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FEASIBILITY STUDY OF MODERN AIRSHIPS PHASE I, VOL. II
PARAMETRIC ANALYSIS (TASK III)

GOODYEAR AEROSPACE CORP.
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(PHASE I)

Volume II - Parametric Analysis (Task III)

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FOREWORD

This final technical report was prepared for the Ames Research Center, Moffett Field, Calif., by Goodyear Aerospace Corporation, Akron, Ohio, under NASA Contract NAS2-8643, "Feasibility Study of Modern Airships." The technical monitor for the Ames Research Center was Dr. Mark D. Ardema.

This report describes work covered during Phase I (9 December 1974 to 9 April 1975) and consists of four volumes:

- Volume I - Summary and Mission Analysis (Tasks II and IV)
- Volume II - Parametric Analysis (Task III)
- Volume III - Historical Overview (Task I)
- Volume IV - Appendices

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FEASIBILITY STUDY OF MODERN AIRSHIPS
VOLUME II - PARAMETRIC ANALYSIS (TASK III)

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SUMMARY

Various types of lighter-than-air (LTA) vehicles from fully buoyant to semi-buoyant hybrids were examined. Geometries were optimized for gross lifting capabilities from 1360.8 kg to 2,721,600 kg (3000 lb to 6,000,000 lb) for ellipsoidal airships, modified delta planform lifting bodies, and a short-haul, heavy-lift vehicle concept.

Neutrally buoyant airships employing a rather conservative update of materials and propulsion technology offer significant improvements in productivity. Advanced fabric applications for non-rigid airships offer great potential for improved performance.

Propulsive lift for VTOL and aerodynamic lift for cruise can significantly improve the productivity of low to medium gross weight ellipsoidal airships. For large gross weights, neutrally buoyant flight maximizes productivity.

For the CTOL lifting body hybrid, no optimum ratio of buoyant lift to gross weight, β , was found, based on productivity, between 0.1 and 0.6. For all but very large ranges the productivity of the $\beta = 0.1$ hybrid exceeds that of the $\beta = 0.6$ hybrid. Depending on gross weight and range, semibuoyant lifting body hybrid vehicles can offer improved productivity relative to ellipsoidal airships, particularly at the large gross weights. However, in comparison with commercial cargo aircraft at equal gross weight and range, their productivity appears to be significantly lower.

The short-haul, heavy-lift vehicle, consisting of a simple combination of an ellipsoidal airship hull and existing helicopter componentry, offers significant potential for low-cost, near-term applications for ultra-heavy lift missions. Results indicate useful load-to-empty weight ratios of approximately 1.0 can be maintained to gross weights of approximately 907,200 kg (2,000,000 lb).

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INTRODUCTION

One of the overall objectives of Phase I was to examine the general principle of lighter-than-air flight as it applied to concepts leading to more efficient vehicles. The specific objective for Task III, as specified by the statement of work, was "to identify concepts for airships which are fully or partially buoyant and conduct a parametric study of these concepts to investigate the tradeoffs among aerodynamic performance, propulsion requirements, and structural requirements."

The parametric analysis was the major task activity during Phase I. The statement of work further defined the objective of the parametric study "to optimize the geometry of the families of vehicles for gross lifting capability of from 1360.8 kg to 2,721,600 kg (3000 lb to 6,000,000 lb). The scope of the study included LTA vehicles ranging from fully buoyant to combinations of buoyant and aerodynamic lift (hybrids). As specified by the statement of work, "specific shapes to be considered are ellipsoidal for fully buoyant concepts and delta planforms for hybrids."

The figure of merit for the parametric evaluation, as specified in the statement of work, was "payload ton-miles per hour and range, if applicable."

BACKGROUND

Prior to the modern airship feasibility study, many years had lapsed since detailed airship design work had been conducted other than the Goodyear-sponsored efforts, which principally dealt with non-rigid airships.

One of the important aspects of Phase I was to evaluate the application of modern technology for airship vehicle designs, particularly materials usage and structural design. Conventional designs from the 1930's as well as new or different concepts were to be considered during Phase I.

Recent work at the NASA Ames Research Center at Moffett Field, Calif., had indicated that a semibuoyant, hybrid vehicle might be attractive. Preliminary studies indicated that, for the same buoyant volume, hybrid vehicles may have several times the payload capability of fully buoyant airships. No such vehicles had ever been produced or operated, however, and there was no historical data base to permit accurate estimates of vehicle inert weights and costs. The validity of the initial indications were, therefore, subject to question, and conventional airships were retained as a base point for the Phase I study by statement of work definition.

Over the years Goodyear Aerospace has developed a number of computer-based analytical tools for continuing corporately supported research and development in LTA technologies. Several of these programs and analyses were ideally suited to becoming principal elements of the Goodyear airship synthesis program (GASP) to be used during the parametric analysis of conventional airships and adapted for the analysis of lifting body hybrid vehicles.

A second major effort was a structural design update of conventional rigid and metalclad airship technology. This activity was prompted by several major considerations:

1. The considerable lapse in time since detailed "rigid" airship design work had been conducted
2. The need to assess the impact of current materials technology and other design knowledge developed during the last several decades in the company's non-rigid airship activities
3. Recognition of the importance of the structural design and weight characteristics to airship performance evaluation

Preliminary comparisons of conventional airships and several hybrid concepts had indicated the fundamental importance of structural efficiency and the resulting empty weight-to-gross weight ratio (EW/GW) to vehicle productivity.

Depending on the EW/GW ratio of the hybrid vehicle vis a vis the conventional airship, hybrids either could be highly competitive (in terms of productivity measured in useful load times cruise velocity, UL times V_C) or rather poor.

Recognizing the critical dependency of relative vehicle productivity on structural efficiency resulted in the following general philosophy for Phase I:

1. The hybrid performance evaluation must be based on a sound definition and design evaluation of the required structure and associated empty weight
2. As a base point for comparison, the conventional airship structural design and empty weight characteristics must be realistically evaluated and defined employing current technology

OBJECTIVES

The objectives of the parametric analysis were as follows:

1. Optimize the geometry of a family of modern airship vehicles with gross lifting capabilities from 1360.8 kg to 2,721,600 kg (3000 to 6,000,000 lb), including neutrally buoyant ellipsoidal airships and delta planform hybrids in terms of productivity (payload ton-miles per hour and range, if applicable)
2. Define, parametrically, the configuration and performance characteristics of the vehicles for combination with mission requirements defined in Task II (Reference 1)

SCOPE

The scope of the parametric study can be defined in terms of primary and secondary study variables. The primary variables considered for the bulk of the parametric optimization study consist of:

1. Configuration geometry
 - a. Aspect ratio and thickness ratio for delta planform hybrids
 - b. Fineness ratio and type of construction for ellipsoidal airships
2. Gross weight, GW
3. Cruise velocity, V_C
4. Static lift-to-gross weight ratio, β
5. VTOL vs CTOL (vertical takeoff and landing propulsion capability versus conventional takeoff and landing capability)

In addition to those primary variables, several secondary variables and design options were briefly evaluated as discussed in Appendix H of Reference 2.

1. Secondary variables
 - a. Design head wind, VW
 - b. Design altitude, h_D
2. Design options
 - a. Alternate buoyant gases
 - b. Gaseous fuel propulsion augmentation
 - c. Artificial superheat
 - d. Stern propulsion
 - e. Boundary layer control
 - f. Ballast recovery

The bulk of the parametric analysis dealt with the performance evaluation and configuration optimization with respect to the primary study variables of three vehicle types: conventional airships; modified delta planform hybrids, and short-haul, heavy-lift VTOL vehicles.

GENERAL APPROACH

The overall approach to the parametric analysis consisted initially of screening and evaluating candidate hybrid configurations that were broadly grouped into two categories: lifting body vehicles and winged airships. A

modified delta planform lifting body configuration was selected for detailed parametric analysis. Three types of conventional ellipsoidal airships were retained as baseline study vehicles: rigid, pressurized metalclads, and pressurized fabric non-rigids. The vehicle selected for the short-haul, heavy-lift VTOL vehicle was a simple combination of a conventional airship hull and conventional helicopters. Appendix I of Reference 2 presents the results of the hybrid configuration evaluation, including the winged airship configuration results.

After the baseline study vehicles were selected, aerostatic, aerodynamics, structural weight, and propulsion relationships were developed or finalized based on precontract efforts for each type of vehicle.

The general methodology used for the parametric optimization procedure is presented in Figure 1 for conventional takeoff performance evaluation. Methodology for VTOL vehicles is presented in Figure 2.

METHODS OF ANALYSIS

To analyze the conventional airships and modified delta planform hybrid vehicles, a hybrid vehicle and "conventional" airship synthesis program was developed at Goodyear Aerospace using the general methodology of aircraft synthesis programs developed at NASA Ames Research Center (References 3 and 4). Based on this methodology, the program is designated GASP (Goodyear airship synthesis program) and is shown schematically in Figure 3. The program has been developed for compatibility with the detailed mission profile and economic assessments required for Phase II. GASP consists of a control program and several subroutines to perform the various tasks required for the parametric evaluation and configuration optimization of hybrid and conventional airships.

The program is controlled by input data that dictates the vehicle type and takeoff option and subroutines required in each stage of calculation. Figure 3 also is an example of the processing flow through the subroutines for a delta planform hybrid vehicle.

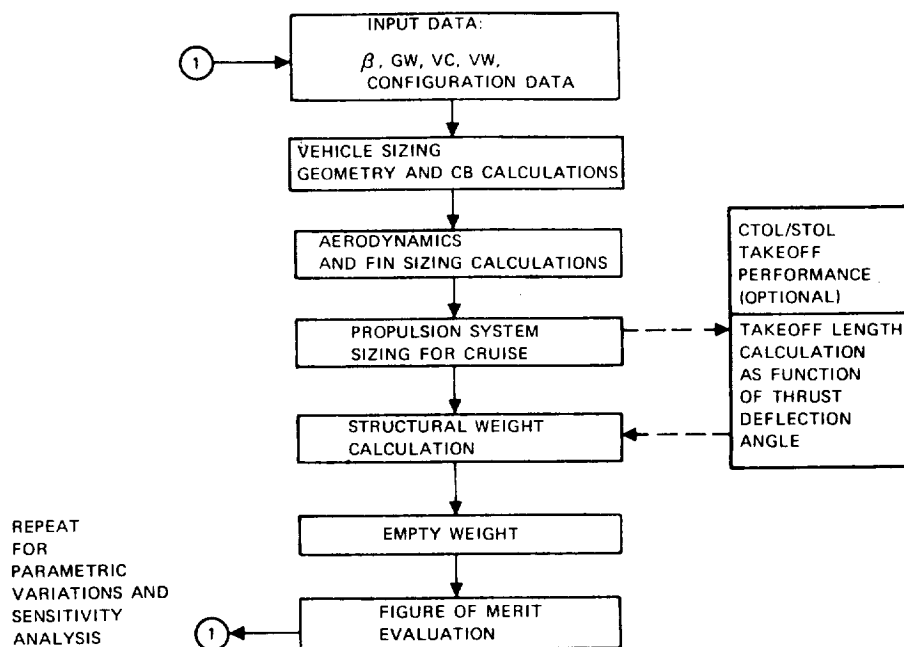


Figure 1 - STOL/CTOL General Methodology

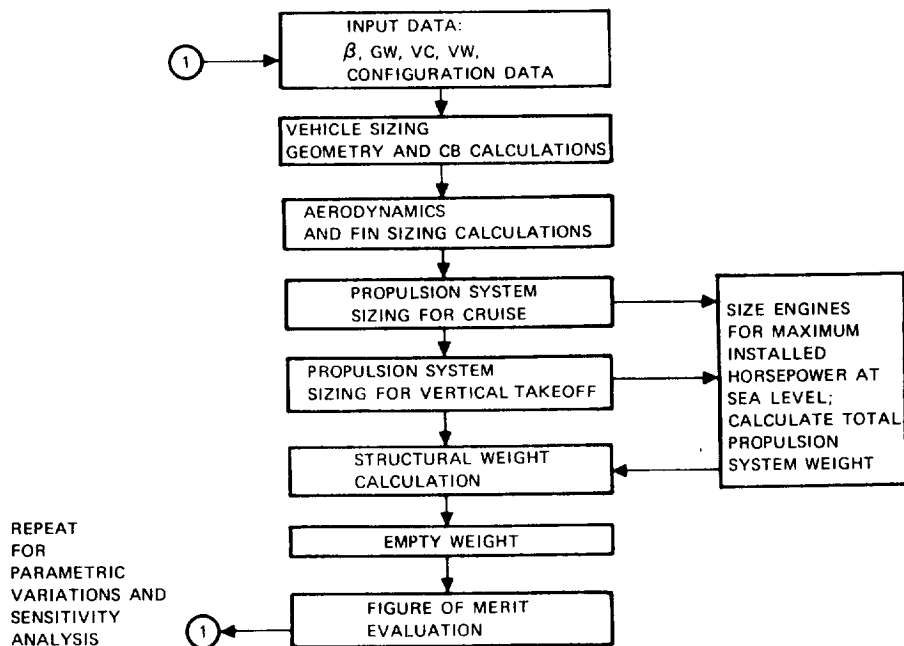


Figure 2 - VTOL General Methodology

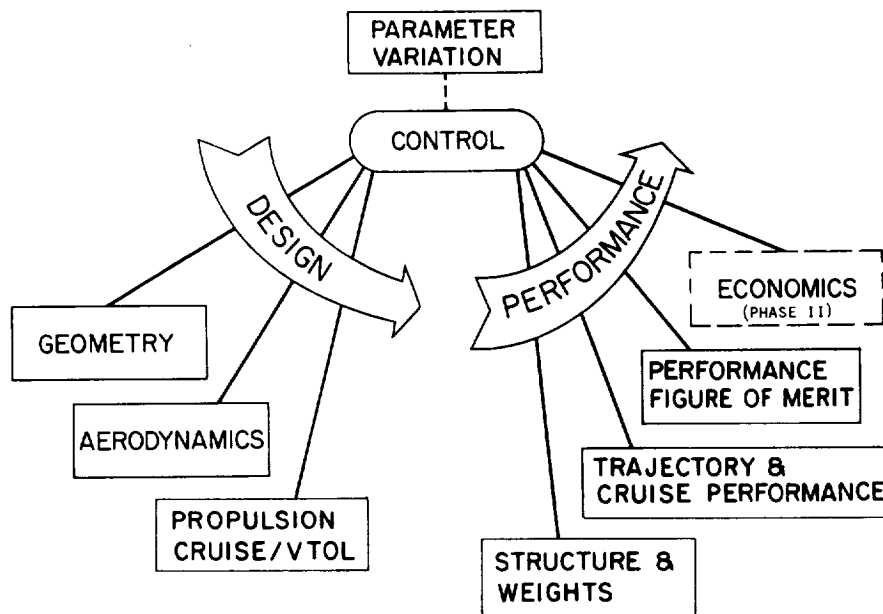


Figure 3 - Goodyear Airship Synthesis Program (GASP)

The control program reads the input data and calls the geometry subroutine to calculate the modified delta vehicle geometry as a function of gross weight, GW ; static lift-to-gross weight ratio, β ; aspect ratio, AR ; and thickness ratio, (t/c) ; hull efficiency, η_H ; lifting gas characteristics; and design altitude, h_D . After the geometry calculations are complete, the aerodynamics subroutine is called to estimate the vehicle lift, drag, and pitching moment and aerodynamic bending moment characteristics. Horizontal and vertical tail surface requirements are calculated as a function of input static stability margin (positive or negative) or are optionally sized for static stability. The methods used in this subroutine and all GASP subroutines are detailed in Reference 2. Once the aerodynamics of the configuration have been established, the aerodynamic lift required $[(1-\beta) \times GW]$ is defined and the cruise drag calculated. Turboprop engine horsepower requirements are calculated using Hamilton Standard propeller efficiencies. If VTOL is required, the propulsion system requirements for vertical takeoff are defined and compared with the sea level installed horsepower required for cruise. The engines are sized based on the largest sea

level installed horsepower. Total propulsion system weight is calculated based on bare engine weight; propeller weight; gear box weight; and a nacelle, accessories, outrigger, and installation weight factor.

Depending on the input options, a conventional takeoff length can be evaluated or thrust deflection requirements for a (input) short takeoff can be evaluated. In addition, the structural weight subroutine is called and the vehicle non-propulsive weight calculated and combined with the propulsion system weight for the total vehicle empty weight.

Based on the vehicle design characteristics, a trajectory/cruise performance subroutine is entered and the fuel required for a given design range, or fuel consumed as a function range (or both), is calculated. A separate vertical takeoff to horizontal flight transition analysis program, which was used separately from the GASP during Phase I (see Reference 2), will be incorporated in GASP by Phase II.

Based on the design and performance calculations, the figure of merit subroutine is called to evaluate the performance figures of merit used in Phase I. Two different iteration loop capabilities are available for parametric analysis: (1) a primary variable iteration loop (V_C , V_W , h_D , GW , β , l/d , AR , t/c) and (2) a sensitivity variable loop. The sensitivity study allows $\pm K\%$ variations in all key design or performance variables calculated or input to the basic program (SFC, engine weight, vertical takeoff thrust to weight, nonpropulsive structural weight, tail area, design bending moment coefficient, design load factor, prismatic coefficient, C_{D0} , C_L , stability margin, and design gust velocity). An economics module will be developed for Phase II to calculate the mission-dependent economic figures of merit and conduct the performance-economic tradeoff studies required during Phase II.

The GASP was used extensively during Phase I. The main value of this synthesis program is to provide reasonable estimates of conventional and hybrid airship performance and allow consistent comparisons of vehicle performance using the same ground rules, assumptions, and constraints. As such, the program is merely a means to an end and not an end item in itself. Its value lies in the capability to integrate the many technological interactions defining vehicle performance. Any program is only as good as the methods

and analysis on which the computations are based. These methods and the analysis from which they were derived are briefly discussed in the following sections and in Reference 2.

PARAMETRIC STUDY OVERVIEW

The parametric analysis constitutes a rather substantial study in itself. Thus, the following overview of the study and material may be a helpful "road map" to the parametric study results. Three major subsections are presented corresponding to the three vehicle types: conventional airships, lifting body hybrids, and the short-haul, heavy-lift vehicle.

Conventional airships are treated first. The analysis of the conventional airships represents both a vehicle class themselves and a baseline for comparison with the hybrid vehicle. Hence, the results of the conventional airship analysis are fundamental to interpretation of the results of the hybrid vehicle.

The term "conventional airship" as used herein implies only a vehicle of ellipsoidal geometry. Conventional airships are analyzed using large amounts of aerodynamic lift for cruise flight with propulsive lift sufficient for vertical take-off. Thus, the "conventional airships" as investigated are actually "hybrids" in the true context of the study.

Analysis and results of the lifting body hybrid vehicle, based on a family of modified delta planform lifting bodies, are presented following the conventional airship results. The final subsection deals with the short-haul, heavy-lift vehicle concept.

Each subsection is organized in a similar manner. A design description is presented following by a discussion of the key elements of the technical analysis used in the study. This discussion generally follows the logic employed in the synthesis program: geometry, aerodynamics, propulsion, and structural weights. The final portion of each subsection presents the results of the parametric analysis of the vehicle type or class. Reference 2 gives further details of the GASP methods of analysis.

CONVENTIONAL AIRSHIPS

Three basic types of conventional airships were analyzed: conventional rigids, conventional (pressurized fabric envelope) non-rigids, and pressurized metalclads.

Design Description (Conventional Rigid)

Figure 4 shows the general design features of a conventional rigid airship.

The outer shell of a conventional rigid airship is made up of longitudinal and shear wires covered by an impregnated cloth supported by the longitudinals and flutter tie wires. The internal structure consists of (1) main frames that compartment the airship and distribute such concentrated loads as would originate from the keel structure, outriggers, and fins to the shell structure and (2) intermediate frames that are spaced between the main frames and serve as struts between the longitudinals assisting them in connection with the shear wires to maintain the longitudinal rigidity of the airship. The lifting gas is contained within fabric cells located between the main frames. These cells transmit the gas pressure loads to gas bag wires to the longitudinals located on the surface of the shell, and to the bulkhead wires located in the plane of the main frames.

In this parametric study, the girders and trusses that make up the longitudinals, main frames, intermediate frames, empennage frames, and empennage longitudinals will be made from 7050 aluminum alloy. The fabric components will be made from coated dacron; the wires will conform to Federal Specification QQ-W-470b.

The principal structural components and key structural design assumptions are presented below. The structural components are:

1. Main frames
2. Axial girder
3. Intermediate frames

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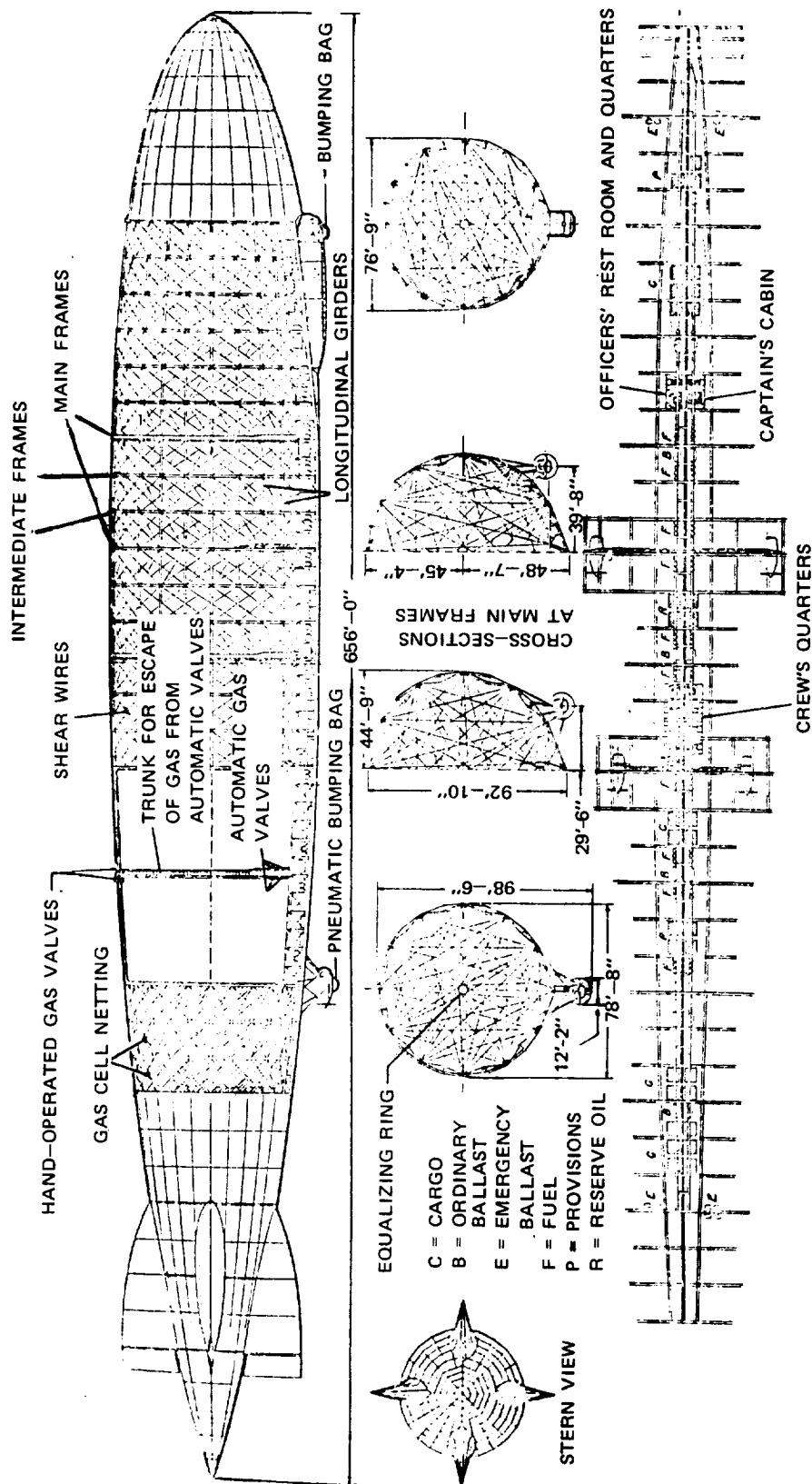


Figure 4 - Design Features of Conventional Rigid Airship

4. Longitudinals
5. Shear wires
6. Outer cover and outer cover wires
7. Gas cells and gas cell wires
8. Empennage and cruciform

Main Frames

Wire-braced rings will be used that, in effect, act as a spoked wheel. The circumference of the wheel consists of triangular aluminum girders (see Figure 5). The main frames serve two principal functions: (1) distribute concentrated loads to the outer shell and (2) restrain the gas pressure loads that occur if there is an accidental deflation of a gas cell on one side of the main frame.

Axial Girder

In order to reduce the loads to which the main frames are subjected in the deflated cell condition, an aluminum axial girder is connected to the hub of the wire braced main frames. This permits the radial wires to transmit a portion of the gas pressure load to the axial girder rather than to the ring of the main frame, thus resulting in a weight savings.

Intermediate Frames

Unlike the main frames, the intermediate frames are not wire braced and consist simply of a ring structure. The cross-section of the ring is similar to the main frame in that it consists of a triangular girder. Since the loads to which the intermediate frames are subjected are not as great as those of the main frames, the size of the intermediate frame girders is smaller than that of the main frame.

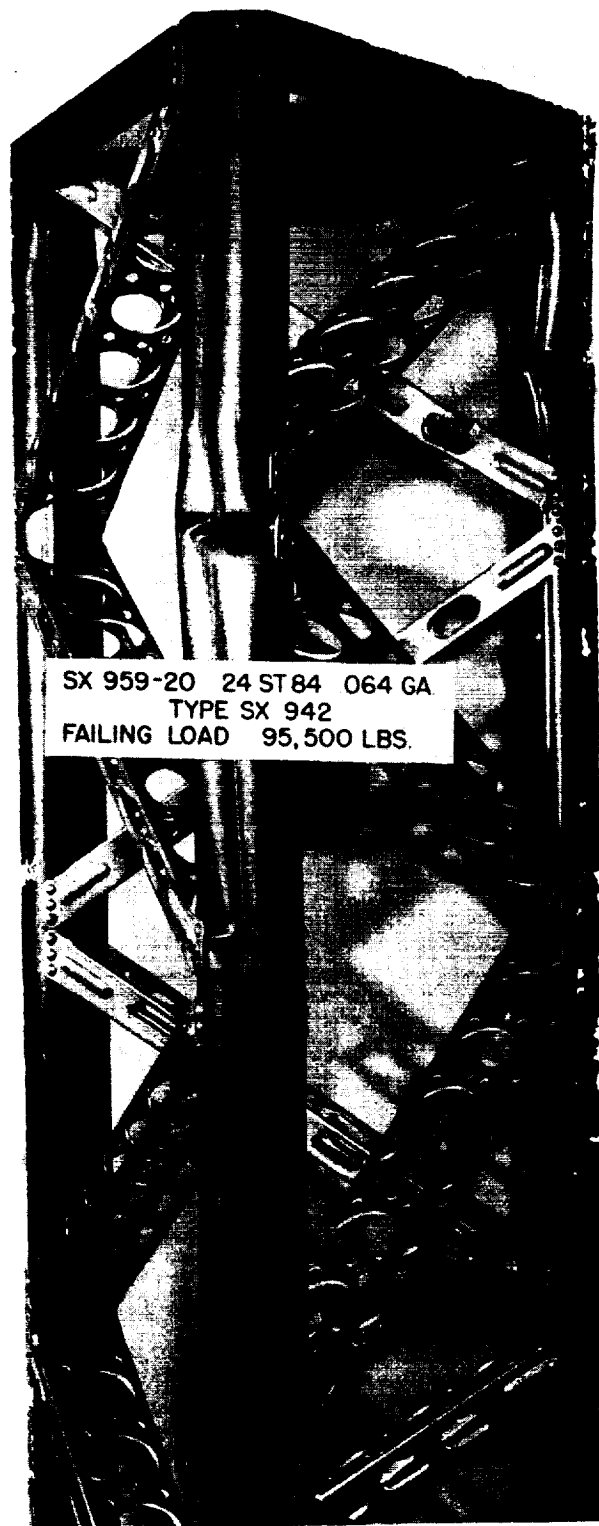


Figure 5 - Triangular Aluminum Girders (Main Frames)

Together with the longitudinals and the diagonal shear wires, the intermediate frames form a shear panel. The intermediate frames, therefore, are subjected to shear loads in addition to gas pressure loads.

Longitudinals

The longitudinals also are aluminum triangular girders similar to those employed in the main and intermediate frames. Their principal function is to provide the bending strength needed in the airship. The bending moments produce axial loads in the longitudinals. The longitudinals also resist bending loads resulting from the gas pressure and aerodynamic pressure transmitted to them by the gas cells and outer cover, respectively.

Shear Wires

In this study it has been assumed that the shear wires are made from hard wire (Federal Specification QQ-W-470B). It is conceivable that in the larger sized airships stranded cables may be required. The shear wires provide the necessary shear strength. They are attached to the intersection points of the longitudinals and intermediate rings.

Outer Cover and Outer Cover Wires

The outer cover is a synthetic material having the tradename of Ceconite. This material has the advantage over cotton cloth in that the material can be made taught by the application of heat, thus requiring fewer finish coats of dope.

To prevent fluttering of the outer cover and to reduce the tensile stresses in the fabric and the bending stresses in the longitudinals, the outer cover is supported at intervals by outer cover wire stretched between the intersection points of the longitudinals and intermediate frames (see Figure 4).

The purpose of the outer cover is to form a smooth aerodynamic surface and to transmit the aerodynamic pressure loads to the shell structure.

Gas Cells and Gas Cell Wires

The gas cells consist of coated dacron fabric. They are placed between the main frames and are free to expand or contract with changes in temperature and altitude. To keep the stresses in the gas cell fabric to a minimum, the cells are supported at frequent intervals by a network of gas wires and netting (see Figure 4).

Empennage and Cruciform

The empennage is of conventional construction and consists of aluminum trussed frames and longitudinals covered with a coated fabric (see Figure 4). To reduce high bending loads in the supporting rings, a cruciform construction will be used.

Pressurized Metalclad

General

The pressurized metalclad airship combines some structural features of the non-rigid airship and some of the rigid airship. The metalclad obtains its bending and shear strength through the pressurization of a metal hull. The empennage structure is similar to that of the rigid airship.

The metalclad transfers the car structure loads into the metal hull skin through the use of frames rather than an internal and external catenary system. Any concentrated loads such as those that would result from engine and outrigger loads also are transferred to the metal hull skin through the use of frames.

The frames are similar in construction to those employed on the rigid airships. The metal skin is assumed to be made from 7050 alclad aluminum sheet.

Three types of metalclad airships were considered:

1. A pressurized and compartmented airship has the safety feature that permits the airship to operate if one compartment is damaged and loses pressure.
2. A pressurized metalclad with ballonets. This type is basically a metal "non-rigid" airship. While it has main frames to transmit loads, it is not compartmented. Consequently, the main frames do not have to be designed for a deflated cell condition.
3. A pressurized metalclad with gas cells is similar to Type 2 except that it eliminates the ballonets and substitutes gas cells.

Metalclad 1

Main Frames - The main frames of the metalclad serve the same function as the main frames of the rigid airship. They will be of the same construction as used in the rigid airships (a wire-braced ring). Compartmentalization will be obtained by covering the main ring with a fabric diaphragm.

Intermediate Frames - These frames are of the same construction as that used on the rigid airship. Their function is to maintain the shape of the hull during construction and to act as vertical stiffeners in the tension field beam condition that occurs in the deflated compartment condition.

Longitudinal - The longitudinals are of the same construction as that used on the rigid airship. The function of the longitudinals is to help maintain the shape of the hull during construction and to provide bending strength in a deflated compartment condition.

Ballonets - The ballonets will be of coated cloth construction. Since the airship is compartmented by the main frames, the ballonets will have to be

located between the main frames. They will be of cylindrical construction and attached to some solid structure in the airship such as the keel.

Outer Cover - The outer cover will be of 7050 aluminum alclad sheet. No minimum gage constraints are included in the metalclad weight equations.

Empennage - The empennage will be the same type of construction as that used in the rigid airships.

Metalclad 2

Metalclad 2 will use the same type of construction as that used for Metalclad 1 except that since compartmentalization is not required the fabric diaphragms on the main frames will be eliminated. As a result the main frames, the longitudinals, and the intermediate frames will not have to be designed for the deflated cell condition.

Metalclad 3

Metalclad 3 will use the same type of construction as that used for Metalclad 2 except that the ballonets will be eliminated and the gas cells substituted.

Non-rigid Airship (See Figure 6)

The non-rigid hull obtains its bending and shear strength through the pressurization of a fabric envelope; the car loads are transferred to the envelope through an internal and external suspension system.

The internal suspension system (see Figure 6) consists of a series of steel cables extending from the car structure to a catenary cable, which in turn is attached to a fabric catenary curtain that distributes its load to the envelope through a double Y seam. The principal function of the internal suspension system is to transmit the vertical component of the car loads into the envelope.

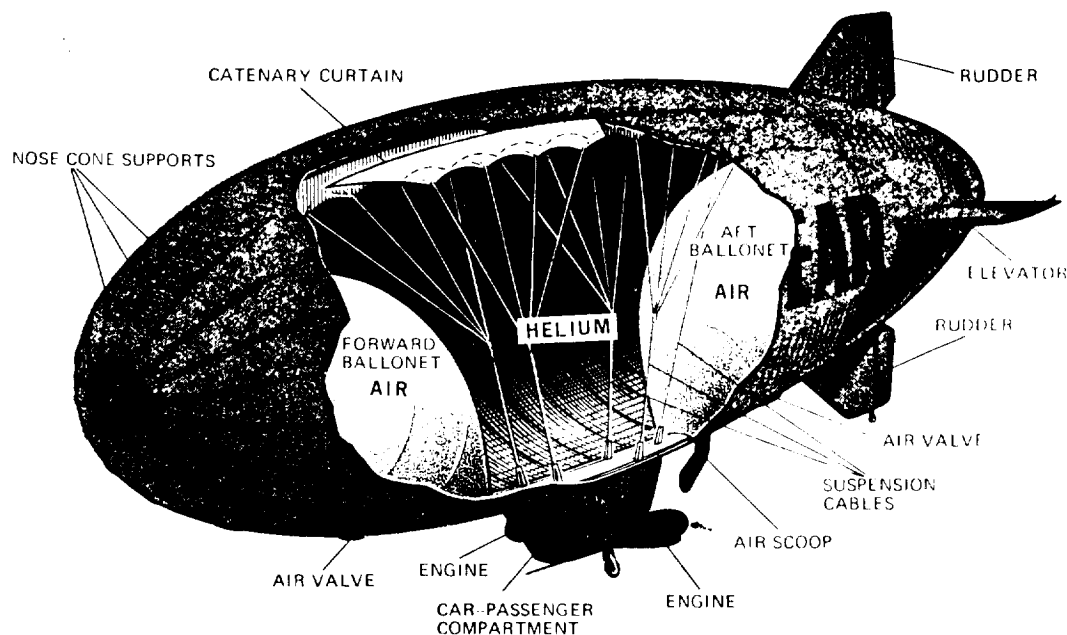


Figure 6 - Typical Non-rigid Airship Design

The external suspension system attaches to the outside of the envelope. Its principal function is to transfer the longitudinal components of the car loads into the envelope structure. These components arise principally from pitched flight, propeller thrust, and landing gear drag loads. It also supports a portion of the vertical component of the car loads. The construction of the external is similar to that of the internal system except that the cables are much shorter in length and there is no need for a double Y seam.

