate operating altitudes. For this limited sample, the following maximum and highest monthly average wind speeds were measured at an altitude of 21 km (which is a pressure regime of 50 mb).

Location	Max Speed Recorded (m/s)	Highest Monthly Average average (m/s)
Northern Locations		
Churchill, Manitoba	57	14
Fort Smith, NWT	68	15
Southern Locations		
Edmonton, Alberta	42	17
Trout Lake, Ontario	53	14

The SHARP vehicle operating during the winter over these locations must be designed to remain on station in the presence of winds which occasionally exceed 50 m/s, with the winds reaching higher maxima at the northern locations.

(ii) The SHARP vehicle operating during the spring/summer period over these locations will fly in winds which seldom exceed 10 m/s. Indeed, it is observed that winds generally change direction by up to 180° at or about this altitude range, going through a minimum speed approaching zero. Operation of the SHARP vehicle in the spring/summer period could take advantage of these wind speed characteristics to minimize the needed propulsion power.

2.2 Key Technical Factors

It has been found that three recent technical advances make it feasible to consider flying platforms at altitudes of 21 km for extended periods of time. These key technical advances are:

(i) The design and demonstrated performance of very lightweight and yet very airworthy unconventional aircraft (i.e. the Solar Challenger). In this report, the characteristics and performance of a suitable aircraft for the SHARP mission have been calculated. (This aircraft has been termed SHARP-I). In operation, the aircraft would circle (if the wind speeds were low) or maneuvre upwind (if wind speeds were higher than the aircraft stall speeds).

(ii) The demonstrated capability to efficiently convert high level microwave power into electrical energy. This advance by the Raytheon Co. (US), using devices known as rectennas, makes it feasible to power a SHARP aircraft from the ground, using a steerable beam of microwaves. (The effective weight of specially fabricated rectennas is only about one kilogram for power conversion capability up to one kilowatt, and the conversion efficiencies are as high as 82%.)

(iii) The demonstrated performance of very efficient brushless electrical motors with very high power to weight ratios (of about 0.5 kw/kgm). Such motors have been developed and used on the Solar Challenger aircraft.

2.3 Comparison of SHARP Vehicle Performance

2.3.1 Types of SHARP Vehicles

Three types of vehicles were investigated to assess their suitability for the SHARP communications mission of altitude of 21 km:

(i) Neutrally-buoyant and Aerodynamic Airships

(ii) Hybrid vehicle (i.e. winged balloon)

(iii) Unconventional aircraft

(i) Propulsive Power for Lightweight Mission

It was found that an unconventional, lightweight aircraft is most feasible for early application in Canada, for lightweight communication payloads (60 kgm). For example, the propulsive power was calculated to be significantly lower for the aircraft than for other types of vehicles. For operation at wind speeds of 60 m/s:

Vehicle	Volume (m^3)	Wing Area (m^2)	Propulsive Power (kW)
1. Airplane (Solar Challenger Type)	-	39	10
2. Hybrid Vehicle (Wing-Balloon)	29 -	- -	23 23
3. Aerodynamic Lifing Airship	366	-	19
4. Neutrally-Buoyant Airship	24075	-	315

(ii) Onboard Reserve Battery Power

In the case of the airships, it was found that providing reserve (battery) powering, for one hour of flight (without microwave powering) increased the volume by a factor of ten and increased the propulsive power by a factor of five. In the case of the aircraft, it was found that providing reserve (battery) powering for one hour of flight increased the wing area and propulsive power fractionally at lower structural wing loading. As the wing loading increased, the wing area and propulsive power increased to unacceptable levels. The addition of reserve (battery) powering will be required, however, the duration of power will be less than a Δt of one hour making it feasible to construct a vehicle.

3.0 SHARP COMMUNICATIONS MISSION (BASED ON WORK BY LILLEMARK AND JULL)

3.1 Introduction

The SED/UTIAS study has not concerned itself with analysis of the costs and benefits of using SHARP for relaying various types of telecommunications services. Indeed, until the performance of particular types of SHARP vehicles is known through demonstration, it will not be possible to confidently evaluate communications relay applications of SHARP systems as a complement to existing terrestrial and satellite networks.

In the meantime, DOC has developed preliminary communications mission concepts, based on known general characteristics of SHARP relay platforms. These general characteristics are:

(i) The radius of coverage of one SHARP platform is somewhat greater than 500 km, for an operating altitude of 21 km. (This would permit one SHARP to provide communications over an area about 40 times greater than a 350 meter high tower, or over a large fraction of a prairie province.)

(ii) It is readily appreciated that within its coverage area, transmission to a relay platform would be over line-of-sight paths which are considerably shorter than terrestrial-satellite paths (i.e. ranging from about 40 to over 1000 times shorter). Thus, for point-to-point communications in particular, the powers needed for reliable communications and hence costs and sizes of transmission equipment for SHARP relay, would be significantly lower than for satellite relay. Indeed, they are also potentially lower than for terrestrial relay for other than line-of-sight paths.

(iii) It is foreseen that SHARP relay applications will be constrained by the following characteristics:

(1) The platform will move slowly about within a station-keeping volume. In the case of an aircraft SHARP, this volume will likely be about 2x2x2$(km)^3$ in size.

(2) Again, in the case of an aircraft SHARP, the vehicle will circle when wind speeds are less than about the stalling speed. Thus, omni-directional communications antennas are likely to be most suitable, at least initially.

(3) Further, in the case of the initial application of an aircraft SHARP, the proposed communications payload weight will likely be low (i.e. not greater than 60 kgm). This will help to ensure that the primarily objective of "maintaining station" under all foreseen wind conditions is more easily achieved. Therefore, using only one SHARP aircraft, only a small selection of services requiring only lightweight (i.e. solid state) equipment is feasible in the near future.

(4) In the case of the airship SHARP, in principle the weight limitations on payload are much less critical. For example, from the SRI study (Reference 1, below) it is noted that an airship with the capability of ATS-6 (payload weight of 720 kgm) is calculated to have a volume about three times greater than that of a small airship, with a capability of the Japanese Broadcast Satellite (payload weight of about one fifth of that of the larger airship at 130 kgm). However, in practice, the airship SHARP is not attractive for Canada. The feasibility of launching and maintaining on station a large low density airship does not appear to be easily achievable at Canadian latitudes within the next decade.

(5) The communications equipment on the SHARP platform must operate in the presence of very high microwave fields needed to power the platform (the levels of these fields are between 20 and 400 watts/m^2 at the powering frequency of 2.45 GHz).

3.2 Possible Communications Services

Based on the foregoing, the following are considered to be strong service candidates for initial and extended future SHARP missions. For this study the power levels, frequency bands, antennas and cost estimates are to be considered as design objectives only.

3.2.1 Broadband Services (TV and Data)

(i) Initially: For 14/12 GHz TV broadcasting with one or two channels per SHARP aircraft

A/C transponders:	5 watts/channel (solid state)
A/C antenna:	wide angle horn
Ground TVRO:	0.25 to 1m. diameter antennas (Cost <$1000)

Later, in heavier weight missions:

(ii) For 14/12 GHz TV/Data Incasting

(A/C transponders as above (i))
Ground Tx: 5 watts/channel
.25 to 1 m. diamter antennas

(This option has application to TV program incasting, two-way telemedicine, teleducation and teleconferencing.)

(iii) For 14/12 GHz Data Broadcasting

(This option could be used for full TV bandwidth, interactive Telidon.)

(iv) For UHF TV Broadcasting on two channels

A/C Transponders:	6 KW /channel
Ground TVRO:	10 element YAGI antenna

3.2.2 Narrowband Services (Voice and Data)

For Mobile Radio Telephony and Data Services at 800 MHz

(a) From base stations to mobile sets:

A/C transponder:	1.25 MHz bandwidth
	100 watts total power

(b) From mobile sets to base stations:

A/C transponder:	1 watt/channel
	10 MHz passband

The system as defined above could be compatible with either of two proposed systems at 800 MHz:

(i) Automatic Mobile Phone Service (AMPS) with 40, two-way FM channels (as proposed by AT&T and Bell Canada)

(ii) Terrestrial or satellite-based systems with 250, two-way SSB channels (as under study in the US and Canada)

SECTION 3.0 REFERENCES

(1) High Altitude Powered Platform Cost and Feasibility Study
J.W. Sinko, SRI Project 5655-502.

4.0 AEROPHYSICS

4.1 Introduction

The purpose of this section is to define the limits of investigation of the aerophysical aspects of this study and to briefly examine the impact of each aerophysical aspect on the SHARP operation.

For the purposes of this study, the following aerophysical qualities of the upper atmosphere in the altitude range of 18.5 km to 30 km (70 to 10 mb) will be examined. The winds throughout the year, the expected solar isolation, the temperature profile, and the cooling capacity of the atmosphere. Each of these aerophysical qualities has a significant impact on the SHARP mission and will be examined in greater detail in the following paragraphs.

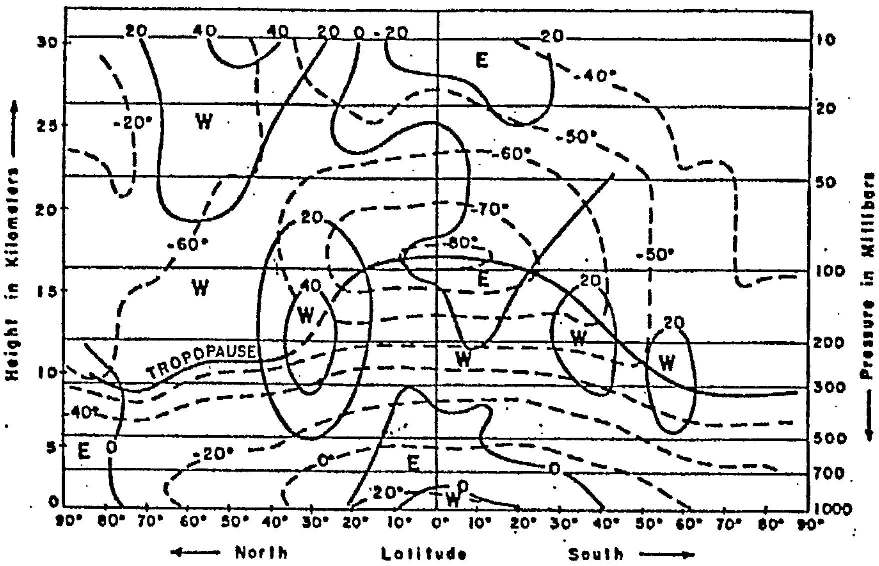
4.2 Wind

The success of the SHARP vehicle on station to perform expected missions, either extended or short duration, is dependent on the ability to null out the prevailing winds. The two contributors to the power requirement is the propulsion system and the on board systems. The existence of upper atmospheric winds requires a propulsion system to hold the platform within a station-keeping volume with respect to the ground. To reduce the propulsion power requirement, it is desirable to seek out operational altitudes where the winds are minimum.

Investigation of published data on the nature of the Upper Atmospheric winds revealed the general character of the wind. The general character of the winds is shown in Figure 4.1/1.a and 4.1/1.b. The most significant features of these figures are:

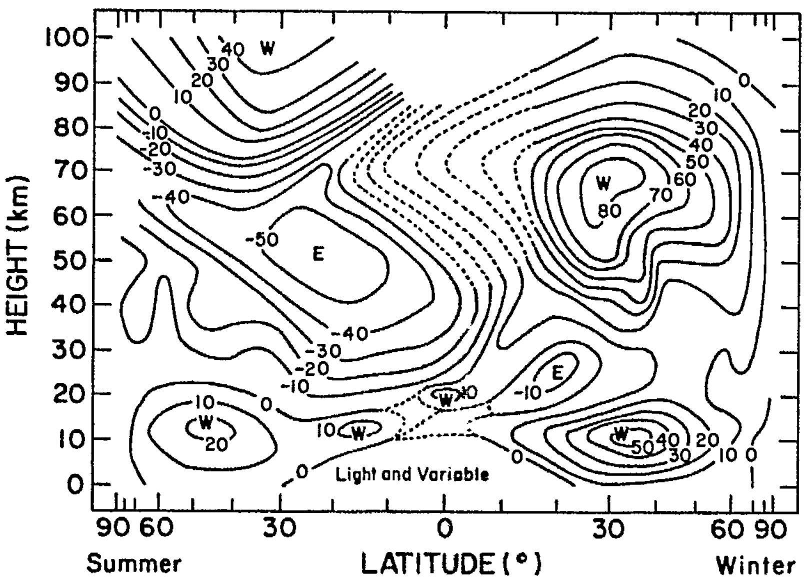
- the existence of a stratum of low wind velocities at 20 km altitude.
- the strong westerlies of higher altitudes in winter.
- the strong easterlies of higher altitudes in summer.
- the domination of the westerlies in the mid-latitudes, summer and winter, in the 10-25 km altitude range.

The data presented in this report has been taken from the Atmospheric Environment Service monthly bulletins for the Canadian Upper Air (3). The data selected to be reduced from these bulletins was for Upper Air Stations; Edmonton, Alberta; Fort Smith, N.W.T.; Churchill, Manitoba; and Trout Lake, Ontario. The selection of these sites (from the Canadian network) will present a picture of the upper winds over the heart land of Canada, reference Figure 4.2/2.



Mean vertical cross section of wind and temperature at 75°W longitude for January 1958. Temperature in degrees Centigrade, wind in meters/second. Adapted from U.S. Weather Bureau, "Monthly Mean Aerological Cross-sections," U.S. Govt. Printing Office, Washington, D.C., 1961. (1)

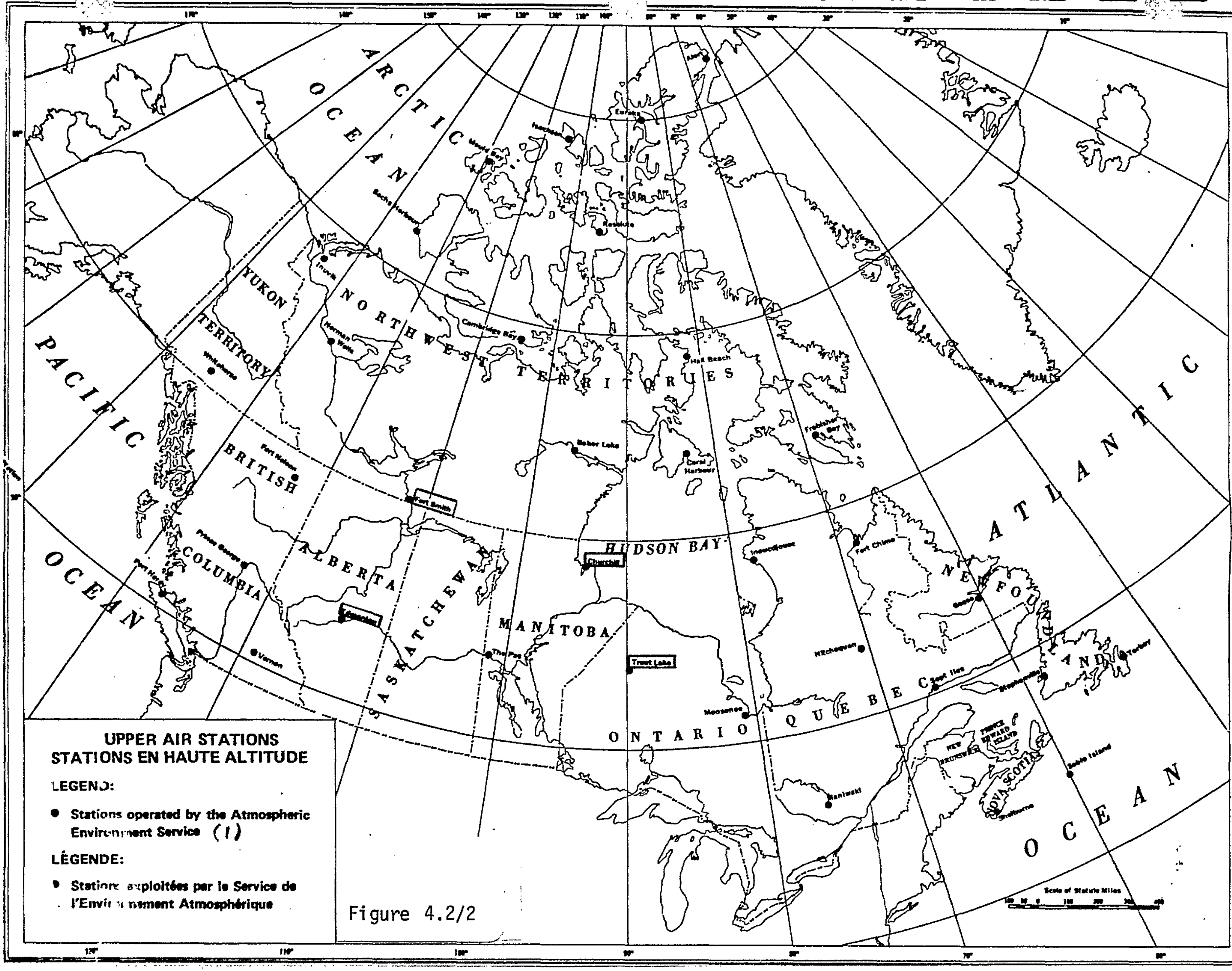
Figure 4.1/1.a



Mean zonal wind in summer and winter, after Palmén and Newton (2)

Figure 4.1/1.b

FIGURE 4.1/1 VERTICAL CROSS SECTION OF WIND VELOCITY



UPPER AIR STATIONS
STATIONS EN HAUTE ALTITUDE

LEGEND:

- Stations operated by the Atmospheric Environment Service (*l*)

LÉGENDE:

- Stations exploitées par le Service de l'Environnement Atmosphérique

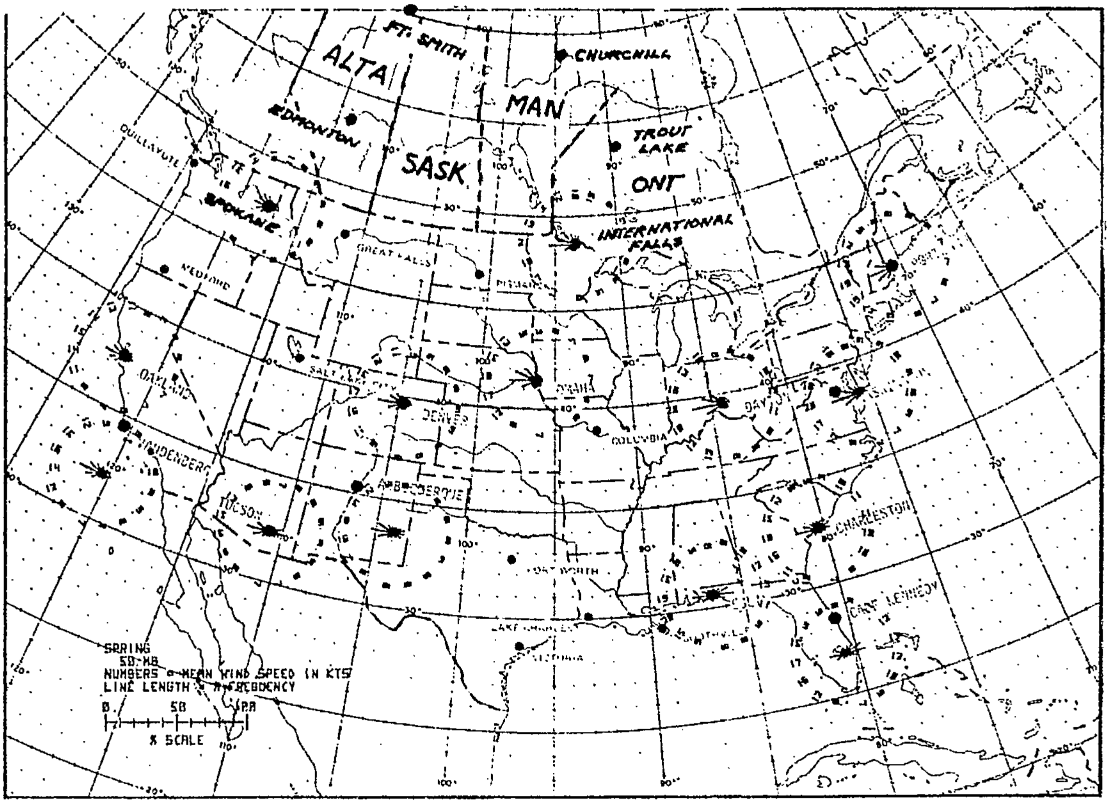
Figure 4.2/2

At the altitude levels of interest, the winds are nearly horizontal and in general they are nearly zonal, i.e. from either east or west (2). Significant to the long duration, SHARP mission is the interim period between the established summer/winter winds which are not as strong but are subject to change in direction.

Extensive studies of the upper atmospheric wind performed in the United States for use as a guideline in high altitude platform design (4), indicate a significant reduction of wind velocities in the 50 mb altitude. Figure 4.2/3 and 4.2/4 give a continental overview of the wind direction in the United States. Included on the maps are the Canadian sites chosen. It is plausible to assume that the wind regimes for Spokane and International Falls in the United States would be similar to those over Western Canada. Figures 4.2/5 and 4.2/6 show the seasonal wind variations for the 50 mb altitude.

Due to the time constraints and the format in which the data is presented in the monthly bulletins, the following method was used to determine the wind profiles. Three years, 1963, 1969, and 1975 were selected from the published monthly bulletins from 61 through 76. For each site, the maximum and minimum wind velocity and air temperature was recorded for 00 and 12 GMT at pressures from 70 to 10 mb. The maximums and minimums were used to find the mean wind velocity. A table of maximum velocities was also recorded. These tables are shown in Appendix C, Tables, C.1 through C.18.

From these tables, graphs of the mean monthly wind velocities and maximum velocities for each site were constructed, reference Figures C.1 through C.8. From the curves for the mean monthly wind velocities, the 50 mb altitude, for each site, was in general the lowest velocity. The mean wind velocities for the 50 mb altitude



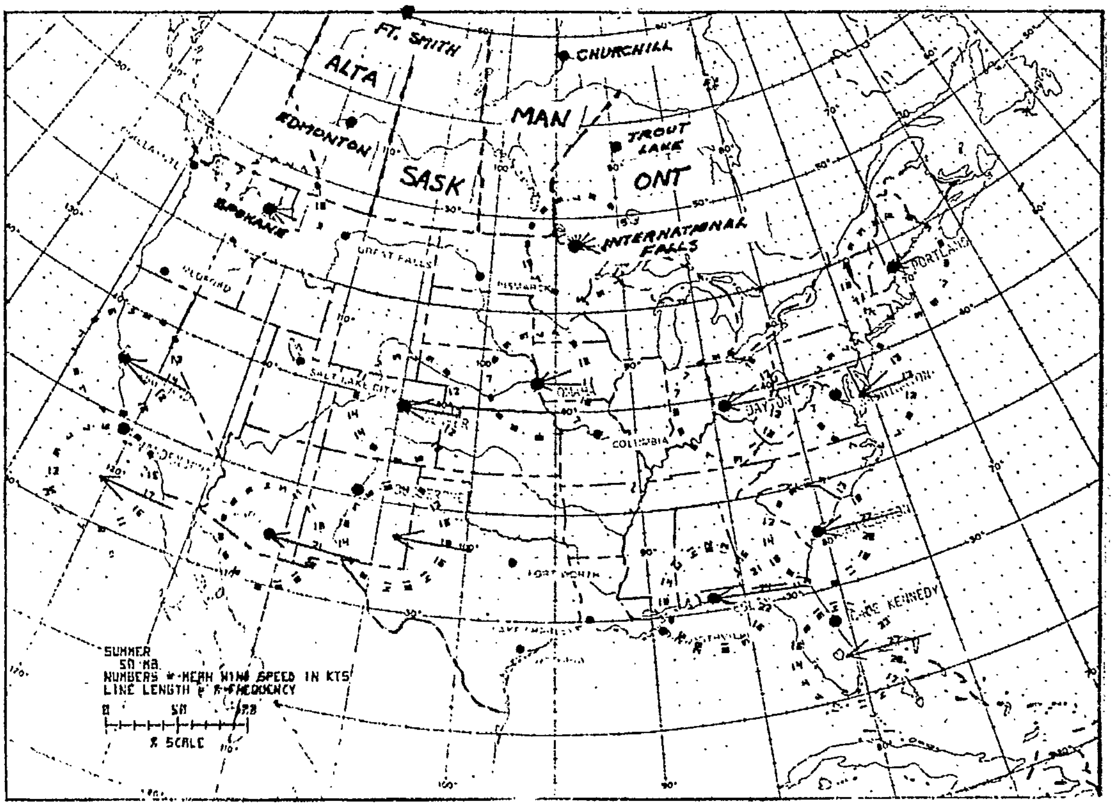
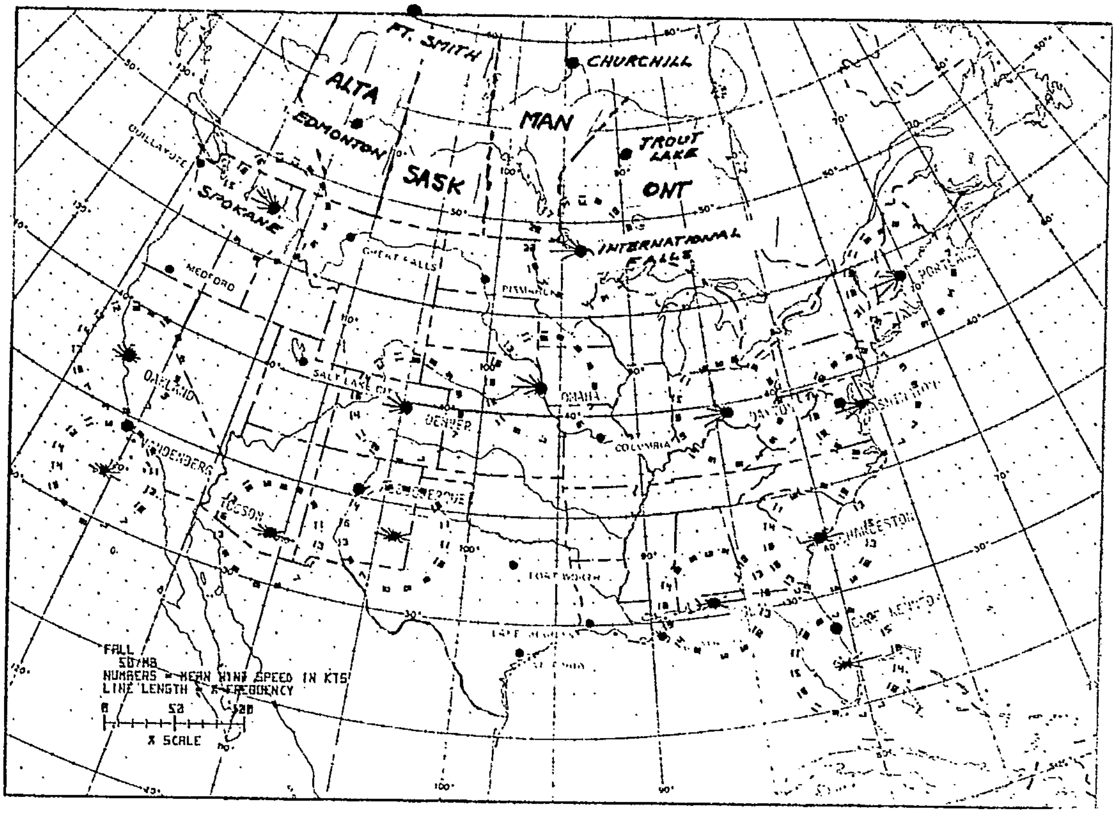


Figure 4.2/3 SPRING AND SUMMER WIND DIRECTION FOR NORTHERN UNITED STATES SITES (1) FOR 50 mb ALTITUDE



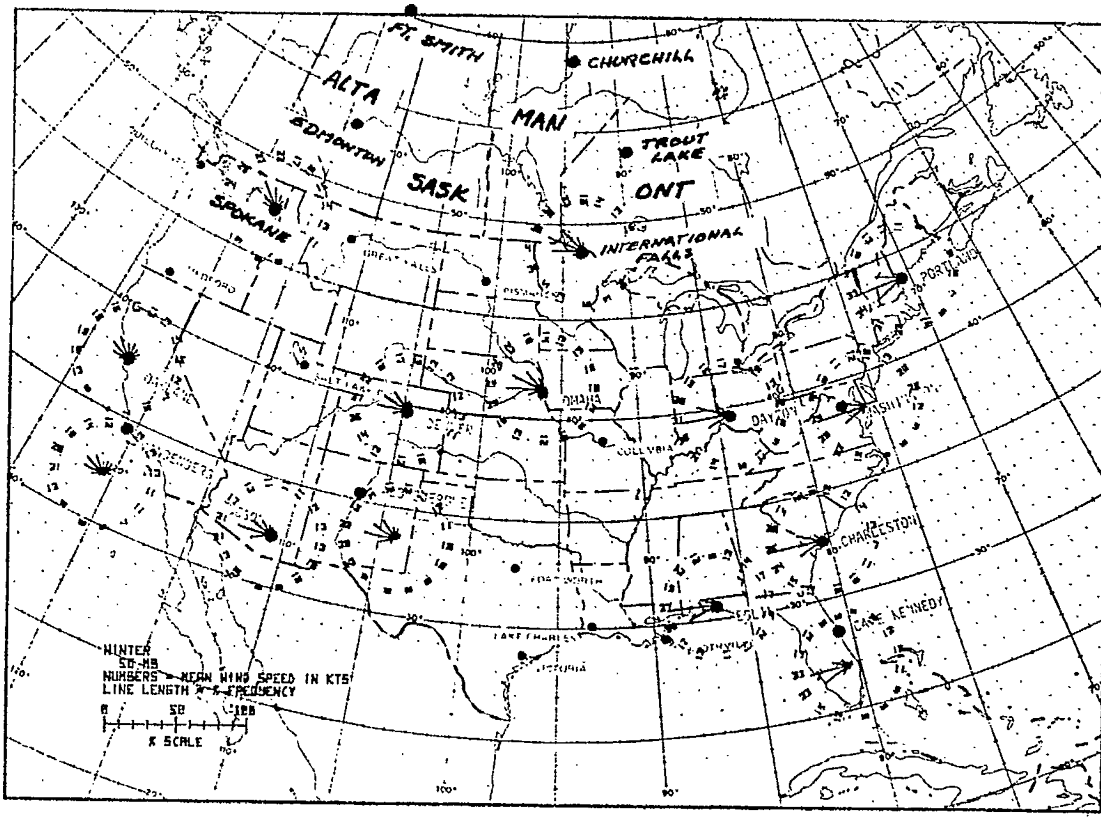


Figure 4.2/4 FALL AND WINTER WIND DIRECTION FOR NORTHERN UNITED STATES SITES (1) FOR 50 mb ALTITUDE

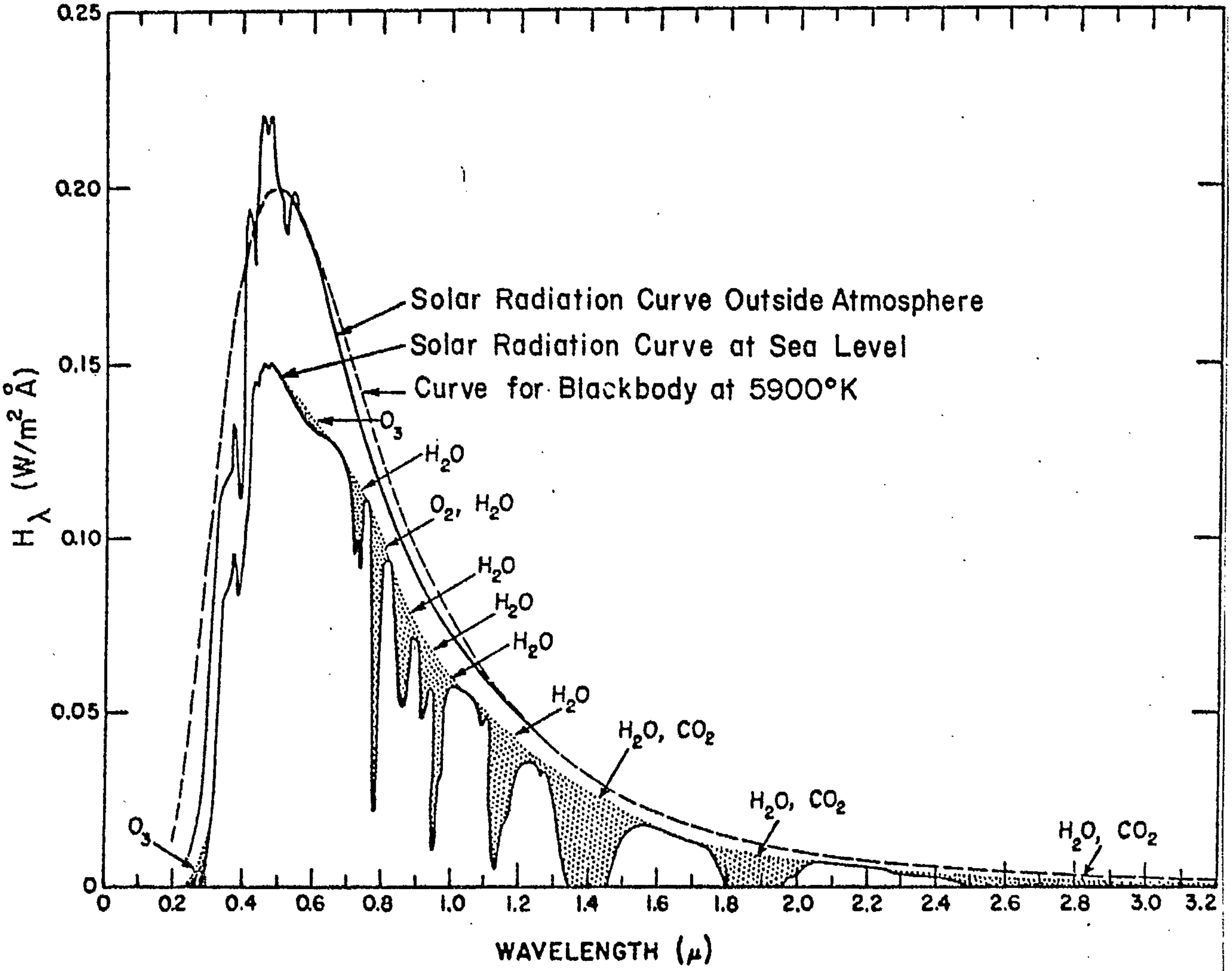
4.3 Solar Insolation

The solar insolation received at an altitude of 18-32 km is of significance to the feasibility of the SHARP. The quantity of solar insolation, i.e. solar energy, may be utilized for the production of electrical power required by the platform. The solar insolation is important because of its potential or actual effect on the platform materials, especially synthetic "plastic" materials.

The solar insolation is comprised in a narrow wave length band between 0.2 and 4μ, as shown on Figure 4.3/1. As is indicated on the figure, the earth's atmosphere absorbs and scatters the incoming solar insolation such that it is attenuated by the time it reached the earth's surface. The establishment of the solar insolation at SHARP operational altitude of 18-32 km is required to evaluate the potential for the use of photo voltaic cells and heating. The effects of absorption and scattering, for the most part, take place below the altitude of 16 km (7). The major exception is the seasonal change of the ozone layer altitude and dry atmosphere effects. Figure 4.3/2.a indicates that the water vapor content is essentially zero above 16 km. Figure 4.3/2.b indicates that above 16 km the attenuation of the solar constant is essentially small. The ratio of the solar irradiance to the solar insolation is approximately 97%.

The solar constant has been evaluated to be $1360^{watt}/m^2$ ($1.95\ cal/cm^2.min$) (6). For the purposes of this study, the more conservative evaluation will be used. Consequently, at the SHARP altitudes, the solar insolation on a surface normal to the earth's surface will receive $1319^{watt}/m^2$ ($1.89\ cal/cm^2.min$) (7).

The transformation of this solar energy into energy utilizable by the SHARP will be addressed specifically in Section 5.4.



Spectral distribution of solar radiation in space and at sea level. (6)

Figure 4.3/1

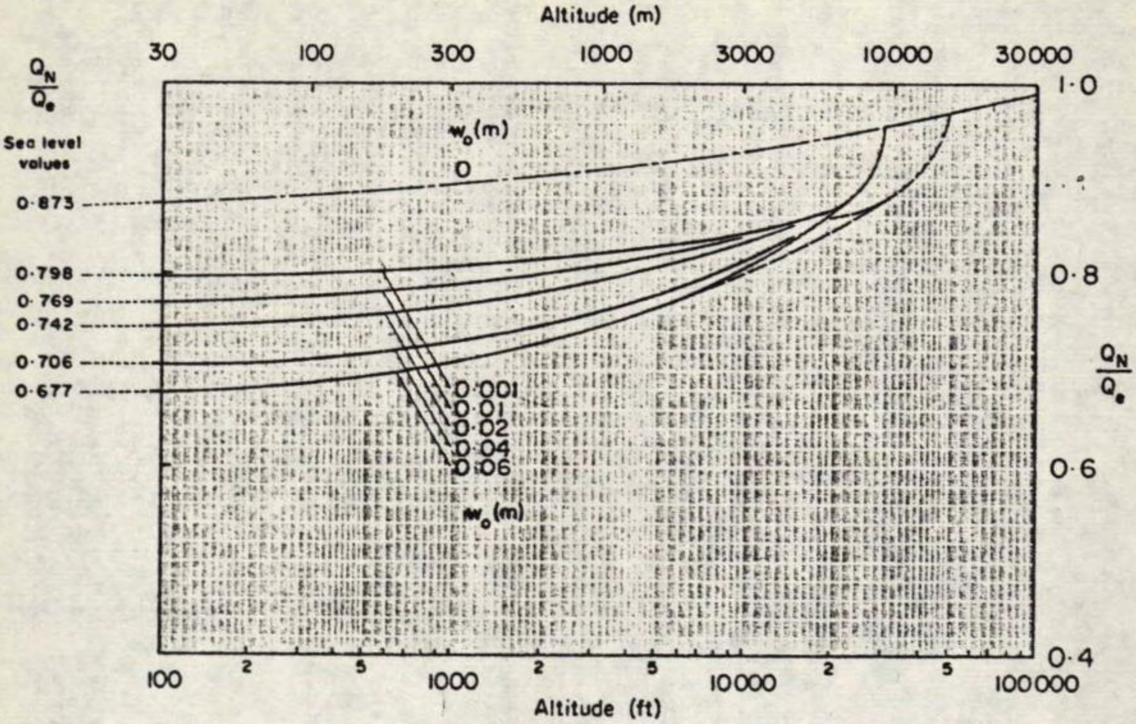


Figure 4.3/2.b TOTAL IRRADIANCE NORMAL TO THE EARTH'S SURFACE

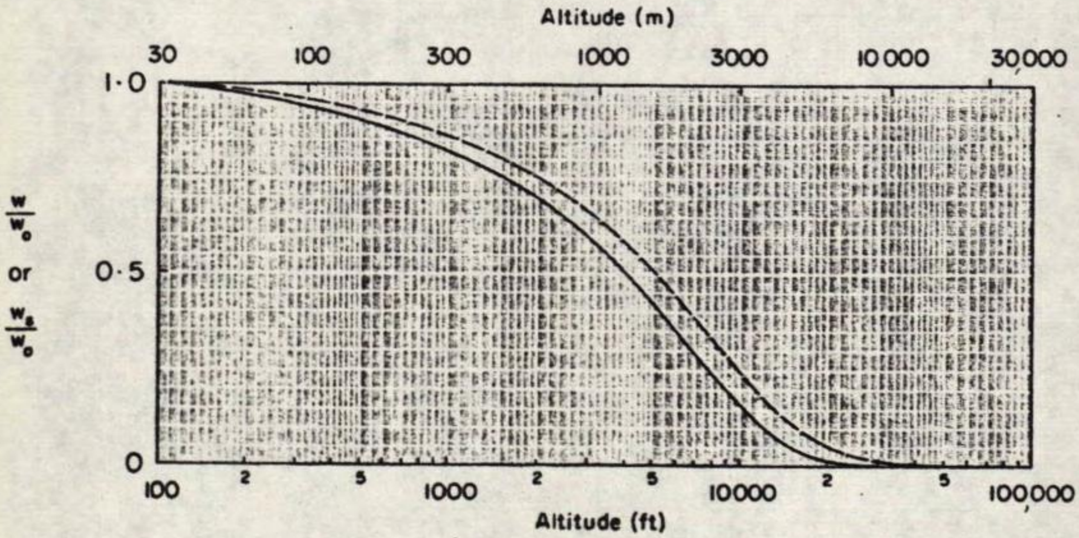


Figure 4.3/2.a ATMOSPHERIC WATER VAPOUR CONTENT

FIGURE 4.3/2

The duration of sunlight hours determines the total amount of solar energy available to the SHARP. Figure 4.3/3 depicts the time of sunrise and sunset for three northern latitudes of 48^0, 56^0 and 64^0 at ground level (8). The additional daylight time, due to the altitude, has been neglected since it only adds an approximate 36 minutes to the duration shown on the figure. These hours will be totally available to the SHARP since it is above the normal cloud altitudes.

With the establishment of the solar insolation at proposed SHARP operational altitude and the hours of insolation available, it is required to estimate the insolation received by a horizontal and vertical surface to be able to estimate the possible energy available to the SHARP. Figures 4.3/4 and 4.3/5 depict the solar insolation variation throughout the year above the atmosphere, and the expected insolation for a horizontal and vertical surface at ground level and at SHARP altitudes respectively. It is apparent that at altitude, an array of photo voltaic cells will receive approximately twice the solar energy as on the earth's surface. These curves will serve as the basis of solar power availability in later sections.

The quality, i.e. the wave length constituants of the solar insolation as shown on Figure 4.3/1, will be very near the spectral constituants as shown for the outer atmospheric condition. For the SHARP, material selection must be consequently play an important role in the platform design. This study does not permit such detailed examination or recommendations, these activities would properly belong in the platform design activity.

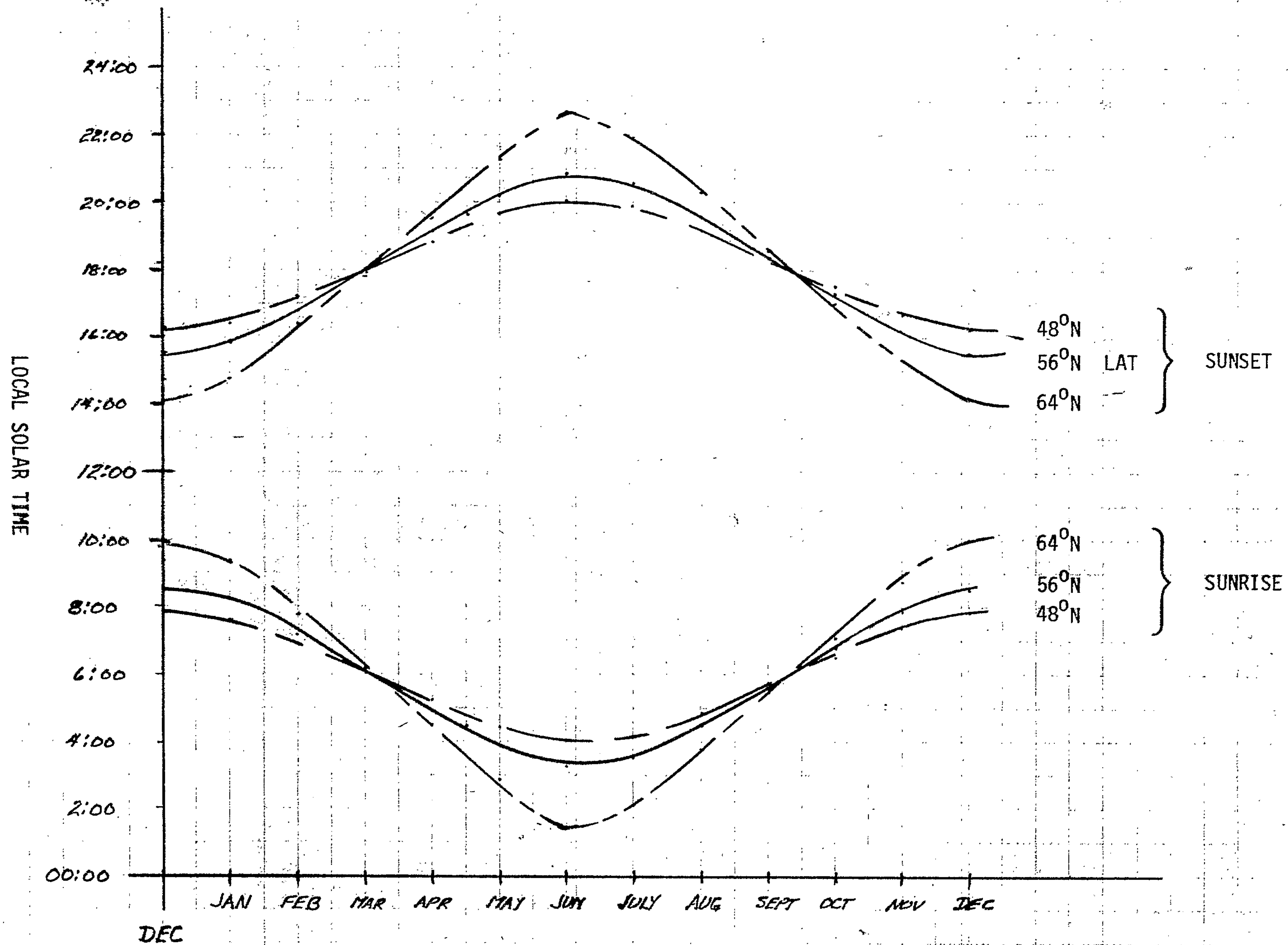


Figure 4.3/3 SUNRISE AND SUNSET TIMES FOR 48°, 56° and 64° N LATITUDE VS MONTH OF YEAR

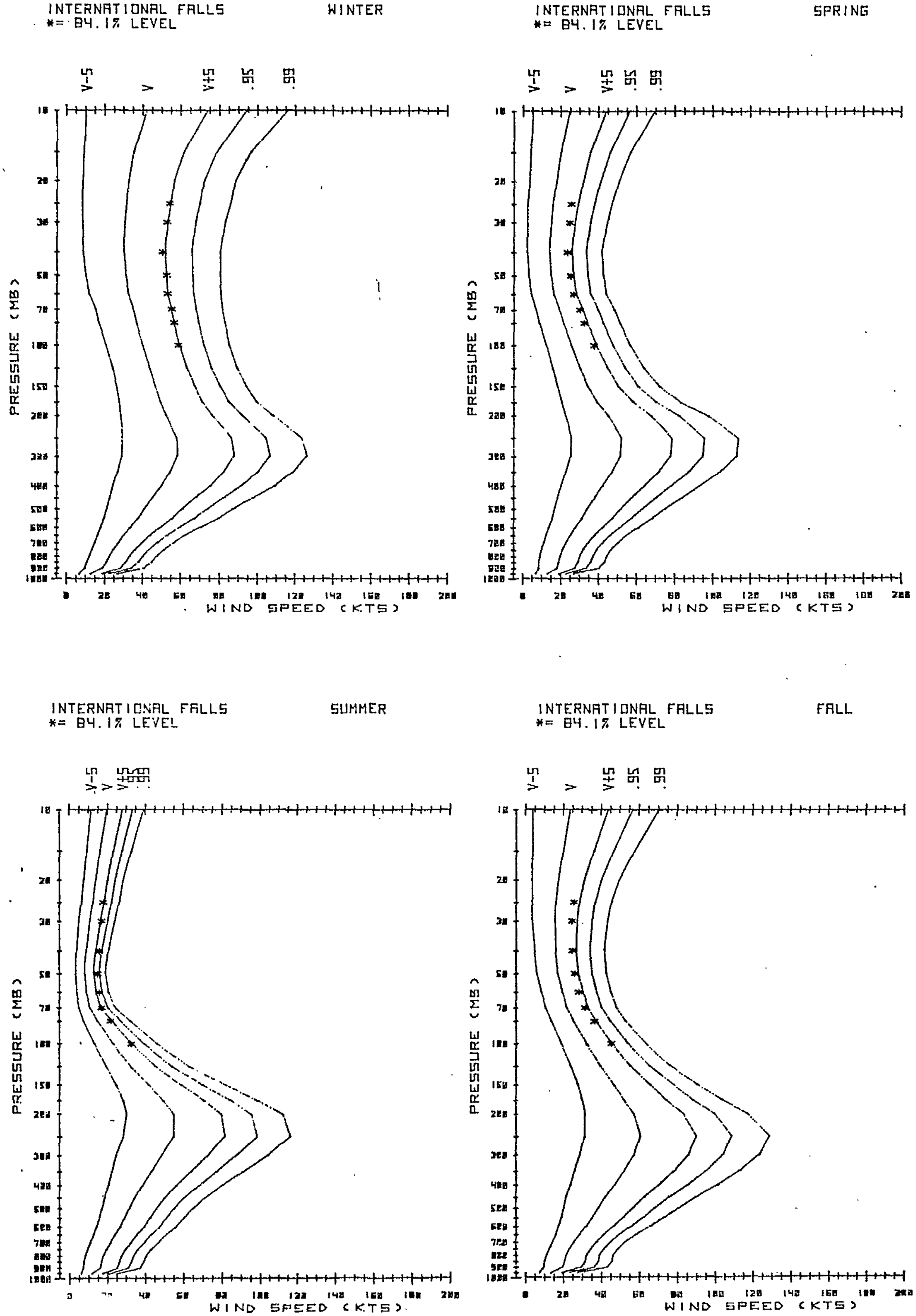


Figure 4.2/5 SEASONAL WIND VELOCITY IN KNOTS VS ALTITUDE IN mb FOR INTERNATIONAL FALLS, MN

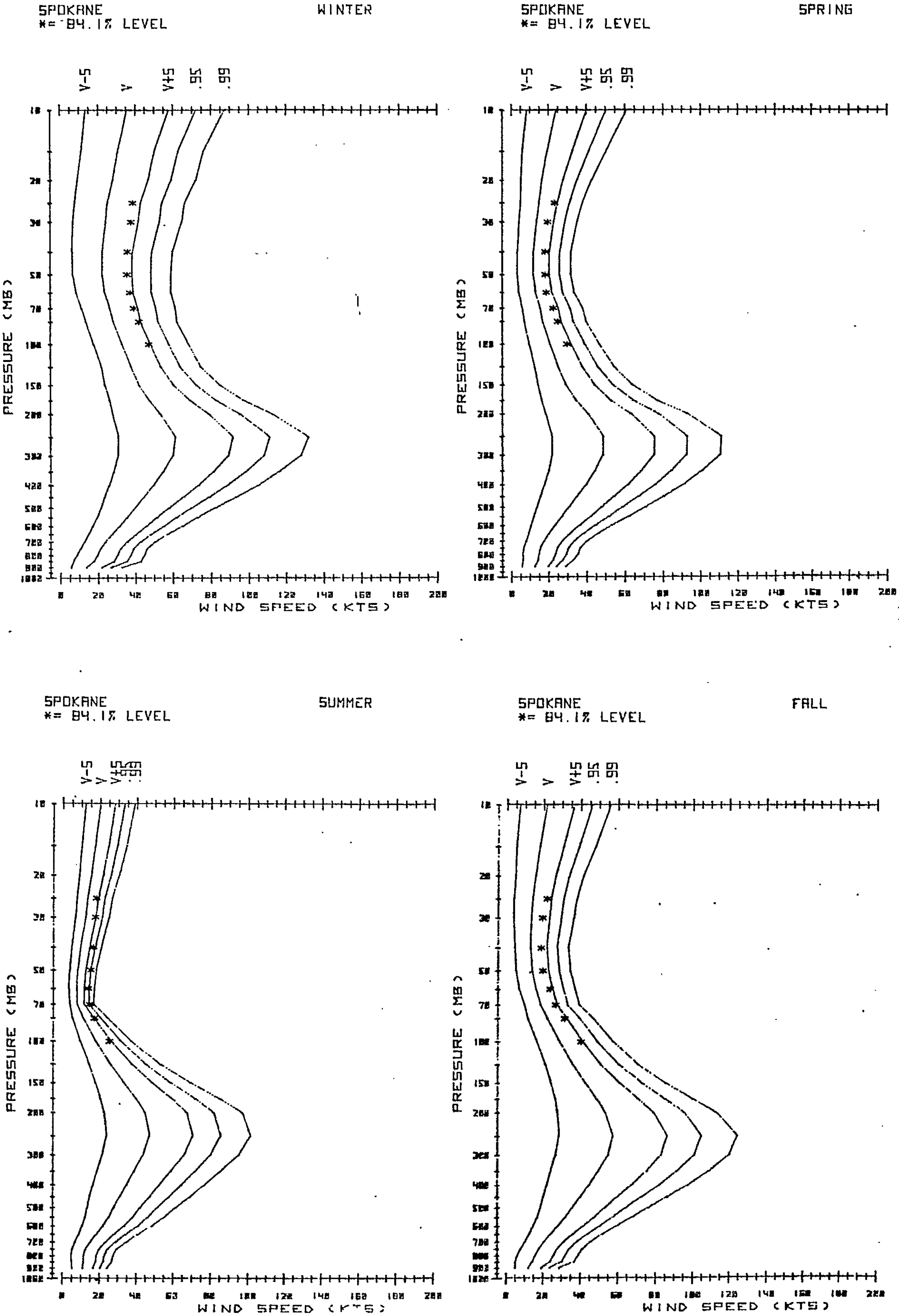


Figure 4.2/6 SEASONAL WIND VELOCITY IN KNOTS VS ALTITUDE IN mb FOR SPOKANE, WA

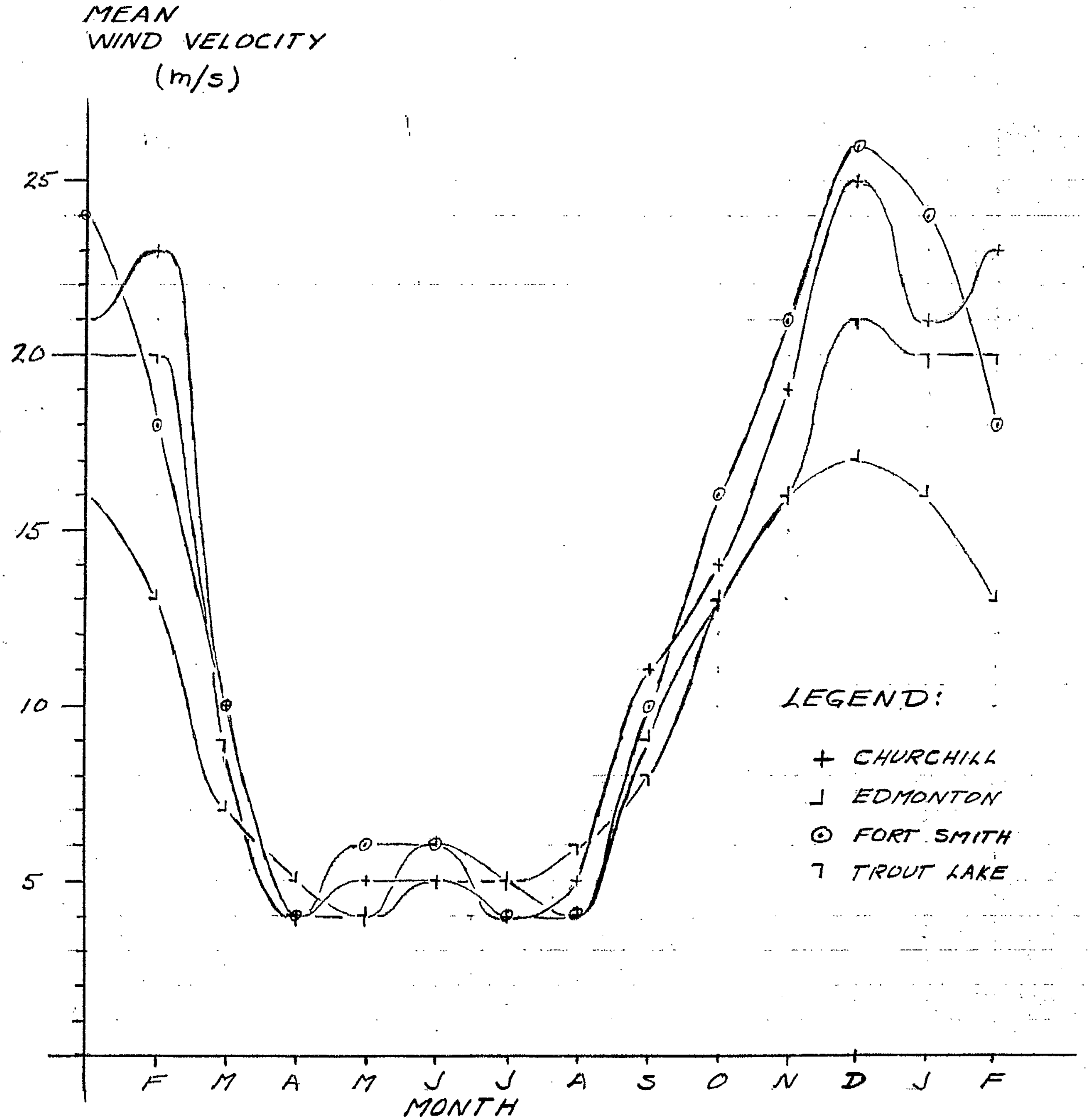
were extracted, for each site, and presented on Figure 4.2/7. Comparison of Figure 4.2/7 to the seasonal values for the mean velocity for the season on Figures 4.2/5 and 4.2/6 compare closely, indicating a close relationship and that the analytical approach is not in gross error.

Figures 4.2/7 and 4.2/8 do indicate that the SHARP vehicle with a design cruise speed of 20 m/s would be able to stay on station for the majority of the year based on the mean wind velocity curve, reference Figure 4.2/7. The maximum velocity curve, reference Figure 4.2/8 indicates that the vehicle could survive the Spring and Summer seasons but must have the ability to increase its flight speed to 60 m/s to survive the Fall and Winter winds.

The results of the wind analysis in the United States indicates (5):

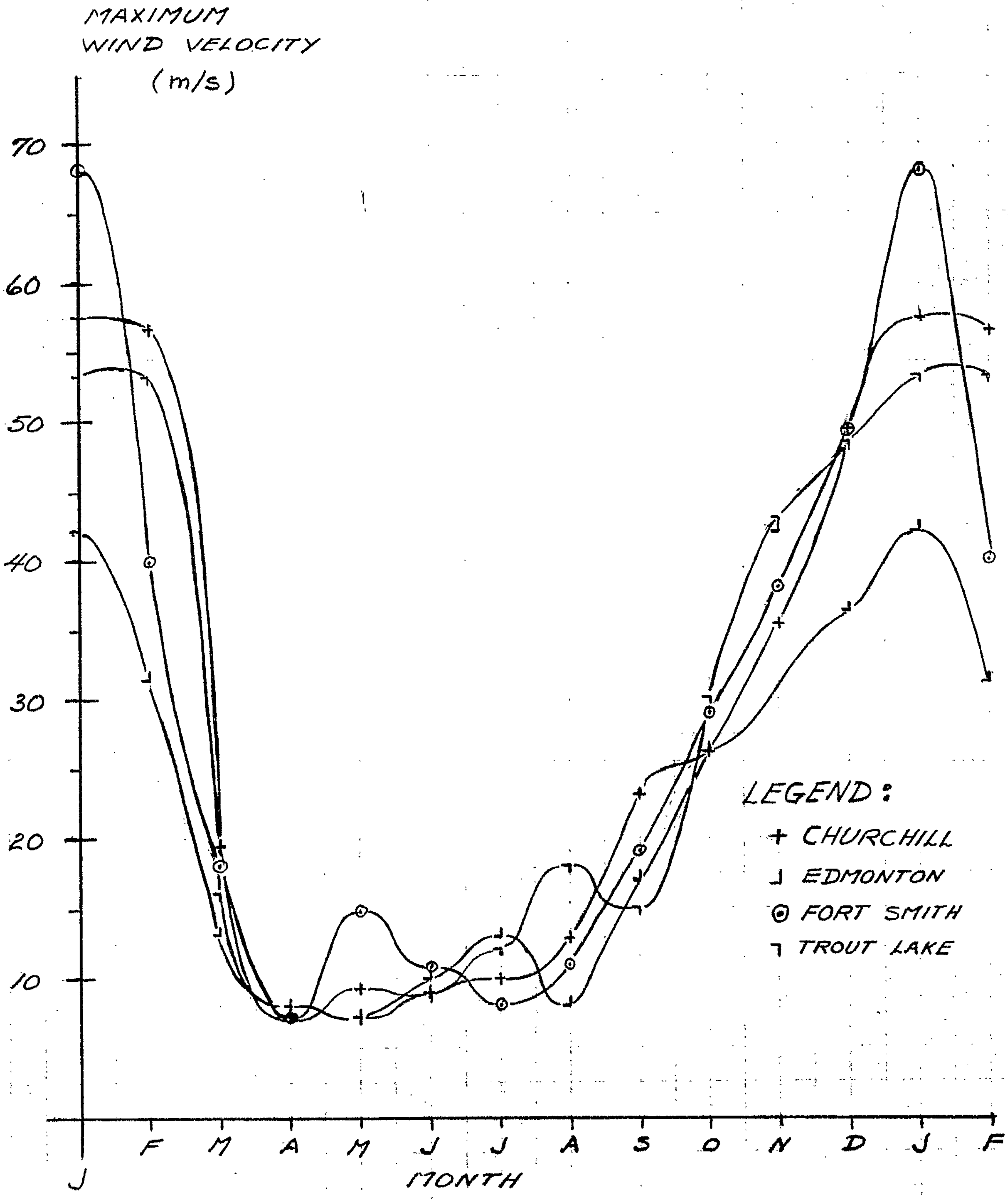
- a design speed of 26 m/s (50 Knots) would survive 98% of non-winter winds and 85% of winter winds for 100% of the United States.
- the 95 percentile wind speeds for the worst case United States site at an altitude of minimum speed is 18 m/s (35 Knots) for the non-winter seasons and 34 m/s (66 Knots) for the winter season.
- the altitude regime of minimum wind speeds is 21 to 22 km for non-summer applications and 18 to 19 km for summer applications.

Throughout the foregoing discussion, three aspects of the atmospheric motion have not been addressed: direction of the air movements, the time duration of wind velocity, and the vertical component of velocity. These aspects of the atmosphere have not been given the attention the wind velocity has for the following reasons:



MEAN WIND VELOCITIES AT 50 mb Vs MONTH OF YEAR

FIG. 4.2/7



MAXIMUM WIND VELOCITIES
AT 50 mb Vs MONTH OF YEAR

FIG. 4.2/8

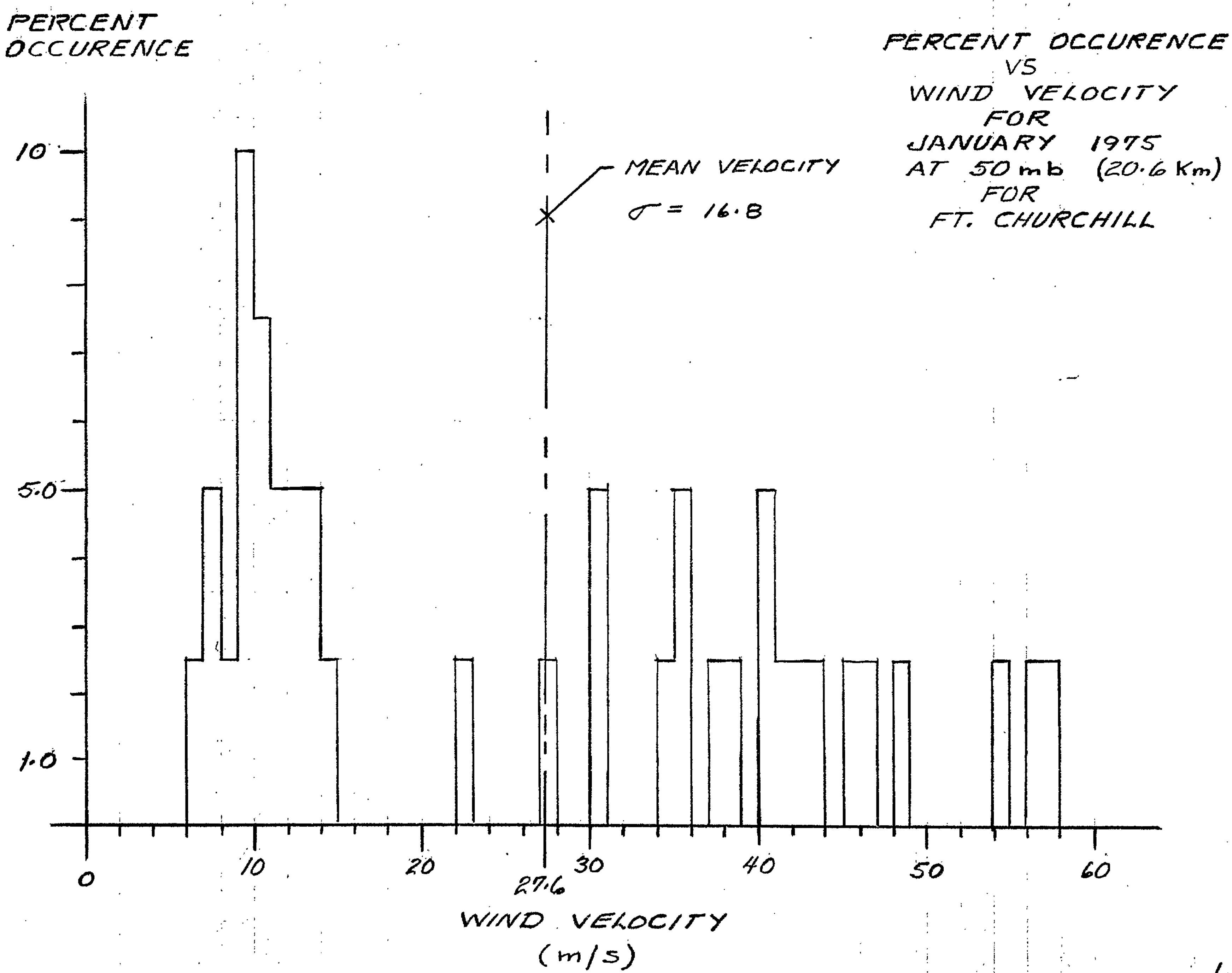

PERCENT OCCURENCE
PERCENT OCCURENCE VS WIND VELOCITY FOR JANUARY 1975 AT 50 mb (20.6 Km) FOR FT. CHURCHILL
MEAN VELOCITY
σ = 16.8
10
5.0
1.0
0
10
20
27.6
30
40
50
60
WIND VELOCITY
(m/s)

FIG. 4.2/9

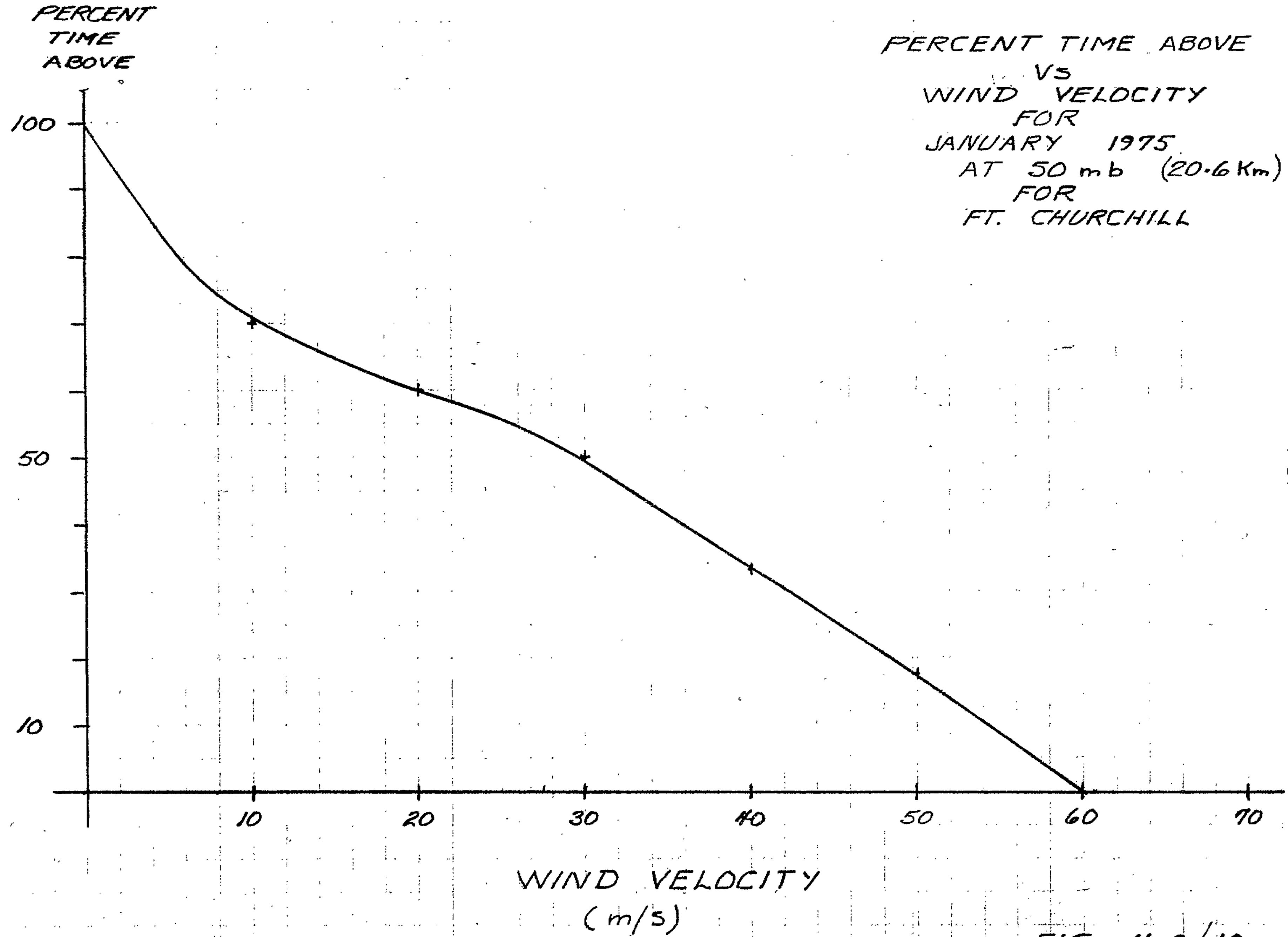

PERCENT TIME ABOVE
100
50
10
10
20
30
40
50
60
70
WIND VELOCITY (m/s)
PERCENT TIME ABOVE VS WIND VELOCITY FOR JANUARY 1975 AT 50 mb (20.6 Km) FOR FT. CHURCHILL

FIG. 4.2/10

- First and foremost, is the study time constraints.

- The platform vehicle must be able to adjust to changes in wind direction both in the vertical and especially the horizontal.

- The time duration of a particular wind velocity may be determined from existing wind data with proper analysis.

To gain an insight into duration of specific wind velocities the month of January 1975 was selected because of its high wind velocity recordings. Each wind velocity occurrence was totaled and the sum of all the recorded velocities was totaled for the month. The percent of occurrence was obtained and plotted on Figure 4.2/9, the mean and standard deviation was calculated. This data was recalculated, in increments of 10 m/s, to give a percent of time for the month at or above the increment of wind velocity. Figure 4.2/10 is a plot of these results.

Complete data analysis will result in curves similar to these shown but will be a more accurate statistical representation of the data.

Recent measurements of the winds by radar techniques may give a greater insight into both the vertical component and the time duration of the wind speed.

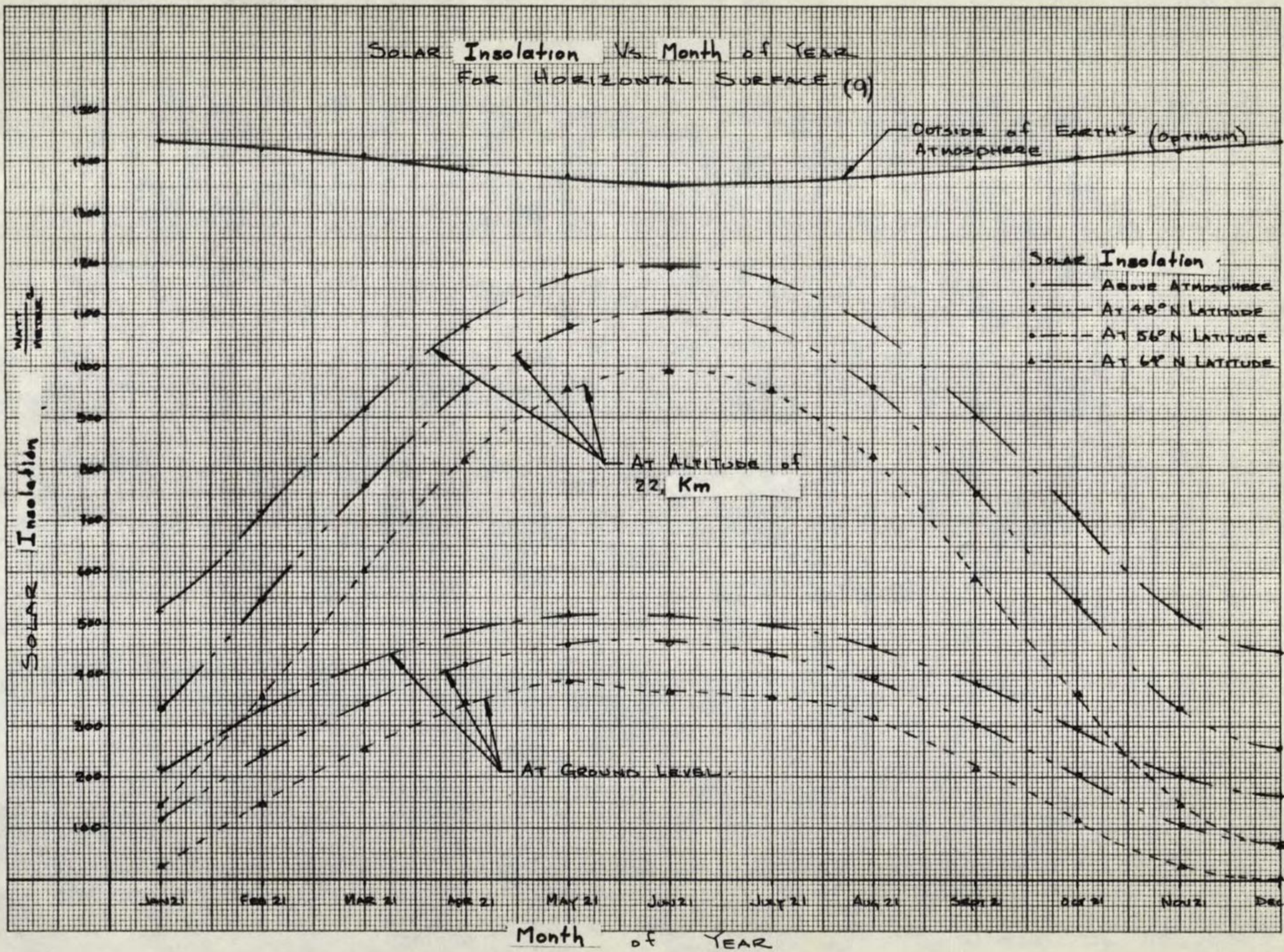

SOLAR Insolation Vs. Month of YEAR
FOR HORIZONTAL SURFACE (9)
OUTSIDE of EARTH'S (OPTIMUM) ATMOSPHERE
SOLAR Insolation
ABOVE ATMOSPHERE
AT 48° N LATITUDE
AT 56° N LATITUDE
AT 64° N LATITUDE
AT ALTITUDE of 22 Km
AT GROUND LEVEL
SOLAR Insolation
WATT/METRE²
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
JAN 21
FEB 21
MAR 21
APR 21
MAY 21
JUN 21
JULY 21
AUG 21
SEPT 21
OCT 21
NOV 21
DEC 21
Month of YEAR

Figure 4.3/4

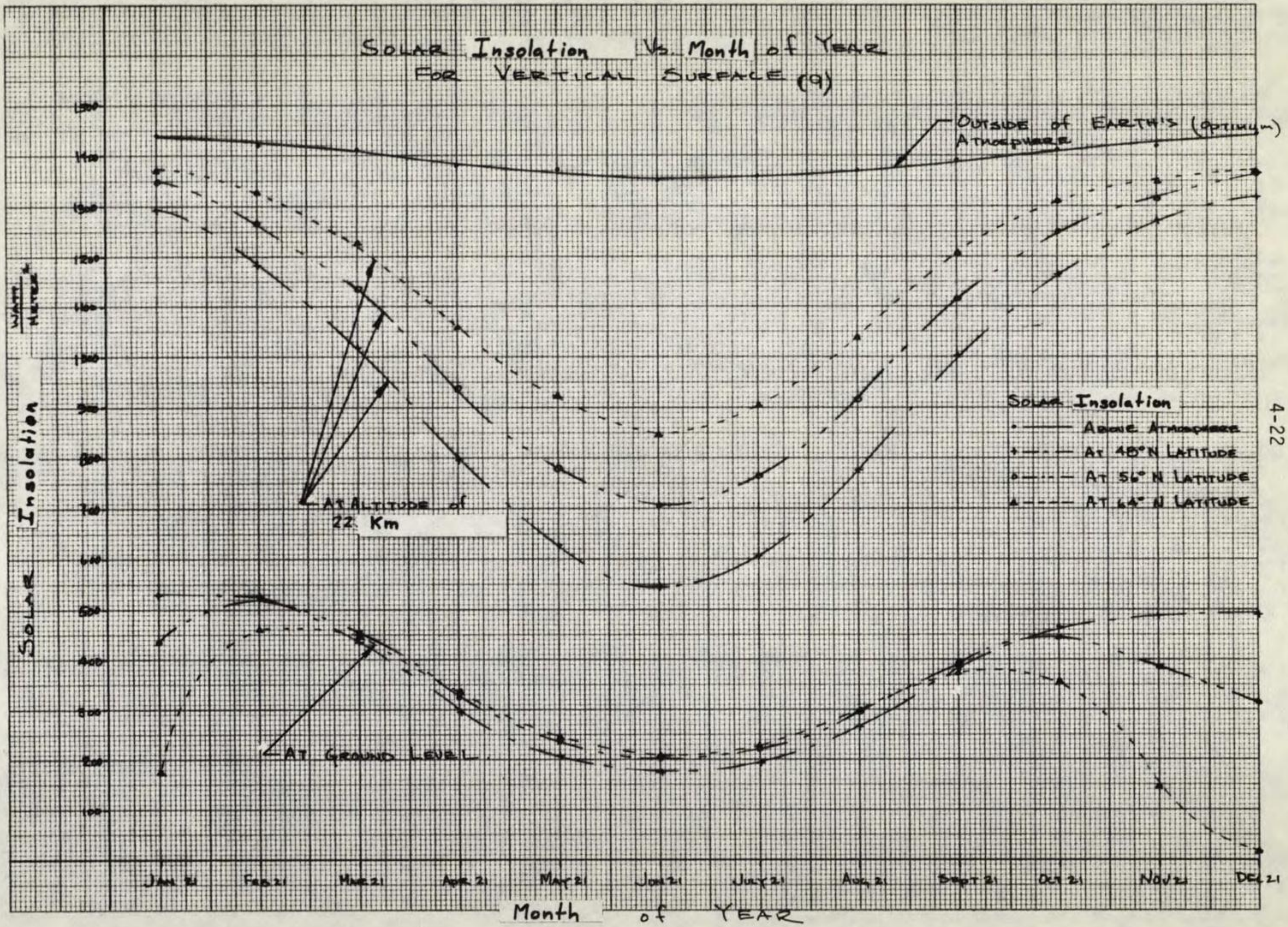
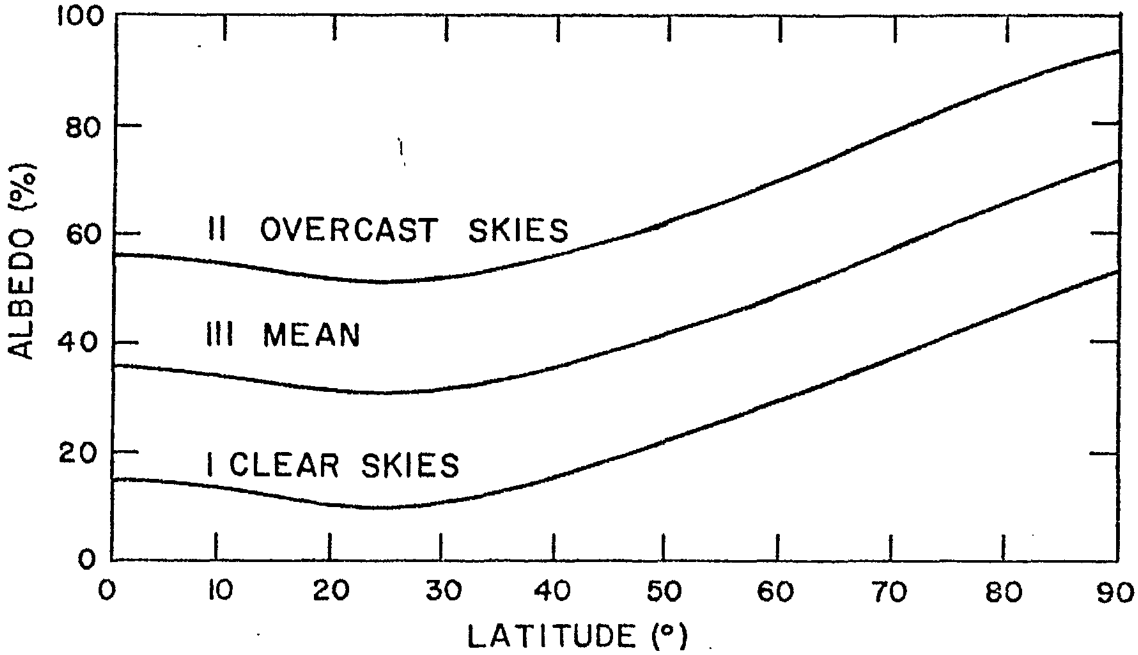

Solar Insolation Vs. Month of Year
For Vertical Surface (9)
Outside of Earth's (optimum) Atmosphere
At Altitude of 22 Km
At Ground Level
Solar Insolation
Above Atmosphere
At 48° N Latitude
At 56° N Latitude
At 64° N Latitude
Solar Insolation
Watts/Meter²
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Jan 21
Feb 21
Mar 21
Apr 21
May 21
Jun 21
July 21
Aug 21
Sept 21
Oct 21
Nov 21
Dec 21
Month of Year

Figure 4.3/5

4.3.1 Reflected Solar Insolation

A potential source of power and a definite source of heating to the SHARP is reflected solar insolation, albedo. Although the determination of the amount is less exact than the direct solar insolation, mathematical equations have been developed which satisfactorily approximate the reflected insolation received by vehicles above 15 km (50,000 ft.) (6).

The purpose in this study is to acknowledge this effect and to present an approximate method of estimating the amount. Figure 4.3/6 presents a graph which may be used to estimate the reflected energy. Referring to Figure 4.3/4 and 4.3/5, this would be a significant source of electrical power with the proper placement of photo voltaic arrays. For example, using the mean curve in Figure 4.3/6 and assuming a June solar insolation of 1320 w/m^2 at 50^o N latitude would mean that approximately 42% would be reflected or 528 w/m^2. A horizontal 20 m^2 panel below the platform would receive approximately 10.56 Kw of energy. At a conversion rate of 18% would net 1.9 Kw of usable electrical energy.



Albedo as a function of latitude under various sky conditions. (6)

Figure 4.3/6

4.4 Temperature

The air temperature varies from the earth's surface to 40 km as shown in Figure 4.4/1 along with the thermal conductivity of the ambient air. The curve is for the U.S. Standard Atmosphere and has been taken from reference (9). Both properties are significant to the SHARP thermal design considerations.

The packaging of electronic equipment required for a SHARP vehicle control and attendant telemetry equipment for relay of communications and vehicle control must consider the conversion loss of heat due to the ambient air temperature. If proper attention is not considered, semi-conductor devices used in modern electronic equipment may not function if there lower operating temperature is suppressed. High quality semi-conductors have a lower temperature limit in the order of -20^{o}C.

Of the equipment on board the SHARP, the most significant is the electric motor to propel the vehicle. This motor must be cooled to prevent overheating. The thermal conductivity is greatly reduced at 18-30 km operating altitudes. Careful attention will be required to provide adequate thermal balance in all modes of power applications.

The temperature curve shown is for the Standard Atmosphere from ground level to 40 km and does not take into account seasonal variation. Figure 4.4/2 is a portion of the standard Atmosphere curve with actual seasonal mean temperatures plotted. It appears that the air temperature shifts to a higher temperature in the summer and translates and rotates in the winter. The use of the U.S. standard air temperature curve is valuable as a general guide. However, if there is a critical thermal parameter on board the SHARP, actual seasonal temperatures should be used.

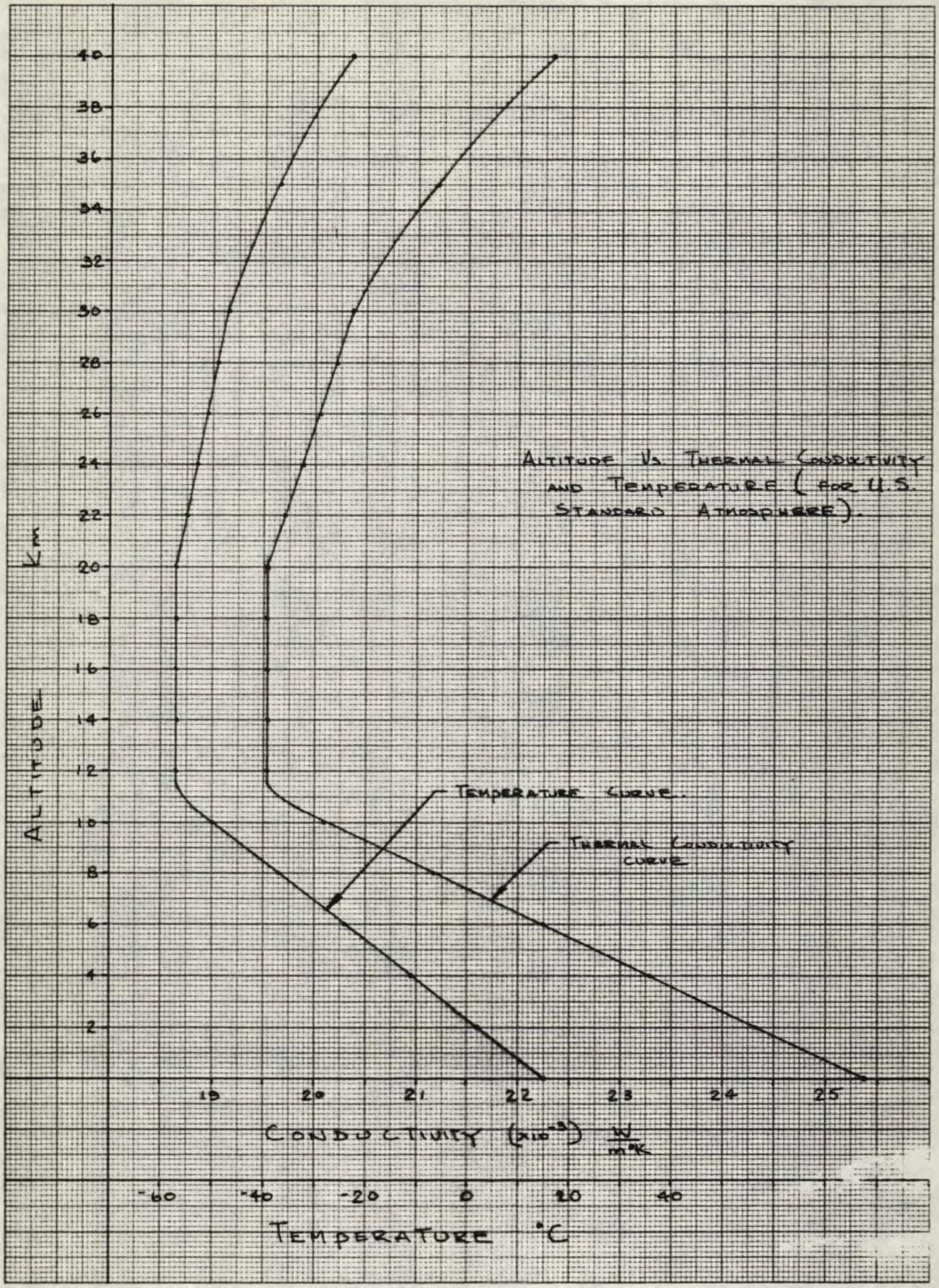

ALTITUDE VS THERMAL CONDUCTIVITY AND TEMPERATURE (FOR U.S. STANDARD ATMOSPHERE).
TEMPERATURE CURVE.
THERMAL CONDUCTIVITY CURVE
ALTITUDE Km
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
19
20
21
22
23
24
25
CONDUCTIVITY (x10^-3) W/m°K
-60
-40
-20
0
20
40
TEMPERATURE °C

Figure 4.4/1

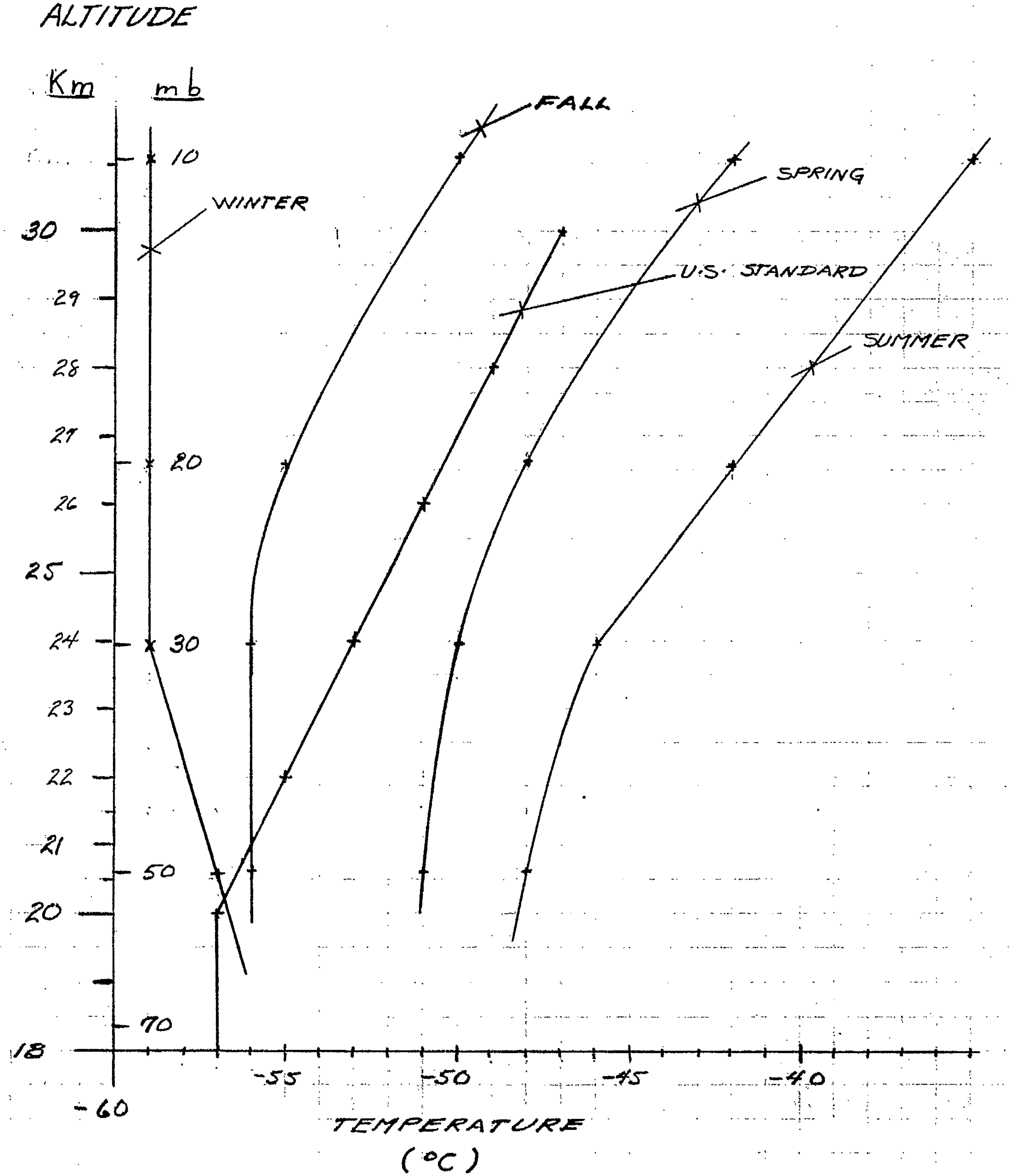


Figure 4.4/2

U S STANDARD TEMPERATURE VS SEASONAL VARIATION

Table 4.4/1 lists the seasonal mean temperature and standard deviation for SHARP altitudes derived from Tables in Appendix C. Noting that the thermal conductivity closely follows the standard air temperature curve, the seasonal shifts should be taken into account for critical design.

mb	Spring $\bar{T}$	Spring σ	Summer $\bar{T}$	Summer σ	Fall $\bar{T}$	Fall σ	Winter $\bar{T}$	Winter σ	Geometric Altitude Km
10	-42	10.4	-35	5.9	-50	10.8	-59	12.0	31.16
20	-48	5.5	-42	4.3	-55	9.4	-59	9.4	26.6
30	-50	3.9	-46	3.8	-56	8.3	-59	8.2	23.92
50	-51	3.98	-48	3.3	-56	7.3	-57	7.6	20.6
70									18.36

TABLE 4.4/1 SEASONAL MEAN TEMPERATURES AT SHARP OPERATIONAL ALTITUDES

4.5 Thermal Aspects of Air

A significant thermal characteristic of the atmosphere at SHARP altitudes is the fact that the specific heat of air is substantially the same on ground level (9). However, the volume of air required to achieve the same cooling has increased approximately 14 times.

Figure 4.5/1 is a family of curves which is derived from the following equation:

$$Q = m\,C_p\,(t_2 - t_1)$$

where: Q = heat input to the air, watt

m = mass flow rate of air, kg/min

C_p = specific heat of air of SHARP altitudes

$1.004\ \frac{KJ}{Kg^{o}C} \quad (.24\ \frac{cal}{g^{o}C})$

t_1 = temperature air before being heated

t_2 = temperature air after being heated

The family curves make it easy to determine the mass flow rate or temperature rise to cool a body liberating a quantity of heat. These curves will be critical in cooling the electric motor for the propulsion system and in maintaining the proper temperatures for the rectifying diodes used in the rectenna array.

TEMPERATURE RISE Vs. MASS FLOW RATE
AT ALTITUDE of 20 km to 40 Km.

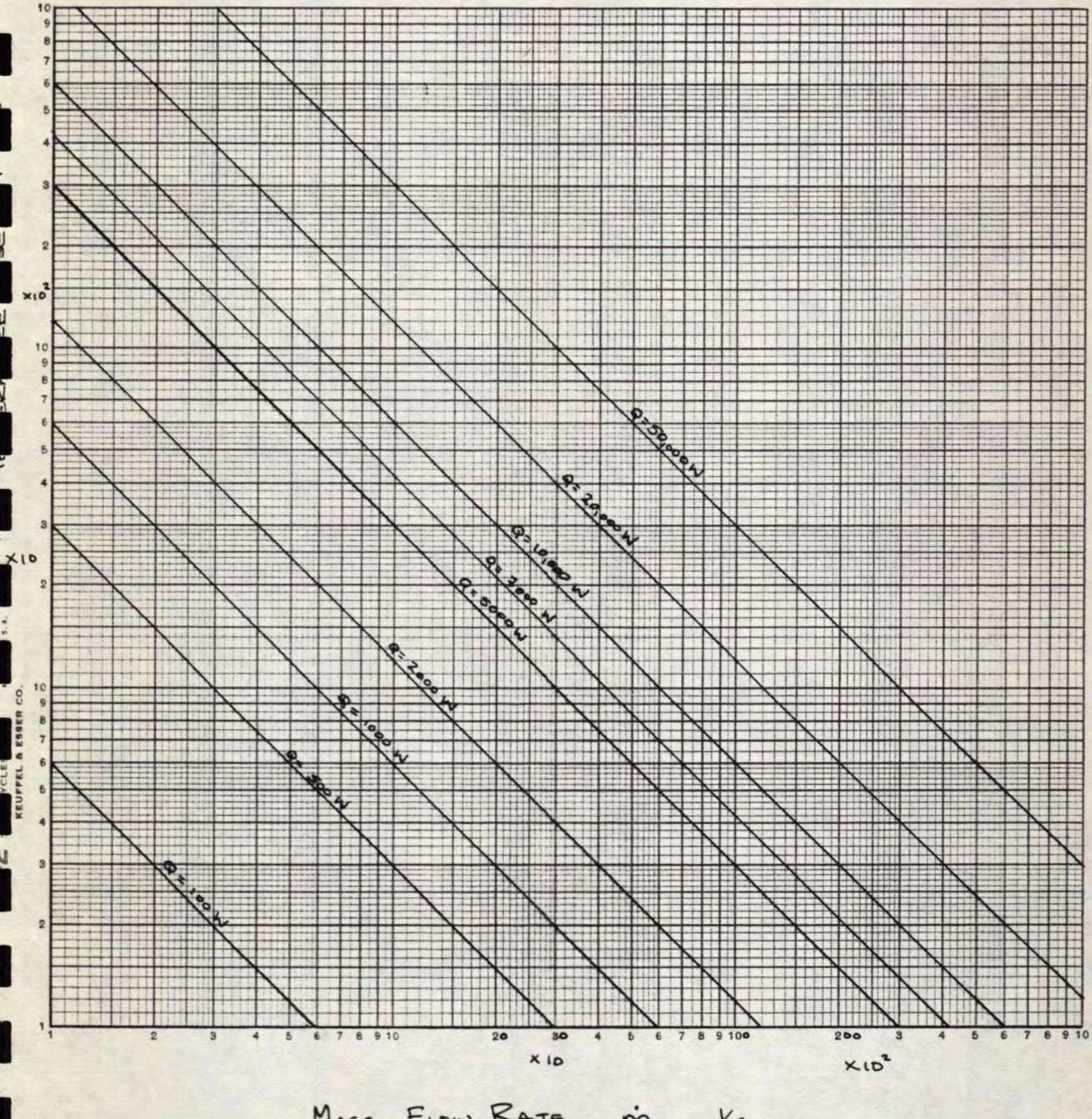


Figure 4.5/1

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5.0 POWER

5.1 Introduction

The key issue to a SHARP concept is power. To enable a vehicle of some configuration to remain stationary in the upper atmosphere will require a continuous source of energy for the control, propulsion and mission electronics systems. Recent technological developments have given credibility to the SHARP concept. The major technologies being microwave power transmission, photo voltaic efficiency increase and cost decrease, research and development or rechargeable storage cells with increased energy to weight parameters.

Other technological developments that have a significant impact on a SHARP concept power requirements are rare earth high efficiency motors, and low power electronics for control and communications. These will be dealt with in separate sections but are mentioned here because they are contributors to the overall power requirements of a SHARP.

One significant technology which must be addressed in the development of high power klystron tubes and research and development of low power magnetron phased array antennas. It is now possible to purchase CW klystron tubes providing 50 Kw continuous power (4). Predictions indicate that continuous port generation up to 400 Kw will be available (5). The magnetron is capable of generating 1 Kw of power, by creating a field of these generators it is possible to create a phased array of varying power density and to be steerable to some extent.

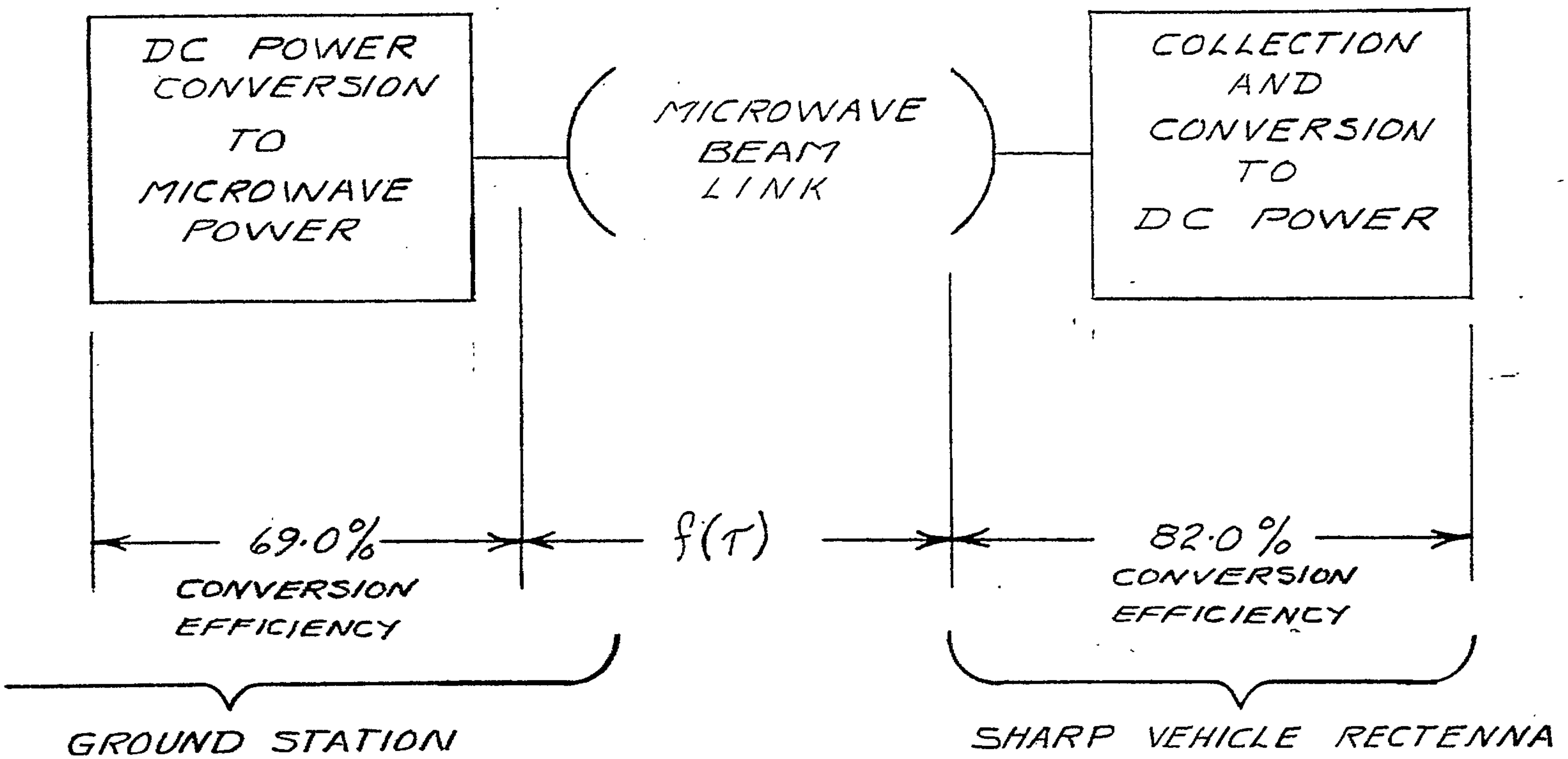
5.2 Microwave Powering of SHARP

5.2.1 Overview of Microwave Powering

Power needed for propulsion of a SHARP vehicle could be transmitted from the ground, using microwaves. This study has found that cost-effective microwave powering of the SHARP vehicle is one of the three essential technical elements needed to make the SHARP concept feasible today.

The state of the art in microwave powering has advanced markedly since W. Brown, G. Goubau, and others commenced research in the field over a decade ago (see, for example, Reference (1)). Since then, research by Raytheon (US), and various NASA organizations has achieved remarkably high efficiencies of power transfer (the order of 80%) on terrestrial line-of-sight paths. But to our knowledge, no large or high flying vehicle has as yet been powered with microwaves. (Brown has made a start in this direction by powering a small tethered helicopter model.) Thus it still remains to demonstrate that sufficiently high levels of power can be delivered to a SHARP vehicle at altitude, and that for all intents and purposes, the powering beam can be "locked onto" the vehicle as it flies within its station-keeping volume.

This report provides only a broad overview of the characteristics of microwave powering needed for the SHARP application. The elements of a system are presented in Figure 5.2/1. The ground installation would consist of facilities to convert electrical power from the grid (or from other electrical power generators) into microwave power. Low cost magnetrons, currently used for microwave ovens, and operating at the IMS frequency of 2.45 GHz, have been shown to be well suited for this purpose (Reference (1)).



MICROWAVE POWER TRANSMISSION ELEMENTS (1)

Figure 5.2/1

The power transmission antenna could, in principle, be a large (parabolic or spherical) antenna, capable of being steered to follow the motion of the SHARP vehicle. In practice this approach seems far less attractive than that of using an array of many small antennas and microwave sources, phased together to form a focussed beam. As seen below, this is because the overall aperture of either type of antenna must be very large indeed. At the present state of the art for large antennas, the phased array approach is believed to be most economic and effective.

The SHARP vehicle would be equipped to receive and convert a fraction of the transmitted microwave power back to electrical power for propulsion and other purposes. An efficient and potentially lightweight receiving device to accomplish both these functions (called a rectenna) has been developed by Raytheon. This device consists of an array of half wavelength dipoles for reception and diodes for rectifying the microwave signals (Reference (6)). Conversion efficiencies of over 70% have been achieved with rectennas. Furthermore, at maximum capability, the rectenna achieves these efficiencies at a weight penalty of only about one kilogram for every kilowatt of power converted.

5.2.2 The Transmitting System

Consider now the transmitter power and antenna sizes required to provide power levels needed at the SHARP vehicle. One approach is to employ a sufficiently large aperture antenna to focus the energy onto an area about the size of the vehicle rectenna itself, using techniques of beam forming optics. Following this approach, it is calculated that a high efficiency of power transfer could be achieved, with the attendant disadvantages of very precise steering of the beam onto the vehicle, and more importantly, the construction and reliable operation of an extremely large aperture antenna. How large this aperture would have to be, can be estimated using calculations presented originally by G. Goubau and used by Brown in power transmission studies (Reference (2)).

As illustrated in Figure 5.2/2, the efficiency of a power transmission system, η, or the fraction of transmitted power that impinges on the rectenna, can be expressed by a parameter τ (Reference (2)). In turn, the parameter τ can be used to develop relationships between the relative sizes of the transmitting antenna area, A_t (assumed to be circular) and the rectenna array area, A_r (also assumed circular):

$$\tau = \frac{(A_t A_r)^{1/2}}{\lambda D} \qquad (1)$$

where λ is the microwave wavelength (0.12m)

and D is the operating altitude

For convenience in comparing relative sizes of transmitter and rectenna array antennas, take:

$$N = A_t/A_r \qquad (2)$$

So that, from (1)

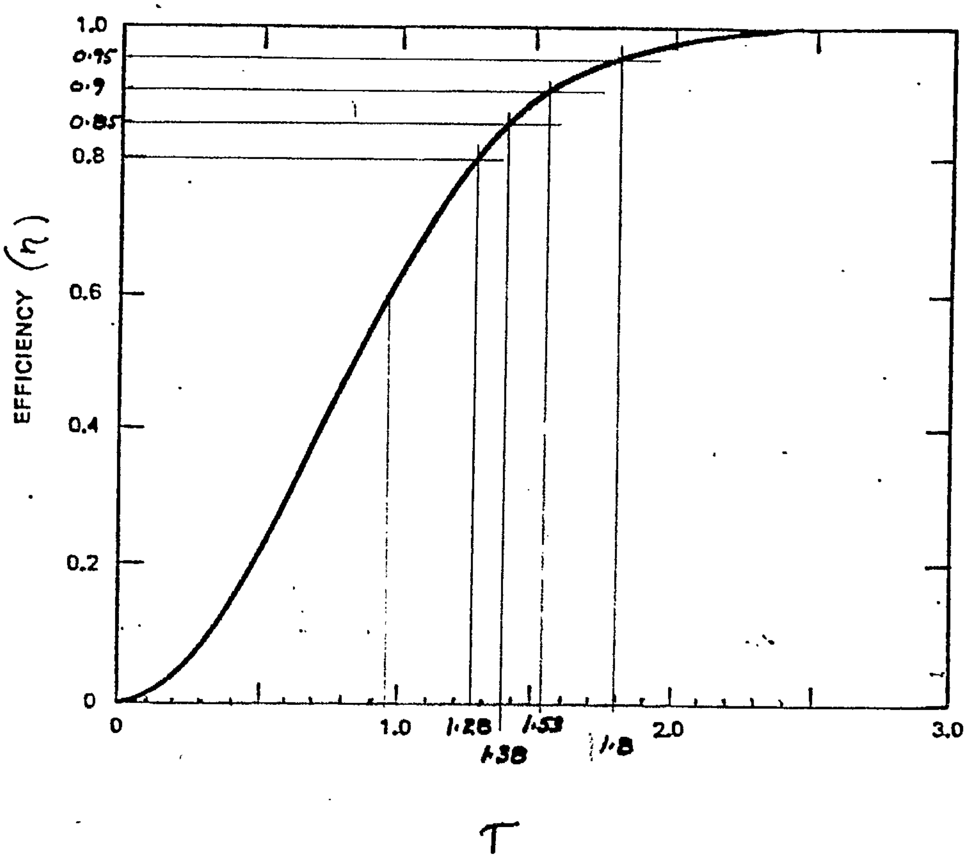
$$N = \frac{\tau^2 D^2 \lambda^2}{A_r^2} \qquad (3)$$

Figures 5.2/3 to 5.2/7 present D and N for various values of τ (taken from Figure 5.2/2 for various efficiencies).

By way of example, assume a desired efficiency:

η = 80%

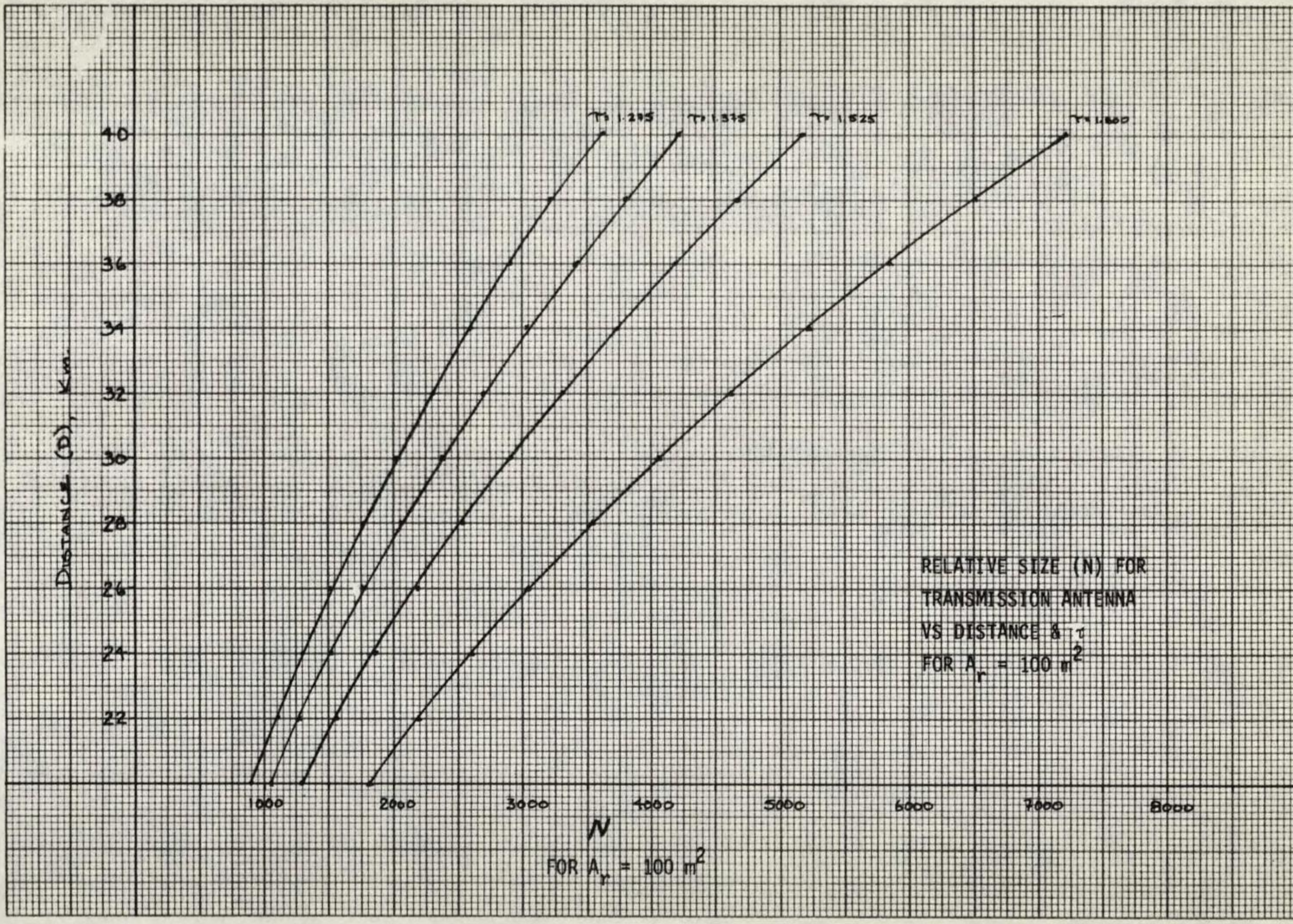
so that, from Figure 5.2/2, τ = 1.375.



FRACTION OF TRANSMITTED MICROWAVE POWER THAT IMPINGES ON RECTENNA AS A FUNCTION OF THE PARAMETER τ (2)

Figure 5.2/2

Figure 5.2/3



τ = 1.375
τ = 1.525
40
38
36
34
32
30
28
26
24
22
DISTANCE (D), Km.
1000
2000
3000
4000
5000
6000
7000
8000
N
FOR A_r = 100 m^2
RELATIVE SIZE (N) FOR
TRANSMISSION ANTENNA
VS DISTANCE & τ
FOR A_r = 100 m^2

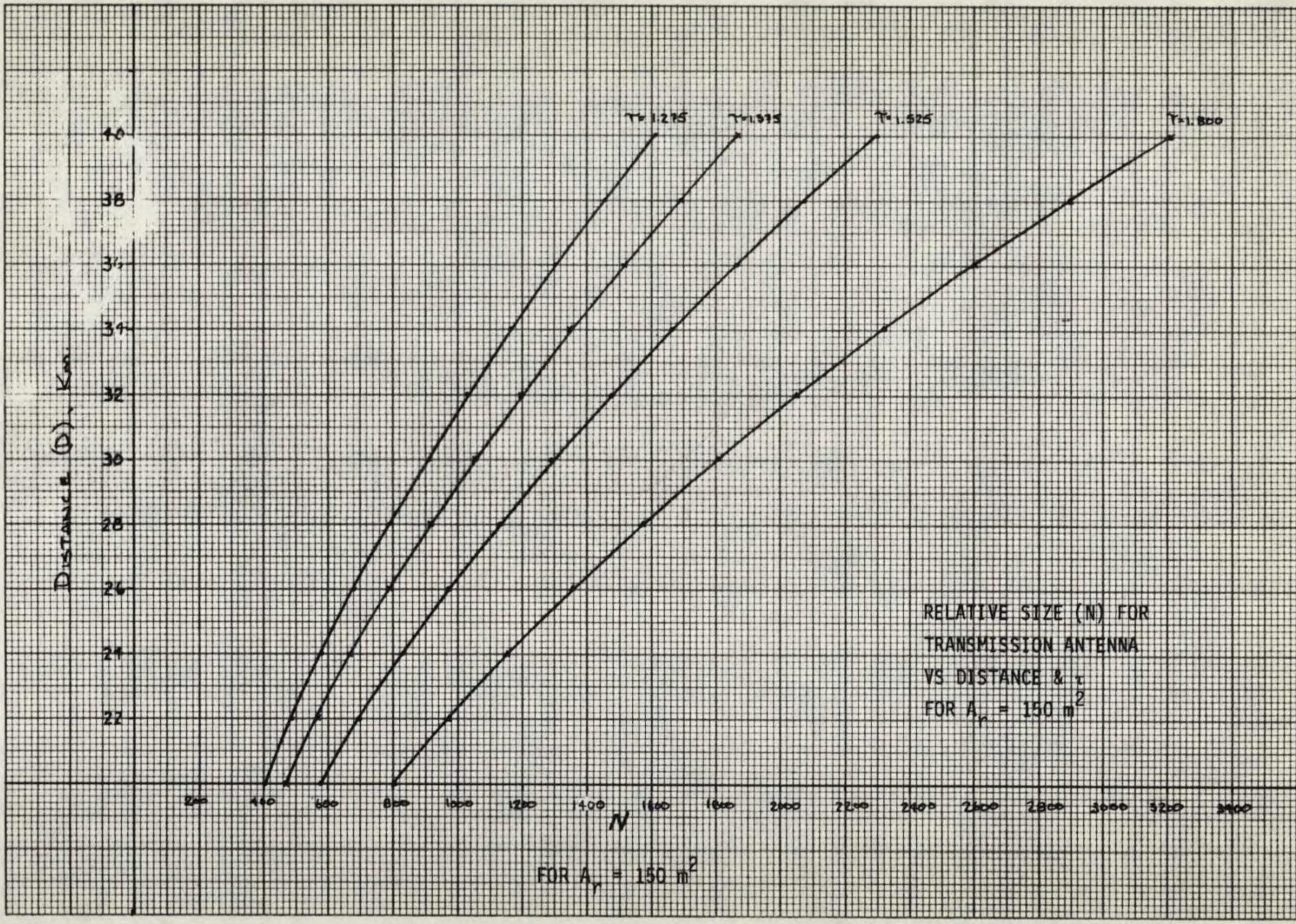

τ = 1.275
τ = 1.375
τ = 1.525
τ = 1.800
DISTANCE (D), Km
40
38
36
34
32
30
28
26
24
22
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
N
RELATIVE SIZE (N) FOR
TRANSMISSION ANTENNA
VS DISTANCE & τ
FOR A_r = 150 m²
FOR A_r = 150 m²

Figure 5.2/4

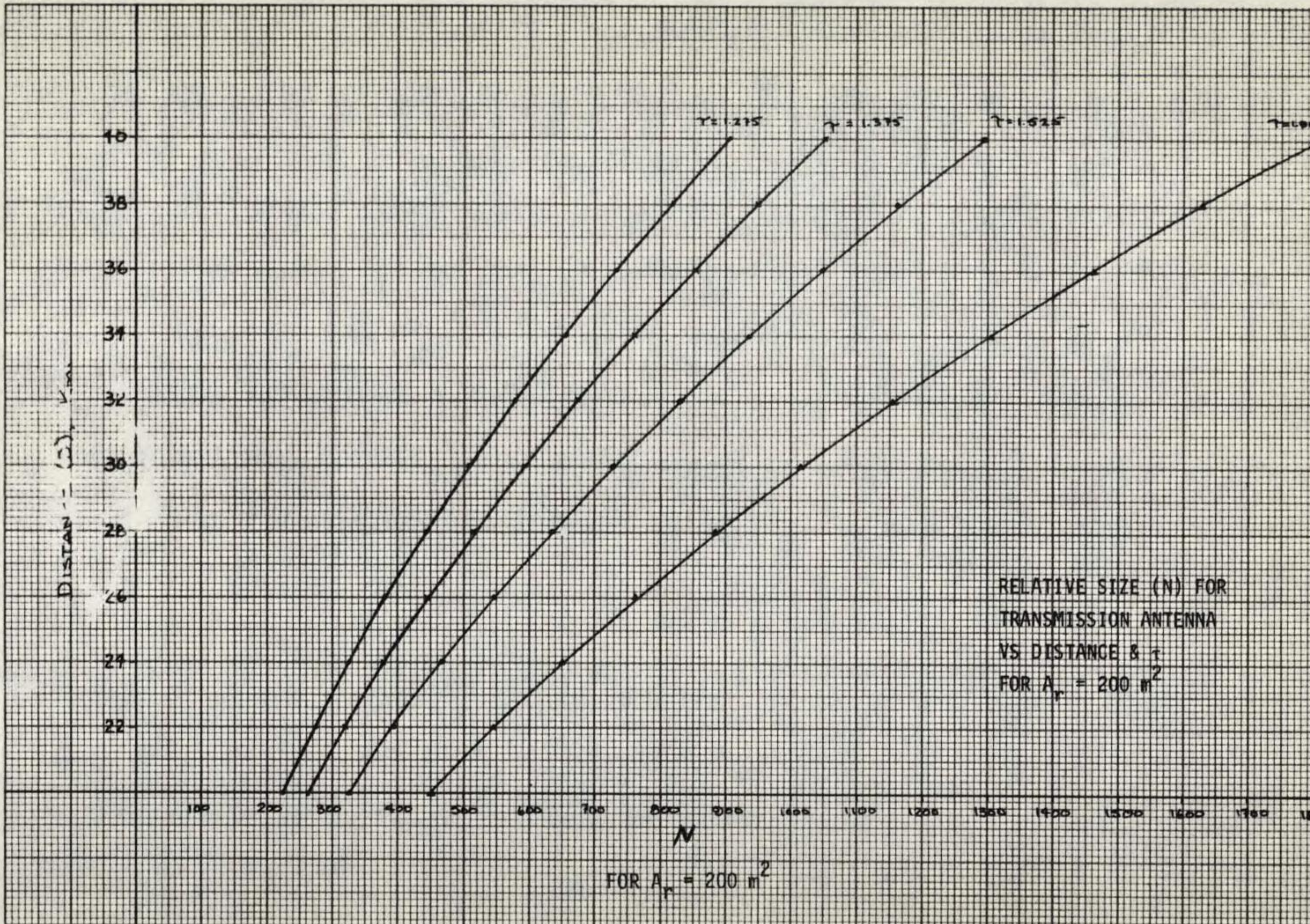

τ=1.275
τ=1.375
τ=1.525
40
38
36
34
32
30
28
26
24
22
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
N
FOR A_r = 200 m^2
RELATIVE SIZE (N) FOR
TRANSMISSION ANTENNA
VS DISTANCE & τ
FOR A_r = 200 m^2

Figure 5.2/5

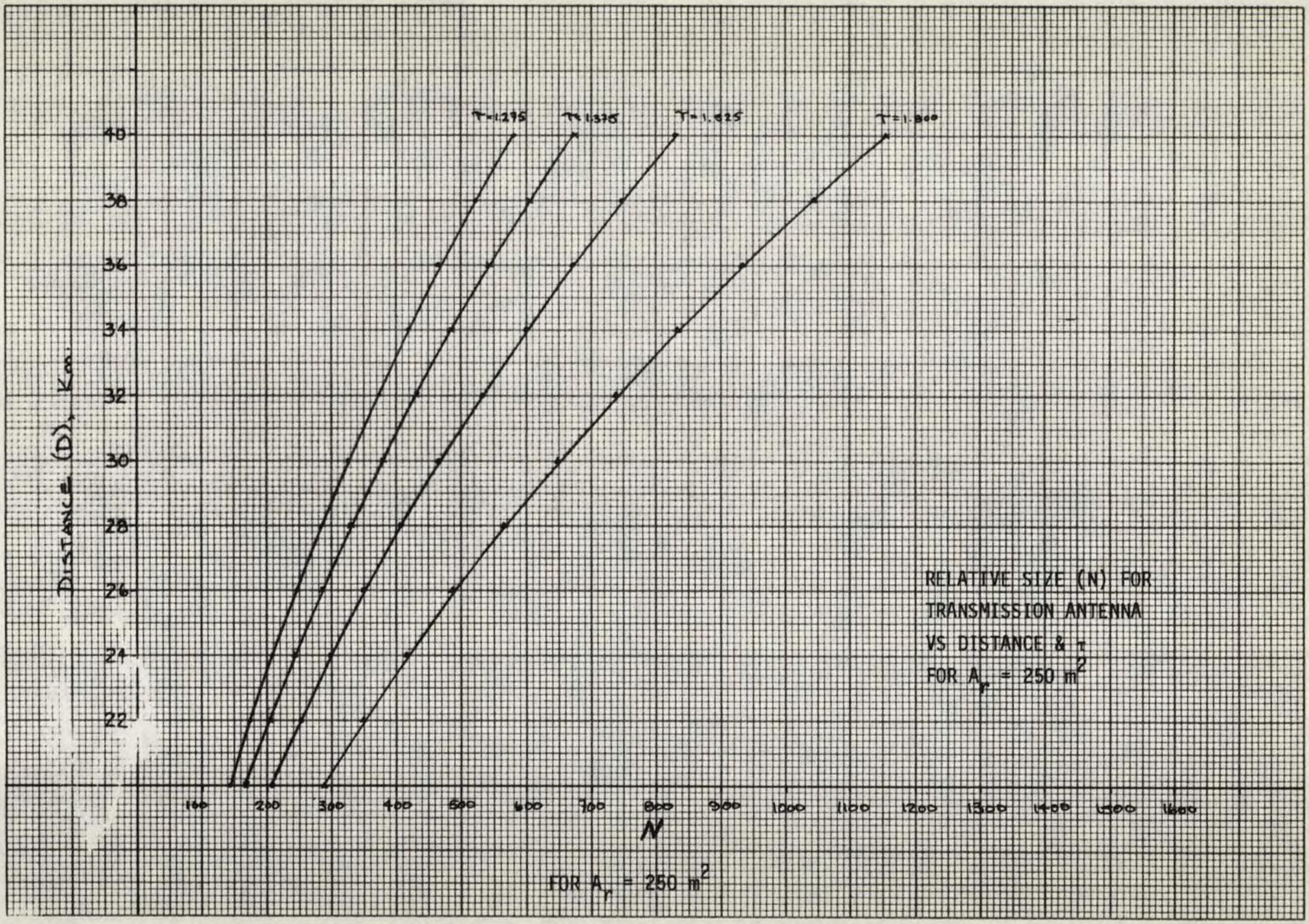

τ=1.295
τ=1.375
τ=1.625
τ=1.900
DISTANCE (D), Km.
40
38
36
34
32
30
28
26
24
22
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
N
FOR A_r = 250 m^2
RELATIVE SIZE (N) FOR
TRANSMISSION ANTENNA
VS DISTANCE & τ
FOR A_r = 250 m^2

Figure 5.2/6

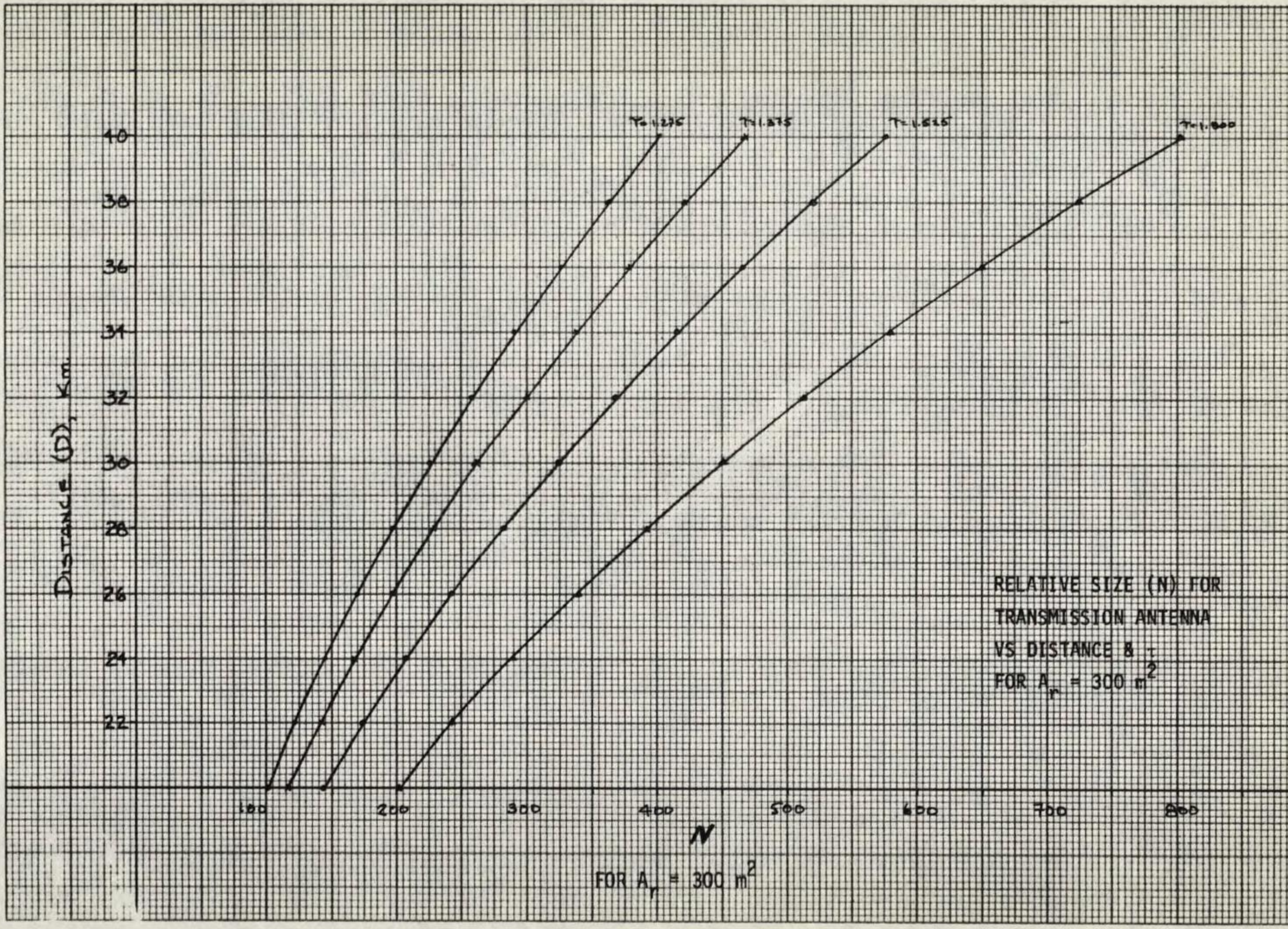

T=1.275
T=1.375
T=1.525
40
38
36
34
32
30
28
26
24
22
DISTANCE (D), Km.
100
200
300
400
500
600
700
800
N
FOR A_r = 300 m^2
RELATIVE SIZE (N) FOR
TRANSMISSION ANTENNA
VS DISTANCE & τ
FOR A_r = 300 m^2

Figure 5.2/7

Then, for a circularily shaped rectenna, with area:

$$A_r = 100\ m^2$$

Figure 5.2/3 shows that for D = 21 km

$$N = 1150$$

So that $A_r = 1.150 \times 10^5\ m^2$, and $(A_t)^{\frac{1}{2}} = 340$ m.

In conclusion, for efficient transmission of power over distances as large as the proposed SHARP operating altitude, the antenna aperture will be considerably larger than those which are normally built for communications and radar purposes.

It remains to assess the economic tradeoffs between aperture size and transmitter power levels to achieve needed power levels for various SHARP vehicles.

In the meantime, we note simply that the product of the transmitter power, P_t, and the antenna aperture A_t, P_tA_t, is approximately constant for a specified level of flux density of the SHARP vehicle, for example:

Eff. Antenna Aperture $(A_t)^{\frac{1}{2}}$	Power Tx Efficiency	Required Tx Power*
340 m	80%	35.6 KW
115 m	8%	356 KW

* (the total output power required to provide a microwave flux density of about 286 watts/m^2 at the SHARP rectenna array, corresponding to electrical power density of 200 watts/m^2 with 70% conversion efficiency).

5.3 Power-Handling Capability of Rectennas

The power-handling capability of the microwave power collection system would be of major importance in determining the upper limits of performance of the SHARP vehicle, and hence the feasibility of operation under severe flying conditions. In particular, the upper limit on the power which could be handled by the rectenna array on the vehicle would effectively determine the maximum available propulsive power. At the present state of the art, the stated limit on rectified power densities is about 200 watts/m^2, for rectennas developed by Raytheon. (The limit is set by the power-handling capabilities of the rectifying diodes - about one watt per diode - with about 200 diodes being used per square meter of array) (Reference (6)). This power-handling limit then sets a limit on the electrical power available for driving SHARP electric motors and for other purposes. This becomes 200 $A_r$watts, where A_r is the effective area of the rectenna. Thus, for a sailplane-type SHARP or the dart-shaped SHARP-I (Section 7.0), with a wing area of about 100 m^2, the maximum electrical power which could be delivered by the rectenna would be about 20KW.

It remains for the future to determine whether or not the power-handling capabilities of alternate energy collection systems could be significantly increased over those currently available with the Raytheon rectennas, with no significant penalty in weight or conversion efficiency. There do not appear to be any technical reasons to prevent the upper power handling capability from being increased to about 400 watts/m^2.

5.4 Solar and Chemical Storage

5.4.1 Solar

The current technological research and development of photo voltaic cells has been given great impetus by the rising cost of fossil fuels (11). The development of these semiconductor devices has been primarily directed to the development of solar energy for use in private homes and small businesses, providing a source of energy for remotely located instrumentation in conjunction with batteries (12).

At present, the prime elements and the compounds that show the most promise, are shown on Figure 5.4/1 along with their potential efficiencies.

Table 5.4/1 indicates the current state of the art efficiencies of photo voltaic solar cells. A comparison with Figure 5.4/1 indicates that much research is required to even approach the theoretical efficiencies. At present, the most available cell is the silicon cell with an 18% efficiency.

Table 5.4/2 lists some of the manufacturers of photo voltaic cells and their test characteristics. Figure 5.4/2 demonstrates the characteristic change in efficiency with increased solar influx. Refering to Figure 4.3/4, the solar insolation at 56^{o} N latitude in June will be approximately $47 \times 10^{-3} W/cm^2$ and $110 \times 10^{-3} W/cm^2$ at the ground and at 22 km altitude respectively for a horizontal surface. At the expected operational altitude of 22 km, the SHARP will receive just slightly more than one sun concentration on a horizontal surface.

Though the band gaps of compound semiconductors range widely, many have potentially high efficiency, as this plot shows. The elemental semiconductors Si, Se, and Ge are included for comparison.

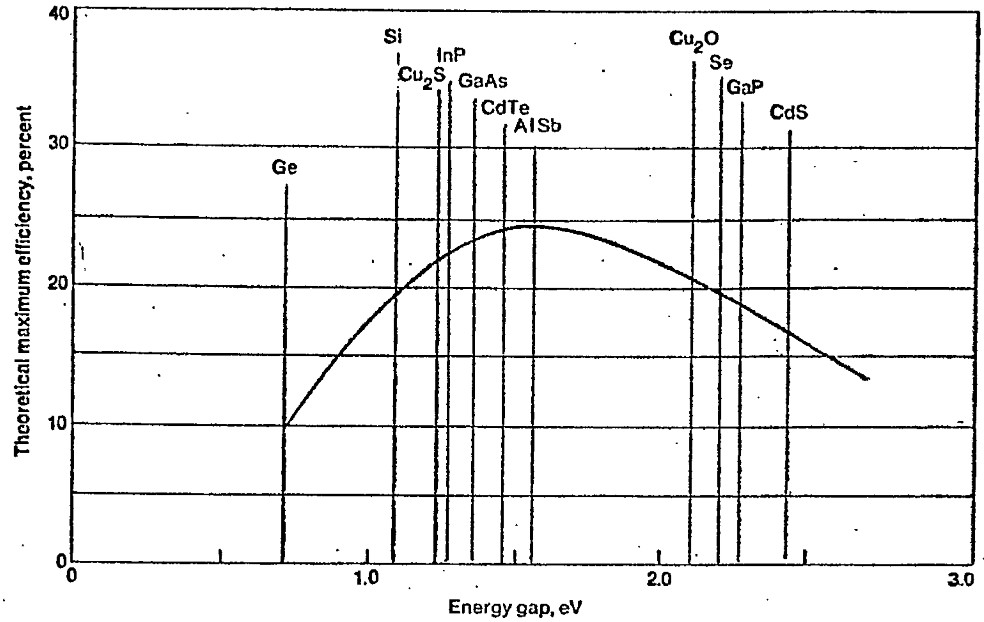


Figure 5.4/1 (14)

Photovoltaic solar cells with efficiency of 5 percent or more

Type of Cell	Semiconductor Constituents	Highest Efficiency (Air Mass 1 Condition), Percent
Homojunction	Silicon	18
Homojunction	Gallium arsenide	22
Homojunction	Indium phosphide	6
Heterojunction	pCu_2S/nSi	5
Heterojunction	pInP/nCdS	14
Homojunction heterostructure	$Al_xGa_{1-x}As$, GaAs	18
MIS*	Silicon	12
MIS	Gallium Arsenide	15
SIS†	Indium tin oxide/silicon	12
SIS	Tin oxide/silicon	12
Heterojunction	pCdTe/nCdS	8
Schottky barrier	WSe_2	5
Polycrystalline	Silicon	8
Thin-film/thin-film heterojunction	$pCu_2S/nCds$	9
Thin-film heterojunction	$pCu_2Te/nCdS$	6
Thin-film amorphous semiconductor, Schottky barrier	Silicon	6

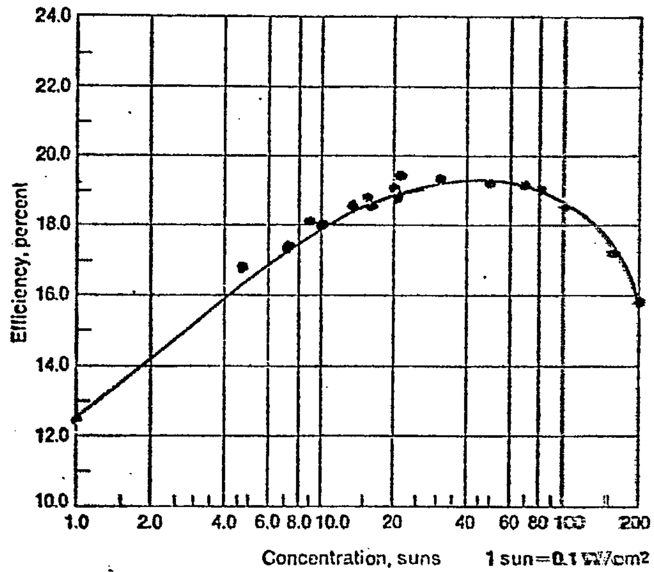
* Metal-insulator-semiconductor cell.
† Semiconductor-insulator-semiconductor cell.

Table 5.4/1 (11)

Representative efficiencies of solar cells with concentration, as tested at Arizona State University at 28°C

Manufacturer	Cell Area, cm^2	Cell Geometry	Efficiency at One Sun, percent	Open Circuit Voltage at One Sun, V	Peak Efficiency, percent	Approximate Concentration at Peak Efficiency, suns
Applied Solar Energy Co., City of Industry, Calif.	6.32	Square	14.9	0.590	16.6	20
Applied Solar Energy Co.	2.75	Rectangle	12.4	0.56	19.2	30
Motorola, Phoenix, Ariz.	10.18	Rectangle	15.3	0.610	18.6	40
Solar Energy Research Associates, Palo Alto, Calif.	0.32	Circle	12.2	0.587	16.5	90
Solarex, Rockville, Md.	19.48	Circle	12.0	0.597	15.2	60
General Electric, Philadelphia, Pa.	12.00	Rectangle	12.2	0.574	14.1	17
RCA, Princeton, N.J.	0.22	Circle	13.5	0.563	17.8	250

Table 5.4/2 (13)



A typical solar cell designed especially for concentrating applications shows essentially constant efficiency between 10 and 100 suns. The cell, made by the Applied Solar Energy Co., City of Industry, Calif., has a surface of 2.75 cm^2 and is 50 μm thick.

Figure 5.4/2 (13)

Figure 5.4/3 indicates the relationships of efficiency of a photo voltaic cell with cell temperature. The effect of temperature increase is to lower the cell efficiency. This factor must be accounted for is a SHARP is to be partially or totally powered by solar energy.

5.4.2 Electro-Chemical Power

5.4.2.1 Introduction

The requirement for a stored source of energy on a vehicle such as SHARP is self evident. If all other sources of power should fail or otherwise not be available, i.e. it is night or the μ-wave beam power fails or the platform is blown off the beam, power must be available to control the platform.

5.4.2.1 Batteries

The most common form of stored energy is the electro-chemical storage cell - the battery. Recent interest in energy conservation and utilization has prompted research and development in the electro-chemical storage cell. Table 5.4/3 lists some of the more promising storage cell types and characteristics. The table attempts to list them in a time frame, i.e. Near Term, Advanced-Several Years, or Research and Development-Long Term.

For the purposes of this study, only the near term and advanced will be considered. Figure 5.4/4 shows the relationship of specific power vs specific energy of batteries for near term and advanced classified batteries.

The SHARP concept would use a battery in the starting battery category. This requirement is based on the requirement for a moderately high specific energy for continuous use and to

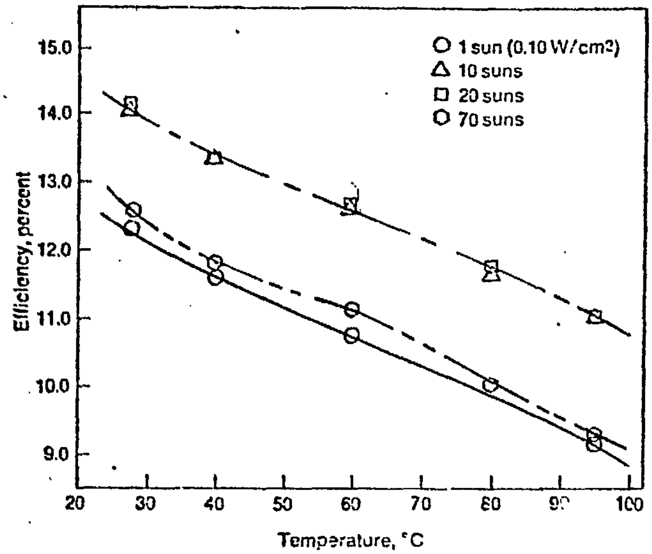
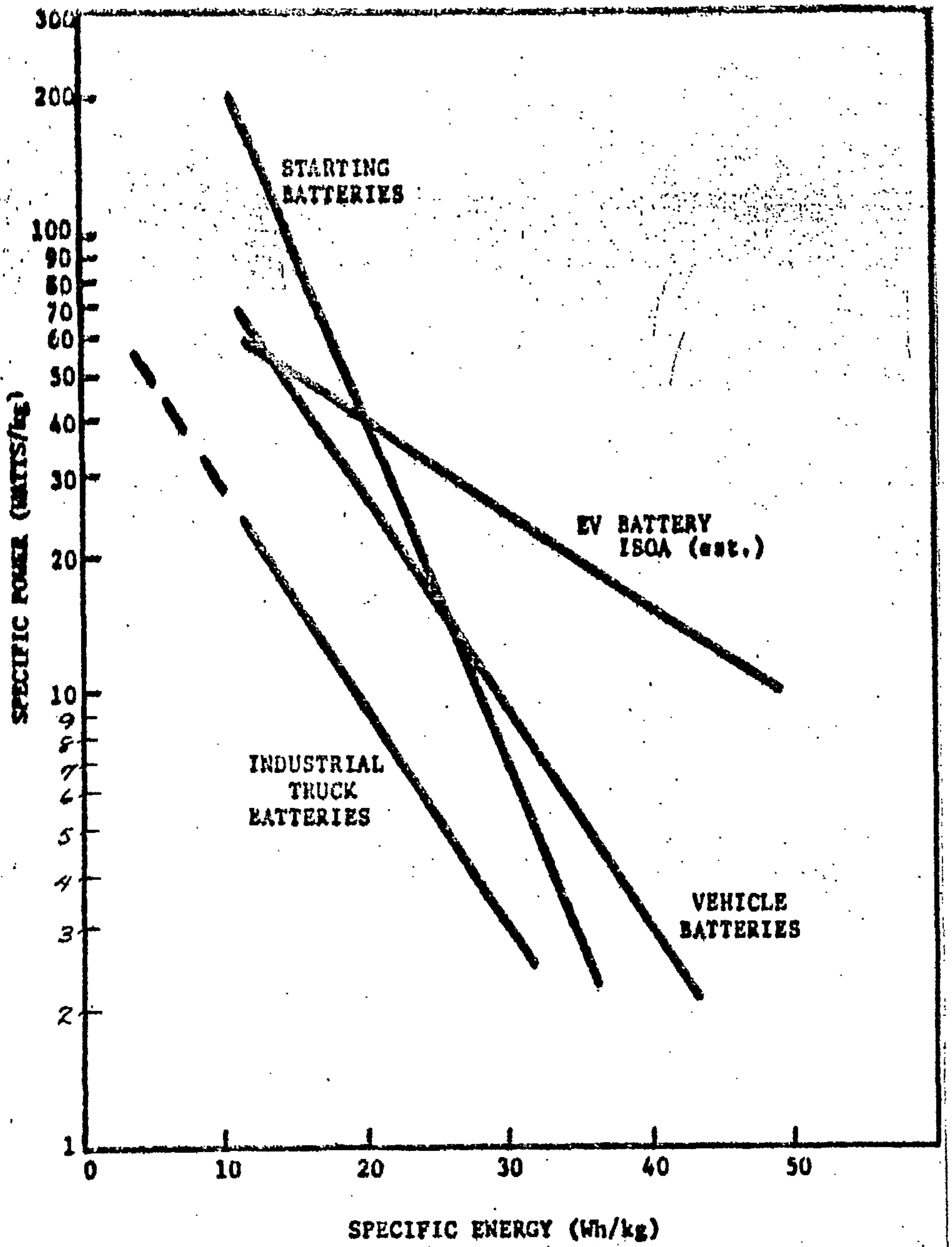


Figure 5.4/3 (13) Measurements of a typical silicon concentration cell from General Electric of Philadelphia show how efficiency drops as cell temperature increases. For a given temperature, the higher the concentration, the more heat must be removed from the cell.

EXPECTED DEVELOPMENT	STORAGE SYSTEM	OPEN CIRCUIT VOLTAGE ($V_{o.c.}$)	(a) SPECIFIC ENERGY (Whr/Kg)				(b) SPECIFIC POWER (W/Kg)		
			THEORITICAL	ACTUAL	150A	ADVANCED	ACTUAL	150A	ADVANCED
NEAR TERM	LEAD - ACID	2.08	175	26	40	60	REF. FIG.	100	150
	NICKEL - IRON	1.37	266	50		60	150		175
	NICKEL - ZINC	1.70	351	70		70	125		> 125
ADVANCED	LITHIUM - METAL SULFIDE			TABLE 3.2/2		TABLE 3.2/3			TABLE 3.2/3
	ZINC - CHLORINE	2.12	834						
R & D	IRON - AIR	1.17	698			140			100
	LITHIUM - AIR	3.45	13300						
	ALUMINIUM - AIR	2.75	8195						
	ZINC - BROMIDE	1.83	435						
	HYDROGEN - CHLORINE	1.33	978						
	REDOX								
	FERRIC FERROUS	1.18	111						
	IRON REDOX COUPLE	1.18	145						

(a) C/3 RATE DISCHARGE : 8HR CHARGE. The 3 hr rate is defined as a 3 hr capacity of a battery to 1.75V/cell @ 26.7°C
(b) PEAK BATTERY : 15 sec. average

Table 5.4/3 (15)



SPECIFIC ENERGY (Wh/kg) CHARACTERISTICS OF VEHICLE BATTERIES (C&D)

Figure 5.4/4 (15)

have a moderately high specific power capability to meet high demand requirements, i.e. wind gusts. These types of batteries are presently available in the marketplace.

One interesting battery that is in the advanced category is shown on Tables 5.4/4 and 5.4/5. A battery of this type would be ideal for the SHARP requirements having high specific power and energy characteristics.

Figure 5.4/4 and Tables 5.4/4 and 5.4/5 indicate that stored power is feasible for the SHARP. Consideration for packaging to protect the batteries have not been addressed here but are a prime consideration in the design of a SHARP Power System.

PROJECT PERFORMANCE OF MARK I BATTERIES

Eagle-Picher Industries

	Mark IA	Mark IB
Type of Battery	LiAl/FeS	LiAl/FeS
Capacity, kW-hr	40	50
Specific Energy, W-hr/kg	60	75
Maximum Volume/L	400	400
Maximum Heat Loss, W	400	400
Delivery Date	February 1979	December 1979

TABLE 5.4/4 (15)

PROGRAM GOALS FOR THE LITHIUM/IRON SULFIDE ELECTRIC VEHICLE BATTERY

	1979 Mark I	1981-83 Mark II	1983-86 Mark III	Long-Range
Specific Energy, Wh/kg				
Cell (average)[a]	100	125	160	200
Battery	75	100	130	155
Energy Density, Wh/liter				
Cell (average)	320	400	525	650
Battery	100	200	300	375
Peak Power, W/kg[b]				
Cell (average)[a]	100	125	200	250
Battery	75	100	160	200
Jacket Heat Loss, W	300	150	125	75-125
Lifetime				
Deep Discharges	400	500	1000	1000
Equivalent Miles	40000	60000	150000	200000

[a] Individual cells for Mark I will have 10 percent excess capacity and power above that shown to allow for cell failures and mismatching; individual cells, for Mark II will have 4 percent excess capacity and power.

[b] Peak power sustainable for 15 sec at 0 to 50 percent of battery discharge; at 80 percent discharge, peak power is to be 70 percent of value shown.

TABLE 5.4/5 (15)

5.5 Laser Power System

The possibility of transporting large quantities of power using microwaves has already been discussed and it is inevitable that even higher frequency waves and, in particular, light waves, should be considered. Lasers produce very intense beams of coherent light and one capable of transporting energy.

A laser power system has a configuration similar to that of the microwave power system. AC power is first converted to DC which is then used to power the laser beam generator. The resulting beam of coherent light is transmitted by reflection off a suitable mirror. At the receiving end, laser light can be converted to useful energy in three different ways:

(1) The beam can be used to drive a high efficiency heat engine.

(2) It can be converted to DC using optical diodes - in this case the principle of operation is similar to that of the rectenna.

(3) The beam can be converted to DC by photo voltaic cells tailored to the laser frequency.

However, the conversion efficiencies of these three processes do not match their microwave counterpart - maximums of 60%, 80% and 40% respectively have been quoted (17).

The principal advantage of laser light stems from its extremely short wavelength. Light waves in the visible and near infra-red regions of the electromagnetic spectrum have wavelengths for orders of magnitude smaller than microwaves. This means that extremely narrow beams can be generated from very small apertures. Since the aperture area decreases as the square of the wavelength, there is a decrease by a factor of 10^{f} in the size of the corresponding microwave structures (16). The attendant decrease in weights and dimensions of the transmitting and receiving antennas are great advantages indeed.

As an alternative to microwave power transmission, lasers offer one further important potential benefit - the laser option is not subject to concerns regarding the possibility of long term low level microwave energy effects on the environment. However, the much larger energy densities of laser beams create greater risks of damage to objects passing through them. Unlike microwaves, which penetrate deeper and therefore heat from within, laser light is absorbed at the surface only. It is expected, however, that the much narrower laser beam will require a much smaller safety zone and adequately fast positioning mechanisms will allow rapid repointing of the beam to harmless directions if objects should approach the safety zone.

At present, there are several major problems plaguing this option, the most serious of which is the low operating efficiency. The conversion from DC into a laser beam is the most inefficient link in the chain. It is believed that a conversion efficiency exceeding 50% may be difficult to achieve. The current state of the art continuous operation lasers such as CO_2, EDLs (electronic discharge lasers) can claim no more than about 20-30% (2).

One other important drawback of the laser option is that weather will be much more of a problem that it would be for microwaves. Rain, snow, clouds, and other particulate matter cause much greater beam absorption and scatter. The receiving stations would have to contend with power outages which would be more frequent and of longer duration.

Given these serious drawbacks and the fact that the laser technology is still comparatively young, it is unlikely that lasers would be a viable alternative for powering the SHARP in the near future.

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6.0 SHARP PROPULSION

6.1 Introduction

The SHARP concept implies that the craft will be able to propel itself against the upper atmospheric winds in order to remain in a quasi-static position. The purpose of this section is to consider the various types of propulsive systems currently available and to assess which would suit the SHARP craft most economically and practically.

6.2 Propellers

Since the SHARP will be at an altitude where there is atmosphere, admittedly quite thin, it is logical to think of propulsion by means of propellers. The technology for propeller design and fabrication is readily available in Canada.

The recent success of the Solar Challenger indicates that very efficient propellers may be developed for slow rotating propeller system. The estimated efficiency of 86% is quite high for the 3.35 m (11 ft.) diameter propeller, which weighs 1.45 kg (3.2 lb) (1). This efficiency is achieved by making the propeller from a graphite-epoxy composite material and having a manual pitch control (2). It is then possible to have the propeller tailor-made for the SHARP application without having to require expensive tooling of fabrication processes.

6.3 Motors

As discussed in Chapter 5, the most suitable power for propulsion of the SHARP vehicle will be derived from beamed microwave power, with possible solar power augmentation, and/or on board batteries. This implies that the primary source of on board power will be electric. Recent development of the Delco Samarium-Cobalt brushless DC motor with a power to mass ratio of 1.44 KW/kg (874×10^{-3}HP/lb) makes it possible to use electrical energy efficiently (3). This development is considered to be one of the key technical factors influencing the feasibility of the mission.

The Solar Challenger used a similar type of motor with a power to mass ratio of 548 W/kg (333×10^{-3}HP/lb) (2). This motor was developed specifically for the Solar Challenger by Astro Flight Inc.

Propulsion Power vs Mass

In order to estimate the weight of motors needed to propel the SHARP vehicle, we have extrapolated the stated propulsion power/ mass characteristics of each of these motors to the power levels required. (This relationship is defined by the parameter C_6 of Table 7.2/1.

The Solar Challenger's Astro Flight propulsion unit has the following characteristics:

Motor mass:	6.8 kg
Motor mount, gearing and propeller control:	4.5 kg
	11.3 kg (25 lb)
Power output at 66V nominal:	3.73×10^3W (5 hp)

We assume that, by appropriate design, we can combine motors to increase the available power in the following manner:

For a single motor:

$$\frac{1\ (6.8\ \text{kg}) + 1\ (4.5\ \text{kg})}{5\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{11.3\ \text{kg}}{3.73 \times 10^{3}\text{W}} = 3.041 \times 10^{-3}\text{kg/W}$$

For a group of two motors:

$$\frac{2\ (6.8\ \text{kg}) + 1.33\ (4.5\ \text{kg})}{10\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{19.59\ \text{kg}}{7.46 \times 10^{3}\text{W}} = 2.63 \times 10^{-3}\text{kg/W}$$

For a group of three motors:

$$\frac{3\ (6.8\ \text{kg}) + 1.66\ (4.5\ \text{kg})}{15\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{27.87\ \text{kg}}{11.19 \times 10^{3}\text{W}} = 2.49 \times 10^{-3}\text{kg/W}$$

And again for four motors:

$$\frac{4\ (6.8\ \text{kg}) + 2\ (4.5\ \text{kg})}{20\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{31.2\ \text{kg}}{14.91 \times 10^{3}\text{W}} = 2.09 \times 10^{-3}\text{kg/W}$$

Now, if we assume the same is possible for the Delco motor and having the following breakdown:

Motor mass:	7.78 kg
Motor mount, gearing and propeller control:	6.00 kg
	13.78 kg
Power output at 300V nominal:	11.19×10^{3}W (15 hp)

Assuming we may do the same as above:

$$\frac{1\ (7.78\ \text{kg}) + 1\ (6\ \text{kg})}{15\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{13.78\ \text{kg}}{11.19 \times 10^{3}\text{W}} = 1.23 \times 10^{-3}\text{kg/W}$$

$$\frac{2\ (7.78\ \text{kg}) + 1.33\ (6\ \text{kg})}{30\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{23.54\ \text{kg}}{22.37 \times 10^3 \text{W}} = 1.05 \times 10^{-3} \text{kg/W}$$

$$\frac{3\ (7.78\ \text{kg}) + 1.66\ (6\ \text{kg})}{45\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{33.3\ \text{kg}}{33.56 \times 10^3 \text{W}} = 992.3 \times 10^{-6} \text{kg/W}$$

$$\frac{4\ (7.78\ \text{kg}) + 2.0\ (6\ \text{kg})}{60\ \text{hp}\ (745.7\ \text{W/hp})} = \frac{43.12\ \text{kg}}{44.74 \times 10^3 \text{W}} = 963.79 \times 10^{-6} \text{kg/W}$$

Tabulating the above for each motor:

Solar Challenger

W	Kg
3.73×10^3	11.3
7.46×10^3	19.59
11.19×10^3	27.87
14.91×10^3	31.20

TABLE

Delco

W	Kg
11.19×10^3	13.78
22.37×10^3	23.54
33.56×10^3	33.30
44.74×10^3	42.12

TABLE

Each of the above may be expressed in the form:

$$y = m x + b$$

For the Solar Challenger:

$$\text{Kg} = (\text{Kg/W})\ \text{W} + \text{Kg}$$

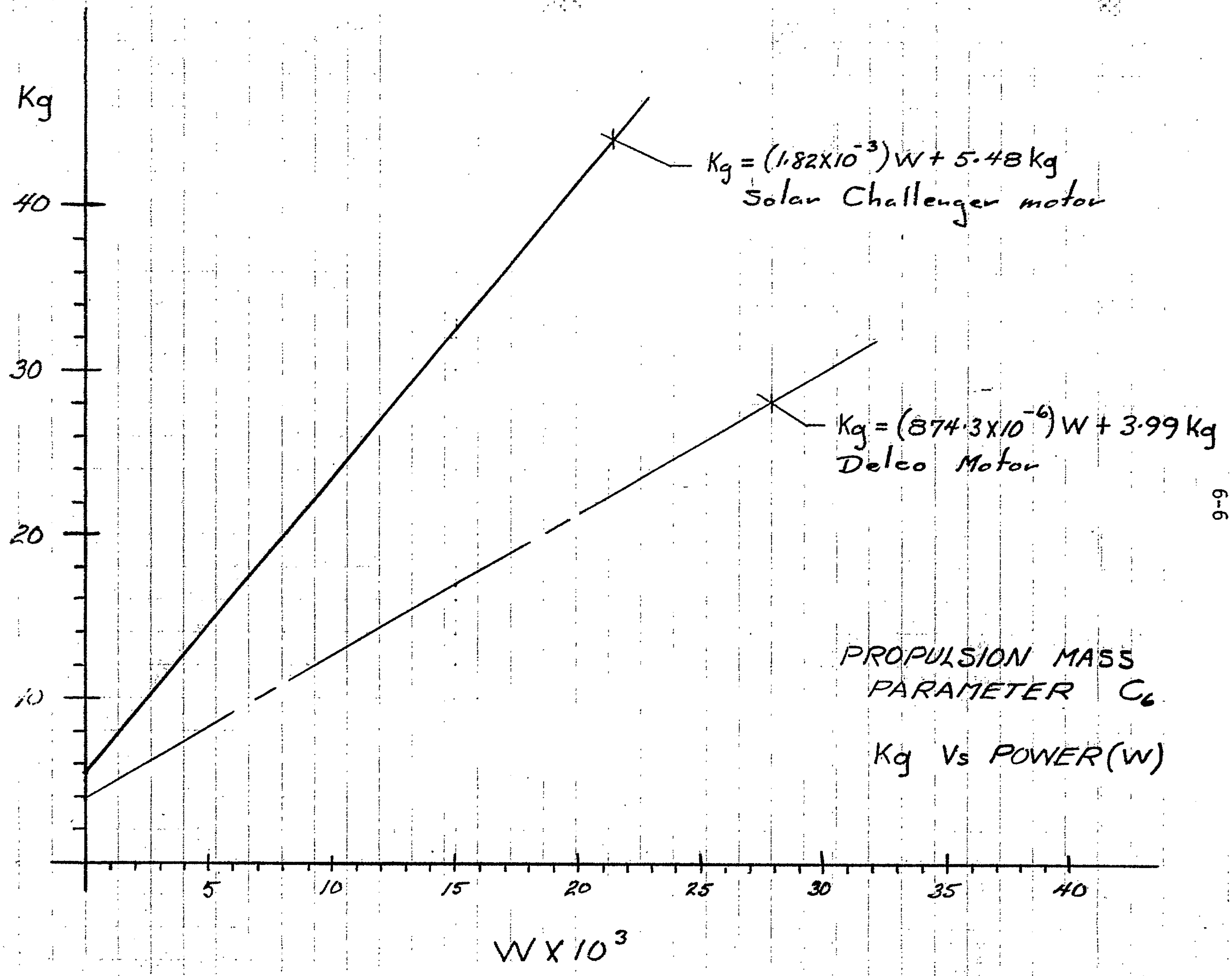
$$\text{Kg} = (1.82 \times 10^{-3})\text{W} + 5.48\ \text{Kg}$$

For the Delco motor:

$$\text{Kg} = (\text{Kg/W})\ \text{W} + \text{Kg}$$

$$\text{Kg} = (874.3 \times 10^{-6} \text{Kg/W})\text{W} + 3.986$$

Each of these equations are presented graphically on Figure 6.3/1.



Kg
40
30
20
10
5
10
15
20
25
30
35
40
W X 10^3
Kg = (1.82X10^-3) W + 5.48 Kg
Solar Challenger motor
Kg = (874.3X10^-6) W + 3.99 Kg
Delco Motor
PROPULSION MASS
PARAMETER C6
Kg Vs POWER (W)

FIG. 6.3/1

The results of this analysis is that the propulsion mass parameter C_6 is quite divergent, depending on the motor chosen. The most conservative is the less powerful motor, i.e. the Challenger based motor with a coefficient of $C_6 = 1.82 \times 10^{-3}$ Kg/W. The constant of 5.48 Kg may be added to the constant terms in the eg for completeness.

The Delco motor based parameter is <u>not</u> ideal because the cost and availability will probably be prohibitive. However, the increase in the development and use of these motors will probably increase due to their superior performance.

The Delco samarium-cobalt motor performance data is presented on Figure 6.3/2. From this data we may tabulate current vs horsepower which is shown on Table 6.3/1.

Using the relationship:

$$I = \frac{(745.7 \text{ W/hp})\ (\text{hp})}{\eta\ E} \qquad (1)$$

where:
- I = current (amperes)
- η = efficiency, %
- E = motor voltage (volts)
- hp = horsepower

The current vs horsepower plot for the 5 hp motor used on the Solar Challenger may be developed, as follows:

Assuming an efficiency of 86% and the stated nominal voltage of 66 VDC, we may write:

$$I = \frac{(745.7 \text{ W/hp})\ (5 \text{ hp})}{(.86)\ (66)} = \underline{65.69} \text{ Amp}$$

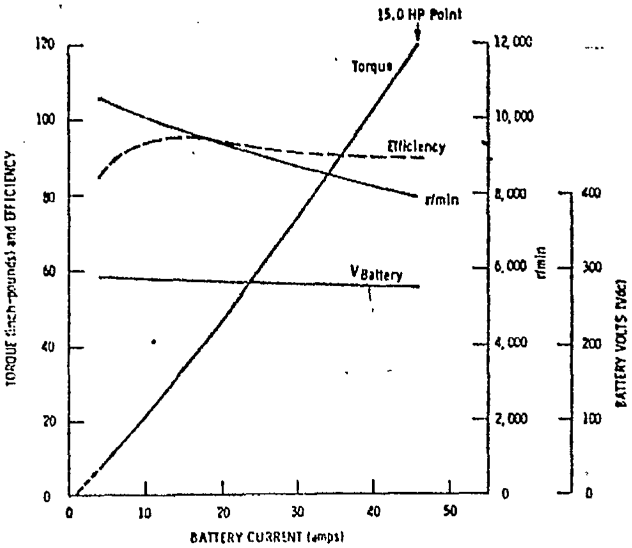


Figure 6.3/2 *Motor Performance Data* (3)

Current (Amp)	Efficiency %	r p m	Battery Volt	Torque (in-lb)	HP
10	93	10,100	290	21	3.37
17.5	95	9400	287.5	38	5.67
20	93.5	9350	285	46	6.82
30	90	8650	282.5	73.5	10.09
40	89.5	8250	280	102	13.35
46	89	7900	277.5	120	15.04

Table 6.3/1 Delco Samarium-Cobalt Performance Data

However, this is more than the solar cell array on the Challenger may develop, i.e. 3000 W at 66 VDC or 45.45 Amp. If we use this current we may then calculate the horsepower available:

$$hp = \frac{I\ E\ \eta}{745.7} = \frac{(45.45)\ (66)\ (.86)}{745.7} = 3.46$$

Again, for various amperages we may tabulate horsepower vs current using the above formula.

hp	Amp
3.46	45.45
2.80	36.95
0.685	9.0

This relationship is shown on Figure 6.3/2 for both the Solar Challenger and Delco motor.