The envelope of existing non-rigid airships is generally a two-ply neoprene coated fabric consisting of one straight ply and one bias ply. The seams are cemented and sewn. The envelope is pressurized to where it can resist all design flight conditions without wrinkling.

The mooring loads are transferred to the envelope through a nose cone and a system of battens (see Figure 6); the battens are aluminum tubing. The nose cone is of typical aircraft construction. The battens serve the additional function of preventing the nose from caving in during high-velocity flight.

The empennage consists of aluminum trussed frames and longitudinals covered with coated Ceconite fabric. The fins are attached to the envelope at their base and are supported by brace wires that extend from the outer portion of the fin to a tangent point on the envelope cross-section, where they attach to a catenary curtain that distributes their concentrated load into the envelope.

The car structure is of conventional aircraft construction.

CONVENTIONAL AIRSHIP AERODYNAMICS ANALYSIS

Aerodynamic drag characteristics for conventional airships utilized in the GASP are based on Goodyear's data base of airship drag data, both model scale and full scale. The basic drag area expression for a complete airship is

$$(C_{D_o} S)_{\text{total}} = (C_{D_o} S)_{\text{hull}} + (C_{D_o} S)_{\text{fins}} + (C_{D_o} S)_{\text{engines \& outrigger}} \\ + (C_{D_o} S)_{\text{car}} + (C_{D_o} S)_{\text{misc}}$$

where $(C_{D_o} S)_{\text{hull}} = C_f \left[1 + 1.5 \left(\frac{d}{l} \right)^{3/2} + 7 \left(\frac{d}{l} \right)^3 \right] S_W,$

and $d/l = \text{the inverse of the vehicle fineness ratio, length/}$
diameter,

$S_W = \text{total hull wetted area}$

The component drag area contributions generally are expressed as percentage contributions of $(C_{D_o} S)_{\text{hull}}$ with the K factors based on experimental and full-scale data of past airships as discussed in Reference 2. C_f is the Schoenherr frictional resistance coefficient. Vehicle volume to the 2/3 power is utilized for the aerodynamic reference area.

Aerodynamic lift estimates are based on the data of Reference 5. Tabulated values of angle of attack, alpha versus lift coefficient, C_L , are used due to the highly nonlinear characteristics of airship lift.

Drag due to lift also is based on the data of Reference 5, which is approximated with sufficient accuracy as

$$C_{D_i} = 0.9 C_L^2$$

GASP also calculates the aerodynamic bending moment, M_A , based on the input gust velocity (35 ft/sec unless otherwise defined) and the bending moment coefficient formulation discussed in Reference 2.

Fin area requirements are calculated as a function of fineness ratio to satisfy a stability index criteria utilized in a broad spectrum of successful rigid and non-rigid airships.

Further details of the conventional airship aerodynamics methodology employed in the GASP are presented in Reference 2.

PROPULSION ANALYSIS (PERFORMANCE)

The propulsion analysis used in the GASP for both the conventional airships and hybrid vehicles is based on momentum theory and is modified by the use of propeller efficiency. The propeller efficiencies are based on data supplied by Hamilton Standard (Appendix F of Reference 2).

Horsepower required for the desired cruise velocity, at altitude, is first calculated. Sea level installed horsepower is determined assuming normal cruise power is 80 percent of the installed power.

If VTOL is required, the propulsion requirements are calculated from the lift thrust requirement. A vertical thrust 20 percent in excess of the gross weight minus static lift is used for VTOL engine sizing. Based on an examination of vehicle characteristics in Reference 6 combined with expected engine-out takeoff safety requirements, a minimum of four engines is allowed for VTOL vehicles. Based on the 20 percent takeoff thrust-to-weight factor, four-engine minimum, and expected degree of partial buoyancy of the VTOL vehicles, engine cross-shafting should not be required and was not assumed in the Phase I parametric study.

The maximum sea level installed horsepower requirement (cruise or VTOL) dictates the engine power requirements. Turboprop engines were used throughout the bulk of the parametric study. Engine specific fuel consumption was based on data for the General Electric T64 turboprop. Propulsion performance estimates were coordinated with the Hamilton Standard Division of United Aircraft Corporation.

PROPULSION SYSTEM WEIGHTS ANALYSIS

Bare engine weight estimates were derived from Reference 7. In the 3000 horsepower and greater range, this data is some 25 percent higher than weight-per-horsepower data for the GE T64-S4D1S turboprop Model E1176, and therefore may be slightly conservative.

Shaft torque is calculated at takeoff and is used to calculate gear box weight based on the data of Reference 8. Propeller weights are based on data supplied by Hamilton Standard.

Engine installation, accessories, nacelle weight, and an outrigger weight penalty are estimated to arrive at the total propulsion system weight estimate. Further details of the propulsion system performance and weights analysis used in the GASP are presented in Appendix F of Reference 2.

STRUCTURAL WEIGHTS ANALYSIS

No other single technology or perhaps even combination of technologies is of greater significance to the design and performance of airships than structural efficiency: adequate strength at minimum weight. Burgess in Reference 9 states: "The design of airships, particularly of the rigid type, is mainly a structural problem; and theoretical aerodynamics has nothing like the relative importance which it bears in airplane design."

Total vehicle empty weight or empty weight-to-gross weight ratio, EW/GW , is one of the most important factors in modern airship performance, either conventional or hybrid. Indeed, as will be shown in the parametric analysis results, it is the dominant factor in the configuration/performance optimization study.

With the current propulsion technology representing almost an order of magnitude improvement since the last rigids, the total vehicle nonpropulsive empty weight or structural weight becomes the driving factor in vehicle empty weight and hence performance.

Goodyear fully appreciates the importance of structural design and structural weight to the success of modern airships. Structural weight estimating equations for each type of conventional airship were updated using current materials technology plus the information gained during the last several decades in company-sponsored efforts on airship R&D and operations. The objective was twofold: First, to update the structural design data base to provide a starting point or baseline for further investigations of the cost effectiveness of more advanced structural design concepts (such as composite structures) and, second, to parameterize the resulting structural design and weight characteristics into a detailed set of weight estimating equations for the GASP during the Phase I study.

Much of the original structural weight estimating relationships were derived by Mr. K. Bauch (Reference 10) with the direction and consultation of Dr. K. Arnstein. Because of the overwhelming importance of the structural weight characteristics and structural weight estimating relationships to the configuration/performance optimization and tradeoff study results, this technology area was emphasized during the Phase I study.

The complete derivation of the weight estimating relationships (WER's) for each type airship is presented in Appendix D of Reference 2 and summarized in Tables I through V.

TABLE I - WEIGHT ESTIMATING RELATIONSHIP, WER SUMMARY:

RIGID AIRSHIPS

Main frames	$W_1 = (a + b\rho v)V^{4/3}(L/D)^{-4/3}$
Intermediate frames	$W_2 = \left[cM_A(L/D)^{-2/3}V^{-1/3} + dV + \right. \\ \left. \rho V^{1/3}(L/D)^{-1/3} \right] \left[6.2762V^{1/3}(L/D)^{2/3} - 11 \right]$
Diagonal wires	$W_3 = K_1M_A + K_2V^{4/3}(L/D)^{2/3}$

TABLE I - WEIGHT ESTIMATING RELATIONSHIP, WER SUMMARY:

RIGID AIRSHIPS (CONT'D)

Longitudinals	$W_4 = K_3 M_A (L/D) + K_4 V^{4/3} (L/D)^{2/3}$
Outer cover	$W_5 = K_5 V^{2/3} (L/D)^{1/3} \rho^{1/2} v$
Outer cover wires	$W_6 = K_6 V^{2/3} (L/D)^{1/3} \rho v^2$
Gas bag wires and netting	$W_7 = K_7 V$
Gas cells	$W_8 = V^{2/3} [K_8 (L/D)^{1/3} + K_9 (L/D)^{-2/3}]$
Gas valves	$W_9 = K_{10} V$
Stern and bow	$W_{10} = K_{11} V$
Misc gas cells, valves	$W_{11} = K_{12} V$
Misc hull weight	$W_{12} = K_{13} V$
Empennage and cruciform	$W_{13} = K_{14} u v \rho V^{1/3} (L/D)^{-1/3} A$
Corridors, control car, crew quarters	$W_{14} = K_{15} V^{1/3} (L/D)^{2/3}$
Mooring and handling	$W_{15} = K_{16} V$

Effect of flight heaviness

Main frames	$W_{16} = K_{17} H$
Intermediate frames	$W_{17} = K_{18} H V^{1/3} (L/D)^{-1/3} [6.2762 V^{1/3} (L/D)^{2/3} - 11]$
Diagonal shear wires	$W_{18} = K_{19} H V^{1/3} (L/D)^{2/3}$

TABLE I - WEIGHT ESTIMATING RELATIONSHIP, WER SUMMARY:

RIGID AIRSHIPS (CONT'D)

Longitudinal	$W_{19} = K_{20} H V^{1/3} (L/D)^{5/3}$
Misc hull weight	$W_{20} = K_{21} H$

where*

V = volume
 L/D = length/maximum diameter
 M_A = aerodynamic moment
 ρ = mass air density
 v = airship velocity
 u = gust velocity
 H = airship heaviness
 a, b, c, d = constants

$K_1 - K_{21}$ = proprietary constants

TABLE II - NON-RIGID AIRSHIP WER SUMMARY

Envelope	$W_1 = K_7 V^{2/3} (L/D)^{1/3} \left\{ K_8 V^{1/3} (L/D)^{-1/3} \right.$ $\left[K_9 V^{-1} (L/D) M_A + K_{10} V^{1/3} (L/D)^{-1/3} + \right.$ $\left. K_{11} \rho v^2 + K_{12} \right] + K_{13} \left. \right\}$
Suspension system	$W_2 = K_{14} \rho \dot{V} + K_{15} \rho v V^{2/3} (L/D)^{1/3}$
Bow stiffening	$W_3 = K_{16} V$
Ballonets and air lines	$W_4 = K_{17} V$
Miscellaneous envelope	$W_5 = K_{18} V$

*Nomenclature also applies to Tables II through V.

TABLE II - NON-RIGID AIRSHIP WER SUMMARY (CONT'D)

Empennage	$W_6 = K_{19} A_{uv} \rho V^{1/3} (L/D)^{-1/3}$
Pressure system	$W_7 = K_{20} V$
Car structure and outriggers	$W_8 = K_{21} \rho V + K_{22} \rho V^{2/3} (L/D)^{1/3}$
Landing gear	$W_9 = KV$
Effect of heavy flight	$W_H = K_{29}^H \left[K_{30} V^{1/3} (L/D)^{5/3} + 1 \right]$

TABLE III - METALCLAD I WER SUMMARY

Main frames	$W = (a + b \rho V) V^{4/3} (L/D)^{-4/3}$
Intermediate frames	$W = \left[c M_{40} (L/D)^{-2/3} V^{1/3} + d V \right] \left[6.2762 V^{1/3} (L/D)^{2/3} - 11 \right]$
Longitudinals	$W = K_1 M_{40} (L/D)$
Outer cover	$W = V \left[K_5 V^{-1} (L/D) M_A + K_6 V^{1/3} (L/D)^{-1/3} + K_7 \rho V^2 + K_8 \right]$
Gas diaphragm	$W = K_2 V^{2/3} (L/D)^{-2/3}$
Gas valves	$W = K_{10} V$
Stern and bow	$W = K_{11} V$
Misc gas cells, valves	$W = K_{12} V$
Misc hull weight	$W = K_{13} V$
Empennage and cruciform	$W = K_{14} u v \rho V^{1/3} (L/D)^{-1/3} A$
Control car, corridors	$W = K_{15} V^{1/3} (L/D)^{2/3}$

TABLE III - METALCLAD 1 WER SUMMARY (CONT'D)

Mooring and handling	$W = K_{16} V$
Pressure system	$W = K_{20} V$
Ballonets and air lines	$W = K_{17} V$
Effect of flight heaviness	$W_H = H \left[K_4 V^{1/3} (L/D)^{5/3} + K_5 \right]$

TABLE IV - METALCLAD 2 WER SUMMARY

Main frames	$W = 1/2(a + b\rho v)V^{4/3}(L/D)^{-4/3}$
Intermediate frames	$W = 1/4(a + b\rho v)V^{4/3}(L/D)^{-4/3}$ $\left[6.2762V^{1/3}(L/D)^{2/3} - 11 \right]$
Longitudinal	$W = K_1 M_{40} (L/D)$
Outer cover	$W = V \left[K_5 V^{-1} (L/D) M_A + K_6 V^{1/3} (L/D)^{-1/3} + K_7 \rho v^2 + K_8 \right]$
Gas valves	$W = K_{10} V$
Stern and bow	$W = K_{11} V$
Misc gas cells, valves	$W = K_{12} V$
Misc hull height	$W = K_{13} V$
Empennage and cruciform	$W = K_{14}^{uv} \rho V^{1/3} (L/D)^{-1/3} A$
Control car, corridors	$W = K_{15} V^{1/3} (L/D)^{2/3}$
Mooring and handling	$W = K_{16} V$
Ballonets, air lines	$W = K_{19} V$
Pressure system	$W = K_{20} V$
Effect of flight heaviness	$W_H = H \left[K_4 V^{1/3} (L/D)^{5/3} + K_5 \right]$

TABLE V - METALCLAD 3 WER SUMMARY

Main frames	$W = 1/2(a + b\rho v)V^{4/3}(L/D)^{-4/3}$
Intermediate frames	$W = 1/4(a + b\rho v)V^{4/3}(L/D)^{-4/3}$ $\left[6.2962V^{1/3}(L/D)^{2/3} - 11\right]$
Longitudinals	$W = K_1 M_{40}(L/D)$
Outer cover	$W = V\left[K_5 V^{-1}(L/D)M_A + K_6 V^{1/3}(L/D)^{-1/3} + K_7 \rho v^2 + K_8\right]$
Gas cells	$W = V^{2/3}\left[K_8(L/D)^{1/3} + K_9(L/D)^{-2/3}\right]$
Gas valves	$W = K_{10}V$
Stern and bow	$W = K_{11}V$
Misc gas cells, valves	$W = K_{12}V$
Misc hull weight	$W = K_{13}V$
Empennage and cruciform	$W = K_{14}uv\rho V^{1/3}(L/D)^{-1/3}A$
Control car	$W = K_{15}V^{1/3}(L/D)^{2/3}$
Mooring and handling	$W = K_{16}V$
Pressure system	$W = K_{20}V$
Effect of flight heaviness	$W_H = H\left[K_4 V^{1/3}(L/D)^{5/3} + K_5\right]$

CONVENTIONAL AIRSHIP PARAMETRIC ANALYSIS

Introduction

The parametric performance analysis and configuration optimization study of conventional airships is based on the geometrical, aerostatic, aerodynamic, propulsion, and structural weights analyses of the preceding subsections and Reference 2. The results of the conventional airship parametric analysis provide not only a basis

for comparison with the delta planform hybrid vehicle results but also provide insight into the fundamental interactions of aerodynamics, aerostatics, propulsion, and structural efficiencies that result in "optimum" airship performance.

A few words of elaboration are worthwhile at the outset regarding the word "optimum". Reference is frequently made throughout this section to "optimum" β , "optimum" V_C , and "optimum" (l/d) . At best, the results represent local rather than global "optimums" and a more accurate description would surely be "the value of a given parameter (say V_C) that maximizes the specified figure of merit for the specified set of conditions and constraints." A great many factors influencing the performance of airship vehicles have not been included in this limited analysis. Admitting these limitations and true implication of "optimum," it is nonetheless used frequently throughout this section for the sake of brevity in discussing the results.

The major portion of the conventional airship parametric analysis dealt with five primary variables over the following range of values:

1. Type of construction (rigid, non-rigid, pressurized metalclad)
2. Gross weight, GW (from 2268 kg to 2,721,600 kg, or 5000 to 6,000,000 lb)
3. Static lift-to-gross weight ratio, β (1.0 to 0.2)
4. Cruise velocity, V_C (36.04 m/s to 92.66 m/s, or 70 knots to 180 knots)
5. Fineness ratio, length/diameter, l/d (3 to 8)

Initially, the criteria or figure of merit for the Phase I study was productivity in terms of useful load times cruise velocity normalized by empty weight (useful load ton-miles per hour per ton empty weight), $UL \times V_C / EW$. This figure of merit was chosen as a rough measure of operating income relative to acquisition cost. Range is not included in this figure of merit. This was purposely done to eliminate range as an independent variable in the configuration optimization tradeoff study. The configuration performance/optimization results are strongly dependent on range. Failure to incorporate range (fuel consumption) into the performance evaluation will result in misleading and/or

erroneous results. Thus, the bulk of the final parametric study results is presented in terms of payload ton-miles per hour at specified range values.

The overall approach to the conventional airship parametric study was as follows:

1. Optimize vehicle fineness ratio for rigid and non-rigid vehicle over the gross weight range. Figure of merit (FOM) for fineness ratio optimization study equals $(UL \times V_C / EW)$
2. Determine the best productivity metalclad of the three types discussed in the structural design description and optimize the fineness ratio for this vehicle.
3. Determine the "optimum" β and V_C ; that is, the β and V_C for maximum productivity for each of the three vehicle types over the range of gross weights where the particular type of construction appears most competitive.
4. Compare the overall performance of the three types of construction.

The type of construction (rigid, pressurized non-rigid, and pressurized metalclad) concepts have essentially been included as primary study variables, rather than as design options as specified in the statement of work. The justification for this approach is that few questions have created more controversy during the history of LTA as "which type of LTA construction is best over which range of gross weights or volumes." The results in this report will not resolve this question. The complete answer can only be obtained once a specified set of mission requirements has been defined and all factors considered that ultimately determine the worth of one concept versus another. These factors must include not only the acquisition cost, operating cost, and total life cycle cost or return on investment but also all critical problems unique to LTA vehicles; ground handling, cargo transfer, flight control and handling characteristics; and adaptability to the many promising advanced technology design options such as boundary layer control, stern propulsion, and artificial super heat.

Thus, the final answer to which construction concept is best must ultimately be resolved via more detailed economic/mission analysis studies. However, the performance analysis results that follow offer considerable insight

into the relative performance capability of the alternative design/construction approaches described in the preceding subsection. In many cases, distinct regions are indicated where one concept appears superior to the others for the specified figure of merit. In this respect, the subsequent analysis of the conventional LTA vehicles is possibly unique in LTA history.

The three major construction/design approaches are compared on an equal basis using comparably derived weight equations, propulsion systems, aerodynamic, and aerostatic relationships over a gross weight (volume) range from virtually the smallest manned vehicle, to sizes with gross lift approximately equal to the Saturn V launch vehicle. In the critical technology area of structural weight estimating relationships, the equations used in the analysis probably are the most detailed and comprehensive ever assembled for a "head-to-head" comparison based on equal design assumptions and constraints. The results offer a uniform and unbiased starting point for further evaluation in the detailed mission/economic analysis in Phase II and subsequent studies.

There is an additional purpose to the detail of the analysis and results presented on the rigid airship. The modified delta planform hybrid discussion following the conventional airship discussion has many structural design similarities to the conventional rigid airship. Thus, the results of the rigid airship heaviness tradeoff studies will be used extensively to interpret the results of the hybrid optimization study.

Fineness Ratio Tradeoff Study

The first parameter considered in the conventional airship configuration optimization study was vehicle length-to-diameter or fineness ratio, l/d . Baseline assumptions for this performance evaluation are listed below:

1. Neutrally buoyant airships
2. Turboprop propulsion
3. Design altitude, $h_D = 1524\text{m}$ (5000 ft)
4. Unit gas lift $\Delta\rho = 0.9932 \text{ kg/cu m}$ (0.062 lb/cu ft): helium at 94 percent purity
5. Wind velocity, $V_W = 0$

6. Conventional propellers
7. Propeller efficiency $\eta_P = 0.9$
8. Hull efficiency, η_H $\frac{\text{lifting gas volume}}{\text{external hull volume}}$
 - a. Rigid, $\eta_H = 0.94$
 - b. Metalclad, $\eta_H = 0.97$
 - c. Pressure fabric, $\eta_H = 1.0$
9. Neutrally buoyant flight maintained whenever static lift equals vehicle gross weight by consumption of internal lifting gas

Initially, it was felt that some computer expense could be saved by running the basic data at zero wind speed, $\Delta V_W = 0$, and "hand" calculating the correction to the FOM as a function of wind speed. This proved much too time consuming, and the design wind speed was changed to 7.722 m/s (15 knots) for all performance evaluations subsequent to the conventional airship fineness ratio study.

Initial results of the (l/d) runs indicated that the pressurized airship (l/d) range of interest should be limited to 3 to 4.5 and for the rigid about 4 to 8. At the low fineness ratios, horizontal and vertical tail size must be increased to achieve acceptable stability. Lack of inclusion of the increased tail area requirements would result in erroneous vehicle empty weight data and possibly affect the optimum fineness ratio results. Tail area requirements are calculated in the GASP to maintain a constant stability index as discussed in Appendix E of Reference 2.

The results of the l/d tradeoff study for the rigid and pressurized fabric analysis are shown in Figures 7 and 8, respectively. The following conclusions can be drawn from these figures:

1. The optimum l/d for rigid airships is primarily a function of gross weight or volume.
2. The optimum l/d for pressurized (dacron) fabric airships is very insensitive to either volume or velocity.

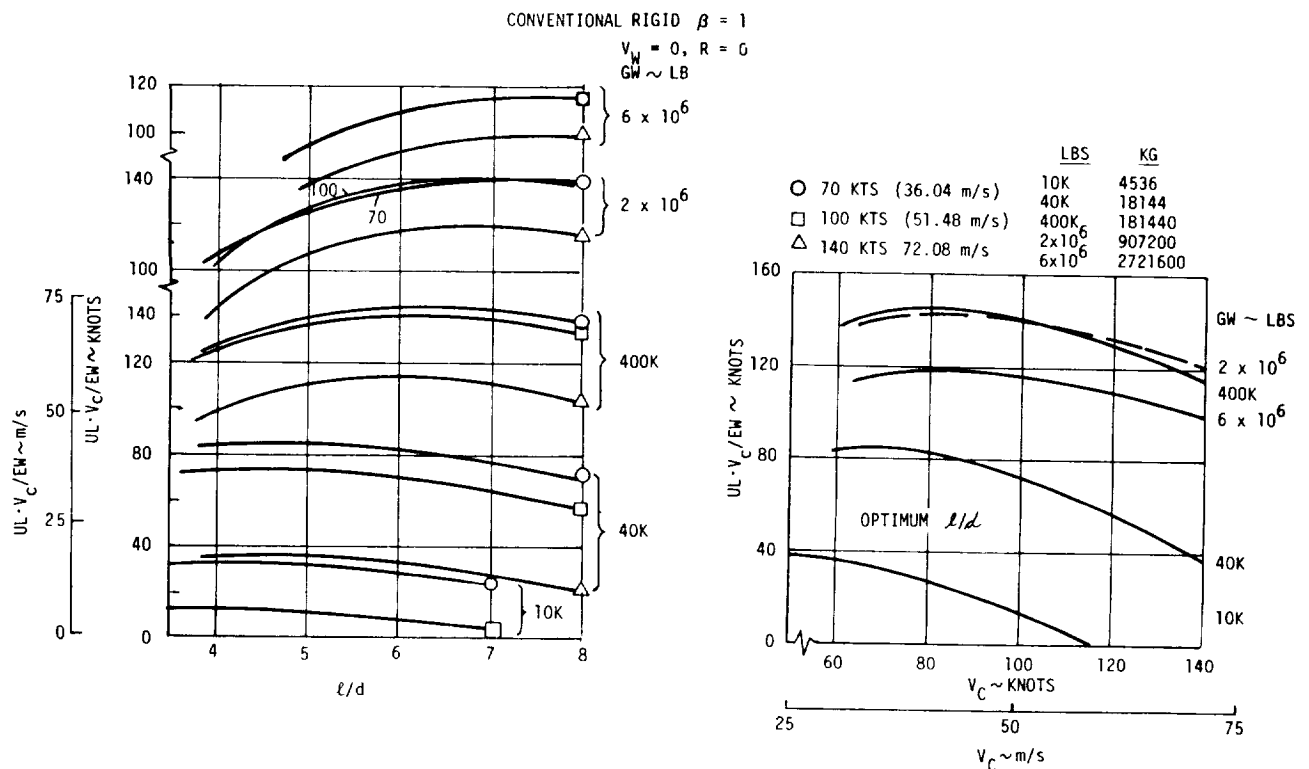


Figure 7 - Conventional Rigid Airship Fineness Ratio Study Results

3. In the region of l/d optimum for any given gross weight, $UL \times V_C / EW$ is relatively insensitive to changes of l/d on the order of ± 0.5

For the non-rigid pressurized fabric, $UL \times V_C / EW$ continues to increase over the study gross weight range with only a slightly reduced rate at the largest gross weights. As discussed in the structural weights section, a new seaming approach is required for pressurized fabric airships above approximately 339,840 cu m (12×10^6 cu ft), or about 272,160 kg (600,000 lb).

The "optimized" $UL \cdot V_C / EW$ for the rigid and pressurized non-rigid fabric is compared in Figure 9 as a function of gross weight. In terms of $UL \cdot V_C / EW$, the rigid becomes superior at 45,360 kg (1×10^5 lb). At larger gross weights equal to or greater than 272,160 kg (600,000 lb), the non-rigid will require a

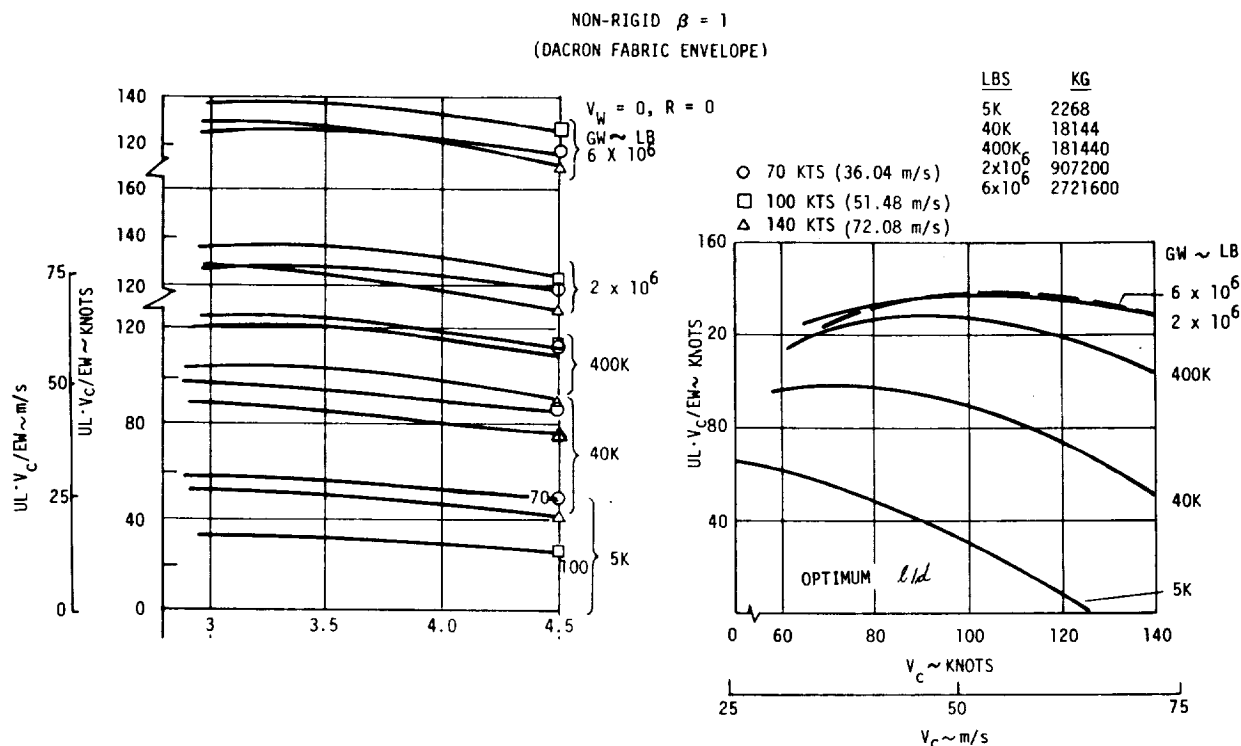


Figure 8 - Pressurized Fabric Airship Fineness Ratio Study Results

new seaming technology and hence is shown only as a dashed line subject to further fabrication technology development.

At the larger gross weights, the rigid airship unit performance begins to degrade somewhat due to the dependence of several major structural weight categories on volume to the 4/3 power.

Metalclads, 1/d Optimization Study

The three metalclad construction airships were analyzed on the same basis as the rigid and pressurized fabric airships. The results for Metalclad 2 are shown in Figure 10, which shows that the optimum 1/d is again primarily dependent on volume and independent of velocity. The clear superiority (in terms of $UL \cdot V_C / EW$) of the construction approach in Metalclad 2 is shown in Figure 11.

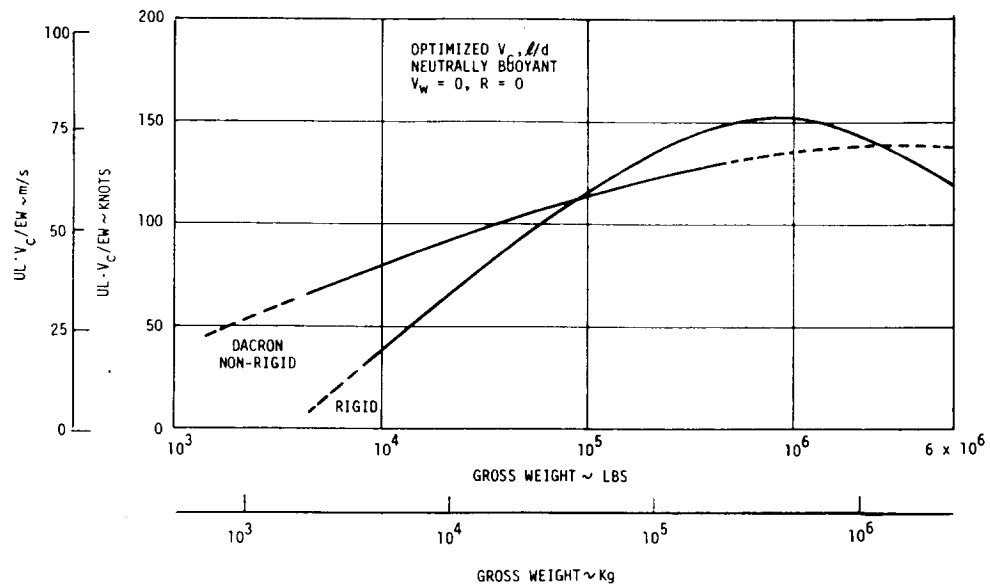


Figure 9 - Rigid and Non-rigid $UL \cdot V_c / EW$ as a Function of Gross Weight

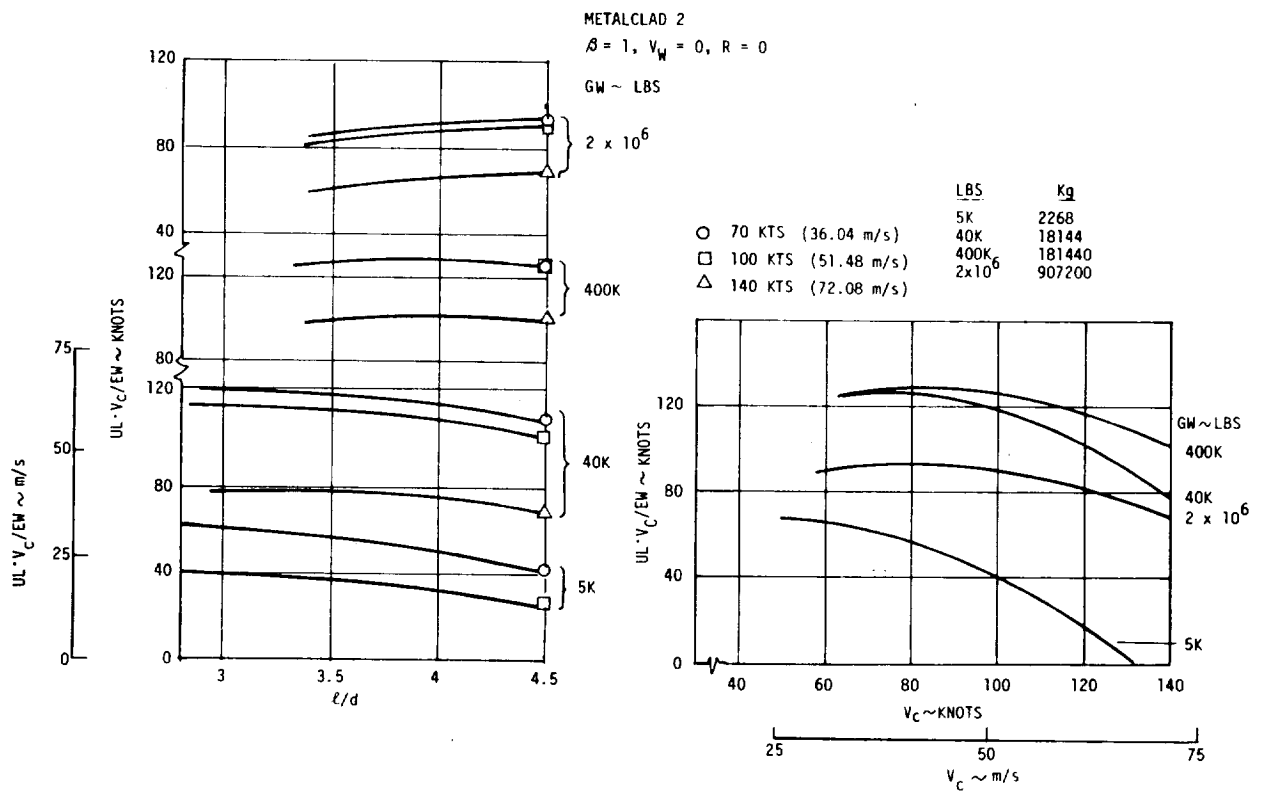


Figure 10 - Metalclad Airship Fineness Ratio Study Results

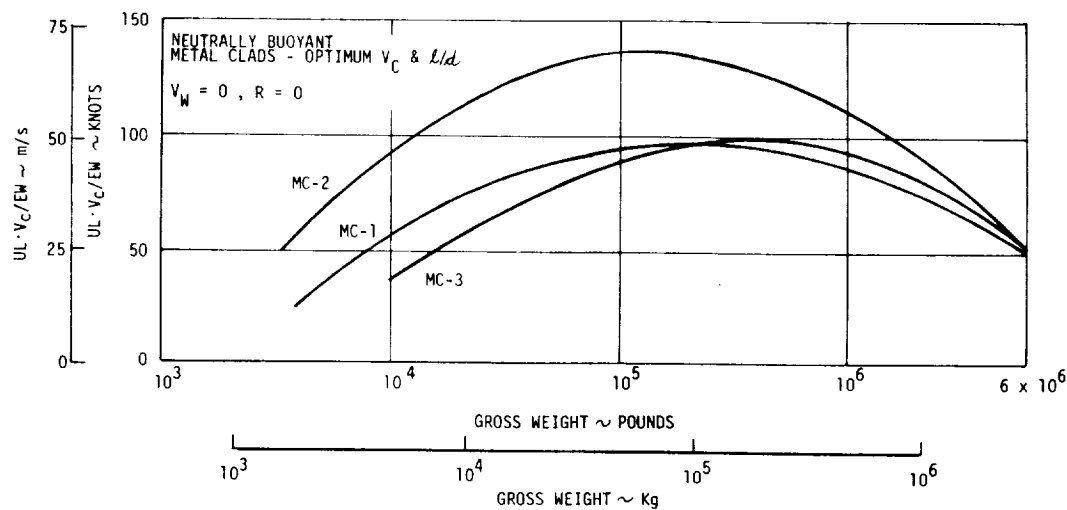


Figure 11 - Comparison of Metalclad Concepts $UL \cdot V_C/EW$ as a Function of Gross Weight

Comparison of the metalclad $UL \cdot V_C/EW$ with the rigid and non-rigid results also indicates that Metalclad 2 appears very promising, in terms of the $UL \cdot V_C/EW$ figure of merit, in the intermediate gross weight range.