Motor Commutator

The transistor circuit, shown in Figure 6.3/4, Q1 through Q6 performs the commutator function with Qm, L1 and Dm providing the chopper circuit. Inductor L1 filters the chopper (Qm) current to the motor and uses free wheeling diode Dm to permit current flow from the stored energy in the inductor when Qm is off.

In braking, Qm is "off", Q6 is "on", which causes current to flow through L1 in the reverse direction.

When Q_b is turned "off" the inductive voltage W adds to the dc voltage from the motor (acting as an alternator) and exceeds the supply voltage E_b. When this occurs, current flows back into the battery via diode D_r until the battery voltage exceeds the sum of these two voltages or the motor current level drops below the commanded level.

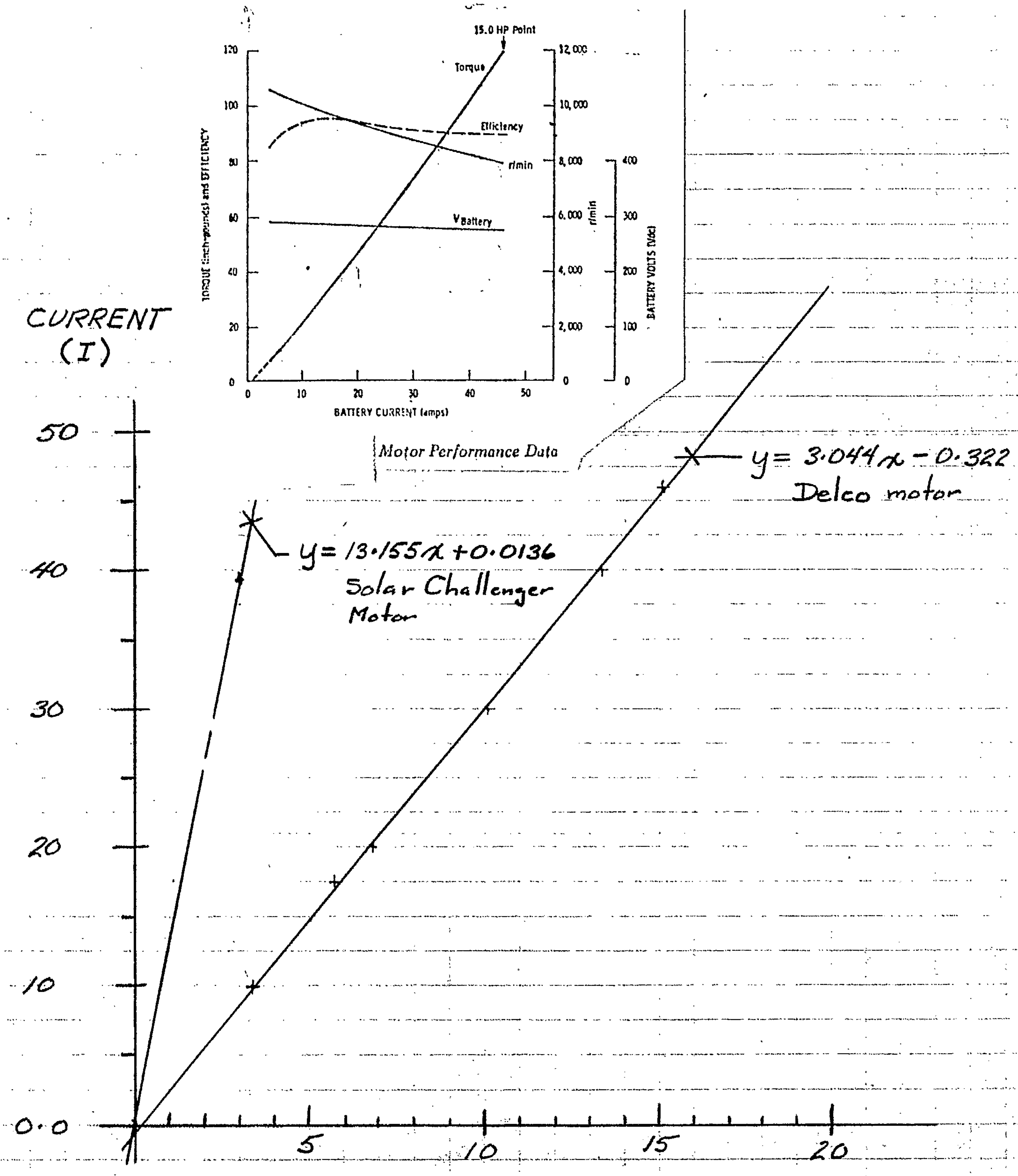
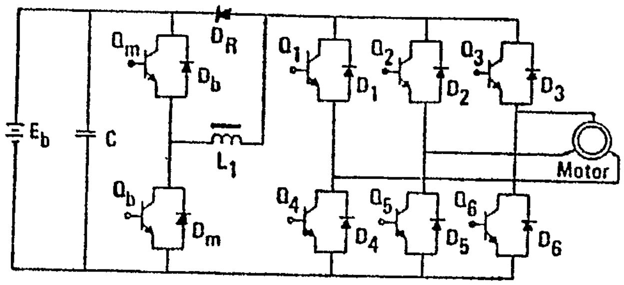


Figure 6.3/3 CURRENT Vs HORSEPOWER FOR SAMARIUM COBALT BRUSHLESS DC MOTOR



Power Electronics Circuits (3)

Figure 6.3/4

6.4 Chemical Engines

The use of internal combustion or Turbojet engines has been considered. However, the fact that fuel must be carried on board for the entire mission mitigates against further consideration of either option for a SHARP mission of many weeks duration.

In addition, internal combustion engines have high internal friction and accessory power requirements and consequently were dismissed for use as the primary power source (5).

Turbojets have much better fuel performance than internal combustion engines. High altitude turbojet engines are available, however, their design has been directed primarily toward military application and specific details are not readily available (6).

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7.0 PLATFORM CONFIGURATION

7.1 Introduction

The candidate aircraft for the SHARP mission are:

- A traditionally-shaped airship (this may be rigid, semi-rigid, or non-rigid). Reference Figure 1/1.

- A hybrid wing-balloon - this is a lighter-than-air craft that has wing-type shape to give aerodynamic lift. Reference Figure 1/2. This shape of craft has been studied for use in the logging industry.

- An airplane. This configuration was chosen because of the advent of a "New" class of aircraft with very light construction methods, such as the "Solar Challenger" which flew across the English Channel this year and demonstrated the feasibility of this type of lightweight structure.

The parametric analysis of each of these configurations was performed by Dr. James De Laurier of the University of Toronto, Institute for Aerospace Studies.* For the sake of conciseness, in this section only the parametric equations and coefficients will be presented. The complete analysis will be found in Appendix A.

* To determine the propulsive power and size for various wind velocities.

g = gravitational constant

M_T = vehicle total mass (including internal air and gas)

T = propulsive thrust

P = power required for equilibrium flight

Pob = power used by onboard equipment (payload and control system)

U_{max} = maximum speed, relative to the wind, that the vehicle has to maintain to keep from being blown off station

$M_{structure}$ = the mass of the complete vehicle excluding engines, payload, control system or internal batteries (airframe mass)

M_{ia} = the mass of the air in a lighter-than-air craft envelope

M_{gas} = the mass of the lifting gas in the envelope of a lighter-than-air craft

M_{pl} = the mass of the communications payload on board the craft

M_{ps} = the mass of the propulsion system consisting of motor, propeller, structural supports and gearing

M_{cs} = the mass of the control system required to control the craft

M_{power} = the mass of the power system. For the SHARP vehicle it will consist of:

the microwave rectenna and/or the solar array and the on board batteries consequently;

$$M_{power} = M_{\mu p} + M_{sp} + M_b$$

$M_{\mu p}$ = the mass of the microwave rectenna array

M_{sp} = the mass of the solar array

M_b = the mass of the on board batteries

The above equations may be utilized to write relationships among the various parameters of each aircraft and its characteristic size. Figures 7.2/1 and 7.2/2 are these relationships, which are shown in more detail in Appendix A. The coefficients C_1 through C_{11} are defined on Table 7.2/1. The remaining parameters will be addressed in the following sections.

Throughout these parametric studies, it should be noted that the power is assumed to be supplied by microwave. These studies have not included the use of solar power to any extent. Consequently, the performance coefficient C_9 is zero throughout.

$$C_L q S + \rho g \, Vol = M_T g \qquad (1)$$

$$Vol = C_1 S^{3/2} \qquad (2)$$

$$P_{max} = C_D S \, q_{max} U_{max} / \eta_P \qquad (3)$$

$$q = \rho U^2/2 \qquad (4)$$

$$M_T = M_{STRUCTURE} + M_{ia} + M_{gas} + M_{pl} + M_{ps} + M_{cs} + M_{power} \qquad (5)$$

$$C_L q S/g + \rho Vol = M_T = C_2(Vol) + C_3(Vol) + C_4(Vol) + C_5 + C_6 P_{max} + C_7 + C_8[P_{max} + P_{oe}] + C_9[P_{max} + P_{oe}] + C_{10}[P_{max} + P_{oe}]\Delta t$$

$$\begin{aligned} C_L(\rho U^2/2)S/g + \rho(C_1 S^{3/2}) = {} & C_2(C_1 S^{3/2}) + C_3(C_1 S^{3/2}) + \rho(RATIO)(C_1 S^{3/2}) + C_5 + C_6(C_D S(\rho U_{max}^2/2)U_{max}/\eta_P + C_7 \\ & + C_8[C_D S(\rho U_{max}^2/2)U_{max}/\eta_P + P_{oe}] + C_9[C_D S(\rho U_{max}^2/2)U_{max}/\eta_P + P_{oe}] \\ & + C_{10}[C_D S(\rho U_{max}^2/2)U_{max}/\eta_P + P_{oe}]\Delta t \end{aligned} \qquad (19)$$

$$\begin{aligned} & C_1 \rho S^{3/2} - C_1 C_2 S^{3/2} - C_1 C_3 S^{3/2} - C_1 \rho(RATIO) S^{3/2} + C_L \rho U^2 S/2g - C_6 C_D \rho U_{max}^2 U_{max} S/2\eta_P - C_8 C_D \rho U_{max}^2 U_{max} S/2\eta_P \\ & - C_9 C_D \rho U_{max}^2 U_{max} S/2\eta_P - C_{10} C_D \rho U_{max}^2 U_{max} \Delta t \, S/2\eta_P - C_5 - C_7 - C_8 P_{oe} - C_9 P_{oe} - C_{10} P_{oe} \Delta t = 0 \end{aligned}$$

$$\begin{aligned} & [C_1 \rho - C_1 C_2 - C_1 C_3 - C_1 \rho(RATIO)] S^{3/2} + [C_L \rho U^2/2g - C_6 C_D U_{max}^3/2\eta_P - C_8 C_D \rho U_{max}^3/2\eta_P - C_9 C_D \rho U_{max}^3/2\eta_P - C_{10} C_D \rho U_{max}^3 \Delta t/2\eta_P] S \\ & - [C_5 + C_7 + C_8 P_{oe} + C_9 P_{oe} + C_{10} P_{oe} \Delta t] = 0 \end{aligned}$$

THIS EQUATION HAS THE FORM OF:

$$A S^{3/2} + B S + C = 0$$

WHERE:

$$A = [C_1 \rho - C_1 C_2 - C_1 C_3 - C_1 \rho(RATIO)]$$

$$B = [C_L \rho U^2/2g - C_6 C_D U_{max}^3/2\eta_P - C_8 C_D \rho U_{max}^3/2\eta_P - C_9 C_D \rho U_{max}^3/2\eta_P - C_{10} C_D \rho U_{max}^3 \Delta t/2\eta_P]$$

$$C = -[C_5 + C_7 + C_8 P_{oe} + C_9 P_{oe} + C_{10} P_{oe} \Delta t]$$

FIGURE 7.2/1

$$C_L\, q\, S = M_T\, g \qquad (1)$$

$$P_{max} = C_D\, S\, q_{max}\, U_{max}/\eta_p \qquad (3)$$

$$q = \rho U^2/2 \qquad (4)$$

$$M_T = M_{STRUCTURE} + M_{pl} + M_{ps} + M_{cs} + M_{power} \qquad (5)$$

$$C_L(\rho U^2/2)S/g = C_{11} S + C_5 + C_6(C_D S(\rho U_{max}^2/2)U_{max}/\eta_p + C_7 + C_8[C_D S(\rho U_{max}^2/2)U_{max}/\eta_p + P_{oe}]$$
$$+ C_9[C_D S(\rho U_{max}^2/2)U_{max}/\eta_p + P_{oe}] + C_{10}[C_D S(\rho U_{max}^2/2)U_{max}/\eta_p + P_{oe}]\Delta t$$

$$[C_L \rho U^2/2g - C_{11} - C_6 C_D \rho U_{max}^3/2\eta_p - C_8 C_D \rho U_{max}^3/2\eta_p - C_9 C_D \rho U_{max}^3/2\eta_p - C_{10} C_D \rho U_{max}^3 \Delta t/2\eta_p]\, S$$
$$-[C_5 + C_7 + C_8 P_{oe} + C_9 P_{oe} + C_{10} P_{oe}\Delta t] = 0$$

THIS EQUATION HAS THE FORM OF :

$$B' S + C = 0$$

WHERE :

$$B' = C_L \rho U^2/2g - C_{11} - C_D \rho U_{max}^3/2\eta_p (C_6 + C_8 + C_9 + C_{10}\Delta t)$$

$$C = -[C_5 + C_7 + C_8 P_{oe} + C_9 P_{oe} + C_{10} P_{oe}\Delta t]$$

FIGURE 7.2/2

SHARP PERFORMANCE COEFFICIENTS

COEFFICIENT UTIAS	COEFFICIENT SED	DEFINITION	PARAMETRIC VALUE OR RANGE INITIAL	PARAMETRIC VALUE OR RANGE REFINED	UNIT	COMMENT
C_1	C_1	Shape Parameter	1.0 & 0.1828	1.0 & 0.1828	Dimensionless	AIRSHIP & HYBRID
C_2	C_2	Volumetric Mass Parameter	0.056-0.047-0.039	0.01 — 0.1	Kg/m^3	
	C_3	Internal Air Ratio	≈0.0	≈0.0	Kg/m^3	Taken to be at Float Altitude
	C_4	Lift Ratio $(\rho_a - \rho_g \%)$(helium)	1−0.862 %	1−0.862 %	Kg/m^3	% = 98
GIVEN	C_5	PAYLOAD MASS	60	25	Kg	Payload Dependent on Mission
C_3	C_6	Propulsion Mass Parameter	7.091×10^{-3}	9.4×10^{-4}	Kg/W	+3.3 Kg Constant term
GIVEN	C_7	Control System Mass	42.85	18	Kg	
C_4	C_8	Power System: $M_{\mu p}$	1.1803×10^{-3}	1.1803×10^{-3}	Kg/W	Evaluated at $500 W/m^2$
	C_9	Power System: M_{sp}		7.567×10^{-3}	Kg/W	Evaluated at $1.09 KW/m^2$
C_5	C_{10}	Power System: M_b	9.0×10^{-6}	9.0×10^{-6}	Kg/Joule	
C_6	C_{11}	WING LOADING	2.00	2.50	Kg/m^2	Stabilizer operates 1/2 Wing Lift

TABLE 7.2/1

7.3 Airship Analysis

Two types of airships were analyzed. The first is neutrally-buoyant and the second, which is geometrica-ly identical, has an aerodynamic lift by virtue of flying "heavy" at an angle of attack.

The airships' performance were analyzed by varying certain parameters such as mean and maximum speeds, battery duration, and airframe density (structural-mass parameter). The coefficients used are shown in Table 7.3/1 and 7.3/2 for the two vehicles. By utilizing these parameters, and the parameters on Table 7.2/1, with equation (21) shown on Figure 7.2/1, the airship performance and size may be related to the structural-mass parameter.

7.3.1 Neutrally-Buoyant Airship

The performance coefficients used in the analysis of the neutrally-bouyant airship are listed on Table 7.3/1.

The parametric-analysis results are shown in Figures 7.3/1, 7.3/2, and 7.3/3, with some surprising results. The volume and vehicle area do not change significantly, in the lower region of the structural-mass parameter, with respect to the wind velocity U_{max}. Beyond a value of 0.03 Kg/m^3, these characteristics change rapidly and reach an asymptotical mass parameter limit of approximately 0.055 Kg/m^3.

When reserve power, in the form of batteries, is considered, the volume increases dramatically as shown in Figure 7.3/2.

The vehicle volume, with batteries asymptotically, approaches the vehicle structural-mass parameter 0.05 Kg/m^3.

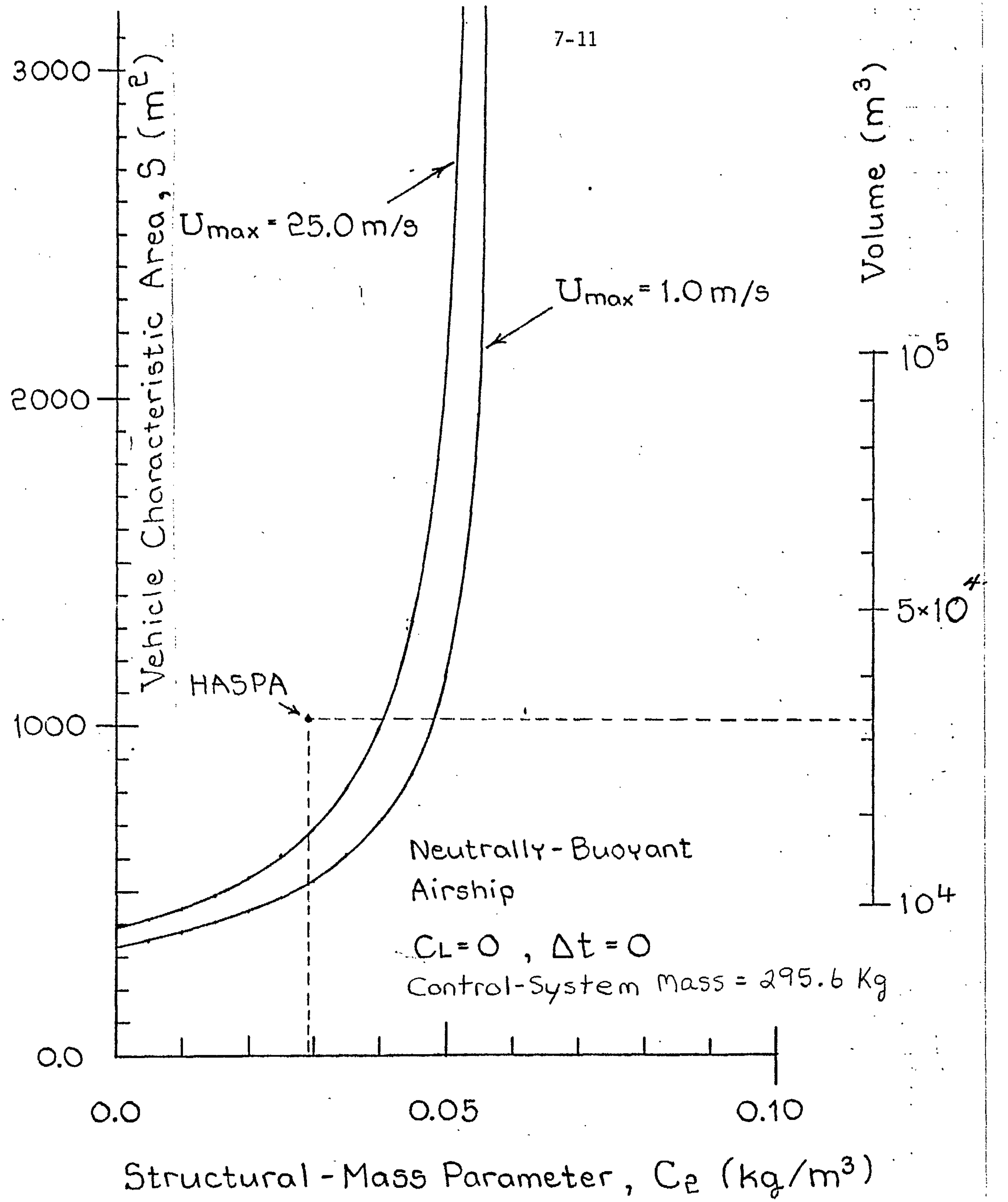
SHARP PERFORMANCE COEFFICIENTS					NEUTRALLY BUOYANT
COEFFICIENT	DEFINITION	PARAMETRIC VALUE OR RANGE		UNIT	COMMENT
		INITIAL	BASE-LINE		
C_L	LIFT COEFFICIENT	≈ 0	0.0		
ρ	ATMOSPHERIC DENSITY	0.060 – 0.080	0.07754	Kg/m^3	
C_D	DRAG COEFFICIENT	0.02 – 0.06	0.04		
U	CRUISE SPEED	1.0 – 10.0	0.0	m/sec	
U_{max}	MAXIMUM SPEED	5.0 – 50.0	10.0	m/sec	
Δt	BATTERY POWER TIME	$1.0 \times 10^3 - 10.0 \times 10^3$	3.6×10^3	sec	
η_p	PROPULSIVE EFFICIENCY	0.75 – 0.95	0.80		
P_{OB}	ON-BOARD POWER REQ'D	2295.6		W	

Table 7.3/1

SHARP PERFORMANCE COEFFICIENTS Aerodynamically-Lifting Airship

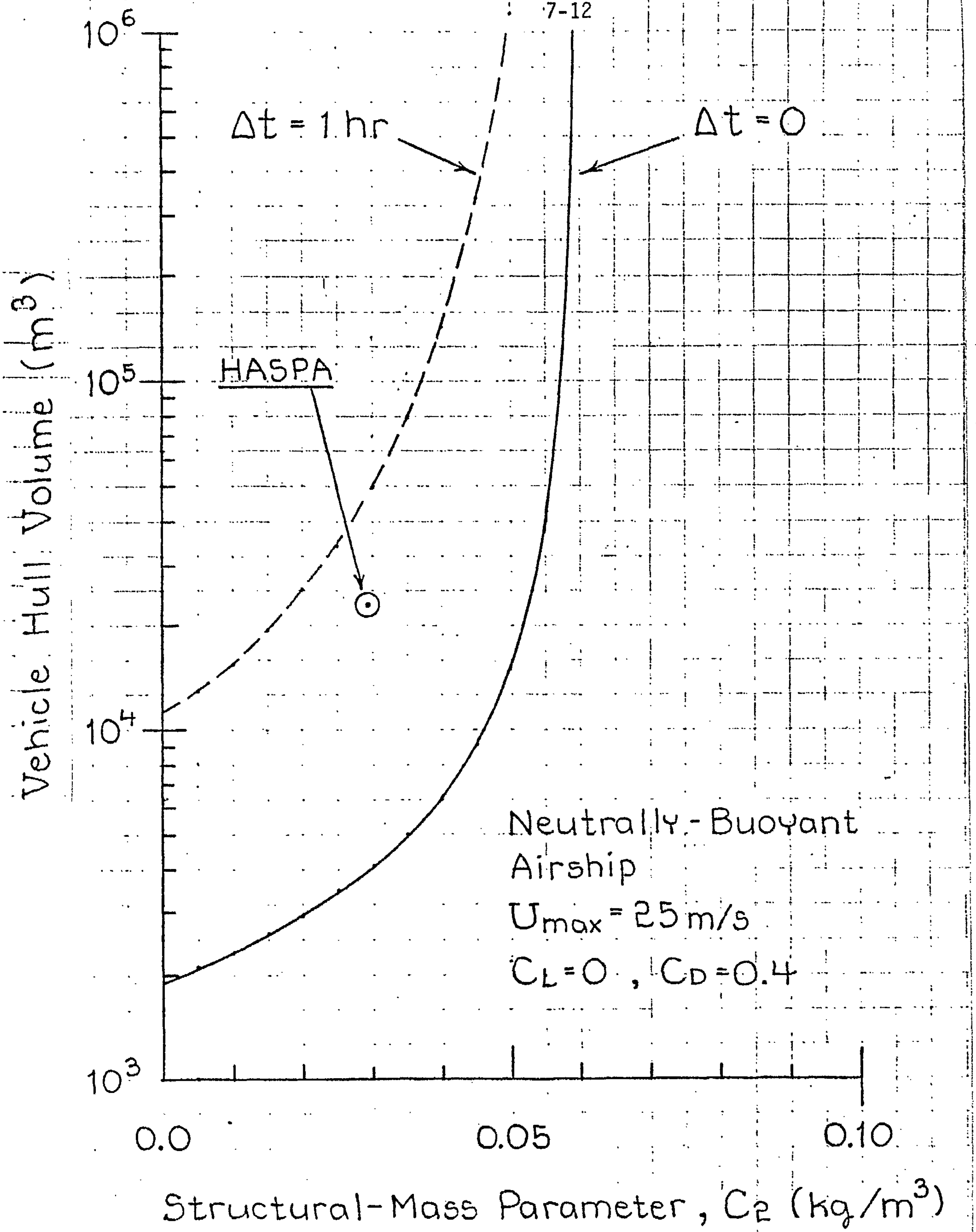
COEFFICIENT	DEFINITION	PARAMETRIC VALUE OR RANGE INITIAL	REFINED	UNIT	COMMENT
C_L	LIFT COEFFICIENT	0.0 – 1.0	0.20		
ρ	ATMOSPHERIC DENSITY	0.060 – 0.080	0.07754	Kg/m^3	
C_D	DRAG COEFFICIENT	0.020 – 0.15	0.04		
U	CRUISE SPEED	1.0 – 10.0	5.0	m/sec	
U_{max}	MAXIMUM SPEED	5.0 – 50.0	25.0	m/sec	
Δt	BATTERY POWER TIME	$1.0\times10^3 - 10.0\times10^3$	3.6×10^3	sec	
n_p	PROPULSIVE EFFICIENCY	0.75 – 0.95	0.80		
P_{OB}	ON-BOARD POWER REQ'D	2295.6		W	

Table 7.3/2



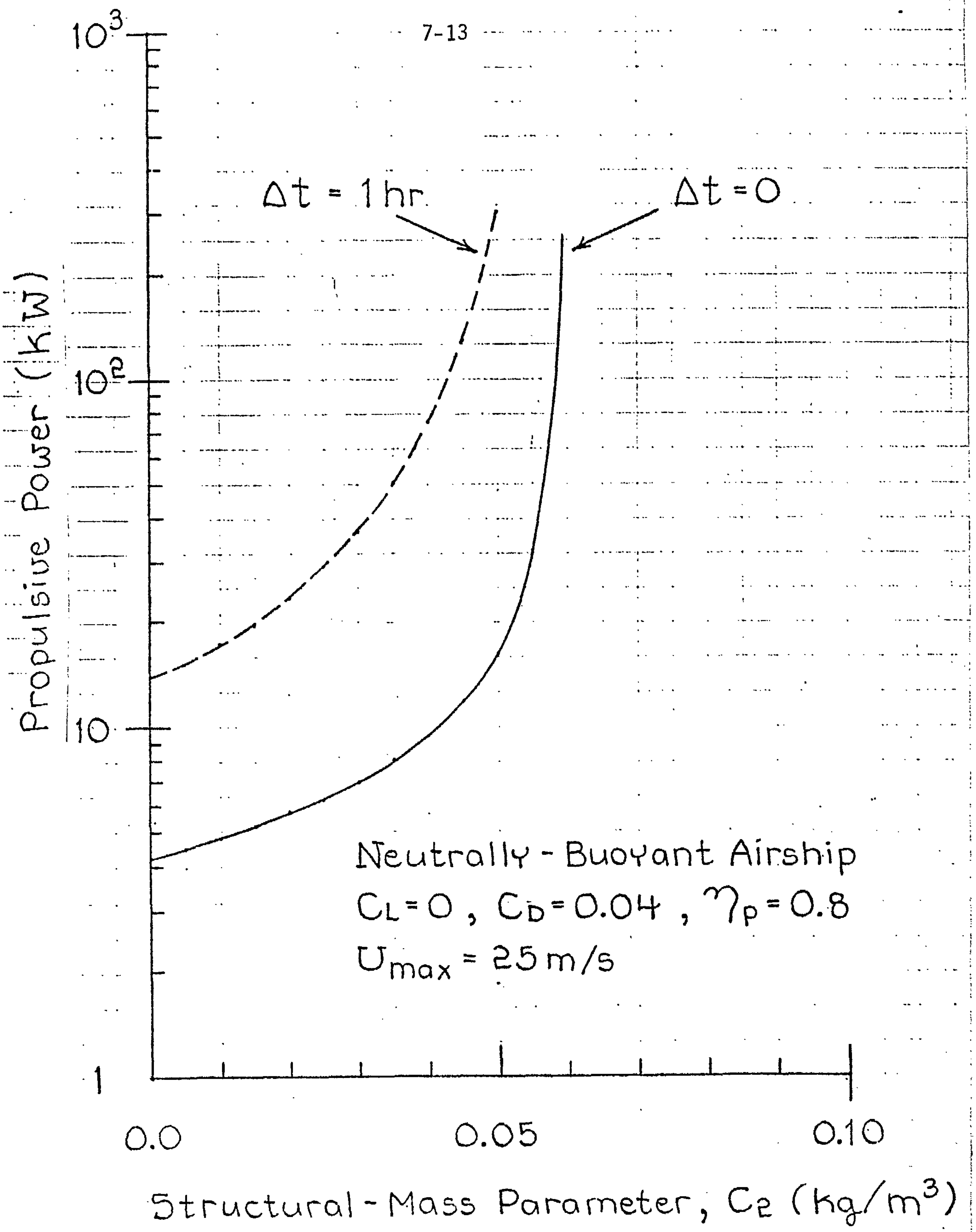
3000
2000
1000
0.0
Vehicle Characteristic Area, S (m²)
Volume (m³)
10⁵
5×10⁴
10⁴
Umax = 25.0 m/s
Umax = 1.0 m/s
HASPA
Neutrally-Buoyant Airship
CL = 0 , Δt = 0
Control-System Mass = 295.6 Kg
0.0
0.05
0.10
Structural-Mass Parameter, C2 (kg/m³)

Figure 7.3/1



10^6
10^5
10^4
10^3
Vehicle Hull Volume (m^3)
Δt = 1 hr
Δt = 0
HASPA
Neutrally-Buoyant Airship
U_{max} = 25 m/s
C_L = 0 , C_D = 0.4
0.0
0.05
0.10
Structural-Mass Parameter, C_2 (kg/m^3)

Figure 7.3/2



10^3
10^2
10
1
Δt = 1 hr
Δt = 0
Propulsive Power (kW)
Neutrally - Buoyant Airship
$C_L = 0$, $C_D = 0.04$, $\eta_p = 0.8$
$U_{max} = 25$ m/s
0.0
0.05
0.10
Structural - Mass Parameter, C_2 (kg/m^3)

Figure 7.3/3

The power required to maintain position in a 25 m/s wind is shown in Figure 7.3/3. For a structural-mass parameter of 0.04 Kg/m^3, the power requirement increases 40 times with the addition of on board battery power.

In general, these results point out that a neutrally-buoyant vehicle should be of lightweight, and hence inflatable, construction in order to minimize size and power required.

7.3.2 Aerodynamically-Lifting Airship

The aerodynamically-lifting airship is geometrically similar to the neutrally-buoyant design, however it requires a relative air velocity to maintain lift. The vehicle parameters are listed in Table 7.3/2, which were used in conjunction with equation 21 in Figure 7.2/1, and Table 7.3/1. These results are shown in Figures 7.3/4, 7.3/5, and 7.3/6.

The aerodynamic-lift capability is indicated by the fact that less volume is required to support a heavier craft (Reference Figure 7.3/4). However, the craft is still in the lightweight inflatable class as is indicated by a structural-mass parameter of approximately 0.05 Kg/m^3.

Figure 7.3/5 points out, as would be expected from the neutrally-buoyant airship's results, that a dramatic increase in volume is required to have reserve power with on board batteries.

The power requirements are reduced by the aerodynamic-lifting capability as is shown in Figure 7.3/6, as compared to Figure 7.3/3. This shows the advantage of flying the airship "heavy", even though zero-wind hover is no longer possible.

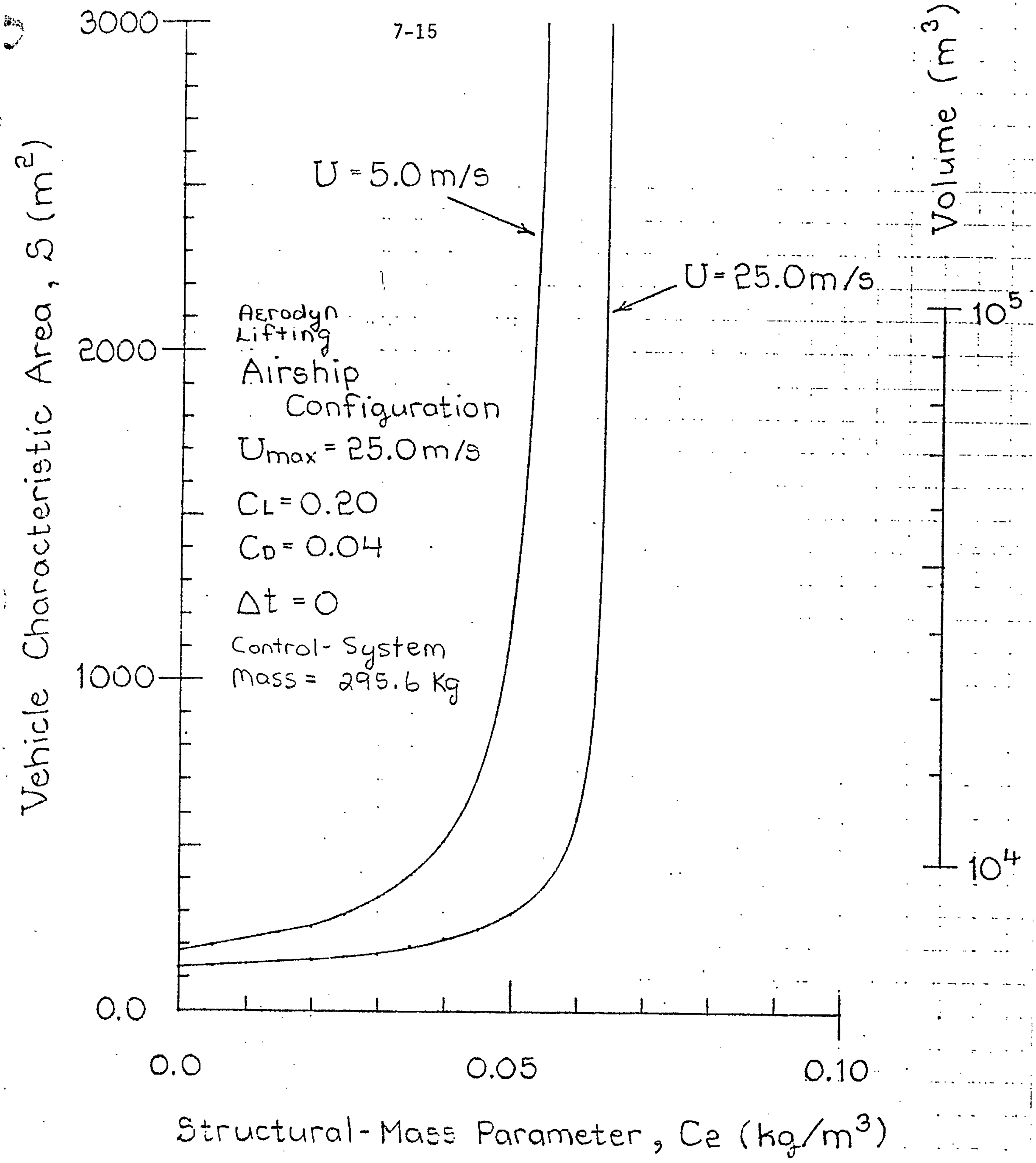
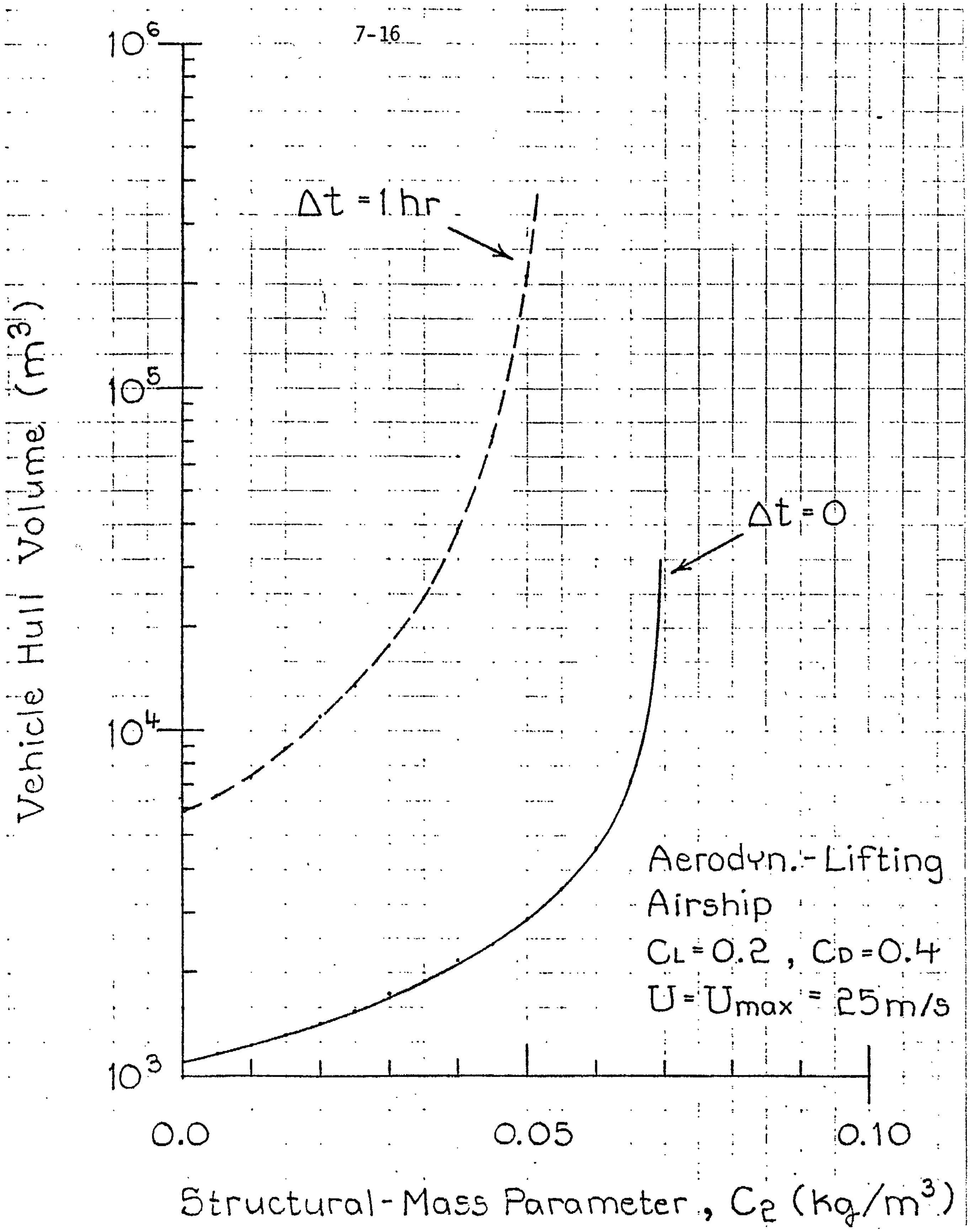
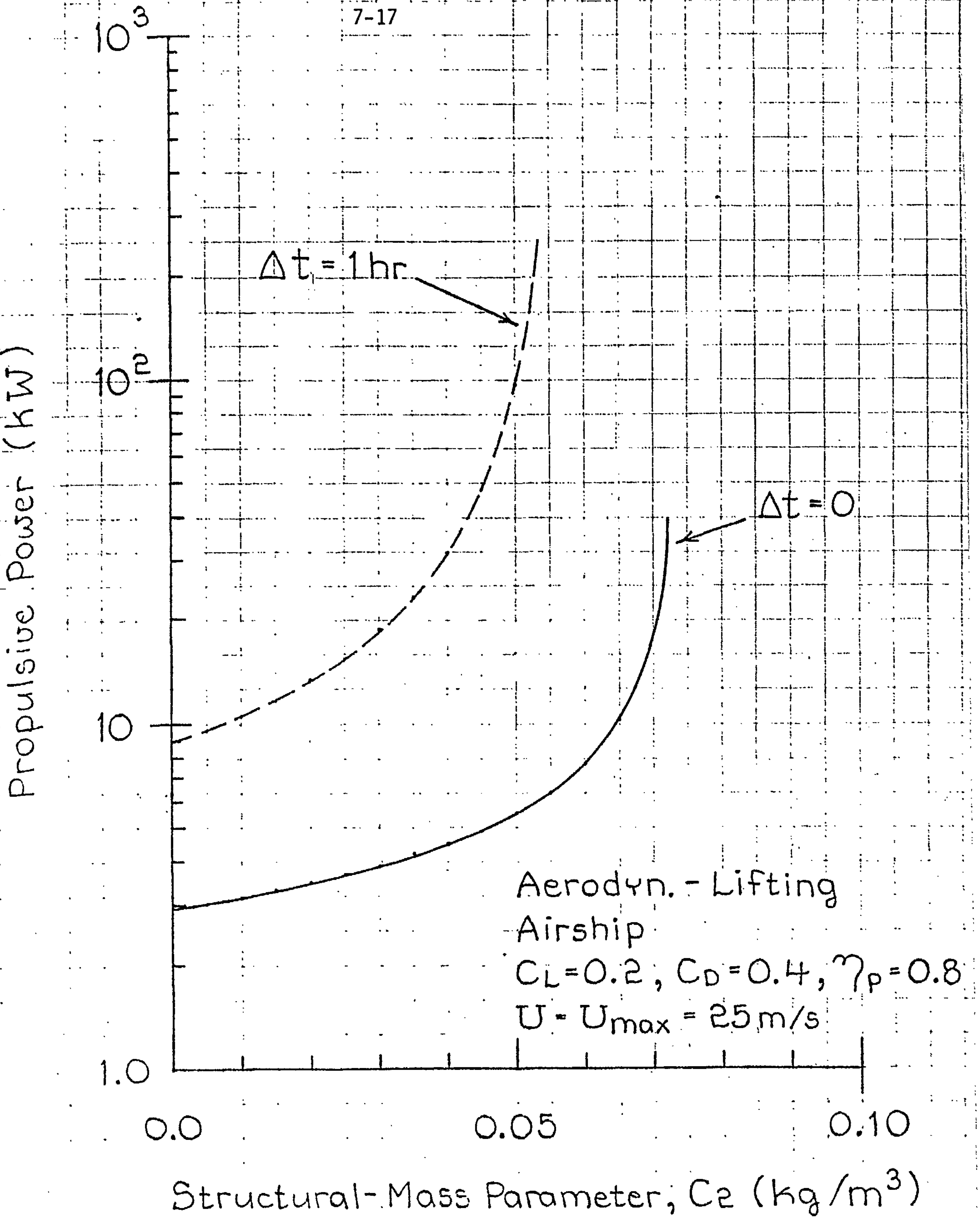

3000
2000
1000
0.0
Vehicle Characteristic Area, S (m²)
U = 5.0 m/s
U = 25.0 m/s
Aerodyn Lifting
Airship Configuration
Umax = 25.0 m/s
CL = 0.20
CD = 0.04
Δt = 0
Control-System mass = 295.6 Kg
Volume (m³)
10⁵
10⁴
0.0
0.05
0.10
Structural-Mass Parameter, C2 (kg/m³)

Figure 7.3/4



10^6
10^5
10^4
10^3
Vehicle Hull Volume (m^3)
Δt = 1 hr
Δt = 0
Aerodyn.-Lifting
Airship
CL = 0.2 , CD = 0.4
U = Umax = 25 m/s
0.0
0.05
0.10
Structural-Mass Parameter , C2 (kg/m^3)

Figure 7.3/5



10^3
10^2
10
1.0
Propulsive Power (kW)
Δt = 1 hr
Δt = 0
Aerodyn. - Lifting Airship
$C_L = 0.2$, $C_D = 0.4$, $\eta_p = 0.8$
$U = U_{max} = 25$ m/s
0.0
0.05
0.10
Structural-Mass Parameter, C_2 (kg/m^3)

Figure 7.3/6

7.4 The Hybrid Vehicle

The hybrid vehicle may be envisioned as a wing-shaped balloon (Reference Figure 1/2). It combines lift capability from buoyancy and aerodynamic lift from its shape.

The parameters listed in Table 7.4/1 are used in conjunction with equation 21 in Figure 7.2/1, and Table 7.3/1. The results of these analyses are shown in Figures 7.4/2, 7.4/3, and 7.4/4.

The hybrid configuration was evaluated by holding the U_{max} value constant and varying the value of U. As seen in Figure 7.4/2, for values below 15 m/sec the hybrid is flimsy and outsized, and requires excessive propulsive power. Its interior to the airship configurations. However, if the value of U is grater than 15 m/sec the performance becomes very good - especially above 20 m/sec. This is particularly true when on board batteries are considered (Reference Figure 7.4/3).

The most appealing property shown is the power requirements versus the structural-mass parameter, as shown in Figure 7.4/4. It is obvious that this type of vehicle would perform better in the higher-wind regimes.

SHARP PERFORMANCE COEFFICIENTS HYBRID

COEFFICIENT	DEFINITION	PARAMETRIC VALUE OR RANGE INITIAL	REFINED	UNIT	COMMENT
C_L	LIFT COEFFICIENT	0.50	FIG. 7.4/1		VARIED WITH C_D FOR MAX C_L/C_D
ρ	ATMOSPHERIC DENSITY	0.060 - 0.080	0.07754	Kg/m^3	
C_D	DRAG COEFFICIENT	0.10	FIG. 7.4/1		VARIED WITH C_L FOR MAX C_L/C_D
U	CRUISE SPEED	1.0 - 10.0	5.0 - 25.0	m/sec	
U_{max}	MAXIMUM SPEED		25.0	m/sec	
Δt	BATTERY POWER TIME	$1.0 \times 10^3 - 10.0 \times 10^3$		sec	
η_p	PROPULSIVE EFFICIENCY	0.75 — .95	0.8		
P_{OB}	ON-BOARD POWER REQ'D	2295.6		W	

Table 7.4/1

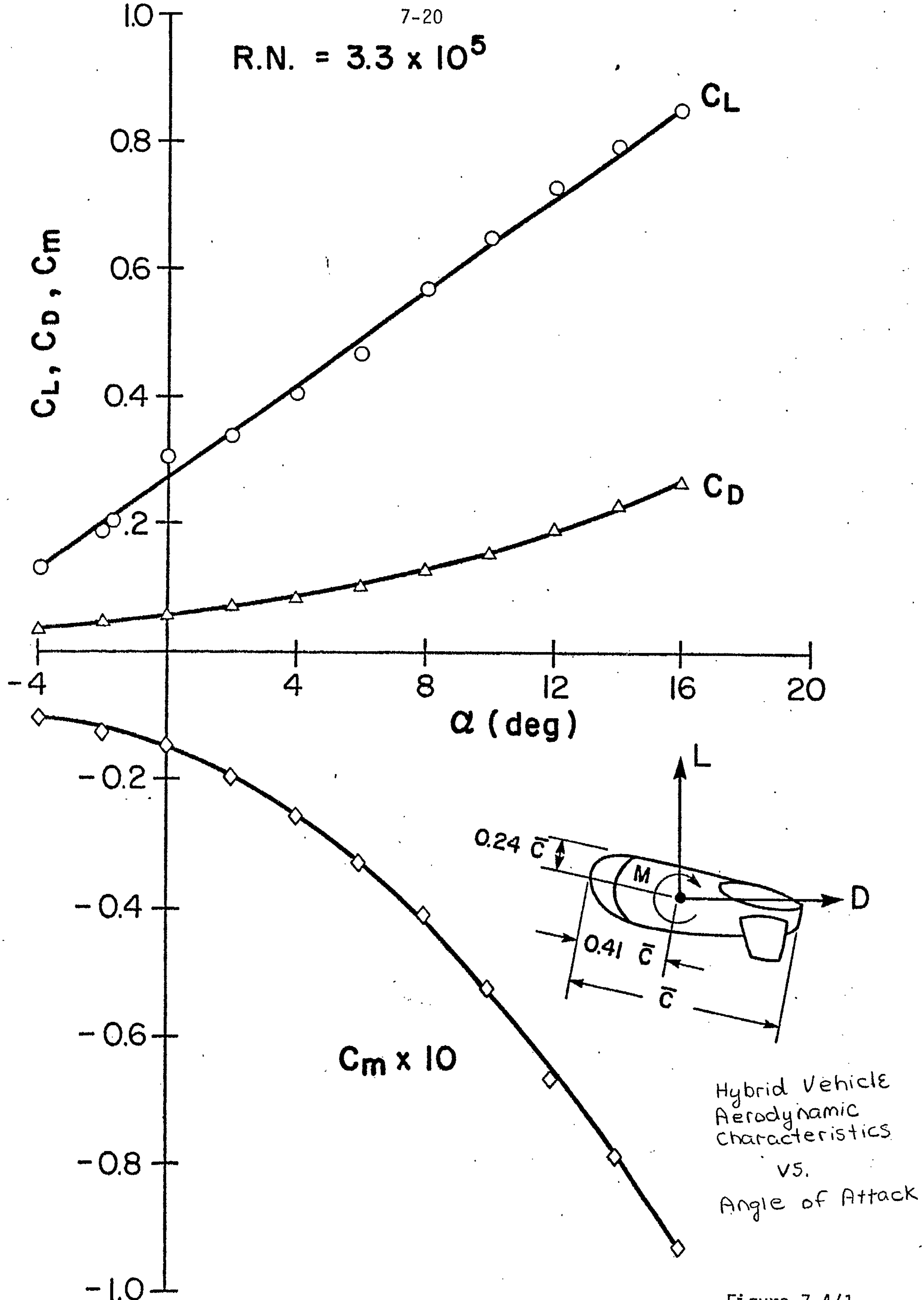

R.N. = 3.3 x 10^5
C_L
C_D
C_L, C_D, C_m
1.0
0.8
0.6
0.4
.2
-0.2
-0.4
-0.6
-0.8
-1.0
-4
4
8
12
16
20
α (deg)
L
D
M
0.24 c̄
0.41 c̄
c̄
C_m x 10
Hybrid Vehicle Aerodynamic Characteristics vs. Angle of Attack

Figure 7.4/1

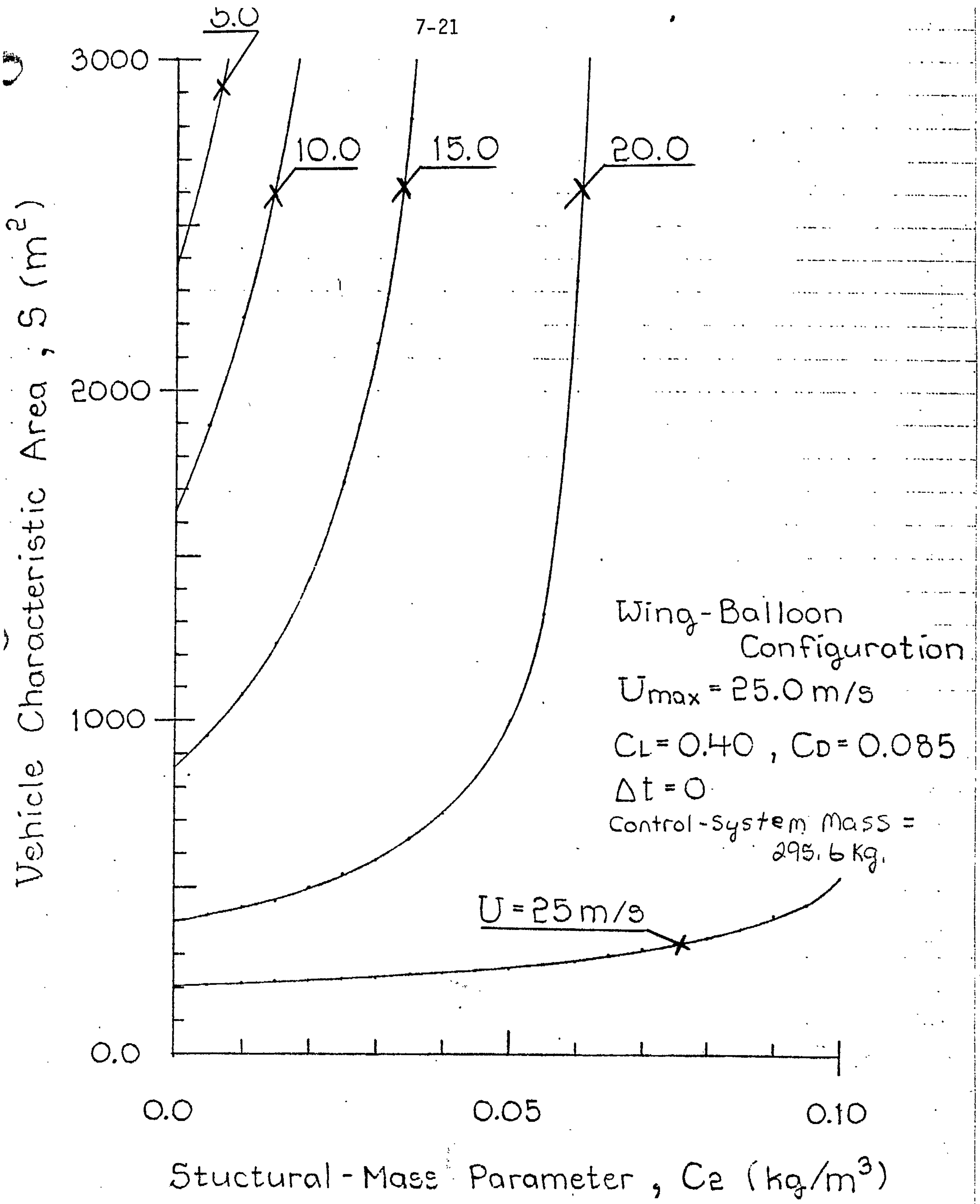

5.0
10.0
15.0
20.0
3000
2000
1000
0.0
Vehicle Characteristic Area, S (m²)
Wing-Balloon Configuration
Umax = 25.0 m/s
CL = 0.40, CD = 0.085
Δt = 0
Control-System Mass = 295.6 Kg.
U = 25 m/s
0.0
0.05
0.10
Stuctural-Mass Parameter, C2 (kg/m³)

Figure 7.4/2

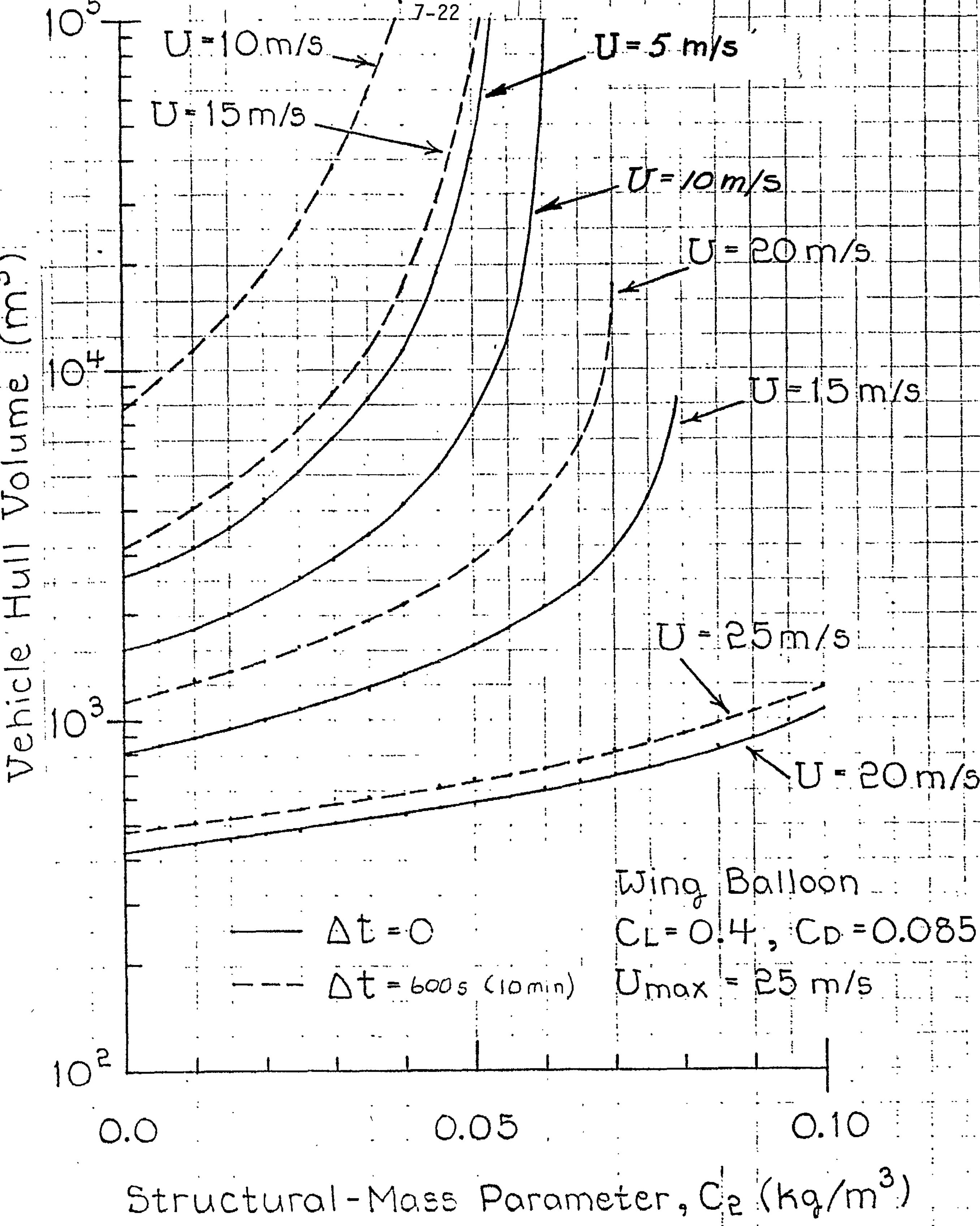
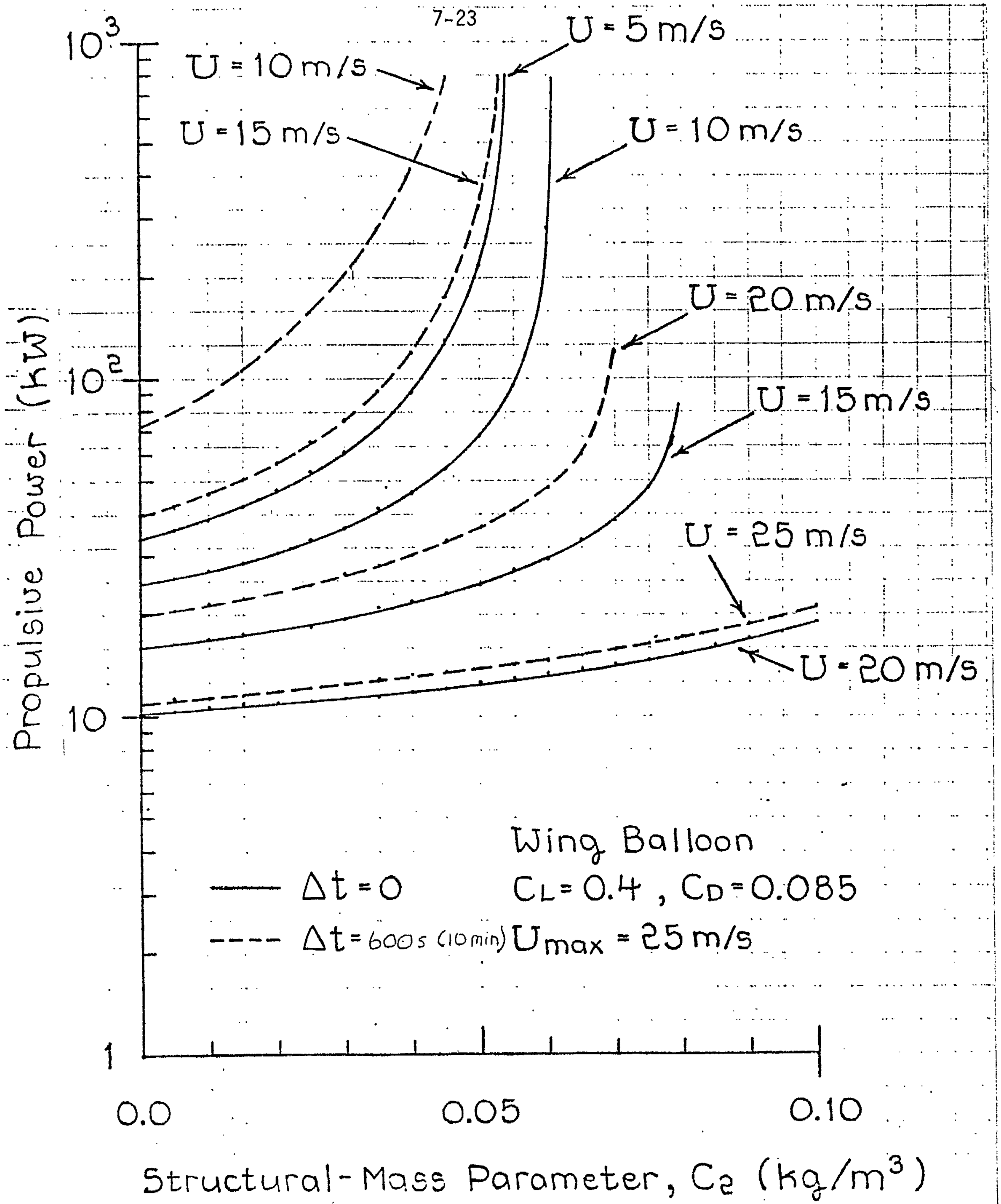

10^5
10^4
10^3
10^2
U = 10 m/s
U = 15 m/s
U = 5 m/s
U = 10 m/s
U = 20 m/s
U = 15 m/s
U = 25 m/s
U = 20 m/s
Vehicle Hull Volume (m^3)
Wing Balloon
CL = 0.4 , CD = 0.085
Umax = 25 m/s
Δt = 0
Δt = 600 s (10 min)
0.0
0.05
0.10
Structural-Mass Parameter, C2 (kg/m^3)

Figure 7.4/3



U = 5 m/s
U = 10 m/s
U = 15 m/s
U = 10 m/s
U = 20 m/s
U = 15 m/s
U = 25 m/s
U = 20 m/s
10³
10²
10
1
Propulsive Power (kW)
0.0
0.05
0.10
Structural-Mass Parameter, C₂ (kg/m³)
Wing Balloon
—— Δt = 0
---- Δt = 600 s (10 min)
CL = 0.4 , CD = 0.085
Umax = 25 m/s

Figure 7.4/4

7.5 Airplane Analysis

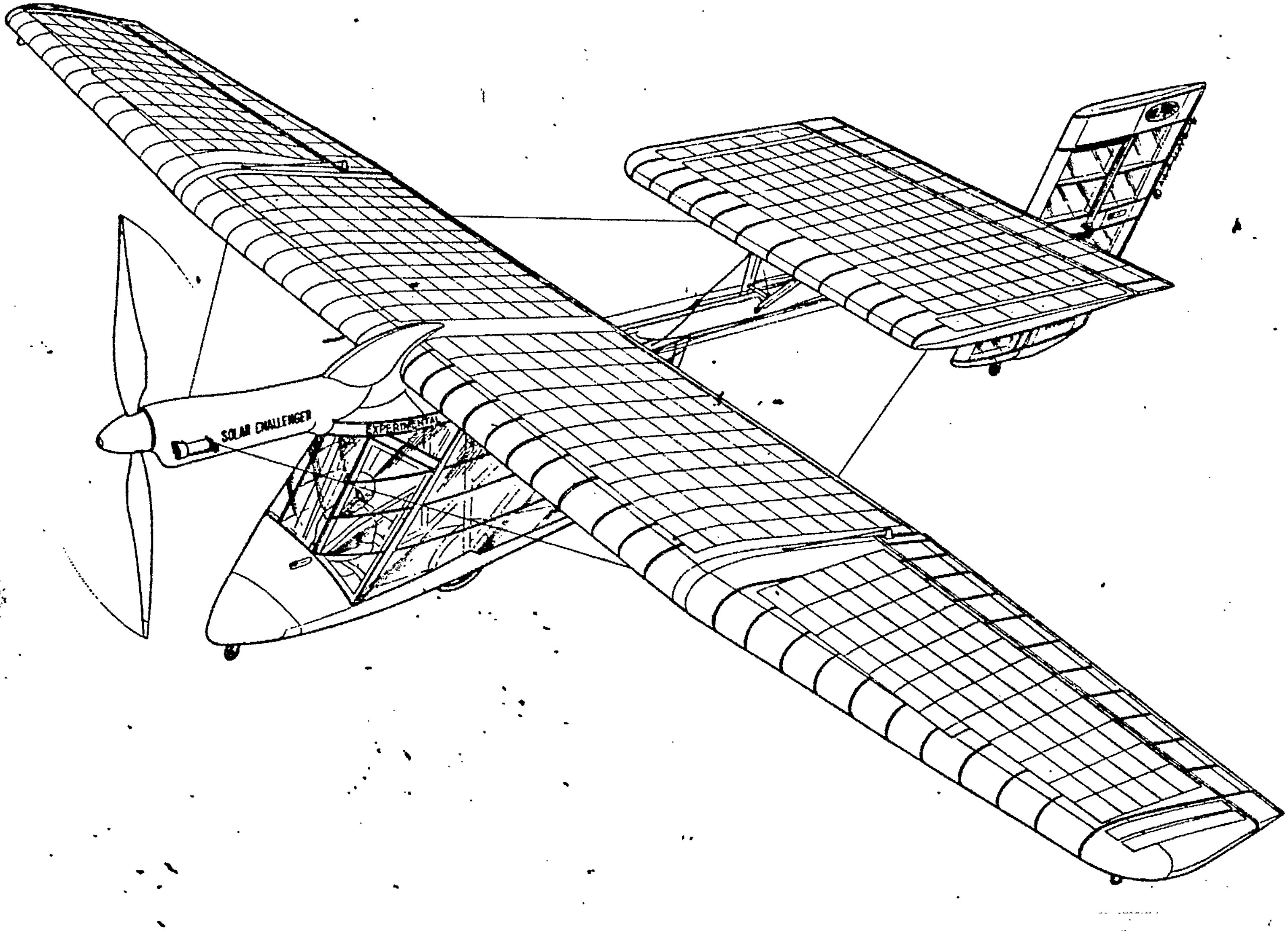
It was planned, from the beginning of this work, to study an airplane-type vehicle so as to complete the spectrum of candidate aircraft. However, it was initially thought that a lighter-than-air vehicle would be superior for the mission by virtue of the fact that it requires no power for its lift, and could fly on-station in low winds with low power consumption. Hoever, wind data at 21 km made it clear that a U_{max} higher than 25 m/s is required to stay on-station during winter months. In fact, U_{max} = 60 m/s is desirable. This is impossible for the lighter-than-air concepts studied, but perfectly feasible for the type of airplane described below.

In this section two airplane designs are considered. The first is a craft that would be similar in configuration to the "Solar Challenger" (Reference Figure 7.5/1). The second would be different shape tailored to the initial SHARP requirements (Reference Figure 7.5/2).

The analysis of the airplane configuration required a slight modification to the sizing equation, and this is shown in Figure 7.2/2 with the appropriate coefficients being taken from Tables 7.2/1 and 7.5/1 for both configurations.

The results of the analysis of the Solar Challenger-type vehicle are shown in Figures 7.5/3 and 7.5/4 and the results of SHARP-I configuration being shown in Figures 7.5/5 through 7.5/8. Figures 7.5/5 and 7.5/6 are based on flight at maximum lift/drag ratio, and Figures 7.5/7 and 7.5/8 are based on maximum power factor (CL^3/CD^2). These are indicated on the figures for clarity.

As the figures show, the airplane's size and propulsive power generally decrease with increasing mean speed, which shows its superiority over the airship concepts for station-keeping flight against strong headwinds. It should be noted that the addition of on board power dramatically increases the propulsive power and size requirements.



Isometric sketch of Solar Challenger.

Figure 7.5/1

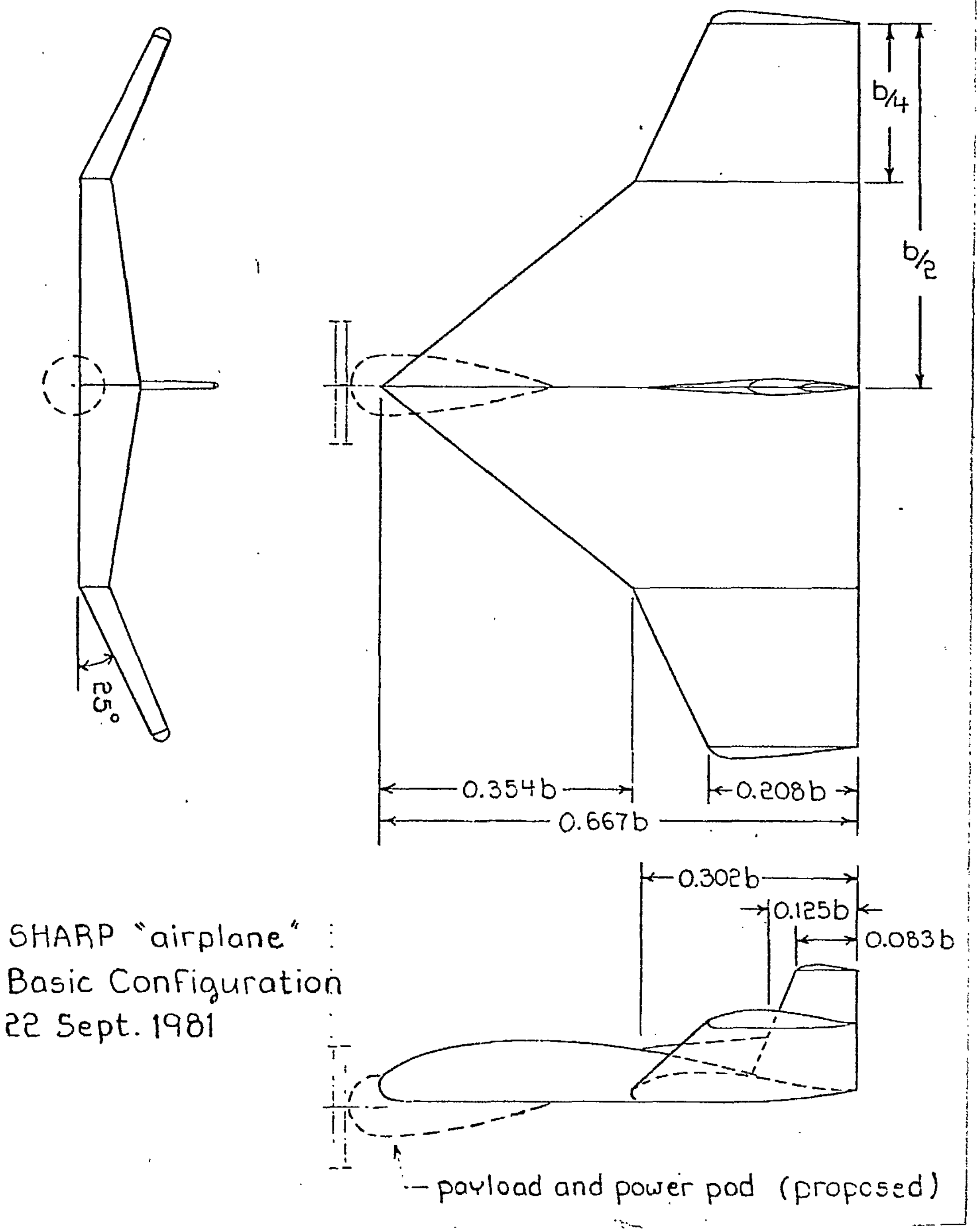
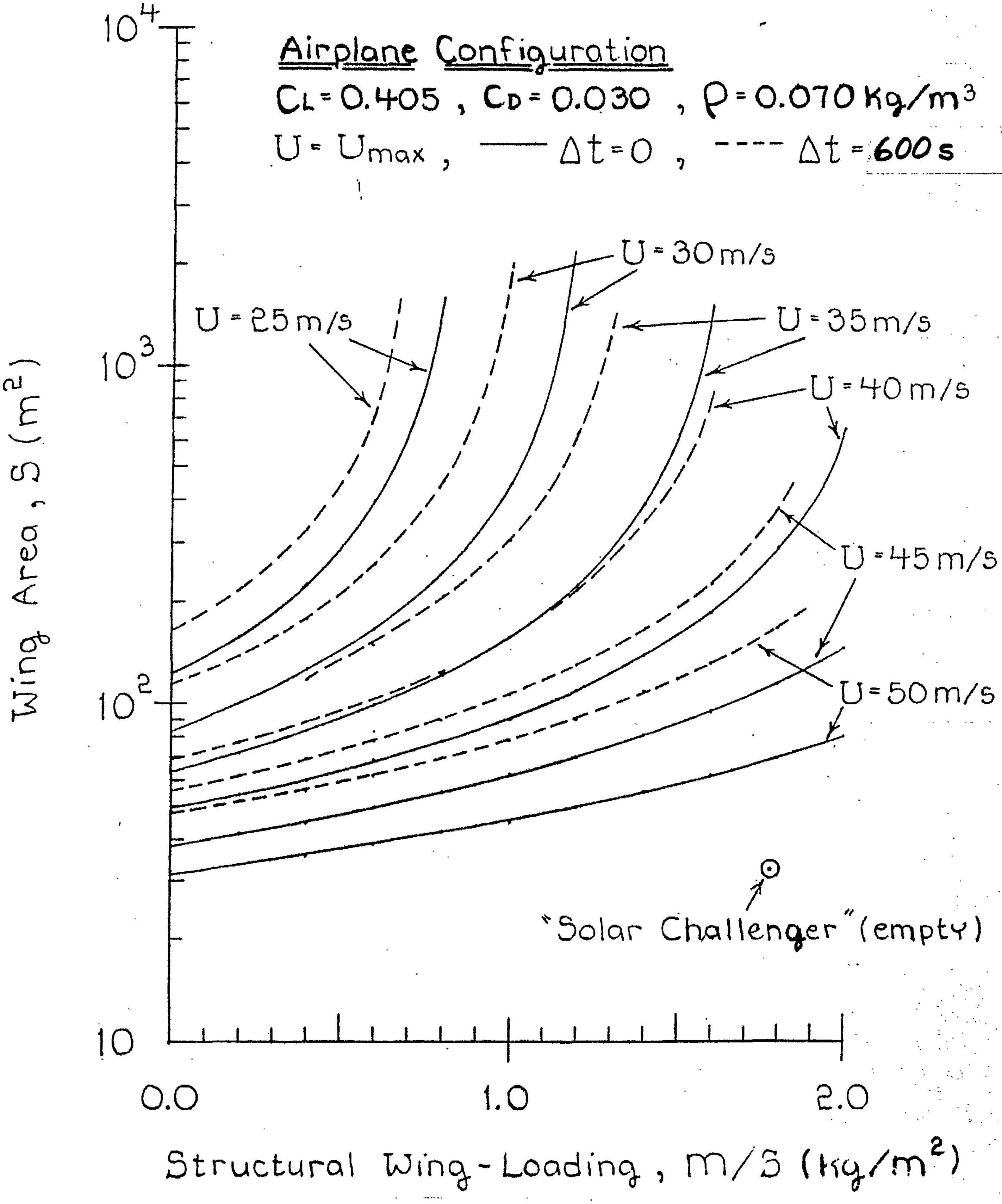

b/4
b/2
25°
0.354b
0.208b
0.667b
0.302b
0.125b
0.083b
SHARP "airplane"
Basic Configuration
22 Sept. 1981
payload and power pod (proposed)

Figure 7.5/2

SHARP PERFORMANCE COEFFICIENTS — AIRPLANE

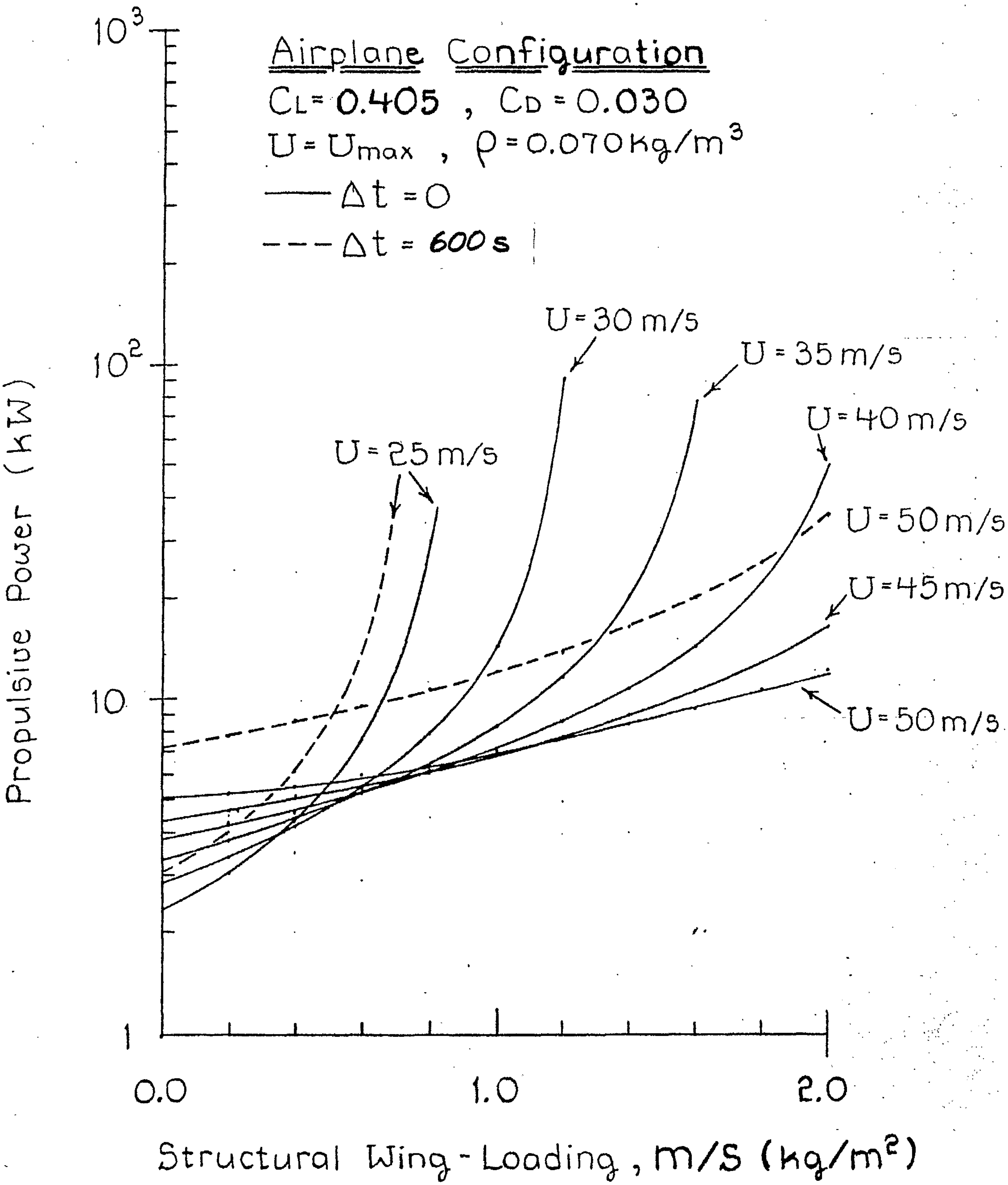
COEFFICIENT	DEFINITION	PARAMETRIC VALUE OR RANGE INITIAL	PARAMETRIC VALUE OR RANGE REFINED	UNIT	COMMENT
C_L	LIFT COEFFICIENT	0.50	0.0405		
ρ	ATMOSPHERIC DENSITY	0.060 – 0.080	0.07754	Kg/m^3	
C_D	DRAG COEFFICIENT	0.05	0.03		
U	CRUISE SPEED	1.0 – 10.0	$U = U_{max}$	m/sec	
U_{max}	MAXIMUM SPEED	5.0 – 50.0	25.0 – 45.0	m/sec	
Δt	BATTERY POWER TIME	$1.0 \times 10^3 - 10.0 \times 10^3$	3.6×10^3	sec	
η_p	PROPULSIVE EFFICIENCY	0.75 – 0.95	0.86		
P_{OB}	ON-BOARD POWER REQ'D	2295.6		W	

Table 7.5/1



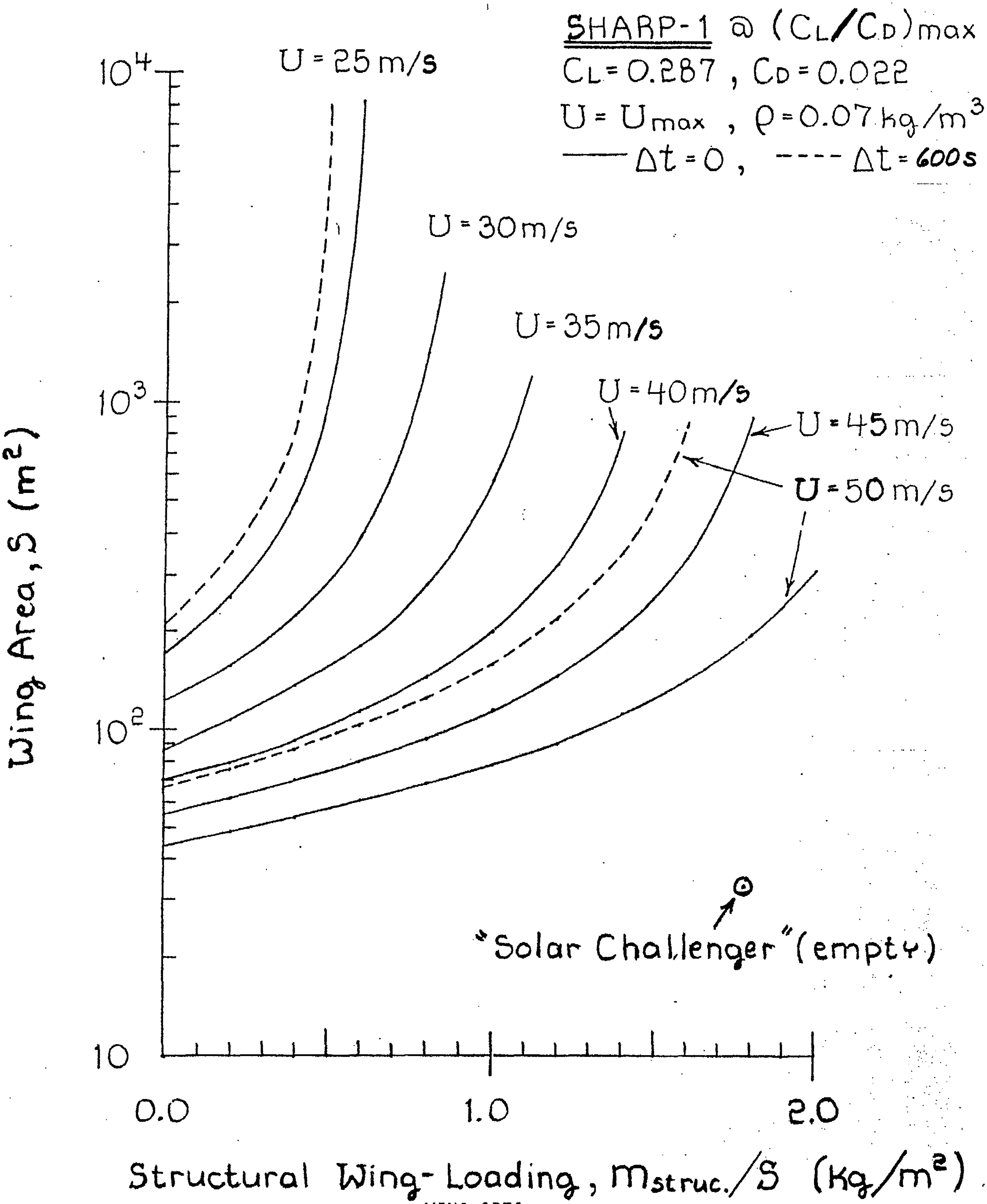
WING AREA
VS
AIRPLANE STRUCTURAL WING-LOADING

FIGURE 7.5/3



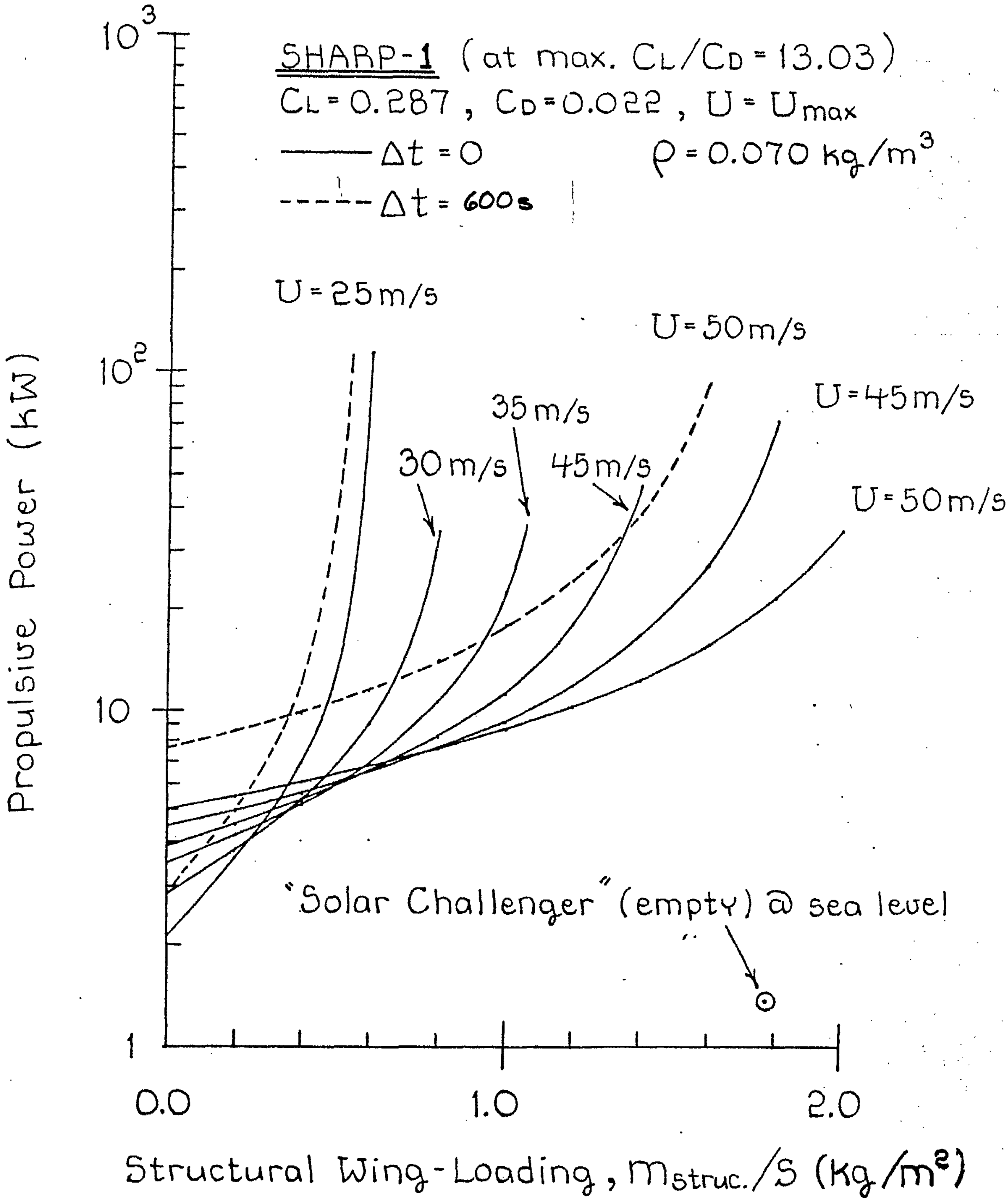
PROPULSIVE POWER
VS
AIRPLANE STRUCTURAL WING-LOADING

FIGURE 7.5/4



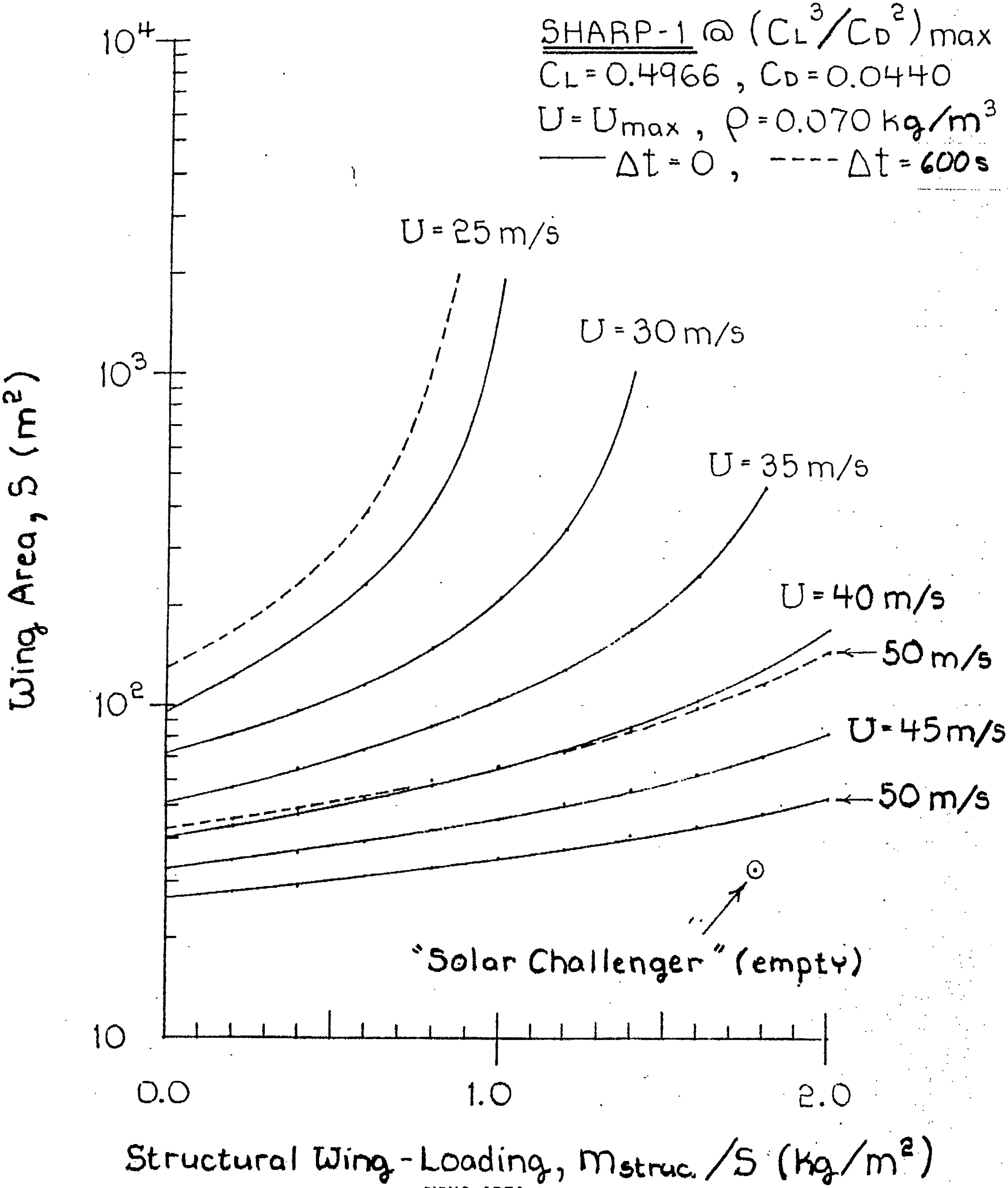
WING AREA
VS
SHARP-I STRUCTURAL WING-LOADING

FIGURE 7.5/5



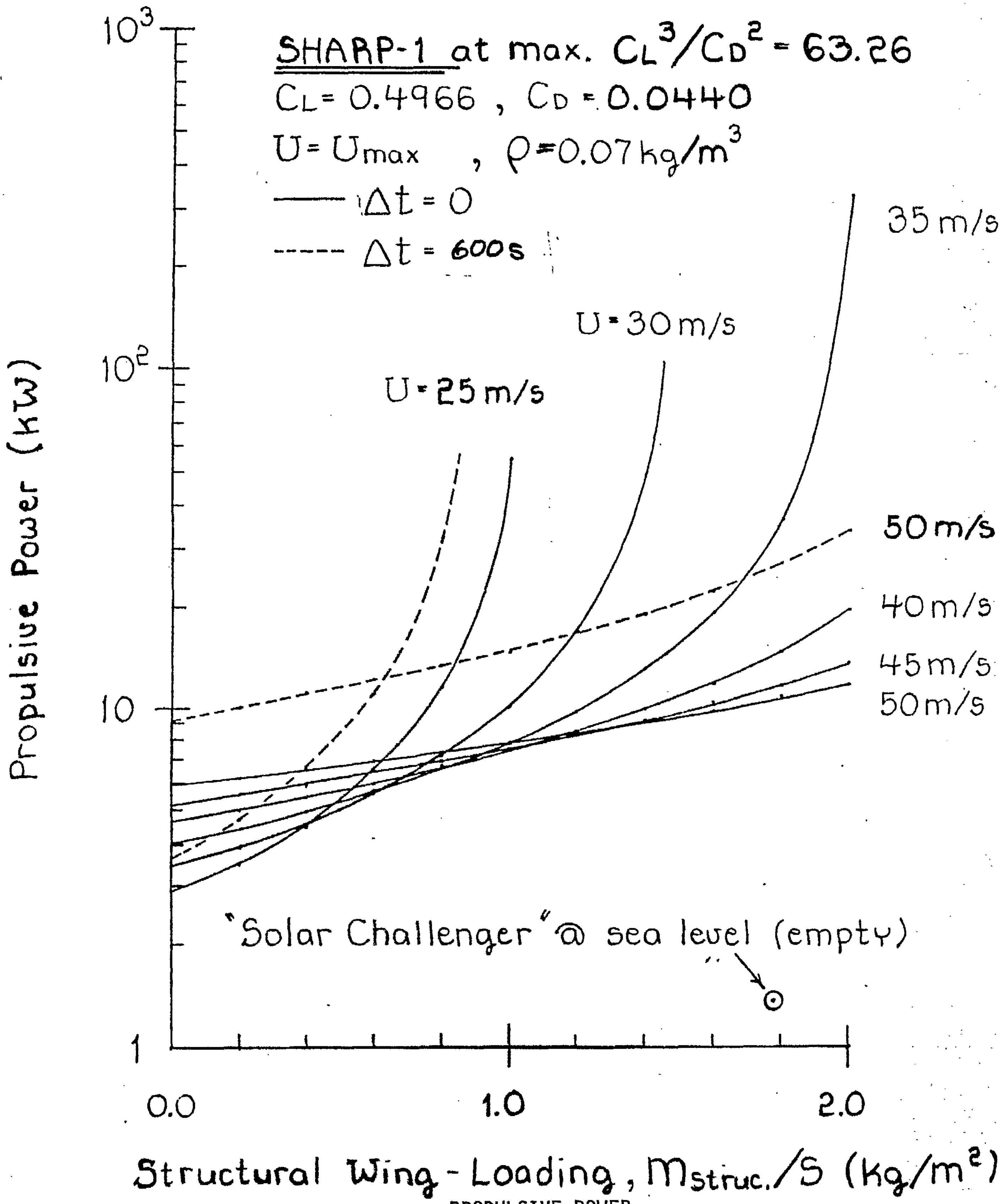
PROPULSIVE POWER
VS
SHARP-I STRUCTURAL WING-LOADING

FIGURE 7.5/6



WING AREA
VS
SHARP-I STRUCTURAL WING-LOADING

FIGURE 7.5/7



PROPULSIVE POWER
VS
SHARP-I STRUCTURAL WING-LOADING

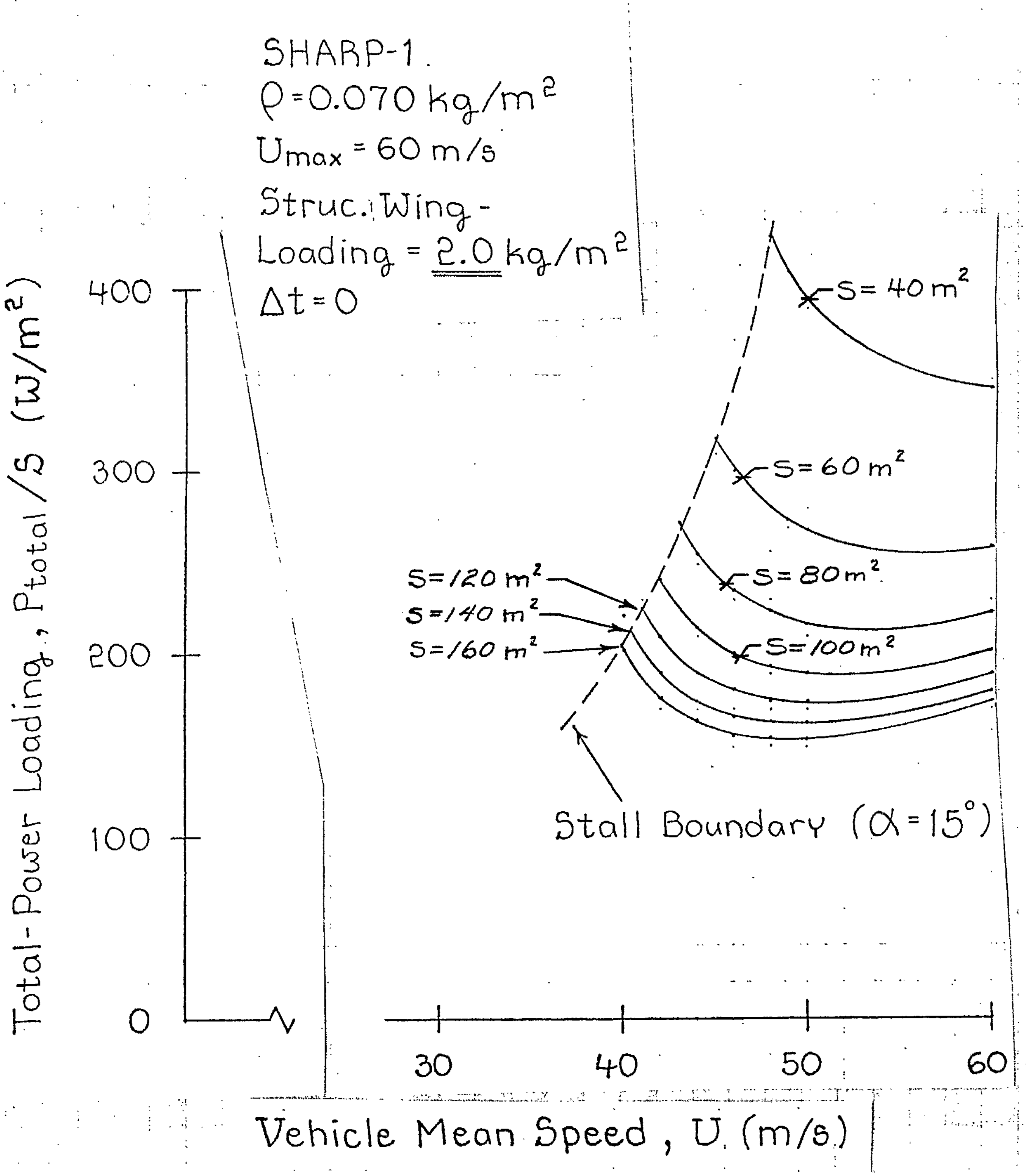
FIGURE 7.5/8

Up to this point, the results have been plotted in a way which allows a survey to be conveniently made of the effects of parameter variation. Also, these figures have readily allowed comparisons to be made of the size and power requirements of all the candidate aircraft. However, valuable additional results for the airplane-type vehicles may be obtained by fixing the structural wing-loading parameter at some realistic value and varying the flight speed. The airplane's angle of attack will bee such as to give level flight, although it will not be allowed to exceed the stall value.

One important result from this variation is the Total-Power Loading (or Power Flux Density) which is the total power required by the airplane (including the on board power) divided by the wing area. This provides a measure of the microwave power flux density required for flight.

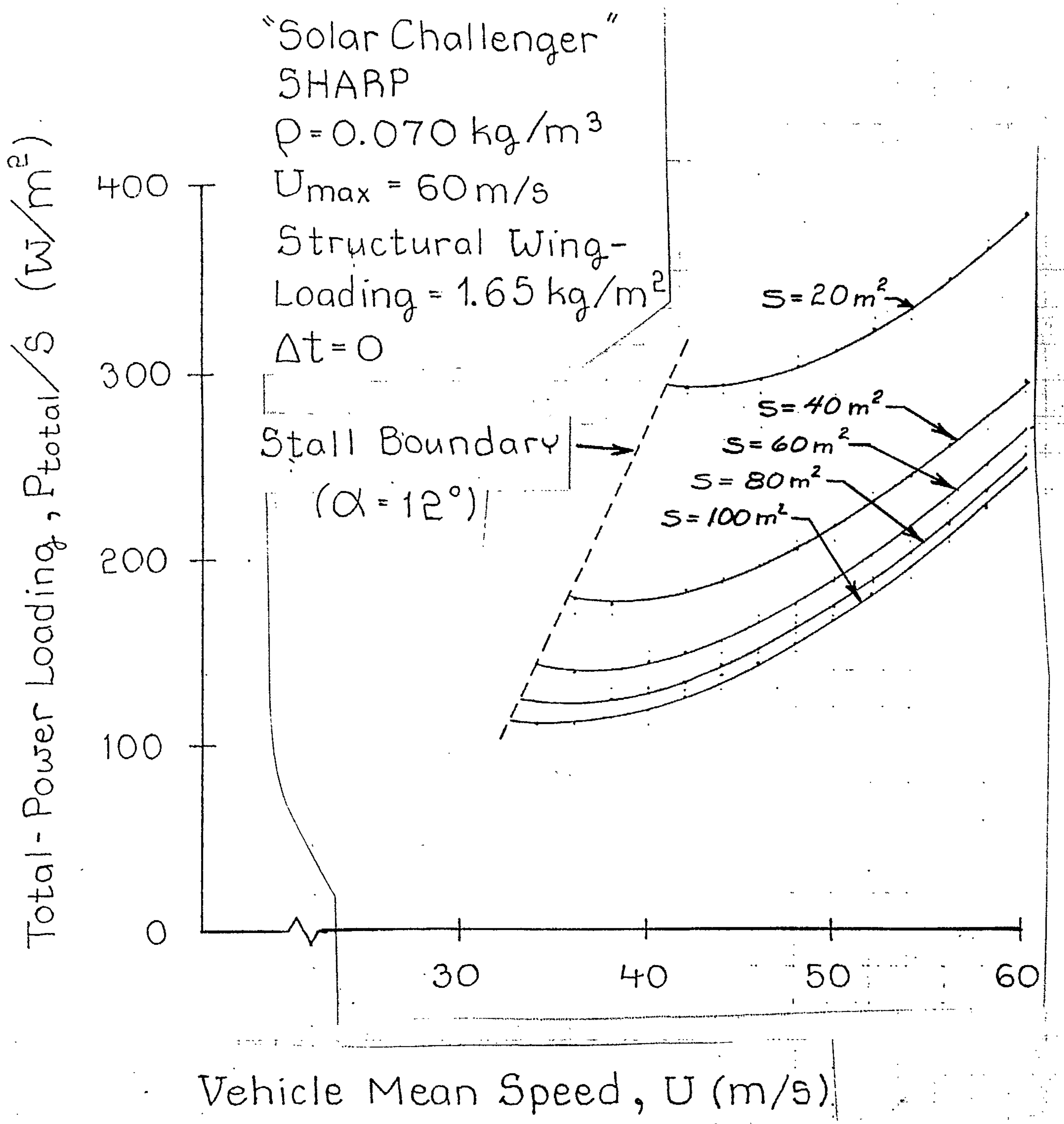
These results for the two example airplanes are shown in Figures 7.5/9 and 7.5/10 where it is seen that the Solar Challenger-type airplane has a wider operational-speed range and smaller size, for any given Total-Power Loading, than the SHARP-I design. This is because the Solar Challenger configuration attains its maximum lift/drag ratio (which is the same value as for the SHARP-I) at a higher lift coefficient. Following this reasoning, a new airplane-type vehicle was designed which is a derivative of the Solar Challenger, specialized to the SHARP mission. This aircraft, called the AR-20, has a highly-cambered airfoil on a wing with a very high aspect ratio of 20.

The Total-Power Loading results for the AR-20 are shown in Figure 7.5/11. It is seen that the AR-20 has significantly better performance than the Solar Challenger-type airplane in that, for any given Total-Power Loading, the operational-speed range is wider and the wing area is smaller. It is felt that this represents the limits for the best performance that could possibly be expected for a SHARP-specialized airplane, and that other design considerations may compel an airplane which is a compromise between the AR-20 and the Solar Challenger. Even yet, it should be noted that this would still be within the range of practical vehicle sizes and achievable microwave power transmission.



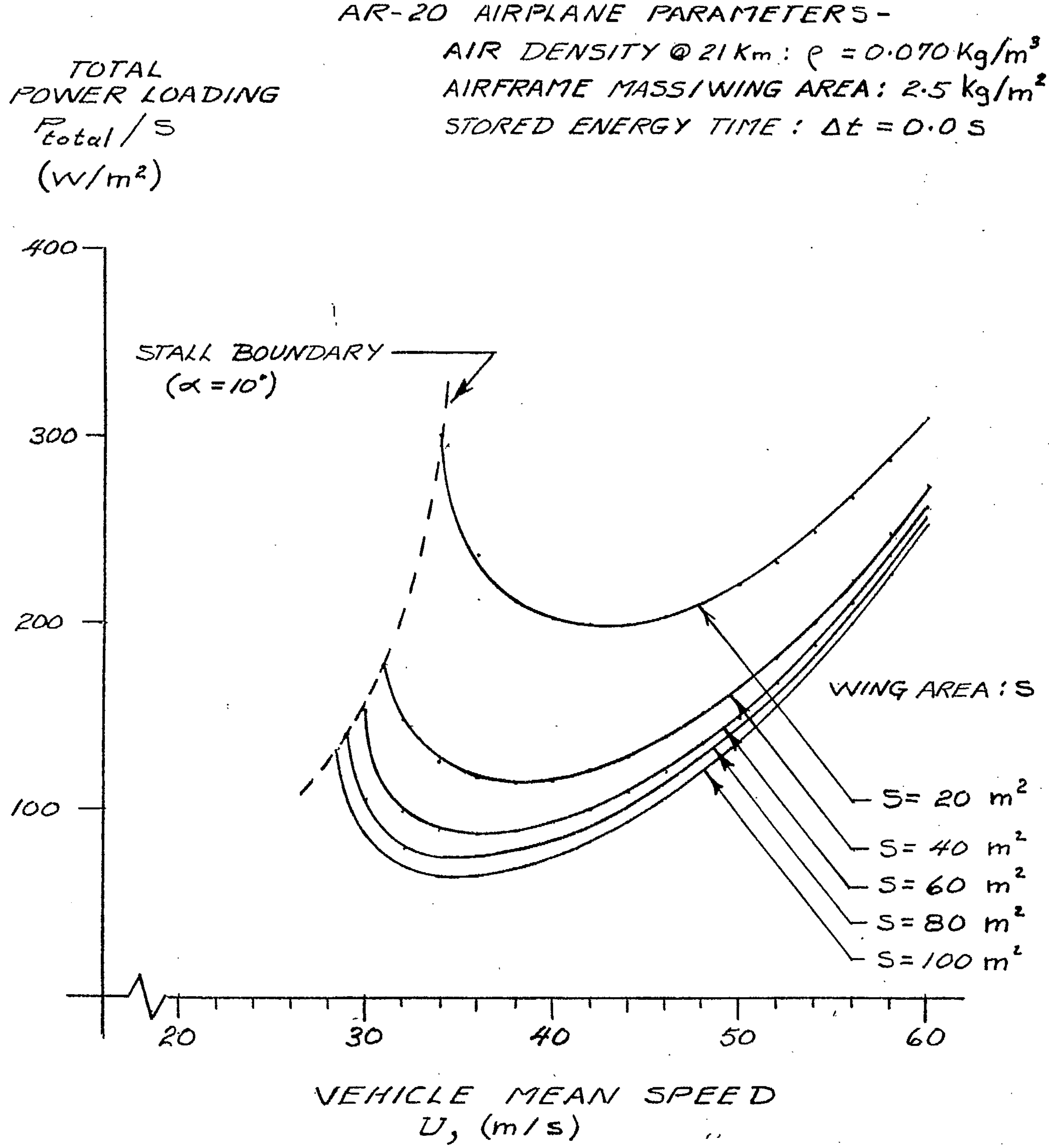
Total-Power Loading vs. Speed
for Struc. Wing-Loading = 2.0 kg/m²

FIGURE 7.5/9



Total-Power Loading vs. Speed for "Solar Challenger" SHARP

FIGURE 7.5/10



TOTAL POWER LOADING
Vs
VEHICLE MEAN SPEED
FOR
THE AR-20 SHARP AIRPLANE

FIGURE 7.5/11

7.6 SHARP-Aircraft Construction

The foregoing analysis assumes that a vehicle meeting all the assumed mass and aerodynamic qualities can be built. A preliminary study gives considerable promise that this is so, but the fundamental requirement of material selection for the SHARP must be more carefully studied before the vehicle may be constructed. The mission goal for a SHARP is to remain on-station at altitude for 9 to 12 months. The environmental requirements imposed on the vehicle materials, for this duration, are rigorous.

Regardless of which aircraft type is chosen, the strength to weight ratio of the materials must be high. Today, many light, high-strength plastics are used in aircraft in place of metal. Also, high-strength adhesives are used in lieu of conventional riveting methods.

For the SHARP platform, the use of modern plastics is very attractive. But a major source of material degradation that must be considered is that caused by ultra-violet light. This will possibly limit the type of plastic used for the outer skin, or require special coatings.

For Lighter-Than-Air craft (LTA), the permability of the material is of prime consideration. Estimates for 6.35 micron gas barrier for a 56.6×10^3 m^3 airship indicates a loss of approximately 28.3 m^3/day for Helium (3).

The successful use of epoxy resins and graphite fiber reinforced composition in the structure of the Solar Challenger shows that the candidate airplanes can be constructed with very high strength-to-weight ratios (2).

The current availability of candidate materials for the SHARP is extensive. But sufficient attention must be given in the design stages of the vehicle to the environmental and flight requirements. These aspects of material selection were beyond the scope of this initial project.

SECTION 7.0 REFERENCES

(1) Sun Powered Aircraft Design
AIAA-81-0916
Paul B. MacCready, Peter Lissaman, Walter Morgan, Aero Vironment Inc., and J. Burke, Jet Propulsion Lab, pg. 7

(2) ibid, pg. 8

(3) Investigation of Powered Lighter-than-Air Vehicles
Jerome J. Voracheck, Goodyear Aerospace Corp.
Akron, Ohio 44315
November 27, 1968, Project No. 6665 Final Report, pg. 38

8.0 TELEMETRY, ELECTRONICS AND COMMAND SYSTEM

8.1 Introduction

The SHARP mission concept is one primarily directed toward improving communications, particularly in areas where it is difficult and/or expensive to establish and maintain communications that are to be found in the more populated areas of Canada. This aspect places heavy demands on the platform for reliability, and as much as possible to use standard communications wave lengths.

For the system to be reliable it must be able to maintain a relatively constant position and altitude over a particular geographical area. To achieve this, the platform must have on board flight controls to maintain altitude of the craft, station keeping controls to maintain its position, as well as systems to monitor equipment status, such as the telemetry operational status, power conditioning, and platform environmental conditions.

The status of the on board systems should be able to be monitored by the ground station and to respond to ground commands as required.

The degree of sophistication of each of the systems will be proportional to the degree of sophistication of the mission. The mission concept here will be limited to the elementary requirements for any mission. The requirements for the platform systems and the associated ground systems will be discussed.

8.2 Platform Systems

The following systems are those that will be on the SHARP. The total system has been broken into two parts, the Power Distribution System, Figure 8.2/1 and the Vehicle Control System, Figure 8.2/2. These diagrams pictorially show the interconnections between the systems.

8.2.1 Power Conditioning and Distribution System

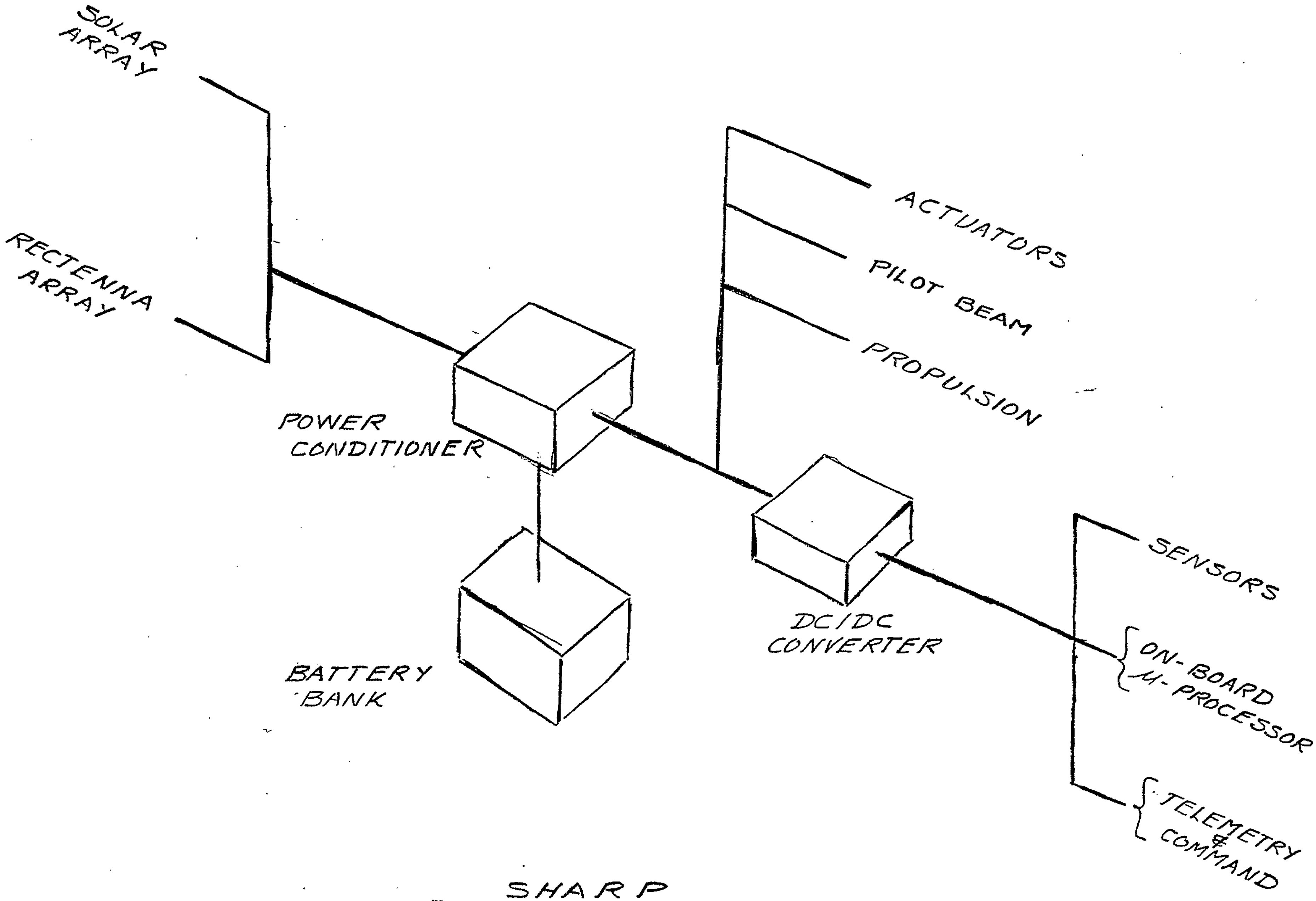
The single line diagram, Figure 8.2/1, shows the basic concept of the SHARP platform power distribution and conditioning system.

There are three prime power sources shown: the Rectenna, the Solar Panel, and the Battery Bank. The solar panel has not been considered as a prime power source in this study, however, it is included for completeness.

The role of the power conditioner is multi-purpose. The first function is to control the input voltage and current received by the rectenna or solar panel inputs.

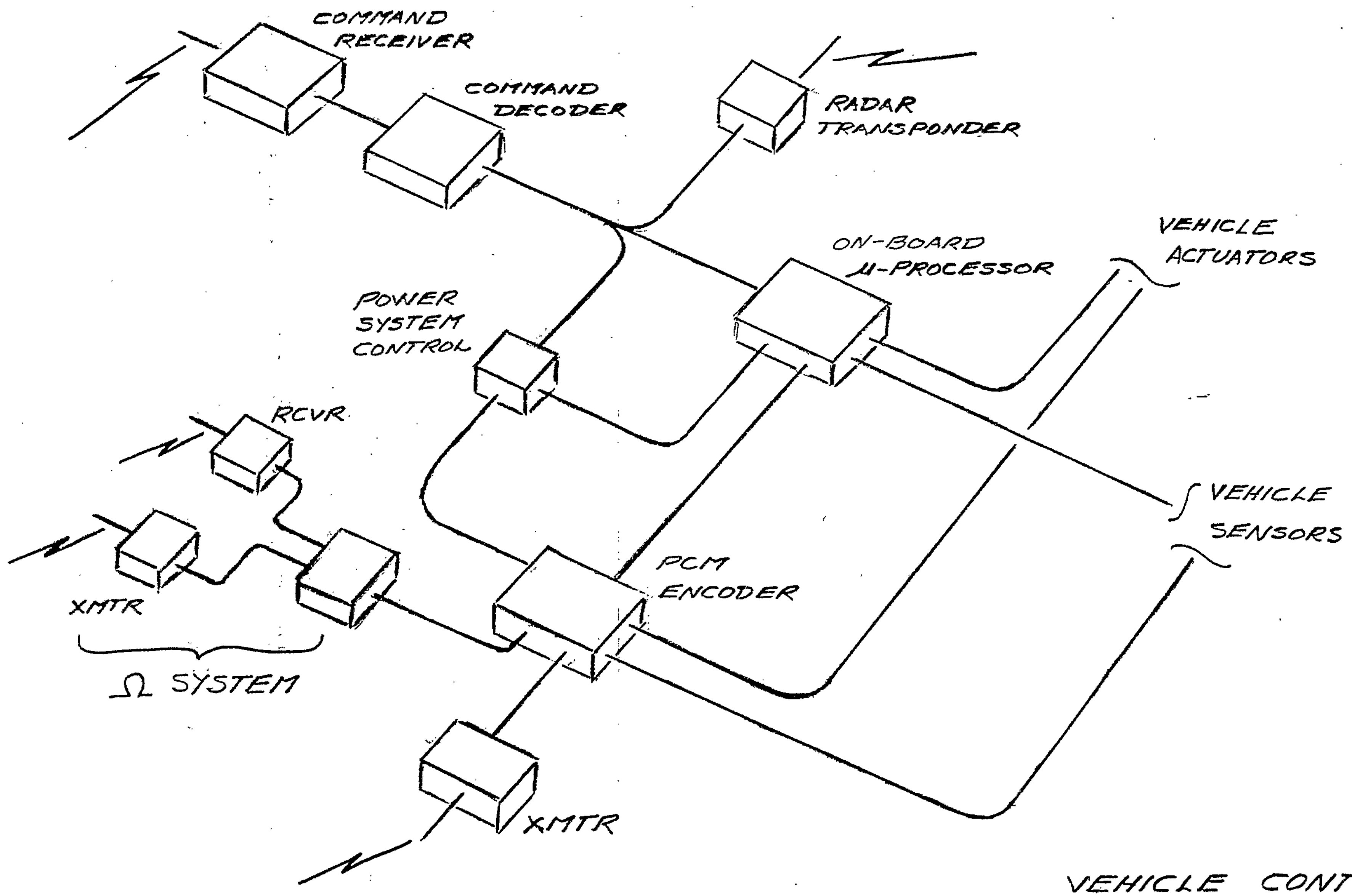
This control may be accomplished by electronic switching. This capability will control the voltage fluctuation to the rest of the power system and enabling the battery to charge or discharge as the voltage input varies.

The second portion of the system is the battery bank. In this study, a maximum reserve of power for 3.6×10^3 sec (1 hr) was considered. The results indicate that this reserve time is too great and results in a prohibitive battery mass. Further analysis on the flight power profile is recommended to reduce this reserve power requirement and mass. The battery bank is connected into the power circuit at all times so there is no loss of power to the vehicle controls should the microwave beam power be lost.



SHARP
PRIMARY POWER DISTRIBUTION

FIG. 8.2/1

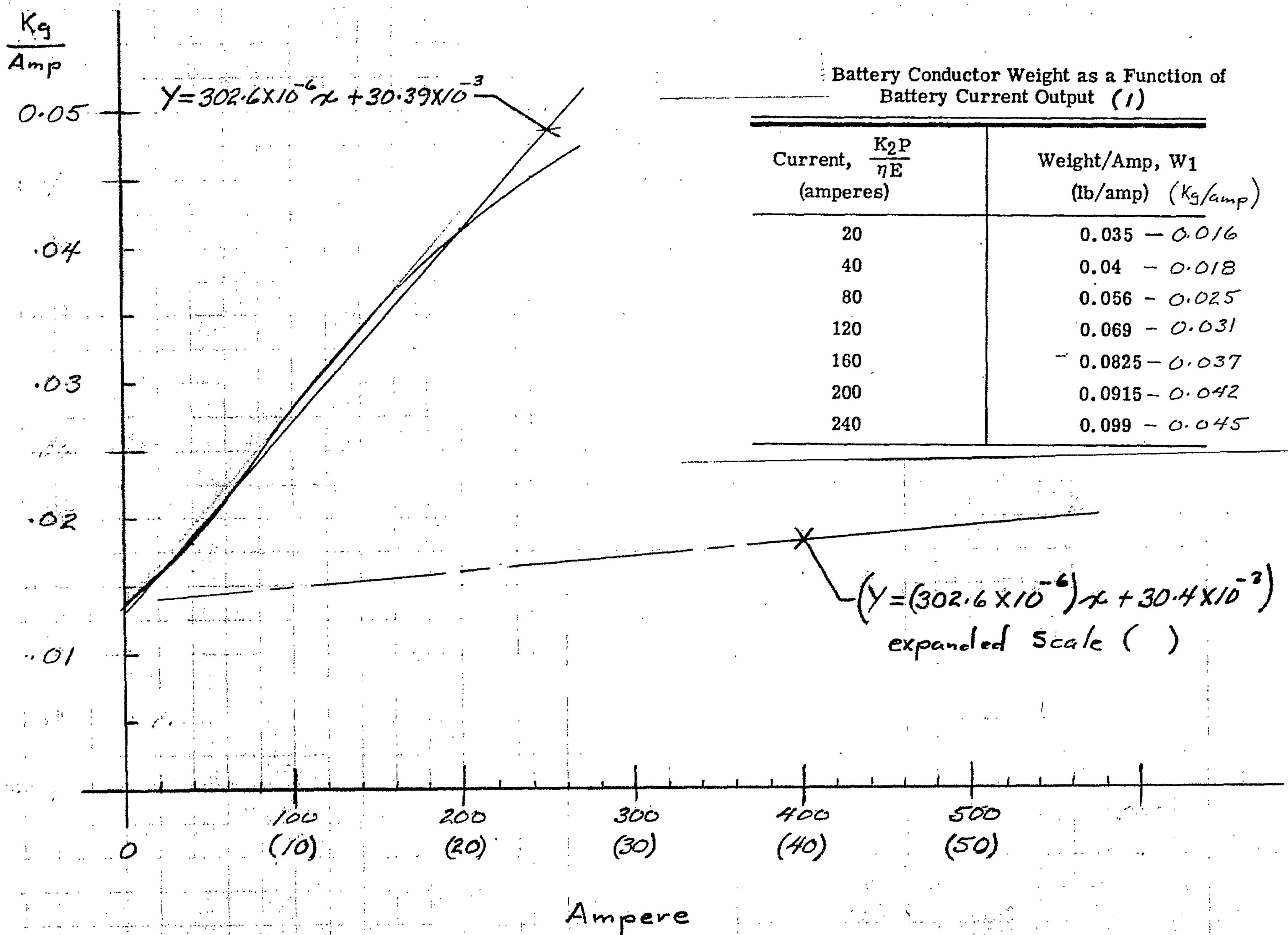


VEHICLE CONTROL SYSTEM COMPONENTS

FIG. 8.2/2

SYSTEM - ELEMENT	POWER REQM'T		WEIGHT (Kg)	VOLUME (M^3/cm^3)	COMMENT
	ESTM	ACTUAL			
POWER DISTRIBUTION					
DC/DC CONVERTER		60%	2.2		Power Requirement dependent on load
POWER CONDITIONER		80%	68.0		Power Loss dependent on Load
BATTERY BANK					Function of Vehicle power requirement. Ref C_{10}
RECTENNA			Ref Sec 5.3		Function of Transmitted Power
SOLAR ARRAY			Ref Sec 5.4		
BATTERY/ RECTENNA CABLE			Ref FIG 8.2/3		Function of Power Requirement

POWER DISTRIBUTION REQUIREMENTS
TABLE 8.2/1



Battery Conductor Weight as a Function of Battery Current Output (1)

Current, $\frac{K_2P}{\eta E}$ (amperes)	Weight/Amp, W_1 (lb/amp) (Kg/amp)
20	0.035 — 0.016
40	0.04 — 0.018
80	0.056 — 0.025
120	0.069 — 0.031
160	0.0825 — 0.037
200	0.0915 — 0.042
240	0.099 — 0.045

FIG 8.2/3

The last portion of the power distribution system is a DC/DC converter. This unit will supply regulated DC power to those system elements that require closely controlled power inputs such as the on board micro-processor and telemetry and command elements and the communications equipment.

The weight and power requirements are listed on Table 8.2/1.

8.2.2 Attitude Control

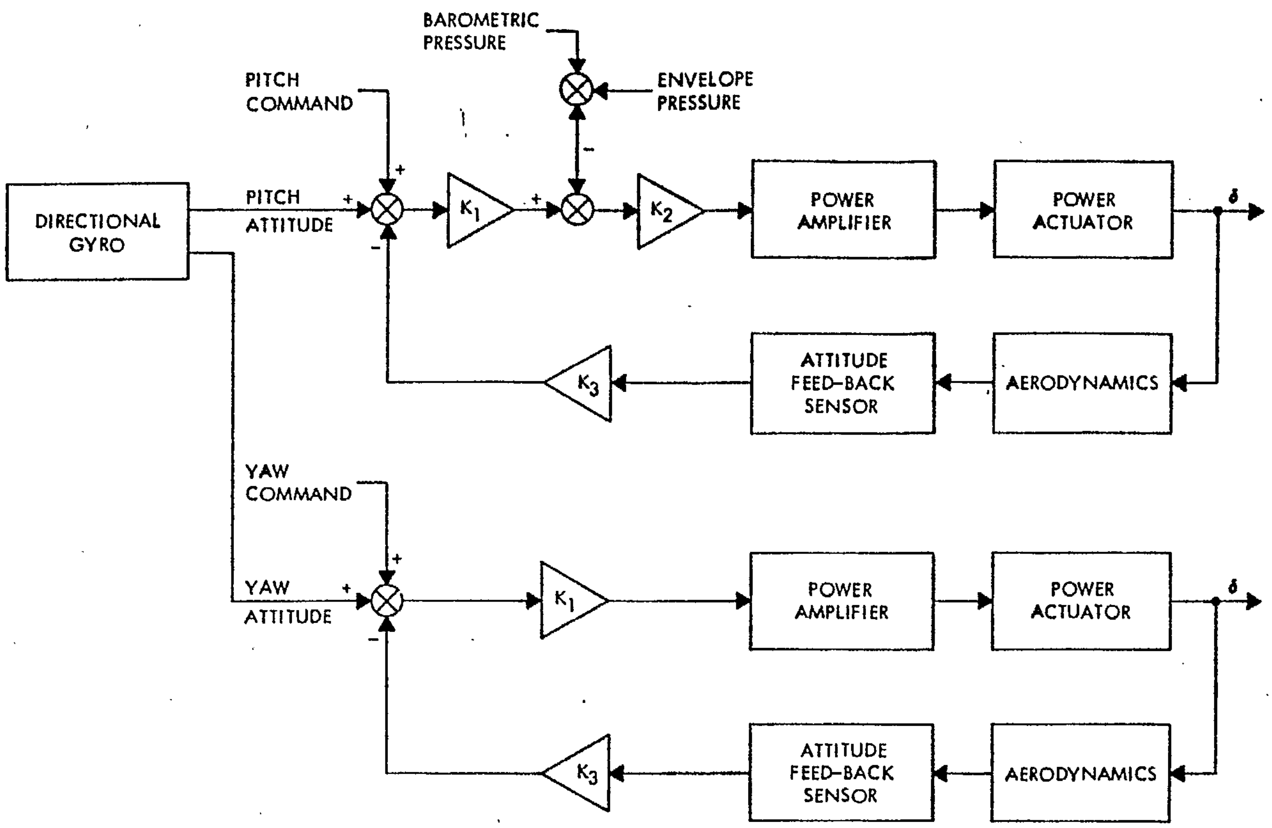
The attitude control system of the SHARP provides the platform a level of stability and direction. The controller consists of an on board micro-processor which controls the stability of the platform. Its function is to receive attitude information from sensors such as rate gyros, altitude sensors, magnetometers, roll and pitch sensors. The micro-processor will then compare the actual attitude to the required altitude, if differences are determined, actuators such as motors will be operated to correct the difference and maintain the desired attitude. A typical system is illustrated in Figure 8.2/4.

An experimental model helicopter used the microwave beam as inputs to the control system. The general configuration is shown in Figure 8.2/5 (2).

The weight and power estimates for the system are listed on Table 8.2/2.

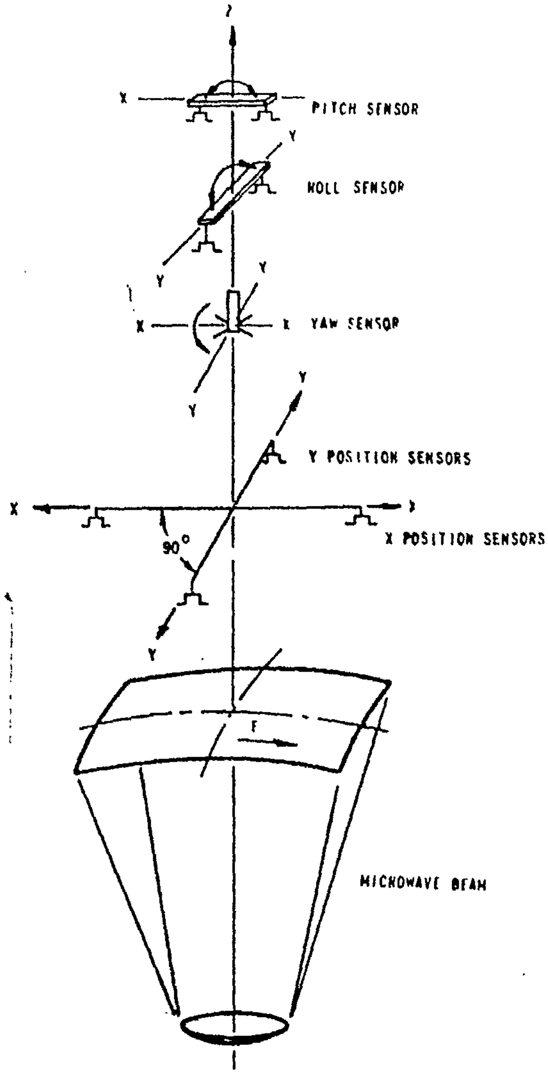
8.2.3 Station Keeping Control

Two major tracking systems will be incorporated on the SHARP. The major requirement is an air traffic control radar transponder which allows the radar operators to identify the platform in the midst of many aircrafts. The transponder is turned on during assent and deccent of the platform when it passes through the air lanes of commercial and private aircraft. This is used to prevent any mid air collisions.



Block Diagram of Airship Automatic Control System (1)

Figure 8.2/4



General configuration of the five sensor elements of a beam-riding helicopter.

Figure 8.2/5

SYSTEM - ELEMENT	POWER REQM'T		WEIGHT (Kg)	VOLUME (M^3/cm^3)	COMMENT
	ESTM	ACTUAL			
ATTITUDE CONTROL					
Rate Gyro		16 W	1.3		28VDC @ 1.75 Amp startup; 28VDC @ 0.57 Amp running
MICRO-PROCESSOR	20 W		0.7		
I/O Board	20 W		0.7		
ACTUATOR	40 W		1.5		
ACCELEROMETER	1 W		.3		
WIND SENSORS	0.5 W		.1		
CABLE & CONNECTORS			4.5		

ATTITUDE CONTROL WEIGHT AND POWER ESTIMATES

TABLE 8.2/2

The second tracking system is called an Omega tracking system. This system receives very low frequency signals from continuous wave transmitting stations, situated around the world. Each station is phase synchronized to each other such that lines of position or locations between two transmitters where the phases are equal. When using three or more stations, the position can be determined by counting the number of lines of position that the platform has crossed. The advantage to using this system is that it is a continuous tracking system and that very little power is taken up by the electronics in the platform because the majority of the equipment is located at the platform control center.

Knowing the platforms position, the appropriate control commands may be sent to the platform to alter its position through the attitude control system.

The on board micro-processor could receive inputs from the beam sensors and activate controls to maintain position, Reference Figure 8.2/5.

The weight and power estimates are shown on Table 8.2/3.

8.2.4 Platform Monitoring System

The telemetry system performs the function of providing monitor information to the ground controllers of the SHARP. The information such as altitude, temperature, status of attitude control system, voltage levels, power consumption and position is acquired and combined together to be transmitted to the ground. The telemetry system will consist of a PCM encoder and a frequency transmitter. A PCM encoder is chosen because of its accuracy and its immunity to noise in the RF system. The PCM encoder will be a low power lightweight unit with the data

SYSTEM - ELEMENT	POWER REQM'T ESTM	POWER REQM'T ACTUAL	WEIGHT (Kg)	VOLUME (M^3/cm^3)	COMMENT
STATION KEEPING CONTROL.					
ALTITUDE:					
Pressure	0.6W		0.1		
Accelerometer	1 W		0.3		
Altimeter	1.5 W		0.2		
POSITION:					
Omega	3 W		.6		
VCO	3		.6		
Transmitter	30		.6		
Antenna			.2		
Cable			4.5		
RADAR Transponder	40		1.2		USED ONLY ON ASCENT/DESCENT

STATIONKEEPING WEIGHT AND POWER ESTIMATES

TABLE 8.2/3

format optimized for minimum bandwidth of the telemetry transmitter.

The RF transmitter is a lightweight package which can telemeter data from the PCM encoder to a receiving station, tuned at the specific transmitter frequency.

The weight and power estimates are listed in Table 8.2/4.

8.2.5 Telemetry and Command System

The Command Receive system provides the ground platform control centre with the capability of manipulating and controlling the operation of the platform. Operators have the capability of changing the platform's position, altitude, operational characteristics and its length of time that it is stationed at a certain position by overriding the on board microprocessor.

The system consists of a command receiver and decoder where the decoded outputs can provide switch functions and later on, an optional inflight reprogramming of the attitude control system software to fit the characteristics of the environmental conditions. The prime function of the command system is to have ground operator based control the altitude of the platform and be capable of returning the payload back to the ground.

The weight and power estimates are listed in Table 8.2/5.

SYSTEM - ELEMENT	POWER REQM'T		WEIGHT (Kg)	VOLUME (M^3/cm^3)	COMMENT
	ESTM	ACTUAL			
MONITORING SYSTEM					
Antenna			0.2		
PCM ENCODER		15 W	2.2		
I/O BOARD			.2		
CABLE			9.5		
Transmitter		30 W	.6		

MONITORING WEIGHT AND POWER ESTIMATES

TABLE 8.2/4

SYSTEM - ELEMENT	POWER REQM'T ESTM	POWER REQM'T ACTUAL	WEIGHT (Kg)	VOLUME (M^3/cm^3)	COMMENT
TELEMETRY AND COMMAND SYSTEM					
Antenna			0.2		
Receiver	2 W		0.4		
Decoder	20		0.4		
I/O Board			0.3		
CABLE			9.5		

TELEMETRY AND COMMAND
WEIGHT AND POWER ESTIMATES

TABLE 8.2/5

8.3 Ground Based Systems

The ground based systems necessary to support the SHARP are considered in the following paragraphs. The major areas covered are the antenna and systems required to maintain control of a SHARP.

The ground support requirements of grid power, emerging back-up generators, manned or unmanned stations are not dealt with as part of this study. It is assumed, quite idealistically, that power is always available.

8.3.1 Microwave Antenna

The key element in the ground based system of the SHARP is the microwave transmission antenna. It has been shown in Section 5.0 of this report, that the ground antenna must be quite large to achieve a high transmission efficiency at an altitude of approximately 20 km.

To construct a steerable parabolic or spherical ground dish would be costly and have many attendant problems. It is not considered practical, by this author, to construct such ground antennas except in some particular cases.

The concept of the retrodirective array for the transmission of the microwave beam seems the most practical method of construction for the ground antenna.

The retrodirective principle assures that the microwave beam will always be pointed towards the center of the rectenna on the platform. To apply the principle, the transmitting antenna is broken up into many identical subarrays. In the center of each subarray there is a receiver, whose source is a transmitting antenna at the center of the rectenna in the atmospheric platform. The control center also accepts signals from a phase reference source within the transmitting antenna itself. The control center compares the phase of these two signals and then sees that the subarray radiates power in the conjugate phase. This arrangement assures that the total aperture, even though it has mechanical distortions, will radiate a coherent beam which is centered on the rectenna in the atmospheric vehicle. The principle is depicted in Figure 8.3/1.

Figure 8.3/2 shows diagramatically how the magnetron directional amplifier is used in conjunction with a slotted waveguide array and the system for conjugating the phase comparison between an internal clock phase reference and the phase of the pilot beam arriving from the center of the rectenna location.

8.3.2 Platform Station Keeping

The ground station must have the ultimate control of the SHARP. The control of the platform would be through the Telemetry and Command System described in Section 8.2.5. A possible method of station keeping will be described in the following sections from a ground station aspect.

8.3.2.1 Optimum Altitude Determination

The operational performance of a SHARP is dependent on configuration and wind velocities. Section 9.0 of this report summarizes the performance of the configurations considered versus the wind velocity.

Depending on the configuration of the platform, it is desirable to situate it in the wind regime that has the lowest wind velocity.

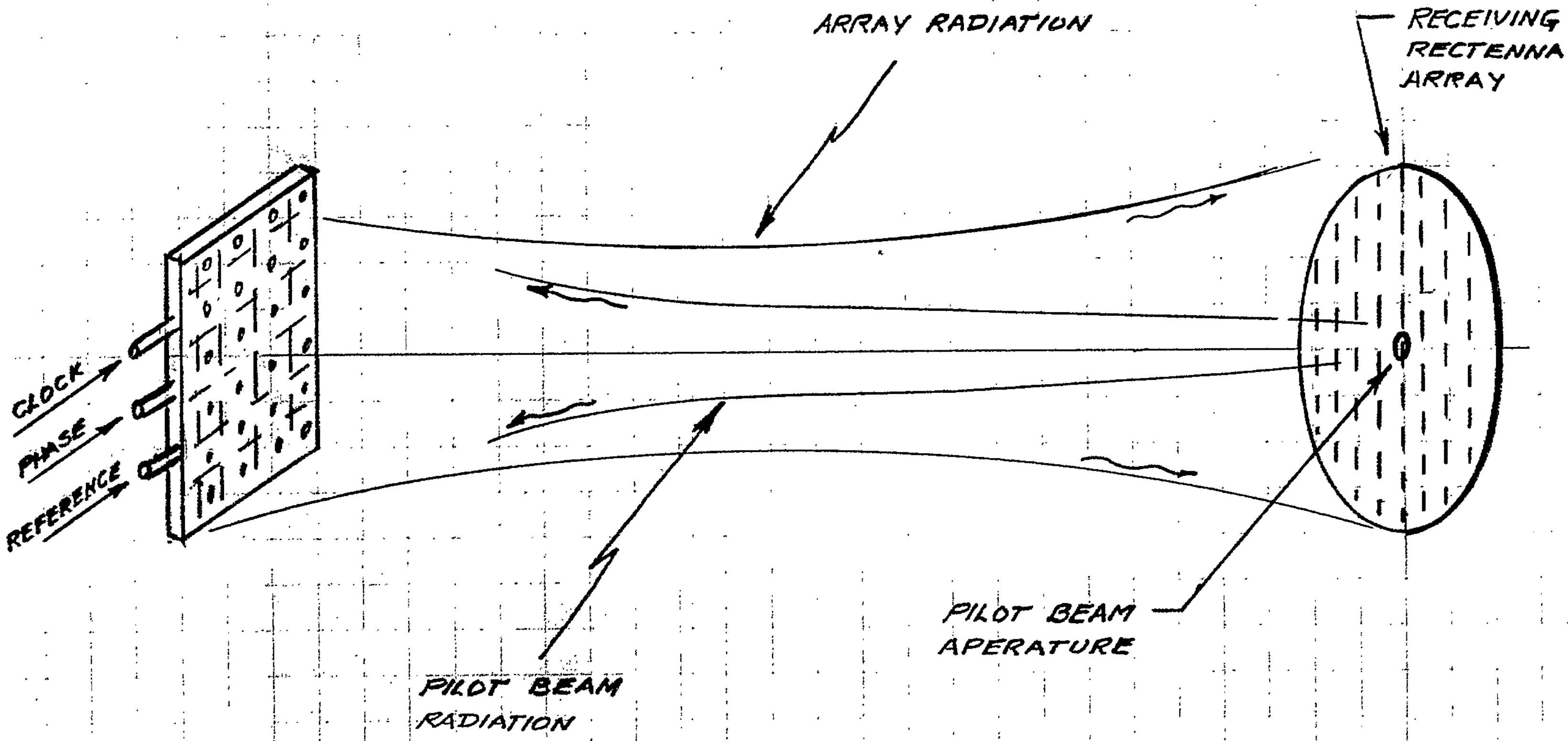
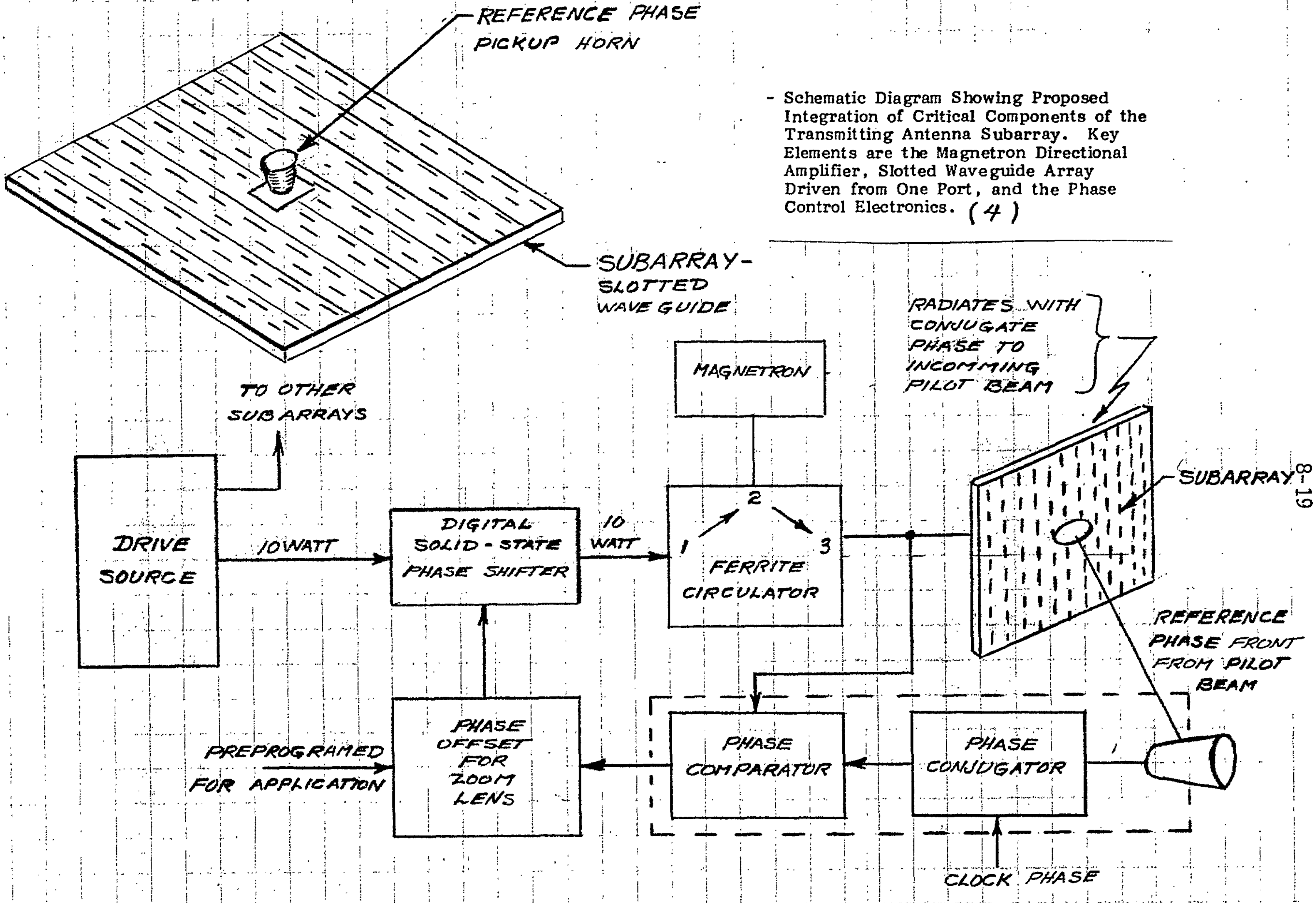


DIAGRAM OF RETRODIRECTIVE ARRAY (4)

FIG. 8·3/1



- Schematic Diagram Showing Proposed Integration of Critical Components of the Transmitting Antenna Subarray. Key Elements are the Magnetron Directional Amplifier, Slotted Waveguide Array Driven from One Port, and the Phase Control Electronics. (4)

FIG. 8.3/2

Recent studies of the atmosphere in the 15-90 km altitude range by RADAR has given an insight into the dynamics of the atmosphere (5). However, at this point in time, these methods have not been fully developed and would not be useful for wind condition determination. A more practical method would be done by establishing wind conditions from past data and correlating to current data from the Atmospheric Services. This would require a station based computer which would be linked to the ADRES system used by AES and predicting the best altitude by comparing to past trends to the current wind velocities. The altitude would be selected through the Platform Telemetry and Command System.

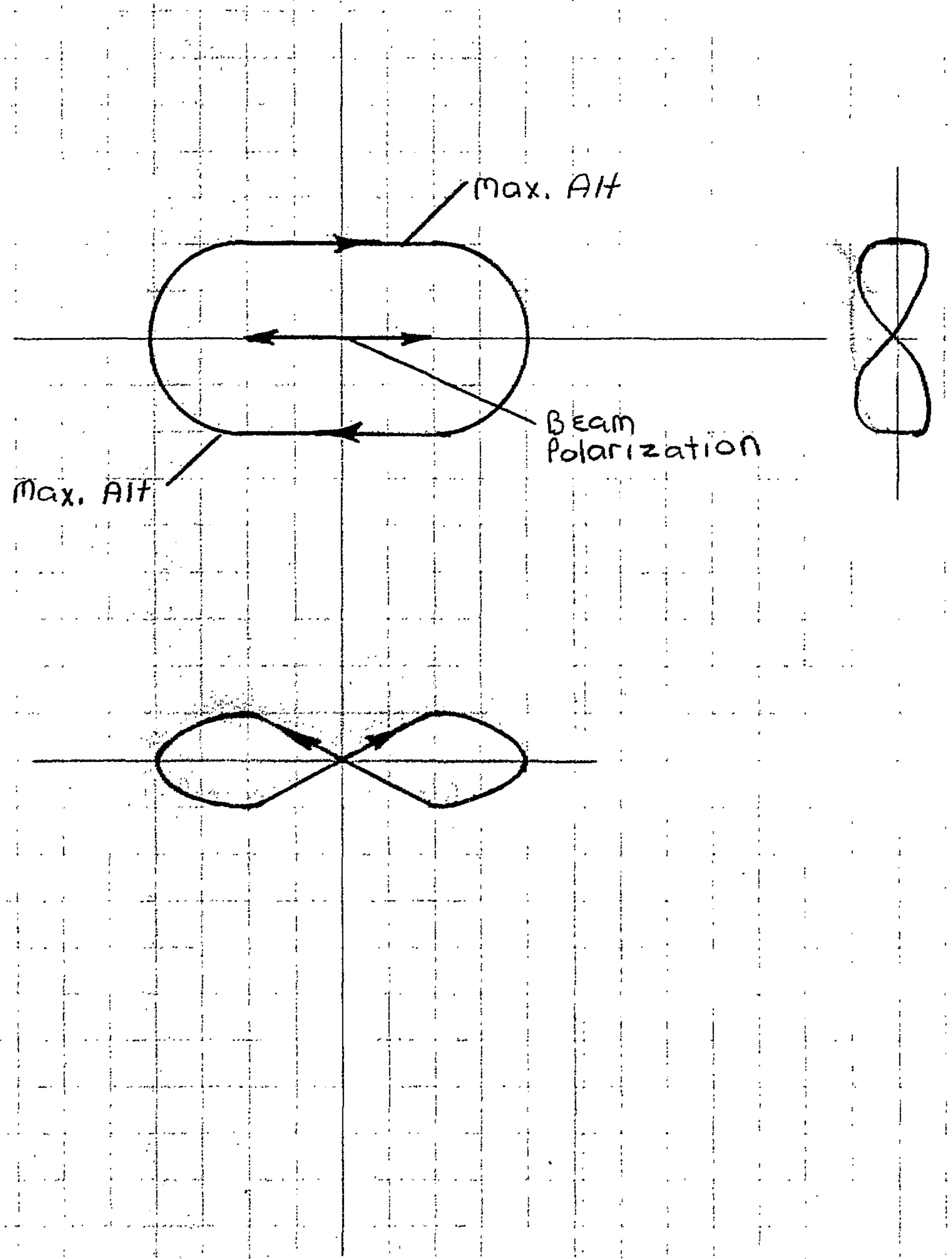
8.3.2.2 Platform Control

Control of the platform will be primarily through the on board micro-processor for attitude and altitude. Changes required because of operational requirements will be accomplished by the ground station through the Telemetry and Command System.

The flight pattern for each vehicle is a function of its particular performance characteristics, the polarization pattern of the microwave beam and the orientation of the rectenna on the platform. The flight strategy must be analyzed prior to programming the on board processor or the ground based computer for each platform type.

The neutrally-buoyant and aerodynamic lifting platform will be required to change direction to propel itself into the wind. As a consequence, the rectenna must be capable of rotating independently of the platform to maintain maximum power.

The hybrid and airplane platform will be required to fly a pattern to maintain lift. The pattern must be orientated with respect to the power beam polarization pattern to obtain maximum power, Reference Figure 8.3/3.



PROROSED
FLIGHT PATTERN
FOR
SHARP AIRCRAFT

FIG. 8.3/3

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9.0 PLATFORM PERFORMANCE

9.1 Introduction

High Altitude balloons have proven capability of reaching 15 to 30 km for periods ranging from 1 to 38 days (1). Lighter-than-air craft have the capability of carrying payloads to a desired position and hovering (2).

The SHARP concept is a combination of these two concepts. The SHARP vehicle should have an operational altitude of 15-25 km and be capable of hovering in a semi-fixed position for periods of 9-12 months. The results of this study indicate that such a platform is well within the bounds of possibility and it is within the technological capability of Canada to manage the development of such a program.

In Section 7.0 the analysis of the platform configurations was discussed at some length and in detail in Appendix A. The purpose of this section is to compare the performance analysis of each with respect to the SHARP performance goals.

9.2 Platform Performance

As has been stated previously, the principle factor determining SHARP feasibility is the ability to ensure provision of adequate levels of power to a vehicle throughout its mission life. The parametric analysis in Section 7.0 on the various configurations considered the effect of carrying batteries on board to supply maximum power for one hour. Two major results were demonstrated; the first is the effect on the vehicle Volume or Wing Area, and the effect on the propulsive power requirements.

The first performance comparisons to be examined are presented in Figures 7.3/2, 7.3/5, and 7.4/3 for the lighter-than-air vehicles and the hybrid configuration, Figure 7.5/3, 7.5/5, and 7.5/7 for the airplane configurations. These parametric analyses show how, for a given Structural-Mass or Structural-Wind Load, the vehicle volume/ wing area changes with respect to maximum air speed with which the vehicle must contend. Two cases are analyzed: First, the case of Volume/Wing Area required for the vehicle with no on board batteries. Second, the case for carrying the weight of batteries need to supply the total power requirement for up to 3.6×10^3 sec (1 hr.). The penalty in the later case is extremely high for the airships. The penalty for this insurance against power loss is that the volume increases approximately one order of magnitude or more. For the airship configuration of SHARP, only some of the cases could be plotted on the graph - the others are off-scale! The penalty for the hybrid is significant in the lower wind speeds and diminishes rapidly as the vehicle speed increases. This points out that a trade-off may be accomplished between weight and vehicle speed because of the aerodynamic lift gained from the shape of the hybrid. Note, that the storage time, Δt is 600 seconds not 3.6×10^3 sec (1 hr.).

From these analyses, it may be concluded that at current weights per energy storage, a one hour reserve of battery power (for full power requirement) would not be practical to provide in the case of the airships or winged balloon at low air speeds. The aircraft wing areas suffer the same effect as the full volume of the lighter-than-air craft. The wing area, increases as the weight increases for a given design speed. The result of adding additional weight for 600 seconds is not as pronounced in the lower speeds but increases with increasing wing load and speed. The more sensible approach for vehicle on board power would appear to be to assume a "power down" condition. Provide power for propulsion and only for equipment required to maintain ground control and maneuver back to the power beam.

The second performance comparisons to be examined are Figures 7.3/3, 7.3/6, 7.4/4, 7.5/4, 7.5/6, 7.5/8, 7.5/9, 7.5/10, and 7.5/11. These figures illustrate the propulsive power required for each vehicle again for the case with no on board batteries and the case for up to 3.6×10^3sec (1 hr.) maximum reserve power capability. For both the neutrally-buoyant and the aerodynamic lifting airship show significant increases in propulsive power requirements.

The winged balloon (hybrid) is not desirable in the low mass and wind regimes. However, in the higher wind and mass regimes, the power requirement does increase dramatically. This vehicle appears to be most satisfactory for intermediate wind regimes between 15 and 25 m/s.

Figure 7.5-8 for the SHARP-I aircraft shows an almost flat power requirement with increase in structural-wing loading. The figures also show that providing batteries for survival propulsive power would essentially be unfeasible.

Figures 7.5/9, 7.5/10 and 7.5/11 show the power density required to be received on the rectenna for the SHARP-I, the Solar Challenger and the AR-20 designs. These curves indicate that an aircraft of the proper wing loading is feasible and within the current state of the art.

9.3 Conclusions and Recommendations

Comparison of the vehicle characteristics and vehicle mission goals results in some positive and negative conclusions. The conclusion may be listed as follows, these are not listed in any priority.

9.3.1 Conclusions

- The neutrally buoyant airship does not perform well. The power required to maintain its position is the highest of all the vehicles.
- The winged balloon has good characteristics in the higher wind regimes but has poor characteristics in low wind regimes.
- The aerodynamic lift airship shows good response to added weight and power requirements. This vehicle would perform well for large payloads. The development of this type of vehicle would be the most difficult and costly because of the attendant material selection and lack of the basic technology.
- The airplane slope requires the least power in the higher wind regimes. The technology for development of this type of vehicle is available.
- The power transmission by microwave is within the technological relm of reality. Development costs would be required since the transmission of microwave is usually only for communications and not for power. The phased array concept will have to be developed since none exists today.

- Development of the microwave rectenna will be required. Small panels have been used for tests but none for the actual reception of usable power.
- The reserve power supplied by on board batteries should be reduced. A power down scheme would increase the time factor for available power.
- The airplane has the best maneuverability characteristics and consequently the possibility of recapting the microwave beam.
- The Solar Challenger type aircraft construction lends itself very well to development by scale models. High technology such as machines and special tools are not required.
- The airplane flight pattern should be initially a modified "D" or a figure "8". This bears more investigation to maximize the reception of the linearized microwave beam power reception.

9.3.2 Recommendations

The SHARP concept is one that is within the present technological capability of Canada. There are areas in this report that have just been mentioned "in passing". The scope of this report does not permit an in depth investigation. As a consequence, these areas should be investigated in a follow-on project or projects. The following recommendations are not in any priority, but serve to point up those areas that require further study or development.

- The wind data from our Canadian stations should be more completely analyzed. This should be done by computer and models be constructed such that the rate of change in velocity could be analyzed, the duration of wind velocity be estimated.

- The retrodirective array concept for microwave transmission be developed. It clearly meets the concept requirements but will need development.
- Solar power be used to augment the power requirements particularly for take-off and landing.
- The samarium-cobalt motor concept be tested for cooling requirements at operational altitudes.
- The AR-20 airplane concept for a platform be further developed. This should be done by modelling so its aerodynamic characteristics may be determined.
- Material investigation be pursued such that light weight construction is possible. These materials will have to be tested for endurance in the 20 km environment plus exposure to microwave.
- The microwave powering concept for the SHARP has the distinct possibility of causing interference in the platform communications equipment. This interference has been alluded to but very little has been done in the way of actual experiment. It is recommended that experimentation with a tethered platform be performed.
- The effect of a microwave beam on the instrumentation and electronic equipment found on commercial and private planes should be investigated.
- The cooling requirement of the rectenna at operational altitude should be investigated.

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10.0 ASSOCIATED CONSIDERATIONS

10.1 Introduction

The primary purpose of this feasibility study is to determine if a SHARP is possible in light of Canadian technology and current equipment and material availability.

This study would be unrealistic if it did not consider such things as launch and recovery operations, regulatory requirements as set forth by Governmental agencies. The coverage of these areas will be general in nature because the study has considered the SHARP in several configurations, each of which will have attendant specific operations' requirements. To the extent possible, time and budget, the significant aspects of operations and regulatory requirements will be addressed to point up important aspects of these areas and the significance of each on the SHARP project when it is launched.

10.2 Operations

This segment of the report will address itself to the aspects of the SHARP required to launch, control, recover and maintain one or more SHARPs.

10.2.1 Launch and Recovery

To launch and recover a vehicle such as the SHARP concept will by necessity require some modifications of the existing facilities available in Canada through the National Research Council. The SHARP concept is that the platform will remain over a fixed location on the earth for an extended period of time. The following aspects are foreseen requirements for these activities.

Locations

At the onset of this study, a visit was made to NRC to determine the existing facilities available to launch a vehicle of the SHARP concept. The essentials of a particular location are basically space, preferably an old airport or an emergency landing strip. Locations that have been used in the past are:

- Gimli, Manitoba
- Churchill, Manitoba
- Yorkton, Saskatchewan

These sites were the locations of Atmospheric Environmental Services high altitude balloon launch campaigns dating from the mid 70's. Gimli is presently the site of NRC's balloon launch facilities. The Gimli site contains complete launch facilities for ballooning, housing of crew and ground telemetry.

Equipment

The equipment required to launch a SHARP would be very similar to the requirements of a balloon launch. The following equipment are essential but by no means is intended to be a complete shopping list because the exact SHARP configuration and payload is not defined.

- Lifting gas trailer and cylinders.
- Spool trailer, used to hold down the vehicle, if it is lighter-than-air.
- Launch vehicle, used to carry the vehicle payload and to maneuver it under the line of ascent after the spool releases the balloon.
- Pre-launch equipment bay, required to house the payload prior to launch such that it may be assembled and checked out.
- Communications; a portable van or a room which houses the telemetry equipment necessary to control, monitor and receive information from the craft.
- Power Transmitter - a steerable or semi-steerable antenna to transmit μ-wave power to the SHARP.
- Standby Generator - if station has grid power this would supply power in case the grid power failed. This is essential to the SHARP concept.

Crew/Manpower

To launch or recover a SHARP in the operational concept, say one platform per Province initially, would require a mobile crew. This crew would be able to trend to launch/recovery sites in each Province and launch a refurbished SHARP, place it in its stationary position and recover the SHARP in need of refurbishment. The following crew is foreseen for a lighter-than-air vehicle:

- Spool Truck	3
- Launch Truck	2
- Launch Director	1
- Platform Communicator	2
- Platform Technician	2
- Crew Stewarts	3

The crew is envisioned as a highly skilled and well coordinated team. The ownership of the SHARP would depend on how much travel or how the team is occupied between recoveries and launches.

10.2.2 Station

The SHARP station is envisioned as being removed from the launch and recovery site. The indications are that the μ-wave antenna would be large and would have some attendant μ-wave "leakage" associated with it. Consequently, a remote site at present seems essential. Remoteness would also reduce the risk of intrusion.

The station would by necessity have to be as self-contained and self-governing as possible. Once the SHARP has been brought under the control of the station, a launch site computer would maintain the SHARP in position by commanding on board controls in response to telemetered information from the platform and ground based sensors.

The station site should be able to steer the beam in response to tracking antenna at the launch site. The possibility exists that the μ-wave beam power could be varied such that increases in upper atmospheric winds from weather stations surrounding the station indicate increased power will be required to maintain platform position.

Should the SHARP break station it would be required that the situation be alarmed to the air traffic control network. The possible scenarios for recovery and the re-installation to the beam or the recovery of the platform are numerous. To go through them at this stage would defeat the purpose of this investigation. It is sufficient to say that a break away will be a serious portion of a SHARP design phase.

10.2.3 Maintenance

The SHARP mission concept entails both complex and sophisticated equipment on the ground as well as the platform and its equipment. For equipment of this complexity it is mandatory that a well-documented and easily maintained system be designed.

The ground station equipment must be easily replaceable by personnel. Some equipment should be redundant such that platform control is not lost during replacement of a malfunctioning unit. For rapid identification of faulty equipment, extensive self-checking would be required; which implies the use of a large resident site computer. Faulty station equipment once replaced would be sent to a central maintenance depot for repair.

One of the key items at a SHARP station is the μ-wave generator. Design of the system must include switch over capability for replacement and/or maintenance.

The ground station design and operation should be a major portion of the SHARP System Design.

The launch site is an ideal place for the platform recovery by controlled descent. The site should have a building of sufficient size to prepare the platform for launch and to perform recovery maintenance and repair. When a platform has been brought down for normal recycling the facility should have sufficient equipment and space to dismantle the platform and to pack the equipment for shipment to the central maintenance depot. Again, the equipment should be modular such that the platform equipment can be readied for emergency replacement of a platform or preparation for the next flight.

In summation, the SHARP concept as a network of communication platforms requires that an extensive system design be performed to reduce costly breakdown and that reliability be a prime requisite of the system. To reduce manpower requirements, the equipment should have extensive self-check capability.

10.2.4 Launch and Recovery

Old airport in the permanent local of SHARP launch, recovery, and maintenance site.