The final resulting "optimum" (l/d) for conventional rigid (R), pressurized dacron non-rigid (D-NR), and pressurized metalclad (Metalclad 2) is presented in Figure 12. For the D-NR, (l/d) optimum is 3.25 ± 0.25 for all volumes. For the rigids, (l/d) optimum increases considerably with volume, and Metalclad 2 displays a combination of both vehicle characteristics based on the structural design description of the preceding subsection.

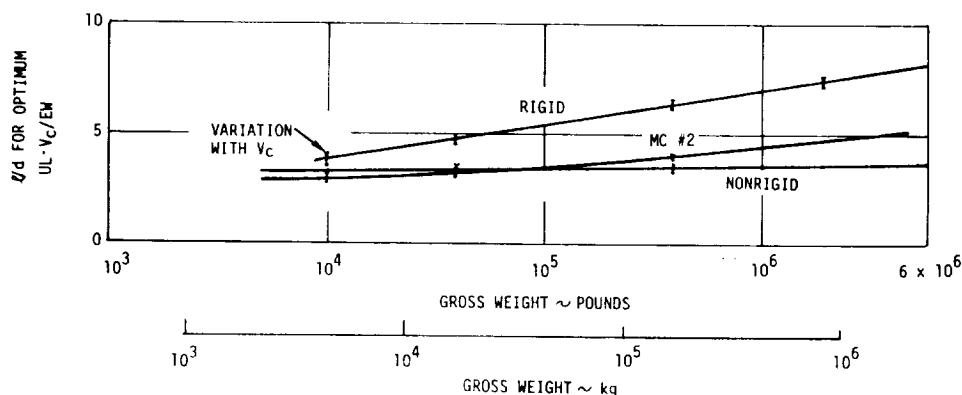


Figure 12 - Optimum Fineness Ratio for Neutrally Buoyant Airships as a Function of Gross Weight

The basic pressurized non-rigid weight equation was modified for the material characteristics of a Kevlar envelope. The $(1/d)$ values from the dacron envelope results were used to calculate the $UL \cdot V_C/EW$ performance capability of the Kevlar non-rigid. The final optimized $UL \cdot V_C/EW$ for the rigid, dacron, and Kevlar non-rigids and Metalclad 2 are compared in Figure 13 as a function of GW. To clearly illustrate the relative structural efficiency of the basic construction types, the vehicle structural weight-to-gross weight characteristics are compared in Figure 14.

In calculating these vehicle performance values, two changes were incorporated in the baseline performance assumptions:

1. Wind speed, $V_W = 7.722 \text{ m/s}$ (15 knots)
2. Design speed, $V_D = 1.08$ (cruise speed)

When a cruise speed such as V_C is defined, it is the relative groundspeed into a head wind of V_W .

The importance of structural efficiency, W_{str}/W_{gross} , to airship performance was discussed earlier. In addition, several key observations can be made from Figure 14.

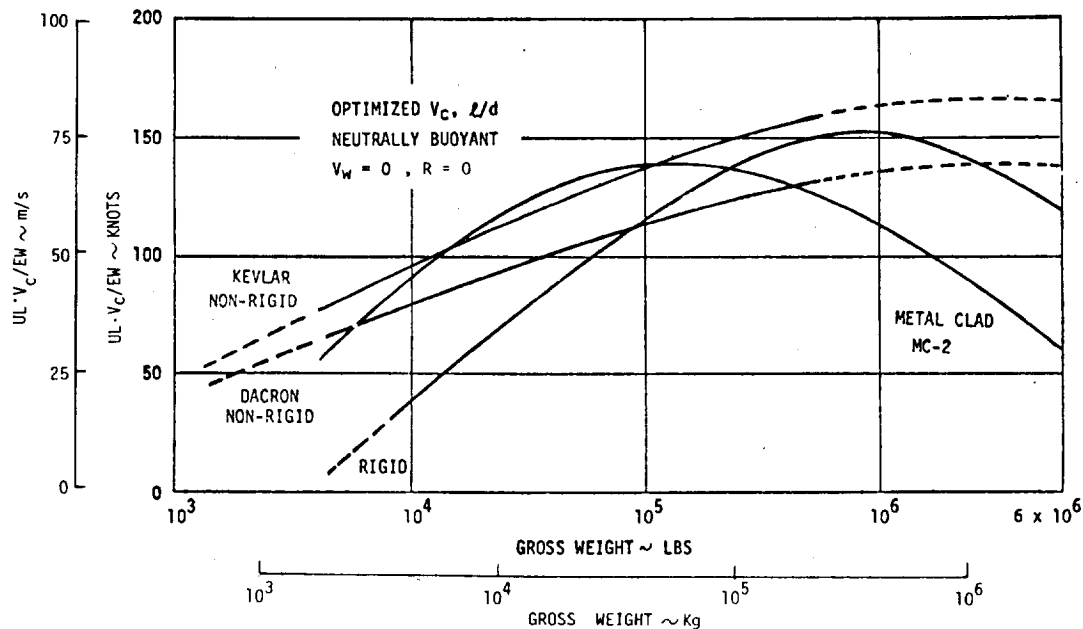


Figure 13 - Neutrally Buoyant Airship $UL \cdot V_C/EW$

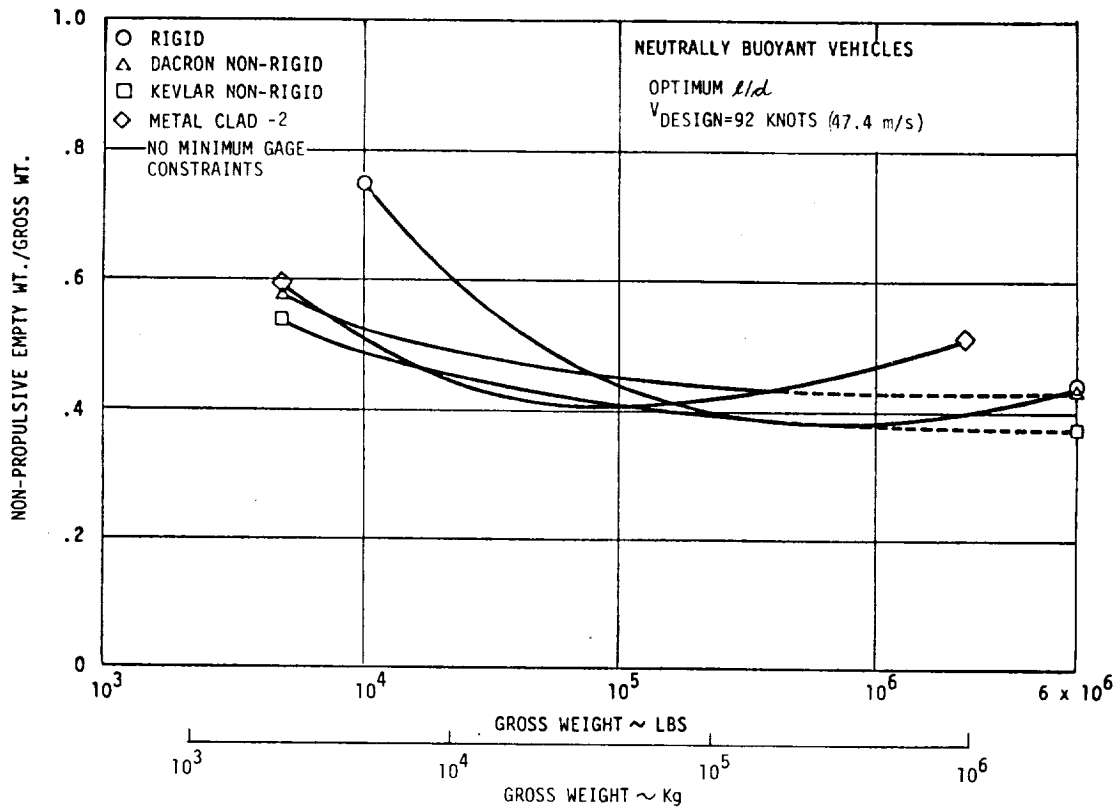


Figure 14 - Neutrally Buoyant Airship Structural Efficiency Comparison

1. Vehicle structural weight-to-gross weight ratios of 0.4 or less can be achieved over a very large gross weight range.
2. Vehicle structural efficiency definitely improves as gross weight is increased up to some "optimum" gross weight and then slightly decreases as gross weight is increased. The reduction in structural efficiency (increase in W_{str}/GW) is not extreme of the study gross weights range.
3. Each type of airship construction appears to be "optimum" from a $UL \cdot V_C/EW$ or structural efficiency standpoint over some gross weight range.

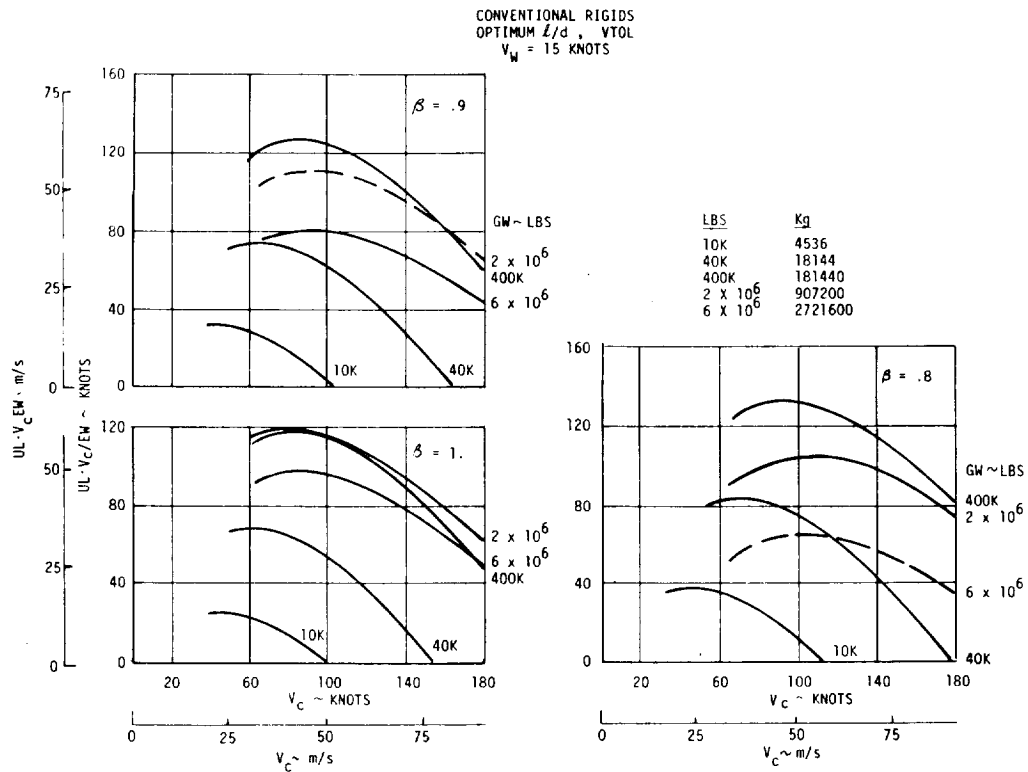


Figure 15 - Initial Heaviness Trade Study Results - Conventional Rigid Airship

The increase in the metalclad EW/GW at the intermediate gross weights can possibly be explained by the nature of the structural design concept assumed and the "optimum" (l/d) found for Metalclad 2. Per the structural design description, Metalclad 2 is a pressurized airship similar to a non-rigid (optimum $l/d \approx 3.25$) incorporating several structural components of a rigid airship whose optimum (l/d) increased significantly with gross weight. At low (l/d)'s, on the order of 3 to 4, and large gross weights, the rigid airship components are considerably "off optimum" as shown in Figure 7. Several important qualifications must be added to the above conclusions.

First, a best or optimum construction approach cannot be defined on the basis of structural efficiency alone or on the basis of any "performance only" figure of merit.

The true "best" vehicle must be defined on the basis of cost effectiveness, cost benefit, or rate of return on investment considering all aspects of the

vehicle life cycle or total cost, R&D cost, and performance capability for a specified mission or spectrum of mission and operational requirements. Further considerations, such as ground handling, manufacturing and assembly considerations, and safety, must be considered in the ultimate selection of one type of construction versus another.

Second, the data of Figures 12 and 14 should not be considered as the best achievable technological capability for future airships. These data are intended to represent a reasonable update of airship technology based on rather conventional structural design and materials concepts. As such, they become a point of departure or baseline from which to evaluate more advanced structural design/material applications such as advanced composites and filament structures.

One such approach, a sandwich monocoque rigid airship, was briefly analyzed near the end of Phase I and is discussed at the end of this subsection. Regarding some of the more exotic structural design and material concepts, however, these technologies can only be thoroughly evaluated on a cost effectiveness basis relative to the more conventional construction for a specified set of mission requirements and economic figures of merit.

Finally, no minimum gage constraints have been included in the WER's and will change the rigid and metalclad results at the low gross weights.

Conventional Airship Heaviness Tradeoff Studies Based on $UL \cdot V_C / EW$

The original plan for the heaviness tradeoff study for conventional airships was to consider static lift-to-gross weight ratios, β , of 0.9 to 0.8. Preliminary results in Figure 15 for the rigid airship over this range indicated that continued improvements might result in the $UL \cdot V_C / EW$ figure of merit if lower β 's were considered for rigids of gross weight less than 907,200 kg (2×10^6 lb). For the larger rigids, heavy flight reduced the performance. Typical results of reducing β to 0.65, 0.5, and 0.3 are shown in Figure 16.

The results of Figure 16 were somewhat unexpected: optimum β 's of approximately 0.3 or less for an Akron gross weight airship and optimum cruise velocities of approximately 77.22 m/s (150 knots). Similar trends were being

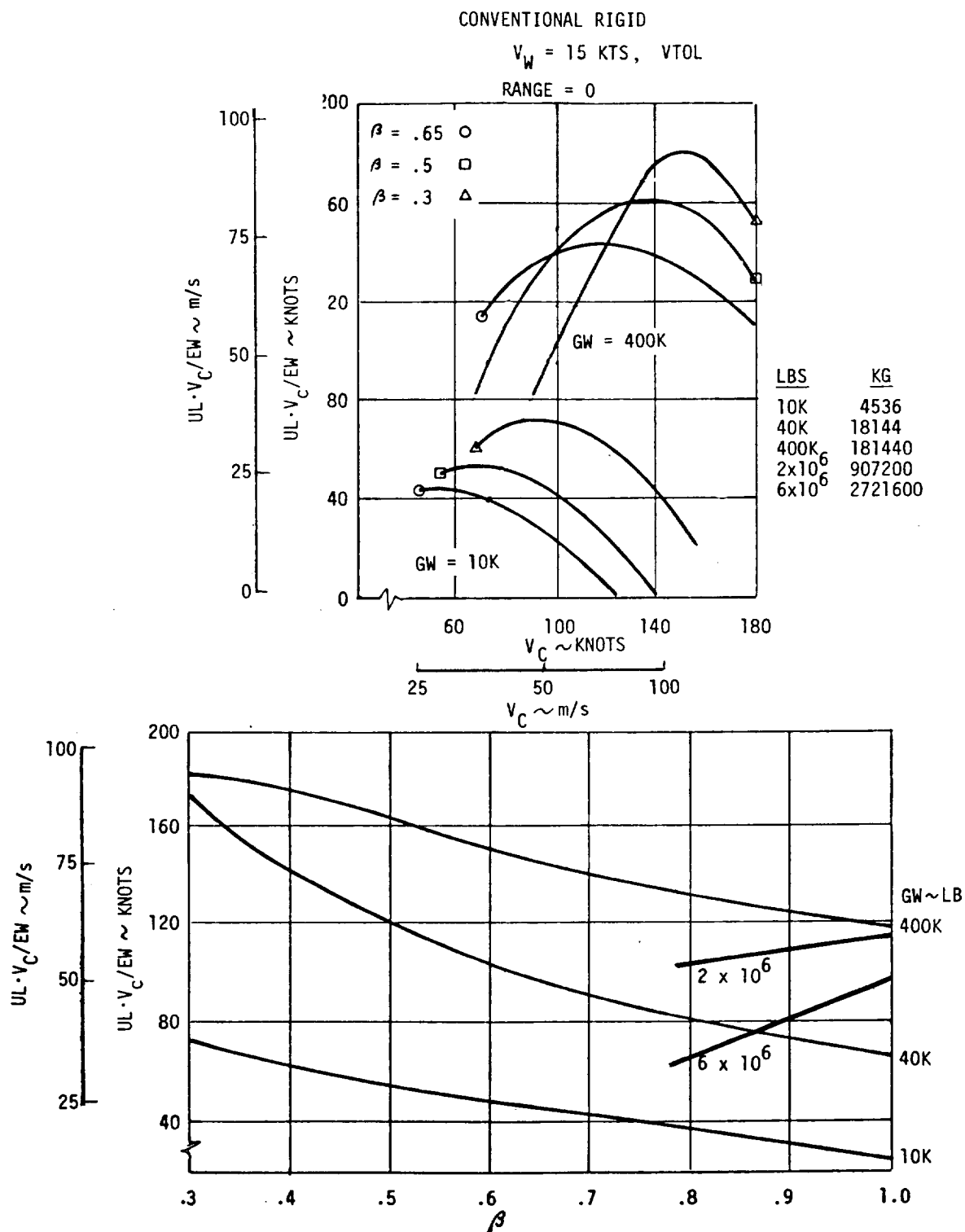


Figure 16 - Conventional Rigid Heaviness Trade Study Results
 Based on $UL \cdot V_c / EW$

obtained for some of the early hybrid WER checkout runs that were just getting underway. Several possible reasons for these results were considered:

1. Improved horsepower per unit weight of turboprop propulsion reducing the importance of propulsion system required horsepower, hence vehicle drag, hence cruise speed.
2. Higher cruise speeds allowing more efficient use of aerodynamic lift (lower cruise lift coefficient and drag due to lift) for a given heaviness.
3. A transportation productivity figure of merit much different from measures of worth traditionally used in airship design.
4. A transportation productivity figure of merit independent of range.

A few calculations of the payload ton-miles per hour at given range increments for the Akron size airship clearly demonstrated the importance of range of the "optimum" β and V_C . Therefore, range was a parameter in the final β and V_C optimization runs.

The first three reasons appear, however, to be quite valid.

Conventional Airship Heaviness Optimization Study Based on Payload Ton-Miles Per Hour as a Function of Range

Recognizing the sensitivity of the optimum β and V_C to range, the range capabilities as a function of gross weight for neutrally buoyant, $\beta = 1.0$, airships were reviewed in conjunction with the expected mission-related performance requirements. This resulted in the "design" range values for figure of merit evaluation shown on the next page.

<u>Gross Weight</u>		<u>Design Range for FOM Evaluation</u>
<u>kg</u>	<u>lb</u>	<u>(statute miles)*</u>
2,268	5,000	0, 100
18,144	40,000	0, 500, 1500
181,440	400,000	0, 1500, 5000
907,200	2×10^6	0, 3000, 5000
2,721,600	6×10^6	0, 3000, 5000

Vertical takeoff was assumed for all heavy airships via tilting turboprops. The complete set of baseline design and performance assumptions for the "final" β and V_C optimization study are listed below:

1. Tilting turboprop engines for VTOL
2. Conventional propellers using Hamilton Standard propeller performance data
3. Propeller efficiency, $\eta_P = 0.90$
4. Hull efficiency: NR; $\eta_H = 1.0$
MC; $\eta_H = 0.97$
R; $\eta_H = 0.94$
5. Design altitude = 1524 m (5000 ft)
6. Wind velocity = 7.72 m/s (15 knots)
7. Propulsion sized for maximum sea level installed horsepower required for cruise or for VTOL requirements, whichever is greater
8. Thrust to weight (weight heaviness = $(1-\beta) \times$ gross weight) = 1.2 at takeoff
9. Neutrally buoyant flight maintained if achieved during flight by consumption of internally stored buoyancy control gas (see Appendix H of Reference 2)
10. V_{cruise} - Ground speed into 7.72-m/s (15-knot) headwind
11. V_{design} = Design speed for structural weight calculations = $1.08 \times$ cruise velocity ($V_C + V_W$)

* km/SM equivalents are 100 SM = 160.9 km, 500 SM = 804.5 km, 1500 SM = 2413.5 km, 3000 SM = 4827 km, 5000 SM = 8045 km.

12. Optimum fineness ratio as defined in fineness ratio tradeoff studies
13. All nonstatic lift required for cruise supplied by aerodynamic lift; no propulsive lift component during cruise

Rigid Airships

Typical results for a 18,144-kg (40,000-lb) gross weight conventional rigid are presented in Figure 17 and are summarized in Figure 18 in terms of payload ton-miles per hour as a function of cruise velocity at specified values of range and β . The trend of FOM with respect to β is not changed by including range as a parameter although the optimum cruise velocity is reduced. Specifically, for this "low" gross weight airship, productivity in payload ton-miles per hour or useful load ton-miles per hour per ton empty weight increases significantly as β is reduced.

As shown in Figure 18, for this "small" airship, even to ranges of 1500 miles, the optimum β trend is to zero; that is, the optimum productivity FOM vehicle configuration is converging to all propulsive lift for VTOL and all aerodynamic lift for cruise.

As will be discussed at the conclusion of this subsection, this trend is precisely what should be expected. In fact, this result is one of the most interesting interactions of aerodynamic, acrostatic, structural, and propulsive efficiencies identified as a result of the parametric study.

Figure 19 presents representative results of the variation of payload ton-miles per hour for a large gross weight rigid airship as a function of range, V_C , and β . Two observations should be made from this figure. First, at range = 0, the FOM trend with β is the same as for a small airship. However, this trend is rapidly reversed at larger ranges and further substantiates the requirement for a range-dependent FOM. At reasonable ranges for an airship of this size, heavy flight does not improve productivity but rather reduces it. This fact is clearly indicated in Figure 20, where the maximum productivity for two large gross weight airships is presented as a function of range and β . Heaviness offers no FOM improvement at 2,721,600 kg (6×10^6 lb). At 907,200 kg

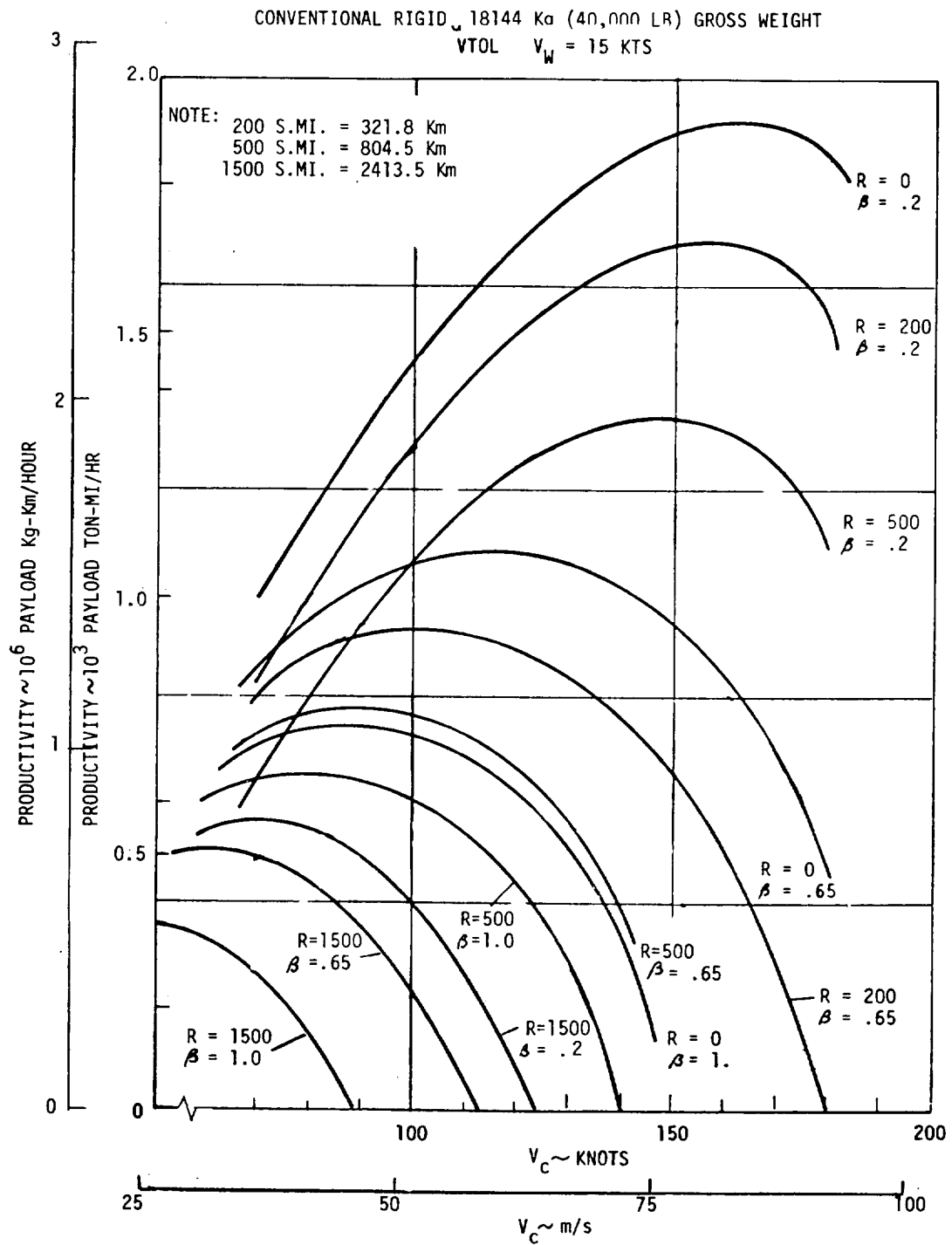


Figure 17 - Effect of Range and β on Productivity - 18,144-kg (40,000-Lb) Conventional Rigid Airship

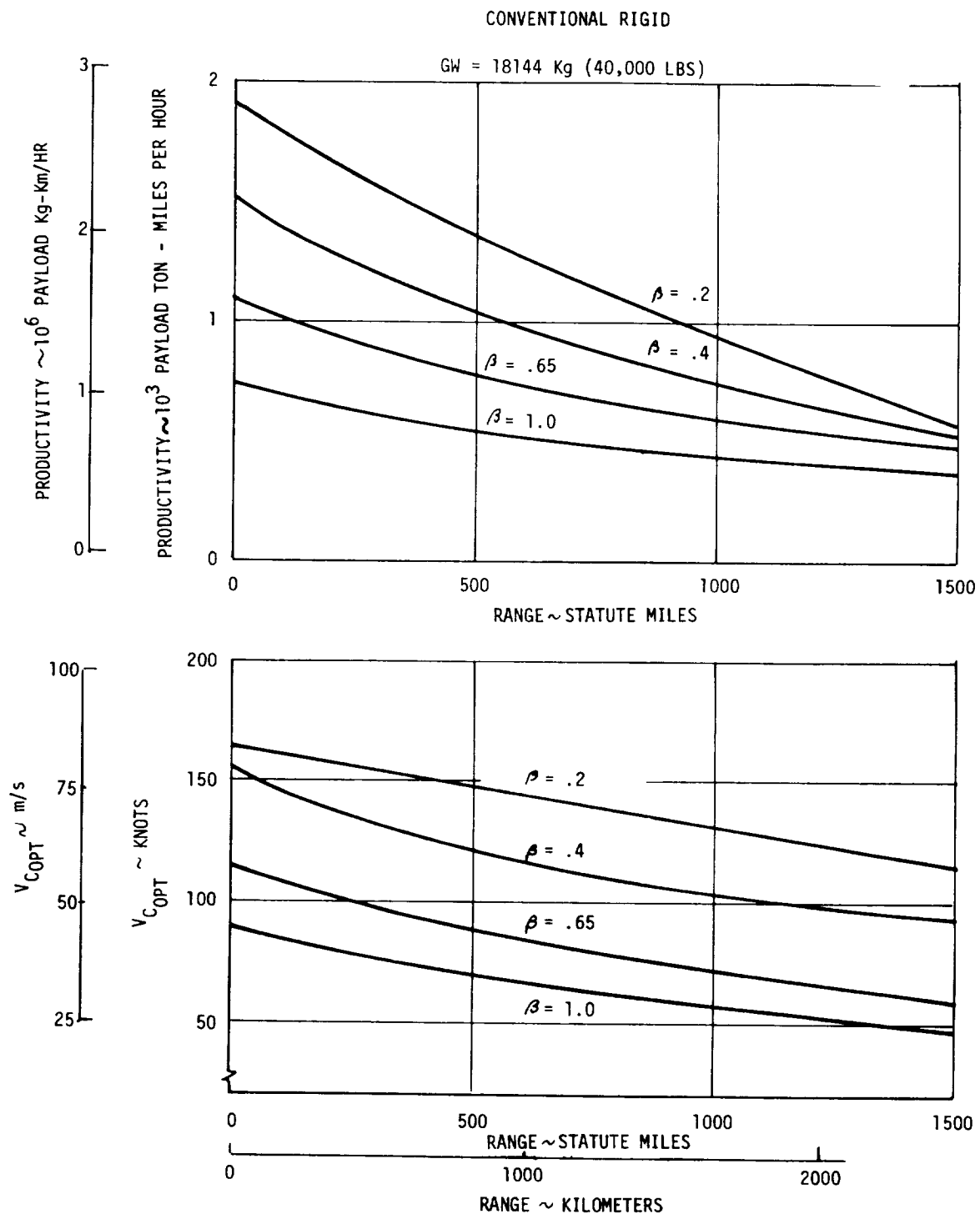


Figure 18 - Optimized Productivity and Cruise Velocity - 18,144 kg (40,000 Lb) Conventional Rigid Airship

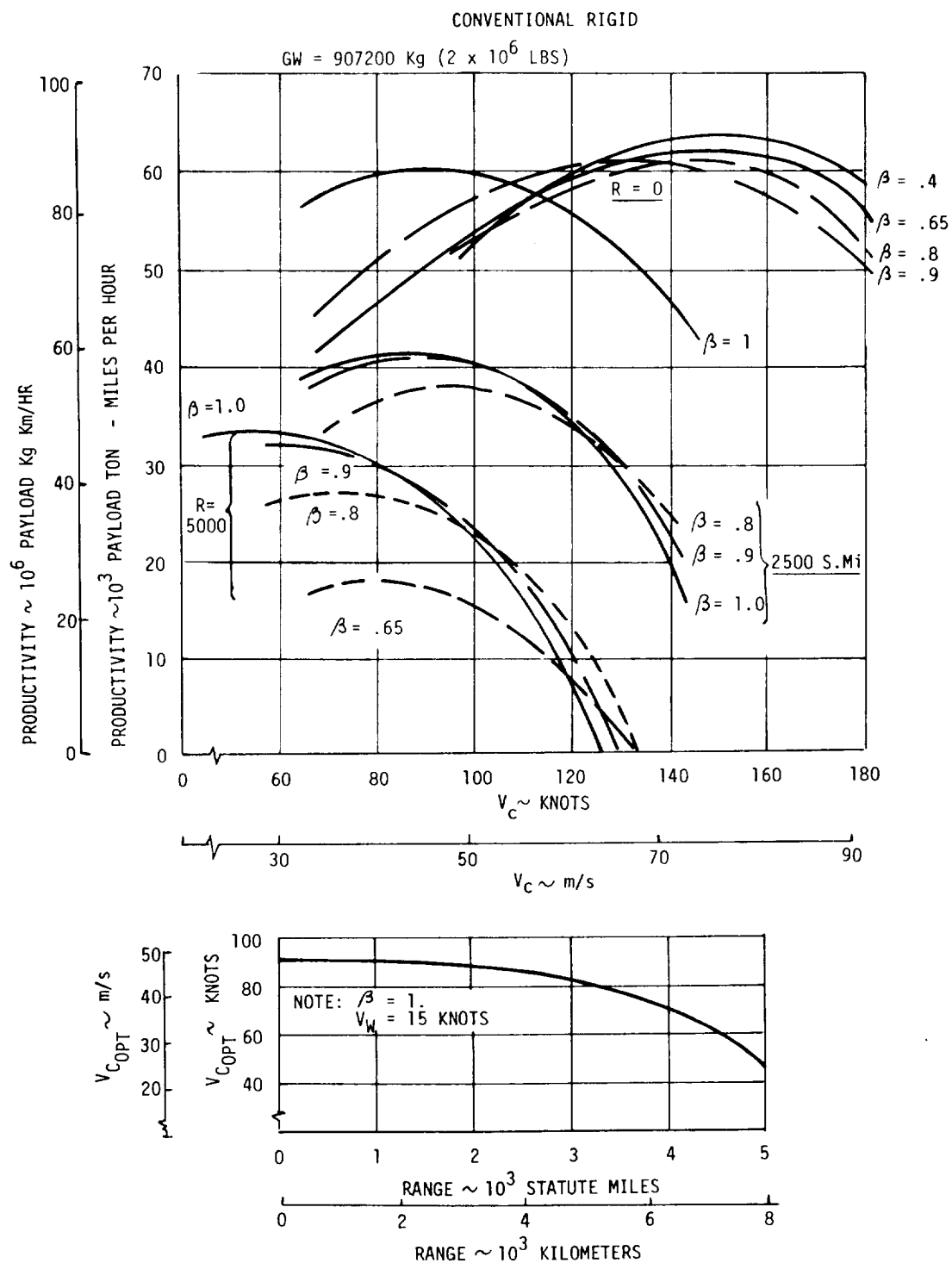


Figure 19 - Effect of Range and β on Productivity - 907,200-kg (2×10^6 Lb) Conventional Rigid Airship

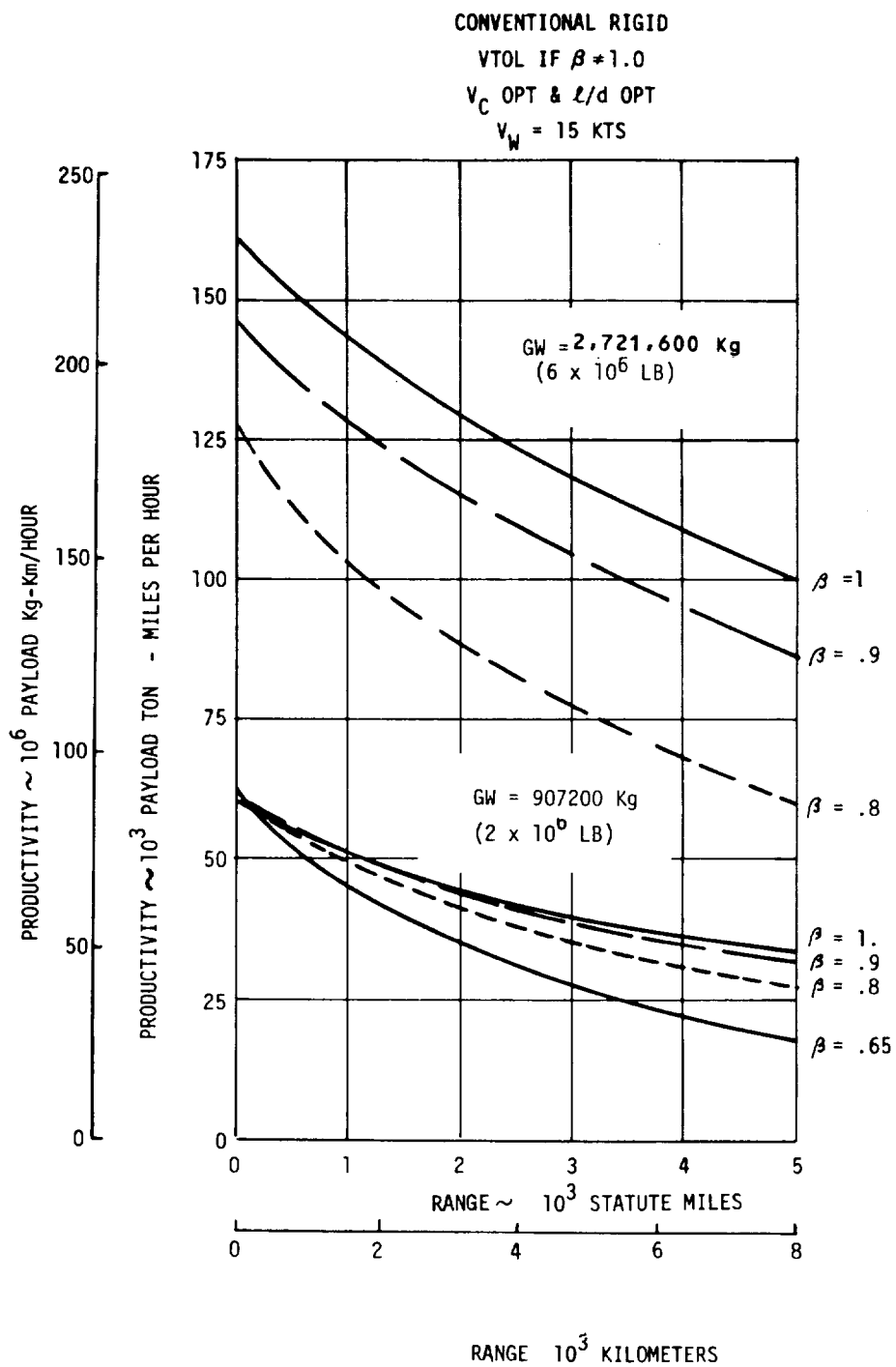


Figure 20 - Optimized Productivity versus Range: 907,200 kg (2,000,000-Lb) and 2,721,600-kg (6,000,000-Lb) Conventional Rigid Airships

(2×10^6 lb), only at approximately zero range does FOM increase with heaviness. In general, for the large airships, heaviness only reduces the productivity. This result can again be traced to the comparative interactions of structural, aerodynamic, and aerostatic efficiencies.