The SHARP is launched ideally early morning - this gives the following advantages:

- calm surface winds
- solar power for "n" hours
- space to launch
- small craft visibility

The launch of a LTA ship (airships) would require a "cherry picker" type vehicle in association with the spool. This would enable the launch crew to lift the vehicle off the ground and still control it.

The SHARP has battery or solar power only at this point.

At lift off, the SHARP is under launch crew command.

At the launch site, there is a steerable μ-wave antenna.

The power does not have to be all that great:

- efficiency $\propto T = \frac{A_t A_r}{\lambda D}$ distance is small, say initially 1 km

once off the ground there is power from

- microwave, the batteries go to charge mode
- control is still by launch crew

Presently, the operational "SHARP" is being recovered in the "beam" at a location several km away.

- Air Traffic has been notified.
- The descending SHARP has its radar transponder turned on -
  - i) by site command
  - ii) back up by barometric switch
- The descending SHARP is still on line - acting as a relay, etc.
- The trick is to lower the "active" SHARP to such an altitude that it is still operational while getting the replacement SHARP up and in the beam.

- The replacement SHARP should be brought up by the launch tractor beam above approximately 12 km (40 K ft.). This removes the platform from commercial air traffic.
- The replacement SHARP is directed to the site beam.
- When the replacement platform is up to a safe altitude, it is introduced into the site beam. The operational SHARP is then cut off from the site μ-wave beam.
- The new SHARP now must be raised in the site beam to operational altitude. Simultaneously - the recovery crew is locking the SHARP to be recovered in the tractor beam.
- The SHARP being recovered is brought down in control of the recovery crew with power being supplied by the steerable dish and solar panel.
- The SHARP is brought down to the launch/recovery site for repair and maintenance.
- An important question that remains is - when does the communications relay changeover occur.

10.3 Regulatory

10.3.1 Environmental Effects

The principal effect of microwaves on living matter that is recognized now is that of heating and the safe exposure level in the U.S. and Canada for human and animal life was derived on the basis of this effect alone. The current U.S. standard for continuous exposure is 10 mW/cm^2 (9.29 W/ft^2) while the Russian standard is 1000 times less. In Canada, the present standard has recently been revised downwards to 1 mW/cm^2 for the general public, averaged over one minute. The corresponding figure for microwave radiation workers is 5 mW/cm^2, averaged over one hour, or 25 mW/cm^2, averaged over one minute (Reference 2).

Antennas proposed for the U.S. HAPP program have power densities at the surface of the earth below the 10 mW/cm^2 level. Because of beam focusing, the intensity levels will be greater at higher altitudes and therefore could pose a threat to objects passing through the beam. Because of their speed, aircraft passing through the beam at very high altitudes will be exposed to the more intense microwave radiation for a fraction of a second only. Furthermore, the metal surface on the aircraft would shield the occupants adequately. Hence, there is low risk of damage from such exposure.

Birds would fly through the beam at low altitudes (no more than several thousand feet) and therefore would encounter a much weaker beam than the high flying aircraft. Nevertheless, the intensity would be greater than that near the earth's surface.

The long term effects on living matter, especially that of low power microwaves are not well understood and there is considerable controversy as to what constitutes a safe level. If the prevailing standards should be deemed unsafe in the future, measures would have to be taken to minimize the exposure of humans to microwave radiation. One possibility is to designate a safety zone surrounding the beam path. This zone would be kept small if there is adequate suppression of the side lobes in the beam.

A second important environmental effect is microwave interference. While the transmission system will be operating at some nominal frequency (say 2.45 GHz), there will always be some energy generated and radiated outside the IMS band. In addition to the interference being generated by the transmitting antenna, there is also interference due to the harmonics produced by the rectenna. This interferences from both of these sources could potentially interfere with the communications equipment of SHARP. However, Sinko (1) estimates that if sufficiently directional antennas are used with such equipment, reception of noise will be minimized. (He estimates a noise level of about -84 dB with a 5 MHz BW receiver operating at 3 GHz.)

The harmonics generated by the rectenna may cause interference with microwave equipment of other users operating at these harmonic frequencies. Investigation is needed to determine the degree of interference caused by the above mentioned sources.

10.3.2 Air Traffic

Without appropriate measures SHARP does present a hazard to air traffic during launch and recovery operations. Measures similar to those commonly used for upper atmospheric balloon launches, involving close cooperation with air regulatory bodies. When a platform is being prepared for launch or recover, the air traffic control network is informed and all commercial air traffic is warned. When launch or recovery is eminent, the zone to be avoided would be signalled to all air traffic.

To further reduce the possibilities of any mishaps, the SHARP would be equipped with a radar reflector and a beacon transponder. The transponder would only need to be operative on ascent and decent to operating altitude. This device would warn all commercial air traffic in an active fashion and complement the air traffic warnings.

Small private air traffic is warned prior to take off. Usually they do not have radar equipment and visual avoidance is required by the pilot. Usually this is possible because lighter-than-air craft require calm, clear weather to launch.

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APPENDIX A

Performance Calculations for SHARP Configurations

The equations for equilibrium flight are:

$$C_L q S + \rho g Vol = m g \quad (1)$$

$$T = C_D q S \quad (2)$$

$$P = C_D q S U / \eta_p + P_{OB} \quad (3)$$

where

C_L = vehicle lift coefficient

C_D = vehicle drag coefficient

q = dynamic pressure, $\rho U^2/2$

ρ = atmospheric density

U = flight speed relative to air

S = vehicle characteristic (reference) area

Vol = vehicle molded volume

g = gravitational constant

m = vehicle total mass (incl. internal air + gas

T = propulsive thrust

P = power required for equilibrium flight

P_{OB} = power used by onboard equipment (payload and control system).

For a given geometry, Vol is related to S by

$$Vol = C_1 S^{3/2} \quad (4)$$

Also, the mass breakdown is

$$m = m_{structure} + m_{internal\ air} + m_{gas} + m_{pl} + m_{propulsion\ system} + m_{control\ system} + m_{power} \quad (5)$$

where $m_{structure}$ will be assumed to be proportional to Vol, so that

$$m_{structure} = C_2 Vol = C_1 C_2 S^{3/2} \quad (6)$$

Assume operation at altitude, so that

$$m_{internal\ air} \approx 0 \quad (7)$$

$$m_{gas} = \rho_{gas}(Vol)_{gas} \approx \rho_{gas} Vol =$$

$$m_{gas} = \rho\,(Ratio)\,C_1 S^{3/2}, \quad (8)$$

where Ratio = 1.0 - 0.862 × (helium purity)

The payload mass will be assumed to be a fixed given amount, so that

$$m_{pl} = given \quad (9)$$

The propulsion system mass is assumed to consist of the motor / prop / support / etc. unit(s). Also, it is assumed to be a linear function of the maximum propulsive power required:

$$m_{ps} = C_3 (P_{propulsion})_{max} \tag{10}$$

where $(P_{propulsion})_{max} = C_D S q_{max} U_{max} / \eta_p$

so, $m_{ps} = C_3 C_D S q_{max} U_{max} / \eta_p$ (11)

The mass for the control system will be assumed to be given, so that

$$m_{control\ system} = given \equiv m_{cs} \tag{12}$$

The power-source mass depends on the type of power generation and storage system chosen. For the SHARPS, assume microwave transmission for continuous 100% power supply, with an onboard battery for emergency supply. Therefore The mass of the microwave structure will be a linear function of the maximum power required,

$$(m_{power})_{\mu\text{-}wave} = C_4 P_{max} \tag{13}$$

where $P_{max} = (P_{propulsion})_{max} + P_{OB} =$

$C_D S q_{max} U_{max} / \eta_p + P_{OB}$, so that

$$(m_{power})_{\mu\text{-}wave} = C_4 C_D S q_{max} U_{max} / \eta_p + C_4 P_{OB} \tag{14}$$

where $P_{OB} = given$ (15)

Also, the battery mass is a linear function of its maximum stored energy.

$$(m_{power})_{battery} = C_5 E_{max} \tag{16}$$

A worse-case estimate for E_{max} may be to assume that it has to supply P_{max} for a duration Δt, so that

$$(m_{power})_{battery} = C_5 P_{max} \Delta t =$$

$$(m_{power})_{battery} = C_5 \Delta t \left(C_D S q_{max} U_{max} / \eta_p + P_{OB} \right) \tag{17}$$

Now, eq. (1) may be rewritten as

$$\frac{C_L q S}{g} + \rho Vol = m \tag{18}$$

which, from (6), (7), (8), (9), (11), (12), (14), and (17) becomes

$$\frac{C_L \rho U^2}{2g} S + \rho C_1 S^{3/2} = C_1 C_2 S^{3/2} + \rho (Ratio) C_1 S^{3/2} + m_{pl} + C_3 C_D S q_{max} U_{max} / \eta_F + m_{cs} + C_4 C_D S q_{max} U_{max} / \eta_p + C_4 P_{OB} + C_5 C_D S q_{max} U_{max} \Delta t / \eta_p + C_5 P_{OB} \Delta t \tag{19}$$

With given design and flight parameters, this constitutes and equation for the vehicle size, S:

$$\left[\rho C_1 - C_1 C_2 - \rho(\text{Ratio})C_1\right] S^{3/2} +$$

$$+\left[\frac{\rho C_L U^2}{2g} - \frac{C_3 C_D \rho U_{max}^3}{2\eta_p} - \frac{C_4 C_D \rho U_{max}^3}{2\eta_p} - \right.$$

$$\left. - \frac{C_5 C_D \rho U_{max}^3 \Delta t}{2\eta_p}\right] S - \left[m_{pl} + m_{cs} + C_4 P_{OB} + \right.$$

$$\left. + C_5 P_{OB} \Delta t\right] = 0 \qquad (20)$$

This has the form of

$$A S^{3/2} + B S + C = 0 \qquad (21)$$

where

$$A \equiv \rho C_1 \left[1 - (\text{Ratio})\right] - C_1 C_2 =$$

$$0.862 \rho C_1 (\text{helium purity}) - C_1 C_2 ,$$

$$B \equiv \rho\left[\frac{C_L U^2}{2g} - \frac{C_D U_{max}^3}{2\eta_p}(C_3 + C_4 + C_5 \Delta t)\right] ,$$

$$C \equiv - m_{pl} - m_{cs} - P_{OB}(C_4 + C_5 \Delta t) .$$

Representative numerical values for the equations:

From Figure 2 in Vorachek,

$$C_2 \cong 0.044 \ \mathrm{lb/ft^3} = 0.70481 \ \mathrm{kg/m^3}$$

For the HASPA (hull + fins)

$$C_2 = \frac{1190.0}{8.0 \times 10^5} = 0.00149 \ \mathrm{lb/ft^3} = 0.02383 \ \mathrm{kg/m^3}$$

For the TCOM "STARS" aerostat,

$$C_2 = \frac{309.079 \ \mathrm{kg}}{754.0 \ \mathrm{m^3}} = 0.4100 \ \mathrm{kg/m^3}$$

GTS wing balloon, (Semi hybrid)

$$C_2 = \frac{89.81 \ \mathrm{kg}}{141.6 \ \mathrm{m^3}} = 0.6343 \ \mathrm{kg/m^3}$$

From NASA's Mayer + Needleman,

C_2 varies from 0.23 to 0.46

They say that the latter value was that for the HASPA. For this study, allow C_2 to vary

$C_2 = 0.01$ to 0.10 (see page 12)

The shape parameter, C_1, is 1.0 for all blimp shapes, and 0.1828 for the GTS wing balloon. These two values will be chosen when appropriate.

For C_3, one may draw on O'Shea's results for an advanced, but state-of-the-art, electric motor for which 7.80 kg produces 11,000 W, so

$$C_3 = 7.8/11000 = 0.00071 \text{ kg/W}$$

NOTE: MOTOR IS 7.8 kg.

Likewise from O'Shea, the microwave structure's (rectenna's) mass/power is

$$C_4 = 1.27 \text{ kg/m}^2 / 1076 \text{ W/m}^2 = 0.001803 \text{ kg/W}$$

The battery's specific energy varies with its specific power. From O'Shea, a reasonable range is 20 to 40 Watt-hours/kg, so

$$C_5 = \frac{1}{20} \text{ to } \frac{1}{40} \frac{\text{kg}}{\text{Watt-hr}} = 0.05 - 0.025 \frac{\text{kg}}{\text{Watt-hr}} =$$

$$= \frac{0.05}{3600} \text{ to } \frac{0.025}{3600} \frac{\text{kg}}{\text{Watt-sec}} =$$

$$C_5 = 1.39 \times 10^{-5} \text{ to } 6.94 \times 10^{-6} \text{ kg/Joule}$$

For the other terms in the eq., note that:

1. $C_L \approx 0$ for neutrally-buoyant vehicle

   C_L varies from 0 to 1.0 for lifting vehicle

2. Atmospheric density, ρ, is around that for the 50 mb altitude, which is 0.07754 kg/m^3, so let

$$\rho = 0.0600 \text{ to } 0.0800 \text{ kg/m}^3$$

3. From O'Shea, the payload mass is 60 kg, so

$$m_{pl} = 60.0 \text{ kg}$$

4. Note that U appears only with C_L in the first term of the equation. Thus, it is not a parameter which determines the size of the neutrally buoyant vehicle. Its value, then, is that for the average cruise speed of the vehicles with aerodynamic lift, and will be chosen to vary from

$$U = 1.0 \text{ to } 10.0 \text{ m/sec}$$

5. Helium purity will be assumed to be 98%, so

helium purity = 0.98

6. The drag coeff., C_D, typically ranges from 0.02 to 0.06 (based on $S = (Vol)^{2/3}$) for traditional airship shapes, and 0.02 to 0.150 (based on wing planform area) for vehicles with aerodynamic lift. So,

C_D = 0.02 to 0.06 (neutrally-buoyant vehicles

C_D = 0.02 to 0.15 (aero-lifting vehicles)

7. U_{max} is maximum speed, relative to the wind, that the vehicle has to maintain to keep from being blown off station. From O'Shea's wind data,

$$U_{max} = 5.0 \text{ to } 50.0 \text{ m/sec}$$

8. Δt, the duration that the battery has to supply P_{max}, will be assumed to vary:

$$\Delta t = 1.0 \times 10^3 \text{ to } 10.0 \times 10^3 \text{ sec}$$

9. The propulsive efficiency, η_p, will be assumed to have a variation which is typical of properly designed propellors:

$$\eta_p = 0.75 \text{ to } 0.95$$

10. From O'Shea, the control-system mass is

$$m_{cs} = 42.84 \text{ kg}$$

11. Also from O'Shea, the onboard power requirement is

$$P_{OB} = 2295.6 \text{ W}$$

Baseline Case(s)

A baseline case will be chosen, about which the parameters will be varied through the ranges indicated above.

a. Neutrally-Buoyant Airship, $C_1 = 1.0$

b. Wing-Balloon Hybrid Design, $C_1 = 0.1828$

c. Airplane HTA Design, $C_1 = 0.0$

$C_2 = 0.03$ (see page 12)

$C_5 = 9.0 \times 10^{-6}$ kg/Joule

a. Neutrally-buoyant airship , $C_L = 0.0$

b. Wing-balloon hybrid design , $C_L = 0.50$

c. Airplane HTA design , $C_L = 0.50$

$\rho = 0.0700$ kg/m^3

a. Neutrally-buoyant airship , $U = 0.0$

b. Wing-balloon hybrid design , $U = 5.0$ m/sec

c. Airplane HTA design , $U = 10.0$ m/sec

a. Neutrally-buoyant airship , $C_D = 0.04$

b. Wing-balloon hybrid design , $C_D = 0.10$

c. Airplane HTA design , $C_D = 0.05$

$U_{max} = 10.0$ m/sec

$\Delta t = 1$ hr $= 3600$ sec

$\eta_p = 0.80$

Appendix 1 : Neutral-Buoyancy Check

If the vehicle only has to support the weight of its basic structure, then eq. (18) becomes

$$\rho \, Vol = m_{structure} + m_{gas} \qquad (22)$$

which gives

$$\rho C_1 - C_1 C_2 - \rho (Ratio) C_1 = 0 \quad \rightarrow$$

$$\rho C_1 (1 - Ratio) - C_1 C_2 = 0$$

and Ratio = 1.0 − 0.862 Pure , so

$$0.862 \rho C_1 Pure - C_1 C_2 = 0 \quad \rightarrow$$

$$0.862 \rho \, Pure - C_2 = 0 \qquad (23)$$

For 50 mb altitude, $\rho = 0.0700 \ kg/m^3$

so $C_2 = 0.05913 \ kg/m^3$

Alternately, for $C_2 = 0.45$,

$$\rho = 0.5327 \ kg/m^3$$

which is much lower than 50 mb altitude.

Example:

Let $C_2 = 0.02$, then from eq. (21),

$A = 0.862 \times 0.07 \times 0.98 - 0.02 = 0.03913$

$B = 0.0$

$C = -60.0 - 295.6 - 2295.6 \times 0.0071 = -371.8988$

so, $S^{3/2} = 371.8988 / 0.03913 = 9504.185$

$Vol = 9504.185\ m^3$

$S = 448.69\ m^2$

checks with program

Note:

From Lagerquist + Keen, the structural wt. of the HASPA (hull + fins) is 1465.0 lb = = 664.51 kg ; and the volume is 800,000 ft^3 = = 22653.48 m^3, so

$C_2 = 0.02933\ kg/m^3$

Exerpts from letter report of 24 June 1981 from
J. De Laurier to J.D. O'Shea

Here are some further results from my analysis. Please note that so far I've assumed no onboard battery ($\Delta t = 0$) and 50mb altitude ($\rho = 0.0700\ kg/m^3$). You already have my Fig. 1 from George Jull's visit to you, which showed the required sizes of a neutrally-buoyant airship for different maximum-speed capabilities. It gave the surprising result that size didn't change much with U_{max}, for structural-mass parameters, C_2, below 0.04 kg/m^3.

Next, I looked at a "heavy" airship which required aerodynamic lift for level flight. I assumed $U_{max} = 25$ m/s and a lift coefficient, C_L, of 0.20. This, with the drag coefficient, C_D, of 0.04, are representative values at the maximum lift/drag ratio of typical airship configurations. The variable parameter was cruising speed, U, where the larger this is, the less buoyancy (and volume) the airship requires. This is shown in Figure 2, where the 25 m/s airship is significantly smaller than the 5 m/s case. Note, though, that we still can't achieve C_2 values much beyond 0.05, which represents a fairly flimsy construction.

The "wing-balloon" design was studied next, where again I chose $U_{max} = 25$ m/s and varied U. The C_L and C_D values were those, from wind-tunnel tests, which gave a maximum lift/drag ratio. The results in Figure 3 show inferior behavior, to the airship, up to U = 20 m/s, but a dramatic improvement at U = 25 m/s. It is clear that if such a cruising speed is operationally acceptable, then the wing balloon could be:

(1) significantly smaller, e.g., $2000m^3$ instead of $8000m^3$,
(2) structurally more rugged, in that the higher C_2 values would allow the use of stronger, coated, fabrics.

In other words, these results confirm our intuitive notion that the wing balloon, or "hybrid", configuration has distinct advantages over the traditional airship shape.

For the last candidate concept, the "airplane" configuration, I used data for the "Solar Challenger" (including that which you supplied) to establish representative parameters. The calculations are in the writeup, which gave a $C_L = 0.405$ and $C_D = 0.03$. Also, U was assumed to be equal to U_{max}, and to vary from 25m/s to 45m/s (at 50mb, the "Challenger" at full weight would fly at U = 54 m/s). An important difference for this vehicle, as opposed to the balloons, is that the structural-density parameter, C_2 is not as meaningful as a "wing loading" parameter, C_6, where

$$C_6 = \text{total vehicle mass/lifting-surface area}$$

For the empty "Challenger", $C_6 = 1.77$ kg/m^2.

Figure 4 gives the results, where it is seen that a large (twice to four times the area) "Solar Challenger" type vehicle is a real possibility for this mission. The required cruise speed is above 25 m/s, and perhaps as high as 50 m/s, but it is clear that one could use the Solar Challenger's constructional methods to build a reasonably-sized vehicle which would fly to the required altitude without any buoyant lift and the complications of helium inflation and storage. This seems like a very exciting prospect, and I'd welcome your thoughts on this.

A decisive factor, at this point, is the type of flight strategy acceptable for a heavier-than-air-vehicle. Would continuous circling or side-to-side "snaking" against a headwind allow accurate microwave aiming?

Appendix 2: Parameters for Airplane Config.

For this case, there is no significant volume, so choose

$$C_1 \cong 0.0$$

However, the product $C_1 C_2$ must be non-zero for structural mass to vary with $S^{3/2}$. From the Solar Challenger data supplied by O'Shea

$$(W_t)_{structural} = 125 \text{ lb}, \quad S = 245 + 100 \text{ ft}^2$$

so $$m_{structure} = 56.7 \text{ kg}, \quad S = 32.05 \text{ m}^2$$

and $$C_1 C_2 = 56.7/(32.05)^{3/2} = 0.3125$$

A more meaningful parameter, for this case, would be the "wing loading", defined by C_6 where

$$m_{structure} = C_6 S \qquad (24)$$

Equation (19) then changes to become

$$\frac{C_L \rho U^2 S}{2g} = C_6 S + m_{pl} + \frac{C_2 C_D S q_{max} U_{max}}{\eta_p}$$

$$+ m_{ce} + \frac{C_4 C_D S q_{max} U_{max}}{\eta_p} + C_4 P_{OB} +$$

$$+ \frac{C_5 C_D S q_{max} U_{max} \Delta t}{\eta_p} + C_5 P_{OE} \Delta t \qquad (25)$$

which gives polynomial:

$$B' S + C = 0 \qquad (26)$$

where

$$B' = \rho\left[\frac{C_L U^2}{2g} - \frac{C_6}{p} - \frac{C_D U_{max}^3}{2\eta_p}\left(C_3 + C_4 + C_5 \Delta t\right)\right]$$

$$C = -m_{pl} - m'_{cs} - P_{OB}\left(C_4 + C_5 \Delta t\right)$$

For the Solar Challenger,

$$C_6 = 56.7 / 32.05 = 1.77$$

U_{max} = 40 mph (17.9 m/s) at 10,000 ft

$P_{max} = 2676 \times \eta_p = 0.86\,(2676) = 2301$ W

at 10,000 ft, $\sigma = 0.7385 \rightarrow \rho = 0.9047\ kg/m^3$

so, $C_D\, \rho \dfrac{U_{max}^3}{2} S = P_{max} \rightarrow$

$$C_D = 2 P_{max} / (\rho\, U_{max}^3 S)$$

$$= 2 \times 2301 / (0.9047 \times 17.9^3 \times 32.05) =$$

$$C_D = 0.0277$$

Also, $C_L = \dfrac{2 W_t}{\rho\, U_{max}^2 S} = \dfrac{2 \times 9.81 \times 136.08}{0.9047 \times 17.9^2 \times 32.05}$

$$(C_L)_{U_{max}} = 0.2874$$

Note that

$$(L/D)_{U_{max}} = 10.38$$

The stated maximum L/D is 13.5, so, assume that in this case

$$C_D = 0.03 \quad , \quad C_L = 0.405$$

Note that at the operational altitude where $\rho = 0.0700\ kg/m^3$,

$$U_{max} = \left[\frac{2W_t}{\rho C_L S}\right]^{1/2} = \left(\frac{2 \times 9.81 \times 136.08}{0.07 \times 0.405 \times 32.05}\right)^{1/2}$$

$$(U_{max})_{50mb} = 54.21\ m/s$$

Exerpts from letter report 29 September 1981 from
J. De Laurier to J.D. O'Shea

Here are plots for the updated results of my analysis, as we discussed in our phone conversation last week. The changes from the results of 24 June are:

(1) the electric motor mass-per-power coefficient, C_3, has been changed from 0.0071 kg/W to 0.00071 kg/W,
(2) the microwave rectenna's mass-per-power coefficient, C_4, has been corrected from 0.001803 kg/W to 0.0011803 kg/W.

Additionally, the new results include on-board batteries which give maximum propulsive power outputs for specified times, Δt. Also, propulsive powers have been plotted for the candidate concepts.

The format has been somewhat changed in that the vertical axis is now a log scale, which allows simultaneous plotting of the battery and no-battery cases. Also, for the LTA concepts, I now plot their molded volume as the size parameter rather than their "characteristic area". I think that this is easier to visualize.

The $\Delta t = 0$ results in Figures 5, 6, 9 and 11 may be compared with Figures 1, 2, 3 and 4, respectively, of the 24 June results. In all cases, the sizes are less for the new results because of the decrease in C_3. Otherwise, the previous conclusions still apply in that at U_{max} = 25 m/s the aerodynamically-lifting airship is smaller than the neutrally-buoyant design, and the wing-balloon is smaller yet. Also, the airplane appears to be reasonably sized at wing areas of $[10^2]$ m^2.

The addition of an onboard battery gave dramatic increases in size for the Δt values considered. The volumes of the two airships increased by a factor of 5 for Δt = 1 hr., and the wing-balloon's volume similarly increased for a Δt of only 10 min. Also, the airplane's wing area increased by nearly an order of magnitude for Δt = 1 hr. In fact, note that the size trend with speed is reversed, in that the battery weight increases faster with speed than the aerodynamic lift.

It's fortunate that the airplane can trade off altitude for speed in a glide mode, since the results show that it couldn't carry any significant battery weight.

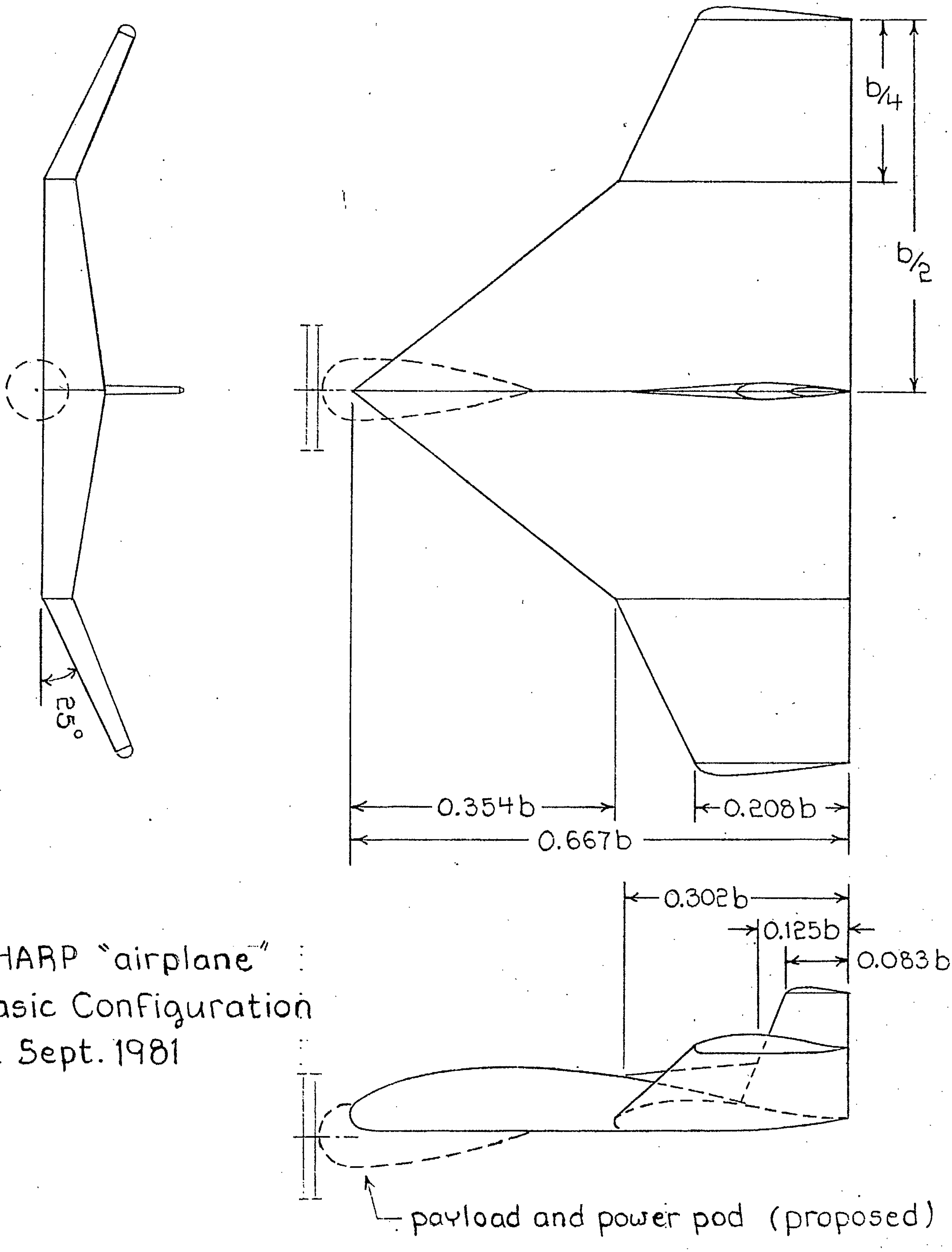
The propulsive power results in Figures 7, 8, 10 and 12 show, first, that the aerodynamically-lifting airship can fly with significantly less power than the neutrally-buoyant airship. For both designs, in the HASPA range of Structural-Mass Parameters, C_2, the power is on the order of 10 kW for $\Delta t = 0$ and 10 to 10^2 kW for $\Delta t = 1$ hr. Next, the wing-balloon's propulsive power is also on the order of 10 kW for cruise speeds above 20 m/s at $\Delta t = 0$ and cruise speeds above 25 m/s for $\Delta t = 10$ min. This compares favourably with the airships for $\Delta t = 0$, but note that no solutions were possible within this speed range for $\Delta t = 1$ hr. Clearly, the wing-balloon has less ability to carry on-board battery energy. Also, the wing-balloon's ability to trade off altitude for speed is significantly limited because of its high drag coefficient.

Finally, the airplane's propulsive power is shown in Figure 12 to be generally lower, at U = 25 m/s, than that for the airships' for both $\Delta t = 0$ and $\Delta t = 1$ hr. In fact, for $\Delta t = 0$, the power is fairly constant with wing loading, varying between 2 and 3 kW. Even for the higher speeds, the power for $\Delta t = 0$ stays below 6 kW. However, as with the wing-balloon, the airplane's required propulsive power dramatically increases with speed for $\Delta t = 1$ hr. In fact, no solutions were possible for speeds above 30 m/s.

In conclusion, though, I think that these new results still favour the airplane concept. Even though the on-board battery capability is limited, if the glide-dive maneuver for recapturing the microwave beam is feasible, the airplane would clearly be a smaller, stronger, flight vehicle than the three LTA concepts. Also, as we had previously discussed, the ability to do away with lifting gas and its management is a significant advantage.

The aerodynamics of the airplane used in these calculations were derived from the "Solar Challenger", but I would like to propose a design which is more specifically tailored to our requirements. The attached sketch shows a cranked-wing flying-wing configuration. The broad centre area gives a concentrated location for the rectenna, and the thick airfoil in this region would allow the rectenna to be internally built in. The outer wings increase the aspect ratio, and provide stabilizing and control surfaces. The geometry and location of the "pod" are preliminary, as is the propeller selection; but I think that the overall configuration would give a strong, stiff, high-g structure with decent aerodynamic properties (I estimate a maximum L/D of ≈ 6). I would very much welcome your thoughts on this.

G. D. DeLaurier



SHARP "airplane"
Basic Configuration
22 Sept. 1981

Exerpts from letter report 30 October 1981 from
J. De Laurier to J.D. O'Shea

Here are the aerodynamic estimates for the SHARP flying-wing airplane ("SHARP-1") which we discussed during our last phone conversation. My initial guess of a maximum lift/drag ratio of ≈6 was way off, since the detailed calculations give a value of 13. This compares with a value of 13.5 for the Solar Challenger. The latter is still a better configuration because it achieves its maximum lift/drag ratio at a higher lift coefficient (C_L = 0.405) than that for the SHARP-1 (C_L = 0.287); but I think that our particular requirements still favour the SHARP-1 configuration. In fact, a comparison of Figures 11 and 13 show that a "Solar Challenger" used for a SHARP mission would be only slightly smaller; and a comparison of Figures 12 and 14 show even less difference in the required propulsive power.

As a further case, I calculated the performance of the SHARP-1 at maximum "Power Factor" (C_L^3/C_D^2), which is the condition for least power required for a given airplane to maintain level flight. Figure 15 shows that the size considerably reduces due to the higher lift coefficient (C_L = 0.497). However, at a given speed, the reduced size does not offset the increased drag coefficient (C_D = 0.0440) in increasing the required propulsive power by ≃ 10%.

In summary, I think that the "SHARP-1" flying-wing airplane looks like a very feasible candidate, if the structural wing loading can be kept in the assumed region. Your thoughts on these results would be much appreciated.

Aerodynamic Estimations for SHARP-1

Airfoil:

Assume an NACA M6, which, from Appendix IV of Technical Aerodynamics by Wood, has the following characteristics for

$AR = 6$ (rectangular), R.N. $= 3.5 \times 10^6$:

$\alpha_{C_L=0} = -0.8°$, $C_{L\alpha} = 0.070/\text{deg} = 4.011/\text{rad}$

$(C_D)_{min} = 0.0077$, $C_{m_{ac}} = 0.015$

The lift-curve slope is given by the Polhamus equation:

$$C_{L\alpha} = \frac{2\pi AR}{2 + \left[\frac{AR^2}{K^2}\left(1 + \tan^2(\Lambda_{c/2})\right) + 4\right]^{1/2}}$$

Which, for this case, becomes

$$4.011 = \frac{12\pi}{2 + \left[\frac{36}{K^2} + 4\right]^{1/2}} \rightarrow \left(\frac{36}{K^2} + 4\right)^{1/2} = \frac{12\pi}{4.011} - 2$$

$$\frac{36}{K^2} + 4 = 54.744, \quad \frac{36}{K^2} = 50.744 \rightarrow$$

$$K^2 = 36/50.744 = 0.7094, \quad \underline{K = 0.842}$$

The turbulent skin-friction drag is given by

$$(C_D)_{fric.} = 0.910/[\log(R.N.)]^{2.58}$$

which, for this case is

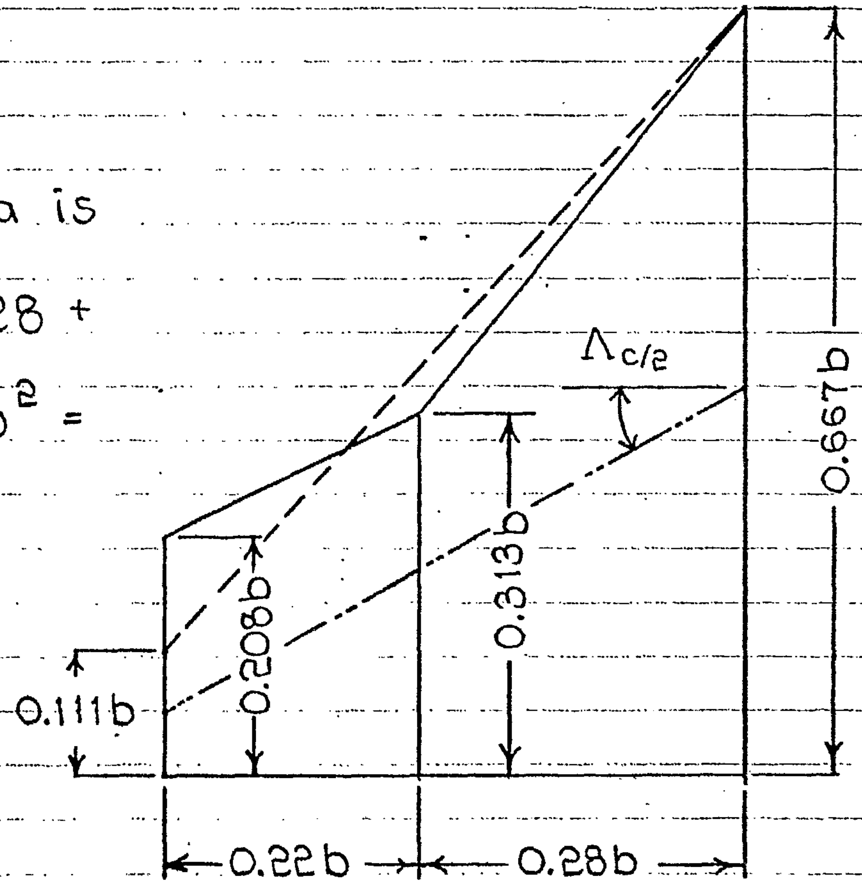
$$(C_D)_{fric} = 0.910 / [\log(3.5 \times 10^6)]^{2.58} = 0.0071$$

so the pressure drag is

$$(C_D)_{press.} = (C_D)_{min} - (C_D)_{fric} = 0.0077 - 0.0071$$

$$\underline{(C_D)_{press} = 0.0006}$$

<u>Wing:</u>



The planform area is

$$S = 2(0.490 \times 0.28 + 0.261 \times 0.22)b^2 =$$

$$S = 0.389\,b^2$$

The "equivalent straight-tapered planform" has the same span and area:

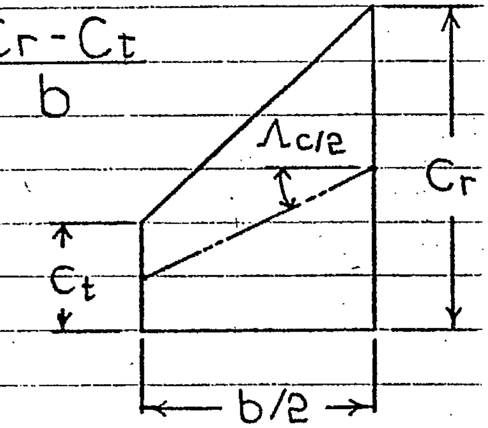
$$S = \frac{(C_{tip} + C_{root})\,b}{2}, \quad C_{tip} = \frac{2S}{b} - C_{root}$$

$$C_{tip} = \frac{2(0.389\,b^2)}{b} - 0.667\,b = 0.111\,b = C_{tip}$$

so the taper ratio is $\lambda = 0.166$

And the midchord sweep angle, $\Lambda_{c/2}$ is

$$\tan(\Lambda_{c/2}) = \frac{(C_r/2 - C_t/2)}{b/2} = \frac{C_r - C_t}{b}$$



$$\tan(\Lambda_{c/2}) = \frac{0.667 - .111}{1} = 0.556$$

$$\Lambda_{c/2} = 29.074^\circ$$

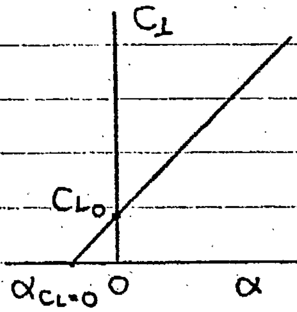
Also, the aspect ratio is

$$AR = \frac{b^2}{S} = \frac{b^2}{0.389\,b^2} = \underline{AR = 2.571}$$

So, from the Polhamus eq.,

$$C_{L\alpha} = \frac{2\pi \times 2.571}{2 + \left[\frac{(2.571)^2}{0.7094}\left(1 + (0.556)^2\right) + 4\right]^{1/2}} =$$

$$\underline{C_{L\alpha} = 2.681}$$



Since $\alpha_{C_L=0} = -0.8^\circ = -0.0140$ rad

then $C_{L_0} = 2.681(0.0140) =$

$C_{L_0} = 0.0374$, thus

$$C_L = 0.0374 + 2.681\,\alpha$$

(α in radians)

4.

For the drag, assume first that the mean chord, $\bar{C}$, is 3m, and mean speed is 50 m/s at altitude where $\rho = 0.0700\ kg/m^3$ and

$$\nu = 21.317 \times 10^{-4}\ \frac{ft^2}{sec} \times \frac{(0.3048\,m)^2}{ft^2} =$$

$$(\nu)_{21,336\,m} = 1.9804 \times 10^{-4}\ m^2/sec$$

So the representative Reynolds number is

$$R.N. = \frac{U\bar{C}}{\nu} = \frac{50.0 \times 3.0}{1.9804} \times 10^4 = 7.574 \times 10^5$$

and the skin-friction drag coeff. is

$$(C_D)_{fric.} = \frac{0.910}{[\log(R.N.)]^{2.58}} = 0.0094$$

when the airfoil pressure drag is added to this, one obtains

$$(C_{D_{C_L=0}})_{wing} = 0.0100$$

Now, for the polar, note that this has the form

$$C_D = C_{D_{C_L=0}} + \underbrace{C_1 C_L^2}_{\text{section polar}} + \underbrace{\frac{C_L^2}{\pi A\!R}}_{\text{"induced drag"}}$$

From an NACA test on an $A\!R = 6$ M-6 wing, the following data were obtained:

$\alpha°$	C_D	C_L	$C_D - (C_D)_{C_L=0}$	$\frac{C_L^2}{\pi AR}$	$\Delta(C_D)_{sec.}$
0	0.0084	0.0	0.0	0.0	0.0
3	0.0109	0.220	0.0025	0.0026	-0.0001
6	0.0212	0.457	0.0128	0.0111	0.0017
9	0.0351	0.663	0.0267	0.0233	0.0034
12	0.0560	0.874	0.0476	0.0405	0.0071
15	0.0816	1.072	0.0732	0.0610	0.0122

Choose the $\alpha = 12°$ values for finding C_1:

$$\Delta(C_D)_{sec} = C_1 C_L^2 \rightarrow C_1 = 0.0093$$

Also, for the $\alpha = 9°$ values,

$$C_1 = \Delta(C_D)_{sec} / C_L^2 = 0.0034 / 0.663^2 =$$

$C_1 = 0.0077$, and $\alpha = 6°$ gives $C_1 = 0.0082$

Also, from same source as given on page 1.,

$dC_D / dC_L^2 = 0.069 = C_1 + 1/\pi AR$, so

$C_1 = 0.069 - 0.0531 = 0.0159$

And from above, for $\alpha = 15°$, $C_1 = 0.0106$

So, for this estimation, choose $C_1 = 0.010$

so, $$(C_D)_{wing} = 0.0100 + \left(0.010 + \frac{1}{2.571\pi}\right) C_L^2 =$$

$$(C_D)_{wing} = 0.0100 + 0.1338\, C_L^2$$

Complete Vehicle:

The wetted area of the vertical fin is

$$(S_{wet})_{fin} \cong 2(0.0191 + 0.0087)b^2 =$$

$(S_{wet})_{fin} \cong 0.0555\, b^2$, and the skin-friction coeff., C_f, is

$$C_f = 0.455 / [\log(B.N.)]^{2.58} \quad \text{where}$$

$$(B.N.)_{fin} \cong \frac{50.0 \times 1.0}{1.9804} \times 10^4 = 2.525 \times 10^5$$

so, $C_f = 0.0059$, $(C_D)_{fin} = \dfrac{C_f (S_{wet})_{fin}}{S}$

$$(C_D)_{fin} = 0.0059 \times \frac{0.0555\, b^2}{0.389\, b^2} = 0.0008$$

Also, a $\Delta C_D = 0.0002$ may be allotted for misc. additional drag sources, so that for the entire vehicle,

e = 0.93

$$C_D = 0.0110 + 0.1338\, C_L^2$$

$$C_L = 0.0374 + 2.681\, \alpha$$

which also gives:

$$C_D = 0.0112 + 0.0268\, \alpha + 0.9617\, \alpha^2$$

Now, from the polar eq.,

$$\frac{C_D}{C_L} = \frac{0.0110}{C_L} + 0.1338\, C_L$$

In order to find the minimum value of C_D/C_L (and inversely, $(C_L/C_D)_{max}$),

$$\frac{d}{dC_L}(C_D/C_L) = 0 = -\frac{0.0110}{C_L^2} + 0.1338$$

which gives $\frac{0.0110}{C_L^2} = 0.1338 \rightarrow$

$$C_L^2 = 0.0110/0.1338 \rightarrow (C_L)_{L/D=max} = 0.2867$$

Also, $C_D = 0.0110 + 0.1338 \times 0.0822 \rightarrow$

$(C_D)_{L/D=max} = 0.0220$, so, in summary,

For maximum C_L/C_D:
$C_L = 0.2867$, $C_D = 0.0220$,
$C_L/C_D = 13.03$, $\alpha = 5.328°$

Also, for minimum power required, the parameter to be minimized is

$$\frac{C_D}{C_L^{3/2}} = \frac{0.0110}{C_L^{3/2}} + 0.1338\, C_L^{1/2}$$

$$\frac{d}{dC_L}(C_D/C_L^{3/2}) = -\frac{3}{2}\frac{0.0110}{C_L^{5/2}} + \frac{1}{2}\frac{0.1338}{C_L^{1/2}} = 0$$

so, $0.0330 = 0.1338\, C_L^{(5/2-1/2)} =$

$0.0330 = 0.1338\, C_L^2 \rightarrow C_L^2 = 0.24664$

$(C_L)_{C_L^3/C_D^2 = max} = 0.4966$ and

$(C_D)_{C_L^3/C_D^2 = max} = 0.0110 + 0.1338 \times 0.24664 =$

$= 0.0440$

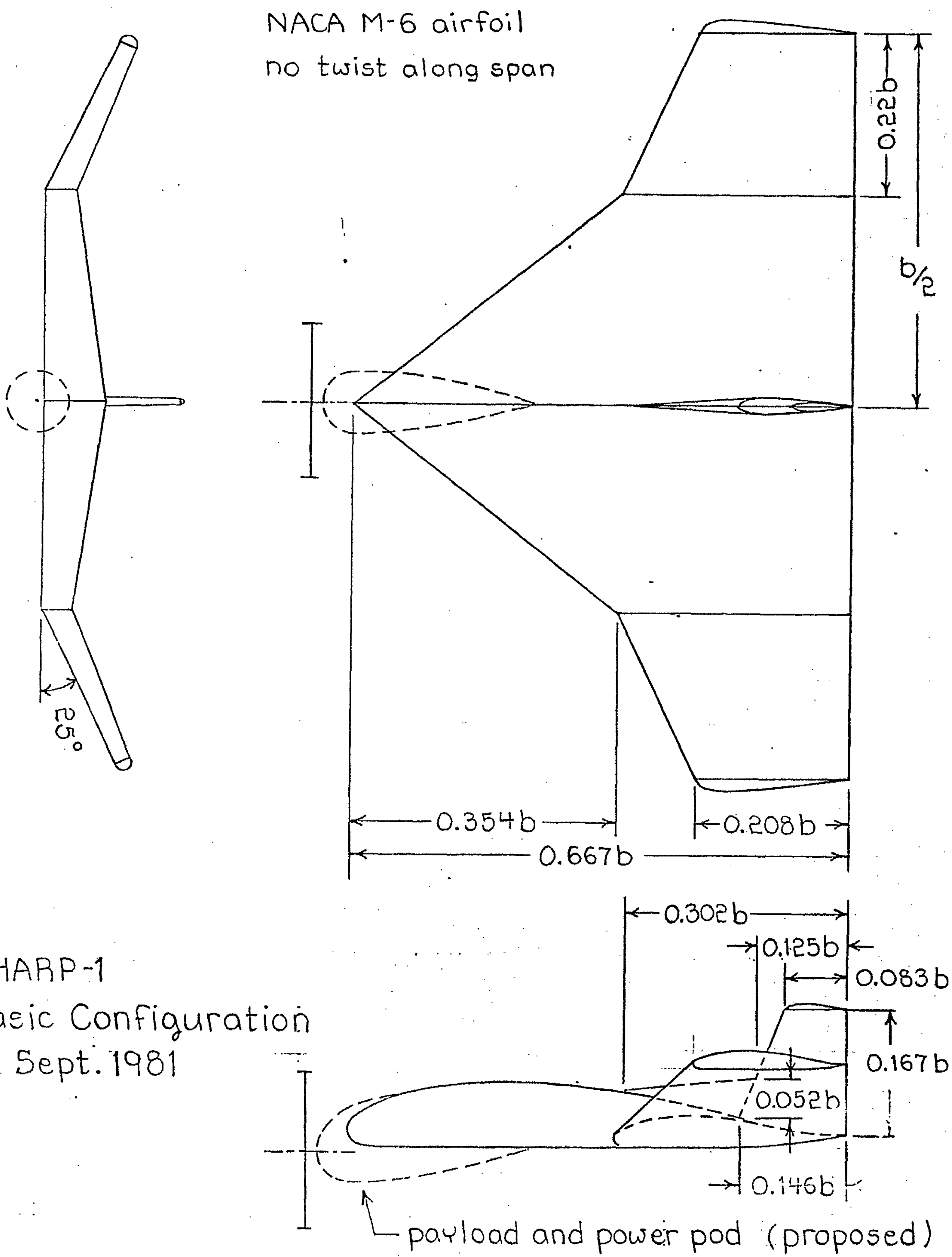
so, in summary ,

For maximum C_L^3/C_D^2 :

$C_L = 0.4966$, $C_D = 0.0440$

$C_L^3/C_D^2 = 4.22 \times 10^3$, $C_L^{3/2}/C_D = 64.94$

$\alpha = 9.815^\circ$



SHARP-1
Basic Configuration
22 Sept. 1981

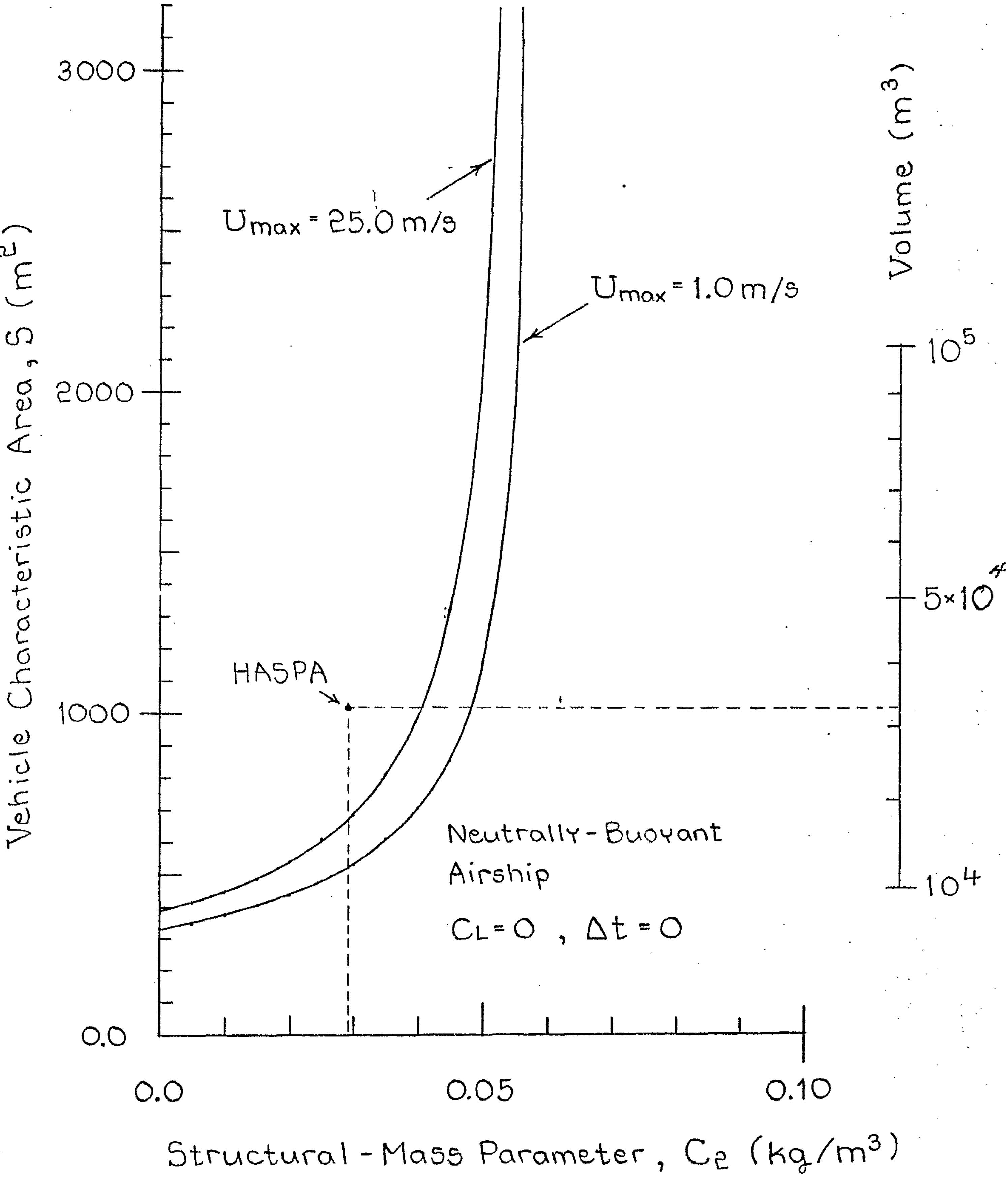


Fig. 1 S (and Vol.) vs C_2 for Neutrally-Buoyant Airship

12 June 1981

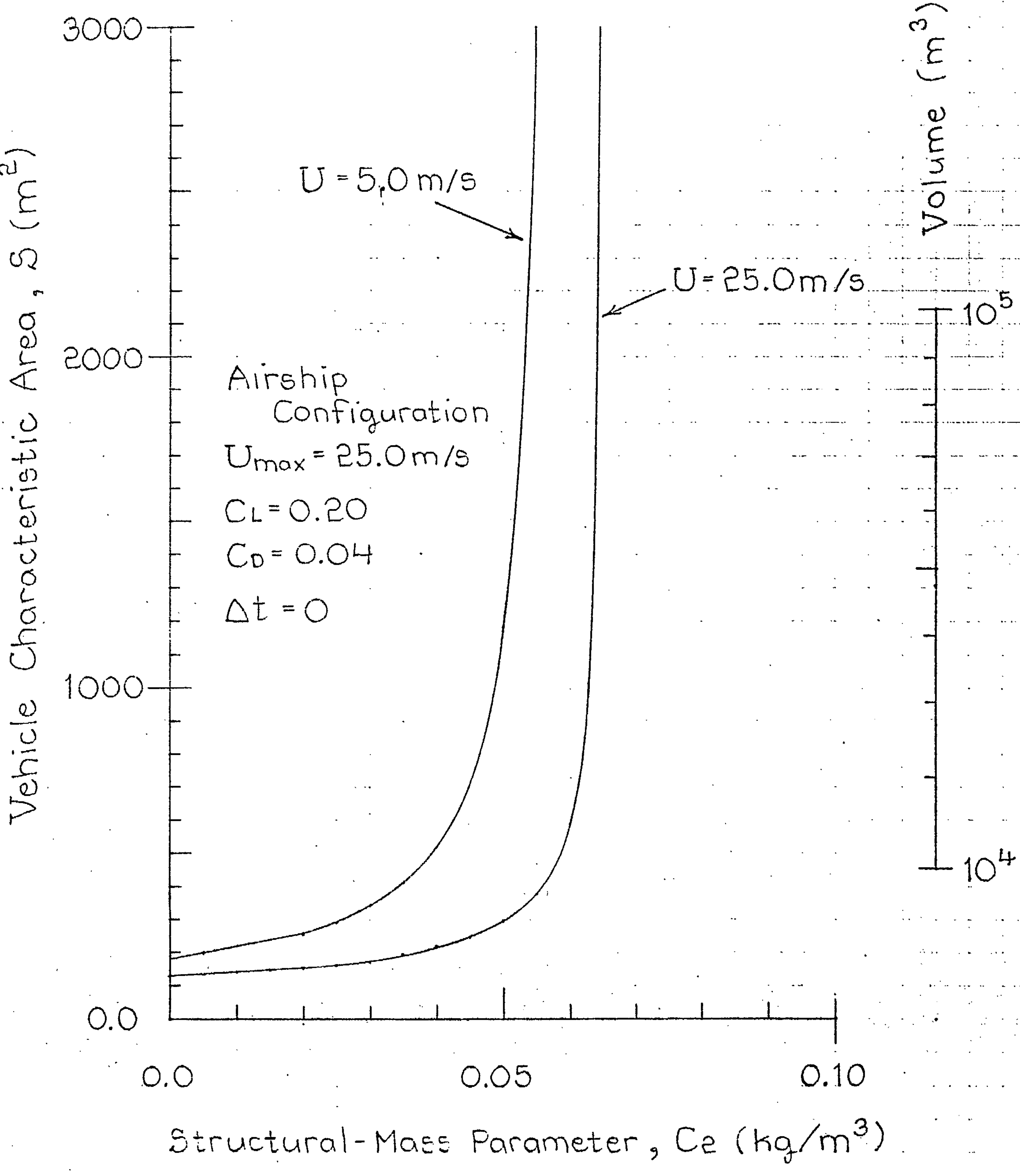


Fig 2 S (+ Vol) vs. C_2 for Aerodynamically-Lifting Airship

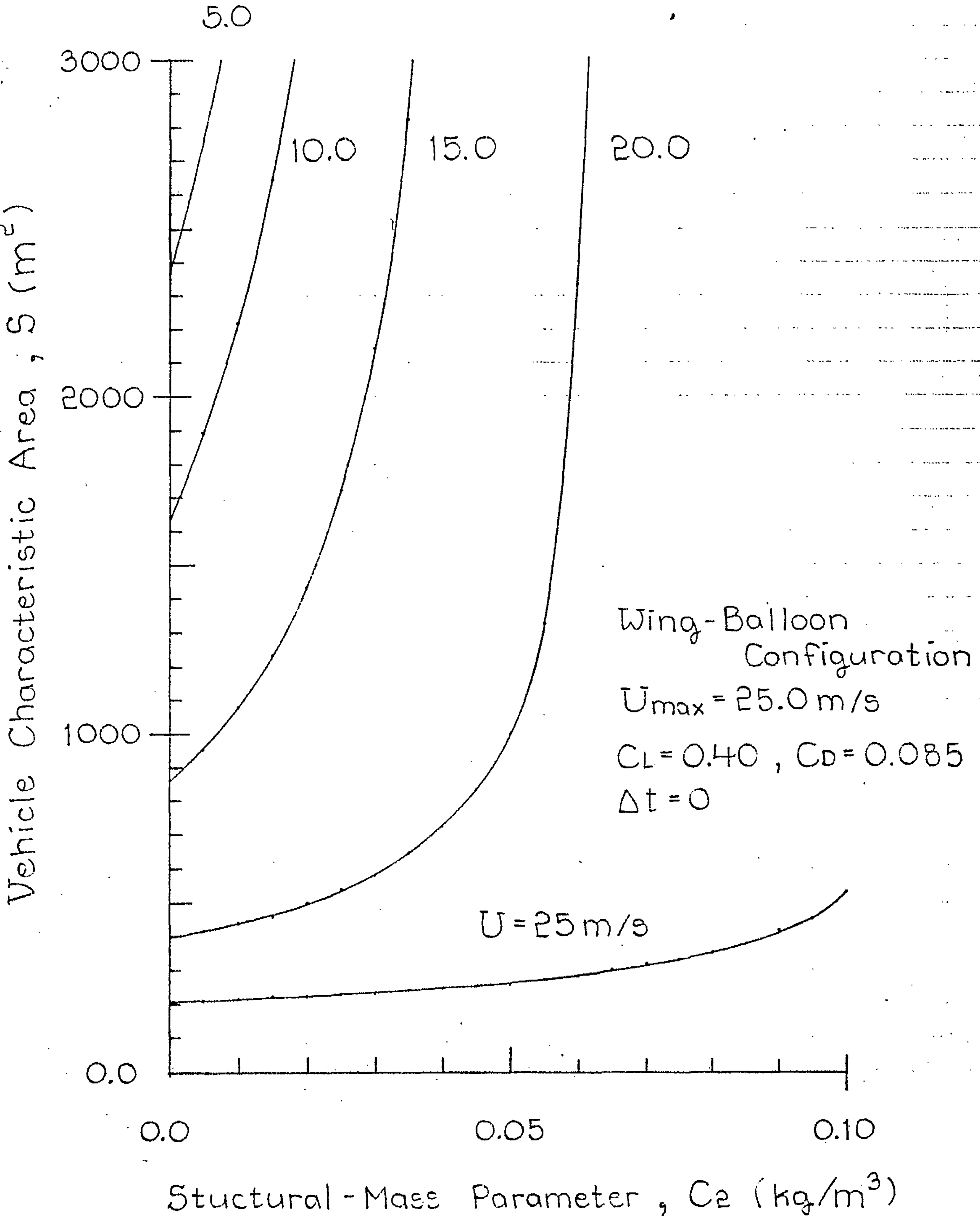
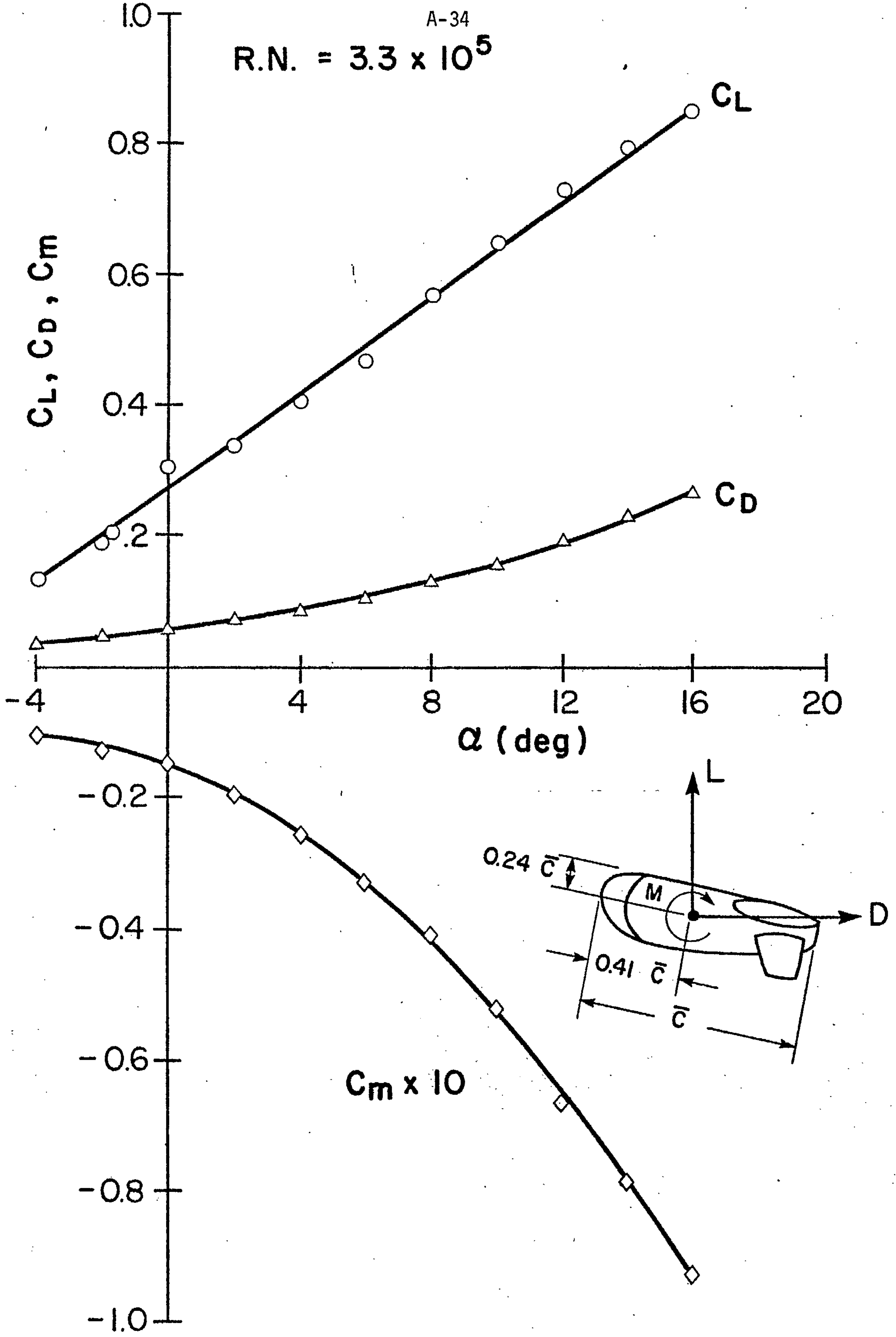


Fig. 3 S vs. C_2 for Wing-Balloon Configuration


R.N. = 3.3 x 10^5
C_L
C_D
C_L, C_D, C_m
1.0
0.8
0.6
0.4
.2
-0.2
-0.4
-0.6
-0.8
-1.0
-4
4
8
12
16
20
α (deg)
C_m x 10
L
D
M
0.24 $\bar{c}$
0.41 $\bar{c}$
$\bar{c}$

24 June '81

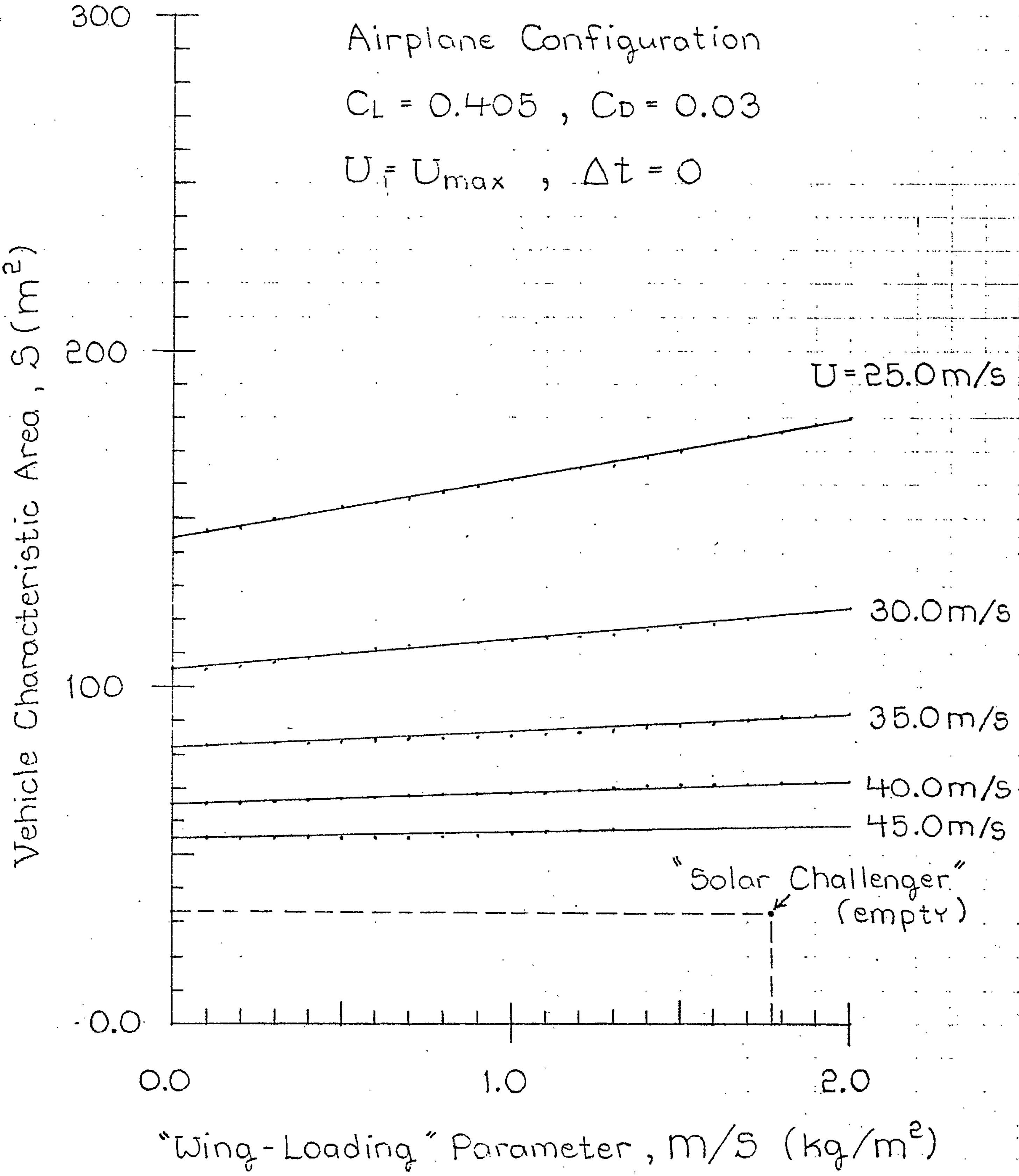


Fig. 4 S vs. Lifting-Surface Loading for Airplane Config.

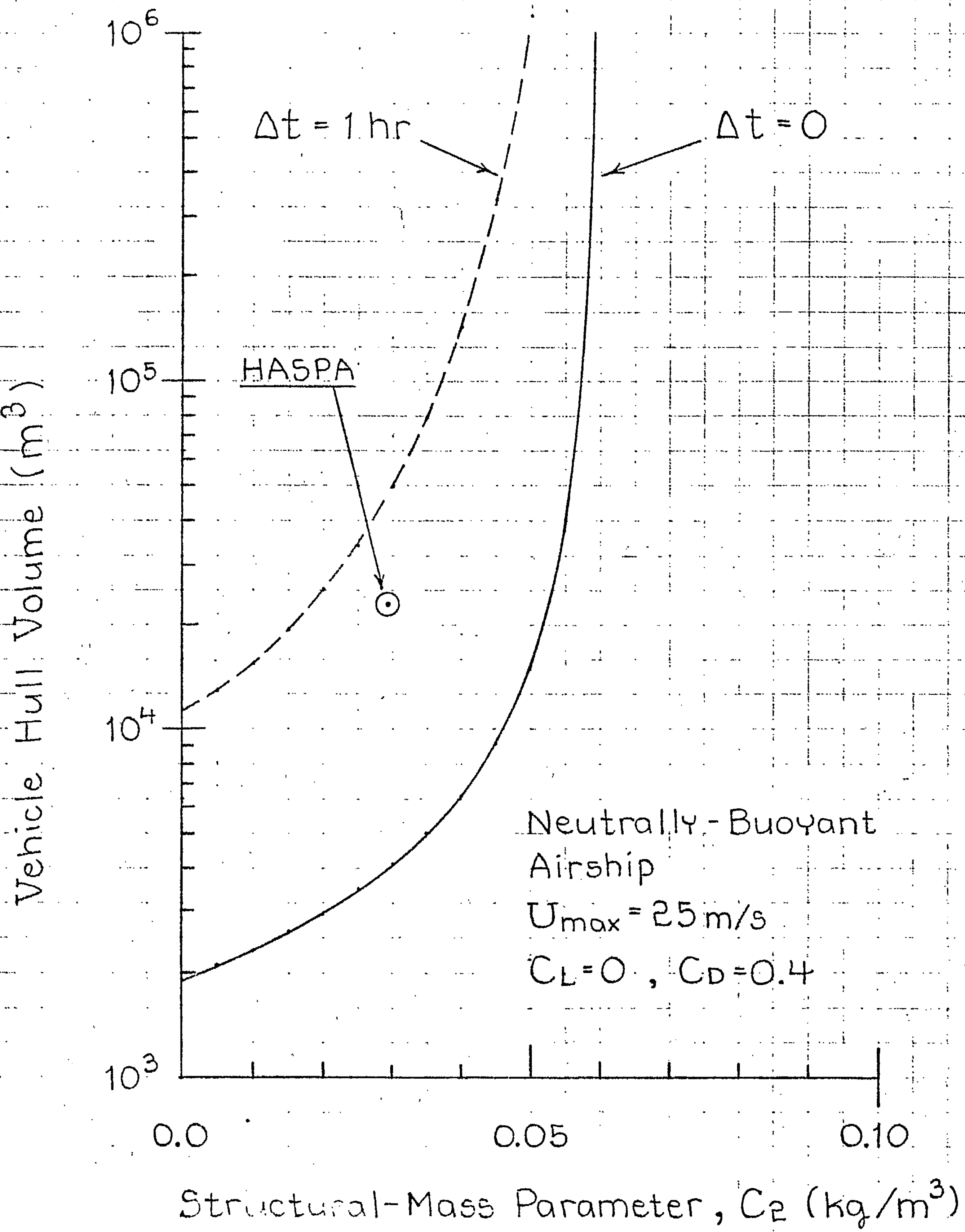


Fig. 5 Hull Volume vs. C_2 for Neutrally-Buoyant Airship

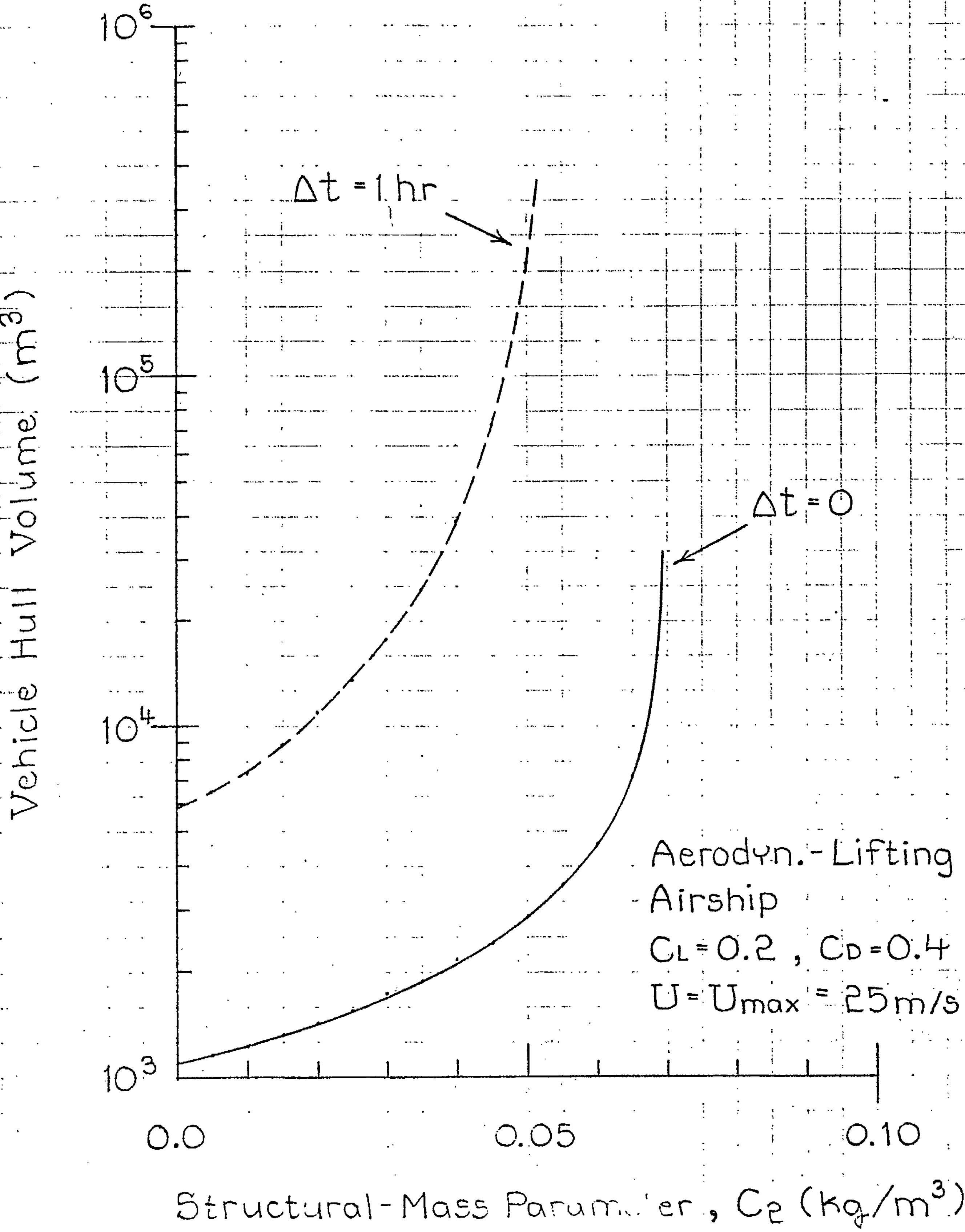


Fig. 6 Volume vs. C_2 for Aerodyn.-Lifting Airship

25 Sept. 1981

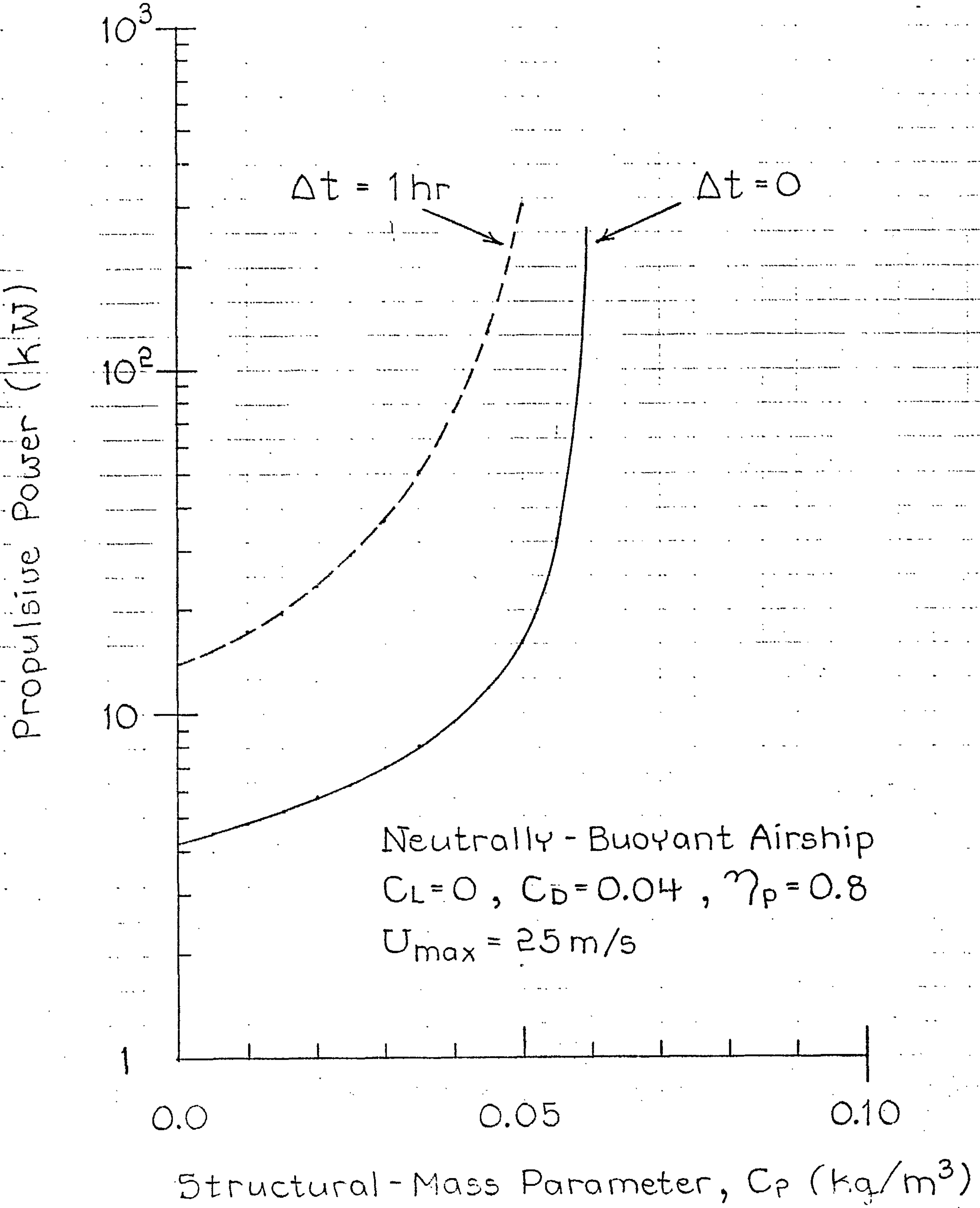


Fig. 7 Propulsive Power vs. C_2 for Neut.-Buoy. Airship

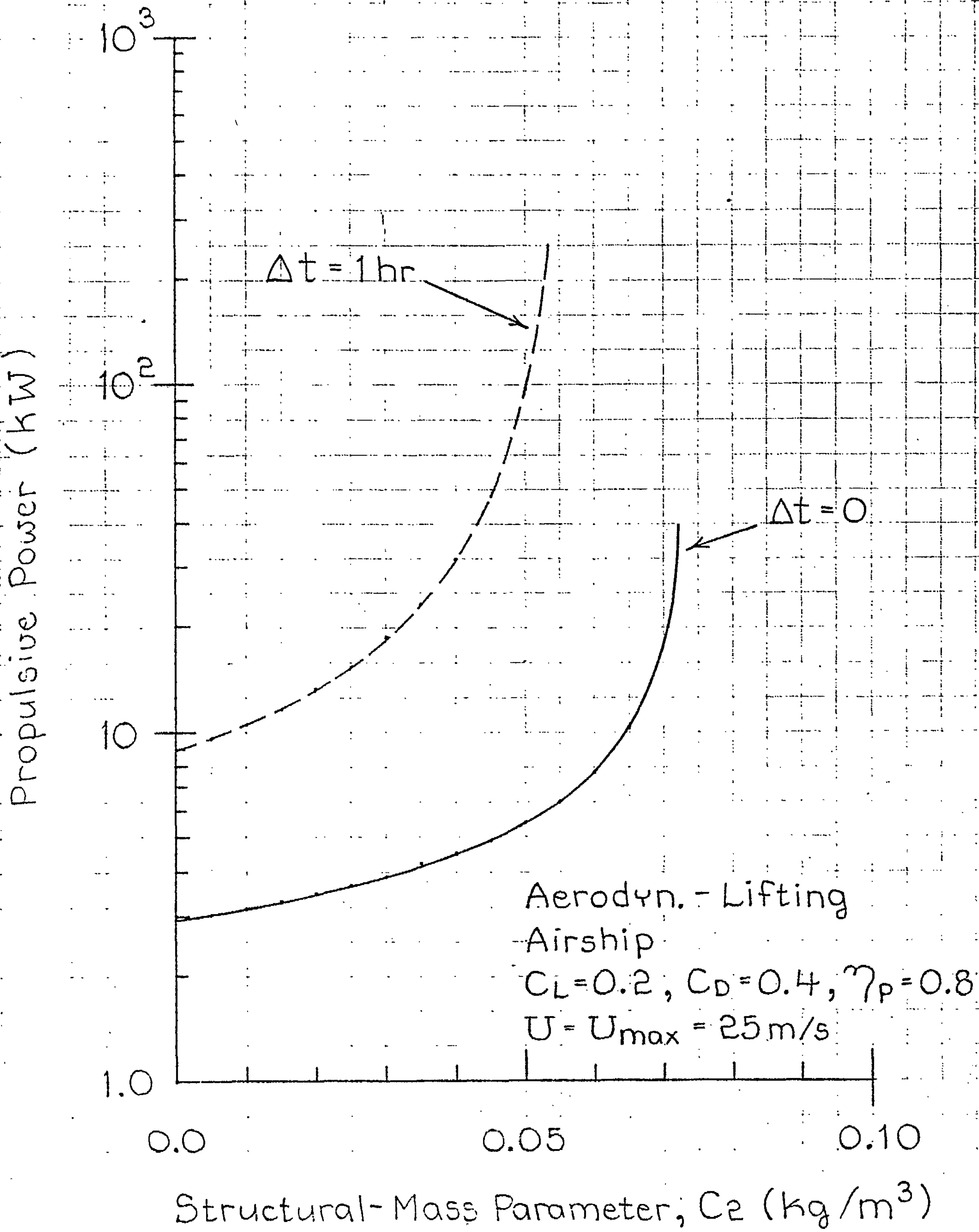


Fig. 8 Propulsive-Power vs. C_2 for Aero.-Lifting Airship

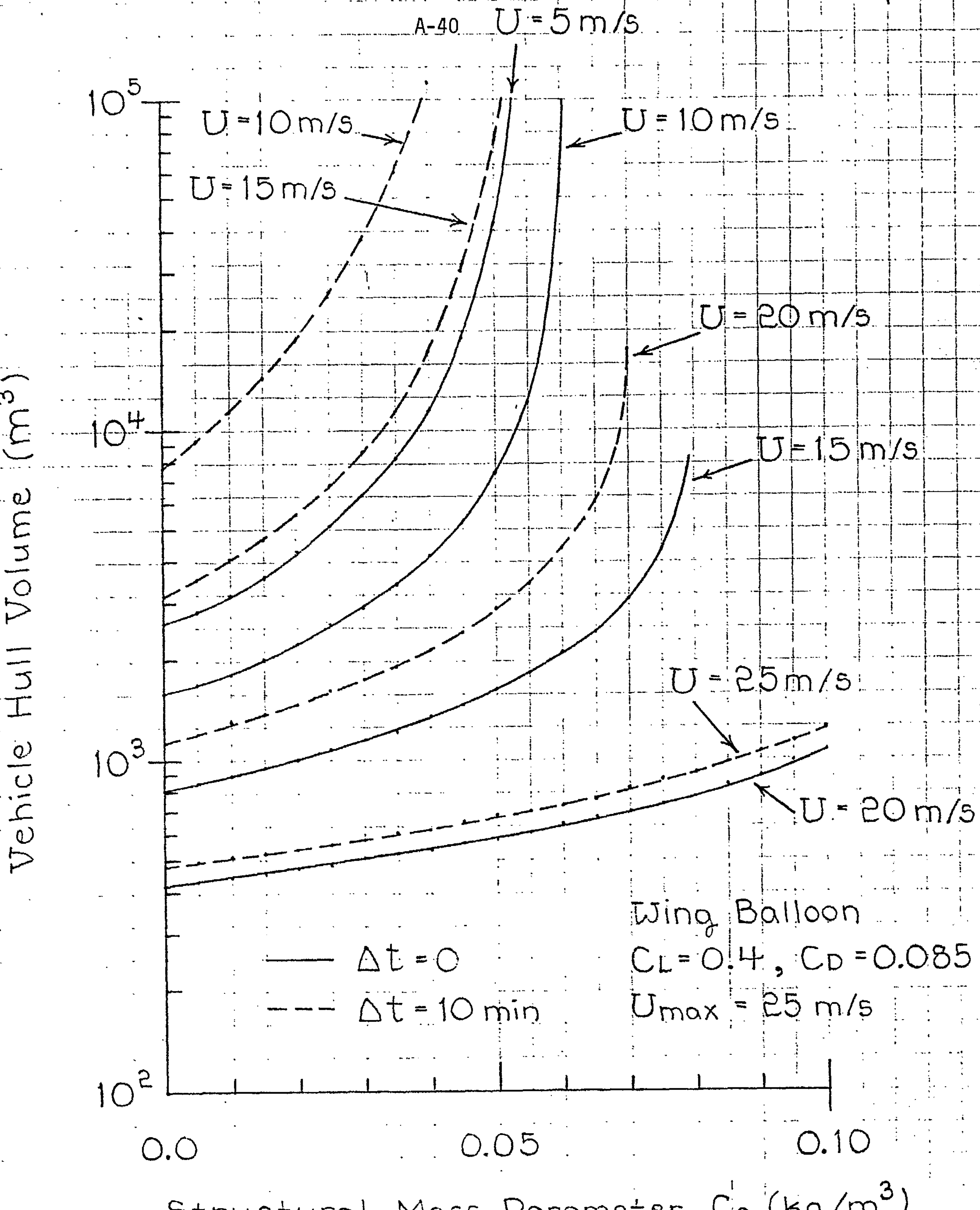


Fig. 9 Hull Volume vs. C_2 for Wing-Balloon Airship

27 Sept. 1981

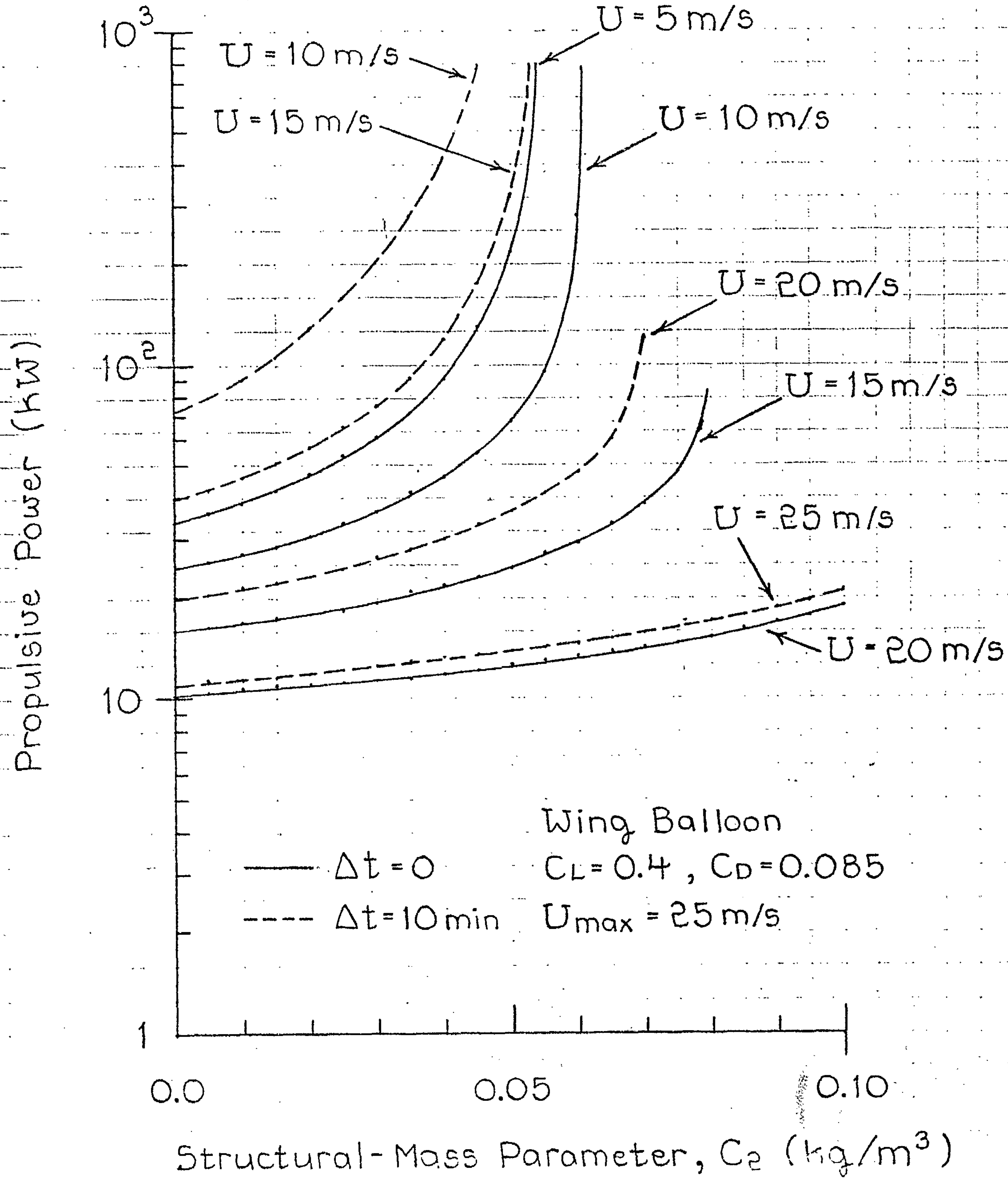


Fig.10 Propulsive Power vs. C_2 for Wing Balloon

Exerpts from letter report 30 November 1981 from
J. De Laurier to Dr. G. Jull

Here are some further calculations on the SHARP-1 which allow a comparison with Arne Lillemark's Power-Flux calculations. In this case, the mass characteristics are those from SED, which I've been using for my analysis all along. Therefore, even though the structural wing-loading is assumed to be a constant value of 2.00 kg/m^2, the overall wing loading varies with speed because of the fixed payload and mass terms which are functions only of the maximum speed (chosen to be 50 m/s).