Thus, in going from small to large rigid airships, the optimum trend of the productivity FOM with β reverses. At small gross weights, β pays at all ranges; at large gross weights, β pays only at 0 range. The crossover is clearly illustrated in Figure 21 for a 181,440-kg (400,000-lb) gross weight airship. As shown, at any finite range, a β will exist that will maximize productivity. Of further interest is that for this medium size (Akron gross weight) rigid airship, some degree of initial heaviness is desirable for even extremely long ranges. Figure 22 summarizes the optimized productivity capability, including the effects of heaviness and range, for rigid airships over the study gross weight range.

For some of the parametric results, particularly for the pressurized metal-clad and rigid airships, minimum gauge constraints may modify the results presented - particularly at the low gross weight, low beta combinations. These considerations will be explored more fully in Phase II.

Pressurized Airships

Fabric Airships. - Representative results of the parametric analysis of the effects of β and V_C and range on FOM for pressurized fabric airships (both dacron and Kevlar envelopes) are presented in Figures 23 and 23A for low gross weight vehicles. The data trends are similar to those for the rigid vehicles.

Again, the potential of the Kevlar envelope is illustrated. A productivity figure of merit is probably not pertinent to the extremely low gross weight airships. Probable missions for these small vehicles will likely be of a surveillance or platform nature and, as such, an endurance figure of merit is most appropriate. This is discussed further under the alternative FOM subsection.

Metalclad. - A similar sample of the V_C , β , and range FOM data is presented in Figures 24 and 25 for a pressurized metalclad at 18,144-kg (40,000 lb)

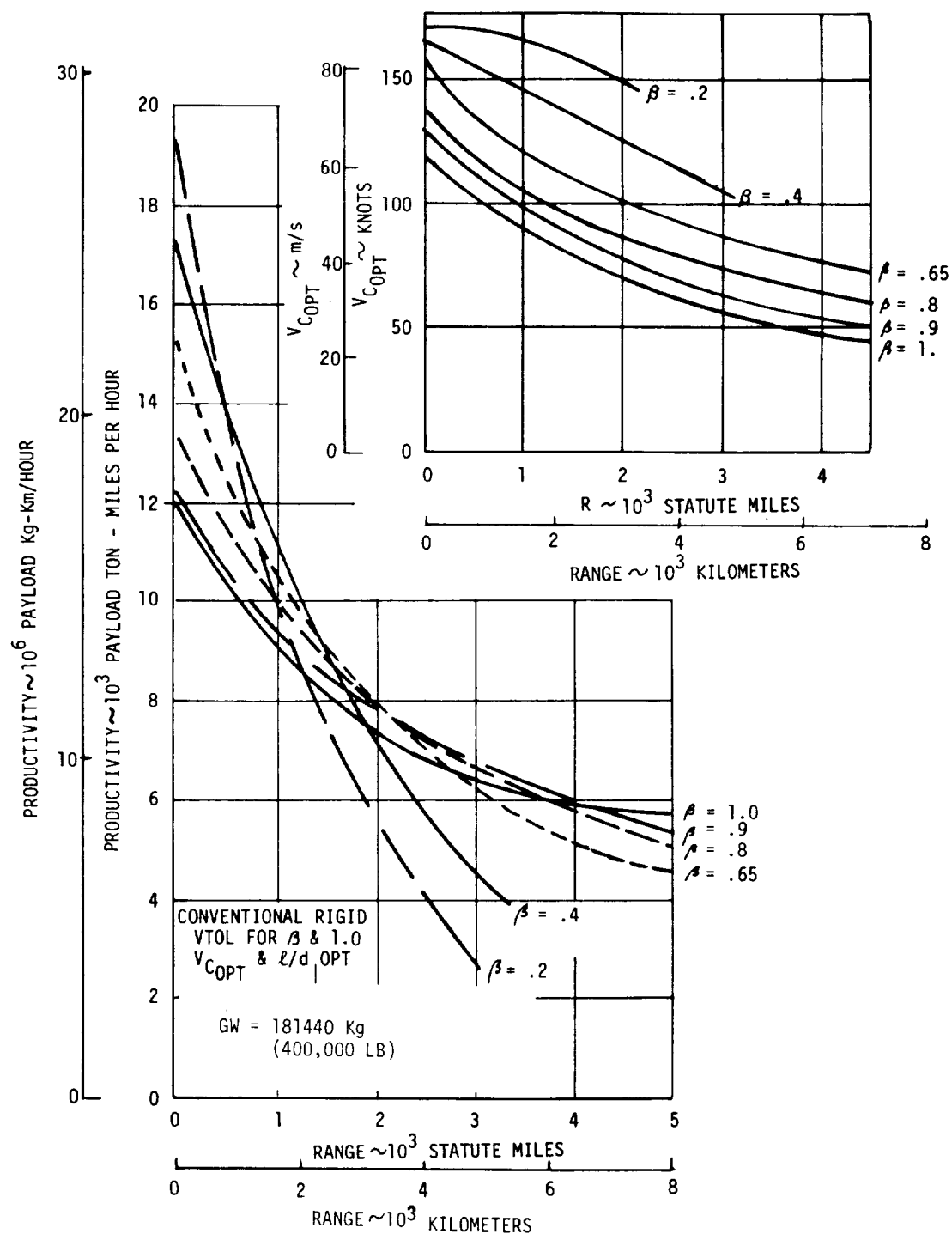


Figure 21 - Optimized Productivity and Cruise Velocity - 181,440-kg (400,000-Lb) Conventional Rigid Airship

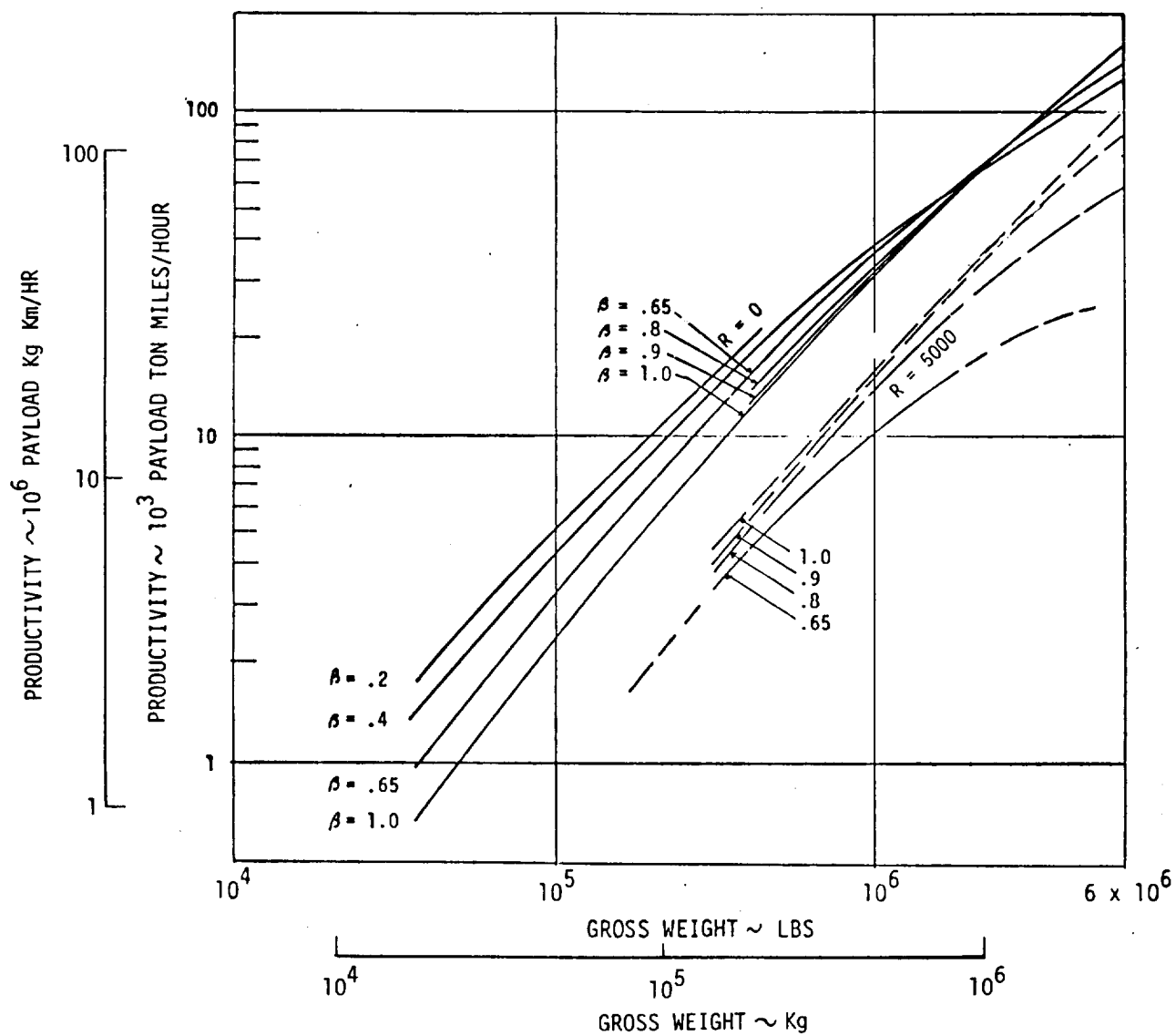


Figure 22 - Optimized Conventional Rigid Airship Productivity versus Gross Weight

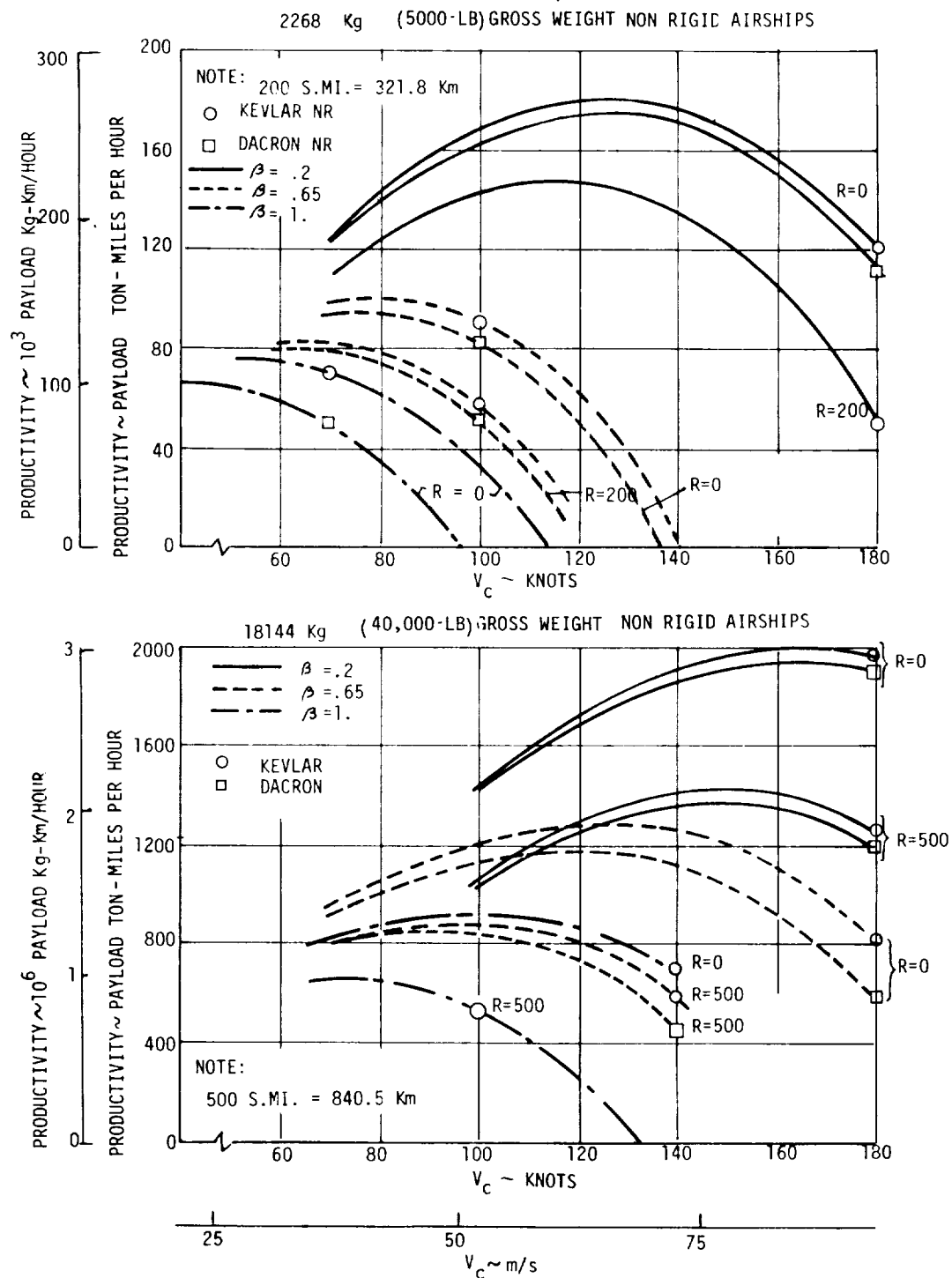


Figure 23 - Effects of Range and β on Productivity - 2268-kg (5000-Lb) and 18,144-kg (40,000-Lb) Pressurized Fabric Airships

181400 Kg (400,000 LB) GROSS WEIGHT NONRIGID AIRSHIPS

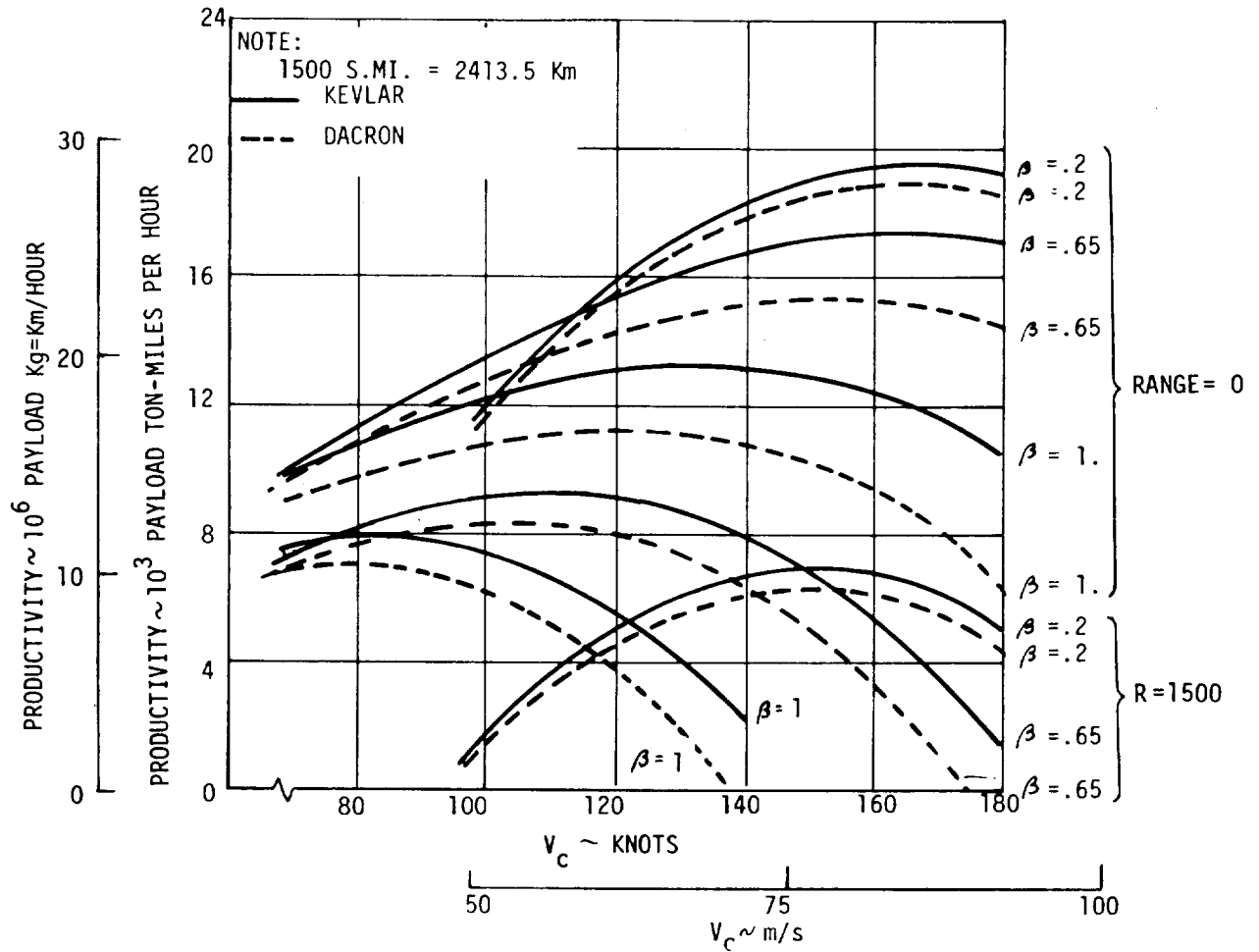


Figure 23A - Effects of Range and β on Productivity - 181,440-kg (400,000-Lb) Pressurized Fabric Airships

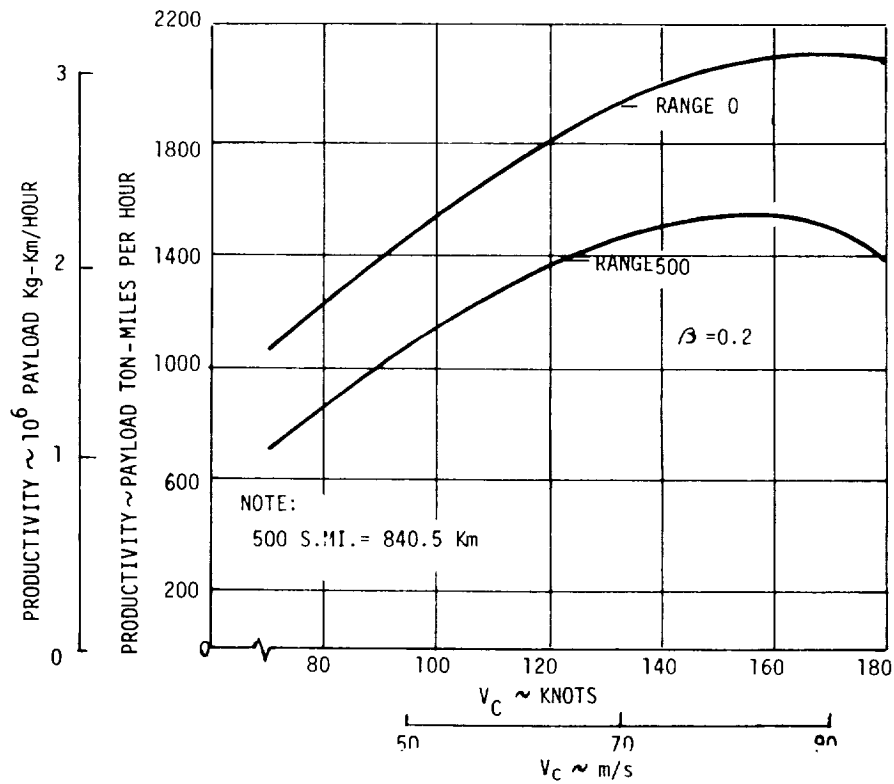
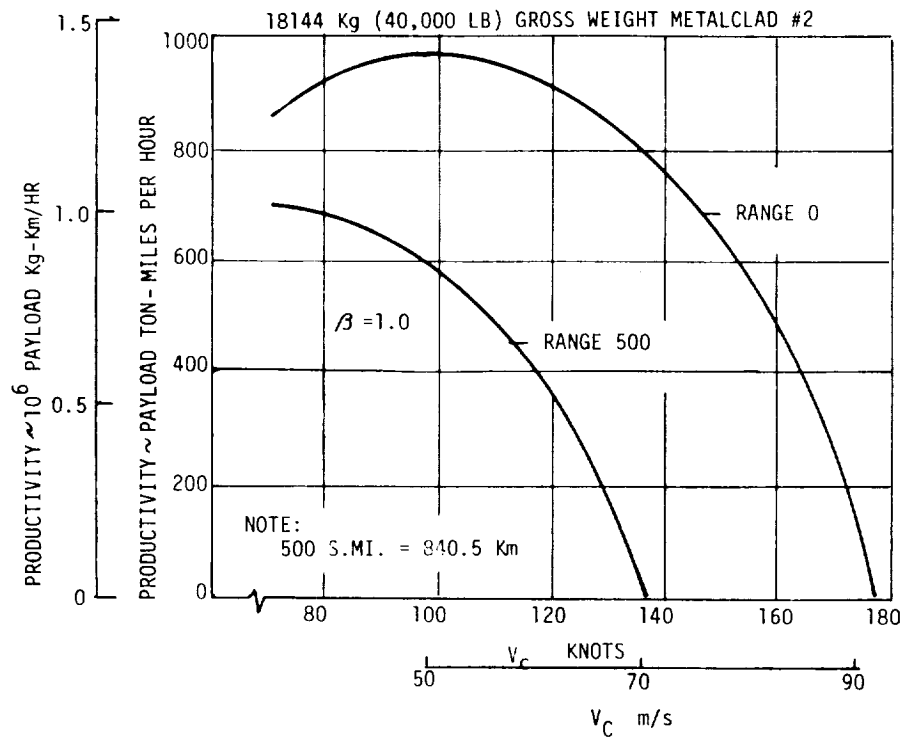


Figure 24 - Effects of Range and β on Productivity - 18,144-kg (40,000-Lb) Metalclad Airship

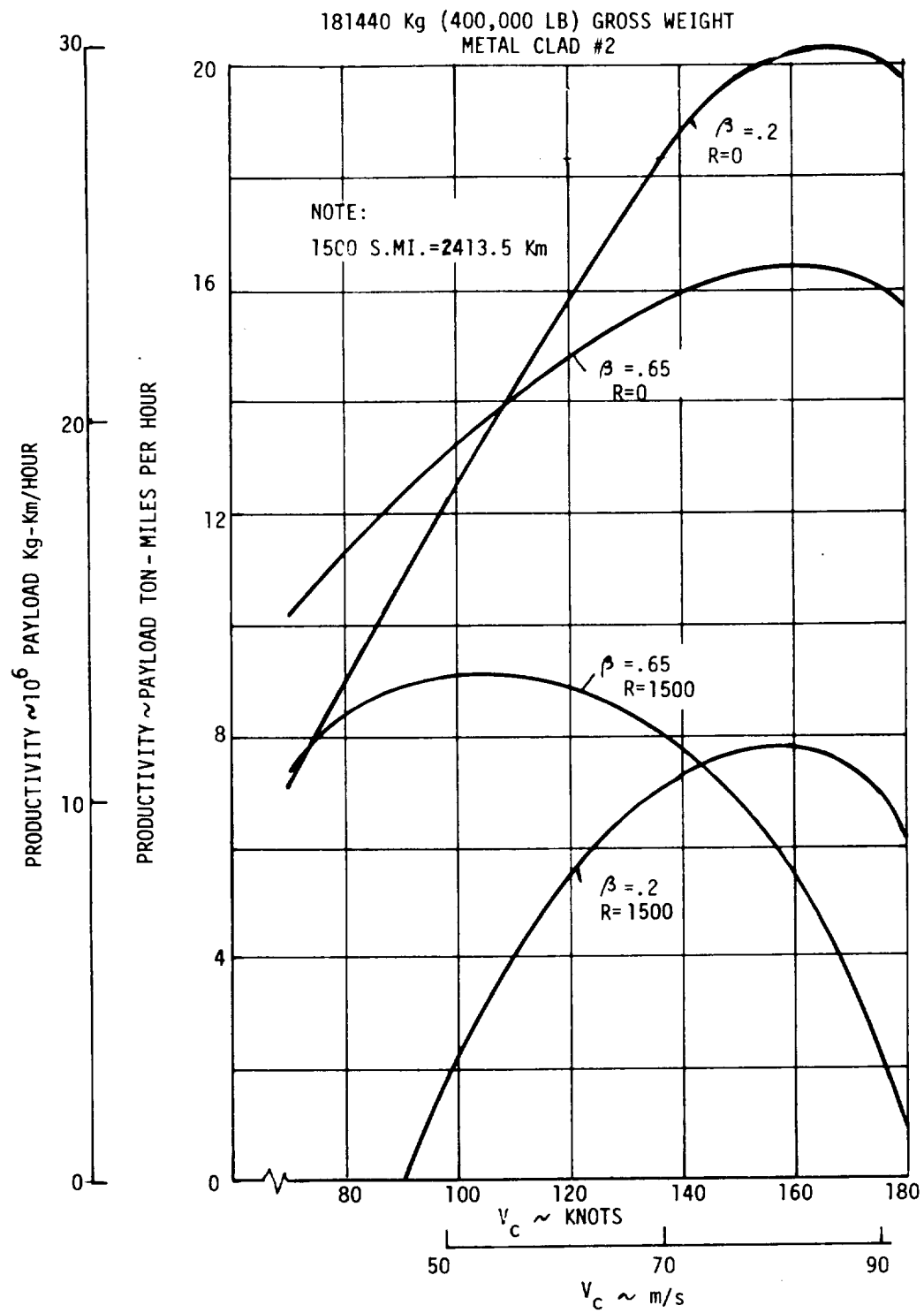


Figure 25 - Effects of Range and β on Productivity - 181,400-kg (400,000-Lb) Metalclad Airship

gross weight. Again, the data trends are quite similar to those for both the rigid and pressurized fabric airships.

Figures 26 and 27 present the optimum V_C and optimized productivity of the three different pressurized vehicles at 2268 kg, 18,144 kg and 181,440 kg (5000, 40,000 and 400,000 lb) gross weights.

Possibly the most reasonable conclusion to be drawn from these two figures is the general similarity of the behavior between the three types of vehicles. Cruise velocities for maximum productivity are very nearly the same at any given range and β indicating that neither type is particularly more sensitive to velocity than any other. At 18,144 kg (40,000 lb) gross weight, the metalclad is slightly superior to the Kevlar non-rigid. At low gross weight, only a very slight difference exists between the Kevlar and dacron non-rigids in productivity FOM. At 181,440 kg (400,000 lb) gross weight, the Kevlar NR is superior to the metalclad at all β 's greater than 0.35. For range = 0, β optimum tends to zero but at a range of 2413 km (1500 mi), β optimum is approximately 0.6.

A final comparison of rigid, pressurized fabric (Kevlar envelope), and pressurized metalclad is presented in Figure 28 in terms of useful load ton-miles per hour as a function of gross weight at $\beta = 1.0$ and at $\beta = 0.2$. This data is for optimized vehicles in terms of $(1/d)$ and V_C at zero range. At $\beta = 0.2$, the three airship types are essentially equal in productivity with the metalclad being a mild optimum in the 18,144 kg to 181,440 kg (40,000 to 400,000 lb) gross weight range. At $\beta = 1$ (neutrally buoyant vehicles), the metalclad and Kevlar non-rigid are approximately equal up to approximately 68,040 kg (150,000 lb). Above this gross weight, the Kevlar non-rigid is superior up to the limits of seaming technology of approximately 272,160 kg (600,000 lb). Above this gross weight, the neutrally buoyant conventional rigid is the superior construction choice.

In Figure 28, the $UL \cdot V_C / GW$ is approximately constant as a function of GW for the three types of airship construction, both at $\beta = 1.0$ and at $\beta = 0.2$.