The results are summarized in Figure 17 which shows that the Total-Power Loading (includes 2295.6 W onboard power) decreases with increasing wing area, S. Acceptable values ($\simeq$ 200 w/m^2) are reached for wing areas about 100m^2. This is a rather large vehicle (about 50 ft. span), but the size should considerably decrease if the Structural Wing Loading is less. I'll be looking at this next.

An interesting result is that the Total-Power Loading generally decreases with increasing mean speed. This is because the vehicle is operating at C_L values above those for maximum C_L/C_D (see Fig. 18), for the range of wing areas considered. A conclusion from this is that it would be much better to always fly at maximum speed if the Structural Wing-Loading cannot be reduced below 2.0 kg/m^2. This conclusion may differ for the lower wing loadings.

Appendix 3: Performance Calcs. for SHARP Airplane

Case 1:

given: S, $m_{struc.}/S \equiv C_6$, ρ, $C_D = fn(C_L)$, $m_{p\ell}$, C_3, U_{max}, η_p, m_{cs}, C_4, P_{OB}, C_5, Δt

find: Total Power Density, P_{total}/S, versus equilibrium-flight speed, U

solution:

For equilibrium flight, $L = mg$ →

$$\frac{\rho U^2}{2g} S\, C_L = (m_{struc.} + m_{p\ell} + m_{propul.\ system} + m_{control\text{-}system} + m_{power})$$

where $m_{struc.} = C_6 S$ (24)

$$m_{propul.\ system} = \frac{\rho U_{max}^3}{2\eta_p} S\, C_D C_3 \equiv A_1 C_3 C_D \quad (11)$$

$$m_{power} = \frac{\rho U_{max}^3}{2\eta_p} S\, C_D C_4 + C_4 P_{OB} + C_5 P_{OB} \Delta t + \frac{\rho U_{max}^3}{2\eta_p} S\, C_D C_5 \Delta t = A_1 (C_4 + C_5 \Delta t) C_D + P_{OB}(C_4 + C_5 \Delta t) \quad (27)$$

Also, $C_D = K_1 + K_2 C_L^2$ (28)

so the eq. becomes

$$\frac{\rho U^2}{2g} S C_L = C_6 S + m_{p\ell} + A_1 C_3 C_D + m_{cs} + A_1(C_4 + C_5 \Delta t) C_D + P_{OB}(C_4 + C_5 \Delta t) =$$

$$= \left[C_6 S + m_{p\ell} + m_{cs} + P_{OB}(C_4 + C_5 \Delta t)\right] + \left[A_1 C_3 + A_1 (C_4 + C_5 \Delta t)\right](K_1 + K_2 C_L^2)$$

Define the following:

$$\Pi_1 \equiv K_2 A_1 (C_3 + C_4 + C_5 \Delta t) \quad , \quad \Pi_2 = -\frac{\rho U^2}{2g} S$$

$$\Pi_3 \equiv C_6 S + m_{p\ell} + m_{cs} + P_{OB}(C_4 + C_5 \Delta t) + K_1 A_1 (C_3 + C_4 + C_5 \Delta t)$$

So that the eq. becomes

$$\Pi_1 C_L^2 + \Pi_2 C_L + \Pi_3 = 0 \qquad (29)$$

Numerical Example:

For SHARP-1 where $S = 60\,m^2$, $C_6 = 2.0\,kg/m^2$, $\rho = 0.070\,kg/m^2$, $K_1 = 0.0110$, $K_2 = 0.1338$

$m_{p\ell} = 60.0\,kg$, $C_3 = 0.00071\,kg/W$,

$U_{max} = 50\,m/s$, $\eta_p = 0.86$, $m_{cs} = 42.84\,kg$

$C_4 = 0.0011803\,kg/W$, $P_{OB} = 2295.6\,W$

$C_5 = 9.0 \times 10^{-6}$ kg/Joule , $\Delta t = 0$, $U = 30$ m/s

so, $A_1 = \dfrac{0.07 \times (50.0)^3 \times 60.0}{2 \times 0.86} = 3.0523 \times 10^5$

$\Pi_1 = 0.1338\, A_1\, (0.00071 + 0.0011803) =$

$\Pi_1 = 77.2001$

$\Pi_2 = -\dfrac{0.07 \times (30.0)^2}{2 \times 9.81} \times 60.0 = -192.6606$

$\Pi_2 = -192.6606$

$\Pi_3 = 2.0 \times 60.0 + 60.0 + 42.84 + 2295.6 \times$

$\times 0.0011803 + 0.0110 \times A_1\, (0.00071 +$

$+ 0.0011803) = 120.0 + 60.0 + 42.84 +$

$+ 2.7095 + 6.3468 = 231.8963$

$\Pi_3 = 231.8963$

so the eq. becomes :

$77.2001\, C_L^2 - 192.6606\, C_L + 231.8963 = 0$

$\rightarrow \quad C_L^2 - 2.4956\, C_L + 3.00383 = 0$

$C_L = 1.2478 \pm \dfrac{(6.2280 - 12.01532)^{1/2}}{2}$

Complex No. ; no real soln.

Note that for a real soln. to be possible,

$\Pi_2^2 \geq 4\Pi_1\Pi_3 = 71609.6702$, so

$|\Pi_2| \geq 267.60$, so that

$$U \geq \left(\frac{267.60 \times 2 \times 9.81}{0.070 \times 60.0}\right)^{1/2} = 35.356$$

at which speed, $C_L = 1.2478$, which gives

$C_D = 0.0110 + 0.1338\, C_L^2 = 0.21933$, so that

$$P_{total} = \frac{C_D}{\eta_p} \frac{\rho U^3}{2} S + P_{OB} = \qquad (30)$$

$$= \frac{0.21933}{0.86} \times 0.07 \frac{(35.356)^3}{2} \times 60.0 + 2295.6 =$$

$P_{total} = 25966.1$ W $\rightarrow$ $P/S = 432.77$ W/m^2

Also, note that $C_L = 0.0374 + 2.681\alpha$, so

$\alpha = (1.2478 - 0.0374)/2.681 = 0.4515$ rad,

$\alpha^\circ = 25.869^\circ$, so it's stalled anyway.

Clearly, for the C_6 chosen, larger S must be selected. In conclusion,

$$C_L = \frac{-\Pi_2 - (\Pi_2^2 - 4\Pi_1\Pi_3)^{1/2}}{2\Pi_1} \qquad (31)$$

The example's total mass is calculated as follows:

$m_{total} = \Pi_1 C_L^2 + \Pi_3 = 77.2001\,(1.2478)^2 +$

$+ 231.8963 = m_{total} = 352.097$ kg

so the wing loading is

$K = m_{total}/S = 352.097/60.0 = 5.8683$

From A. Lillemark's eq.,

$P_{total}/S = 9.8\, U\, K\, C_D/(C_L\, \eta_p)$

$= 9.8 \times 35.356 \times 5.8683 \times 0.21933/(1.2478 \times 0.86)$

$= 415.58$ ~~kg~~ w$/m^2$; This checks closely with previous calc.

Aside:

The derivation of A. Lillemark's eq. is as follows:

$P = \frac{DU}{\eta} = \frac{\rho U^2}{2\eta} S\, C_D\, U$, but

$L = mg = \frac{\rho U^2}{2} S\, C_L = mg \rightarrow \frac{\rho U^2}{2} = \frac{mg}{C_L S}$

so, $P = \frac{mg}{C_L S} \frac{S\, C_D\, U}{\eta} \rightarrow \frac{P}{S} = g\, U\, K\, \frac{C_D}{C_L} \frac{1}{\eta}$ ✓

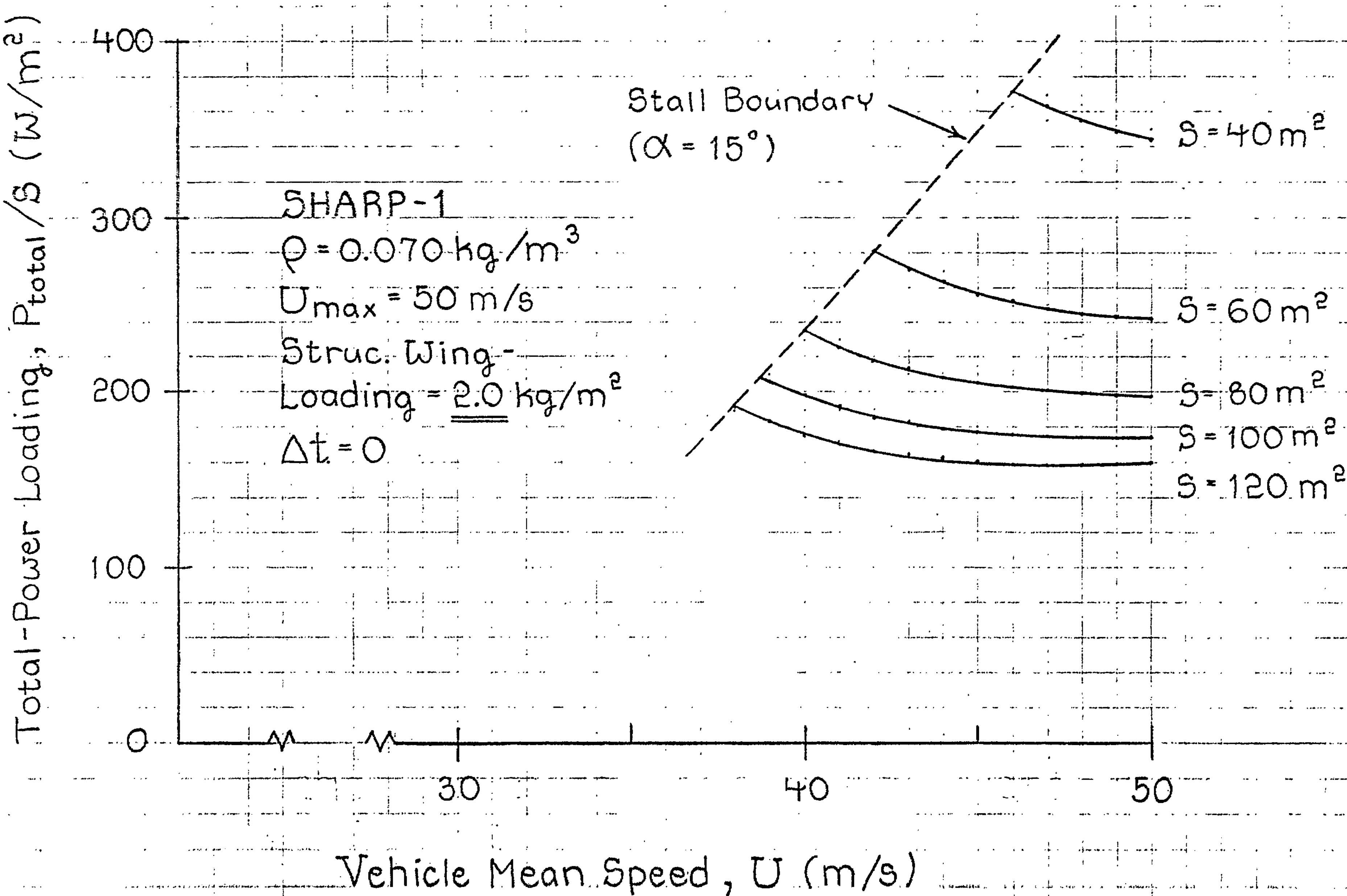


Fig. 17 Total-Power Loading vs. Speed for Struc. Wing-Loading = 2.0 kg/m^2

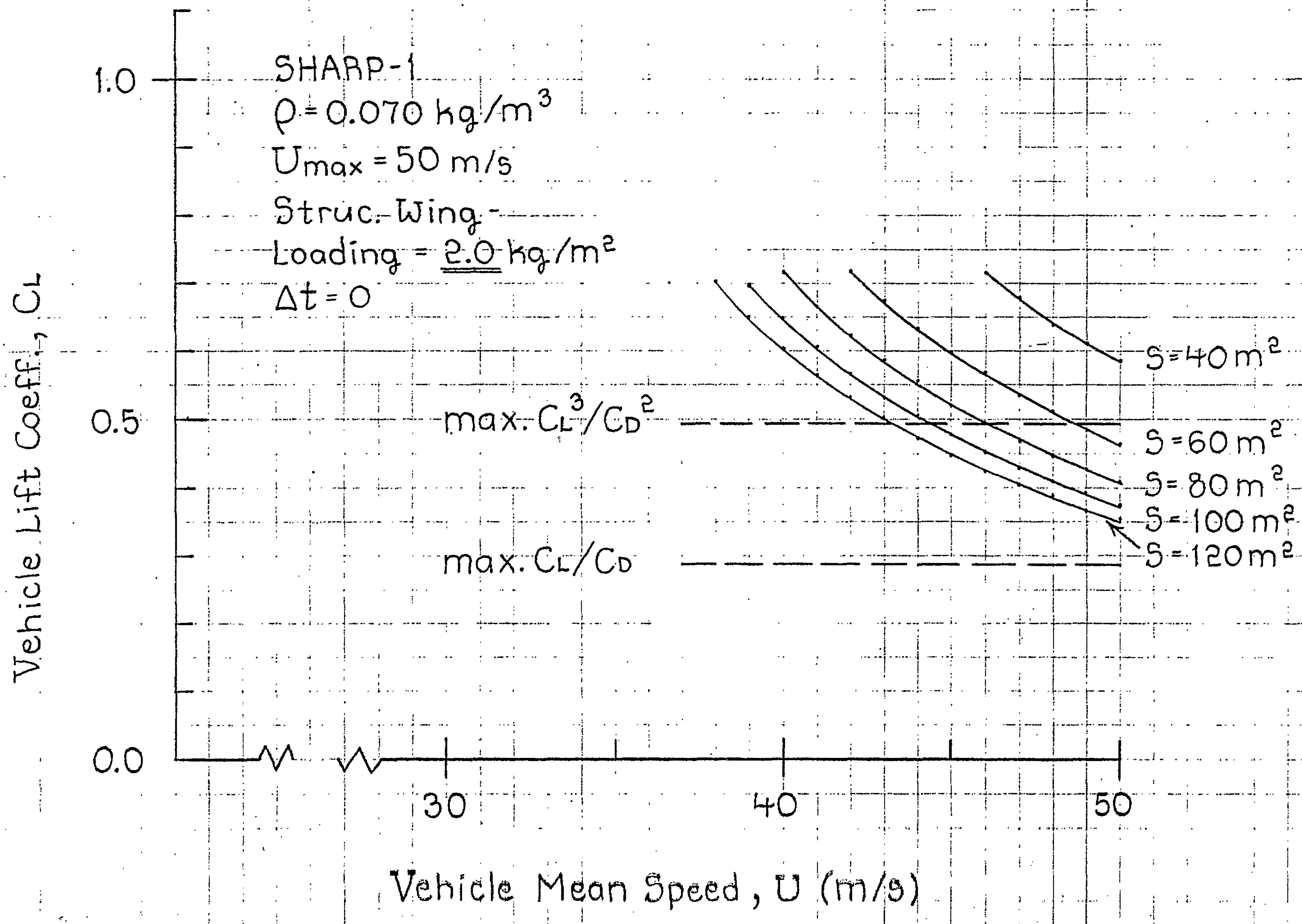


Fig. 18 Lift Coefficient vs. Speed for Struct. Wing-Loading = 2.0 kg/m²

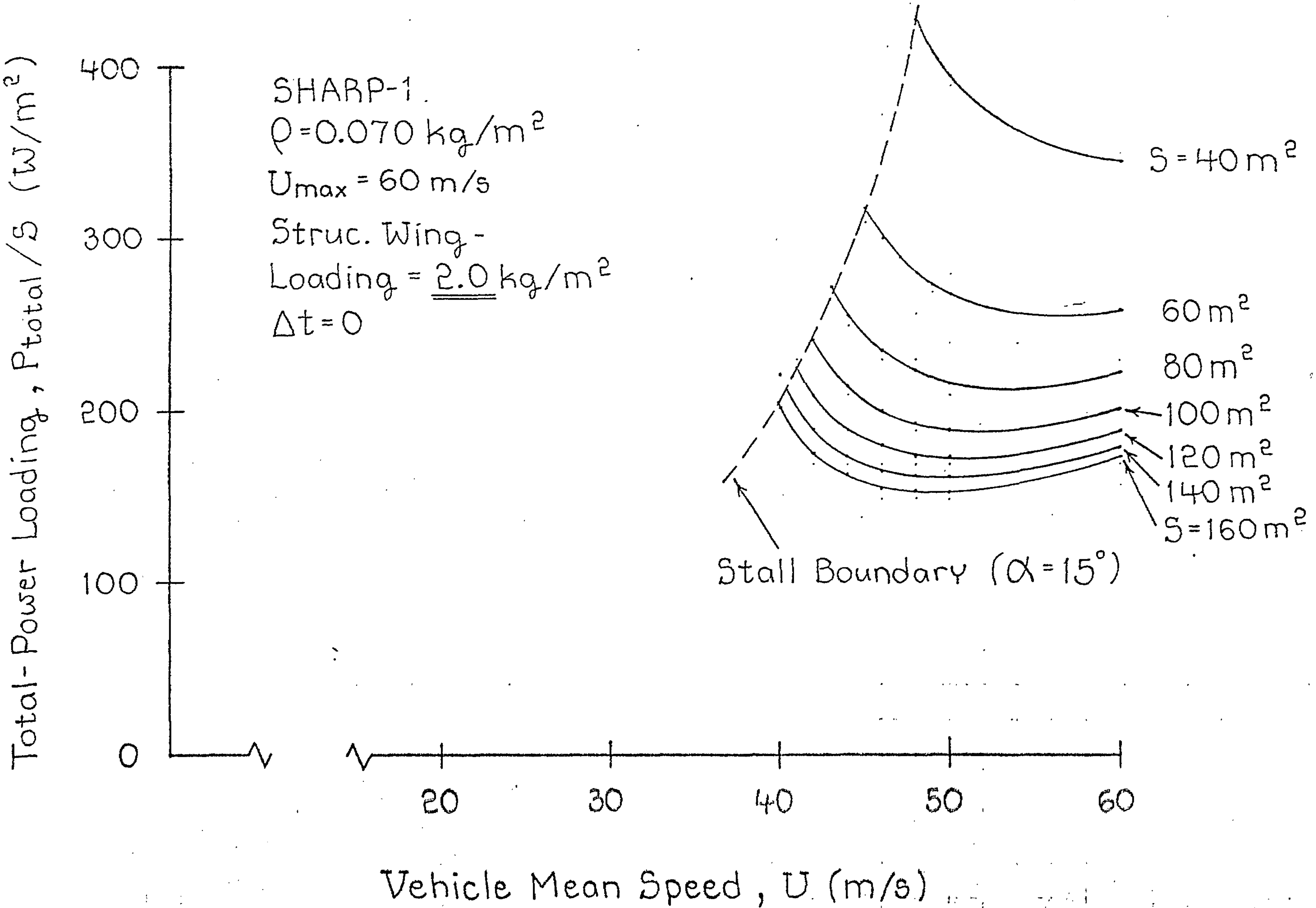


Fig. 19 Total-Power Loading vs. Speed for Struc. Wing-Loading = 2.0 kg/m²

Exerpts from letter report 16 December 1981 from
J. De Laurier to G. Jull

Here are the corrected figures for the size and propulsive power of the "Airplane Configuration" (Figures 11 and 12) and the "SHARP-1" (Figures 13, 14, 15 and 16). From these, it isn't so clear that an airplane is superior to a buoyant (or semi-buoyant) vehicle. This is because a comparison is possible only for U=25 m/s, at which speed the airships look very reasonable and the airplanes can barely sustain themselves. Therefore, I performed a separate calculation for the candidate vehicles at 60 m/s. The details are enclosed, but the summarized results are:

Vehicle	Volume (m^3)	Wing Area (m^2)	Propul. Power (kW)
Neutrally-Buoyant Airship	24075	-	315
Aerodyn.-Lifting Airship	366	-	19
Wing-Balloon	29	-	23
Airplane (Solar Challenger)	-	39	10

These results reconfirm our earlier conclusion that an airplane configuration is a more attractive candidate if 60 m/s capability is desired. Note that even though the Aerodyn.-lifting airship and Wing-Balloon are markedly better than the neutrally-buoyant airship, this is because they're acting like mediocre airplanes, where the buoyant lift is an insignificant portion of the aerodynamic lift. Clearly, that buoyant lift is not worth the trouble of lifting-gas management.

In accordance with our discussions last week, I'll be looking at other airplane configurations, namely, ones with higher aerodynamic efficiency so as to reduce the power-flux density required for flight. Also, I would appreciate any revisions on control-system mass, etc.

15 Dec. 1981

Power and Size Comparisons for Candidate Vehicles at $U_{max} = 60 m/s$

Neutrally-Buoyant Airship ($C_2 = 0.03\ kg/m^3$):

Wrt. eq. (21) in 22 May '81 writeup,

$$A = 0.862 \times 0.070 \times 1.0 \times 0.98 - 1.0 \times 0.03 = 0.02913$$

$$B = 0.070\left[-\frac{0.04\,(60.0)^3}{2 \times 0.80}(0.00071 + 0.0011803)\right]$$

$$= -0.71453$$

$$C = -60.0 - 42.84 - 2295.6 \times 0.0011803 = -105.5495$$

So, the eq. to be solved is

$$0.02913\, S^{3/2} - 0.71453\, S - 105.5495 = 0$$

$$\equiv f(S) \text{ , so}$$

$$f'(S) = 0.043695\, S^{1/2} - 0.71453$$

① choose $S = 10^3$,

$$f(S) = 101.09198 \text{ , } f'(S) = 0.667227$$

$$(S)_2 = (S)_1 - f(S)/f'(S) = 848.489$$

② $S = 848.489$

$$f(S) = 8.142281 \text{ , } f'(S) = 0.558255$$

$$(S)_3 = 833.9038$$

③ $S = 833.9038$

$f(S) = 0.079774$, $f'(S) = 0.547268$

$(S)_4 = 833.758 = S$

$\therefore S = 833.758\ m^3$

$Vol = S^{3/2} =$ **$Vol = 24075\ m^3\ (850188\ ft^3)$**

$$\text{Propulsive Power} = \frac{C_D U_{max}^3}{2\eta_P} \rho S =$$

$$= \frac{0.04(60.0)^3}{2 \times 0.80} \times 0.070 \times 833.758 = 315.161\ kW$$

Propulsive Power = 315.161 kW

Aerodyn. - Lifting Airship ($C_2 = 0.03\ kg/m^3$):

A and C stay the same, but

$$B = \frac{0.070 \times 0.2 \times 60^2}{2 \times 9.81} - 0.71453 = 1.854277$$

So the eq. to be solved becomes

$$0.02913\, S^{3/2} + 1.854277\, S - 105.5495 = 0 \equiv f(S)$$

and $f'(S) = 0.043695\, S^{1/2} + 1.854277$

① $(S)_1 = 1000$,

$f(S) = 2669.899$, $f'(S) = 3.236034$

$(S)_2 = 174.9472$

$f(S_2) = 286.2575$, $f'(S_2) = 2.432220$

$(S)_3 = 57.2533$

$f(S_3) = 13.2334$, $f'(S_3) = 2.184899$

$(S)_4 = 51.1965$

$f(S_4) = 0.053985$, $f'(S_4) = 2.166922$

$$S = 51.17159 \text{ m}^2$$

Vol = 366 m³ (12927 ft³)

Propulsive Power = 19.343 kW

Wing Balloon ($C_2 = 0.03$ kg/m³):

$$A = 0.862 \times 0.070 \times 0.1828 \times 0.98 - 0.1828 \times 0.03 = 0.005326$$

$$B = 0.07\left[\frac{0.4 \times 60^2}{2 \times 9.81} - \frac{0.085(60)^3}{2 \times 0.80}(0.00071 + 0.0011803)\right] = 3.619231$$

$C = -105.5495$

So the eq. is

$0.005326\, S^{3/2} + 3.619231\, S - 105.5495 = 0$

$\equiv f(S)$ and

$f'(S) = 0.007989\, S^{1/2} + 3.619231$

choose $S_1 = 30.0$

$f(S_1) = 3.902581$, $f'(S_1) = 3.662989$

$S_2 = 28.934591$

$f(S_2) = 0.000417$, $f'(S_2) = 3.662205$

$S = 28.9345$

$Vol = C_1 S^{3/2} =$ **Vol = 28.451 m³ (1005 ft³)**

Propulsive Power = 23.242 kW

<u>Airplane Configuration ($C_6 = 2.0$ kg/m²):</u>

From Appendix 2 of 22 May'81 writeup:

$$B' = 0.070\left[\frac{0.405 \times 60^2}{2 \times 9.81} - \frac{2.0}{0.07} - \frac{0.03\,(60)^3}{2 \times 0.86} \times (0.00071 + 0.0011803)\right]$$

$B' = 2.703323$, $C = -105.5495$, so

$$S = 39.04435 \text{ m}^2$$

Propulsive Power = 10.297 kW

In summary :

Vehicle	Volume (m^3)	Wing Area (m^2)	Propul. Power (kW)
Neutrally-Buoyant Airship *	24075	—	315
Aerodyn.-Lifting Airship *	366	—	19
Wing-Balloon *	29	—	23
Airplane (Solar Challenger) **	—	39	10

$\rho = 0.070 \text{ kg/m}^3$, $U = U_{max} = 60 \text{ m/s}$

* Structural density = 0.03 kg/m^3 (HASPA value)

** Structural wing loading = 2.0 kg/m^2 (≈ Solar Challenger value)

14 Dec. 1981

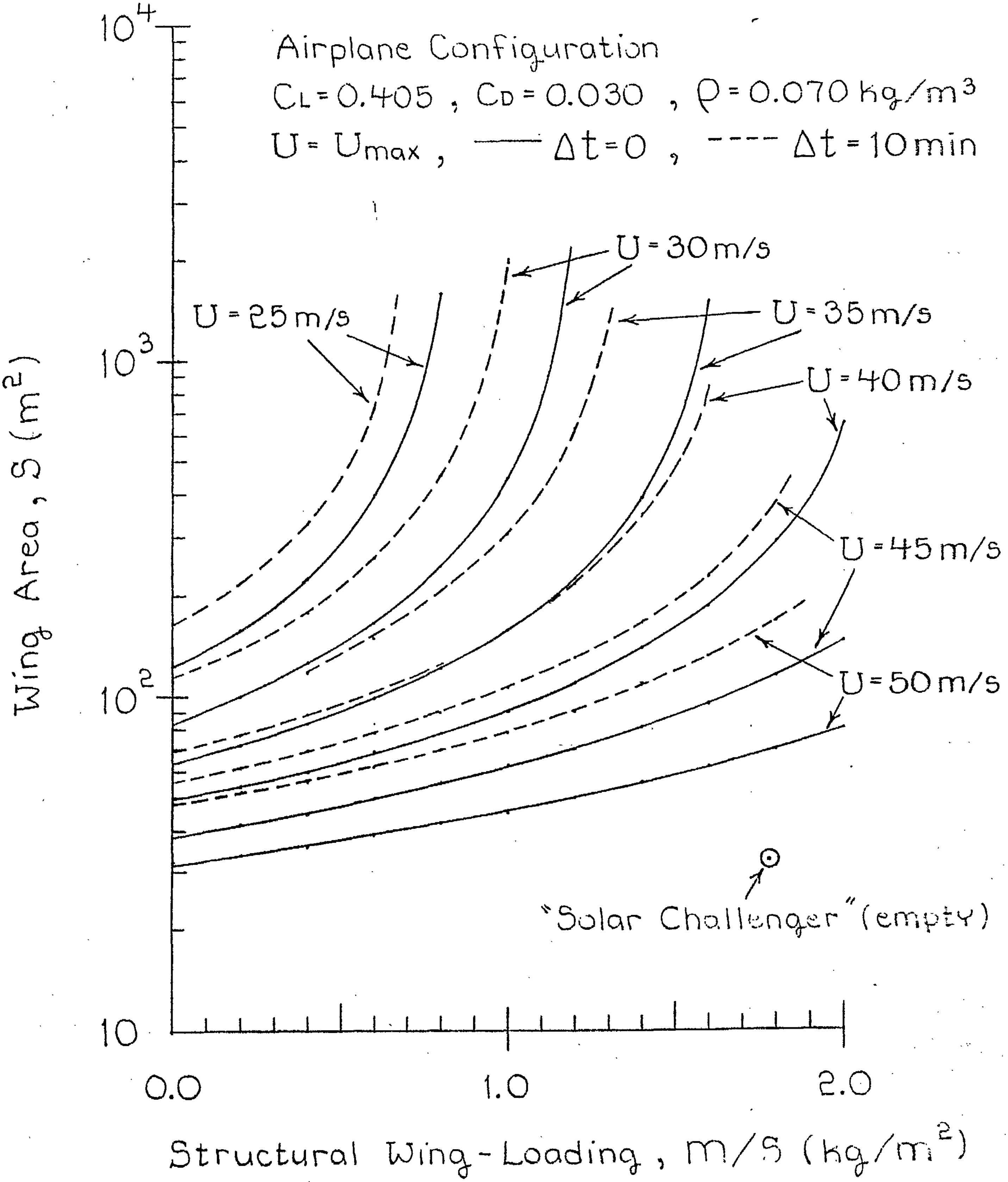


Fig. 11 Wing Area vs. Struc. Wing Loading for Airplane

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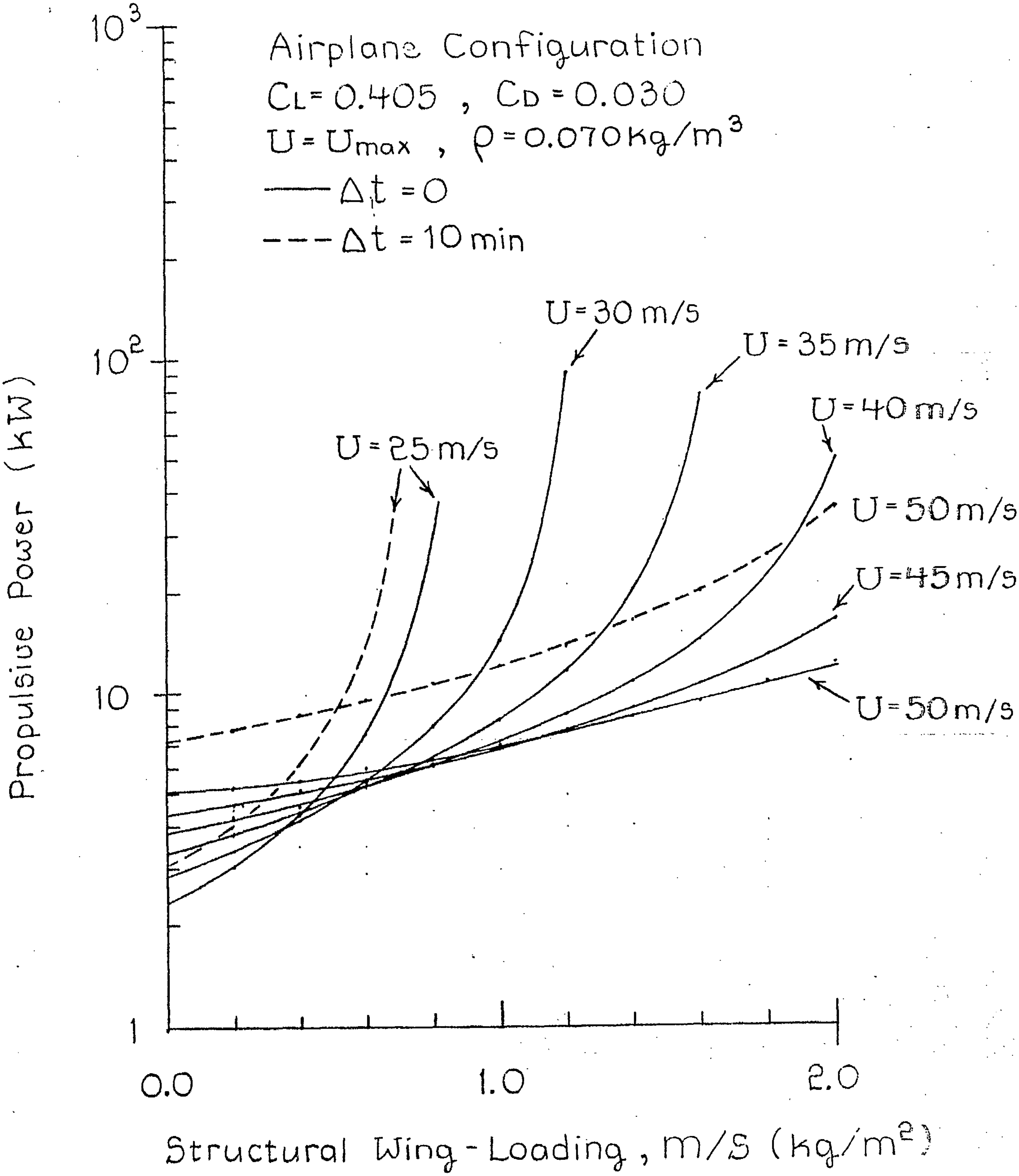

Fig. 12 Propulsive Power vs. Struc. Wing-Loading for Airplane Configuration

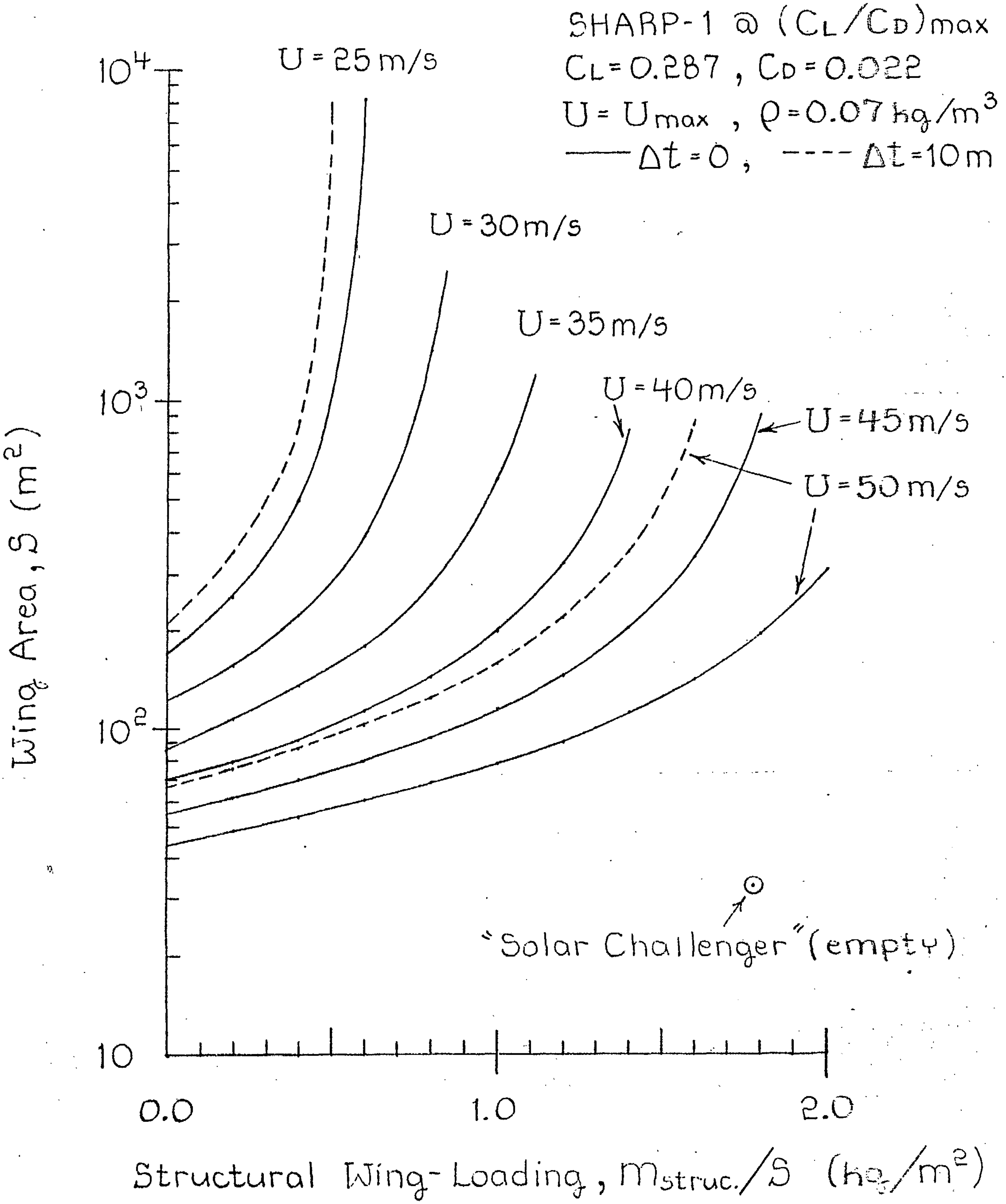

Fig. 13 Wing Area vs. Struc. Wing Loading for SHARP-1 at Max. C_L/C_D.

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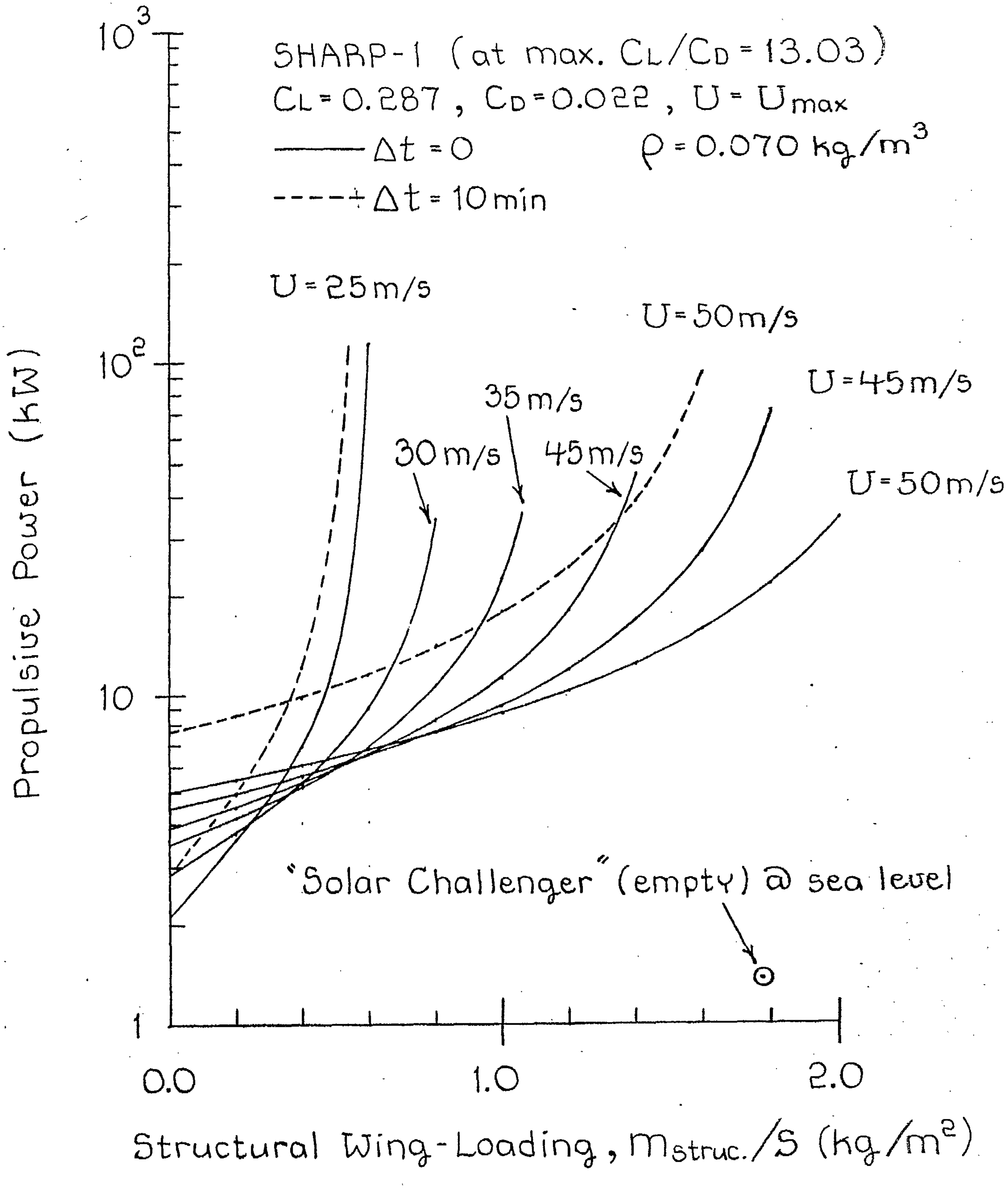

Fig. 14 Propulsive Power vs. Struct. Wing-Loading for SHARP-1 at Max. C_L/C_D

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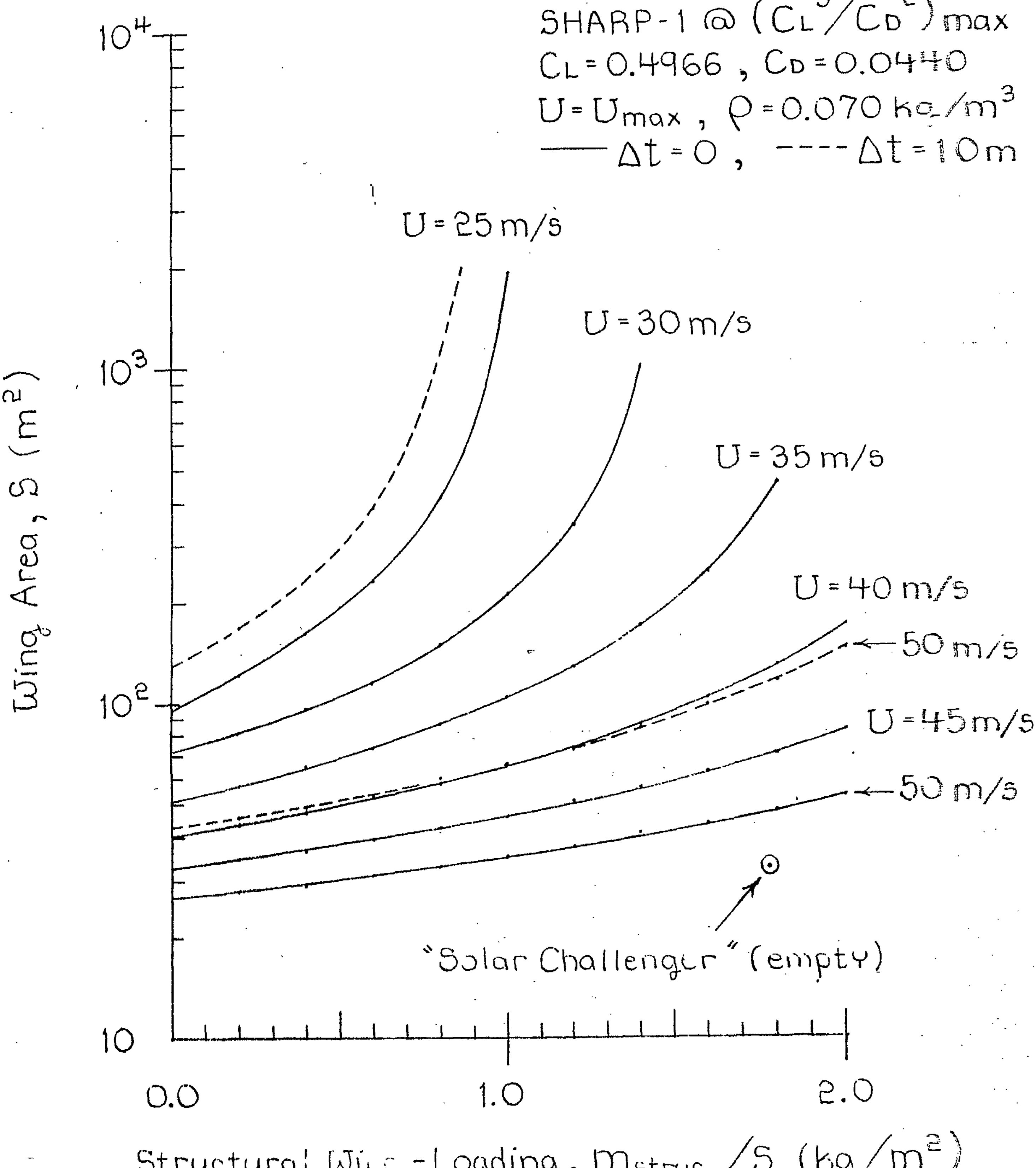

Fig. 15 Wing Area vs. Struc. Wing Loading for SHARP-1 at Max. C_L^3/C_D^2

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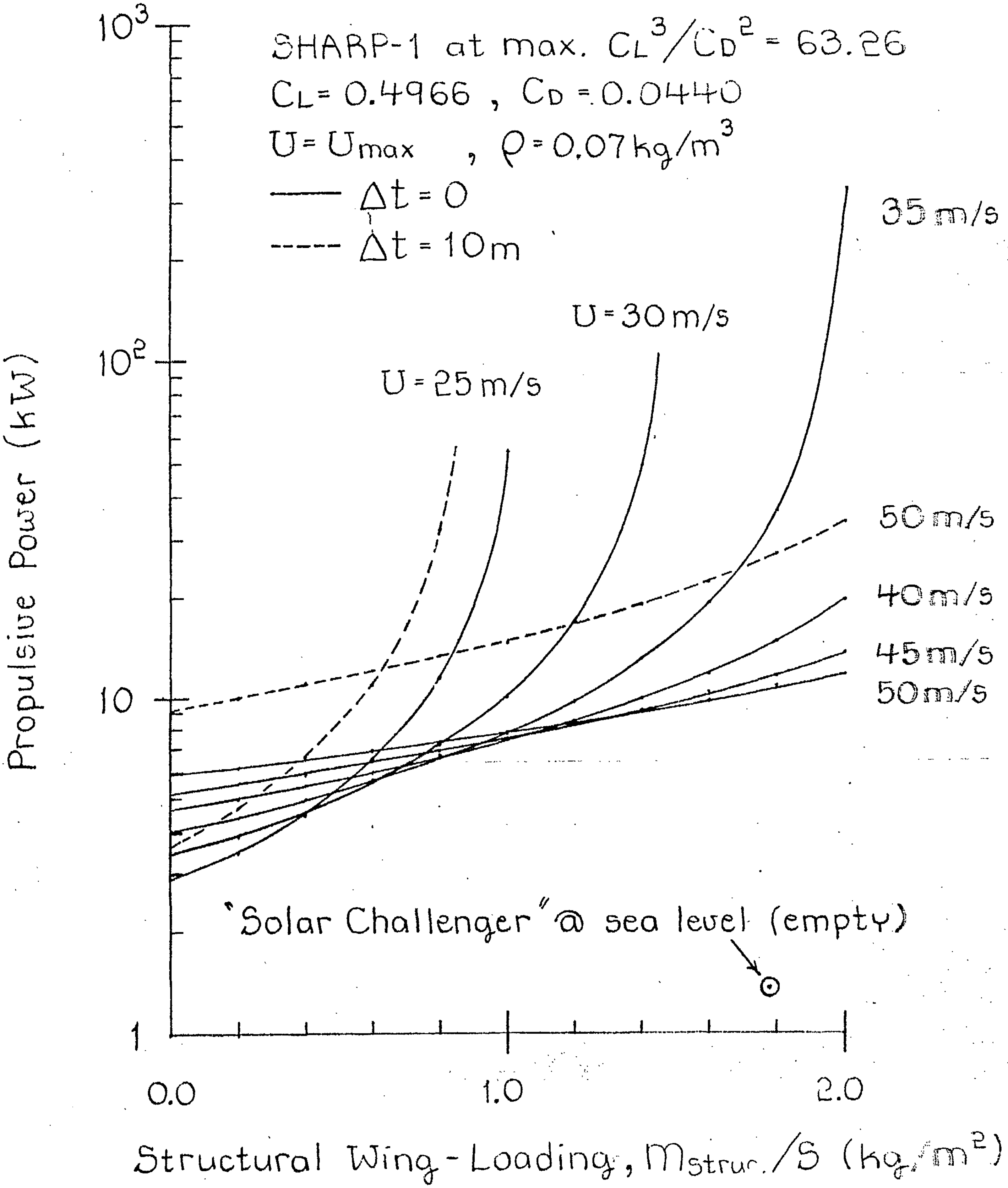


Fig. 16 Propulsive Power vs. Struct. Wing-Loading for SHARP-1 at Max. C_L^3/C_D^2

Exerpts from letter report 22 January 1982 from
J. De Laurier to G. Jull

With reference to the section of the final report entitled Solar Challenger-Type SHARP, here are the results from my calculations on this. First, I revisited the literature on this aircraft, especially "Sun Powered Aircraft Design" by MacCready, et al., which wasn't available earlier. From this, I obtained that,

Wing Area = 23.9m^2; Tail Area = 9.3m^2; Airframe Mass = 54.9 kg

From this,

Structural Wing Loading = 1.65 kg/m^2

At sea level,

Maximum Flying Speed = 16.1 m/s; Required Power from Solar Cells = 2.9kW

At 6100m altitude,

Maximum Flying Speed = 21.9 m/s; Required Power from Solar Cells = 3.9kW

For our SHARP version with a total area (wing plus tail) of 40m^2, altitude of 21 km, Struc. Wing-Loading of 1.65 kg/m^2, maximum flight speed of 60 m/s, Communications Payload of 60 kg, and Control System of 43 kg,

Propulsive Power to Propellers = 11.13kW

So that, with the efficiencies (50%) and Communications/Control powers assumed (2.3kW),

Microwave Power Density = 614 W/m^2

For other areas, with the same conditions:

Reference Area (m^2)	Propulsive Power (kW)	Microwave Power Density (W/m^2)
20	7.78	893
40	11.13	614
60	15.19	544
80	19.41	513
100	23.70	497

For the reduced onboard mass of

Communications Payload = 25 kg; Control System = 18 kg, and with all other parameters the same, one has

Reference Area (m^2)	Propulsive Power (kW)	Microwave Power Density (W/m^2)
20	5.35	650
40	9.55	535
60	13.88	500
80	18.23	485
100	22.60	475

These are not encouraging results. Clearly, the "Solar Challenger" offers no significant improvement over the SHARP-1, despite its higher aspect ratio. I think that this is because the maximum C_L/C_D of the two vehicles are nearly the same (note, though, that the "Solar Challenger" tends to be smaller for given power loadings because it achieves its max. C_L/C_D at a larger C_L).

It seems that aircraft with much higher aerodynamic efficencies are required. I would appreciate your thoughts on this.

17 Jan. 1982

Estimated Drag Polar Eq. for "Solar Challenger"

From published performance data on the Solar Challenger,

$S_{wing} = 257\ ft^2 = 23.88\ m^2$ (from Model Aviation

$S_{stab} = 9.3\ m^2$ (from Sun Powered Aircraft Design

so, $S = S_{wing} + S_{stab} =$ $\boxed{S = 33.2\ m^2}$

Also from S.P.A.D., the 133 kg aircraft at sea level had the following performance:

$U_{max} = 16.1\ m/s$ ✓, $P_{s.c.} = 2.9\ kW$ ✓, so $P_{prop} = \eta_p P_{sc}$

$P_{prop} = \eta_{motor} \eta_{propeller} P_{sc} = 0.85 \times 0.93 \times 2900 =$

$P_{propulsion} = 2293\ W$ ✓

The dynamic pressure, q, at sea level is

$q = 0.5 \rho U^2 = 0.5 \times 1.225 (16.1)^2 = 158.8\ N/m^2$ ✓

so, $C_L = \frac{mg}{Sq} = \frac{133 \times 9.81}{33.2 \times 158.8} = \underline{\underline{C_L = 0.247}}$ ✓

Also, $C_D = \frac{P_{propulsion}}{qSU} = \frac{2293}{158.8 \times 33.2 \times 16.1} =$

$\underline{\underline{C_D = 0.027}}$ ✓

Now, the form of the polar equation is

$$C_D = (C_D)_{C_L=0} + K C_L^2 \qquad (1)$$

so $\left(\frac{C_D}{C_L}\right) = \frac{(C_D)_{C_L=0}}{C_L} + K C_L$, (2) , and

$\frac{d}{dC_L}(C_D/C_L) = -\frac{(C_D)_{C_L=0}}{C_L^2} + K$, which gives

for maximum C_L/C_D ,

$$(C_D)_{C_L=0} - K(C_L)^2_{max\,C_L/C_D} = 0 \qquad (3)$$

Now, from Aviation Week, $(C_L/C_D)_{max} = 13.5$, so (1), (2), and (3) give 3 eqs. for the 3 unknowns, $(C_D)_{C_L=0}$, K, $(C_L)_{max\,C_L/C_D}$:

$$0.027 = (C_D)_{C_L=0} + 0.06101\,K \qquad (4)$$

$$0.07407\,(C_L)_{m.C_L/C_D} = (C_D)_{C_L=0} + K(C_L)^2_{m.C_L/C_D}$$

$$(C_D)_{C_L=0} = K(C_L)^2_{m.C_L/C_D} \qquad (6$$

(5) and (6) combine to give

$$0.07407\,(C_L)_{m.C_L/C_D} = 2(C_D)_{C_L=0} \rightarrow$$

$$(C_L)_{m.C_L/C_D} = 27.00\,(C_D)_{C_L=0} \qquad (7$$

When this is substituted into (6), one has

$$(C_D)_{C_L=0} = K \times 729\,(C_D)^2_{C_L=0} \quad , \text{so}$$

$$729\,K\,(C_D)_{C_L=0} = 1 \rightarrow$$

$$K = 0.001372/(C_D)_{C_L=0} \qquad (8$$

When (8) is substituted into (4), one has

$$0.027 = (C_D)_{C_L=0} + 0.00008369/(C_D)_{C_L=0} \rightarrow$$

$$(C_D)^2_{C_L=0} - 0.027\,(C_D)_{C_L=0} + 0.00008369 = 0 \quad (9$$

Upon solving for $(C_D)_{C_L=0}$, one has

$$(C_D)_{C_L=0} = \frac{0.027}{2} + \frac{(0.000729 - 0.00033476)^{1/2}}{2}$$

$$(C_D)_{C_L=0} = 0.0135 + 0.009928 = 0.02343$$

$$\underline{\underline{(C_D)_{C_L=0} = 0.02343}}$$

From (8), $K = 0.001372/0.02343 =$

$$\underline{\underline{K = 0.05856}}$$

So the Solar Challenger's polar equation is

$$\boxed{C_D = 0.02343 + 0.05856\,C_L^2}$$

Check: when $C_L = 0.247$, $C_D = 0.027$ ✓

$(C_L)_{max\,C_L/C_D} = \left((C_D)_{C_L=0}/K\right)^{1/2} = 0.6325$

$(C_D)_{max\,C_L/C_D} = 0.0469$, so $(C_L/C_D)_{max} = 13.5$ ✓

Note that $AR_{wing} = 8.595$, so $1/\pi AR_{wing} =$

$K = 0.0370$,

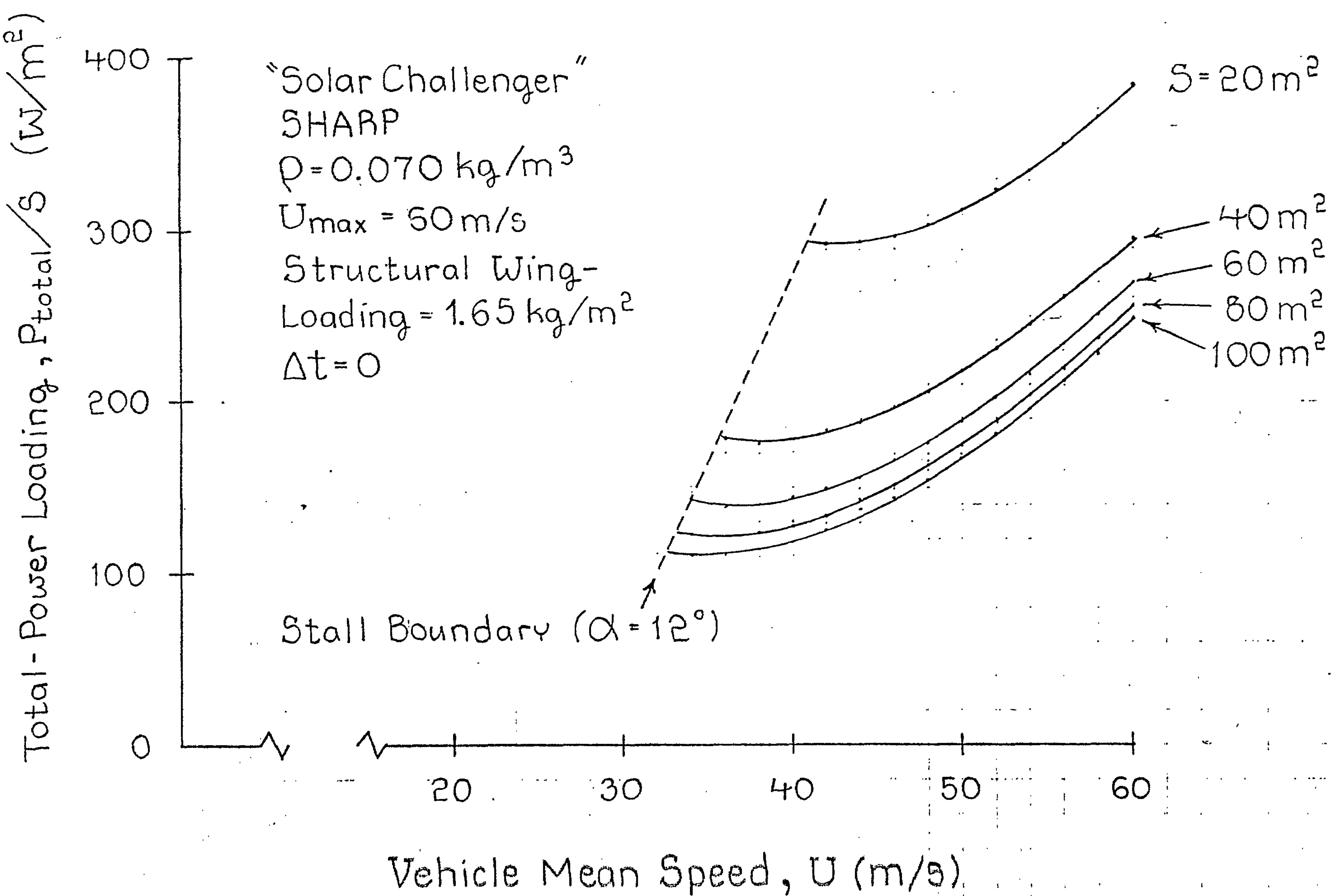


Fig. 21 Total-Power Loading vs. Speed for "Solar Challenger" SHARP

A-69

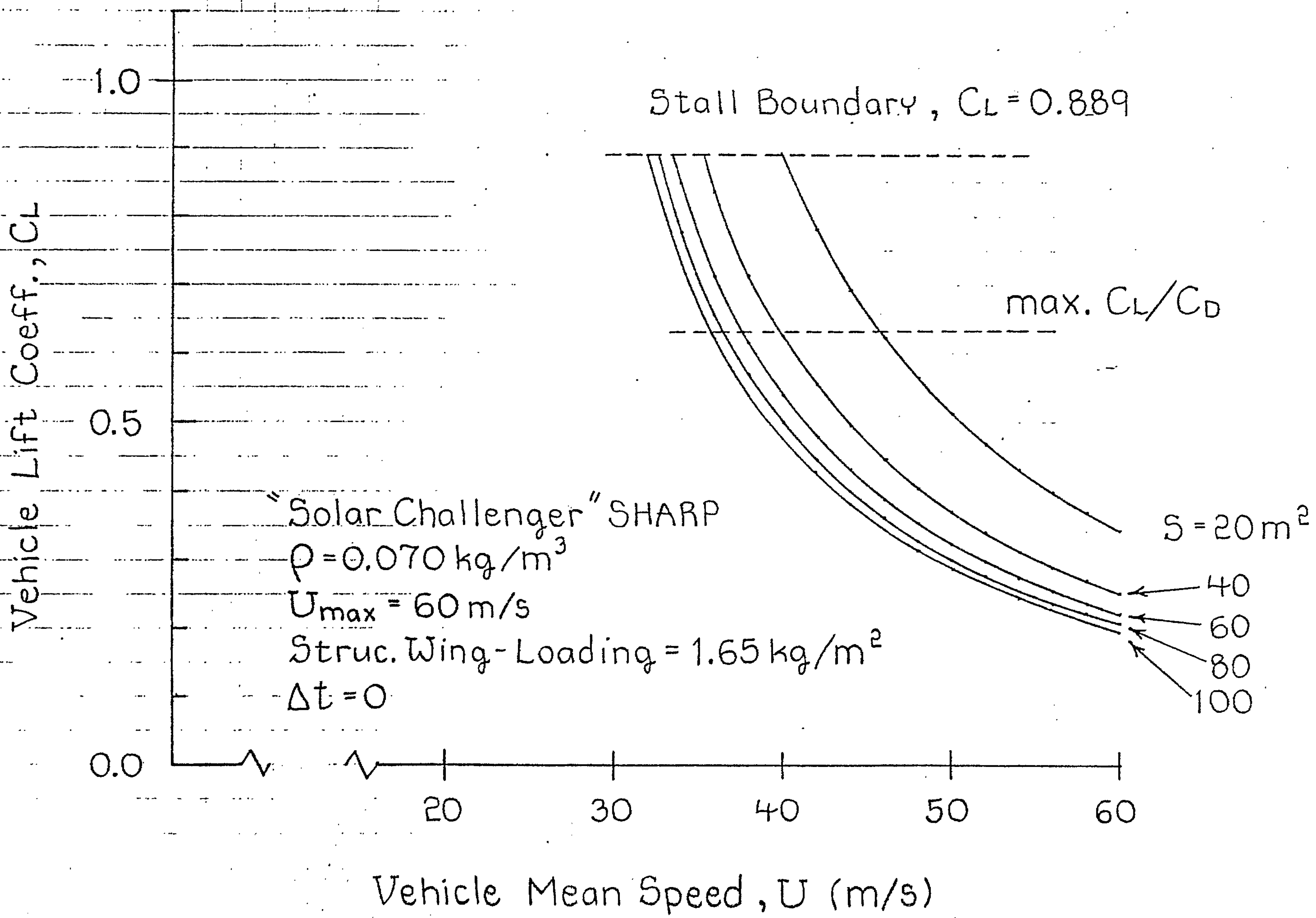


Fig. 22 Lift Coefficient vs. Speed for "Solar Challenger" SHARP

Exerpts from letter report 15 February 1982 from
J. De Laurier to G. Jull

Here are the performance results for a SHARP airplane with an Aspect-Ratio 20 wing. Specifically, it's a conventional rearward-tail configuration with a highly-cambered airfoil (NACA 6412) on the wing. The stabilizer's Aspect Ratio is 3.0 and it has an area which is 38% of the wing's area. The body is assumed to be the minimum required to enclose the payload, motor, etc. and rigidly hold everything together; hence its wetted area is 50% of the wing's area (it might be possible to make this even smaller). The stabilizer has a symmetrical airfoil (NACA 0009) and its aerodynamic centre is located 4.24 wing chords aft of the wing's aerodynamic centre. Note that both planforms are assumed to be rectangular.

As I mentioned on the phone, I initially attempted to estimate the vehicle's lift and drag coefficients by means of conventional-airplane equations such as published by Roskam in "Methods for Estimating Drag Polars of Subsonic Airplanes". These gave the vehicle's maximum Lift/Drag ratio to be 17, which seemed much too small for such a high Aspect-Ratio configuration. Therefore, I looked in detail at Roskam's estimation equations, and discovered that he was assuming vehicles which have:

(1) shallow-cambered airfoils,
(2) higher Reynolds numbers.

It is only with these assumptions that the classical drag-polar equation makes sense. Otherwise, a different formulation is appropriate, which is fortunate for it shows the vehicle to be a far better performer.

The basis for the new formulation may be understood by noting that an airfoil's lift is the vector sum of a force normal to its chord, C_n, and a leading-edge suction, C_T. On an ideal wing of A.R.=∞, C_n and C_T combine to give a C_L which is perpendicular to the wind vector. For a finite A.R. wing, however, the boundary conditions at the wing tips act to modify C_n and C_T so that the resulting C_L is no longer perpendicular to the wind, but is tilted slightly aft. That aft component is the "induced drag". Note that it exists for a finite A.R. wing even if the leading-edge suction is operating as efficiently as possible. In fact, real-fluid effects reduce this efficiency as a function of the leading-edge's Reynolds number, so that the induced drag may be even larger. Roskam's equations were showing a considerable increase in the induced drag of the SHARP vehicle because its leading-edge Reynolds number was so low. The leading-edge suction efficiency was 50%. Note that for a zero efficiency, $C_T=0$, the induced drag is simply the rearward component of the normal force.

However, an important effect missing from these formulations is the airfoil's camber. At a zero geometrical angle of attack, a cambered airfoil generates a finite lift which is nearly perpendicular to the wind, even if the leading-edge suction is zero. For other angles, the induced drag is produced by the additional lift, in the manner previously described. But the fact remains that the total lift is the sum of this additional lift plus the zero-angle lift, so that the overall lift/drag ratio is greatly improved. For the example vehicle, the corrected maximum L/D is 31.9.

Because of this improvement, the vehicle's performance is dramatically better than our previous SHARP examples, as shown in Figures 23 and 24. For a wing area of $40m^2$, the vehicle's minimum power-flux density is 113 W/m^2 at 38 m/s, and the maximum is 269 W/m^2 at 60 m/s. Although an Aspect Ratio of 20 is excessive, this clearly shows how an airplane with a highly-cambered airfoil appears capable of being designed to perform the SHARP mission.

Finally , note that the vehicle's reference area, S, is the wing area, only, whereas that for the "Solar Challenger" SHARP was wing plus stabilizer area. Hence, the "Airframe Mass/Wing Area" (Structural Wing-Loading) is 2.5 for this example.

Drag Polar for SHARP Airplane with Aspect Ratio = 20

Geometry:

Assume a conventional tail-aft layout where the wing's properties are

A.R. = 20, Zero Sweep, Taper Ratio = 0.5, $S_w \cong 40\ m^2$

The stabilizer's properties are

A.R. = 3, Zero Sweep, Taper Ratio = 1.0, $S_s \approx 15\ m^2$

The vertical fin's properties are

A.R. = 2, Zero Sweep, Taper Ratio = 1.0, $S_f \approx 5\ m^2$

The fuselage's wetted area is

$$(S_{wet})_{body} \cong 40\ m^2$$

and its crossectional area is $(S_{c.s.})_{body} \cong 0.5\ m^2$

Zero-Lift Drag Coeff., C_{D_0}:

From "Methods for Estimating Drag Polars of Subsonic Airplanes" by Jan Roskam,

$$C_{D_0} = \frac{1}{S} \sum C_{D_\pi} S_\pi \text{ + drag increments from interference, etc.}$$

where $(C_{D_\pi})_{wing} = 0.0070$, $(C_{D_\pi})_{stab} = 0.0080$

$(C_{D_\pi})_{fin} = 0.0080$, $(C_{D_\pi})_{body} = 0.1100$

and 15 % must be added for interference, etc. So,

$$C_{D_0} = \frac{1.15}{40}\left(0.0070 \times 40 + 0.0080 \times 15 + 0.0080 \times 5 + 0.1100 \times 0.5\right) =$$

$$\underline{\underline{C_{D_0} = 0.0142}}$$

Induced - Drag Parameter, K:

$$K = 1/(\pi A\!\!R\, e) \qquad (1)$$

where, again, from Roskam,

$$\frac{1}{e} = \frac{1}{e_{wing}} + \frac{1}{e_{body}} + \frac{1}{e_{other}}, \qquad (2)$$

Figure 2.4 gives $e_{wing} = 0.3$

Figure 2.5 gives $\dfrac{\Delta(1/e)_{body}}{S_{body}/S} = 1.5 \rightarrow$

$$\frac{1}{e_{body}} = 1.5 \times \frac{0.5}{40} = 0.0188$$

And Roskam recommends $1/e_{other} = 0.5$, so

$$1/e = 3.333 + 0.0188 + 0.5 = 3.852$$

so that $K = 3.852/(\pi \times 20.0) =$

$$\underline{\underline{K = 0.0613}}$$

Drag Polar:

From the C_{D_0} and K values, the drag polar becomes

$$C_D = 0.0142 + 0.0613\, C_L^2$$

From which, $(C_D)_{max\, C_L/C_D} = 2C_{D_0} = 0.0284$

$(C_L)_{max\, C_L/C_D} = 0.4813$, so $(C_L/C_D)_{max} = 16.95$

Alternative Values #1

From Roskam's eq. (3.18),

$$e = \frac{1.1\,(C_{L\alpha_w}/A\!R)}{\eta_{le}(C_{L\alpha_w}/A\!R) + (1-\eta_{le})\pi}, \quad (3) \quad \text{where}$$

$$\frac{C_{L\alpha_w}}{A\!R} = \frac{2\pi}{2 + (A\!R^2/\kappa^2 + 4)^{1/2}}, \quad (4)$$

$$\kappa = (C_{L\alpha})_{section} / 2\pi, \quad (5)$$

η_{le} = lead.-edge radius suction parameter, which is a fn. of the Reynold's no. based on the leading-edge radius,

$$(R.N.)_{le} = \frac{U r_{le}}{\nu}, \text{ where at } 21\,km \text{ alt,}$$

$$\nu = 21.317 \times 10^{-4}\, ft^2/sec = 1.9804 \times 10^{-4}\, m^2/sec$$

$$\text{so, } (R.N.)_{le} = 5.05 \times 10^3\, U r_{le} \quad (6)$$

A typical l.e. radius would be that for the N60 airfoil, which is $r_{le} = 0.014C$. Thus, for this example,

$$U = 45\,m/s,\ C = 1.414\,m \rightarrow (R.N.)_{le} = 4.5\times10^{3}$$

so that from Fig. 3.14, $\eta_{le} = 0.50$

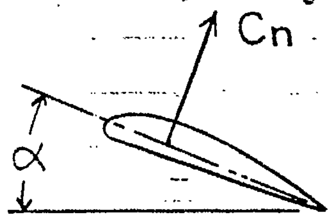
Also, choose $\kappa = 0.95$, so that

$$\frac{C_{L\alpha w}}{AR} = \frac{2\pi}{2 + [(20/0.95)^2 + 4]^{1/2}} = 0.27144$$

$$e = \frac{1.1\times0.27144}{0.5\times0.27144 + 0.5\pi} = \frac{0.2986}{1.7065} = 0.1750$$

This, then, gives $K = 0.09095$

Note that if $R = 0$ (sharp leading edge) then



$$C_{D_i} \cong C_n\alpha = C_{n_\alpha}\alpha^2 \approx$$

$$\approx C_{L\alpha}\alpha^2 = \frac{(C_{L\alpha}\alpha)^2}{C_{L\alpha}} =$$

$$C_{D_i} = C_L^2/C_{L\alpha},\ \text{so}\ K = 1/C_{L\alpha} = 0.1842$$

If a low-speed airfoil with a generous leading edge is chosen, such as the Lissaman 7769 (used on "Gossamer Condor") which has an $r_{le} = 0.0184\,C$,

$$(R.N.)_{le} = 5.91\times10^{3}$$

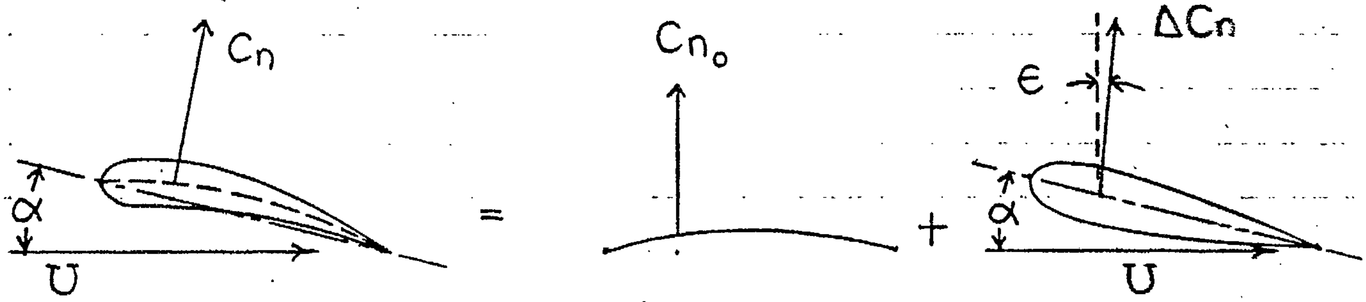
This gives, from Fig. 3.14, $\eta_{\ell e} = 0.57$, so

$$e = \frac{1.1 \times 0.27144}{0.57 \times 0.27144 + 0.43\pi} = 0.1983$$

which gives $K = 0.08025$ ✓

These are even worse than those from the original calculation. However, I think that a reason for this is that Roskam's curves pertain to airfoils with fairly-shallow camber. With highly-cambered airfoils, the lack of 100% leading-edge suction should not so influence the "induced drag" at low angles.