Conventional Airship Heaviness Tradeoff Study Results

Improved productivity potential results from aerodynamic lift augmented cruise for small gross weight airships. At large gross weights, heaviness

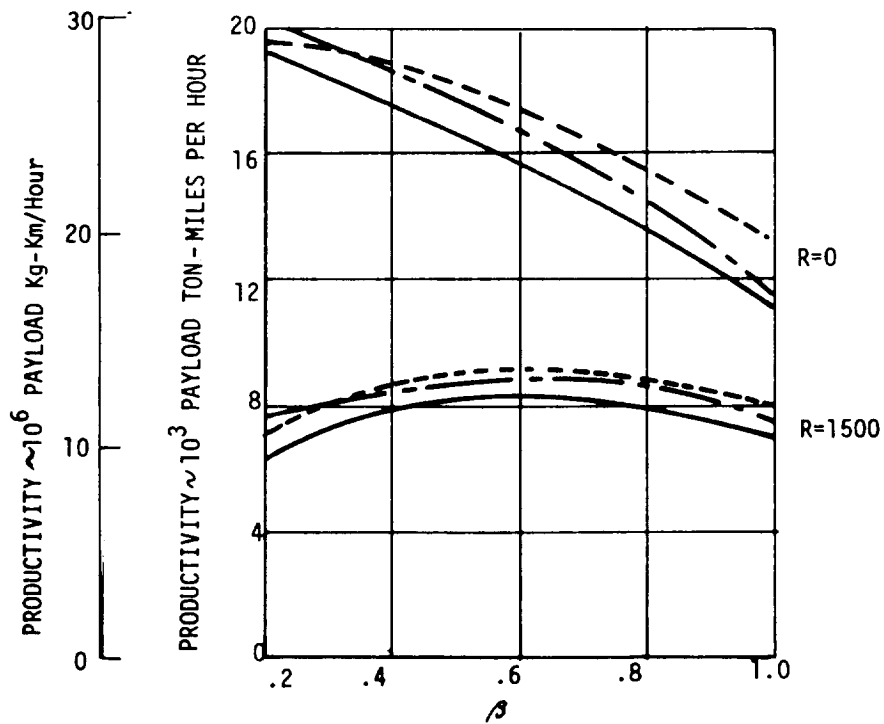
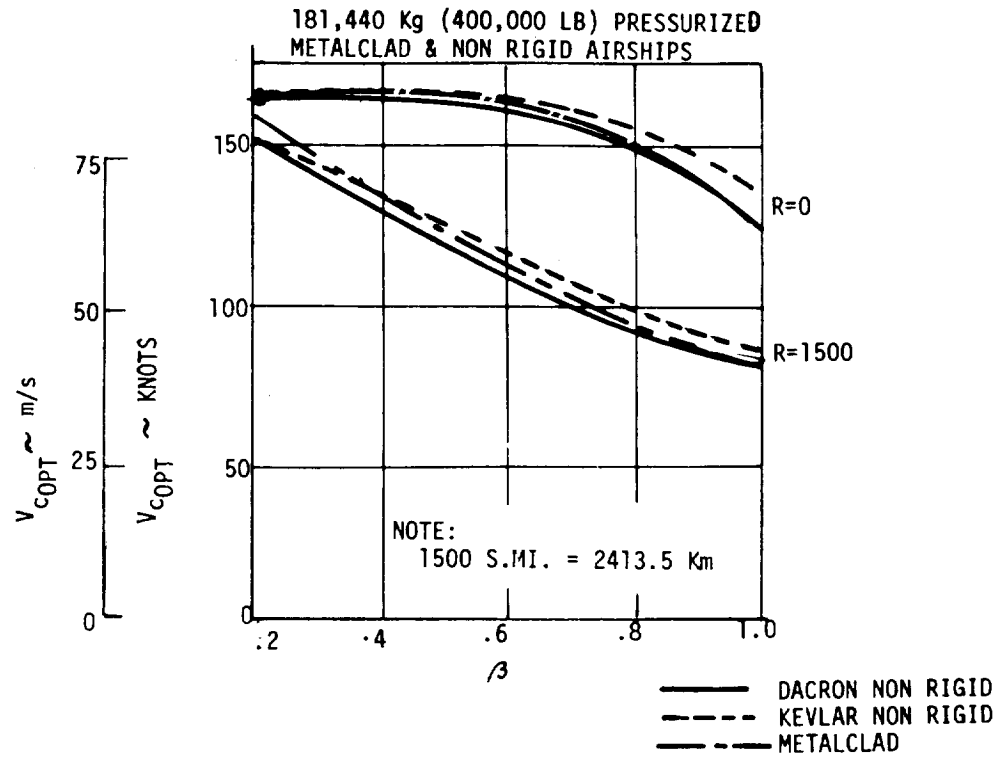


Figure 26 - Optimized Productivity and Cruise Velocity - 2268 kg (5000-Lb) and 18,144 kg (40,000-Lb) Pressurized Airship

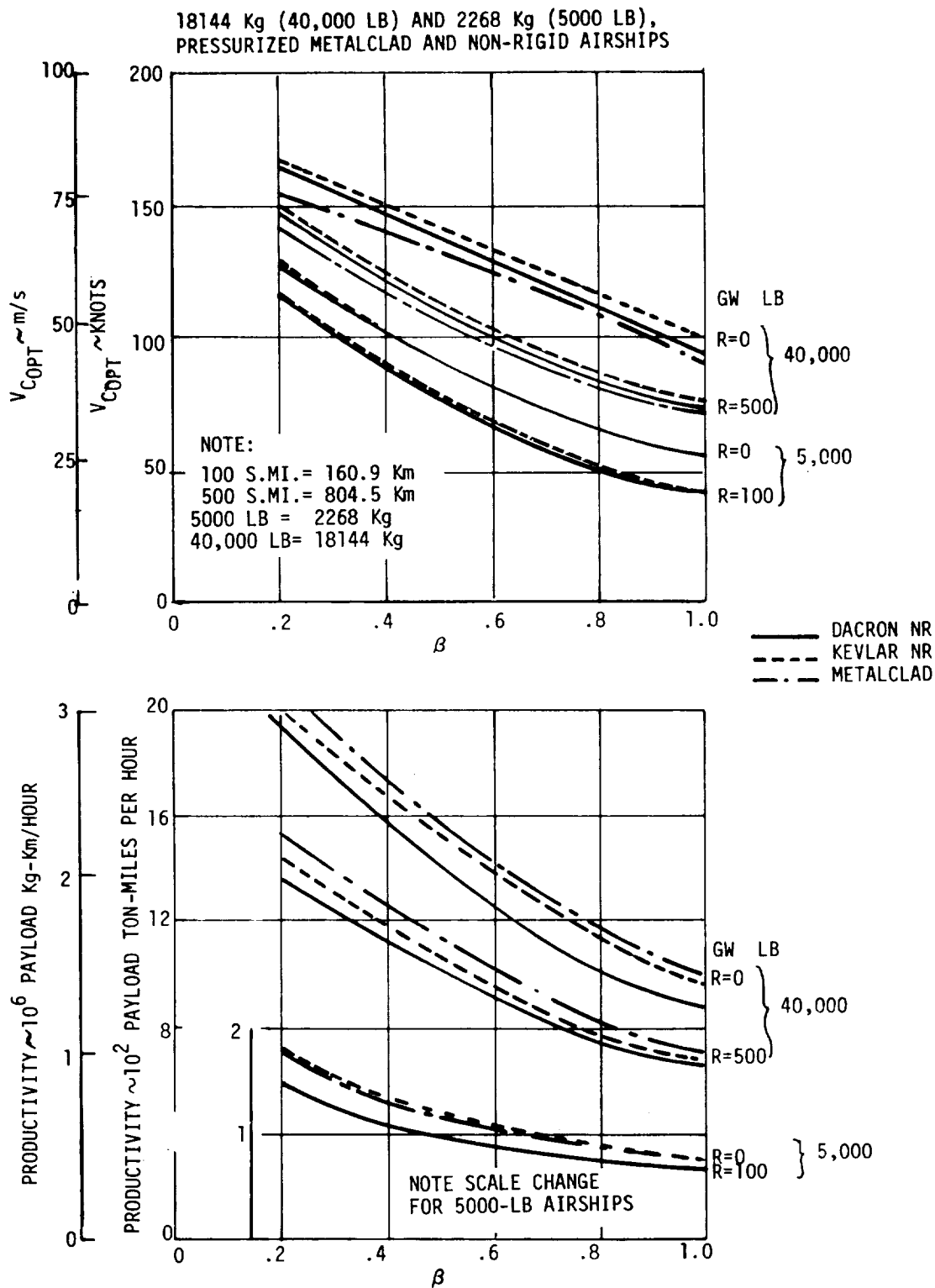


Figure 27 - Optimized Productivity and Cruise Velocity - 181,440-kg (400,000-Lb) Pressurized Airship

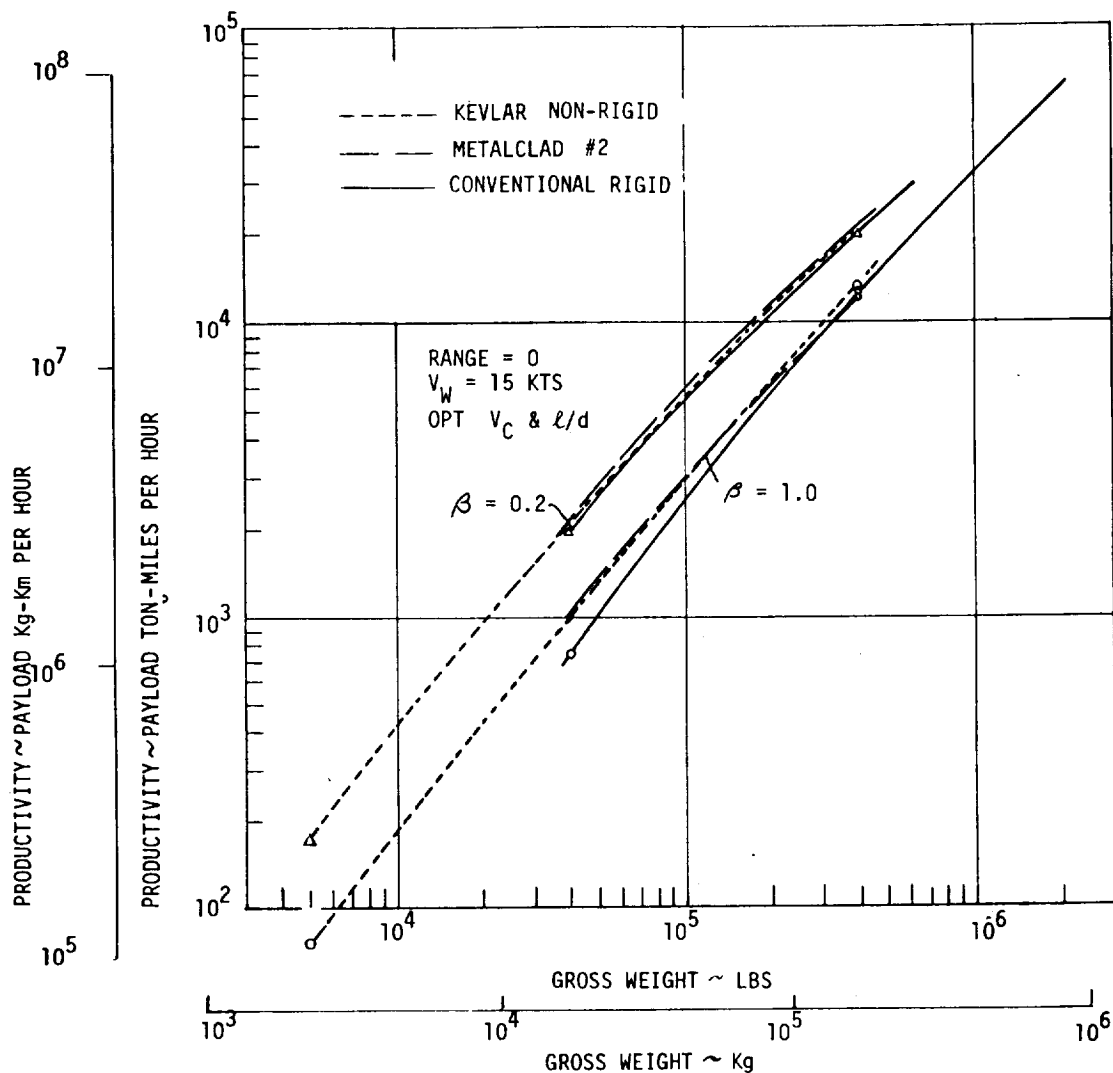


Figure 28 - Comparison of Productivity at Zero Range Versus Gross Weight - Pressurized and Conventional Rigid Airships

appears to offer no improvement in productivity. The following discussion offers a brief explanation of the origin of these results.

At small vehicle gross weights, aerostatic lift is doubly inefficient, in terms of productivity, compared with either aerodynamic lift (for cruise) or propulsive lift (for VTOL). That is, in terms of useful lift per unit gross lift (i.e., $1 - W_{str}/GW$) and in terms of lift per unit drag, (L/D). Useful lift is simply defined as lift available for propulsion, fuel, and payload after the structural weight required to provide the static lift has been subtracted from

the gross lift. Figure 4 shows the useful static lift ($1 - W_{str}/GW$) is low for small airships. Figure 29 further illustrates the useful lift efficiency as a function of volume.

In terms of lift to drag, the basic volume/volume to the $2/3$ power relationship, combined with the reduced friction drag at large Reynolds numbers, clearly dictates large vehicle sizes for efficient use of aerostatic lift. This fundamental relationship is also clearly shown in Figure 29. Conversely, at low gross weights (small volumes for neutrally buoyant airships), aerostatic lift is comparatively inefficient, yielding lift to drag ratios of only 3 to 6 for volumes under 28,320 cu m (one million cubic feet) and speeds of 51.48 m/s (100 knots).

Thus, at low gross weights, the β trend for optimum productivity is toward zero as indicated in Figures 16 and 18. Some degree of buoyant lift may be desirable, however, if other factors such as noise and fuel consumption are considered.

The results illustrate the fundamental interactions of aerostatic, aerodynamic, propulsive, and structural efficiencies for a productivity related figure of merit. The driving factor in these results is structural weight and the variation of structural weight with β . The following discussion illustrates the interactions of the various efficiencies.

First, in order to understand the origin of the productivity-beta trend over the study gross weight range, recall the study methodology.

The most important ground rule of the methodology in the Phase I tradeoff study is that vehicle performance or productivity is compared on an equal gross weight basis; not an equal volume or equal payload, etc. Thus, for a given vehicle gross weight, as β is reduced the vehicle size (volume) is reduced.

Figure 30 shows the interactions between structural, aerodynamic, and propulsive efficiencies for a 18,144-kg (40,000-lb) gross weight conventional rigid airship at a constant V_C of 51.48 m/s (100 knots).

Figure 30A shows the relationship between payload ton-miles per hour and β at 500-mi range. The FOM increases steadily as β is reduced and the optimum V_C tends to higher values (V_C optimum) inversely proportional to β . This trend continues even to large ranges as presented in Figure 18.

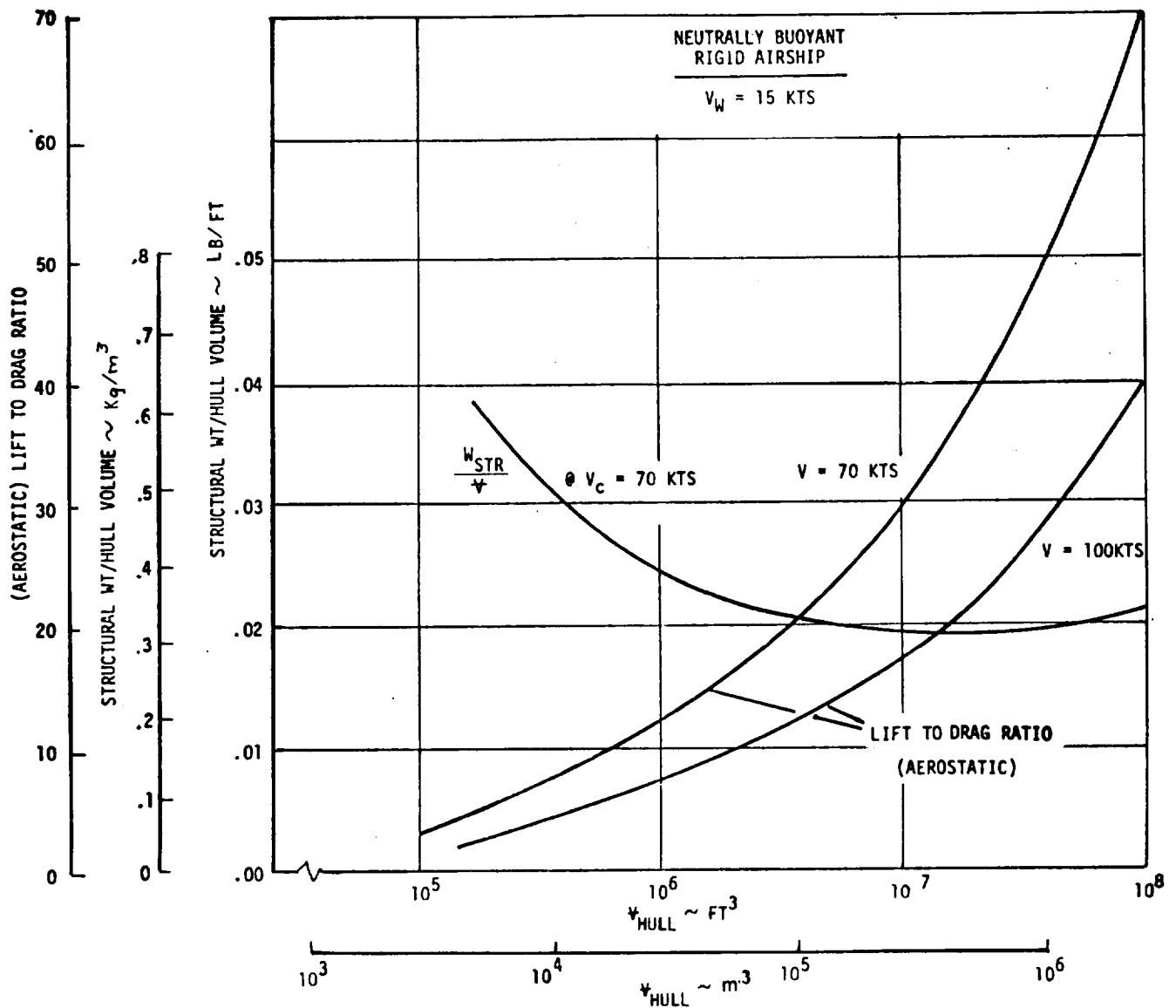
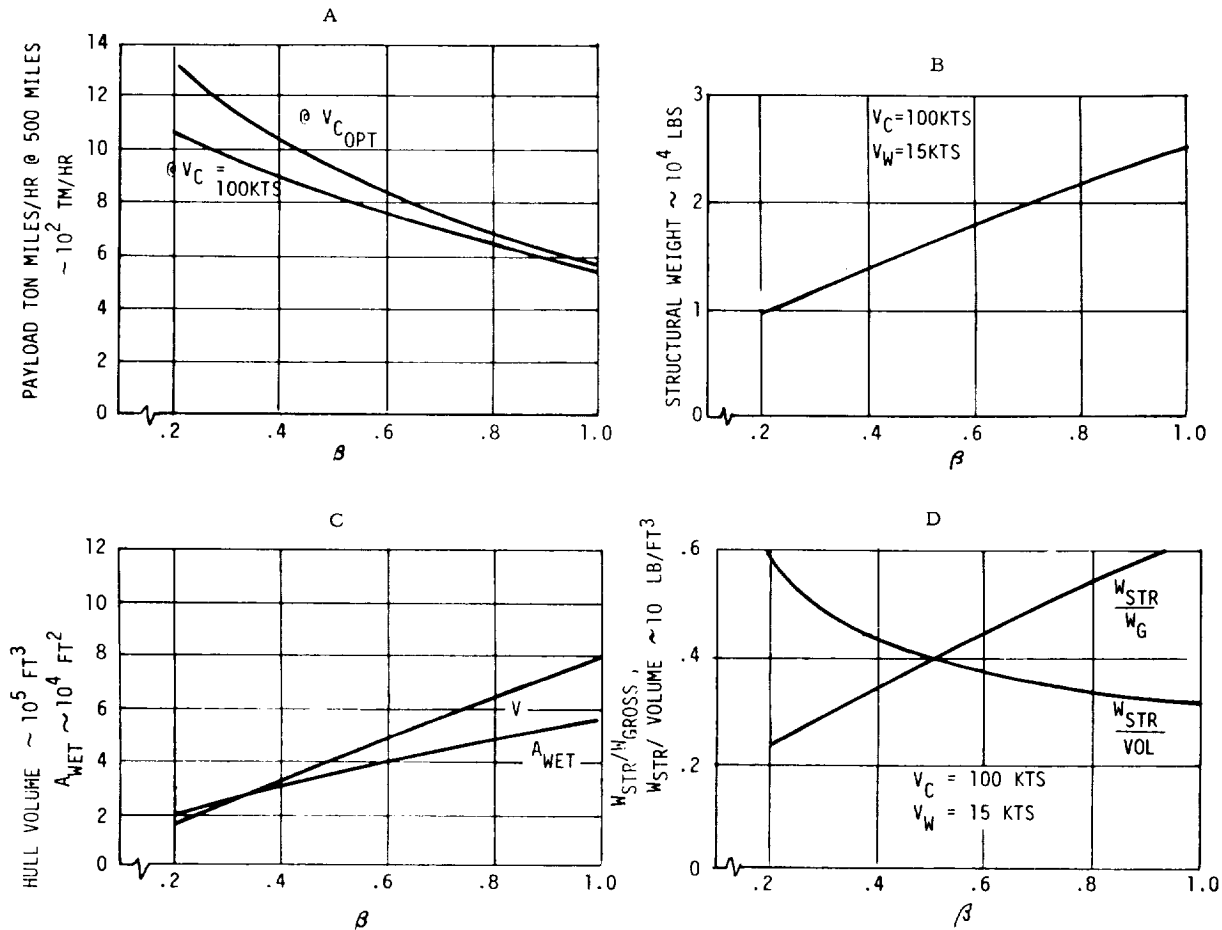


Figure 29 - Variation of Conventional Airship Aerostatic and Structural Efficiency as a Function of Volume

Figure 30B shows the structural weight variation with β . Figure 30C illustrates the linear reduction of volume with β and the $2/3$ power reduction in wetted area. Figure 30D presents various normalizations of structural weight as a function of β . As shown, the structural weight-to-gross weight ratio is decreasing significantly. This variation is the most dominant effect in the parametric study, not only of "conventional airships" but also the hybrid vehicles

18144 Kg (40,000 LB) GROSS WEIGHT RIGID AIRSHIP



NOTE: THESE FIGURES ARE PRESENTED PRIMARILY TO ILLUSTRATE TRENDS - THUS, ONLY THE CONVERSION FACTORS ARE PROVIDED: 1 TON_M/HR = 1460 Kg-Km/HOUR, 1 LB=0.4536 Kg, 1 FT³=0.02832 m³, 1 FT²=0.0929 m², 1 LB/FT³=16.02 Kg/m³

Figure 30 - Basic Structural, Aerodynamic, Aerostatic, and Propulsive Interactions

discussed in the following subsection. One further observation should be made in Figure 30D: the structural weight per unit hull volume increases significantly as β is reduced. That is, the structural density is increasing significantly and, in fact, the airship becomes heavier than air even without the engine weight.

Figure 31A shows that total lift-to-drag ratio is actually increased by flying heavy down to a $\beta \approx 0.65$. Below this point, total L/D is reduced. Nonetheless, productivity continues to increase. The two data points in Figure 31A indicating the total drag decrease as a cruise velocity is increased from 51.48 m/s (100 knots) to 72 m/s (140 knots). The reason for this is shown in Figure 31B. At

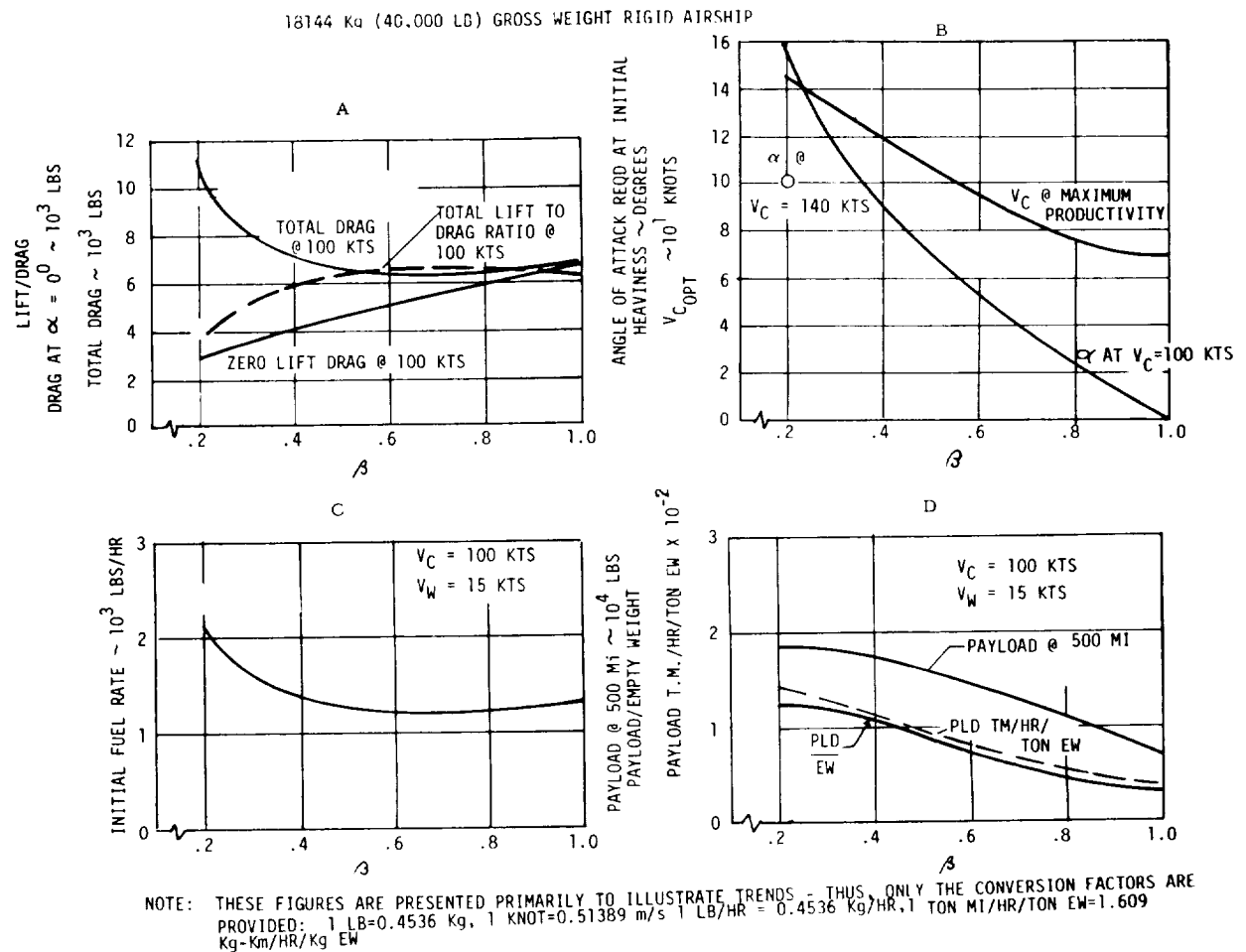


Figure 31 - Resulting Vehicle Performance/Productivity as a Function of β

51.48 m/s (100 knots), the vehicle must fly (initially) at 15 deg angle of attack to provide the aero lift required for cruise. At 72 m/s (140 knots), the (initial) α required is only ≈ 10 deg (a value very close to the aerodynamic maximum L/D, $\alpha \approx 11$ deg) with a corresponding reduction in drag due to lift since drag due to lift is a C_L squared function which, at constant aerodynamic lift, varies with the fourth power of velocity ratio.

Figure 31C shows the initial fuel consumption rate as a function of β , correlating as expected with the total drag in Figure 31A. Figure 31D illustrates the true promise of heaviness for the small airship size: Payload to EW ratios of 1.25 at 804.5-km (500 mi) range with a VTOL vehicle with a 8150-kg (18,000-lb) payload capability.

From the above discussion and the data presented in Figures 30 and 31, the following conclusions seem justified for "small airships":

1. Structural efficiency is by far one of the most important driving functions for optimum productivity.
2. Total lift to drag and fuel consumption rate are of much lesser importance.
3. Several factors interact positively to favor low β 's for small semibuoyant vehicles:
 - a. Their aerostatic lift-to-drag ratio is poor at low volumes due to the large wetted area-to-volume ratios.
 - b. Their structural efficiency (W_{str}/W_{gross}) can be significantly improved (reduced) by reductions in volume, even though the structural weight per unit volume is increased.

An alternate way to summarize the tradeoff study results of the use of aerodynamic lift versus neutrally buoyant flight for small gross weight airships is as follows.

Aerostatic lift at small volumes is relatively inefficient. Aerodynamic lift-to-drag ratios comparable to the aerostatic lift-to-drag capability can be obtained, at extremely low β 's, even with the relatively inefficient aerodynamic shape of the ellipsoidal airships. Even at $\beta = 0.2$, the airship remains of considerable size, with a projected planform area of 2220 sq m (24,000 sq ft) for the 18,144-kg (40,000-lb) gross weight airship. Hence, a pseudo-wing loading, aerodynamic lift over projected plan area, is extremely low: 8.2 kg/sq m (≈ 1.33 lb per square foot) of projected plan area.

The size of the vehicle is, however, small compared with a neutrally buoyant vehicle of the same gross weight. In essence, small vehicles weigh less than large vehicles. Although the weight per unit volume approximately doubles as β is reduced from 1.0 to 0.2, the volume has been reduced by a factor of 5. Hence, the total structural weight is reduced by approximately 2.5 at a constant gross weight.

At the opposite extreme of the study gross weight range, aerodynamic lift or heaviness was in general shown to offer no improvement in productivity. This

result can again be traced to interactions of the fundamental structural, aerodynamic, and aerostatic efficiencies. Consider a 907,200 kg (2×10^6 lb) gross weight vehicle of approximately 113,100 cu m (40×10^6 cu ft): at this volume, aerostatic lift is close to its optimum efficiency in terms of useful lift as shown in Figure 29. Furthermore, the aerostatic lift to drag ratio is on the order of 30 to 50 for velocities on the order of 51.48 to 36.04 m/s (100 to 70 knots), respectively.

The maximum aerodynamic lift to drag at 51.48 m/s (100 knots) would be on the order of 4 + (depending on β), a small percentage improvement.

Structurally, however, the structural weight penalty due to heavy flight increases significantly with vehicle size (volume and length). Figure 32 compares this weight penalty as a function of volume for conventional rigid airships.

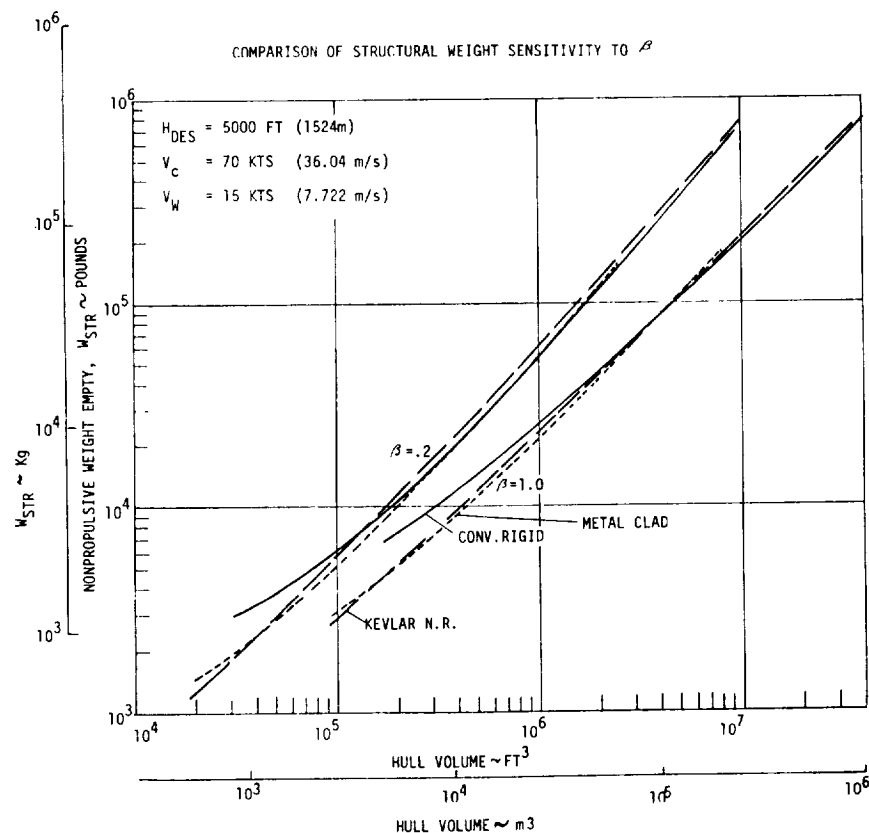


Figure 32 - Conventional Airship Structural Weight Sensitivity to β

Representative values are:

<u>cu m</u>	<u>Volume</u>	<u>% increase in structural weight for β decrease from 1.0 to 0.2</u>
	<u>cu ft</u>	
5,664	200,000	40
28,320	1,000,000	110
283,200	10,000,000	350

The trends are noted from the figure to be essentially the same for each of the three types of airships, with the rigid being slightly less sensitive to aerodynamically heavy flight.

Thus, in going from small to large airships, the optimum trend of the productivity FOM with β reverses. At small gross weights, a low value of β pays at all ranges; at large gross weights, β 's less than 1.0 improve productivity only at 0 range. The crossover, for intermediate gross weights, is clearly illustrated in Figure 21 as a strongly range-dependent phenomenon. At any finite range, a β will exist that will maximize productivity.

Advanced Ellipsoidal Airship Concepts

The promise of the pressurized metalclad airship, particularly when combined with modern materials technology, has been briefly discussed in References 11, 12, and 13. This, plus the parametric analysis results of the more conventional airship structural design concepts, led to the conceptual design evaluation of a honeycomb sandwich airship concept near the end of Phase I. This effort was virtually a competitive design study - self-contained and separate from the major parametric analysis. The analysis and results are presented in their entirety in Appendix G of Reference 2.

The purpose of the analysis was to establish the range of parameters in terms of airship size, design speed, and fineness ratio that lead to an acceptable hull weight fraction for a sandwich monocoque design. A representative value for the hull and empennage weight for a 2,832,000 cu m (100,000,000 cu ft) airship is 929,000 kg (2,054,000 lb).

The following components need to be added to arrive at a total structural weight figure:

1. Pressure control system - 206,500 kg (455,000 lb)
2. Control car, crew quarters, etc. - 13,600 kg (30,000 lb)
3. $W_{str_{tot}} = 1,148,000 \text{ kg (2,539,000 lb)}$
4. $W_{str}/W_{gross} = 0.48$

The structural weight-to-gross weight ratio of 0.48 is comparable to 0.43 for a conventional rigid airship at the same gross weight or volume. However, these values are not exactly comparable due to different (higher) empennage weight estimate used in the monocoque airship analysis. In addition, several conservative assumptions, discussed in Appendix G of Reference 2, could result in a lower structural weight fraction upon further analysis.

The conclusions resulting from the analysis indicate that a large rigid airship constructed as a monocoque sandwich shell exhibits a (structural) weight empty fraction comparable to small airships of conventional construction. Minimum gage considerations tend to limit this approach to very large airships.

The sandwich shell of the 2,830,000 cu m (100,000,000 cu ft) airship exhibits a bending stiffness equivalent to an oak plank 1.64 in. thick. Even at the minimum gage limit, the plank thickness for equal stiffness is 0.82 in. In addition, the airship shell is the dominant weight term of the three major components studied.

In summary, this approach warrants further consideration than was possible within the constraints of this study, particularly for very large airships. The analysis of this concept and preliminary results are presented in Appendix G of Reference 2.

PARAMETRIC ANALYSIS OF HYBRID VEHICLES

Overview

The parametric analysis of the hybrid vehicles began with a review of many hybrid configurations proposed or under study by various investigators. These configurations could be broadly grouped into two classes: winged airships and lifting body vehicles of the general type originally developed for the NASA/DOD space and re-entry efforts. In order to select one or more promising configurations for the detailed structural design and empty weight analysis required for realistic evaluation of the concept, an initial configuration screening and evaluation study was performed. This screening broadly dealt with the two classes of hybrid vehicles: lifting bodies and winged airships.

This exercise resulted in the selection of a modified delta planform lifting body for the baseline point design and structural weight parameterization. Critical structural design conditions were defined and detailed pressure distributions were developed for the vehicle. A design layout was developed, and preliminary airloads, shear, and moment distributions were defined. The resulting structural design and weight characteristics were parameterized into weight estimating relationships for use in the Goodyear airship synthesis program (GASP).

The parametric analysis of the modified delta planform hybrid was conducted to optimize the configuration characteristics in terms of payload-ton miles per hour over the study gross weight range. The results of the parametric analysis include the optimized configuration characteristics, aspect ratio (AR), thickness ratio (t/c), and optimized cruise velocity (V_C) as a function of gross weight, β , and range.

Details of the above efforts are described in this subsection.

Preliminary Configuration Evaluation

The structural efficiency (structural weight-to-gross weight ratio) was known to be one of the most significant factors in the relative productivity of the hybrid vehicle concepts vis a vis conventional airships. Another factor of possible equal or greater importance was the area of stability and control characteristics of semibuoyant vehicles. Detailed stability and control investigations were beyond the scope of the Phase I study. Indeed, they might not influence the productivity figure of merit results to any great extent. However, it was apparent that some consideration must be given to this critical area in the Phase I study.