Note that, to first order, the cambered wing at angle α is the sum of the cambered wing at zero angle plus the symmetrical section at α:



so that $C_n \approx C_{n_0} + \Delta C_n$, which gives

$$C_L \approx C_{L_0} + C_{L_\alpha}\alpha \qquad (7)$$

The "induced drag" is produced by the ΔC_n component:

$$C_{D_i} = \Delta C_n \, \epsilon \qquad (8)$$

thus, in accordance with Appendix A, the induced drag expression for a cambered wing is

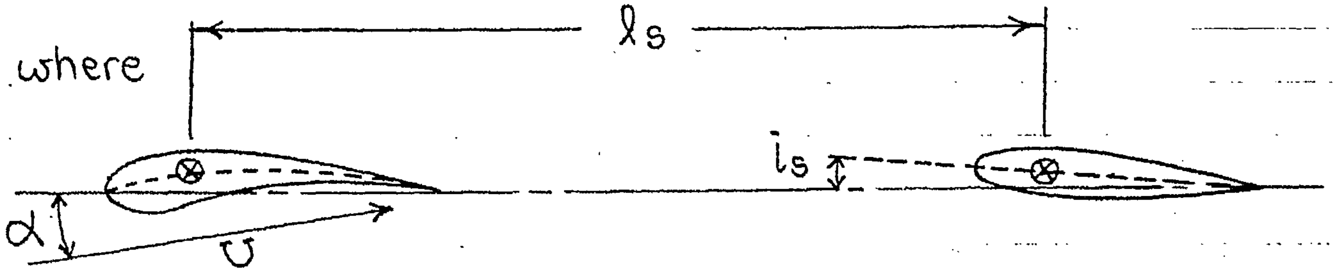
$$C_{D_i} = \frac{(C_L - C_{L_0})^2}{\pi A\!\!R\, e} = \frac{(C_{L_\alpha})^2 \alpha^2}{\pi A\!\!R\, e} \qquad (9)$$

where e is calculated from eq. (3).

This is the value for the wing. For the stabilizer, assume a symmetrical section so that

$$(C_{D_i})_s = \frac{(C_L)_s^2}{\pi A\!\!R_s e_s} \qquad (10)$$

where



$$(C_L)_s = (C_{L_\alpha})_s(\alpha + i_s - \epsilon) \qquad (11)$$

i_s is the stabilizer incidence and ϵ is the downwash angle from the wing, which may be expressed as

$$\epsilon = (\partial\epsilon/\partial\alpha)_w\, \alpha \qquad (12)$$

For this numerical example, choose:

Wing Airfoil: NACA 6412 which gives the α for zero lift to be $-5.7°$ ($\alpha_{ZLL} = 5.7°$)

$i_s = 0$, $l_s = 6.0\,m$, $b_w = 28.3\,m$, $C_w = 1.414\,m$

so that $l_s/C_w = 4.243$, and from Diehl's equation,

$$\frac{\partial\epsilon}{\partial\alpha} = \frac{4 - l_s/3C_w}{A\!\!R_w + 2} \qquad (13)$$

$$\frac{\partial \epsilon}{\partial \alpha} = \frac{4 - 4.24/3}{20 + 2} = 0.1175$$ ✓

Alternately, from the USAF DATCOM,

$$\frac{\partial \bar{\epsilon}}{\partial \alpha} = 4.44 \left[K_A K_\lambda K_H (\cos \Lambda_{c/4})^{1/2} \right]^{1.19} \quad (14)$$

where

$$K_A = \frac{1}{AR} - \frac{1}{1 + AR^{1.7}} = \frac{1}{20} - \frac{1}{1 + 20^{1.7}} = 0.0439$$ ✓

$$K_\lambda = \frac{10 - 3\lambda}{7} = \frac{10 - 3}{7} = 1$$ ✓

$$K_H = (1 - h_H/b) / (2 \ell_H / b)^{1/3} =$$

$$= 1 / (2 \times 6 / 28.3)^{1/3} = 1.3311$$ ✓

So, $\partial \bar{\epsilon} / \partial \alpha = 4.44 (0.0439 \times 1.3311)^{1.19} =$

$$\partial \bar{\epsilon} / \partial \alpha = 0.1513$$ ✓

Choose this.

Also, for the stabilizer, $K = 0.9$, $AR = 3$, so

$$(C_{L\alpha})_S = \frac{2\pi \times 3}{2 + [(3.0/0.9)^2 + 4]^{1/2}} = 3.202$$ ✓

Thus, from (11) and (12),

$$(C_L)_S = 3.202\, \alpha (1 - \partial \epsilon / \partial \alpha) =$$

$$(C_L)_S = 2.7175\,\alpha$$

Also, for the wing, eq. (4) gives

$(C_{L\alpha})_w = 0.27144 \times 20 = 5.4288$, so,

$C_{L_0} = (C_{L\alpha})_w\,\alpha_{ZLL} = 5.4288 \times 5.7/57.3 =$

$$(C_{L_0})_w = 0.5400$$

So, the expression for the lift coefficient is

$$C_L = (C_{L_0})_w + \left[(C_{L\alpha})_w + (C_{L\alpha})_S \frac{S_S}{S}\right]\alpha =$$

$$= 0.5400 + \left[5.4288 + 2.7175 \times \frac{15}{40}\right]\alpha =$$

$$\boxed{C_L = 0.5400 + 6.4479\,\alpha} \qquad (14)$$

From this, one obtains that

$$\alpha = (C_L - 0.5400)/6.4479 \qquad (15)$$

Next, choose

$$C_f = 0.455/[\log(R.N.)]^{2.58}$$

where $R.N. = 5.05 \times 10^3\, U C \cong$

$5.05 \times 10^3 \times 45 \times 1.414 = 3.21 \times 10^5 = R.N.$

So, $C_f = 0.0056$, which gives

$$(C_D)_{fric} \cong C_f\left(2 + 2\frac{S_s}{S} + \frac{S_{body}}{S}\right) =$$

$$= 0.0056\left(2 + 2\times\frac{15}{40} + \frac{20}{40}\right) = 0.0182$$

(aside: note change in $(S_{wet})_{body}$ to $20\,m^2$)

so, allowing for interference drag, etc.,

$$\boxed{(C_D)_{fric} = 0.020}$$

The total induced drag is

$$C_{D_i} = (C_{D_i})_w + (C_{D_i})_s\, S_s/S \tag{16}$$

where, from (9),

$$(C_{D_i})_w = \frac{[(C_L)_w - (C_{L_0})_w]^2}{\pi\, AR_w\, e_w} =$$

$$= \frac{(5.4288\,\alpha)^2}{\pi\times 20\times 0.175} = (C_{D_i})_w = 2.6803\,\alpha^2$$

And for the stabilizer, choose $\eta_{l.e.} = 0.4$ so from (3), one obtains

$$e_s = \frac{1.1(2.7175/3)}{0.4(2.7175/3) + 0.6\pi} = 0.4434$$

So from (10), one obtains

$$(C_{Di})_S = \frac{(2.7175\,\alpha)^2}{\pi \times 3 \times 0.4434} = 1.7672\,\alpha^2$$

and one obtains, from (16),

$$C_{Di} = 2.6803\,\alpha^2 + 1.7672 \times 15\,\alpha^2/40 =$$

$$\boxed{C_{Di} = 3.3430\,\alpha^2} \qquad (17)$$

And so the total drag coefficient is

$$C_D = C_{D_{fric}} + C_{Di} =$$

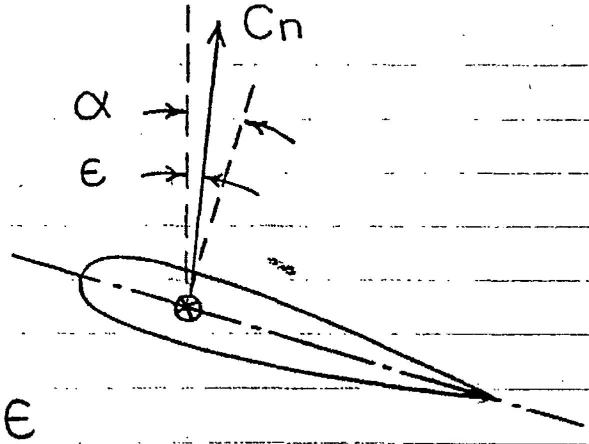
$$\boxed{C_D = 0.020 + 3.3430\,\alpha^2} \qquad (18)$$

and the specific coefficients are:

α (deg)	C_L	C_D	C_L/C_D
0	0.5400	0.0200	27.00
2	0.7651	0.0241	31.75
4	0.9901	0.0363	27.28
6	1.2152	0.0567	21.43
8	1.4402	0.0852	16.90
10	1.6653	0.1218	13.67
12	1.8903	0.1666	11.35
1	0.6525	0.0210	31.07
3	0.8776	0.0292	30.05

Appendix A: Derivation of Roskam's Eq. (3.19)

For a finite Æ wing with a symmetrical section, as shown, the "induced-drag" coefficient is given by



$$C_{D_i} = C_n \epsilon = \frac{C_n^2}{\pi Æ e} = \frac{C_n^2}{C_n} \epsilon$$

so that $\epsilon = C_n / (\pi Æ e)$ (A1)

The leading-edge suction, C_T, is given by

$$C_T = C_n(\alpha - \epsilon) = (C_T)_{ideal}\, \eta_{le} \qquad \text{(A2)}$$

so that, from (A1),

$$C_T = C_n\left(\alpha - \frac{C_n}{\pi Æ e}\right) = \eta_{le} C_n \left(\alpha - \frac{C_n}{\pi Æ}\right)$$

so, upon dividing through by α, one obtains

$$1 - \frac{C_{n_\alpha}}{\pi Æ e} = \eta_{le} - \eta_{le}\frac{C_{n_\alpha}}{\pi Æ}$$

and, when multiplied through by π, this becomes

$$\pi(1-\eta_{le}) + \eta_{le}(C_{n_\alpha}/Æ) = (C_{n_\alpha}/Æ)\, 1/e$$

so that one finally obtains

$$e = \frac{C_{n_\alpha}/Æ}{\eta_{le}(C_{n_\alpha}/Æ) + \pi(1-\eta_{le})} \qquad \text{(A3)}$$

Appendix 4: Alternate Formulation for Airplane

From Appendix 3, one has for equilibrium flight,

$$\frac{\rho U^2 S}{2g} C_L = m_{struc.} + m_{pl} + m_{propul.\ system} + m_{control\ system} + m_{power} \quad (24)$$

where $m_{struc.} = C_6 S$

$$m_{propul.\ system} = A_1 C_3 C_D \quad (11)$$

$$m_{power} = A_1 (C_4 + C_5 \Delta t) C_D + P_{OB} (C_4 + C_5 \Delta t) \quad (27)$$

Now, assume that

$$C_L = C_{L_0} + C_{L_1} \alpha \ , \ C_D = C_{D_0} + C_{D_2} \alpha^2 \quad (32)$$

so that eq. (24) becomes

$$\frac{\rho U^2 S}{2g} C_{L_0} + \frac{\rho U^2 S}{2g} C_{L_1} \alpha = C_6 S + m_{pl} + A_1 C_3 C_{D_0} + A_1 C_3 C_{D_2} \alpha^2 + m_{control\ system} + A_1 (C_4 + C_5 \Delta t) C_{D_0} + A_1 (C_4 + C_5 \Delta t) C_{D_2} \alpha^2 + P_{OB} (C_4 + C_5 \Delta t) \quad (33)$$

Define the following:

$$\Pi_1 \equiv A_1 C_{D_2} (C_3 + C_4 + C_5 \Delta t) \ ; \ \Pi_2 \equiv -\frac{\rho U^2 S}{2g} C_{L_1}$$

$$\Pi_3 \equiv C_6 S + m_{pl} + m_{cs} + P_{OB}(C_4 + C_5 \Delta t) + A_1 C_{D_0}(C_3 + C_4 + C_5 \Delta t) - \frac{\rho U^2 S C_{L_0}}{2g}$$ ✓

So eq. (24) becomes

$$\Pi_1 \alpha^2 + \Pi_2 \alpha + \Pi_3 = 0 \quad (34)$$

From which one obtains

$$\alpha = \frac{-\Pi_2 - (\Pi_2^2 - 4\Pi_1\Pi_3)^{1/2}}{2\Pi_1} \quad (35)$$ ✓

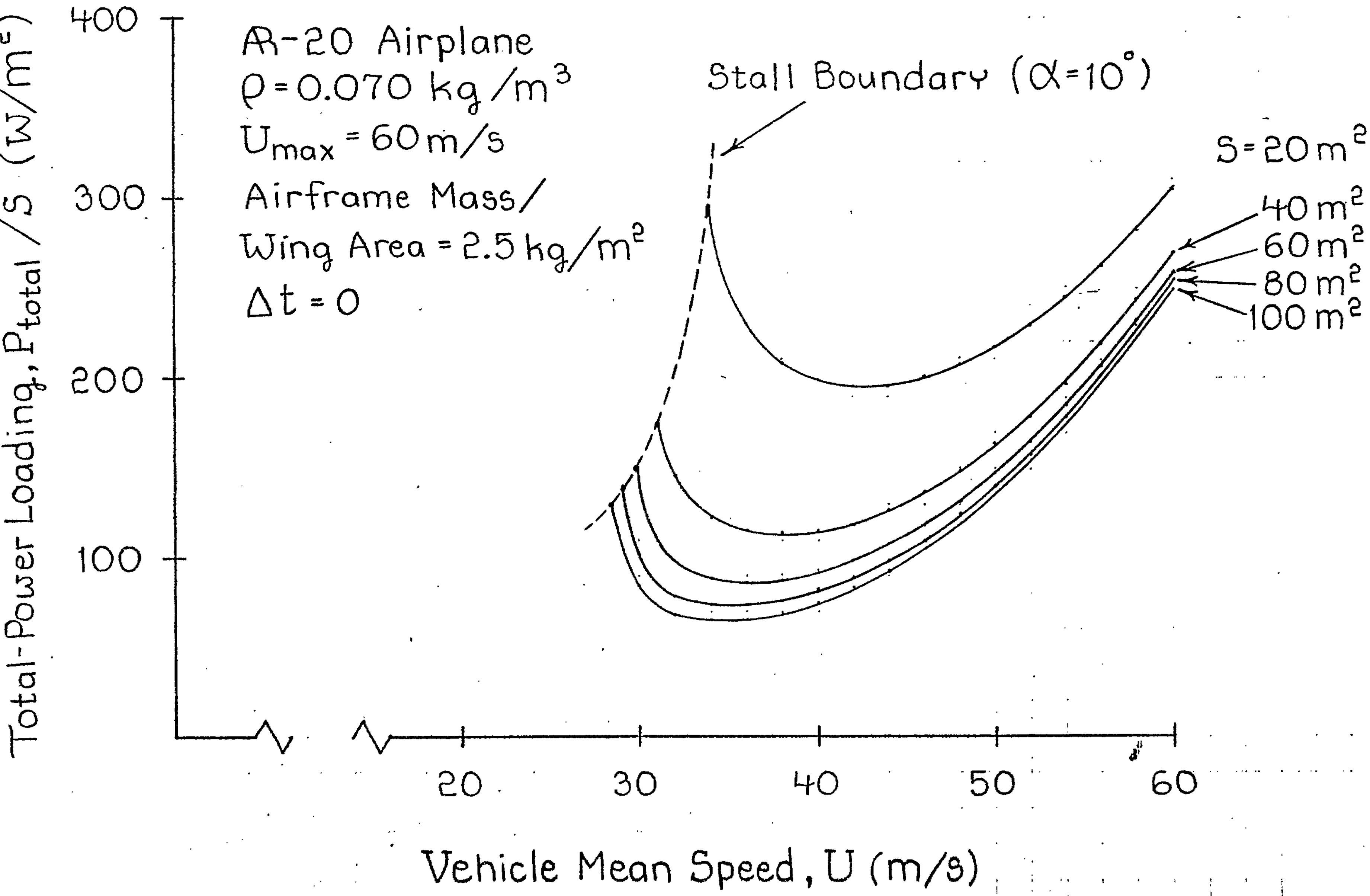


Fig. 23 Total-Power Loading vs. Speed for AR-20 SHARP Airplane

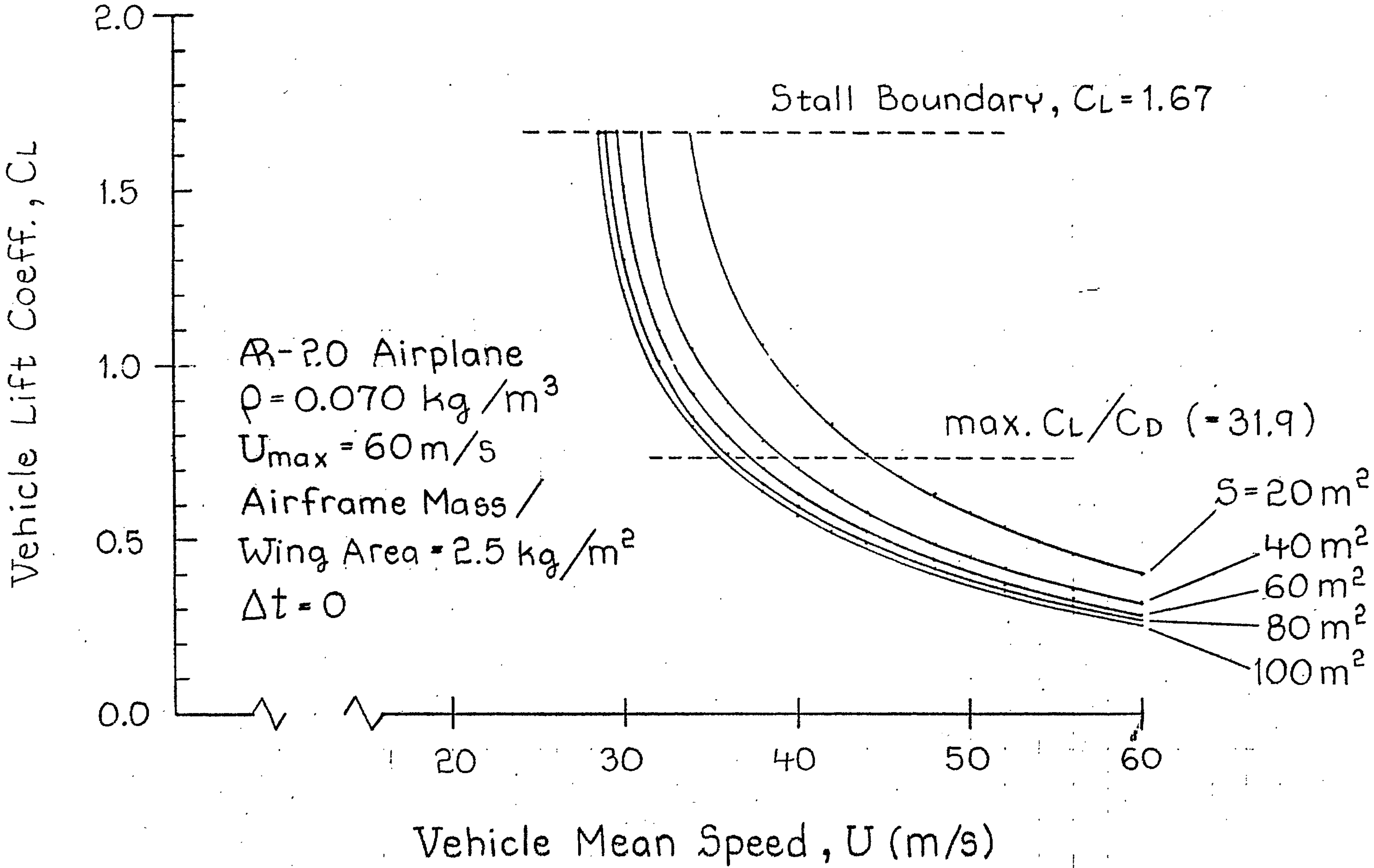


Fig. 24 Lift Coefficient vs. Speed for Æ-20 SHARP Airplane

15 Feb. 1982

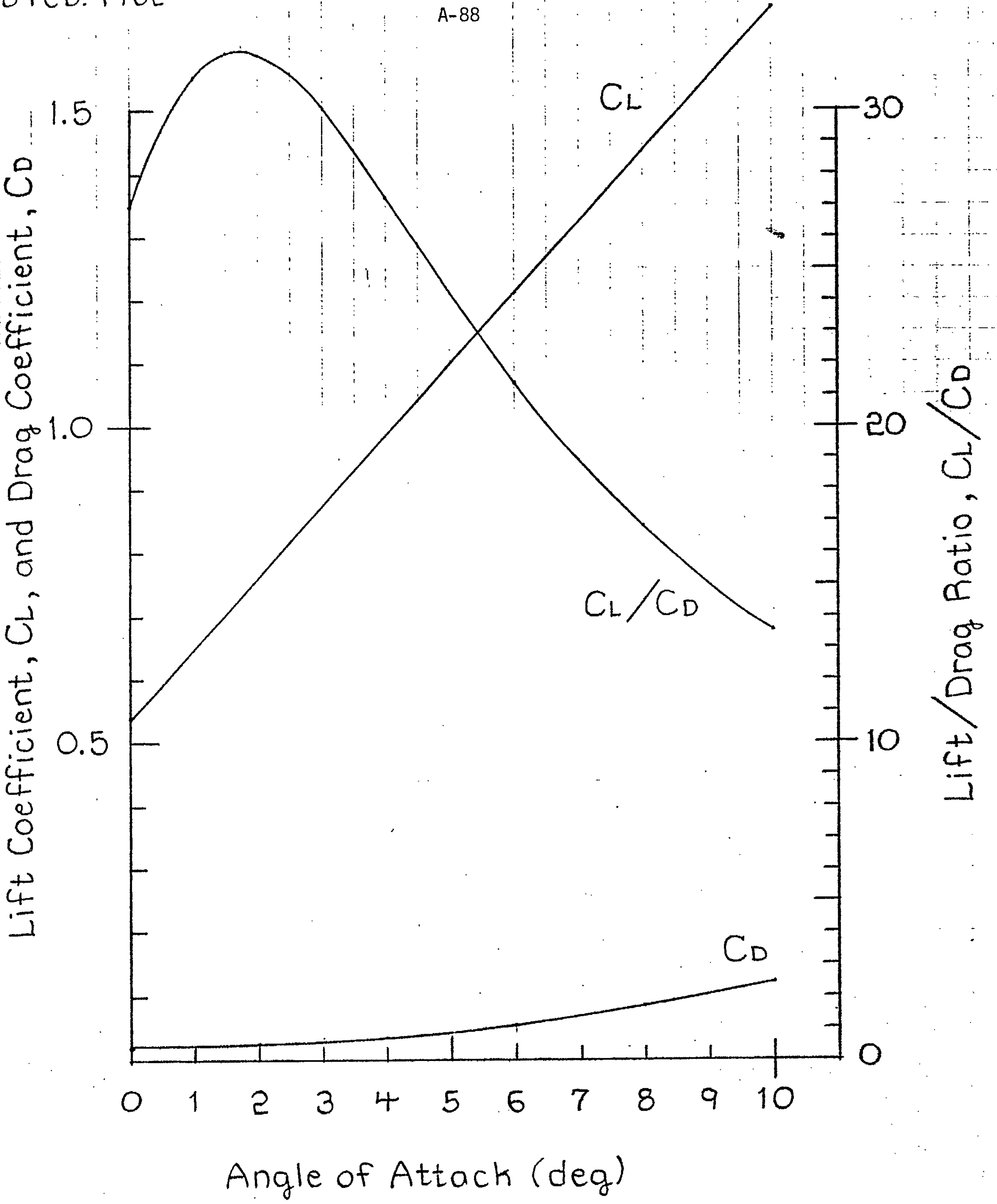


Fig. 25 Estimated Aero. Coeffs. for AR-20 Airplane

APPENDIX B

National Research Council Canada
Conseil national de recherches Canada

FILE NO
DOSSIER NO

DATE 28 August 1981

TO
A Mr. A.D. Wood

Re: Comments on the High Altitude Relay Platform Study

The analytical method employed by Dr. J. De Laurier of the University of Toronto on the study of aeronautical, high altitude relay platforms powered by microwave energy is in principle, essentially correct. The comments on the use of both fixed wing and lighter-than-air concepts for this purpose is as follows:

Fixed-Wing Concept

A parametric study at NAE of fixed-wing aircraft as a high altitude relay platform revealed the feasibility of the concept subject to the following constraints:

a) The Rectenna area must be less than the available wing area. This limits the vehicles concepts to forward speeds of less than about 75 knots.

b) The endurance of the vehicle when operating solely on onboard batteries as an emergency situation after failure of the microware energy source for any reason is limited to somewhat less than fifteen minutes. An emergency endurance of fifteen minutes or more results in the penalty of a tremendous increase in aircraft size. An advance in the development of lightweight batteries could improve this situation.

c) The structural weight of the vehicle would have to be after the style of the "Solar Challenger" aircraft. Any increase in gross weight due to systems or structure would result in dramatic increases in aircraft size.

d) The results of the study at NAE based on the De Laurier figures of 135 lb. payload indicate that the mission could be fulfilled by a fixed wing aircraft of similar construction to the Solar Challenger and having twice the wing area. Almost all the available wing areas would be covered by the rectenna. The approximate specifications of such an aircraft would be:

Operating Altitude	=	65000 ft
Operating Speed	=	75 knots
Wing Area	=	500 ft^2
Gross Weight	=	1000 lb

It is envisaged that a tandem-winged aircraft based on the Solar Challenger wing but having a Glasgow University designed section of GU-25(11)8 of high lift at low Reynolds number would fulfill the requirement with an emergency flight duration power on batteries at only about 10 minutes.

Lighter-Than-Air Concept

A lighter-than-air concept could theoretically fulfill the requirements of the mission with less constraints than a fixed wing aircraft. The reason being that as battery weight (and emergency endurance) increased the volume of the vehicle and hence buoyant lift could be increased to compensate. For example an LTA concept would require a volume of 100,000 ft^3 with no emergency power systems whereas a 0.5 hour emergency endurance would require a fifty percent increase in volume.

Figures

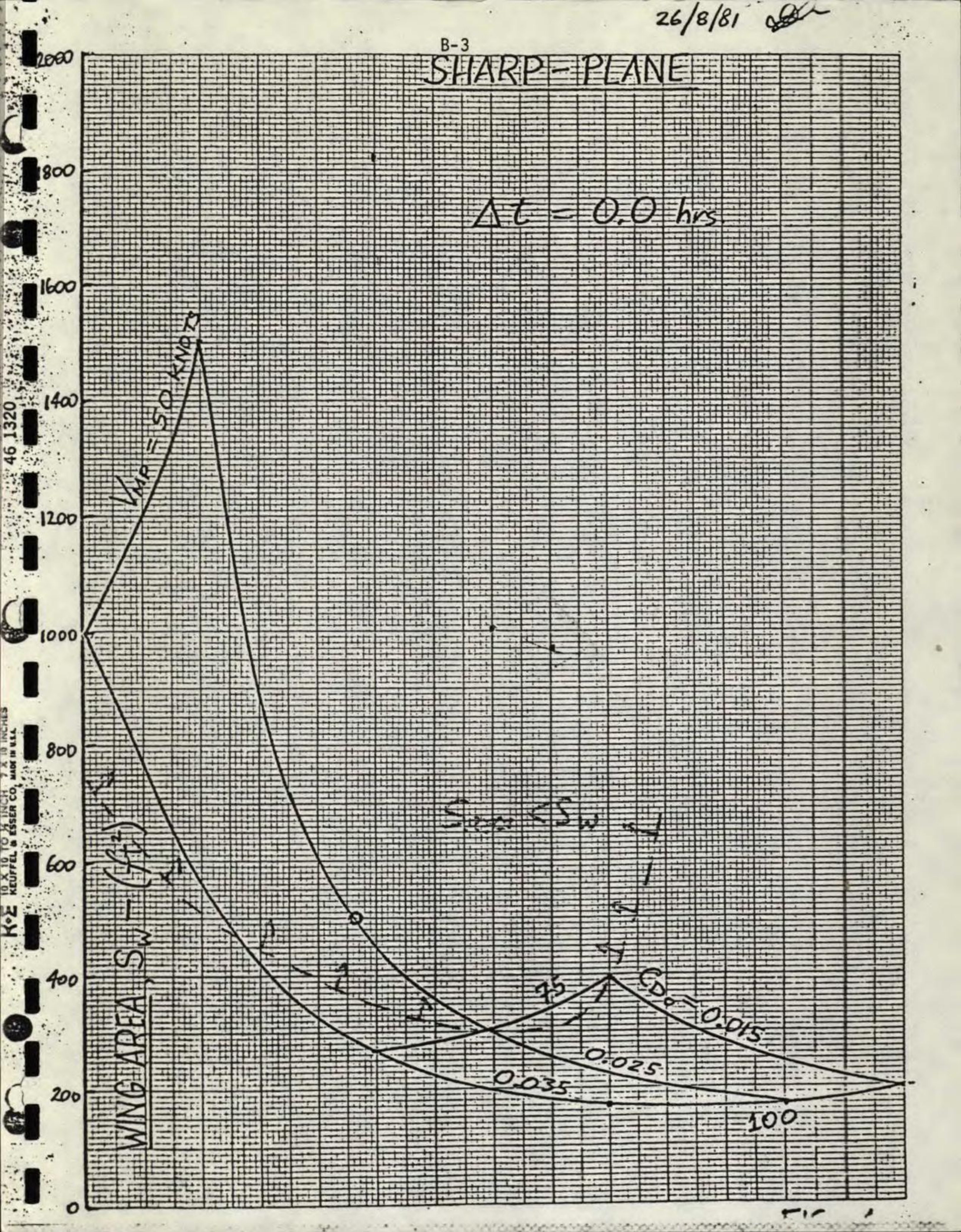
Figures 1 and 2 show the parametric results for a fixed-wing aircraft with no emergency power and with 0.1 hour emergency power.

Figure 3 shows the result of the study for an LTA vehicle.

The Appendix that follows shows the analytical method of the NAE study.

D. Laurie-Lean

B-3


26/8/81
SHARP-PLANE
Δt = 0.0 hrs.
V_{MP} = 50 KNOTS
WING AREA, S_W - (ft^2)
$S_{opt} < S_W$
75
100
C_{D_0} = 0.015
0.025
0.035
2000
1800
1600
1400
1200
1000
800
600
400
200
0

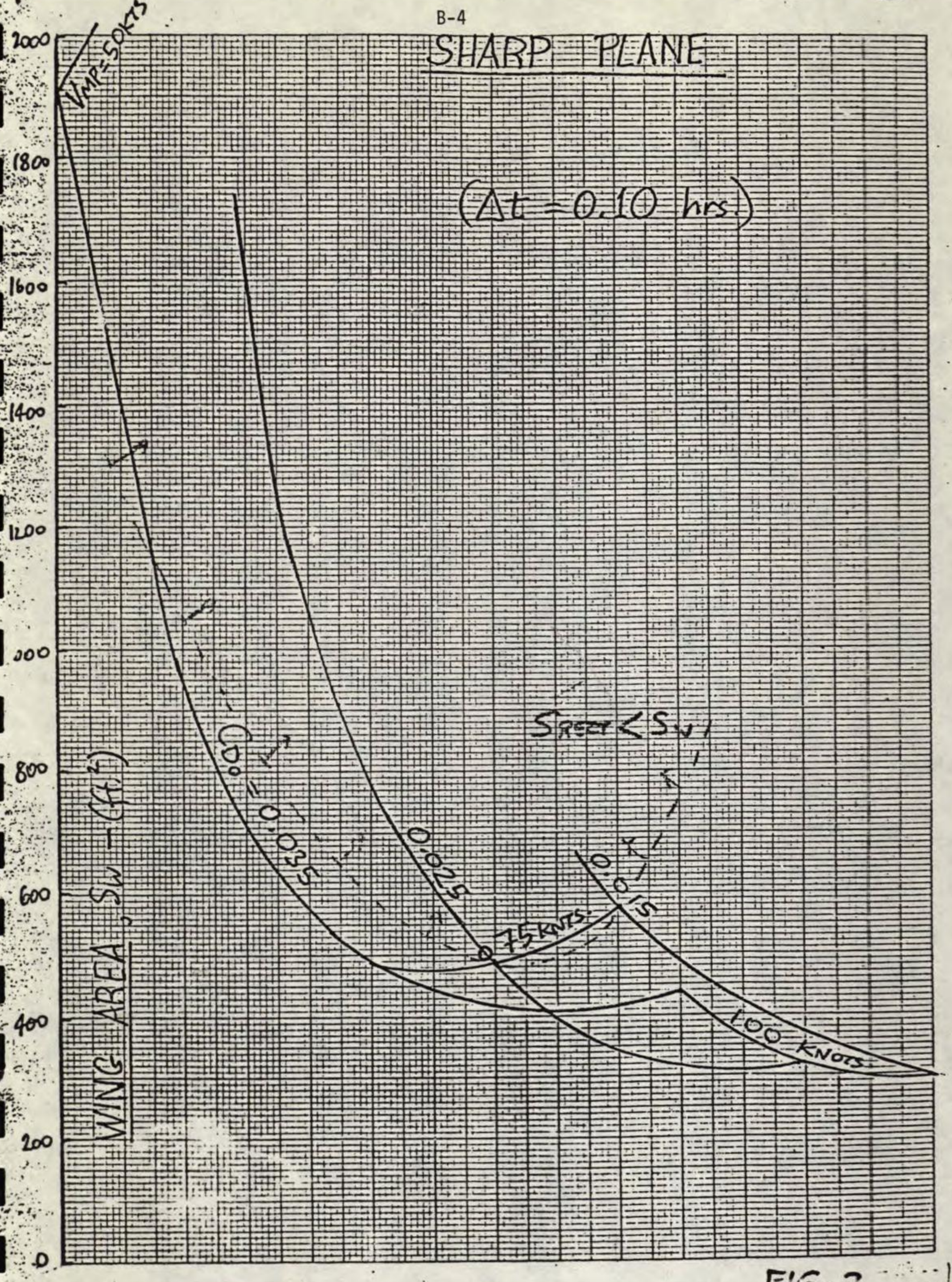
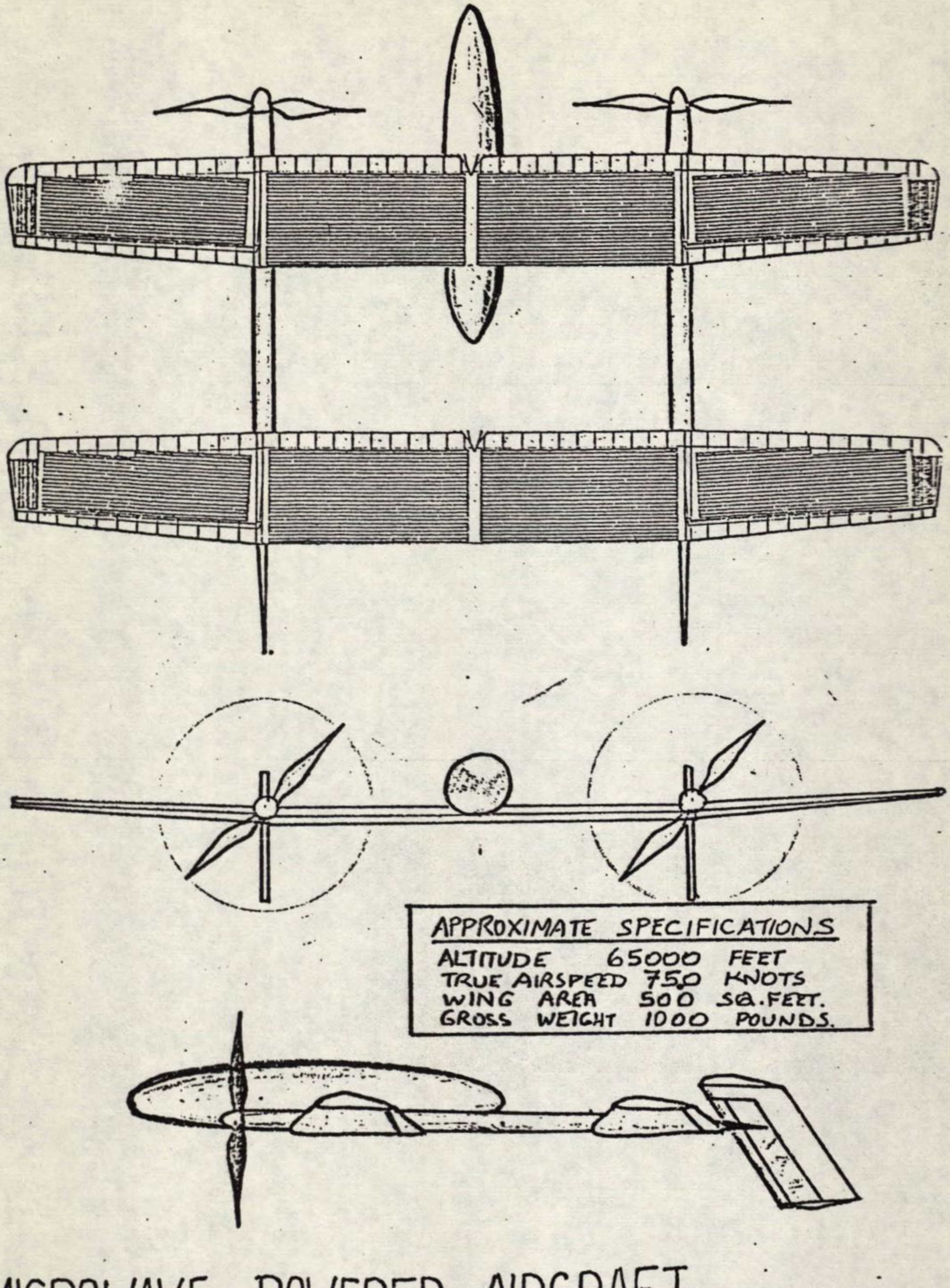

SHARP PLANE
(Δt = 0.10 hrs.)
VMP = 50 KTS
WING AREA, SW - (ft²)
CDO = 0.035
0.025
0.015
75 KNTS
100 KNOTS
SREQ'D < SW
2000
1800
1600
1400
1200
1000
800
600
400
200
0

FIG. 2



MICROWAVE-POWERED AIRCRAFT.

HIGH ALTITUDE RELAY PLATFORM

FIG. 3

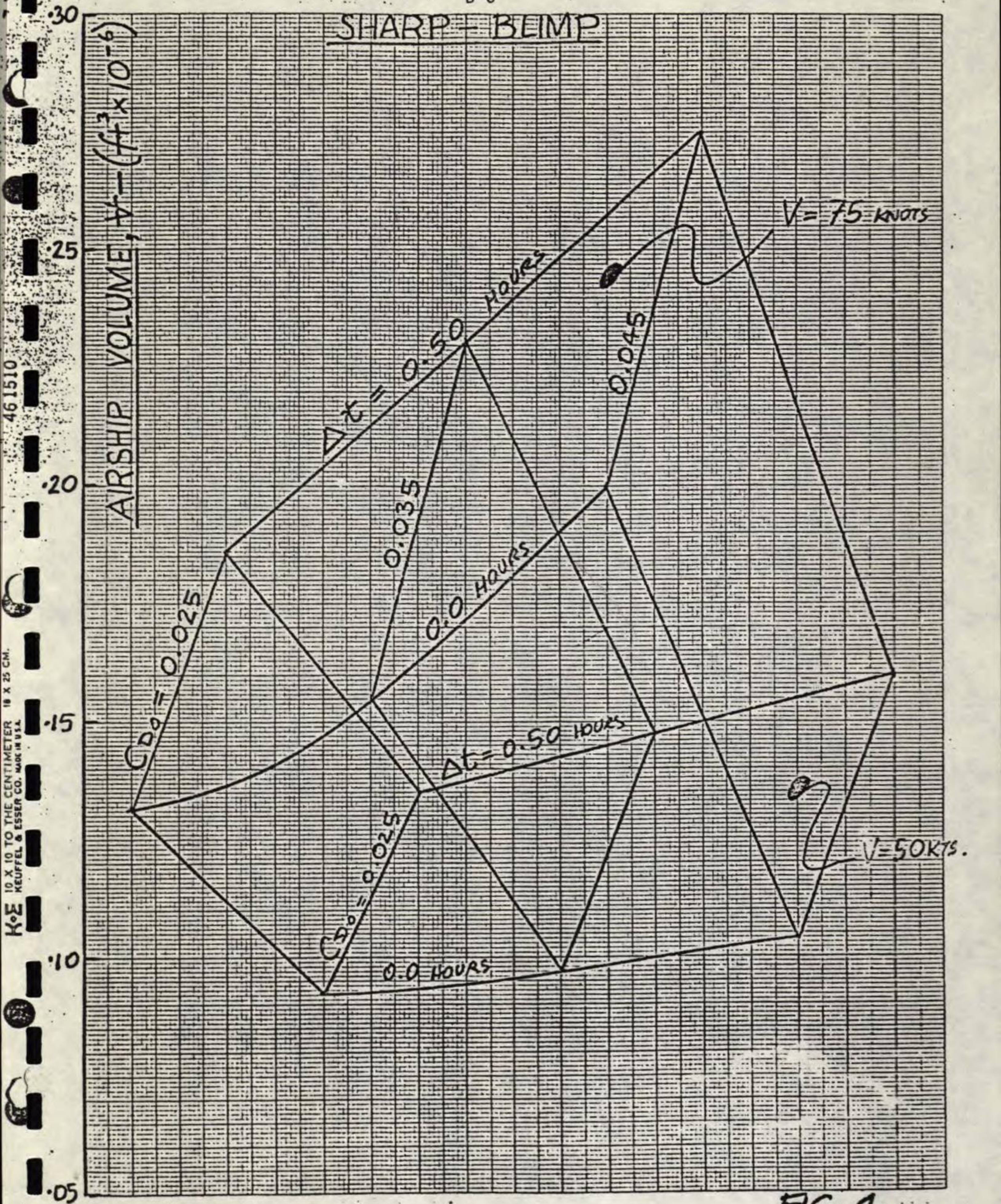
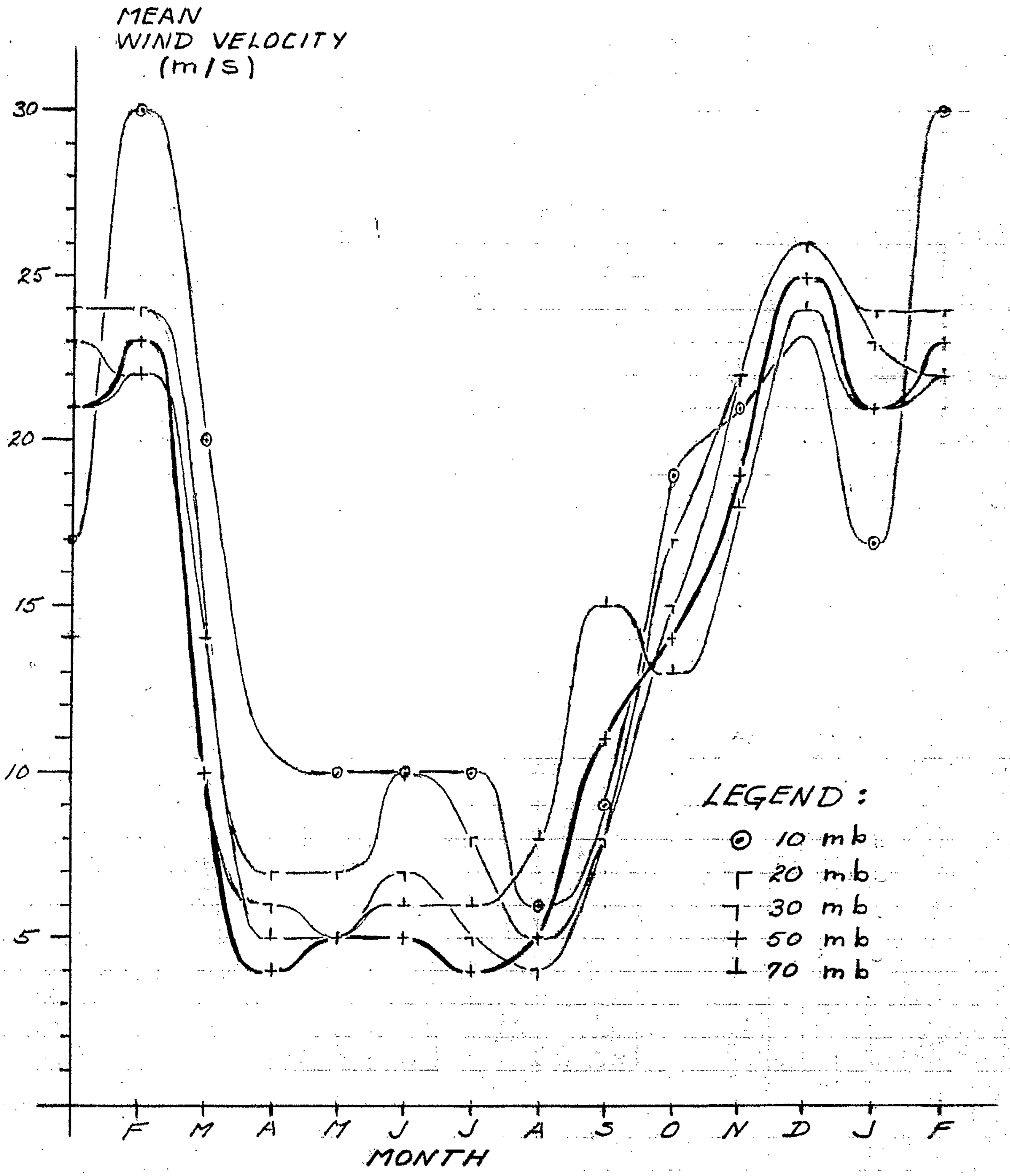

SHARP - BLIMP
AIRSHIP VOLUME, ∀ - (ft³ x 10⁻⁶)
.30
.25
.20
.15
.10
.05
V = 75 KNOTS
V = 50 KTS.
Δt = 0.50 HOURS
Δt = 0.50 HOURS
0.0 HOURS
0.0 HOURS
CDo = 0.025
CDo = 0.025
0.035
0.045
10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1510

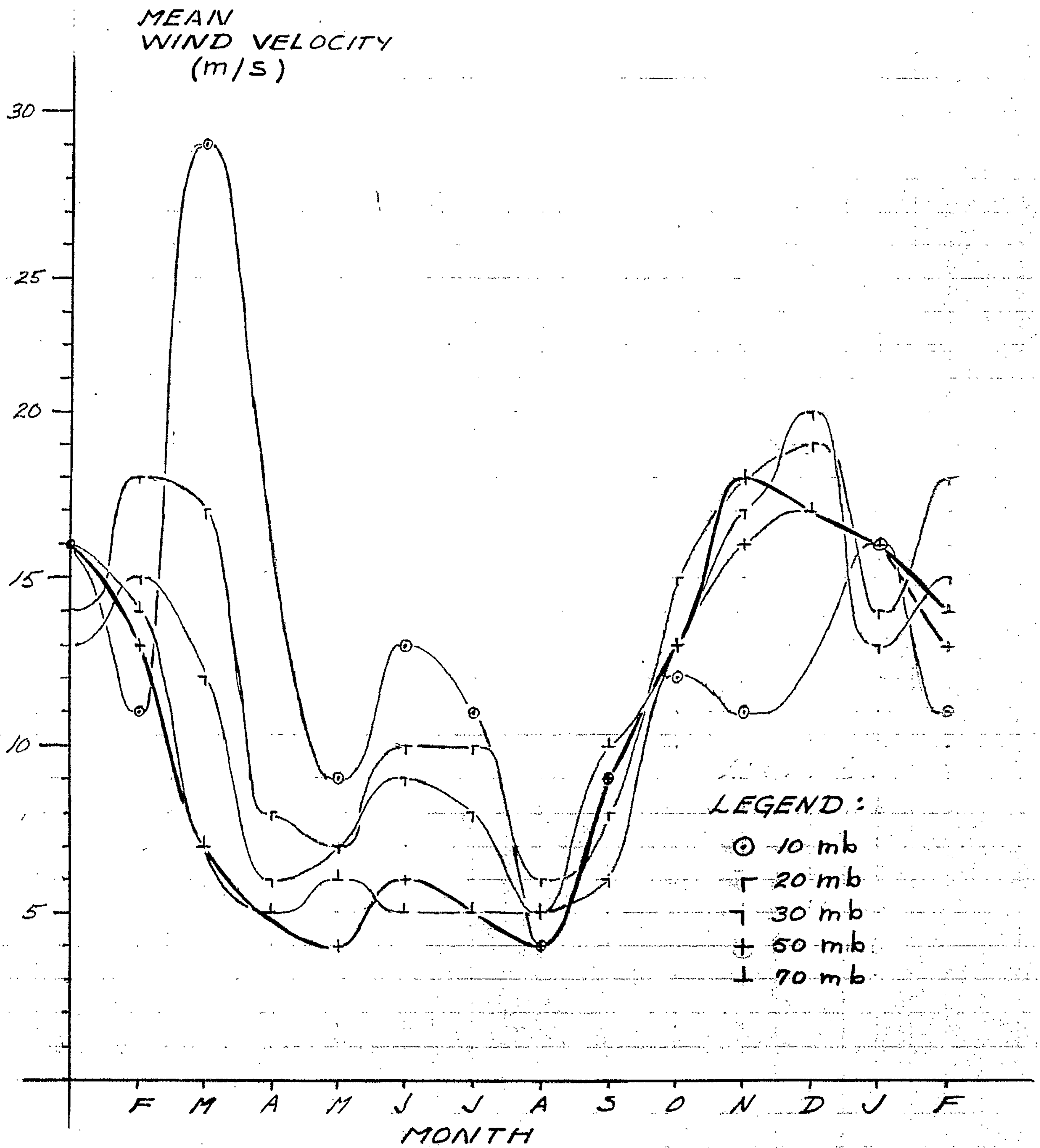
FIG. 4

APPENDIX C



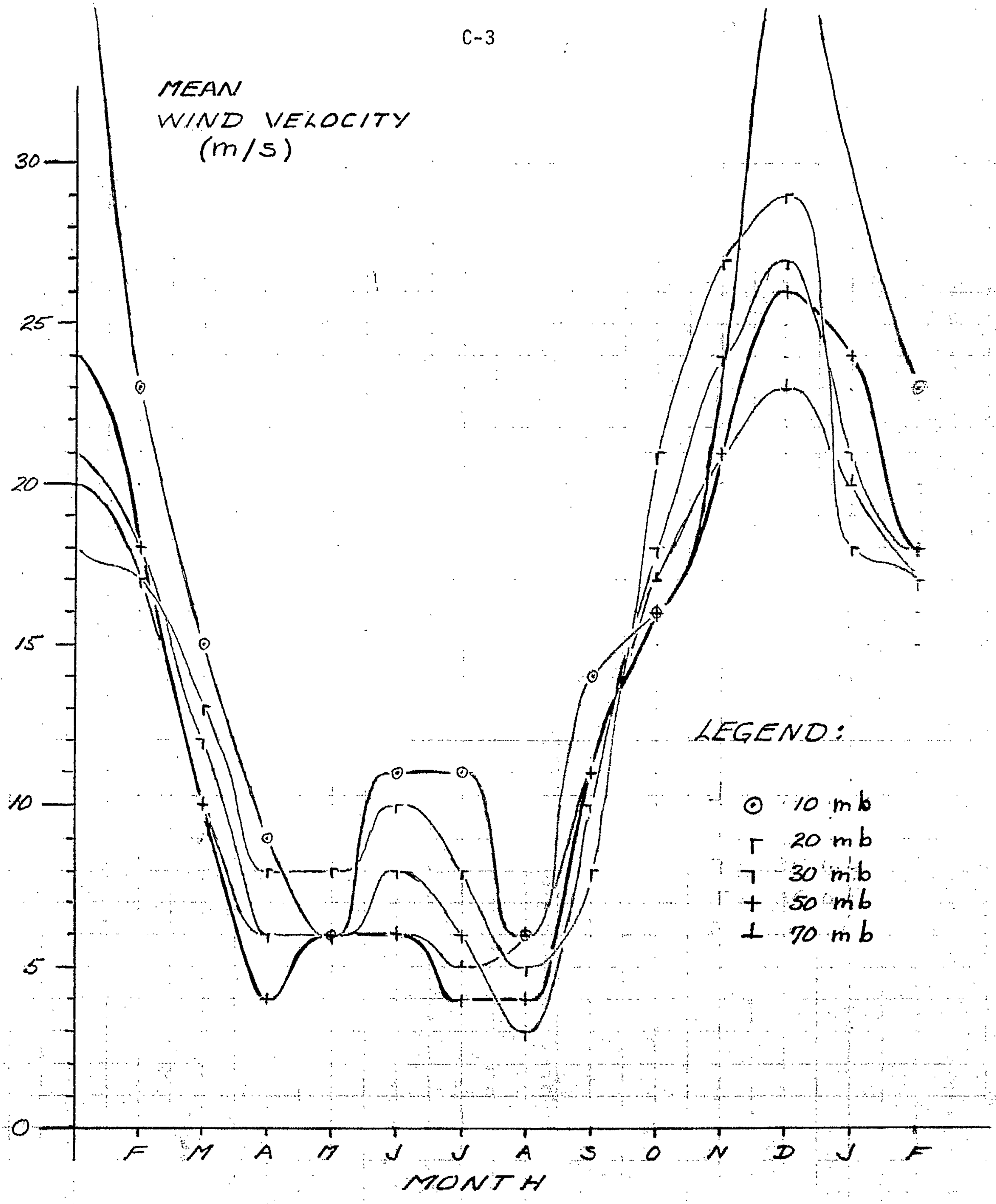
MEAN WIND VELOCITY
VS
MONTH OF YEAR FOR
CHURCHILL

FIG. C.1



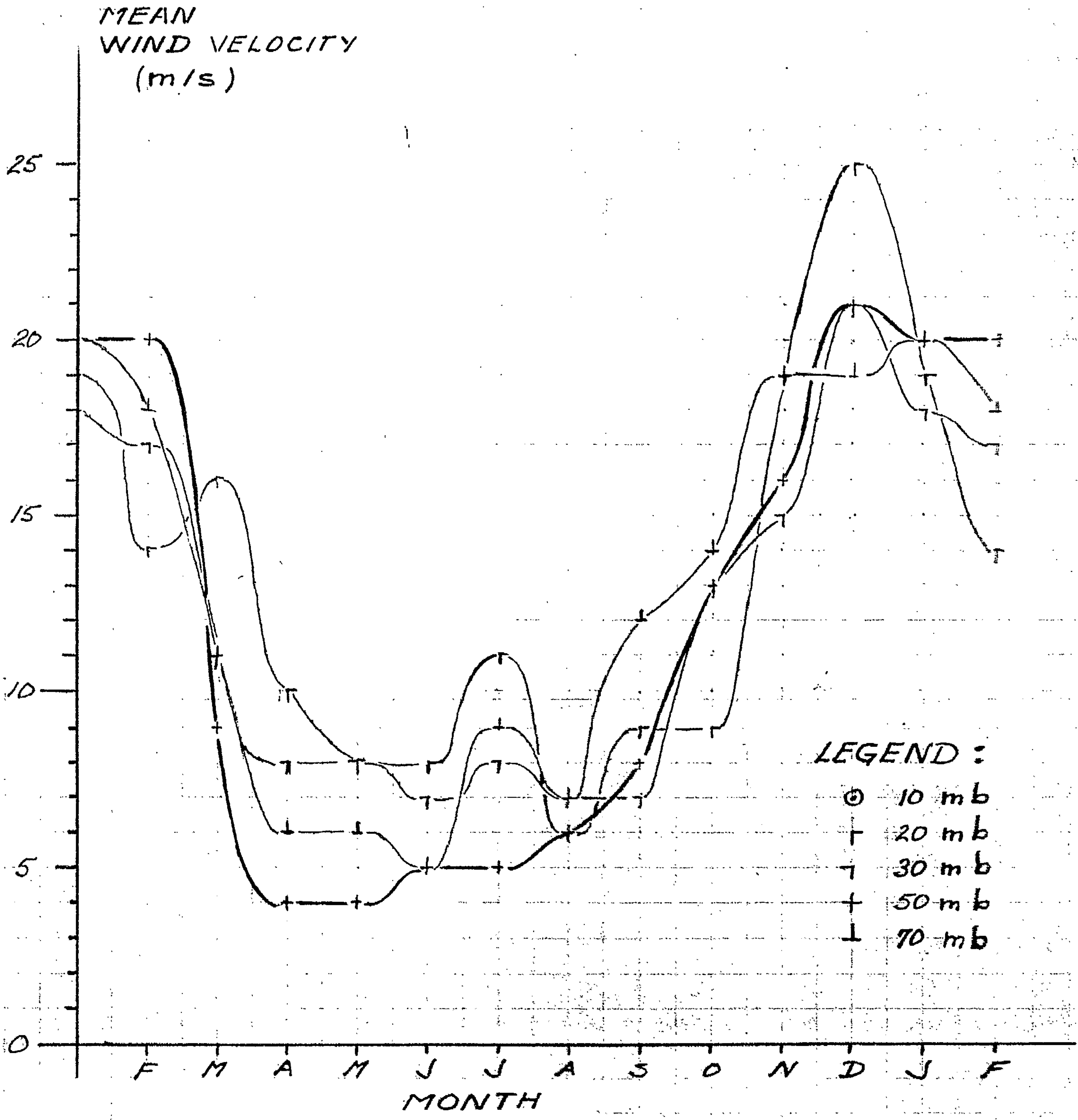
MEAN WIND VELOCITY
VS
MONTH OF YEAR FOR
EDMONTON

FIG. C.2



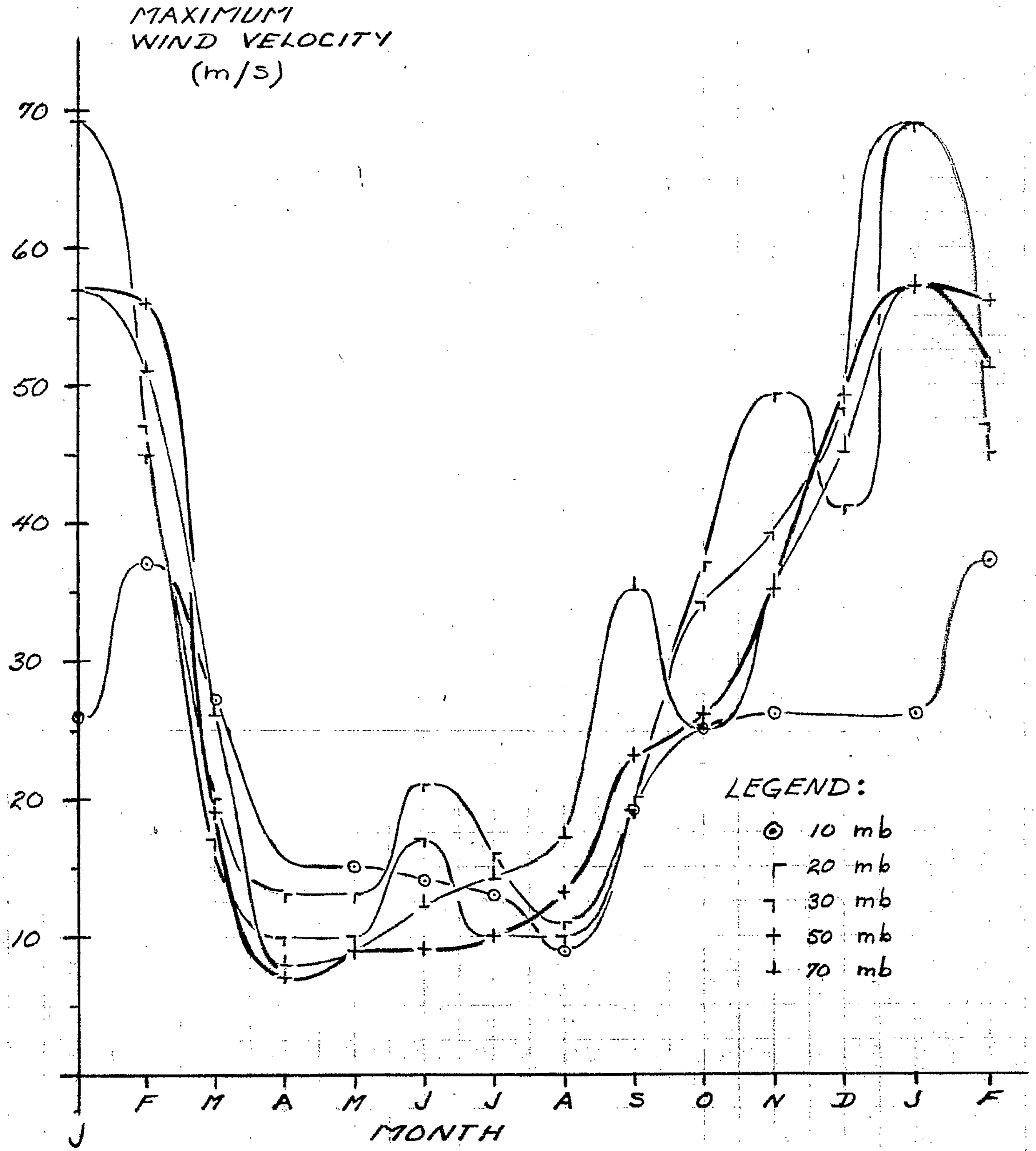
MEAN WIND VELOCITY
VS
MONTH OF YEAR FOR
FORT SMITH

FIG. C.3



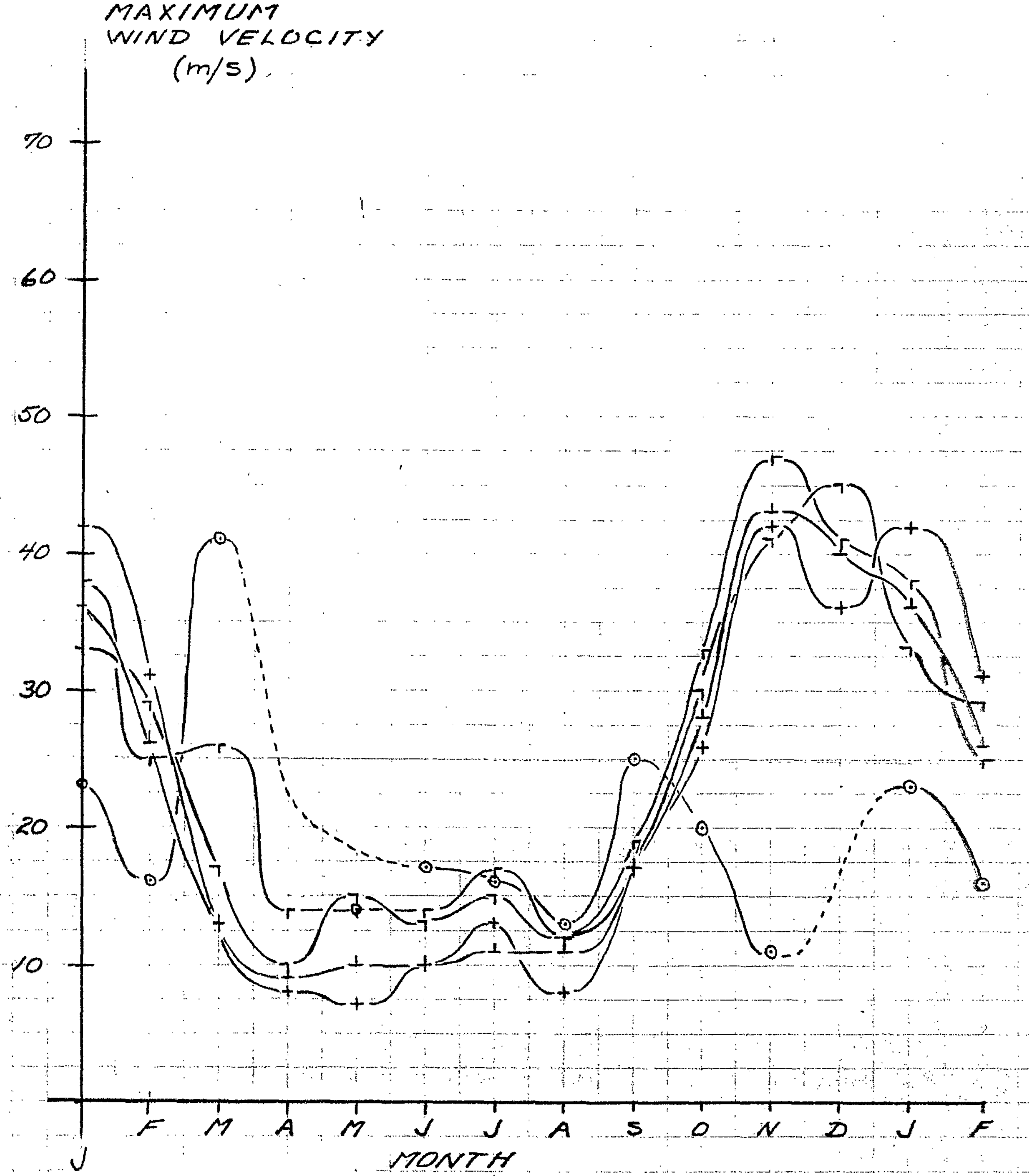
MEAN WIND VELOCITY
VS
MONTH OF YEAR FOR
TROUT LAKE

FIG. C.4



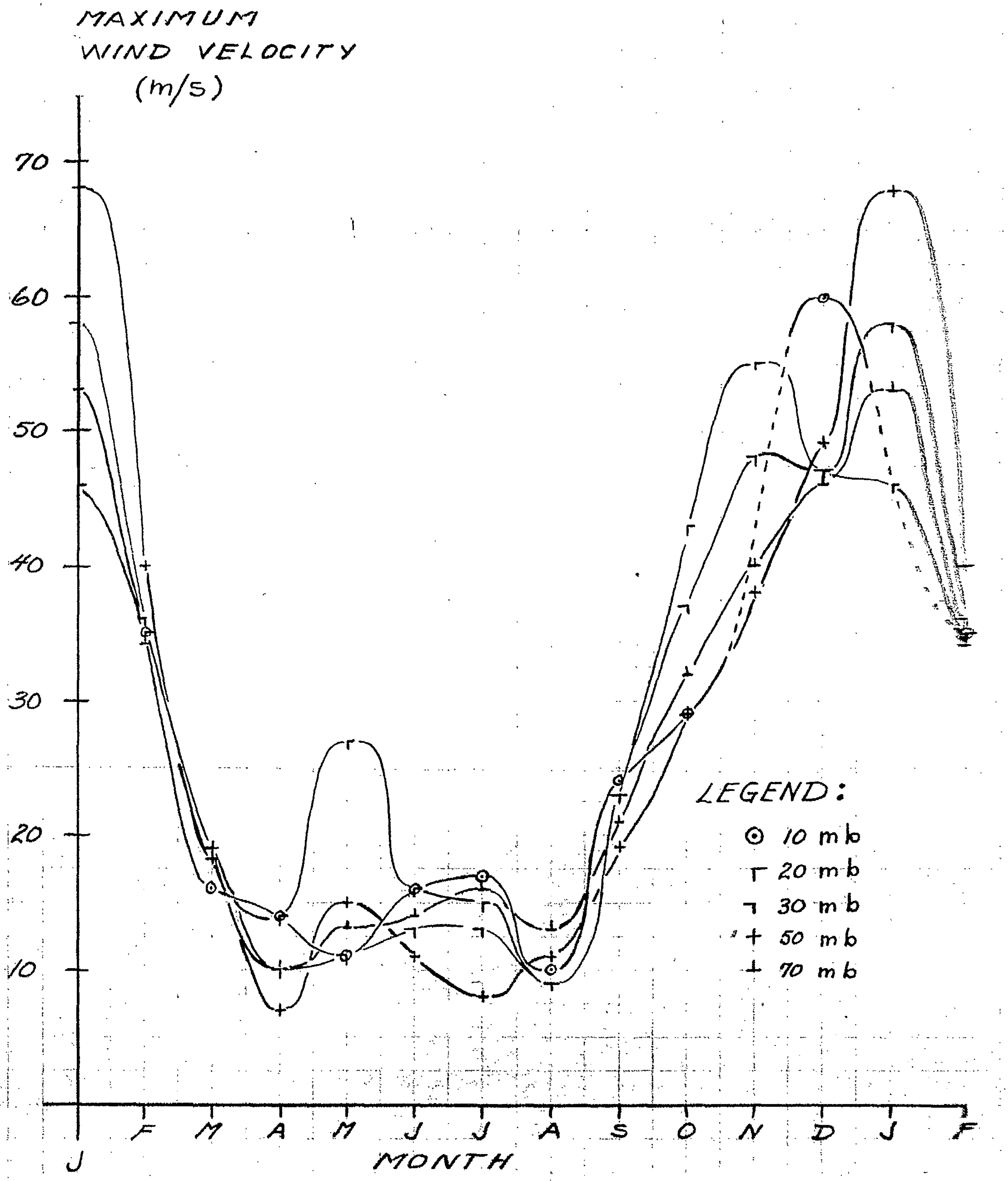
MAXIMUM WIND VELOCITY
VS
MONTH OF YEAR FOR
CHURCHILL

FIG. C.5



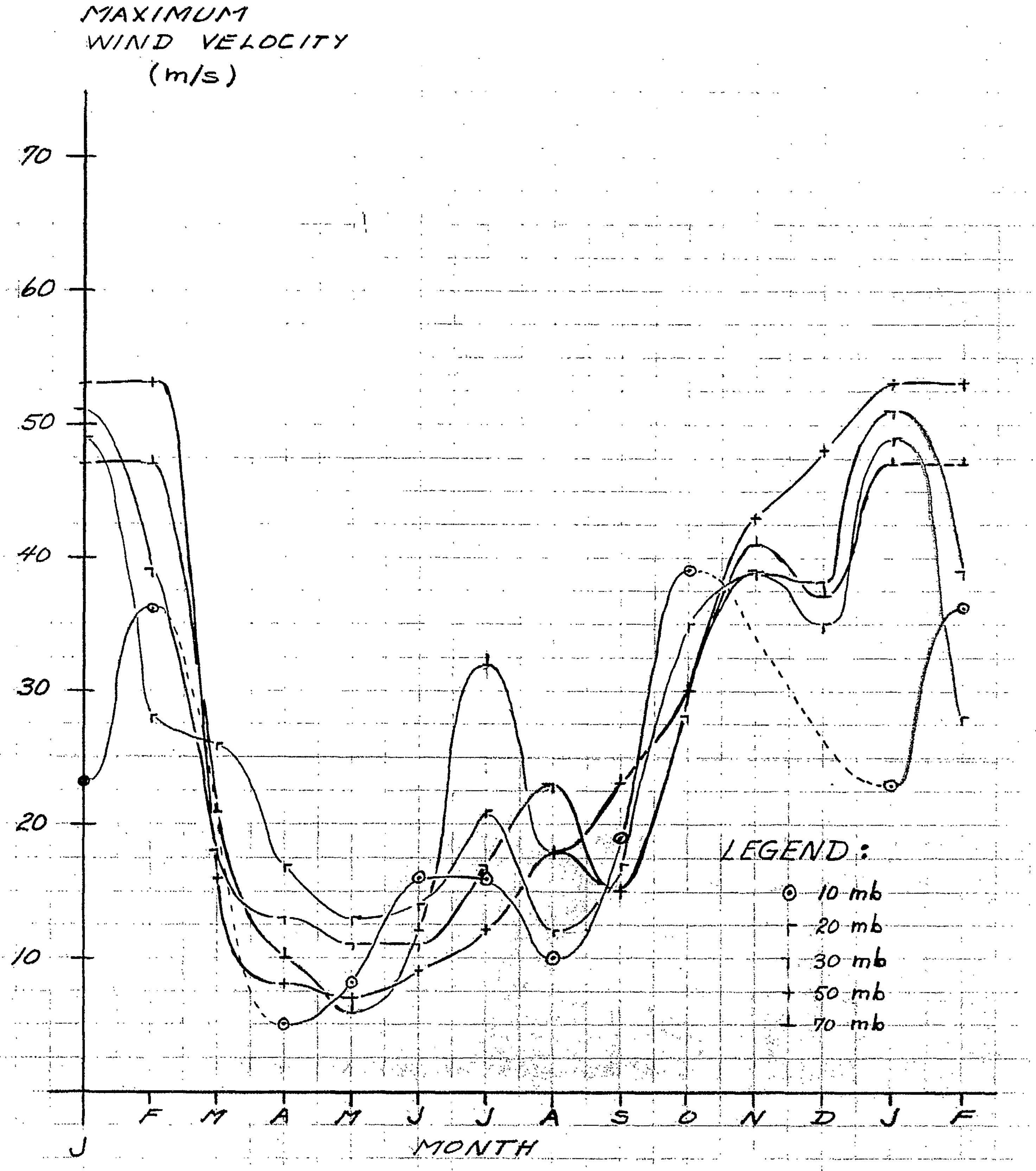
MAXIMUM WIND VELOCITY
VS
MONTH OF YEAR FOR
EDMONTON

FIG. C.6



MAXIMUM WIND VELOCITY
VS
MONTH OF YEAR FOR
FORT SMITH

FIG. C.7



MAXIMUM WIND VELOCITY
VS
MONTH OF YEAR FOR
TROUT LAKE

FIG. C.8

ALT mb	VALUE	LOC	Mar WIND VEL/deg mps	Mar V/deg σ	Apr WIND mps/deg	Apr σ	May WIND mps/deg	May σ	June WIND mps/deg	June σ	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug σ	Sept WIND mps/deg	Sept σ	Oct WIND mps/deg	Oct σ	Nov WIND mps/deg	Nov σ	Dec WIND mps/deg	Dec σ	Jan WIND mps/deg	Jan σ	Feb WIND mps/deg	Feb σ
10	MAX	CH																								
		EDM																								
		FTS																								
		TL																								
	MEAN	CH	20/043	7/33			10/090	4/17	10/068	4.5/23	10/024	2.3/22	6/107	3.4/58	9/212	7/87	19/293	6/34	21/276	5/27			17/166	7/132	30/294	7/23
		EDM	23/074	12/13			9/023	5/11	13/090	3/3	11/020	5/13	4/198	3/101	9/240	2/89	12/231	6/102	17/163	1/100			16/043	[illegible]	11/249	4/124
		FTS	15/092	1/6	9/116	6/13	6/146	4/109	11/083	5/2	11/095	5/18	6/166	4/125	14/277	11/7	16/298	7/33			42/338	19/1			22/360	2/1
		TL			4/103	2/17	6/047	2/32	13/091	4/6	13/090	4/8	7/098	3/40	11/292	3/21	25/289	15/25					12/224	11/17	23/333	13/15
20	MAX	CH																								
		EDM																								
		FTS																								
		TL																								
	MEAN	CH	14/047	6/44	7/182	6/24	7/124	5/68	10/071	8/29	3/127	6/92	5/050	4/32	8/251	7/69	17/278	12/49	22/287	17/42	26/347	15/12	24/236	27/131	24/30[illegible]	17/29
		EDM	17/050	10/23	8/197	7/10[illegible]	7/084	5/49	10/083	4/12	10/020	6/20	6/053	5/36	8/222	7/102	15/214	13/144	12/264	15/92	19/242	16/124	14/270	15/34	18/160	9/129
		FTS	13/078	7/19	8/127	7/29	8/129	11/120	10/057	5/24	2/077	5/71	5/127	4/94	8/227	8/15	21/296	16/27	27/293	19/47	29/323	15/19	18/235	17/113	17/223	14/130
		TL	16/062	11/5	10/069	3/34	8/070	6/29	8/093	3/6	11/077	6/15	6/112	5/77	9/264	7/78	9/94	12/117	19/206	14/75	25/302	12/21	19/252	18/110	14/320	12/12
30	MAX	CH																								
		EDM																								
		FTS																								
		TL																								
	MEAN	CH	10/188	7/162	6/187	5/79	5/104	4/86	7/084	6/26	5/065	4/47	4/163	4/118	8/246	7/112	15/241	12/114	22/241	17/77	26/309	15/23	23/233	27/132	22/310	16/34
		EDM	12/045	6/28	6/207	4/108	7/082	6/12	9/081	4/13	8/104	5/32	5/096	5/108	6/255	5/47	13/215	12/135	17/298	13/38	20/230	16/157	13/321	13/25	15/229	12/132
		FTS	12/037	7/32	6/121	5/19	6/131	5/122	8/055	6/37	6/021	5/41	3/145	3/132	10/289	8/30	18/295	14/27	24/257	17/86	27/297	15/17	21/302	22/29	18/247	14/97
		TL	11/079	7/12	8/228	6/131	2/228	6/131	7/079	3/20	8/132	6/86	7/158	2/115	7/243	6/114	13/219	10/124	15/190	18/130	21/213	11/116	18/193	20/117	17/254	15/129
50	MAX	CH																								
		EDM																								
		FTS																								
		TL																								
	MEAN	CH	10/336	9/8	4/53	4/53	5/112	5/142	5/180	3.6/145	4/167	3.8/130	4.6/156	5/156	11/289	8/23	14/287	10/42	19/279	14/25	25/311	17/19	21/277	21/27	23/239	22/135
		EDM	7/013	7/13	5/154	4/83	4/119	3/124	6/154	3.3/119	5/147	5/137	3.5/106	4/112	9/245	7/92	13/272	11/48	16/285	14/63	17/254	14/108	16/309	16/24	13/171	12/131
		FTS	10/219	9/139	4/177	3/167	6/246	6/84	6/123	4/125	4/073	4/58	4/104	4/139	11/287	7/19	16/277	12/37	21/280	15/54	26/304	19/15	24/213	21/131	18/322	15/36
		TL	9/213	8/88	4/040	4/49	4/090	3/73	5/114	4/136	5/053	5/38	6/247	6/115	8/187	6/119	13/270	11/74	16/209	16/106	21/251	18/108	20/279	20/19	20/235	21/137
70	MAX	CH																								
		EDM																								
		FTS																								
		TL																								
	MEAN	CH	14/287	12.5/57	5/260	4/30	5/184	4/135	6/114	5/133	6/185	5/133	8/297	7/27	15/310	10/21	13/431	11/489	18/277	14/48	24/248	17/110	21/266	21/32	22/314	18/21
		EDM	7/288	6/40	5/216	4/16	6/203	4/71	5/100	5/100	5/172	5/103	5/191	5/139	10/286	7/25	13/265	12/28	18/294	15/42	17/292	15/15	16/292	13/25	14/272	11/20
		FTS	10/333	9/6	6/131	5/73	6/242	5/86	6/176	5/132	5/155	6/138	6/184	5/124	11/288	8/17	17/285	13/28	21/280	13/37	23/296	16/13	20/222	20/128	17/156	13/125
		TL	11/156	11/156	6/188	5/96	6/265	5/36	5/106	5/130	9/129	11/136	7/315	6/24	12/312	7/25	14/241	10/102	19/269	18/26	19/214	14/112	20/276	17/22	18/311	17/41

CH - CHURCHILL FTS - FORT SMITH
EDM - EDMONTON TL - TROUT LAKE

MEAN WIND VELOCITIES AND STANDARD DEVIATION
FOR UPPER AIR STATION

TABLE C.1

ALT mb	VALUE	LOC	Mar		Apr		May		June		July		Aug		Sept		Oct		Nov		Dec		Jan		Feb	
			WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP
			vel/deg mps	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C
10	MAX	CH	27/010	-41			15/058	-31	14/045	-29	13/069	-27	9/088	-31	19/275	-36	25/276	-43	26/302	-58			26/164	-40	37/271	-42
		EDM	41/087	-41		-40	14/093	-28	17/086	-26	16/083	-24	13/084	-28	25/268	-32	20/260	-31	11/262	-46		-53	23/077	-38	16/322	-39
		FTS	16/[illegible]	-39	14/098	-38	11/215	-27	16/054	-26	17/023	-22	10/186	-30	24/250	-38	29/281	-49		-43	60/337	-54		-35	35/310	-40
		TL		-41	5/086	-40	8/090	-32	16/085	-26	16/098	-25	10/101	-27	19/271	-34	39/264	-31					23/267	-39	36/345	-47
	MEAN	CH	20/043	-52			10/090		10/068		10/084		6/107		9/212		19/293		21/276				17/166		30/294	
		EDM	29/074				9/083																			
		FTS																								
		TL																								
20	MAX	CH	20/003	-48	13/098	-47	13/090	-38	21/092	-36	16/083	-37	11/074	-38	19/270	-42	37/265	-51	49/305	-49	41/335	-55	69/302	-42	45/329	-50
		EDM	26/072	-42	14/093	-47	14/088	-38	14/086	-37	17/140	-38	12/084	-40	19/265	-35	33/309	-47	47/322	-48	41/327	-49	38/310	-41	25/136	-45
		FTS	19/059	-41	14/098	-47	27/208	-41	16/068	-36	15/078	-33	9/086	-32	23/294	-43	43/287	-50	55/299	-51	47/323	-49	46/294	-32	35/173	-44
		TL	26/064	-47	17/102	-48	13/086	-41	14/089	-38	21/045	-36	12/236	-39	17/269	-39	35/281	-47	39/265	-47	35/328	-53	49/303	-44	28/317	-48
	MEAN	CH	14/047																							
		EDM																								
		FTS																								
		TL																								
30	MAX	CH	17/350	-47	10/108	-47	10/088	-45	17/099	-39	10/060	-41	10/213	-41	19/283	-44	34/271	-50	39/304	-50	48/313	-51	69/331	-42	47/311	-50
		EDM	17/072	-45	10/099	-49	15/084	-47	13/079	-43	15/083	-42	12/085	-42	17/275	-46	30/299	-49	41/311	-49	45/342	-49	33/309	-44	29/289	-47
		FTS	19/005	-43	10/102	-47	11/211	-44	13/064	-41	13/097	-37	9/231	-41	23/310	-41	37/293	-50	48/311	-48	47/307	-49	58/299	-42	36/324	-49
		TL	18/067	-47	13/097	-49	11/076	-46	11/070	-43	17/324	-41	23/086	-42	15/265	-45	28/290	-50	39/264	-49	38/273	-51	51/306	-44	39/292	-52
	MEAN	CH	10/188																							
		EDM																								
		FTS																								
		TL																								
50	MAX	CH	19/343	-43	7/105	-48	9/224	-46	9/206	-43	10/245	-43	13/311	-43	23/292	-47	26/281	-49	35/300	-48	49/298	-48	57/278	-45	56/308	-51
		EDM	13/026	-48	8/236	-49	7/199	-49	10/089	-46	13/176	-46	8/212	-47	18/212	-47	26/293	-49	42/312	-49	36/298	-49	42/292	-45	31/301	-51
		FTS	18/359	-43	7/343	-47	15/208	-46	11/057	-43	8/107	-44	11/205	-44	19/296	-47	29/276	-48	38/315	-49	49/291	-47	68/322	-42	40/316	-51
		TL	16/301	-44	8/098	-49	7/085	-49	9/344	-44	12/090	-43	18/305	-45	15/302	-47	30/288	-51	43/288	-50	48/274	-48	53/307	-47	53/278	-49
	MEAN	CH	10/336		4/053		5/112		6/142		4/167		5/156		11/289		14/287		19/279		25/311		21/277		23/239	
		EDM	7/013		37/154		4/119		3/124		5/147		4/106		9/245		13/272		16/285		17/254		16/309		13/171	
		FTS	10/219		4/177		6/246		6/084		4/073		4/104		11/287		16/277		21/280		26/304		24/213		18/322	
		TL	9/213		4/040		4/090		3/073		5/053		6/247		8/187		13/270		16/209		21/251		20/279		20/235	
70	MAX	CH	26/343	-42	8/290	-47	9/310	-47	12/167	-44	14/218	-44	17/308	-43	35/314	-47	25/282	-48	35/294	-48	45/300	-47	57/269	-47	51/308	-50
		EDM	13/327	-48	9/231	-49	10/253	-49	10/076	-47	11/250	-46	11/262	-47	17/293	-48	28/285	-49	43/306	-47	40/300	-50	36/306	-46	26/293	-51
		FTS	19/339	-46	10/204	-48	13/298	-47	14/046	-46	16/284	-45	13/291	-45	21/297	-48	32/288	-48	40/312	-49	46/293	-48	53/307	-42	34/280	-49
		TL	21/312	-45	10/284	-49	12/279	-48	12/324	-46	32/314	-46	18/282	-47	23/308	-46	30/281	-50	41/256	-49	37/243	-47	47/305	-46	47/276	-50
	MEAN	CH	14/287																							
		EDM																								
		FTS																								
		TL																								