During the configuration evaluation of the lifting body vehicles, the static stability requirements and the relationship between aerodynamic center of pressure (CP) and center of buoyancy (CB) were examined as an indicator. The desirability of a delta-type planform on the basis of low CP-CB separation was identified. Circular and rectangular planforms may potentially require large horizontal tail areas for acceptable stability characteristics (see References 14 and 15) due to the forward CP and midbody CB. Although stability and control problems could possibly be adequately solved with current technology flight control systems, the selection of a configuration that would minimize potential problems was desirable.

Further investigations of the relationship between AR and β indicated that an inverse relationship existed. That is, for low β , relatively large AR (1 to 2 possibly) might be used. At large β , however, only small AR (0.5 to 0.75) would be required due to the large surface area associated with large β vehicles. Several different configuration concepts were evaluated on a preliminary structural design concept basis and "quicky" weight estimates defined. The exercises generally confirmed the requirement for more detailed structural design and weight evaluation to arrive at reliable structural weight comparisons.

The configuration screening exercise of lifting body vehicles resulted in the selection of the modified delta planform hybrid as discussed in the following subsection.

The other class of hybrid concepts consisted of winged airships. Initial expectations were that some promising configurations might result in combining the high structural efficiency basic airship shape with more aerodynamically efficient wing structures. This effort was continued on a low level during the last part of the study as the analysis of the hybrid lifting body vehicle was pursued. Although the effort was not taken to a final conclusion (but could be finalized during Phase II), the conclusions that appear valid based on the results obtained, including the parametric analysis of conventional airship aerodynamic lift utilization, are as follows:

1. Empirical wing weight estimating relationships are of questionable validity for the low wing loadings and large sizes considered for application to the airship combinations.
2. For such wings, nonoptimum weight contributions - members whose weight is independent of the load applied - contribute substantially to the wing and hull carry through weights.
3. On the basis of the combined structural and aerodynamic efficiency of the basic ellipsoidal airship at small gross weights, application of winged combinations does not appear productive in terms of combined structural and aerodynamic lift requirements. Other considerations, such as improved controllability, utilization of deflected slipstream for VTOL rather than tilting propellers, etc., might change this conclusion. However, such considerations were beyond the scope of the Phase I study.
4. If combined wing/airship configurations do have promise, it is undoubtedly for large airships (gross weight greater than 226,800 kg, or 500,000 lb), where the structural weight penalty and aerodynamic L/D versus aerostatic L/D do not favor heavy flight of the basic ellipsoidal airship. More effort could be directed to this area in the future with greater consideration given low speed control rather than simply productivity-related figures of merit.

Further details of the configuration evaluation and screening efforts are presented in Appendix I of Reference 2.

Modified Delta Planform Hybrid (Selection Rationale and
Configuration Description)

The lifting body configuration evaluation resulted in the following rationale and assumptions for the baseline - point design vehicle selection:

1. The cross-sectional area distribution should make it possible to place the center of buoyancy at or near the aerodynamic center of pressure in order to minimize trim drag penalties and tail area requirements possibly required for dynamic stability of the high-lift capability vehicles.
2. The chordwise distribution of thicknesses resembling a subsonic airfoil is desirable from the standpoint of aerodynamic efficiency.
3. A relatively thick section is required to provide an efficient ratio between surface area (weight, drag) and enclosed volume, e.g., high volumetric efficiency.
4. An aspect ratio sufficient to give a lifting performance considerably in excess of that achievable with a circular cross section is desirable.
5. If possible, the configuration should be geometrically applicable from low aspect ratio's (AR's) of 0.5 to 0.75 to rather high AR's (1 to 2) in order to cover the beta range of interest.

These precepts were implemented as follows:

1. The ellipsoid, as representative of traditional airship shapes, is taken as the starting point.

2. The ellipsoid is transformed into a parabolic planform while maintaining its cross-sectional area. Elliptical cross sections are used. This results in an "airfoil" thickness distribution, described below.
3. The fineness ratio, F, is carried as a parameter and is defined as the length-to-diameter ratio of the ellipsoid having the same cross-sectional area distribution as the hybrid shape. The fineness ratio and aspect ratio together with the required volume uniquely define the entire configuration geometry.

The transformation results in the shape function:

$$z = \frac{3}{(AR)F^2} (x^{1/2} - x^{3/2}) \left(1 - \frac{9}{(AR)^2} \frac{y^2}{x}\right)^{1/2}$$

where
 x = measured toward trailing edge from the nose,
 y = measured laterally from root chord, and
 z = measured from planform plane.

and x , y , and z are normalized to the root chord yielding a pure shape function involving dimensionless ratios. The volume of such a shape is defined as:

$$V = \frac{\pi}{6} \frac{C_o^3}{F^2}$$

where C_o is the root chord.

The planform area is

$$S_{\text{plan}} = \frac{4}{9} (AR) \left(\frac{6F^2}{\pi} \right)^{2/3} \pi^{2/3}$$

The maximum thickness ratio occurs at the 30 percent chord point and is

$$\left(\frac{t}{c} \right)_{\text{max}} = \frac{2.31}{(AR)F^2}$$

The nondimensionalized coordinates of the hybrid vehicle airfoil section are comparable to the generalized NACA 00XX section shown in Figure 33.

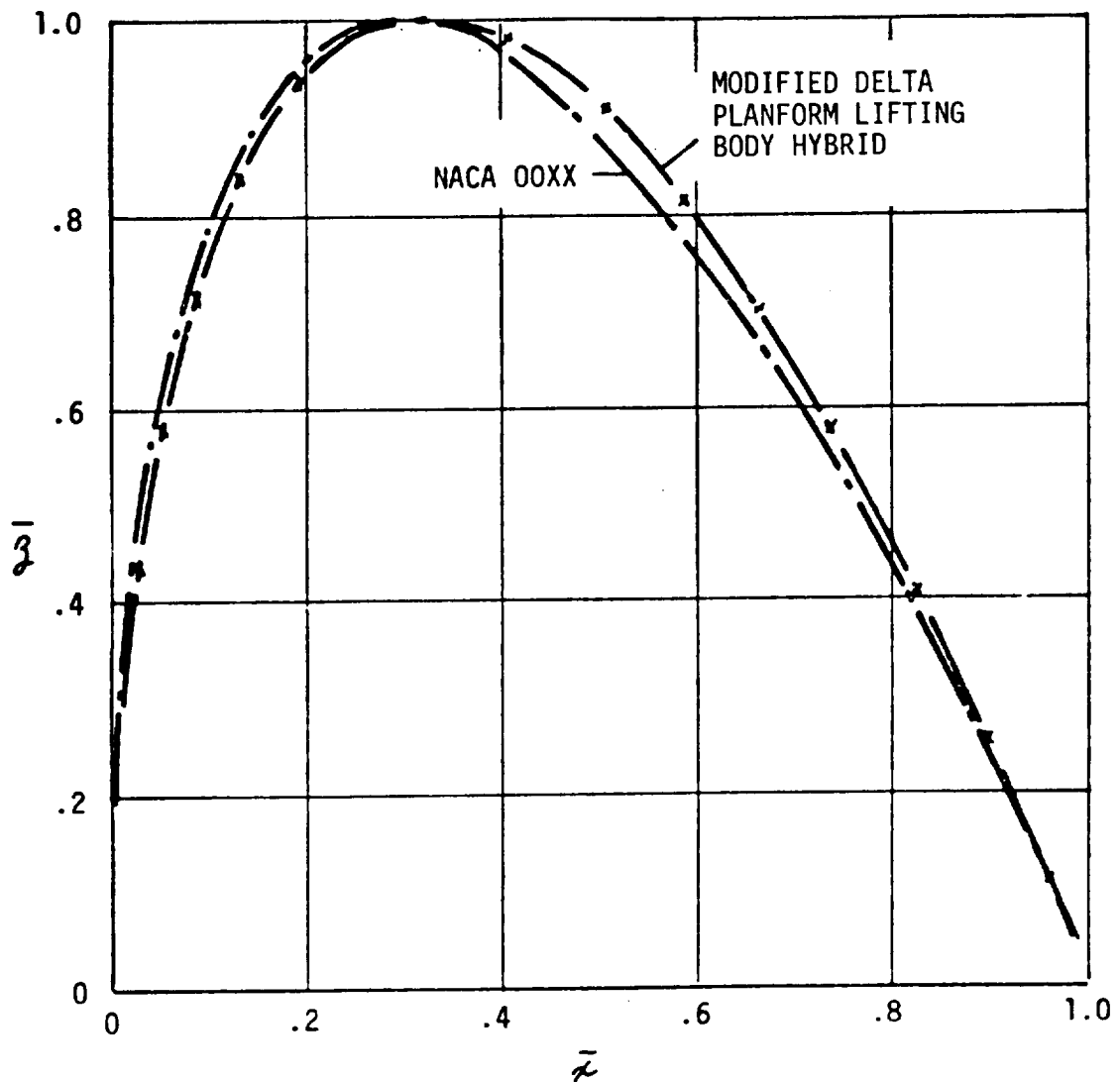


Figure 33 - Comparison of Hybrid Airfoil Coordinates with Generalized NACA 00XX Section

The maximum thickness is

$$t_{\max} = \frac{2.86 \sqrt[3]{V}}{(AR) F^{4/3}}$$

Parameters chosen for the point design study were:

1. $V = 283,200 \text{ cu m } (10 \times 10^6 \text{ cu ft})$
2. AR, aspect ratio = 1.5
3. F, fineness ratio = 2.5

This results in a body 149.66 m (491 ft) long, 149.66 m (491 ft) wide, and 36.73 m (120.5 ft) thick at the point of maximum thickness (see Figure 34). Beta for the point design configuration was 0.33. The structural design concept is based on conventional rigid construction concept as described below.

Structural Description

Mainframes

The airship volume is divided into more or less cubical compartments by main frames running chordwise and spanwise at approximately 30.48-m (100-ft) centers. The webs of the main frames are designed to provide a shear path from the upper surface to the lower surface and to resist cell-to-cell gas pressures. No more than 10 percent of the buoyant lift resides in the largest gas cell.

The webs are designed to be capable of resisting the loads associated with loss of lifting gas in any one cell. To assist in these loadings, struts tie the centers of each main frame web to its neighbors, running through the gas cells with suitable gas-tight joints at the points of cell penetration.

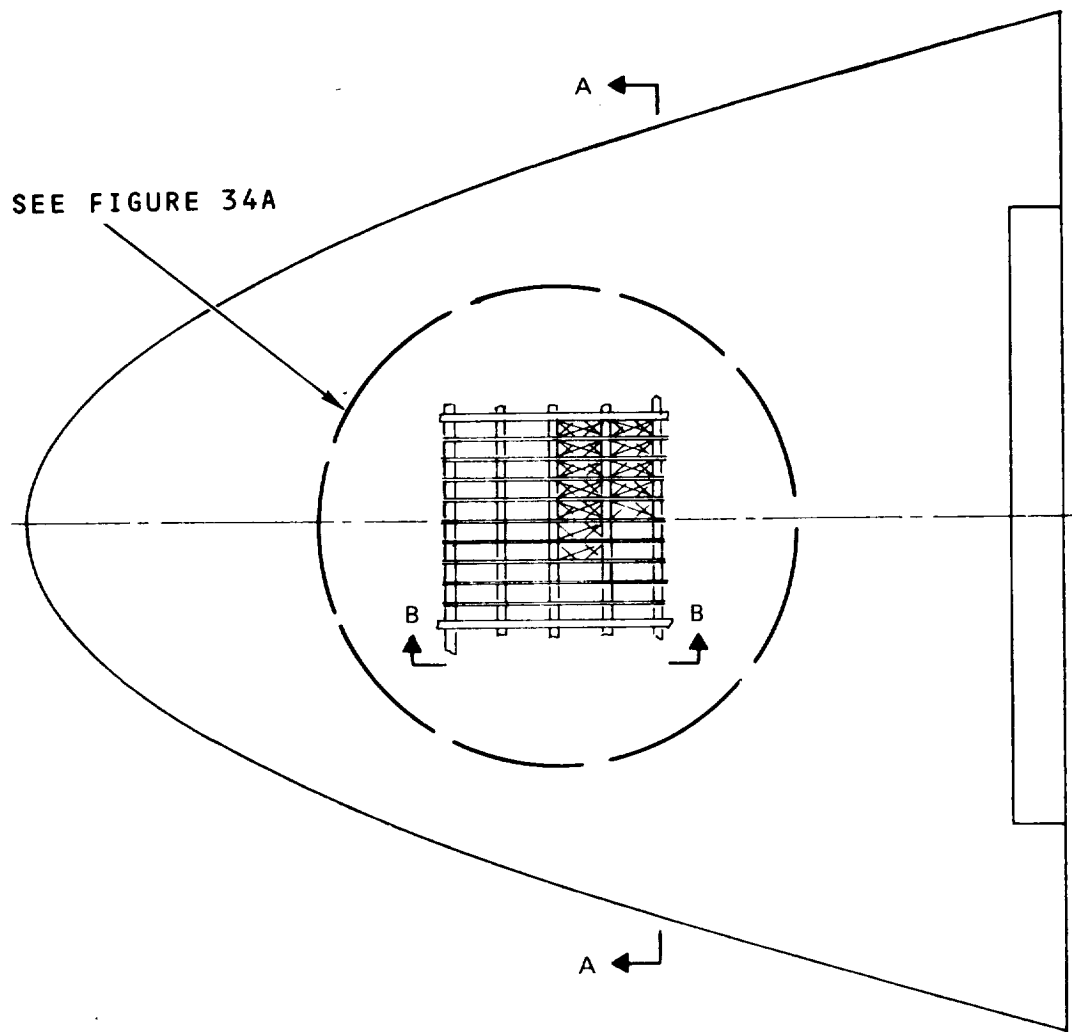


Figure 34 - Hybrid Configuration Construction

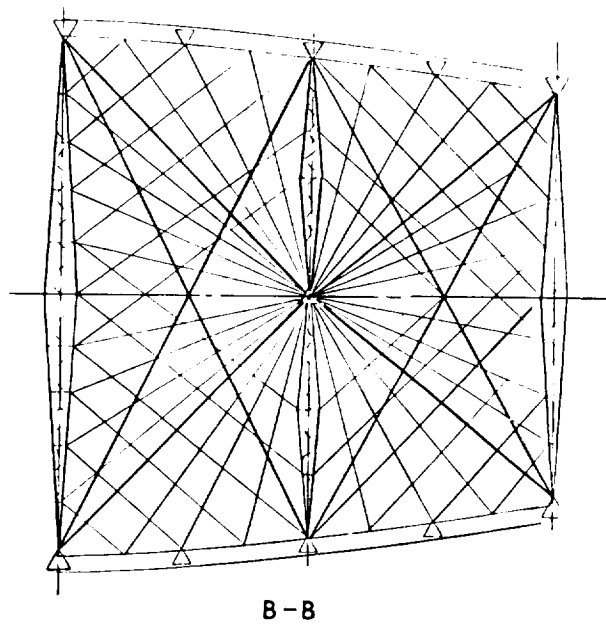
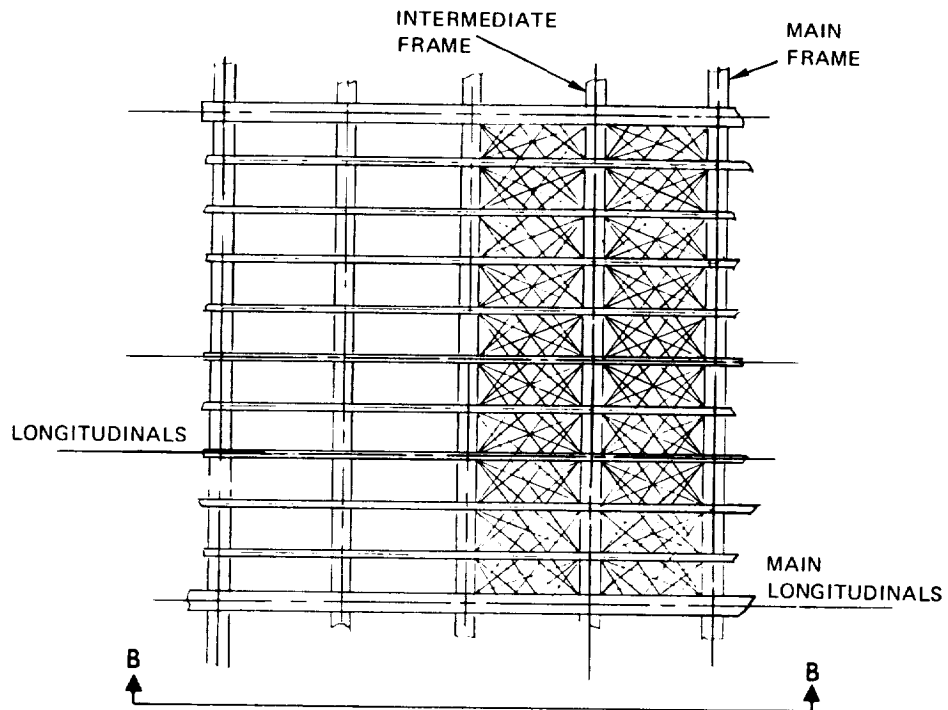


Figure 34A - Hybrid Configuration Construction Details

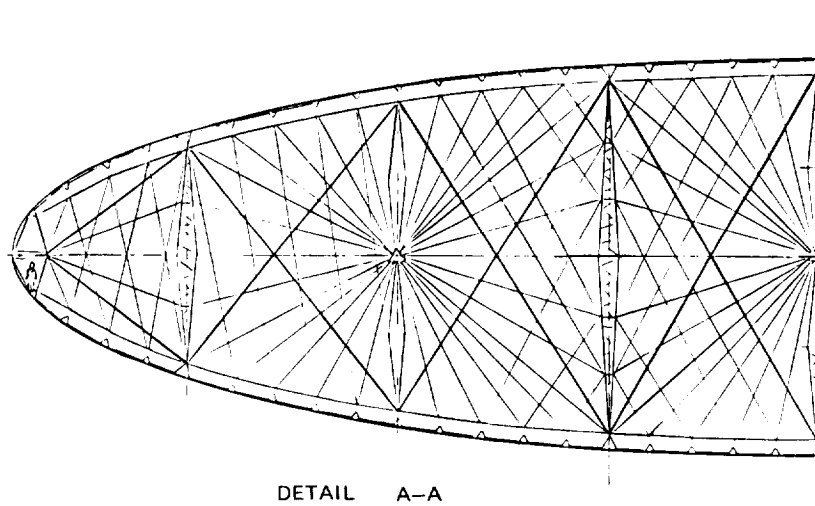
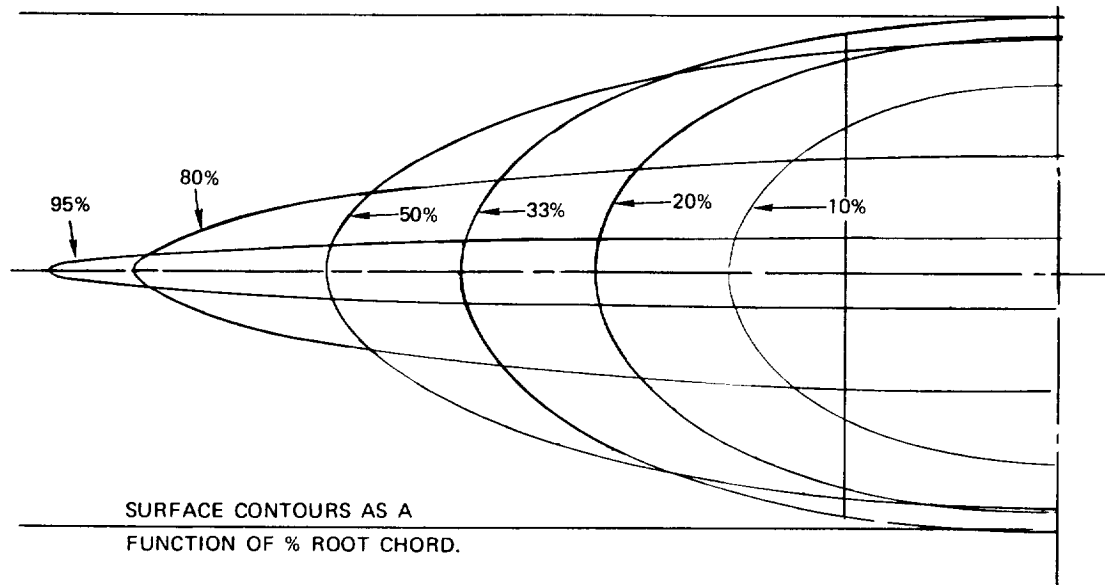


Figure 34A - Hybrid Configuration Construction Details (Concluded)

Surface Support

Top and bottom surfaces are supported by a framework on longitudinal girders placed at 3.048 m (10 ft) centers and intermediate transverse girders placed at 6.1 to 10.15 m (20 to 33.3 ft) centers based on minimum weight trade-offs. This arrangement results in a 30.48 m by 30.48 m (100 ft by 100 ft) surface panel to be designed to resist transverse aerodynamic and gas pressure loads as well as shear and axial stresses associated with overall hull loads. A fabric covering similar to that used on the historical rigid airships was found to provide the lightest approach.

The outer cover is supported by wires as necessary to prevent fluttering. Gas cell pressures are supported by wires and netting in an arrangement similar to that used on the Akron and Macon airships.

Shear Structure

The shear forces in the hull are resisted by wires or cables running diagonally from joints in the longitudinal and transverse framing. Vertical struts in the main frames form an important part of the shear structure.

Delta Planform Hybrid Aerodynamics Analysis

Detailed aerodynamic pressure distributions were developed by Neilsen Engineering and Research (NEAR) for use in the airloads calculations required for the point design structural and weight analysis. Subsequently, the initial results were confirmed by the results of a modified vortex lattice computer analysis. A synopsis of the NEAR aerodynamic analysis of the baseline lifting body is presented in Appendix E of Reference 2.

GASP Aerodynamics Estimating Procedures

The aerodynamic estimating procedures used in GASP were developed during the precontract efforts. Since it was not known what type of configuration(s) would be selected for further study, the methodology was required to be generally applicable to a broad range of delta and modified delta configurations. The DATCOM methodology (Reference 16) was selected. It was developed for the subsonic aerodynamics and landing flare analysis of low aspect ratio lifting body configurations and has been shown to predict with reasonable accuracy the aerodynamic characteristics of a broad range of delta and modified delta configurations.

Aerodynamic characteristics are calculated in the body fixed axis system based on empirically derived correlations of experimental data. The method reasonably predicts the nonlinearities associated with the vortex flow characteristic of low aspect ratio delta configurations.

Vehicle center of pressure is based on the theoretical delta planform center of pressure corrected for thickness and nose blunting. The resulting C_P prediction was in surprisingly good agreement with the NEAR analysis.

Zero normal force axial force is based on the method of Reference 17. In this reference, an expression is developed that adequately predicts the minimum profile drag characteristics of thick cambered (Clark Y model) airfoil section delta planform lifting bodies up to thicknesses of 0.3c.

Vertical tail sizes for the hybrid vehicle are based on an empirical correlation of re-entry body data, corrected for buoyancy by a β factor but limited to values no less than those of a conventional airship of the same volume and fineness ratio.

A very preliminary investigation of the longitudinal stability characteristics of the baseline hybrid vehicle was conducted. The entire area of both directional and longitudinal stability of semibuoyant hybrid vehicles is hampered both by the lack of a specific stability criteria that would provide acceptable flying qualities and the uncertainty in the values of the stability derivatives required for evaluation of the vehicle stability. The preliminary effort included a preliminary

layout of actual and apparent mass and inertia characteristics as well as a best estimate of the required coefficients. The results, although of the most preliminary nature, indicated that the baseline vehicle would be dynamically stable despite the small static instability margin for β greater than or equal to approximately 0.5. For these β 's, horizontal tail surfaces would be required primarily for control. Between $\beta = 0.5$ and 0, the vehicle might become dynamically unstable. Thus, it was decided to use a smooth fairing between a tail size of 2 percent of the planform area at $\beta > 0.5$ and the tail size required for static stability at intermediate β 's < 0.5 . Even at the lowest β 's, however, the horizontal tail area required was small due to the small $C_P - C_B$ separation. Further investigations into the specifics of the configuration geometry showed that the C_B could be shifted forward of the C_P by leaving a small percentage of the trailing edge portion of the vehicle empty of lifting gas. This was the final configuration assumed for the parametric analysis; hence, the horizontal tail area was taken as 2 percent of the planform for control.

Total vehicle characteristics (C_A , C_N , C_M) are obtained by summing the component characteristics and transforming them into a wind axis coordinates system for use in the synthesis program. The result is total vehicle C_L , C_D , and C_P as a function of α .

Details of the point design aerodynamics analysis and the GASP aerodynamics methodology are presented in Appendix E of Reference 2.

Propulsion

The propulsion system characteristics (both performance and weight) used in the hybrid analysis are the same as those in the conventional airship parametric analysis (Appendix F of Reference 2).

Structural Analysis and Weights Analysis

Detailed airload shear and moment distributions were calculated for the point design vehicle. The results, shown in Figure 35, were used to develop the parametric weight estimating relationships for use in the GASP configuration optimization and performance evaluation of the modified delta planform lifting body hybrid.

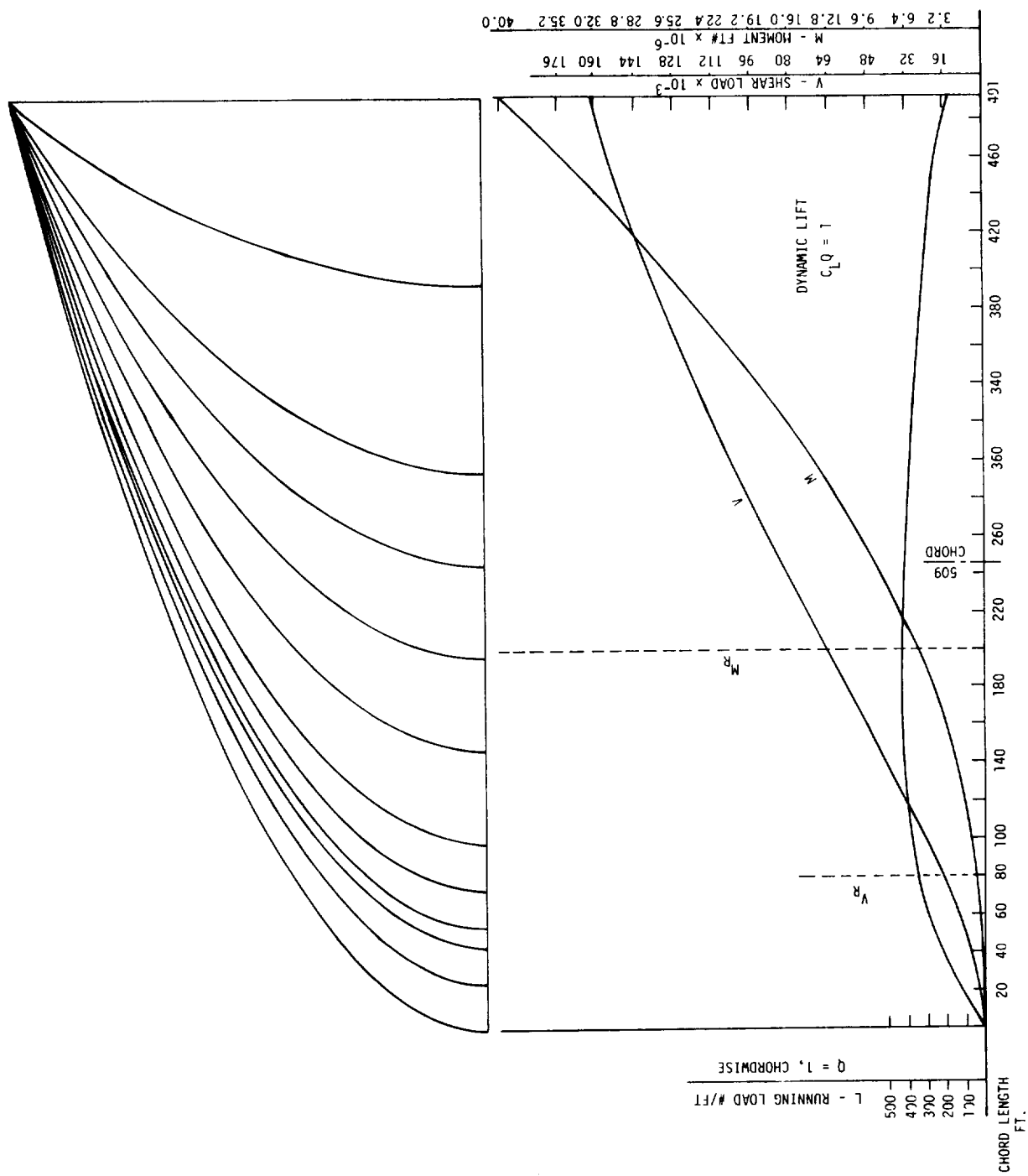


Figure 35 - Air Load, Shear, and Moment Distribution for Point Design Hybrid

The approach used was to study the point design as representative of one member of the hybrid configuration family and then to generalize the weight variation as a function of the parameters of interest.

Design Loads

Surface Pressures - The design pressure for the 30.48-m (100-ft) square surface panels is taken as the sum of three components: (1) aerodynamic pressure associated with the airfoil thickness function at zero angle of attack, (2) aerodynamic pressures associated with dynamic lift, and (3) gas cell pressures.

Analysis of data in Reference 18 revealed that (1) above can be taken as a linear function of the thickness to chord ratio and that (2) can be taken as 70 percent of the lift on the upper surface. The gas pressure is taken as 0.062 times the thickness. From the results of the point design analysis, the weight of the surface support structure was found to vary with $p^{0.735}$. Integration of this pressure-dependent weight term over the entire surface showed an overall average effective pressure of:

$$p_e = 1.87 \left(\frac{t}{c}\right) q + 0.70 \left(\frac{nW - B}{S}\right) + 0.062 t$$

where

t/c = thickness-to-chord ratio at the plane of symmetry,

n = design load factor,

W = design gross weight,

B = buoyancy,

S = planform area, and

q = dynamic pressure.

This equation provides a slightly conservative index to the weight of longitudinal and transverse girders required to support the local pressures.

Hull Loads - The hull bending and shear loads were derived by (1) establishing distributions of the gross weight over the planform, (2) distributing the buoyant and dynamic lift over the planform, and (3) performing the integrations. The maximum hull bending moment was found to be

$$M_{\max} = 0.024 nWL$$

and the average shear was found to be 0.087 nW. This value was increased to 0.10 nW for the weight estimate.

The axial loads in the longitudinal girders are estimated on the basis of a uniform distribution of the resistance with respect to the projection of the surface on the planform plane and results in a loading of:

$$N = 0.058 \frac{nWF^{4/3}}{\Psi^{1/3}}$$

where N is expressed in pounds per foot and is multiplied by 10 to get the axial load for the longitudinals spaced at 3.048 m (10 ft) center to center.

Surface Support Structure

Preliminary analysis showed that the lateral pressure loading was dominant on these structures. The longitudinal and intermediate transverse girders were therefore optimized on the basis of bending loads, with additional chord area added as necessary to carry the overall hull bending loads (N).

In order to provide a clean analytical approach to the girder design, the following assumptions were made:

1. All girder members are assumed to be equivalent to tubes of 7075 aluminum alloy with $D/t = 50$.
2. Lightly loaded members are held to a maximum L/D of 36 (this controls secondary bracing members).
3. Girders are designed as equilateral triangles with a tube in each corner; all three planes are braced with tubing in a pattern known as the "warren" truss with verticals.

4. The maximum bending moment is taken as $1/12 w l^2$ over the supports. The girder is oriented so that two chords are in compression at the point of maximum moment. Local reinforcements of the single tension chord at the point of maximum moment are assumed, but no weight allowance is made for these reinforcements since the assumption of constant area chord and shear members will provide enough excess strength to allow redistribution of areas for local reinforcement.

Assumption of elastic "long column" failure of the girder members leads to an optimum stress:

$$\sigma_o = 14000 \left(\frac{P}{L} \right)^{1/2}$$

for the individual members.

The minimum weight of the girder in bending occurs when the chord members are yield limited. The minimum weight design is therefore proportional so that the $(P/L^2) = 25$ for the chord members. This provides an elastic allowable stress of 70 ksi, which is reduced to 60 ksi for design purposes as an allowance for reductions of the Young's modulus in the vicinity of the yield stress.

The loaded diagonals in the lattice planes are designed for elastic failure at

$$\sigma_o = 14,000 \left(\frac{P}{L} \right)^{1/2}$$

and the secondary members (verticals and diagonal in unloaded plane) are designed for $L/D = 36$, $D/t = 50$.

Optimization of the weight of the chords plus web structures for a given design shear and bending moment results in a complex expression for the optimum bracing geometry. For very high shear loads, the optimum ratio of the unbraced length of the chords to the side dimension of the triangle (α) is 1.414. For low shears, $\alpha_{opt} \approx 0.9$. The minimum weight is not very sensitive to this ratio. For simplicity, $\alpha = 1.15$ was used throughout.

Algebraic evaluation yields the following expression for the weight of the supporting structure required to support the lateral pressure:

$$W = \frac{p^{2/3} S_T^{4/3}}{6450 S_L^{1/3}} + \frac{p^{5/6} S_T^{7/6}}{16,900 S_L^{1/6}} + \frac{0.0718 p^{2/3}}{S_T^{1/3}} + \frac{0.01272 p^{5/6}}{S_T^{1/6}}$$

where

W = structure weight in pounds per square foot of surface,
 p = design pressure loading in pounds per square foot,
 S_T = spacing of transverse girders in feet, and
 S_L = spacing of longitudinal girders in feet.

It is assumed that the span of the transverse girders 30.48 m (100 ft)

The above expression was evaluated for $p = 20, 40, 60, 100, 200,$ and 500 :

$$S_T = 16.67, 20, 33.3, 50$$

$$S_L = 10$$

with the result that minimum weights occur with $S_T = 10.1$ or 15.24 m (33.3 ft or 50 ft) over the entire range of pressures with minor weight penalties for $S_T = 25$ ft. Analysis of the data provides a much simpler expression

$$W = \left(\frac{p}{138}\right)^{0.735}$$

which exhibits a maximum error of 2 percent over the range of pressures evaluated and is used for the weight estimates.

Proportioning of the longitudinal girders for minimum weight for carrying the pressure (ρ) results in an L/ρ of:

$$L/\rho = \frac{114 S_T^{1/3}}{(p S_L)^{1/3}}$$

The additional chord area required to carry the axial compression is provided by an added weight of:

$$\Delta W = \frac{N \left(\frac{S_T}{p S_L}\right)^{2/3}}{6280}$$

The total weight of the surface support structure is a combination of the above with additional assumptions:

1. The shape of the hull bending moment envelope is the same as the hull section modulus with constant surface areas so that N is constant over the entire surface.
2. The lower surface weight is 80 percent of the upper surface weight.