CH - CHURCHILL
EDM - EDMONTON
FTS - FORT SMITH
TL - TROUT LAKE

TABLE OF MAXIMUM WIND VELOCITIES FOR CANADIAN UPPER AIR STATIONS

TABLE C.2

ALT mb	TIME GMT	VALUE	Mar WIND VEL/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX													12/284	-36			26/302	-58						
		MEAN											00/000	-35		-40		--		-63						
		MIN													3/234	-44			16/249	-68						
	12	MAX									12/047	-31	7/107	-35	7/286	-43	25/254	-47	23/294	-55						
		MEAN										-33		-39		-44		-50		-61						
		MIN									8/104	-36	2/286	-45	6/240	-44	10/260	-52	9/268	-66						
20	00	MAX									12/078	-39	11/152	-40	16/301	-43	16/266	-51	32/290	-57						
		MEAN										-40		-43		-48		-55		-59		-62				
		MIN									3/331	-42	0/000	-46	4/012	-53	5/242	-59	15/306	-61						
	12	MAX									12/088	-38	11/047	-40	10/338	-42	19/270	-52	34/277	-50		-67				
		MEAN										-41		-43		-49		-55		-58		-68				
		MIN									4/102	-43	0/000	-49	2/299	-54	6/194	-60	6/200	-67	—	-70				
30	00	MAX									10/008	-42	10/298	-41	13/323	-46	18/255	-50	35/290	-50	27/322	-57				
		MEAN									4/056	-44	2/13	-45		-52		-55		-58		-62				
		MIN									0/000	-46	0/000	-47	5/281	-58	0/000	-59	2/186	-64	10/303	-69				
	12	MAX									10/021	-41	8/293	-43	19/308	-46	15/297	-50	37/294	-51	17/328	-61				
		MEAN										-44	2/40	-46	7/303	-51		-55		-56		-65				
		MIN									3/045	-47	0/050	-50	3/335	-57	4/164	-59	2/256	-59	14/34	-71				
50	00	MAX									10/331	-44	10/299	-45	23/320	-48	23/256	-49	31/287	-48	42/296	-55				
		MEAN									3/013	-47	3/322	-47	11/305	-53	13/278	-55	13/277	-55		-63				
		MIN									2/024	-49	0/000	-51	6/302	-58	8/237	-59	2/275	-59	10/340	-75				
	12	MAX									9/303	-43	13/311	-43	21/320	-48	18/254	-50	30/288	-51	35/304	-53				
		MEAN									2/044	-47	3/334	-48	12/304	-53	12/281	-54	15/274	-56		-62				
		MIN									1/140	-50	2/296	-52	6/308	-59	7/217	-58	3/281	-59	7/331	-74				
70	00	MAX									12/316	-45	13/305	-46	21/328	-48	25/249	-49	33/279	-48	44/293	-50				
		MEAN										-48		-48		-52		-53		-53		-61				
		MIN									1/072	-50	3/298	-52	9/306	-57	6/299	-58	2/295	-56	9/284	-70				
	12	MAX									8/300	-45	17/320	-43	35/340	-49	24/323	-48	31/279	-49	33/295	-51				
		MEAN										-48		-48		-52		-53		-54		-62				
		MIN									2/330	-51	4/309	-52	9/312	-57	4/240	-56	3/255	-57	12/261	-73				

TABLE C.3 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR CHURCHILL UPPER AIR STATION 1963

ALT	TIME	VALUE	Mar		Apr		May		June		July		Aug		Sept		Oct		Nov		Dec		Jan		Feb	
mb	GMT		WIND vel/deg mps	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C
10	00	MAX					12/083	-31	13/094	-29	11/099	-27	9/055	-31	19/258	-37		-55		-60		-62	26/319	-61	24/270	-42
		MEAN					7/080	-39	8/081	-34	10/089	-31	3/056	-35	10/260	-41		-57		-61	-	-70	21/325	-63	23/[illegible]	-57
		MIN					4/068	-48	5/091	-41	8/092	-35	0/000	-39	8/228	-49		-62		-63		-77	17/335	-69	23/317	-75
	12	MAX					10/088	-32	14/085	-29	13/091	-28	7/060	-32	19/266	-37	23/288	-46		-61		-69	21/276	-61	37/271	-52
		MEAN					9/080	-39	10/079	-34	12/094	-32	3/075	-35	11/266	-41	17/298	-55		-62		-72	14/303	-65	32/271	-58
		MIN					7/067	-45	8/072	-37	10/097	-37	1/123	-41	1/065	-46	13/352	-59		-64		-77	12/272	-71	29/266	-70
20	00	MAX					11/090	-38	10/079	-39	14/083	-37	8/054	-40	19/268	-43	37/288	-58	49/326	-58	41/335	-58	20/278	-56	36/339	-50
		MEAN					6/078	-46	7/072	-42	7/084	-40	2/072	-43	10/276	-50	16/304	-61	16/302	-64	24/338	-62	10/298	-62	20/313	-60
		MIN					2/074	-50	4/037	-45	4/085	-42	0/000	-47	2/144	-57	12/335	-68	2/326	-72	11/359	-69	6/291	-67	6/275	-71
	12	MAX					10/096	-41	12/091	-38	16/098	-38	8/079	-38	16/267	-45	25/272	-52	38/315	-56	41/327	-55	16/280	-57	29/322	-53
		MEAN					6/081	-46	8/080	-41	8/087	-40	3/080	-44	9/277	-50	13/303	-60	15/302	-63	23/343	-62	9/209	-63	18/307	-60
		MIN					3/114	-50	4/021	-44	6/095	-43	0/000	-47	1/104	-54	9/354	-68	10/254	-71	11/359	-68	6/310	-67	4/269	-72
30	00	MAX					6/120	-45	7/092	-41	7/096	-41	7/049	-43	17/269	-48	32/289	-54	39/328	-53	38/328	-51	17/336	-56	23/326	-53
		MEAN					3/061	-48	5/069	-45	4/076	-43	2/050	-47	9/286	-52	14/305	-60	16/294	-62	18/335	-58	9/305	-61	15/310	-60
		MIN					0/000	-50	2/053	-48	3/080	-45	1/239	-50	2/303	-56	9/329	-67	3/100	-71	5/333	-61	5/260	-65	7/341	-67
	12	MAX					7/084	-45	9/074	-42	8/097	-41	6/275	-44	14/282	-48	34/289	-54	32/304	-54	38/335	-52	16/278	-56	26/346	-52
		MEAN					5/075	-48	6/071	-44	5/081	-44	2/071	-47	8/283	-53	13/301	-59	15/290	-62	18/336	-58	9/291	-62	15/305	-60
		MIN					2/148	-51	3/064	-47	4/046	-46	1/095	-51	0/000	-55	7/352	-67	4/053	-68	6/322	-63	6/277	-66	8/253	-69
50	00	MAX					9/348	-47	9/349	-43	4/346	-43	7/330	-47	16/271	-49	26/291	-52	30/314	-52	29/312	-48	16/247	-53	28/336	-52
		MEAN					02/343	-49	3/026	-46	1/002	-47	2/311	-49	10/295	-53	12/304	-58	14/292	-59	13/330	-54	8/279	-58	11/306	-58
		MIN					01/069	-50	1/294	-49	0/000	-49	0/000	-51	2/302	-57	4/349	-65	3/334	-66	5/011	-59	7/269	-63	7/008	-65
	12	MAX					8/103	-46	7/092	-43	4/080	-45	8/331	-47	14/297	-48	25/294	-52	32/321	-52	27/318	-49	17/238	-52	21/335	-52
		MEAN					2/025	-49	4/039	-46	2/028	-47	2/353	-49	9/294	-53	12/303	-58	13/292	-59	13/331	-54	8/275	-58	11/302	-58
		MIN					0/000	-51	2/031	-49	0/000	-50	0/000	-51	3/317	-56	5/345	-65	3/246	-64	4/338	-62	5/271	-63	7/340	-63
70	00	MAX					8/287	-48	12/329	-44	8/307	-45	12/310	-47	17/298	-48	24/305	-51	24/263	-49	25/321	-47	15/241	-50	25/335	-51
		MEAN					4/300	-49	4/341	-46	4/307	-48	5/292	-50	12/294	-52	13/303	-56	12/289	-57	11/324	-52	8/271	-55	10/303	-56
		MIN					1/113	-53	1/303	-50	2/216	-50	2/239	-53	6/284	-55	2/016	-64	1/176	-64	2/004	-58	2/242	-62	7/347	-61
	12	MAX					8/345	-47	9/332	-44	7/205	-45	14/320	-49	19/318	-48	23/296	-51	28/321	-51	27/321	-48	16/228	-51	19/337	-51
		MEAN					3/309	-49	3/357	-47	3/314	-48	4/307	-51	12/294	-53	12/302	-56	13/289	-57	11/326	-52	8/269	-56	9/307	-57
		MIN					2/290	-53	0/000	-49	1/049	-51	1/244	-53	6/285	-56	0/000	-63	4/322	-62	5/044	-60	3/258	-63	7/310	-62

TABLE C.4 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR CHURCHILL UPPER AIR STATION 1969

ALT mb	TIME GMT	VALUE	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX		-43		-43		-32		-27		-29		-32		-38		-54		-48				-52		
		MEAN		-55		-43	8/112	-37		-33	11/079	-32	11/081	-34		-43		-58		-54				-57		-64
		MIN		-63		-44		-43		-37		-36		-38		-49		-64		-64				-62		
	12	MAX	27/010	-41		-40	15/095	-36		-28		-30	9/102	-32		-40	22/286	-43		-47			20/009	-40		-57
		MEAN	15/052	-47	12/092	-45	12/100	-39		-32		-34	8/098	-36		-40	20/257	-55		-54			11/022	-46	31/307	-58
		MIN	13/076	-61		-48	10/116	-43		-36		-38	7/093	-45		-41	20/319	-62		-69			8/062	-62		-61
20	00	MAX	15/031	-49	13/098	-48	12/095	-41	12/075	-38	10/059	-38	7/080	-39	10/242	-44	20/257	-52	31/293	-49		-59	32/301	-45	37/335	-57
		MEAN	10/063	-51	7/088	-50	5/077	-46	8/085	-42	4/080	-41	2/082	-42	5/267	-49	14/276	-57	22/258	-57	40/278	-65	29/277	-50	27/323	-61
		MIN	8/090	-57	1/265	-52	1/240	-51	2/080	-46	2/083	-46	1/262	-45	2/290	-54	8/304	-62	12/284	-70		-72	27/281	-58	19/300	-67
	12	MAX	20/003	-48	10/062	-47	13/090	-43	21/093	-36	13/073	-39	8/095	-39	8/255	-44	28/307	-51	27/297	-50		-60	69/325	-42	45/319	-56
		MEAN	10/045	-51	4/081	-50	5/088	-47	10/086	-41	8/082	-41	3/099	-43	6/265	-49	13/293	-58	20/275	-58		-66	18/321	-52	27/315	-61
		MIN	8/069	-56	2/070	-52	1/136	-51	7/097	-43	1/097	-43	1/081	-48	3/255	-54	5/276	-62	12/281	-73		-70	2/009	-67	9/277	-68
30	00	MAX	16/350	-47	16/166	-47	9/095	-45	10/089	-39	9/067	-42	5/291	-43	8/272	-46	20/283	-53	39/291	-50	48/282	-56	56/304	-43	47/276	-50
		MEAN	5/041	-50	4/079	-51	4/074	-49	6/084	-45	4/074	-44	4/020	-45	5/280	-52	11/279	-57	19/260	-58	36/292	-63	25/293	-57	26/312	-59
		MIN	3/026	-53	1/265	-53	1/240	-53	1/083	-48	1/130	-47	1/285	-48	3/273	-56	6/316	-64	12/297	-74	26/276	-67	9/301	-63	14/301	-65
	12	MAX	17/350	-47	8/065	-48	10/091	-45	17/124	-40	10/074	-41	5/077	-42	7/262	-44	26/300	-53	29/245	-57	39/303	-55	75/324	-43	43/339	-53
		MEAN	7/041	-49	3/071	-51	5/080	-49	2/092	-45	5/079	-44	2/087	-46	5/275	-50	10/286	-57	17/268	-58	34/293	-63	24/307	-52	25/313	-60
		MIN	4/075	-55	1/320	-53	1/136	-53	4/077	-48	1/352	-46	1/102	-48	2/294	-56	4/280	-62	13/258	-73	26/268	-67	5/325	-63	8/293	-65
50	00	MAX	19/343	-47	7/105	-48	8/100	-48	6/040	-45	7/050	-44	7/292	-46	13/280	-48	21/278	-52	35/293	-49	49/286	-53	56/315	-45	56/279	-51
		MEAN	5/352	-49	2/046	-51	2/040	-51	3/79	-47	3/025	-47	1/282	-48	6/294	-53	9/281	-56	18/262	-58	29/290	-59	24/296	-52	20/316	-58
		MIN	2/092	-53	1/287	-54	1/236	-54	1/086	-50	1/130	-50	1/100	-50	2/289	-56	1/319	-60	10/254	-72	18/300	-65	7/290	-61	3/065	-62
	12	MAX	18/349	-43	6/051	-49	9/099	-48	7/063	-45	8/057	-44	6/310	-45	16/286	-47	24/295	-52	33/263	-51	45/265	-54	57/313	-45	37/339	-51
		MEAN	4/006	-49	2/035	-51	3/058	-51	4/085	-47	3/041	-47	1/337	-48	5/292	-52	10/280	-56	18/265	-58	30/293	-59	26/297	-53	22/318	-58
		MIN	1/328	-53	0/000	-54	0/000	-54	1/012	-50	1/360	-50	0/000	-52	1/250	-57	4/281	-60	10/263	-72	19/291	-62	6/284	-61	1/332	-65
70	00	MAX	22/341	-43	8/290	-47	9/275	-48	7/353	-45	11/295	-45	10/274	-45	16/279	-49	22/307	-50	35/282	-57	43/278	-50	53/315	-47	51/281	-50
		MEAN	6/324	-48	2/330	-51	2/331	-51	1/015	-49	5/309	-48	4/274	-48	8/295	-52	11/275	-55	18/268	-58	27/291	-57	25/296	-53	20/313	-57
		MIN	1/358	-51	1/230	-55	0/000	-54	1/122	-52	3/331	-51	1/321	-52	5/311	-57	1/214	-59	10/282	-70	15/299	-63	9/282	-61	5/331	-66
	12	MAX	26/343	-42	7/295	-47	8/302	-47	9/005	-46	14/031	-44	12/284	-46	19/284	-48	22/291	-50	32/287	-49	45/288	-50	57/310	-47	35/281	-51
		MEAN	6/328	-48	2/332	-51	2/359	-51	2/047	-49	5/325	-48	4/276	-49	8/298	-52	11/275	-54	17/267	-57	27/292	-57	26/298	-53	21/316	-57
		MIN	1/230	-51	1/196	-55	1/132	-54	1/355	-51	2/328	-51	1/316	-53	3/327	-56	1/150	-50	9/310	-70	19/313	-61	9/262	-64	5/300	-64

TABLE C.5 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR CHURCHILL UPPER AIR STATION 1975

ALT mb	TIME GMT	VALUE	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX														-35			11/262	-51						
		MEAN											6/280	-38	9/277	-41	6/034	-53		-56						
		MIN														-44			10/063	-60						
	12	MAX										-36	4/156	-37	12/272	-36										
		MEAN									4/108	-38		-39		-42										
		MIN										-41	2/246	-42	6/237	-49										
20	00	MAX									17/140	-39	7/091	-40	13/284	-44	15/281	-48	12/284	-51	41/344	-57				
		MEAN										-41		-43		-49		-54		-54		-63				
		MIN									3/098	-44	1/121	-46	0/000	-56	2/249	-56	8/245	-59	18/027	-67				
	12	MAX									14/090	-38	12/084	-41	13/288	-43	17/284	-50	18/316	-52						
		MEAN										-41		-45		-51		-55		-56		-57				
		MIN									7/062	-45	1/032	-48	2/330	-57	2/023	-59	7/284	-61						
30	00	MAX									10/095	-44	7/061	-42	15/273	-47	13/285	-50	26/294	-52	36/346	-55				
		MEAN									6/092	-45	2/61	-46		-53		-55		-55		-63				
		MIN									2/170	-48	1/320	-49	1/316	-57	3/234	-58	6/238	-63	10/018	-72				
	12	MAX									15/077	-42	12/060	-44	10/335	-48	13/294	-50	21/307	-53	34/344	-55				
		MEAN									7/088	-45	2/047	-47		-54		-56		-56		-64				
		MIN									3/064	-48	1/127	-51	1/157	-58	2/023	-59	4/295	-62	17/327	-73				
50	00	MAX									9/220	-46	8/264	-48	18/086	-51	23/264	-52	17/307	-53	32/298	-51				
		MEAN									3/113	-48	2/335	-51		-54		-55		-55		-62				
		MIN									1/238	-50	0/000	-52	4/279	-57	4/167	-58	2/253	-60	7/320	-69				
	12	MAX									13/175	-46	8/059	-48	14/236	-52	20/281	-53	18/289	-52	35/296	-51				
		MEAN									4/099	-47	2/ 4	-52		-56		-56		-55		-62				
		MIN									1/353	-51	1/249	-54	5/262	-59	2/172	-60	2/168	-60	6/310	-70				
70	00	MAX									11/281	-48	8/330	-47	12/248	-50	19/245	-51	18/282	-50	23/342	-51				
		MEAN										-49		-52		-55		-54		-54		-60				
		MIN									2/181	-51	2/244	-53	6/289	-59	3/220	-59	4/164	-60	4/306	-68				
	12	MAX									11/189	-46	11/277	-48	15/336	-52	21/262	-50	17/281	-51	33/296	-51				
		MEAN										-50		-53		-56		-55		-54		-61				
		MIN									1/205	-53	1/357	-54	6/312	-60	4/178	-58	3/340	-59	7/290	-69				

TABLE C.6 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR EDMONTON UPPER AIR STATION 1963

ALT mb	TIME GMT	VALUE	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C
10	00	MAX					14/073	-28		-26		-24	13/084	-23
		MEAN					10/089	-33	10/94	-29		-29	6/083	-32
		MIN					4/072	-38		-35		-31	2/144	-38
	12	MAX						-29	17/086	-26	16/083	-27	11/083	-30
		MEAN						-34	14/088	-30	14/081	-30	7/080	-35
		MIN						-40	12/091	-35	13/078	-35	3/080	-40
20	00	MAX					10/97	-38	11/104	-37	13/076	-38	10/075	-40
		MEAN					6/91	-46	9/091	-42	9/087	-40	6/083	-42
		MIN					2/008	-50	7/092	-45	6/077	-42	0/000	-45
	12	MAX					11/097	-42	13/099	-36	15/095	-38	10/073	-41
		MEAN					8/091	-47	10/087	-42	10/088	-41	5/080	-44
		MIN					5/070	-50	7/066	-47	7/098	-44	2/184	-48
30	00	MAX					8/102	-47	13/096	-43	8/096	-43	7/102	-43
		MEAN					3/078	-49	7/084	-46	6/089	-45	3/077	-47
		MIN					1/074	-52	5/082	-50	4/116	-47	1/167	-50
	12	MAX					9/101	-48	11/090	-44	10/081	-44	7/083	-46
		MEAN					5/084	-50	8/082	-47	7/086	-46	4/079	-48
		MIN					2/036	-53	6/063	-49	5/026	-47	0/000	-50
50	00	MAX					7/326	-50	7/073	-46	5/121	-47	7/145	-48
		MEAN					3/324	-52	3/054	-50	1/106	-49	1/192	-50
		MIN					1/006	-55	1/117	-52	0/000	-51	1/310	-51
	12	MAX					6/339	-51	8/073	-46	5/287	-47	4/196	-48
		MEAN					2/334	-53	5/058	-50	2/088	-50	1/183	-51
		MIN					0/000	-55	2/358	-54	0/000	-52	0/000	-53
70	00	MAX					10/315	-50	7/333	-48	8/295	-48	9/211	-49
		MEAN					6/295	-53	3/355	-51	4/246	-50	5/237	-51
		MIN					2/144	-55	1/249	-54	0/000	-52	1/012	-54
	12	MAX					9/299	-51	9/018	-48	10/278	-49	10/258	-50
		MEAN					5/290	-53	4/011	-52	3/259	-51	4/238	-53
		MIN					3/261	-55	2/149	-55	0/000	-53	0/000	-55

ALT mb	TIME GMT	VALUE	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX	25/268	-33	20/267	-45				-48			14/306	-39
		MEAN	14/270	-39	18/311	-50		-61		-58		-68	8/329	-52
		MIN	4/322	-46	8/332	-57				-78			6/034	-64
	12	MAX	17/281	-34	16/323	-48				-51				-45
		MEAN	6/270	-41	13/300	-53				-59		-56		-53
		MIN	3/337	-46	12/330	-57				-73				-68
20	00	MAX	19/265	-35	33/291	-50	19/284	-54	31/357	-52	15/285	-57	22/277	-45
		MEAN	8/280	-48	12/305	-57	8/317	-59	13/004	-55	7/294	-61	9/320	-55
		MIN	1/220	-52	6/001	-69	5/064	-66	3/131	-63	4/016	-63	2/053	-64
	12	MAX	14/265	-46	25/294	-52	26/321	-52	28/354	-49	8/009	-58	23/260	-47
		MEAN	7/284	-50	8/310	-58	16/288	-59	12/012	-55	6/003	-62	10/322	-57
		MIN	2/009	-55	3/356	-71	6/246	-69	2/119	-60	2/331	-66	7/030	-65
30	00	MAX	17/265	-46	25/285	-52	18/326	-54	21/355	-49	15/279	-58	23/004	-49
		MEAN	7/282	-51	9/304	-58	10/306	-57	8/005	-53	7/295	-60	7/317	-55
		MIN	2/106	-54	3/318	-70	5/263	-66	1/176	-57	3/233	-64	4/333	-61
	12	MAX	13/277	-48	30/289	-52	19/297	-53	19/352	-49	14/275	-58	21/002	-50
		MEAN	6/281	-53	8/304	-58	10/293	-59	7/008	-53	6/295	-60	7/330	-57
		MIN	1/246	-57	3/340	-71	5/333	-67	0/000	-56	2/298	-65	4/321	-63
50	00	MAX	15/273	-50	24/288	-51	23/323	-53	11/319	-50	16/271	-52	17/311	-51
		MEAN	7/274	-53	10/301	-57	10/294	-57	5/343	-52	9/276	-58	6/301	-56
		MIN	2/03?	-56	1/293	-67	4/262	-63	1/015	-57	5/314	-62	3/058	-59
	12	MAX	15/272	-51	26/299	-52	24/302	-52	14/321	-49	14/273	-55	16/305	-52
		MEAN	7/280	-54	9/300	-58	10/294	-57	5/342	-52	8/280	-58	6/302	-56
		MIN	1/265	-56	3/022	-66	3/359	-62	3/018	-56	5/304	-62	3/351	-60
70	00	MAX	17/270	-51	28/300	-51	31/294	-52	14/294	-50	20/304	-51	22/269	-51
		MEAN	9/268	-54	9/30?	-55	13/292	-56	6/308	-52	11/273	-55	7/285	-55
		MIN	1/291	-57	2/295	-62	7/280	-63	2/334	-57	5/267	-61	3/035	-59
	12	MAX	16/270	-51	24/284	-52	24/293	-52	14/287	-50	18/320	-53	20/258	-52
		MEAN	8/272	-54	8/299	-57	12/285	-57	6/309	-52	11/276	-55	6/287	-55
		MIN	3/151	-57	1/267	-63	6/284	-62	1/273	-59	5/249	-61	2/243	-59

TABLE C.7 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR EDMONTON UPPER AIR STATION 1969

ALT mb	TIME GMT	VALUE	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C
10	00	MAX	41/087	-41		-41		-32	15/088	-28		-30	8/058	-33
		MEAN	34/077	-48		-44	14/090	-39	12/092	-33	14/098	-34	5/057	-37
		MIN	28/063	-60		-50		-44	9/099	-38		-37	2/350	-43
	12	MAX	35/082	-42		-40		-36	9/113	-31		-32	10/082	-33
		MEAN	26/075	-48	2/315	-45	8/079	-41	9/103	-34	11/097	-36	7/066	-38
		MIN	17/061	-53		-51		-47	9/094	-39		-47	5/079	-42
20	00	MAX	22/072	-42	14/093	-47	13/182	-43	13/089	-38	13/083	-40	9/088	-40
		MEAN	12/059	-49	3/086	-50	6/083	-47	10/089	-42	9/089	-42	4/087	-43
		MIN	7/027	-55	1/301	-52	3/073	-52	6/082	-47	6/105	-44	2/005	-47
	12	MAX	26/072	-43	14/089	-49	14/088	-44	14/086	-38	15/090	-40	9/056	-41
		MEAN	13/072	-51	4/080	-52	6/078	-48	11/085	-43	9/089	-43	4/088	-44
		MIN	8/048	-56	2/313	-54	2/144	-51	7/098	-46	4/092	-47	1/023	-47
30	00	MAX	15/082	-46	10/091	-48	10/087	-48	12/097	-44	11/058	-43	7/091	-44
		MEAN	8/062	-50	2/085	-51	4/084	-50	8/089	-46	7/086	-46	2/092	-46
		MIN	6/091	-53	2/089	-54	2/193	-53	5/094	-48	3/043	-48	6/000	-49
	12	MAX	17/072	-45	10/099	-49	15/084	-48	13/061	-44	12/090	-45	6/093	-45
		MEAN	8/064	-52	3/080	-53	5/062	-51	8/083	-47	7/086	-46	2/084	-47
		MIN	6/017	-56	2/315	-55	1/069	-54	5/083	-51	2/095	-48	0/000	-50
50	00	MAX	13/026	-49	8/236	-49	6/052	-49	9/087	-47	9/059	-48	6/228	-47
		MEAN	3/018	-51	1/113	-52	2/075	-53	4/088	-49	3/082	-50	2/252	-49
		MIN	1/191	-54	1/071	-54	1/128	-56	3/061	-52	0/000	-52	1/350	-51
	12	MAX	11/347	-48	6/218	-49	7/071	-51	10/104	-48	10/066	-48	5/222	-47
		MEAN	4/023	-52	1/077	-53	2/058	-53	5/085	-50	4/081	-51	1/275	-50
		MIN	0/000	-55	1/172	-55	1/077	-56	3/078	-52	1/007	-52	0/000	-52
70	00	MAX	13/327	-48	9/242	-49	9/190	-49	10/134	-47	8/284	-50	9/251	-48
		MEAN	5/314	-51	2/232	-52	1/301	-53	1/085	-51	1/259	-52	5/255	-50
		MIN	1/248	-55	2/019	-56	1/116	-55	0/000	-55	1/077	-55	0/000	-53
	12	MAX	13/328	-49	9/231	-50	9/197	-50	9/125	-48	8/055	-50	8/208	-48
		MEAN	4/322	-52	1/263	-54	1/326	-53	1/060	-51	1/295	-52	4/263	-51
		MIN	2/274	-54	1/200	-56	1/047	-57	0/000	-54	1/210	-55	2/294	-53

ALT mb	TIME GMT	VALUE	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX	15/276	-38	20/255	-43		-46		-53	17/083	-38	16/328	-46
		MEAN	12/285	-41	12/284	-50		-54	27/292	-62	15/062	-45	12/323	-56
		MIN	8/315	-47	8/265	-58		-60		-67	15/038	-57	9/317	-64
	12	MAX	13/274	-37	19/264	-31		-46		-62	23/077	-40		-53
		MEAN	5/282	-42	15/277	-51		-51	38/310	-64	9/028	-51		-61
		MIN	1/052	-48	11/320	-59		-58		-68	8/008	-67		-68
20	00	MAX	11/268	-42	33/326	-49	39/341	-49	38/281	-55	22/333	-42	23/359	-52
		MEAN	5/279	-48	10/285	-53	13/267	-57	26/300	-59	4/023	-52	11/326	-58
		MIN	1/266	-52	5/013	-59	7/268	-72	21/277	-61	2/133	-60	2/355	-62
	12	MAX	10/281	-44	23/304	-47	47/330	-48	35/285	-53	38/334	-41	25/013	-53
		MEAN	5/280	-49	10/287	-54	19/285	-56	23/309	-58	7/339	-52	15/345	-58
		MIN	1/288	-54	4/001	-60	10/250	-70	15/322	-62	1/129	-63	2/312	-64
30	00	MAX	8/287	-46	28/323	-49	41/342	-51	45/325	-53	28/312	-45	29/318	-54
		MEAN	3/293	-51	10/285	-53	15/286	-59	21/298	-57	8/315	-52	12/325	-57
		MIN	1/299	-55	5/013	-59	7/225	-73	13/307	-61	2/196	-58	2/006	-61
	12	MAX	8/301	-47	27/312	-51	40/326	-49	40/320	-53	33/339	-44	23/320	-54
		MEAN	4/293	-52	8/293	-55	17/281	-57	20/301	-57	11/321	-53	11/339	-57
		MIN	1/307	-57	4/029	-59	7/279	-72	9/338	-64	3/167	-59	2/074	-60
50	00	MAX	14/275	-47	21/317	-49	42/343	-49	35/312	-51	28/291	-45	24/279	-52
		MEAN	5/298	-54	9/270	-54	16/282	-58	18/294	-56	11/297	-53	12/312	-56
		MIN	2/272	-58	3/287	-58	9/220	-71	12/312	-61	2/336	-59	2/045	-58
	12	MAX	12/294	-49	21/302	-59	38/331	-50	36/275	-53	42/313	-47	31/291	-54
		MEAN	5/299	-55	8/272	-55	16/279	-58	17/295	-56	15/303	-54	11/317	-57
		MIN	2/243	-58	3/251	-50	7/249	-70	9/304	-63	3/321	-61	1/024	-60
70	00	MAX	17/274	-48	25/293	-49	43/343	-50	40/312	-49	35/302	-46	26/276	-52
		MEAN	8/296	-55	10/263	-54	16/282	-57	19/291	-56	17/292	-53	14/306	-55
		MIN	4/256	-60	3/207	-59	7/218	-67	9/307	-63	4/307	-61	4/298	-60
	12	MAX	17/309	-50	24/276	-51	36/317	-47	35/313	-47	36/308	-47	26/283	-51
		MEAN	8/298	-56	10/265	-55	17/276	-57	17/295	-55	18/298	-53	13/305	-56
		MIN	5/302	-60	2/243	-59	11/273	-66	8/271	-62	6/279	-61	4/005	-59

TABLE C.8 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR EDMONTON UPPER AIR STATION 1975

ALT mb	TIME GMT	VALUE	Mar WIND VEL/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX									10/126	-30	4/105	-34		-36		-54								
		MEAN										-31		-36	7/290	-44		-55								
		MIN									9/089	-33	4/293	-37		-49		-56								
	12	MAX									17/084	-31	10/090	-36		-36										
		MEAN										-32		-36	6/239	-41										
		MIN									14/099	-35	0/000	-39		-45										
20	00	MAX									15/060	-37	7/333	-38	23/316	-44	17/256	-50	25/310	-52		-56				
		MEAN										-40		-42		-51		-55		-56		-63				
		MIN									2/012	-41	0/000	-47	3/267	-59	11/113	-58	6/034	-63		-68				
	12	MAX									13/087	-37	8/082	-39	14/029	-45	18/269	-51	36/328	-53						
		MEAN										-40		-43		-52		-56		-56		-62				
		MIN									5/096	-42	0/000	-47	4/355	-59	4/282	-59	4/217	-66						
30	00	MAX									10/069	-42	9/354	-41	23/324	-47	21/289	-50	22/292	-52	23/351	-55				
		MEAN									4/092	-44		-45		-52		-55		-56		-63				
		MIN									0/000	-47	0/000	-48	6/218	-58	9/334	-59	5/358	-62	14/272	-71				
	12	MAX									13/087	-37	9/280	-42	12/290	-47	17/250	-51	34/314	-52	47/317	-58				
		MEAN										-40		-46		-53		-55		-56		-66				
		MIN									5/096	-42	0/000	-49	3/290	-59	4/264	-60	3/070	-62	14/278	-72				
50	00	MAX									8/144	-45	9/289	-45	19/288	-47	25/078	-49	27/286	-50	40/334	-51				
		MEAN									01/113	-46		-48		-53		-54		-55		-64				
		MIN									0/000	-48	1/010	-50	5/299	-58	10/268	-59	1/184	-61	7/294	-73				
	12	MAX									6/174	-44	11/328	-44	11/301	-49	27/241	-48	22/290	-52	51/296	-52				
		MEAN									2/083	-46	4/320	-49		-54		-54		-55		-64				
		MIN									0/000	-49	1/347	-51	4/250	-59	5/219	-58	3/260	-64	6/314	-74				
70	00	MAX									16/353	-45	9/289	-45	21/301	-49	23/250	-48	27/284	-50	41/314	-51				
		MEAN										-47		-49		-52		-52		-53		-43				
		MIN									0/000	-49	2/316	-51	7/270	-57	11/247	-60	4/252	-60	7/284	-74				
	12	MAX									12/036	-45	11/298	-45	15/241	-50	20/246	-48	27/285	-50	35/305	-50				
		MEAN										-47		-50		-53		-53		-53		-62				
		MIN									0/000	-50	0/000	-52	8/264	-59	6/267	-59	4/241	-60	9/286	-73				

TABLE C.9 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR FORT SMITH UPPER AIR STATION 1963

			Mar		Apr		May		June		July		Aug		Sept		Oct		Nov		Dec		Jan		Feb	
ALT	TIME	VALUE	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP	WIND	TEMP
mb	GMT		vel/deg mps	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C	mps/deg	°C
10	00	MAX					10/120	-27	13/086	-26	12/100	-30	?/282	-31	24/27?	-38	25/294	-49		-56	60/337	-54		-61	35/360	-40
		MEAN					6/079	-38	11/079	-34	8/090	-33	1/124	-36	14/274	-45	16/302	-56	24/27?	-62	42/338	-62		-65	22/316	-56
		MIN					3/054	-46	6/081	-44	3/125	-37	[illegible]	-39	[illegible] 28?	-49	10/353	-70		-73	23/339	-75		-70	11/359	-73
	12	MAX					11/333	-37	16/074	-30	13/082	-35	9/0??	-31	17/274	-39		-53		-58		-52		-60	34/311	-41
		MEAN					2/055	-41	3/080	-34	10/082	-34	2/???	-37	8/282	-45		-59	43/310	-61	27/334	-61		-64	25/317	-57
		MIN					3/338	-46	11/092	-39	5/080	-41	0/000	-41	3/284	-52		-63		-63		-75		-68	18/296	-75
20	00	MAX					9/332	-42	11/073	-38	9/096	-38	9/089	-41	16/280	-46	41/287	-52	55/317	-56	33/329	-49	17/273	-58	28/347	-47
		MEAN					3/062	-46	7/074	-42	6/089	-41	1/115	-44	10/282	-51	17/309	-59	17/299	-62	20/335	-56	7/318	-62	15/307	-57
		MIN					0/000	-50	3/026	-46	2/136	-43	1/255	-48	1/260	-54	6/352	-71	4/357	-71	11/003	-61	4/029	-65	2/305	-68
	12	MAX					27/326	-43	4/046	-39	10/082	-33	6/091	-42	15/280	-47	42/286	-54	53/319	-56	38/338	-50	16/288	-57	27/326	-44
		MEAN					4/051	-47	9/072	-42	7/087	-41	2/089	-45	9/281	-53	19/308	-59	20/304	-62	19/335	-56	8/321	-62	15/307	-58
		MIN					2/354	-51	5/092	-45	1/244	-43	1/308	-48	1/287	-57	8/360	-70	7/029	-69	7/353	-62	2/041	-64	5/110	-72
30	00	MAX					9/321	-45	13/041	-41	7/115	-41	5/260	-43	14/279	-48	35/286	-51	48/316	-54	26/312	-49	19/271	-56	27/357	-49
		MEAN					2/024	-48	6/056	-45	4/091	-44	1/185	-47	9/286	-53	14/307	-58	17/295	-60	14/333	-53	7/303	-60	12/307	-56
		MIN					2/014	-51	0/000	-48	1/073	-46	0/000	-50	1/231	-57	3/351	-70	5/276	-65	6/286	-59	3/345	-63	5/005	-65
	12	MAX					11/332	-45	12/077	-43	8/123	-41	4/282	-44	17/316	-50	35/287	-52	46/315	-54	29/315	-49	15/318	-57	22/323	-49
		MEAN					3/049	-49	7/059	-45	5/090	-44	1/102	-48	9/293	-54	14/309	-60	18/301	-60	15/329	-53	7/322	-60	11/306	-57
		MIN					2/002	-51	2/069	-50	1/091	-47	0/000	-52	1/275	-57	6/346	-71	6/356	-67	6/333	-57	4/026	-63	4/093	-67
50	00	MAX					7/318	-46	10/035	-43	5/068	-45	8/272	-46	14/306	-49	28/285	-50	38/314	-52	23/313	-47	21/378	-53	24/346	-52
		MEAN					3/316	-49	4/030	-47	4/076	-47	3/225	-48	9/253	-53	12/310	-57	16/292	-58	10/316	-51	7/297	-56	9/301	-55
		MIN					1/290	-52	2/050	-50	1/299	-48	0/000	-51	2/278	-55	5/358	-66	5/311	-65	6/311	-56	0/000	-59	5/035	-60
	12	MAX					15/314	-47	11/028	-46	6/101	-45	6/283	-46	17/308	-50	27/287	-51	36/291	-53	28/303	-49	14/288	-52	16/317	-51
		MEAN					3/033	-50	5/032	-48	1/070	-47	2/226	-49	9/239	-54	13/309	-58	18/292	-58	11/322	-52	6/309	-56	9/300	-56
		MIN					1/288	-54	2/336	-50	0/000	-49	0/000	-52	3/3?1	-56	4/331	-68	6/323	-65	5/319	-56	2/025	-59	4/368	-62
70	00	MAX					11/325	-47	13/343	-46	7/280	-46	11/263	-46	15/308	-49	26/231	-50	31/312	-49	26/290	-48	18/301	-50	23/274	-51
		MEAN					6/302	-49	5/355	-48	3/269	-48	5/236	-49	10/278	-52	12/312	-56	16/289	-55	10/308	-51	6/291	-54	9/298	-55
		MIN					1/276	-51	1/093	-50	1/141	-50	3/215	-52	4/252	-55	4/316	-63	8/253	-63	4/306	-60	0/000	-57	6/051	-59
	12	MAX					13/320	-47	14/009	-46	7/298	-46	13/298	-46	17/303	-50	32/324	-57	30/317	-50	27/287	-48	14/289	-50	20/280	-51
		MEAN					5/304	-50	6/002	-48	2/288	-48	6/240	-49	10/282	-53	12/310	-57	16/290	-56	9/306	-51	6/298	-54	8/298	-55
		MIN					2/092	-52	1/296	-51	0/000	-50	2/199	-53	3/261	-55	5/327	-63	7/248	-62	5/317	-57	1/036	-58	5/053	-58

TABLE C.10 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR FORT SMITH UPPER AIR STATION 1969

ALT mb	TIME GMT	VALUE	Mar		Apr		May		June		July		Aug		Sept		Oct		Nov		Dec		Jan		Feb	
			WIND VEL/deg mps	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C
10	00	MAX	16/098	-39		-38	10/097	-30		-28		-26		-31		-33	29/267	-49		-46				-35		-52
		MEAN	15/092	-47	3/024	-45	6/097	-39		-33	-	-31	5/060	-34		-42	23/270	-53		-48		-62	60/371	-46	16/283	-58
		MIN	[illegible]	-58	-	-47	1/100	-43		-36		-44		-37		-48	18/276	-63		-50				-63		-66
	12	MAX		-43	14/098	-41	9/089	-34		-30		-28		-30		-38		-49		-43				-37		
		MEAN		-51	6/093	-46	8/084	-39	12/76	-33		-32		-35		-42		-54		-49			-	-45		-64
		MIN		-60	3/134	-51	6/085	-45		-36		-35		-38		-49		-61		-53				-53		
20	00	MAX	19/059	-41	14/098	-47	12/090	-41	16/089	-36	10/078	-36	6/088	-46	8/272	-43	18/276	-51	42/253	-51	47/307	-58	43/288	-37	35/008	-52
		MEAN	10/048	-47	4/084	-50	4/089	-47	8/087	-41	7/088	-40	2/080	-42	6/285	-50	14/277	-56	28/262	-58	43/297	-64	20/308	-49	19/319	-58
		MIN	6/096	-52	1/155	-53	1/100	-51	6/068	-43	5/093	-44	1/183	-44	4/348	-53	10/278	-63	21/285	-67	36/293	-69	6/287	-60	7/258	-67
	12	MAX	17/356	-42	11/089	-48	10/086	-45	12/058	-39	12/092	-37	8/087	-39	14/287	-43	43/305	-52	42/230	-51	41/30[illegible]	-61	46/315	-32	[illegible]	-53
		MEAN	11/050	-49	5/079	-51	5/079	-47	10/090	-42	9/088	-40	4/082	-42	5/279	-50	15/285	-57	27/253	-59	32/302	-64	18/310	-49	15/312	-58
		MIN	8/050	-53	1/146	-53	3/137	-57	7/094	-45	5/091	-43	1/250	-45	3/283	-58	10/281	-61	23/254	-73	25/312	-68	5/321	-60	4/233	-65
30	00	MAX	16/003	-44	10/102	-47	11/090	-44	12/090	-42	8/096	-41	5/308	-42	15/290	-45	32/312	-51	37/302	-46	44/288	-54	58/326	-43	36/288	51
		MEAN	7/043	-47	3/086	-50	4/082	-48	6/092	-45	5/090	-44	x/355	-45	6/297	-51	13/283	-56	24/355	-59	37/296	-61	23/327	-51	19/320	-57
		MIN	5/069	-51	1/155	-53	1/100	-52	4/090	-47	3/126	-47	1/036	-48	3/015	-55	6/279	-61	17/265	-74	22/306	-69	4/290	-59	6/227	-63
	12	MAX	19/005	-43	9/077	-48	7/086	-47	13/057	-42	11/080	-42	5/078	-42	14/294	-41	37/303	-53	35/240	-49	44/276	-55	56/324	-42	33/309	-52
		MEAN	8/038	-49	3/071	-51	4/074	-49	8/086	-45	6/087	-44	2/069	-45	6/294	-53	13/287	-57	22/261	-58	34/296	-61	21/308	-51	15/323	-57
		MIN	6/084	-52	1/140	-54	2/093	-52	5/076	-47	3/123	-47	1/176	-50	3/282	-58	6/267	-62	18/255	-72	23/319	-69	4/226	-58	3/248	-63
50	00	MAX	18/357	-45	7/343	-47	7/102	-48	9/086	-45	7/054	-45	5/265	-44	16/295	-47	26/304	-56	38/344	-49	49/275	-52	68/315	-42	40/286	-51
		MEAN	5/002	-49	1/098	-51	2/078	-50	3/057	-47	2/039	-47	2/270	-47	7/296	-53	11/275	-55	22/277	-58	31/293	-58	26/301	-57	17/318	-55
		MIN	1/080	-52	1/010	-53	2/278	-54	1/043	-50	1/295	-50	1/345	-50	4/305	-56	2/281	-59	19/286	-70	19/302	-62	9/273	-60	3/288	-59
	12	MAX	16/009	-47	7/345	-50	7/091	-47	8/102	-45	8/060	-45	5/014	-45	17/292	-48	29/300	-49	38/320	-50	43/276	-52	57/299	-43	33/319	-51
		MEAN	5/007	-50	2/058	-52	2/057	-51	4/078	-47	2/047	-47	1/306	-47	8/300	-54	11/275	-55	22/272	-58	29/293	-57	26/304	-51	16/320	-55
		MIN	1/122	-53	1/205	-54	2/310	-54	1/213	-50	1/134	-51	0/000	-51	5/344	-57	3/271	-60	15/237	-73	17/316	-62	7/208	-58	3/342	-62
70	00	MAX	18/354	-46	10/204	-48	7/276	-48	7/082	-47	8/220	-46	8/277	-45	19/287	-48	24/297	-49	40/341	-51	42/283	-51	53/312	-44	34/285	-49
		MEAN	3/330	-48	1/303	-51	1/345	-50	1/068	-48	3/301	-48	4/265	-48	9/293	-53	11/269	-54	22/275	-57	28/292	-56	27/298	-51	17/316	-54
		MIN	1/098	-51	0/000	-53	1/096	-54	1/315	-51	1/075	-52	1/033	-52	3/305	-58	5/238	-57	19/233	-68	17/293	-61	10/278	-62	4/018	-59
	12	MAX	19/339	-46	11/199	-50	7/308	-47	7/091	-47	8/007	-45	7/270	-45	19/292	-48	32/291	-50	38/252	-52	46/279	-49	51/313	-42	32/345	-49
		MEAN	6/335	-49	1/334	-52	1/011*	-51	2/074	-49	2/309	-48	3/272	-48	9/297	-54	11/269	-54	20/274	-57	28/290	-56	26/299	-51	17/319	-54
		MIN	1/327	-52	1/058	-54	3/149	-54	1/219	-50	1/285	-52	1/170	-53	4/326	-58	4/261	-59	14/253	-68	13/305	-61	9/274	-61	4/348	-60

TABLE C.11 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR FORT SMITH UPPER AIR STATION 1975

ALT	TIME	VALUE	Mar		Apr		May		June		July		Aug		Sept		Oct		Nov		Dec		Jan		Feb	
mb	GMT		WIND vel/deg mps	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C	WIND mps/deg	TEMP °C
10	00	MAX												-36												
		MEAN											14/048	-37												
		MIN												-38												
	12	MAX																-53								
		MEAN										-38				-43		-54		-50						
		MIN																-55								
20	00	MAX									21/045	-38	15/300	-39		-39		-52			17/023	-62				
		MEAN										-42		-43	11/006	-49	6/122	-55		-56		-63				
		MIN									5/078	-45	2/23	-46		-53		-57			17/296	-64				
	12	MAX									17/107	-36	12/236	-41	13/283	-43	8/025	-50		-50		-64				
		MEAN										-41		-42		-49		-55	4/293	-58	39/274	-67				
		MIN									6/083	-45	4/013	-43	4/324	-52	5/046	-57		-64	--	-70				
30	00	MAX									17/324	-42	23/086	-43		-45	12/004	-50	3/048	-53	21/275	-60				
		MEAN										-45		-46	9/307	-51		-55		-57		-63				
		MIN									2/098	-47	2/044	-49		-57	3/086	-58	2/346	-63	15/082	-68				
	12	MAX									12/093	-43	17/112	-42	11/310	-48	18/009	-53	8/054	-51	26/268	-62				
		MEAN										-45		-46		-52		-56		-58		-64				
		MIN									3/023	-47	2/097	-49	2/355	-55	5/020	-60	3/288	-65	19/354	-70				
50	00	MAX									11/021	-43	18/305	-45	12/342	-48	18/323	-52	6/267	-52	29/308	-55				
		MEAN										-45		-49		-54		-56		-56		-60				
		MIN									1/083	-47	02/334	-54	6/335	-58	2/108	-61	2/011	-60	5/007	-68				
	12	MAX									12/90	-43	14/004	-47	15/302	-47	14/092	-53	18/267	-52	48/274	-54				
		MEAN										-45		-49		-54		-56		-57		-62				
		MIN									2/122	-47	1/243	-52	5/001	-59	5/280	-58	3/019	-60	1/307	-69				
70	00	MAX									19/053	-49	18/282	-48	18/299	-49	17/294	-51	41/258	-51	29/327	-52				
		MEAN										-51		-50		-53		-55		-55		-60				
		MIN									1/142	-53	5/270	-55	10/285	-57	5/020	-59	3/319	-57	9/254	-72				
	12	MAX									32/314	-48	12/314	-48	14/303	-49	13/327	-51	28/278	-50	35/300	-53				
		MEAN										-50		-50		-54		-55		-55		-41				
		MIN									2/262	-53	3/332	-53	9/346	-57	5/222	-60	1/284	-58	5/090	-68				

TABLE C.12 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR TROUT LAKE UPPER AIR STATION 1963

ALT mb	TIME GMT	VALUE	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX					8/090	-32	16/085	-27	16/091	-26	10/086	-27	19/278	-35	39/254	-31		-58		-56		-58	36/348	-47
		MEAN					6/077	-37	12/091	-30	12/086	-30	4/065	-33	7/284	-40	25/262	-50		-61		-63	14/282	-64	20/332	-55
		MIN					4/049	-45	9/097	-34	9/082	-33	5/087	-42	3/312	-45	16/3[illegible]	-60		-65		-72		-68	10/318	-71
	12	MAX					6/046	-32	15/082	-26	16/078	-25	10/101	-28	19/271	-34	39/264	-40		-57		-55	23/267	-58		-48
		MEAN					5/073	-37	14/087	-32	13/093	-30	6/090	-33	14/266	-38	24/268	-50		-62		-63	16/278	-65		-56
		MIN					5/082	-42	13/084	-38	11/093	-36	4/159	-39	9/263	-44	10/314	-57		-66		-74	11/301	-69		-64
20	00	MAX					13/092	-41	13/094	-38	12/088	-37	9/092	-39	17/269	-43	35/281	-51	30/278	-55	35/328	-53	14/277	-58	24/306	-48
		MEAN					5/083	-46	9/086	-42	8/086	-40	5/091	-42	8/268	-48	16/283	-57	12/281	-62	19/341	-62	9/299	-63	13/301	-59
		MIN					1/020	-49	6/101	-45	5/077	-44	2/112	-54	1/099	-52	9/326	-63	3/183	-74	6/322	-69	7/352	-67	4/339	-69
	12	MAX					12/089	-42	13/085	-38	12/090	-37	9/085	-39	16/263	-45	34/268	-47	30/282	-57	33/330	-53	16/287	-57	23/324	-52
		MEAN					7/084	-46	10/087	-42	9/089	-41	5/087	-43	7/269	-48	16/278	-57	14/289	-63	17/347	-63	8/303	-63	14/[illegible]	-59
		MIN					3/072	-50	7/082	-45	7/102	-45	1/193	-46	2/042	-53	7/322	-62	8/086	-74	5/300	-71	7/277	-67	5/275	-70
30	00	MAX					7/060	-46	8/083	-43	9/061	-41	7/094	-43	13/272	-48	27/299	-53	39/317	-51	29/327	-52	14/263	-56	22/333	-52
		MEAN					3/074	-49	6/081	-45	6/079	-44	3/072	-46	7/279	-52	12/286	-58	12/290	-61	15/343	-58	8/285	-62	12/299	-59
		MIN					1/046	-52	4/084	-49	2/081	-47	1/327	-50	0/000	-57	6/313	-65	3/247	-72	4/055	-64	6/347	-65	5/358	-66
	12	MAX					10/084	-46	8/081	-43	10/095	-41	7/102	-43	15/265	-48	28/290	-53	33/319	-53	27/319	-52	16/262	-57	21/332	-52
		MEAN					4/084	-49	7/085	-46	6/081	-44	4/086	-46	7/282	-51	13/284	-58	11/293	-61	13/351	-58	8/285	-62	11/303	-59
		MIN					1/307	-53	4/054	-50	5/054	-47	2/170	-49	0/000	-55	6/303	-65	2/160	-70	3/024	-64	3/204	-65	6/353	-68
50	00	MAX					5/313	-47	9/344	-44	7/071	-47	8/283	-47	14/273	-50	28/290	-53	28/317	-53	22/325	-49	16/247	-57	19/339	-53
		MEAN					2/317	-50	1/024	-48	2/009	-48	2/014	-50	9/288	-53	13/287	-57	11/282	-58	10/333	-54	9/279	-59	9/299	-57
		MIN					0/000	-54	0/000	-52	0/000	-50	1/036	-53	3/246	-56	5/282	-64	3/217	-65	1/013	-61	6/279	-64	6/321	-63
	12	MAX					6/077	-49	6/087	-45	6/355	-47	7/088	-49	15/278	-50	30/288	-57	26/303	-53	23/336	-48	18/262	-55	17/313	-53
		MEAN					1/014	-51	2/064	-48	2/041	-48	2/032	-50	9/291	-53	13/288	-57	11/284	-59	10/338	-54	9/276	59	9/299	-57
		MIN					0/000	-53	0/000	-51	1/287	-51	0/000	-53	2/042	-57	4/309	-64	1/133	-62	1/072	-60	6/261	-64	6/332	-63
70	00	MAX					10/288	-48	11/334	-46	10/304	-47	10/335	-49	23/308	-57	30/281	-51	25/319	-52	25/332	-48	22/243	-53	17/344	-52
		MEAN					5/293	-51	4/295	-49	5/302	-50	4/310	-52	11/288	-53	14/285	-56	11/284	-56	9/325	-53	10/272	-57	9/297	-56
		MIN					1/290	-55	0/000	-53	1/305	-53	1/355	-54	5/342	-57	6/250	-63	1/261	-60	2/032	-60	7/344	-64	5/265	-61
	12	MAX					10/299	-48	12/324	-47	9/298	-47	15/295	-50	21/307	-50	25/293	-50	25/332	-52	19/334	-48	22/229	-52	16/326	-51
		MEAN					4/301	-51	3/301	-49	4/314	-50	4/313	-52	12/290	-53	13/286	-56	10/285	-56	9/328	-53	10/273	-56	8/300	-56
		MIN					2/309	-57	1/190	-51	0/000	-52	1/332	-56	7/279	-56	6/315	-62	2/206	-60	2/272	-58	5/277	-67	5/327	-61

TABLE C.13 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR TROUT LAKE UPPER AIR STATION 1969

ALT mb	TIME GMT	VALUE	Mar WIND VEL/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	00	MAX		-41		-46		-33		-32				-36		-41		-48		-55				-43		
		MEAN		-46		-44		-37		-35			8/[illegible]	-37	13/[illegible]	-43		-52		-57			7/[illegible]	-50		
		MIN		-52		-47		-47		-37				-37		-48		-56		-60				-59		
	12	MAX		-41	5/083	-44	6/045	-33		-31		-31		-33		-40		-41		-46		-57		-39		-50
		MEAN	7/107	-49	3/096	-45	5/025	-39	17/090	-33	12/033	-34	4/08	-36		-43		-49		-52		-65		-44		-53
		MIN		-60	2/120	-47	5/001	-43		-36		-36		-40		-47		-58		-62		-73		-50		-57
20	00	MAX	26/064	-48	15/100	-48	7/091	-44	9/173	-39			9/074	[illegible]	12/275	-44	18/266	-50	39/265	-47		-59	49/303	-45		-52
		MEAN	10/062	-52	3/095	-50	5/086	-48	8/086	-43	3/0[illegible]	-42	3/075	-43	4/265	-48	8/290	-55	13/277	-57	31/292	-64	13/313	-52	4/265	-58
		MIN	7/064	-60	2/097	-52	3/093	-51	2/140	-47			2/101	-46	1/338	-56	3/314	-62	4/265	-70		-66	4/[illegible]	-65		-63
	12	MAX	21/[illegible]	-47	17/102	-48	12/13[illegible]	-44	14/089	-41	15/087	-39	11/0[illegible]	-42	15/271	-44	25/284	-49	39/253	-48	34/308	-57	23/307	-44	28/317	-53
		MEAN	12/069	-51	7/080	-50	7/078	-47	11/026	-43	10/057	-42	5/085	-43	8/266	-48	11/284	-55	10/253	-58	28/288	-63	5/345	-52	13/309	-59
		MIN	5/059	-59	2/035	-52	3/075	-51	7/077	-46	7/087	-47	1/045	-46	1/230	-52	1/220	-64	2/[illegible]	-69	26/270	-70	4/061	-69	1/317	-67
30	00	MAX	18/067	-49	12/099	-50	10/078	-47	8/108	-44	6/071	-45	7/069	-44	12/271	-47	18/2[illegible]	-50	41/264	-49	34/275	-51	51/3[illegible]	-45	37/272	-53
		MEAN	6/056	-52	2/081	-51	9/0[illegible]8	-50	7/088	-46		-47	2/077	-46	5/3[illegible]	-51	9/274	-55	17/261	-58	25/287	-60	11/301	-53	17/304	-58
		MIN	4/091	-56	2/358	-54	1/007	-52	5/081	-48	5/070	-48	1/310	-50	1/256	-55	4/261	-60	2/237	-73	17/305	-65	1/190	-62	1/034	-67
	12	MAX	17/066	-47	12/097	-49	11/076	-46	11/070	-44	13/079	-43	9/081	-44	11/276	-46	21/285	-57	32/2[illegible]	-51	38/273	-57	46/319	-44	33/322	-52
		MEAN	7/064	-51	7/080	-51	5/071	-50	8/085	-46	8/088	-46	3/087	-46	6/270	-50	3/279	-55	13/263	-58	28/290	-61	16/304	-53	14/308	-58
		MIN	4/099	-55	[illegible]/035	-54	2/040	-53	6/108	-50	5/096	-50	1/090	-50	1/230	-54	1/331	-60	0/000	-71	19/311	-66	0/000	-63	1/317	-67
50	00	MAX	16/301	-44	8/098	-49	7/085	-50	6/117	-46	3/081	-51	8/302	-46	12/217	-48	19/283	-53	43/288	-50	38/290	-49	53/307	-48	53/27[illegible]	-49
		MEAN	4/343	-51	1/033	-52	2/035	-52	4/089	-49		-51	1/314	-49	5/280	-53	9/279	-56	15/266	-58	24/286	-58	22/292	-53	20/300	-58
		MIN	2/355	-54	0/000	-56	1/203	-55	2/034	-51	1/107	-51	1/350	-53	3/308	-57	2/311	-60	3/236	-72	16/314	-61	4/287	-61	0/000	-67
	12	MAX	17/306	-46	8/086	-49	7/294	-49	8/076	-47	9/076	-46	6/298	-47	11/277	-46	18/275	-51	33/280	-51	40/273	-52	51/308	-47	46/269	-50
		MEAN	3/343	-51	2/021	-52	2/050	-52	5/079	-49	4/064	-49	1/315	-49	5/282	-53	9/277	-55	14/262	-59	23/290	-58	23/293	-54	18/300	-58
		MIN	1/125	-55	1/343	-53	2/354	-54	3/071	-51	0/000	-51	1/350	-53	1/233	-57	3/312	-59	5/348	-73	13/302	-62	4/272	-61	3/008	-67
70	00	MAX	20/303	-45	10/274	-49	12/279	-51	5/157	-47	5/320	-53	12/313	-47	12/265	-46	23/271	-51	41/253	-50	37/243	-47	47/315	-46	47/276	-51
		MEAN	6/306	-51	2/312	-52	2/311	-53	1/101	-50		-53	4/284	-50	7/286	-53	11/276	-55	15/265	-58	23/286	-55	23/288	-53	20/299	-57
		MIN	1/132	-53	1/092	-57	1/203	-58	1/015	-52	3/322	-53	1/310	-57	4/291	-59	4/238	-58	5/239	-69	12/295	-63	5/278	-63	4/359	-65
	12	MAX	21/312	-45	10/291	-50	11/280	-50	7/086	-46	11/015	-46	11/309	-48	14/274	-48	22/283	-50	36/247	-49	35/288	-49	44/308	-47	43/301	-50
		MEAN	5/308	-50	3/323	-52	2/331	-53	1/061	-51	3/360	-50	4/284	-50	6/284	-53	10/277	-55	16/267	-58	23/289	-55	24/291	-53	21/300	-57
		MIN	0/000	-54	2/005	-57	1/269	-56	1/151	-54	0/000	-55	1/340	-54	2/304	-57	3/330	-57	6/280	-70	10/296	-60	5/267	-62	5/336	-64

TABLE C.14 MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR TROUT LAKE UPPER AIR STATION 1975

ALT mb	VALUE	YR	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	MAX	63									12/047	-31	7/107	-35	12/234	-36	25/254	-47	26/302	-58						
		69					[illegible]	-3[?]	13/[illegible]	[illegible]	13/[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23/283	-4[?]					21/319	-61	37/271	-4[?]
		75	27/[illegible]	-41			15/[illegible]	-3[?]	—	—			[illegible]/103	-36			22/226	-43			—	—	[illegible]/002	-40	—	-54
	MIN	63									8/104	-36	2/286	-45	3/234	-44	10/260	-52	16/249	-68						
		69					4/028	-42	5/091	-41	8/092	-37	0/000	-41	1/065	-49	13/352	-62					12/272	-71	23/317	-72
		75	13/076	-63			10/116	-43					7/073	-45			20/319	-64					8/062	-62		-61
20	MAX	63									12/073	-38	11/047	-40	16/301	-42	19/199	-51	34/297	-50		-67				
		69					11/090	-38	12/071	-38	16/348	-37	5/079	-38	19/268	-43	37/288	-52	49/326	-56	41/335	-55	20/278	-56	36/339	-50
		75	20/003	-48	13/075	-47	13/070	-41	21/093	-36	13/073	-38	8/085	-39	[illegible]/242	-44	28/307	-51	31/293	-49			29/325	-42	45/319	-57
	MIN	63									3/331	-43	0/000	-49	2/299	-54	5/242	-60	6/200	-67		-70				
		69					2/074	-50	4/021	-45	4/055	-43	0/000	-47	1/104	-57	9/354	-63	2/326	-72	11/359	-69	6/310	-67	4/229	-72
		75	8/090	-57	1/255	-52	1/240	-51	2/020	-46	1/097	-47	1/081	-48	2/290	-54	5/276	-62	12/281	-73			2/007	-67	9/277	-68
30	MAX	63									10/007	-41	10/278	-41	19/308	-46	18/225	-50	37/294	-50	27/322	-57				
		69					7/084	-45	9/074	-41	8/077	-41	7/049	-43	17/269	-48	31/287	-52	39/328	-53	38/335	-51	17/336	-56	24/346	-57
		75	17/350	-47	10/127	-47	10/091	-45	17/124	-39	10/074	-41	5/291	-42	8/272	-44	26/300	-53	39/291	-50	48/282	-55	69/325	-42	47/276	-50
	MIN	63									0/000	-47	0/000	-50	3/335	-58	0/000	-59	2/186	-64	10/303	-71				
		69					0/000	-51	2/053	-48	3/080	-42	1/[illegible]	-51	0/000	-56	7/352	-67	3/100	-71	5/333	-63	5/260	-66	7/341	-69
		75	3/026	-55	1/265	-53	1/240	-53	1/083	-48	1/130	-47	1/103	-48	2/294	-56	4/280	-64	12/247	-74	26/276	-70	2/009	-67	9/277	-68
50	MAX	63									10/331	-43	13/311	-43	23/320	-48	23/256	-49	31/287	-48	42/296	-53				
		69					9/348	-46	9/349	-43	4/346	-43	8/331	-47	16/271	-48	26/291	-52	32/321	-52	29/312	-48	17/238	-52	28/336	-52
		75	19/343	-43	7/105	-48	9/099	-48	7/043	-45	8/057	-44	7/292	-45	16/286	-47	24/295	-52	35/273	-49	49/286	-53	57/313	-45	56/274	-51
	MIN	63									1/140	-50	0/000	-52	6/302	-59	7/217	-59	2/275	-59	7/331	-75				
		69					0/000	-51	1/294	-49	0/000	-50	0/000	-51	2/302	-57	4/349	-65	3/246	-66	4/338	-62	5/271	-63	7/008	-69
		75	1/328	-53	0/000	-54	0/000	-54	1/012	-50	1/130	-50	0/000	-52	1/250	-57	1/319	-60	10/254	-72	18/300	-65	6/284	-61	1/332	-65
70	MAX	63									12/316	-45	17/320	-43	35/340	-48	25/249	-48	33/279	-48	44/293	-50				
		69					8/345	-47	12/329	-44	8/307	-45	14/320	-47	19/318	-48	24/305	-57	28/321	-49	27/321	-47	16/228	-50	25/335	-51
		75	26/343	-42	8/290	-47	9/275	-47	9/005	-45	14/031	-44	12/284	-45	19/284	-47	22/291	-50	35/282	-49	45/288	-50	57/310	-47	51/281	-50
	MIN	63									1/078	-51	3/298	-52	9/306	-57	4/240	-58	2/295	-57	9/284	-73				
		69					1/113	-53	0/000	-50	1/049	-51	1/244	-53	6/284	-56	0/000	-64	1/176	-64	2/004	-60	2/242	-63	7/310	-62
		75	1/230	-51	1/230	-55	0/000	-54	1/122	-52	2/328	-51	1/316	-53	3/327	-57	1/150	-59	9/310	-70	15/299	-63	9/282	-64	5/331	-66

TABLE C.15 MONTHLY MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR CHURCHILL UPPER AIR STATION

ALT mb	VALUE	YR	Mar WIND VEL/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C
10	MAX	63										-36	6/230	-37
		69					14/[illegible]	[illegible]	[illegible]	[illegible]	16/073	-24	13/024	-22
		75	41/037	-41		-40		-32	15/022	-23		-30	10/022	-33
	MIN	63									4/108	-41	2/246	-42
		69					4/072	-40	12/091	-35	13/078	-35	2/144	-40
		75	17/011	-60		-50		-47	9/094	-39		-47	2/350	-43
20	MAX	63									17/140	-38	12/034	-40
		69					11/097	-38	13/099	-37	15/075	-38	10/093	-40
		75	26/072	-42	14/093	-47	14/088	-43	14/086	-38	15/090	-40	9/086	-40
	MIN	63									3/098	-45	1/032	-48
		69					2/008	-50	7/066	-47	6/077	-44	0/000	-48
		75	7/027	-56	1/301	-54	2/144	-52	6/082	-42	4/092	-42	1/023	-47
30	MAX	63									15/077	-42	12/060	-42
		69					9/101	-47	13/096	-43	10/081	-43	7/102	-43
		75	17/072	-45	10/099	-49	15/084	-48	13/061	-44	12/090	-48	7/091	-44
	MIN	63									2/170	-48	1/320	-51
		69					1/074	-53	5/082	-50	4/116	-47	0/000	-50
		75	6/017	-56	2/315	-55	1/069	-54	5/083	-51	2/095	-52	0/000	-50
50	MAX	63									13/175	-46	8/264	-48
		69					7/326	-50	8/073	-46	5/287	-47	7/145	-48
		75	13/026	-48	8/236	-49	7/071	-49	10/104	-47	10/066	-48	6/228	-47
	MIN	63									1/353	-51	0/000	-54
		69					0/000	-55	2/358	-54	0/000	-52	0/000	-53
		75	0/000	-55	1/071	-55	1/077	-56	3/078	-52	0/000	-52	0/000	-52
70	MAX	63									11/189	-46	11/277	-47
		69					10/315	-50	9/018	-48	10/278	-46	10/258	-49
		75	13/327	-48	9/231	-49	9/190	-49	10/134	-47	8/284	-50	9/251	-48
	MIN	63									1/205	-53	1/357	-54
		69					2/194	-55	1/249	-55	0/000	-53	0/000	-55
		75	1/248	-54	1/200	-56	1/116	-57	0/000	-55	1/077	-55	0/000	-53

ALT mb	VALUE	YR	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	MAX	63	12/272	-35			11/262	-51						
		69	25/27[illegible]	-33	21/267	-44							14/306	-39
		75	15/27[illegible]	-32	20/255	-51		-46		-53	23/077	-38	16/338	-46
	MIN	63	6/237	-49	6/034	-53	10/063	-60						
		69	3/337	-46	8/334	-57							6/034	-68
		75	1/052	-48	8/245	-59		-60		-62	8/008	-67	9/317	-68
20	MAX	63	13/288	-43	17/284	-48	18/316	-51	41/344	-57				
		69	19/265	-35	33/291	-50	26/321	-52	31/357	-49	15/285	-57	23/260	-45
		75	11/268	-42	33/326	-47	47/330	-48	38/281	-53	32/334	-41	25/013	-52
	MIN	63	0/000	-57	2/023	-59	7/284	-61	18/027	-67				
		69	1/280	-55	3/356	-71	5/064	-69	2/119	-63	2/331	-66	2/053	-65
		75	1/266	-54	4/001	-60	7/268	-72	15/322	-62	1/129	-63	2/312	-64
30	MAX	63	15/273	-47	13/225	-50	26/294	-52	36/346	-55				
		69	17/265	-46	30/229	-52	19/297	-53	27/355	-47	15/279	-58	23/260	-47
		75	8/287	-46	28/323	-49	41/342	-49	45/325	-53	33/339	-44	29/318	-54
	MIN	63	1/157	-58	2/023	-59	4/295	-63	10/018	-73				
		69	1/246	-57	3/340	-71	5/333	-67	0/000	-57	2/331	-66	4/333	-65
		75	1/299	-57	4/029	-59	7/225	-73	9/338	-64	2/336	-59	2/006	-61
50	MAX	63	18/086	-51	23/264	-52	18/289	-52	35/296	-51				
		69	15/273	-50	26/299	-51	24/302	-52	14/321	-49	16/271	-52	17/311	-51
		75	14/275	-47	21/317	-49	42/343	-49	36/275	-51	42/313	-45	31/291	-52
	MIN	63	4/279	-59	2/172	-60	2/168	-60	6/310	-70				
		69	1/265	-56	1/293	-67	3/359	-63	11/015	-57	5/314	-62	3/058	-60
		75	2/292	-58	3/289	-58	7/249	-71	9/304	-63	2/336	-61	1/024	-60
70	MAX	63	15/336	-50	21/262	-50	18/282	-50	33/296	-51				
		69	17/270	-51	28/300	-51	31/294	-52	14/294	-50	20/304	-51	22/269	-51
		75	17/274	-48	25/293	-49	43/343	-47	40/312		34/308	-46	26/276	-51
	MIN	63	6/289	-60	3/220	-59	3/340	-60	4/306	-69				
		69	1/271	-57	1/269	-63	6/284	-63	1/273	-59	5/249	-61	2/243	-59
		75	4/256	-60	2/243	-59	7/218	-67	8/271		4/307	-61	4/298	-60

TABLE C.16 MONTHLY MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR EDMONTON UPPER AIR STATION

ALT mb	VALUE	YR	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	MAX	63									17/024	-33	[illegible]	-34												
		69					11/233	-27	[illegible]	[illegible]	[illegible]	[illegible]	7/222	-31	24/270	-38	[illegible]	[illegible]		-56	64/337	[illegible]		-60	[illegible]	[illegible]
		75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-30		[illegible]		-36		-30		-38	[illegible]	-63		-43				-35		-52
	MIN	63									[illegible]	-35	[illegible]	-39												
		69					3/054	-46	6/081	-44	3/125	-41	0/000	-41	3/281	-52	10/353	-70		-73	23/339	-75		-70	11/359	-75
		75	[illegible]	-60	[illegible]	-51	1/100	-45		-36		-44		-38		-49	18/276	-63		-53				-63		-66
20	MAX	63									15/066	-37	8/082	-38	23/316	-44	18/269	-50	26/222	-52						
		69					27/326	-42	14/046	-38	10/092	-33	9/089	-41	16/280	-46	42/286	-52	55/317	-56	38/338	-49	17/273	-57	28/347	-44
		75	[illegible]	[illegible]	14/296	-47	12/040	-41	16/087	-36	12/072	-36	8/087	-39	14/287	-43	43/305	-51	42/253	-51	47/307	-58	46/315	-32	35/002	-52
	MIN	63									2/012	-42	0/000	-47	3/267	-59	4/282	-59	4/217	-66						
		69					0/000	-51	3/026	-46	1/244	-43	1/255	-48	1/287	-57	6/352	-71	4/357	-71	7/353	-62	2/041	-65	2/305	-72
		75	6/026	-53	1/155	-53	1/100	-51	6/068	-45	5/091	-43	1/250	-45	3/283	-58	10/281	-63	21/285	-73	25/312	-68	5/312	-60	4/233	-67
30	MAX	63									13/027	-37	9/354	-41	23/324	-47	21/289	-50	34/314	-52	47/317	-55				
		69					11/332	-45	13/041	-41	8/123	-41	5/260	-43	17/316	-48	35/286	-51	48/316	-54	29/315	-49	19/271	-56	27/359	-49
		75	19/005	-43	10/102	-47	11/090	-44	13/087	-42	11/080	-41	5/078	-42	15/290	-41	37/303	-51	37/302	-48	44/288	-54	58/326	-42	36/288	-51
	MIN	63									0/000	-47	0/000	-49	3/290	-59	4/264	-60	3/070	-62	14/272	-72				
		69					2/002	-51	0/000	-50	1/073	-47	0/000	-52	1/231	-57	3/351	-70	5/276	-67	6/286	-59	3/345	-63	4/093	-67
		75	5/067	-52	1/140	-54	1/100	-52	4/090	-47	3/123	-47	1/176	-50	3/282	-58	6/279	-62	17/265	-74	22/306	-69	4/290	-59	3/248	-63
50	MAX	63									8/144	-44	11/328	-44	19/288	-47	27/271	-48	27/286	-50	51/296	-51				
		69					15/314	-46	11/028	-43	6/101	-45	8/272	-46	17/308	-49	28/287	-50	38/314	-52	28/303	-47	21/328	-52	24/346	-51
		75	18/357	-43	7/343	-47	7/102	-47	7/086	-45	8/060	-45	5/014	-44	17/292	-47	29/300	-49	38/344	-49	49/275	-52	68/315	-42	40/286	-51
	MIN	63									0/000	-49	1/010	-51	4/250	-59	5/219	-59	1/184	-61	6/314	-74				
		69					1/288	-54	2/336	-50	0/000	-49	0/000	-52	2/278	-56	4/331	-68	5/311	-65	5/319	-56	0/000	-59	4/368	-62
		75	1/080	-53	1/010	-54	2/278	-54	1/043	-50	1/134	-51	0/000	-51	4/305	-57	2/281	-60	15/237	-73	17/316	-62	7/208	-60	3/288	-62
70	MAX	63									16/353	-45	11/298	-45	21/301	-49	23/250	-48	27/284	-50	41/314	-50				
		69					13/320	-47	14/009	-46	7/280	-46	13/298	-46	17/303	-49	32/324	-50	31/312	-49	27/287	-48	18/301	-50	23/274	-51
		75	19/339	-46	10/204	-48	7/276	-47	7/082	-47	8/220	-45	8/277	-45	19/287	-48	32/291	-49	40/341	-51	46/279	-49	53/312	-42	34/285	-49
	MIN	63									0/000	-50	0/000	-52	2/270	-59	6/267	-60	4/241	-60	7/284	-74				
		69					1/276	-52	1/296	-51	0/000	-50	2/199	-53	3/261	-55	4/316	-63	7/248	-63	4/306	-60	0/000	-58	5/053	-59
		75	1/327	-52	1/058	-54	1/096	-54	1/315	-50	1/075	-52	1/033	-53	3/305	-58	4/261	-59	14/253	-68	13/305	-61	9/274	-62	4/018	-60

TABLE C.17 MONTHLY MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR FORT SMITH UPPER AIR STATION

ALT mb	VALUE	YR	Mar WIND vel/deg mps	Mar TEMP °C	Apr WIND mps/deg	Apr TEMP °C	May WIND mps/deg	May TEMP °C	June WIND mps/deg	June TEMP °C	July WIND mps/deg	July TEMP °C	Aug WIND mps/deg	Aug TEMP °C	Sept WIND mps/deg	Sept TEMP °C	Oct WIND mps/deg	Oct TEMP °C	Nov WIND mps/deg	Nov TEMP °C	Dec WIND mps/deg	Dec TEMP °C	Jan WIND mps/deg	Jan TEMP °C	Feb WIND mps/deg	Feb TEMP °C
10	MAX	63																								
		69					8/020	-32	16/035	-36	16/075	-25	[illegible]	-27	13/271	-34	39/264	-31		-57		-55	[illegible]	-53	34/347	-47
		75		-41	5/054	[illegible]	6/045	-33		-31		-33	[illegible]	-32		-40		-41		-46		-57		-37		
	MIN	63																								
		69					4/049	-45	9/097	-38	9/082	-36	4/159	-39	3/312	-45	10/314	-60		-66		-74	1/301	-69	10/318	-71
		75		-60	2/120	-49	5/061	-44		-37		-36	4/084	-40		-48		-58		-62		-73		-59		-57
20	MAX	63									21/045	-36	12/236	-37	13/283	-39	3/025	-50		-50		-62				
		69					13/092	-41	13/085	-38	12/090	-37	9/092	-39	17/269	-43	35/221	-47	30/222	-55	35/328	-53	16/287	-57	24/306	-48
		75	26/064	-47	17/102	-48	13/080	-44	14/089	-39	15/087	-39	11/0[illegible]	-40	15/271	-44	25/286	-49	39/265	-47	34/308	-57	49/303	-44	28/317	-52
	MIN	63									5/073	-45	2/323	-42	4/324	-52	5/040	-57		-64		-70				
		69					1/020	-50	6/101	-45	5/077	-45	1/193	-54	1/077	-53	2/322	-63	3/123	-74	5/300	-71	7/352	-67	4/339	-69
		75	5/059	-60	2/035	-52	3/088	-51	7/097	-47	7/087	-47	1/045	-46	1/338	-56	1/220	-64	2/093	-70	26/270	-70	4/065	-69	1/317	-67
30	MAX	63									17/324	-46	23/036	-42	11/310	-45	18/009	-50	8/054	-51	26/268	-60				
		69					10/024	-46	8/083	-43	10/095	-41	7/102	-43	15/265	-42	28/290	-53	39/317	-51	29/327	-52	16/262	-54	22/333	-52
		75	18/067	-47	13/097	-49	11/076	-46	11/070	-44	13/079	-43	9/081	-44	12/271	-46	21/285	-50	41/264	-49	38/273	-51	51/306	-44	39/292	-52
	MIN	63									2/098	-47	2/044	-49	2/355	-57	3/086	-60	2/346	-65	15/082	-70				
		69					1/307	-53	4/054	-50	2/081	-47	1/327	-50	0/000	-57	6/313	-65	2/160	-72	3/029	-64	3/204	-65	5/358	-70
		75	4/091	-56	2/358	-54	1/069	-53	6/108	-50	5/096	-50	1/310	-50	1/256	-55	1/331	-60	0/000	-73	17/305	-66	0/000	-63	1/034	-67
50	MAX	63									12/090	-43	18/305	-45	15/302	-47	18/323	-52	18/267	-52	48/274	-54				
		69					6/071	-47	9/344	-44	7/071	-47	2/283	-47	15/278	-50	30/288	-51	28/317	-53	23/336	-48	18/262	-55	19/339	-52
		75	16/201	-44	8/098	-49	7/085	-49	8/076	-47	9/076	-46	8/302	-46	12/267	-48	19/283	-51	43/288	-50	40/273	-49	53/307	-47	53/278	-49
	MIN	63									1/083	-47	1/243	-54	5/001	-59	2/108	-61	2/011	-60	1/307	-69				
		69					0/000	-54	0/000	-52	0/000	-51	0/000	-53	2/042	-57	4/309	-64	1/133	-65	1/013	-61	6/261	-64	6/321	-68
		75	1/125	-55	0/000	-56	1/203	-55	2/034	-51	0/000	-51	1/350	-53	1/233	-57	2/311	-60	3/236	-73	13/302	-62	4/287	-61	0/000	-67
70	MAX	63									32/314	-48	18/282	-48	18/299	-49	17/294	-51	41/258	-50	35/300	-52				
		69					10/288	-48	12/324	-46	10/304	-47	15/295	-49	23/308	-50	30/281	-50	25/319	-52	25/332	-48	22/243	-52	17/344	-51
		75	21/312	-45	10/284	-49	12/279	-50	7/086	-46	11/015	-46	12/313	-47	14/274	-46	23/271	-50	41/253	-49	37/243	-47	47/305	-46	47/276	-50
	MIN	63									1/142	-53	3/332	-55	9/346	-57	5/020	-60	1/284	-59	5/090	-72				
		69					1/290	-57	0/000	-53	0/000	-53	1/355	-56	5/342	-57	6/250	-63	1/261	-60	2/032	-60	5/277	-67	5/265	-61
		75	6/005	-54	1/092	-57	1/203	-58	1/015	-54	0/000	-55	1/310	-57	2/304	-59	3/330	-58	5/239	-70	10/296	-63	5/278	-63	4/359	-65

TABLE C.18 MONTHLY MAXIMUM AND MINIMUM WIND VELOCITIES AND AIR TEMPERATURE FOR TROUT LAKE UPPER AIR STATION