Thus:

$$W_1 = 1.80S \left\{ \left(\frac{1.50p_e}{138} \right)^{0.735} + \frac{1.50N}{2830 (1.5p_e)^{2/3}} \right\}$$

where

S = plan form area,
 p_e = average effective design pressure, and
 N = surface compression from hull bending.

Main Frames

Since overall hull bending loads are resisted primarily by the surface support framework, the chord members of the main longitudinal and transverse frames are taken as the same as the intermediate transverse girders. Basing the weight on a transverse girder spacing of 7.62 m (25 ft) gives:

$$W_2 = \frac{1}{25} (1.5p_c)^{2/3} S$$

Shear Structures

Based on the analysis of the point design airship, the average transverse shear on transverse and longitudinal sections is taken as

$$V = 0.10nW$$

Assuming that the shear flow splits into four paths typically, a shear flow over an area of approximately 3S and of an intensity of (1/40) (nW/t) is taken as representative.

Assuming shears are resisted by steel wires or cables working to 200 ksi, with 100 percent counterwires and with vertical struts and other reinforcements having a weight equal to the brace weight provides an estimated shear structure weight including a 1.5 safety factor of

$$W_3 = 16.2 \frac{nWS}{t} \times 10^{-6}$$

Gas Cells, Outer Cover, Supporting Wires

The weight of the gas cells, outer cover and supporting wires, and netting are derived from data on the Macon airship and are estimated to be:

$$W_4 = 0.208S \text{ for gas cells, wires, netting}$$

and

$$W_5 = 0.066S \left(\frac{V}{122} \right)^2$$

where

S is the planform area

V is the design forward speed in feet per second.

The weight of the landing gears is defined as a function of β between a value representative of slightly heavy airships ($\beta \approx 0.9$) and conventional commercial aircraft (taken conservatively as six percent of the vehicle gross weight):

$$W_6 = \left[0.01 + (1-\beta)0.05 \right] W_{\text{gross}}(\text{landing gears})$$

Tail area requirements as calculated in the aerodynamics subsection are used to calculate tail and control system weights:

$$W_7 = \left(\frac{1.33 (A_{FV})^{1/2}}{382} + 3 \right) A_{\text{fin}} (\text{tail and controls})$$

Control car and furnishings are assumed to be a constant percentage of the gross weight:

$$W_8 = 0.008 W_G \text{ (control car and furnishings)}$$

The final parametric weight estimating relationships used in GASP for the hybrid parametric analysis are summarized below.

W = gross weight

B = buoyant lift

∇ = hull volume

F = fineness ratio

AR = aspect ratio

S = planform area

A_F = total tail area

u = design gust velocity

V_D = design forward velocity

α_c = cruise angle of attack

α_G = gust induced angle of attack

$$t = \frac{2.86 \nabla^{1/3}}{(AR)F^{2/3}} \quad \frac{t}{c} = \frac{2.31}{(AR)F^2} \quad q = \frac{1}{2} \rho V_D^2$$

ΔC_{NG} = incremental gust induced normal force

$$= C_N |(\alpha_c + \alpha_G) - C_N | \alpha_c$$

$$n = 1 + \frac{1}{2} \left(\frac{\rho u V_D \Delta C_{NG}}{W/S} \right) \quad \text{limited in the parametric study to } \geq 3.0$$

$$N = 0.058 \frac{n W F^{4/3}}{\nabla^{1/3}}$$

$$p_e = 1.87 \left(\frac{t}{c} \right) q + 0.70 \frac{(nW - B)}{S} + 0.062 t$$

$$W_1 = 1.80S \left\{ \left(\frac{1.50p_e}{138} \right)^{0.735} + \frac{1.50N}{2830 (1.5p_e)^{2/3}} \right\} \begin{matrix} \text{surface} \\ \text{support} \\ \text{structure} \end{matrix}$$

$$W_2 = \frac{1}{25} (1.5 p_e)^{2/3} S \text{ for chord members of main frames}$$

$$W_3 = 16.2 \frac{nWS}{t} \times 10^{-6} \text{ for shear structure}$$

$$W_4 = 0.208 S \text{ for gas cells, wires, netting}$$

$$W_5 = 0.066 S \left(\frac{V_D^2}{122} \right) \text{ for outer cover}$$

$$W_6 = [0.01 + (1-\beta) 0.05] W \text{ for landing gears}$$

$$W_7 = 0.008 W \text{ for furnishings, control car, etc.}$$

$$W_8 = \left[\frac{1.33 (A_F V_D^2)^{1/2} + 3}{382} \right] A_F \text{ for tail and controls}$$

$$W_{NPWE} = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 \text{ for non propulsive empty weight}$$

Hybrid Parametric Analysis

The parametric performance analysis and configuration optimization of the modified delta planform hybrid vehicle is based on the geometrical, aerodynamic, propulsion, and structural and weights analyses of the preceding subsections. The major portion of the hybrid analysis dealt with six major variables:

1. Gross weight
2. Static lift-to gross-weight ratio, β
3. Cruise velocity, V_C
4. Aspect ratio, AR
5. Thickness ratio (t/c)
6. Range

Range was by necessity included in the parametric analysis as an independent variable. The optimum vehicle characteristics AR and t/c , which result

in maximum payload ton-miles per hour, in general are strongly dependent on design range as well as β . Inclusion of range as an independent variable (rather than simply using useful load ton-miles per hour) required approximately three times as much data reduction and analysis as had been originally planned. Because of this, considerably less time was available to analyze and interpret the results and define their origin than had been originally planned. Thus, the interpretation and discussion of the results is somewhat more abbreviated than might be considered desirable. However, by drawing on the results of the conventional airship heaviness tradeoff study, combined with the summary level analysis of the hybrid results, a fundamental understanding of the performance characteristics of the semibuoyant lifting body hybrid can be obtained.

The objective of the hybrid parametric study was to determine the vehicle aspect ratio, thickness ratio, and cruise velocity, which maximize productivity as a function of range, β , and gross weight (FOM = payload ton-miles per hour at the given range).

The "optimum" degree of partial buoyancy or heaviness (β) was the parameter of first-order interest in the hybrid study. The general approach is illustrated in Figures 36 through 39. At a given gross weight and β , the FOM was evaluated at four aspect ratios (generally 0.6, 0.75, 1.0, and 1.5) and three thickness ratios (generally 0.15, 0.225, and 0.3) as a function of velocity. Typical results, shown in Figure 36, allow determination of the optimum V_C as a function of aspect ratio and thickness ratio. Cross-plots of the optimum FOM and optimum V_C as a function of aspect ratio at constant thickness ratio were constructed to indicate the aspect ratio that maximized the FOM, as shown in Figure 37. This data was used to select the optimum aspect ratio. Cross-plots of the FOM and V_C at the optimum aspect ratio as a function of thickness ratio were constructed to obtain the optimum thickness ratio as shown in Figure 38 and Figure 39.

The entire process was then repeated as a function of range and β to obtain the final desired data: (1) maximum productivity is a function of β and range and (2) the AR, t/c , and V_C that produce the maximum. Repeating the entire process at the other study gross weight values produced the final optimized productivity/performance results and optimized vehicle characteristics presented below.

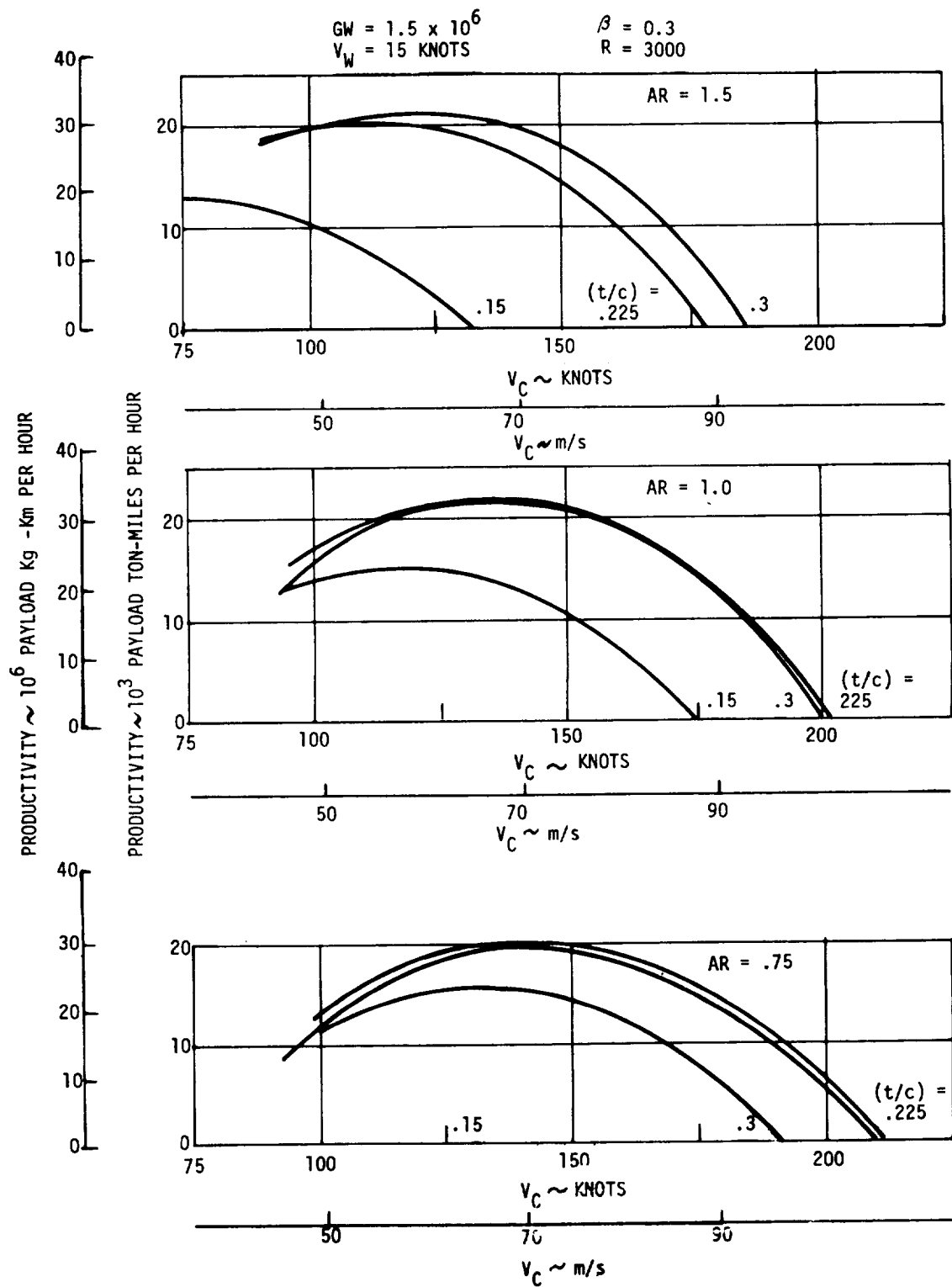


Figure 36 - Typical Variation of Hybrid Vehicle Productivity as a Function of Cruise Velocity

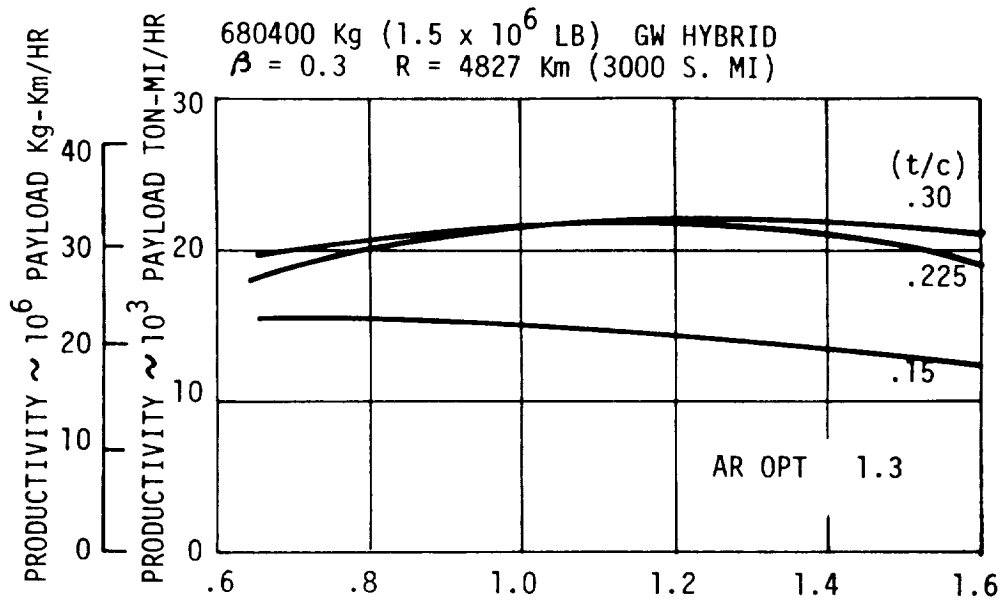


Figure 37 - Variation of Hybrid Vehicle Productivity with Aspect and Thickness Ratios
 $(\beta = 0.6, GW = 1.5 \times 10^6 \text{ lb})$

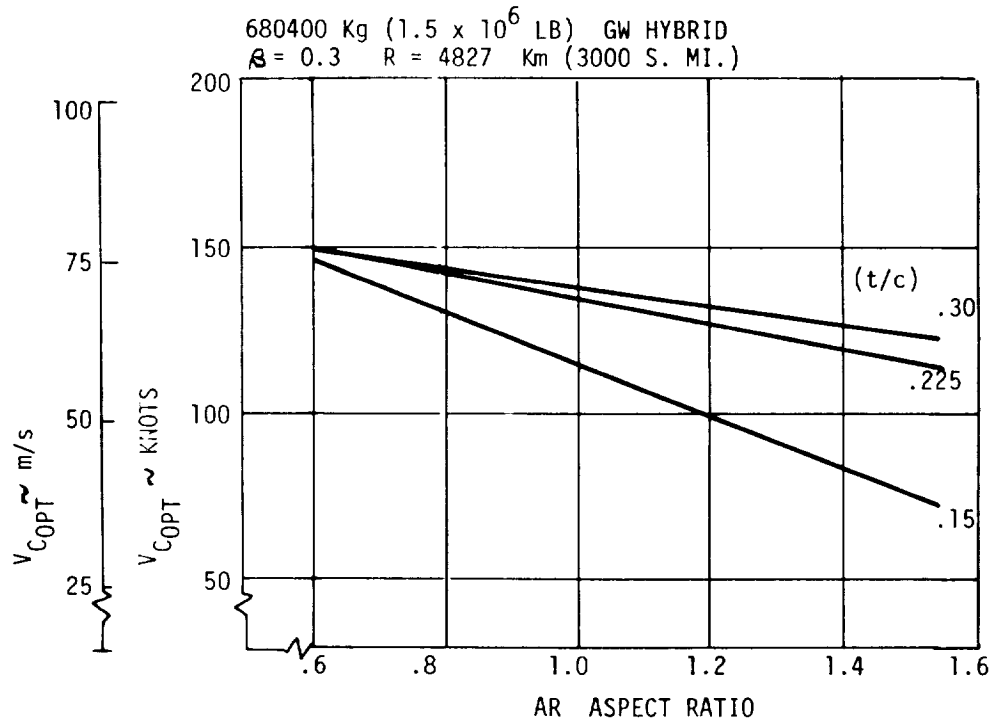


Figure 38 - Variation of Hybrid Vehicle Productivity with Aspect and Thickness Ratios
 $(\beta = 0.3, GW = 1.5 \times 10^6 \text{ lb})$

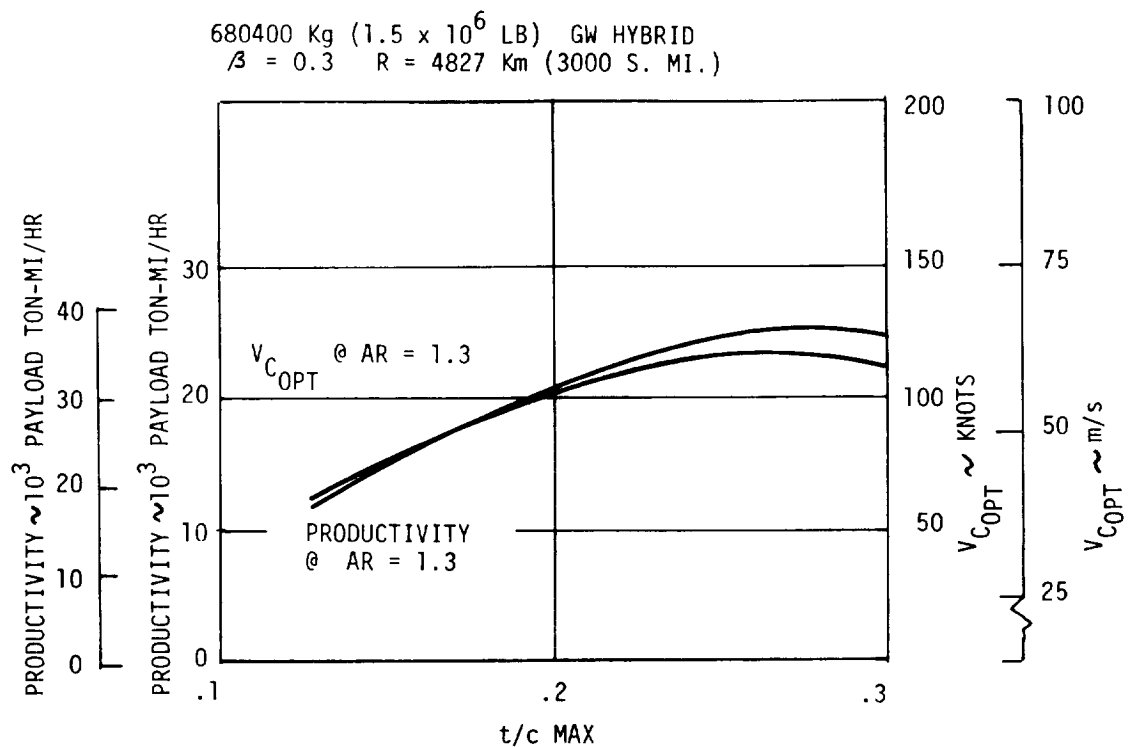


Figure 39 - Variation of Hybrid Vehicle Productivity with Aspect and Thickness Ratio ($\beta = 0.1$, GW = 1.5×10^6 lb)

The lack of an "optimizer" capability as employed in NASA-Ames synthesis programs (References 3 and 4) was a definite handicap* in completing the parametric study. This can be appreciated more fully by considering the sheer quantity of data and analysis required to obtain a given optimum. At a given gross weight and β , a minimum of 27 (typically 36) performance points were generated for a given range (3 to 4 AR's, 3 to 4 V_C's, and 3(t/c)'s, or 27 to 36 performance points). Analysis of the resulting data is used to define maximum FOM and maximum V_C for plotting as a function of aspect ratio. Analysis of these data is used for cross-plotting as a function of (t/c) to obtain the optimum data at this range value. Repeating the entire process at one or two "design" range values gives the final results for one β and gross weight.

*Incorporation of an optional "optimizer" capability such as CONMIN or AESOP is being considered for Phase II and subsequent parametric study efforts.

The purpose of this discussion is merely to indicate that, although fewer final data charts are presented in the hybrid parametric subsection than in the conventional airship parametric subsection, a considerably larger amount of time and analysis was required to obtain the hybrid results.

Hybrid Parametric Performance Results

The true scope of the hybrid investigation is even more significant in terms of the spectrum of optimized configuration characteristics - from aspect ratios of 0.6 and thickness ratios of 0.3 to aspect ratios of 1.8 and thickness ratios of 0.2 (that is from configurations converging to circular cross-sections or even elliptical sections whose major axis is normal to the wing planform and is forward of the maximum (t/c) location to rather thin and high aspect ratio "flying wings"). The final optimized configuration characteristics and optimum cruise velocity are presented in Figure 40, which clearly illustrates the spectrums of configuration characteristics and the dependence of these characteristics with range, β , and gross weight.

Attempts to analyze a 4536-kg (10,000-lb) gross weight hybrid configuration were unsuccessful. The total empty weight exceeded the gross weight in all cases. This result is not surprising for the type of rigid construction used in the hybrid point design. As shown in Figure 4, even a conventional rigid airship at 4536-kg (10,000-lb) gross weight has a structural weight-to-gross weight ratio of 0.7. The lower structural efficiency resulting from the transformation from the rather simple, symmetrical cylindrical shape to the rather complex hybrid configuration geometry is not surprising. If hybrid configurations are desirable at these extremely low gross weights, some alternate form of construction must be employed.

The lowest gross weight analyzed in the hybrid study was 18,144 kg (40,000 lb). The optimized configuration characteristics were introduced in Figure 40. The optimized productivity is presented in Figure 41 as a function of β and range for the 40,000-lb gross weight vehicles. Also shown in Figure 41 is the optimized productivity of a conventional rigid airship over the same β

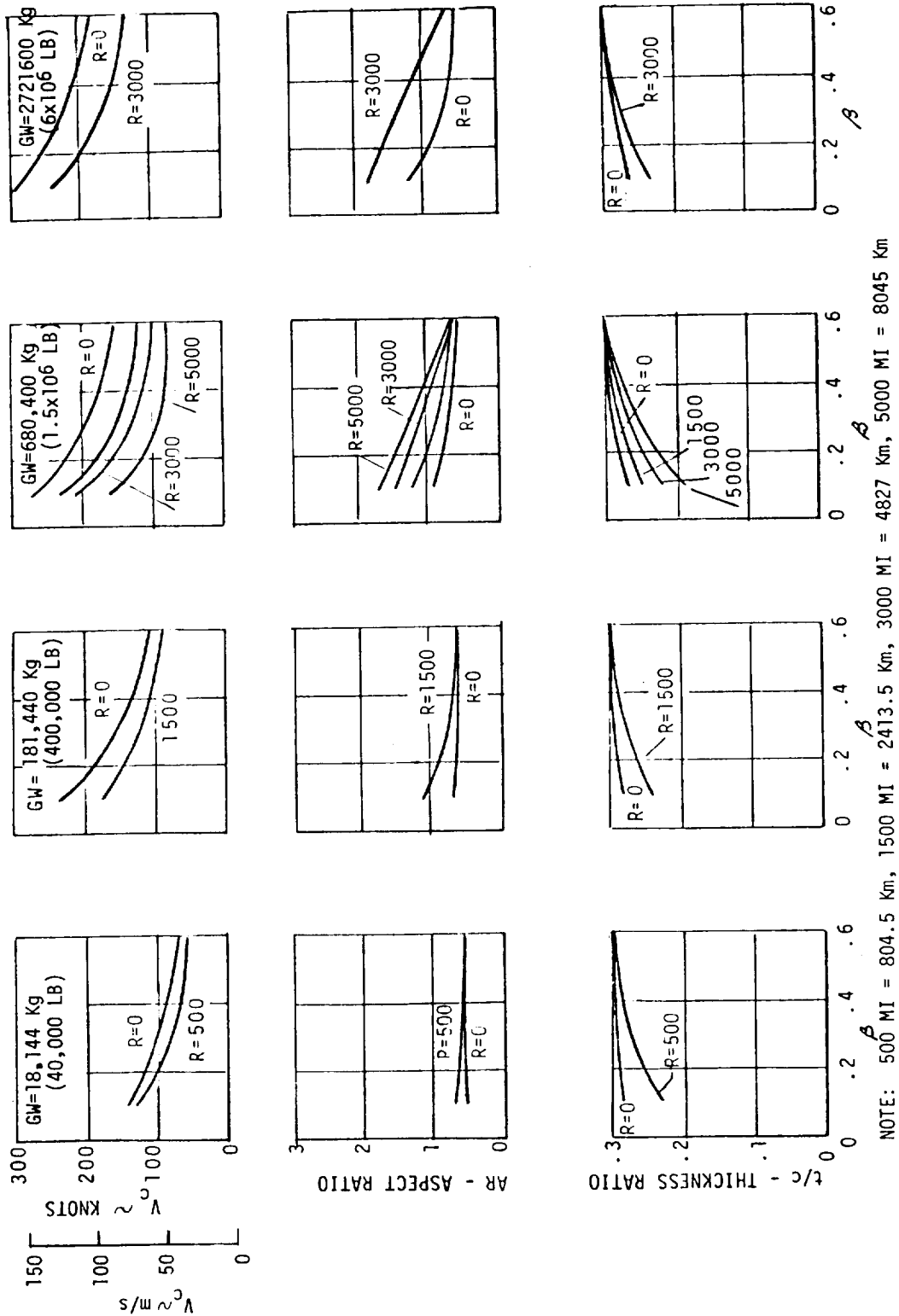


Figure 40 - Optimized Hybrid Vehicle Characteristics

and range values obtained in the preceding subsection. As shown, the conventional airship has higher productivity than the hybrid configuration at any given β with both configurations indicating a trend to $\beta = 0$ for maximized productivity. Referring to interactions and relative efficiencies of aerostatic/aerodynamic/structural and propulsive efficiencies at the conclusion of the conventional airship parametric analyses subsection, the β trend is as expected. The lower productivity of the hybrid can be traced primarily to the lower structural efficiency of the lifting body shape relative to the conventional airship. The relative structural efficiency is compared in Figure 42 as a function of β .

Several observations should be made from this figure. First, the variation of the nonpropulsive structural weight as a function of β demonstrates the same trend for both the hybrid and conventional airships.

Second, as noted by the weight per unit planform area in Figure 42, the hybrid vehicle structural configuration is fairly efficient. However, the hybrid W_{str}/W_{gross} is about twice that of the airship at the same β due to the configuration's complexity. When it is realized that the hybrid configuration structural design incorporates gas cells, netting, and one-cell out design capability, the resulting structural weight estimates probably are optimistic and certainly are not as detailed as the conventional rigid airship structural weight data.

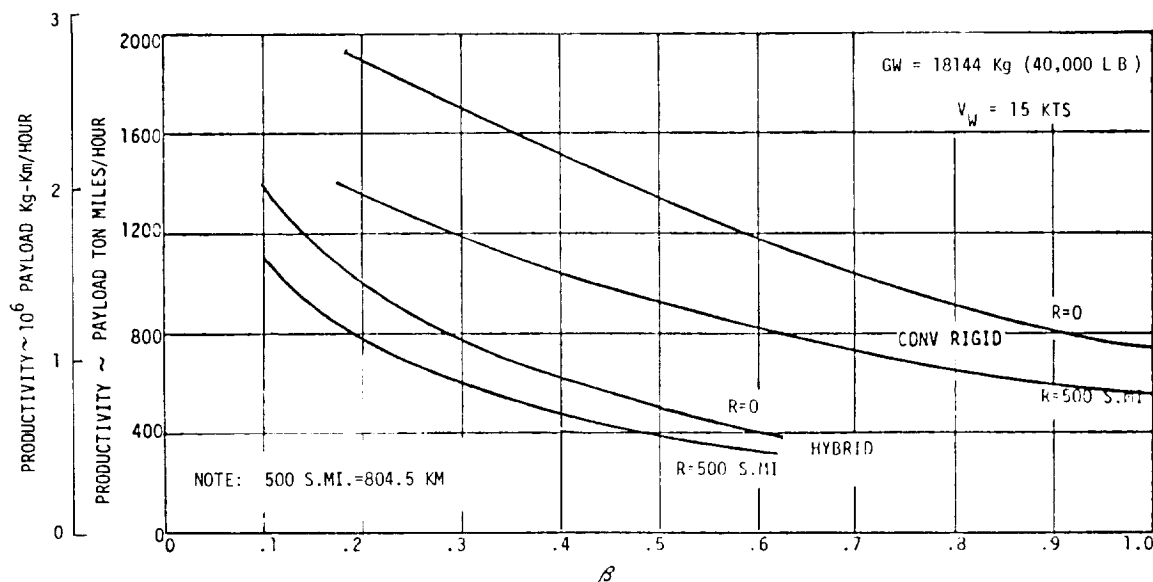


Figure 41 - 18,144-kg (40,000-Lb)

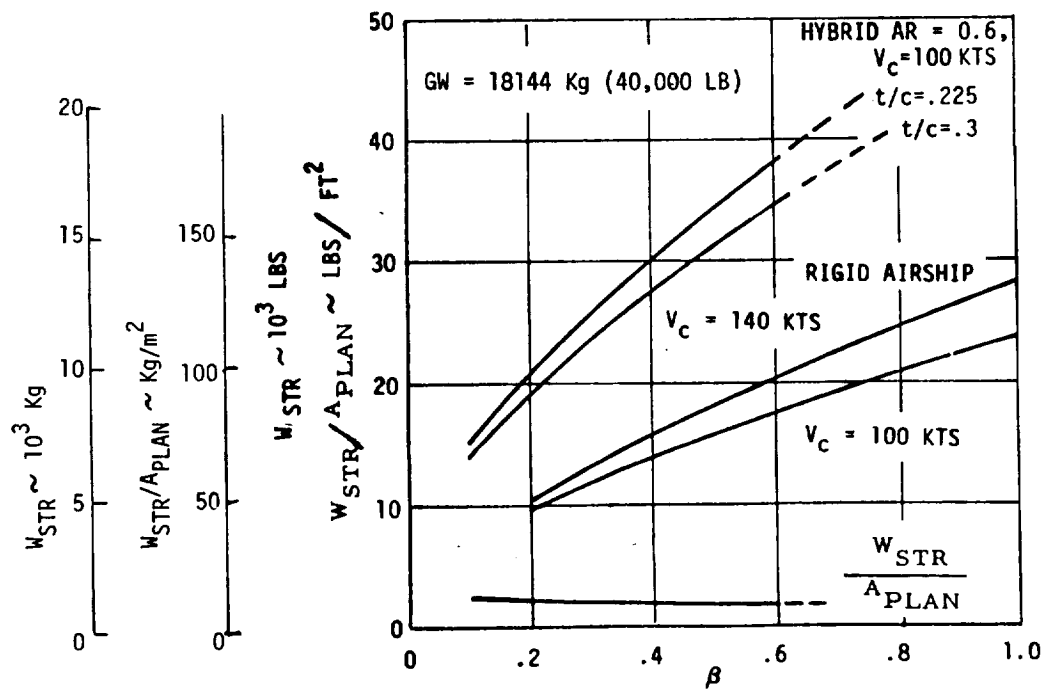
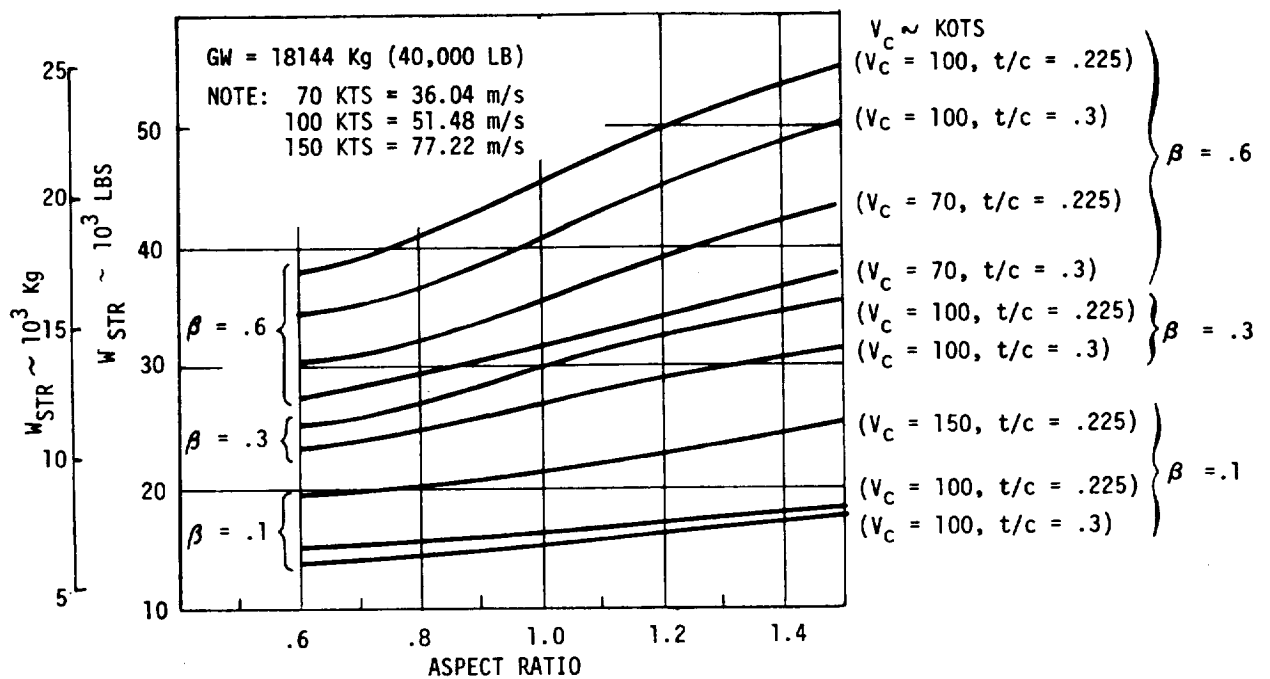


Figure 42 - Hybrid and Conventional Vehicle Structural Weight Characteristics as a Function of β - 18,144-kg (40,000-Lb) Gross Weight Vehicle

Finally, as shown in the top portion of Figure 42, high aspect ratios are not desirable even at the lowest β considered and are particularly undesirable at the higher β 's. At low gross weight (small volumes), the low volumetric efficiency of static lifting vehicles (volume to volume to the $2/3$ power relationship) results in such large surface areas that appreciable amounts of aerodynamic lift (very low β 's) can be provided by relatively inefficient aerodynamic shapes such as a conventional ellipsoidal airship hull. These conclusions regarding the relationship of aerodynamic and aerostatic efficiencies basically are dominated by the structural efficiencies of low gross weight semibuoyant vehicles when evaluated in terms of a productivity figure of merit.

Thus, optimized aspect ratios tend to the lowest value considered (0.6) and tend to stay relatively thick in order to minimize structural weight.

Figure 43 compares the optimized productivity hybrid vehicle with a conventional rigid airship as a function of range and β for 181,440-kg (400,000-lb) GW. Several conclusions can be drawn from these results plus those of Figure 40.

First, at zero range ($R = 0$), FOM continues to increase as β is reduced. This is true for both the hybrid and the conventional airship. The discontinuity in the conventional airship curve results from the transition from cruise engine

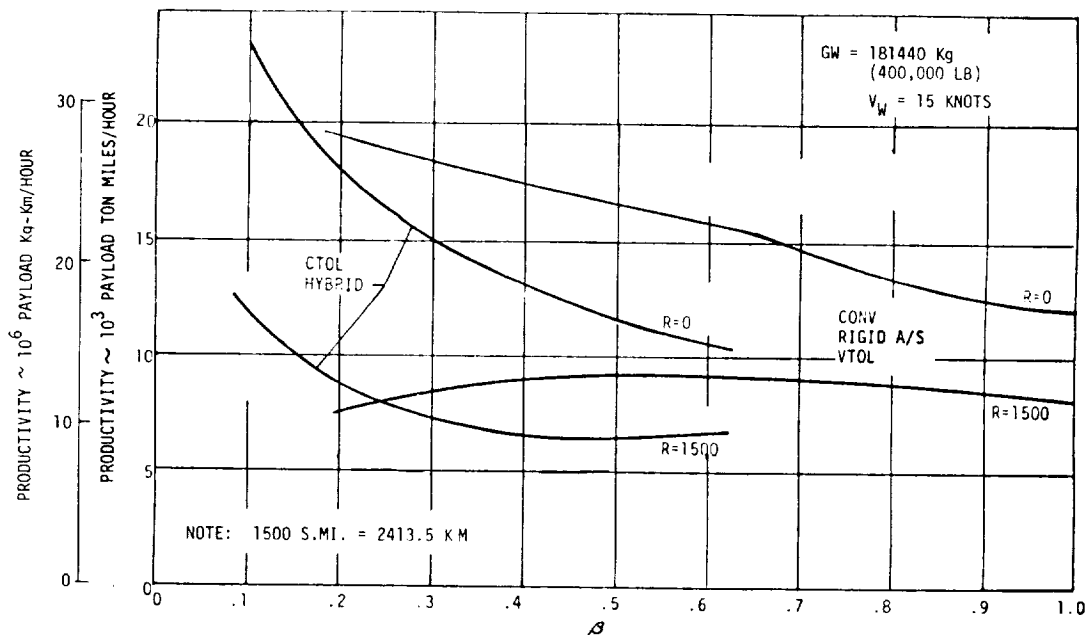


Figure 43 - 181,440-kg (400,000-Lb) Gross Weight
Optimized Vehicle Productivity versus β

sizing at $\beta \gtrsim 0.65$ to VTOL sizing at $\beta < 0.65$. Thus, at $R = 0$, the optimum hybrid appears to be converging to a nonbuoyant vehicle, such as an airplane.

At a nominal range, say 2414 km (1500 mi), the conventional airship has an optimum β . The hybrid, however, begins to show what appears to be a characteristic trend as a function of β . This trend, at least over the range of configurations and variables considered, can be summarized as follows:

At zero ranges, no nonzero optimum β appears to exist. At larger ranges, two distinct trends exist that tend to improve the productivity FOM. At low β (less than about 0.3), the productivity continually improves as β is reduced. That is, the optimum hybrid tends toward a nonbuoyant vehicle. Looking at this trend starting from $\beta = 0$ and asking "what improvement in productivity can be obtained by taking a conventional airplane and increasing its body or wing volume to contain larger and larger amounts of a static lifting gas?", the answer is: no improvement. The increased drag and structural weight only reduce productivity.

The second distinct trend is the "bucket" in productivity curve as a function of β . Continuing the above reasoning from the $\beta = 0$ starting point, the reversal apparently occurs as the volume to V to the $2/3$ ratio begins to increase. Thus, some productivity improvement does occur from the low point in the $\beta = 0.3$ to 0.4 range as β is increased to 0.6. If the zero range productivity (i.e., the useful load times cruise velocity) of a hybrid of β less than 0.4 is compared with a $\beta = 1$ airship, the hybrid does indeed appear better. Two factors modify this comparison - comparison at range (hybrid productivity is more strongly degraded by range) and allowing the airship to use aerodynamic lift to increase productivity.

An additional characteristic trend of the hybrid vehicle is shown in Figure 40. At small β , as the design range is increased, the optimum configuration characteristics tend toward higher aerodynamic efficiency (higher aspect ratios and lower thickness ratios). Also, V_C optimum is reduced. At the larger β , the optimum characteristics universally tend to low aspect ratios of 0.75 to 0.6 and high thickness ratios of 0.3; the optimum hybrid characteristics become more like an airship.

Figure 44 compares the productivity of a 680,400 kg (1.5×10^6 lb) hybrid with an equal gross weight airship. The FOM trend with β and range is exactly as described above. The interesting trend observed in Figure 44 is the similarity between the trend of the conventional airship data and the hybrid data. One is tempted to "connect the curves," but this would be an error. The hybrid design if allowed to go to $\beta > 0.6$ wants to have configuration characteristics like an airship (such as an aspect ratio of < 0.6 and thickness ratio of > 0.3). For such a configuration, the design criteria should surely be changed to those applied to an airship. The structural design concept and associated weight estimating relationship are probably not valid below an aspect ratio of 0.6 or above a thickness ratio of 0.3.

One further note should be made from Figure 44. The airships compared in this section are all capable of VTOL. The hybrid performance is based on CTOL. Original plans had included a more thorough investigation of STOL takeoff capability for the hybrids than time permitted; this was due primarily to the increased data analysis requirements with range as an independent variable plus the more in-depth investigation of heaviness for conventional airships. This is not considered an overwhelming shortcoming of the present investigation.

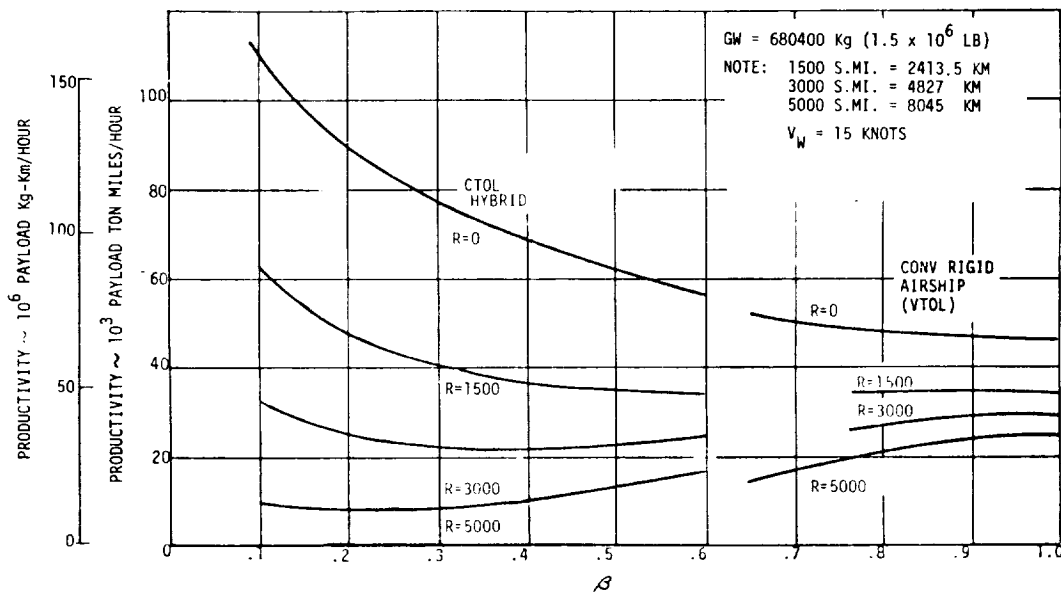


Figure 44 - 680,400-kg (1.5-Million-Pound) Gross Weight
 Optimized Vehicle Productivity versus β

The overriding problem regarding takeoff and landing capability will occur in landing. Takeoff lengths for the HYBRID can be kept quite low even for extremely low β 's due to the very low wing loading (large wing area). However, landing/landing gear and impact loads may present a considerable problem possibly requiring some type of air cushion system to distribute landing loads more uniformly into the extremely lightweight structure. This is certainly an area requiring more in-depth examination for the CTOL hybrid vehicles.

Figure 45 shows the productivity of the 2.7216×10^6 kg (6×10^6 lb) hybrid compared with the same gross weight conventional airship. The trends of this figure, FOM versus β versus range, are the same as with the smaller gross weights with one noticeable exception. At ranges below 4827 km (3000 mi), the hybrid offers rather substantial productivity increases over the conventional airship over the entire β range. Thus, the hybrid lifting body vehicle of the construction assumed in this study shows considerable promise from a productivity basis at the upper extreme of the gross weight range investigated in the Phase I study. The probable source of this is the following.

The structural weight equations used for conventional airships universally have an optimum structural efficiency (minimum W_{str}/W_{gross}) at some volume due to the volume to the $4/3$ power dependent weight components. The hybrid equations, however, have no such dependence.

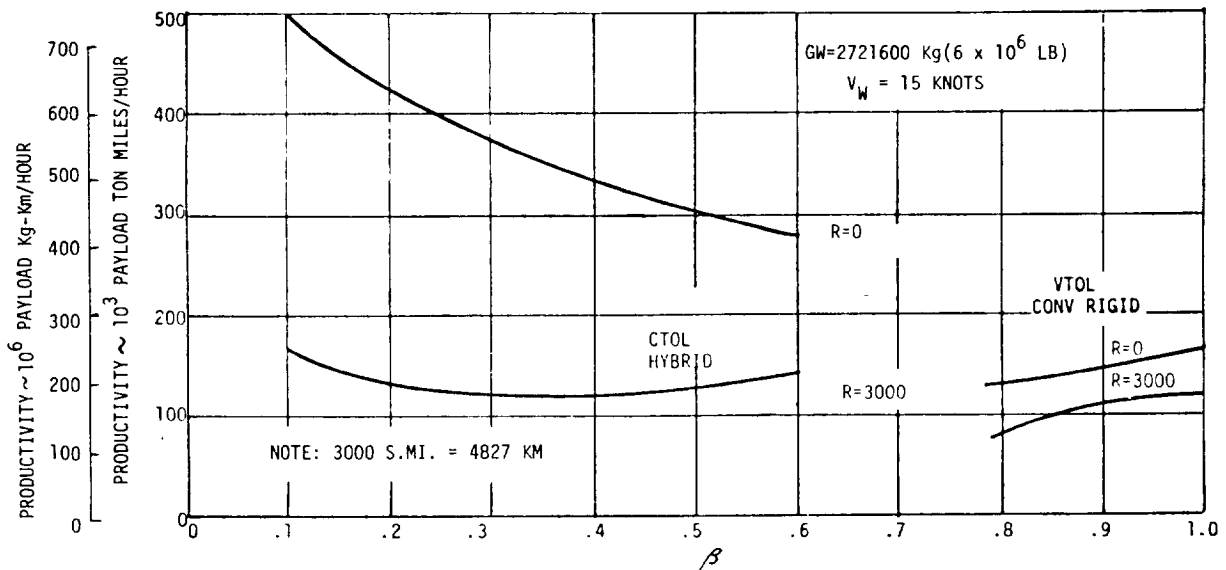


Figure 45 - 2,721,600-kg (Six-Million-Pound) Gross Weight Optimized Vehicle Productivity versus β

Lifting Body Hybrid/Ellipsoidal Airship Productivity Comparison

Figure 46 compares the productivity of the $\beta = 0.1$ lifting body hybrid vehicle with that of an ellipsoidal rigid airship as a function of gross weight for three range values. Figure 47 presents the same comparison for the $\beta = 0.6$ lifting body hybrid. The value of the gross weight at which the optimum productivity configuration switches from ellipsoidal airships to the lifting body vehicle is indicated in both figures.

A further comparison of productivity as a function of range of the lifting body hybrid vehicles and a neutrally buoyant conventional rigid airship at 1,500,000 lb gross weight is presented in Figure 48. The range sensitivity of the lifting body vehicle is shown. The lower the value of β the more sharply productivity is reduced with range. The source of the productivity/range sensitivity is the higher power loadings required by the hybrid vehicles compared to the neutrally buoyant airships as shown in Figure 49.

One final comparison of the optimized $\beta = 0.1$ lifting body hybrid vehicle productivity with that of conventional commercial aircraft is shown in Figure 50. Comparing the productivity of 340,200-kg (750,000 lb) gross weight lifting body hybrid at a 4827 km (3000 stat mi) range with that of the 747F-200 shows the hybrid to be lower by approximately a factor of four.

Figure 51 shows representative structural efficiency characteristics of the hybrid vehicle over the gross weight and configuration range. The hybrid vehicle investigated in this study is very efficient. In fact, from a structural weight standpoint, the weight estimates used in this study are probably optimistic. At low β , extrapolating the W_{str}/W_{gross} ratio to zero results in a lower limit of 0.22, which is comparable to values quoted for the span loader type of aircraft currently under investigation.

On the basis of aerodynamic efficiency, the lifting body hybrid vehicles have rather good aerodynamic lift to drag ratios ranging from a value of approximately 6 at $AR = 0.6$ to approximately 12 at $AR = 1.5$ for a 680,400 kg (1.5×10^6 lb) lifting body hybrid at $\beta = 0.6$ and $t/c = 0.225$.

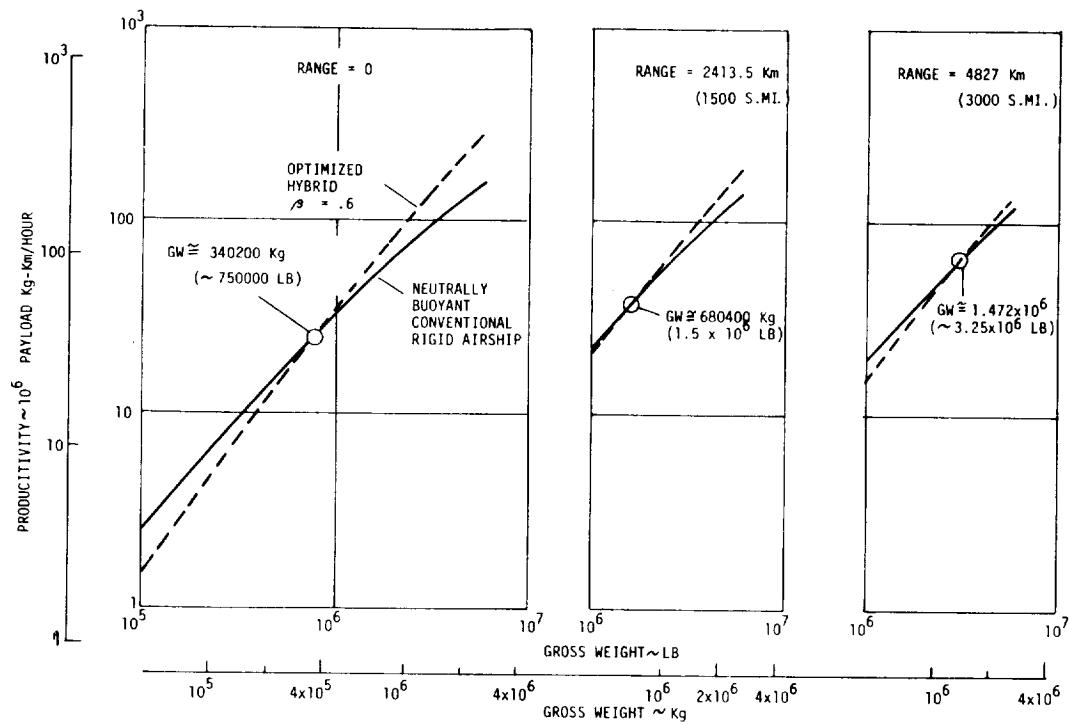


Figure 46 - Comparison of $\beta = 0.1$ Hybrid and Rigid Airship Productivity

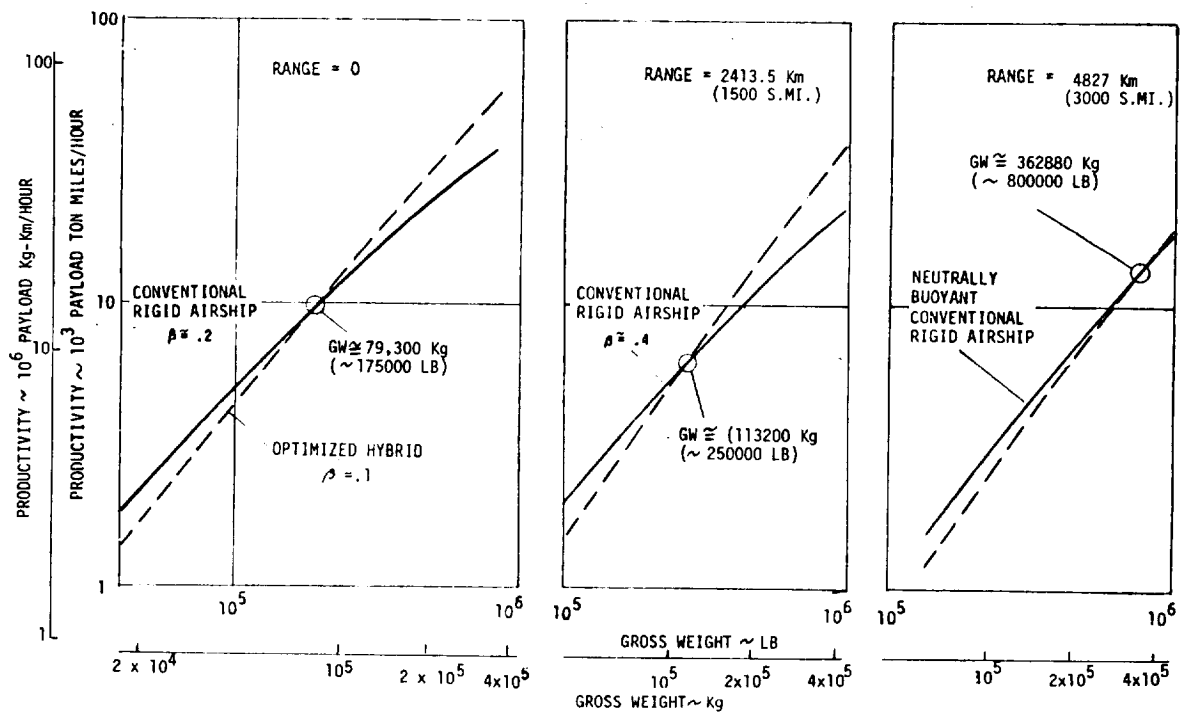


Figure 47 - Comparison of $\beta = 0.6$ Hybrid and Rigid Airship Productivity

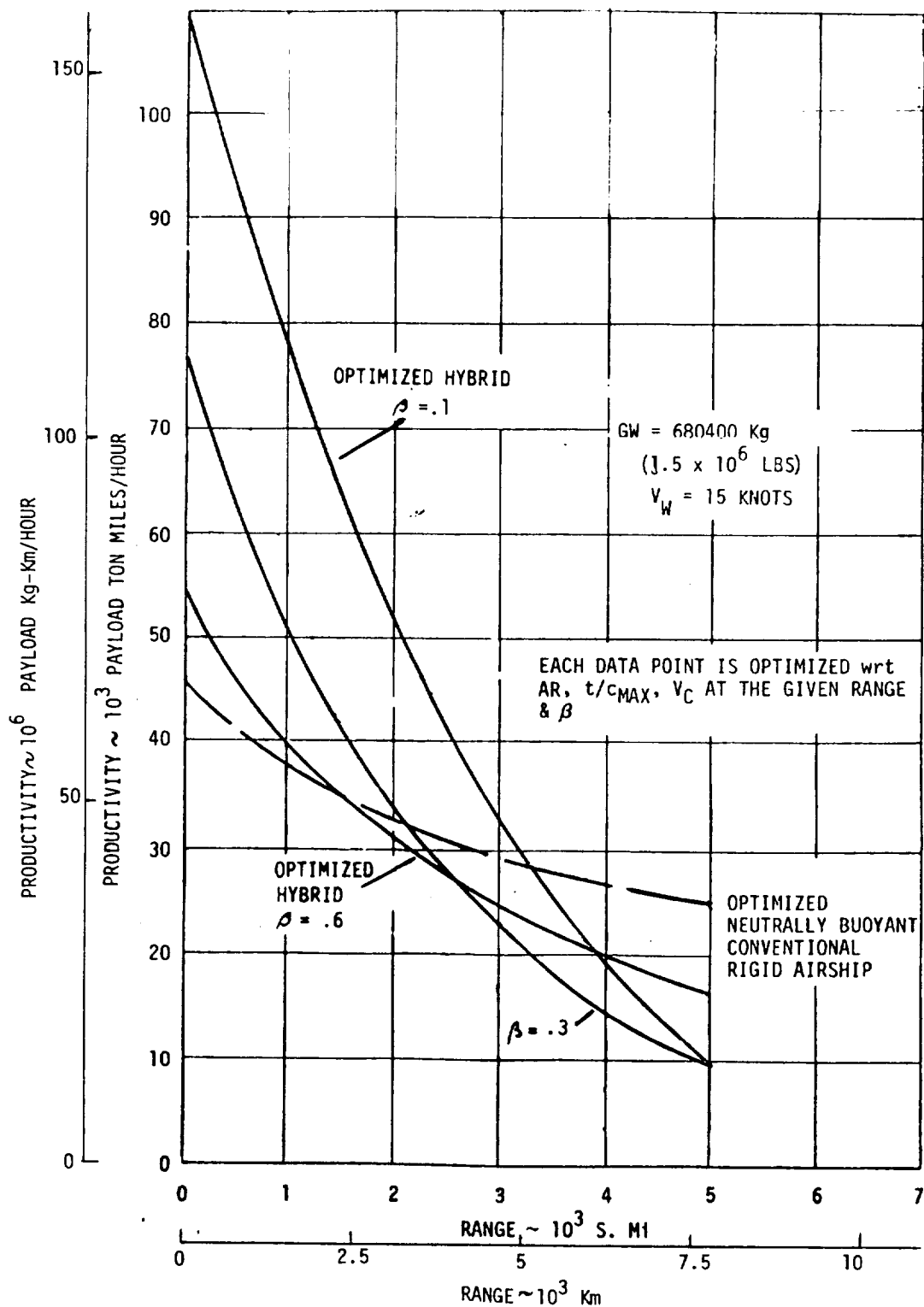


Figure 48 - Comparison of 680,400-kg (1.5×10^6 lb) Hybrid and Airship Productivity versus Range

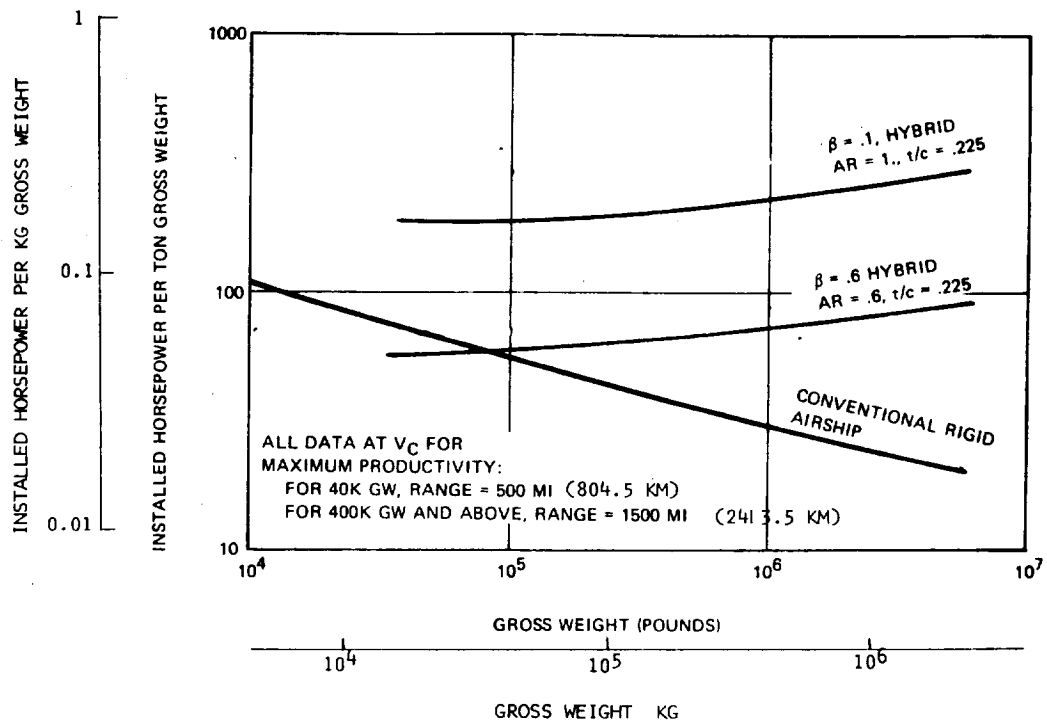


Figure 49 - Power Loading Comparison of Neutrally Buoyant Rigid Airship and Lifting Body Hybrid

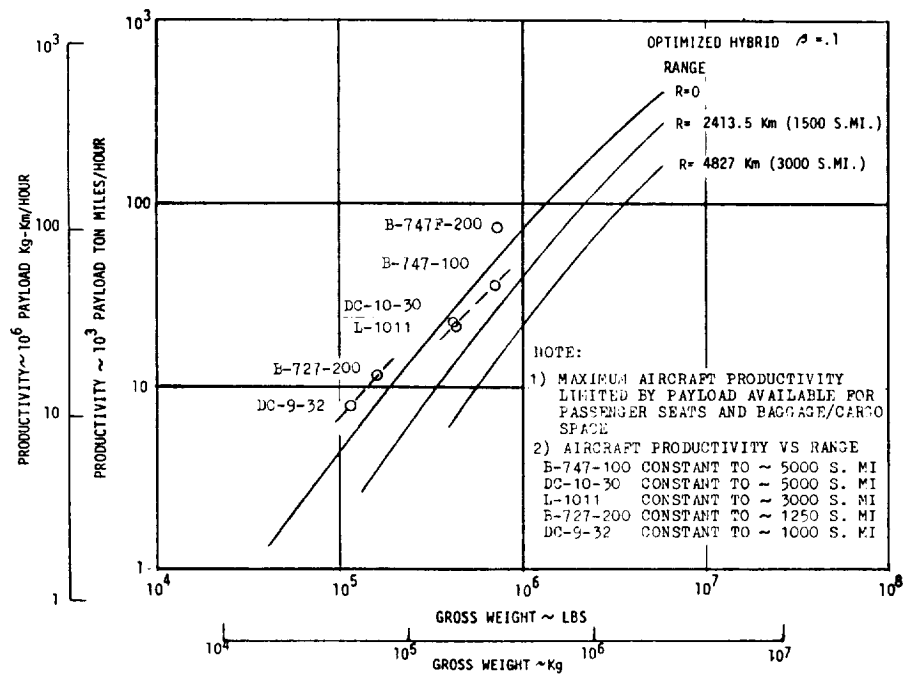


Figure 50 - Comparison of $\beta = 0.1$ Hybrid and Commercial Aircraft Productivity

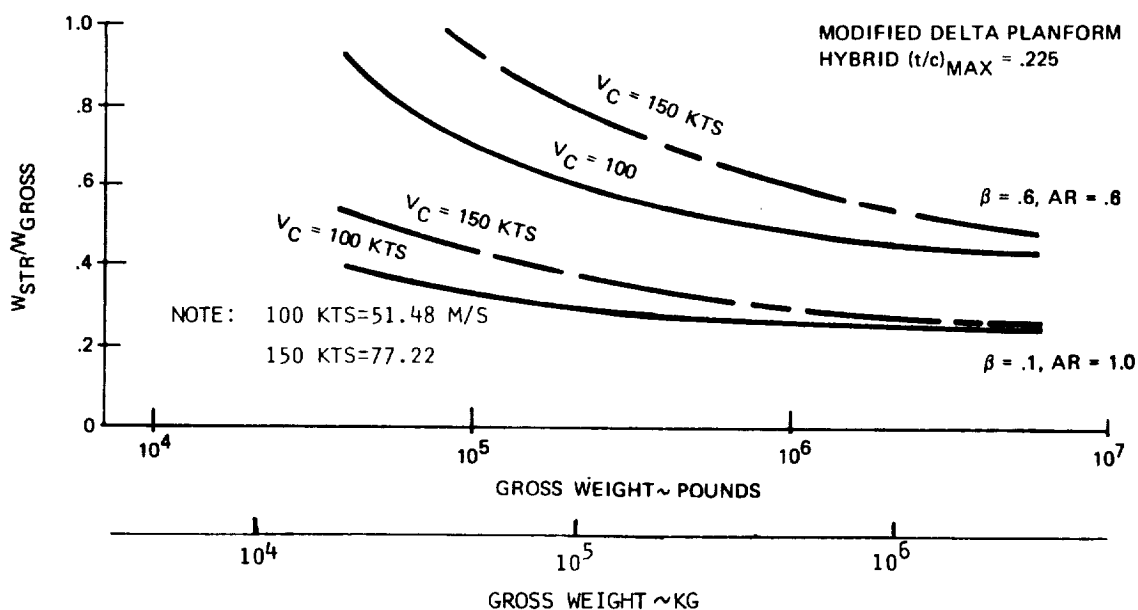
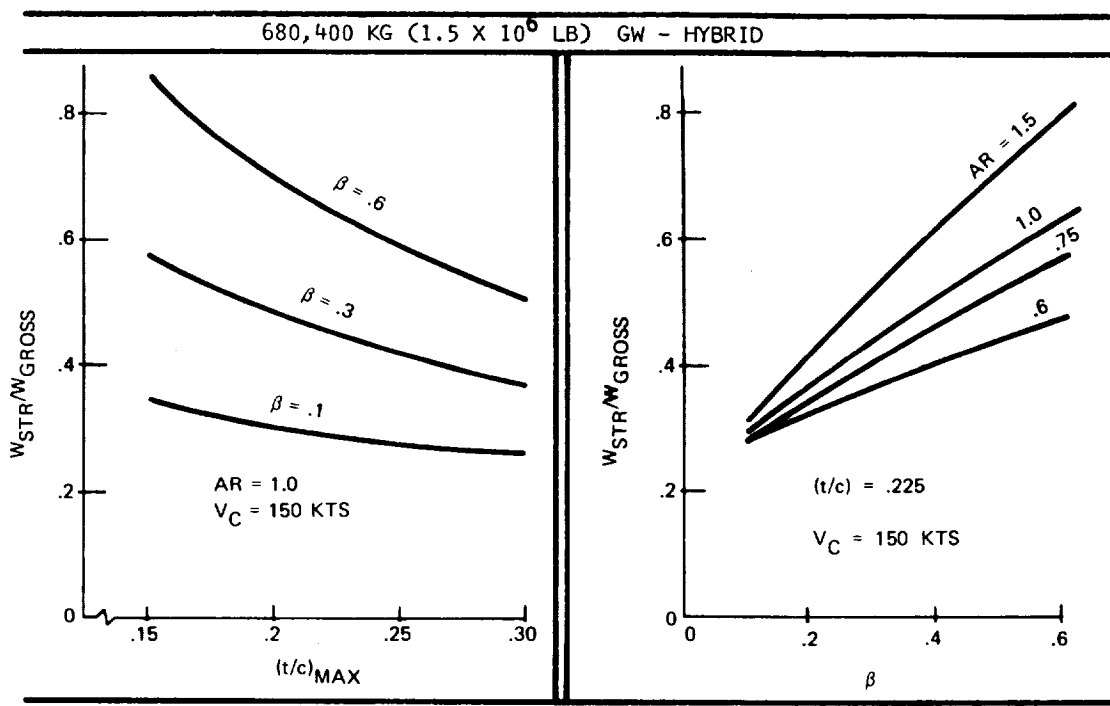


Figure 51 - Representative Structural Efficiency Characteristics of Lifting Body Hybrid

HEAVY LIFT HYBRID VEHICLE CONCEPT

The third configuration class investigated during Phase I was the short-haul, heavy-lift vehicle concept. Several of the more exotic configuration concepts discussed by various sources or currently under consideration were reviewed. The basic decision regarding the configuration for this vehicle class was that the functional and performance requirements could be adequately satisfied by very simply combining a basic airship hull and conventional helicopters. A configuration of this type was therefore selected as the baseline for this vehicle class.

The basic concept of the heavy lift hybrid vehicle is to load the airship hull with helicopters and use the helicopters to lift the useful load. In the basic concept, the empty weight of the vehicle is balanced by buoyant lift, and the useful load is equal to the sum of the gross lifting capacity of the mounted helicopters. This concept produces several advantages over airships or helicopters acting alone:

1. The basic advantage over a pure airship acting alone is that large loads can be picked up and set down with no need for interchanging ballast and payload. The vehicle is able to fly with a wide range between maximum flying weight and minimum flying weight.
2. The basic advantages over helicopters working alone are:
 - a. The helicopters do not need to lift their own dead weight; the entire gross lift of the helicopter is available for lifting payload.
 - b. Several helicopters (or helicopter lift systems) can be mounted on the airship hull to provide a vehicle with a very large lift capability.
3. The integrated concept provides a capability for precision control over the load pickup point in that the helicopters provide fast response with large forces available to overcome wind, gust, and incidental unbalanced forces on the hull of the vehicle. At the same time, the huge mass of the vehicle produces a steadying effect that slows down the dynamic response to such perturbing forces.

4. A degree of immunity to scale effects is achieved since the weight fraction of the airship hull is relatively insensitive to the size of the hull and the growth of the helicopter weight fraction is circumvented by installing multiple rotors of efficient size to achieve the total lifting capacity required.

An alternate concept is to provide more buoyant lift than required to balance the dead weight of the vehicle. In this concept, the helicopter rotors are required to hold the airship down when the vehicle is empty. Tiedown to massive anchors would be required before the rotor power is shut down at cessation of operations. The advantage of this approach is that less helicopter lifting capacity is required to lift a specified useful load. For example, if the down thrust is taken as one-half the up thrust, the number of helicopter rotors required is reduced by one-third. If special rotors were designed so that the down thrust capability is equal to the up thrust, the number of rotors required is cut in half.

Another alternate is to provide less buoyancy than required to balance the empty weight of the vehicle, thus sacrificing some payload lifting capability in favor of the characteristic of maintaining a substantial heaviness in the empty weight condition and possibly alleviating ground handling and tiedown problems.

The probable missions for the heavy-lift, short-haul vehicle indicate that the applicable figure of merit should be the useful load-to-empty weight ratio and not productivity. Thus, the heavy-lift vehicle performance is analyzed in terms of UL/EW.

The question of how much buoyancy and how much helicopter lift to install to achieve the basic design concept or the alternates can be answered in a simple relationship involving the empty weight fractions of the helicopter and the airship hull.

Let:

- B = buoyant lift
- H = helicopter lift
- H' = helicopter down thrust
- K₁ = airship hull empty weight fraction
- K₂ = helicopter empty weight fraction
- K₃ = H'/H

Then:

$$\text{Maximum gross weight (W}_G\text{)} = B + H$$

$$\text{Minimum gross weight (W}_E\text{)} = B - H' = K_1 B + K_2 H$$

$$\text{Useful load (W}_U\text{)} = H + H'$$

$$\text{Helicopter lift required (H)} = \frac{W_U}{1 + K_3}$$

$$\text{Buoyant lift required (B)} = \frac{W_U}{1 + K_3} \frac{K_2 + K_3}{1 - K_1}$$

This results in the following payoff factors: If the weight of the inter-connecting structure and structural weight increases in the airship hull are neglected as a result of the marriage, the helicopters alone could lift

$$W_{UA} = \frac{H}{1 - K_2}$$

and the payoff for the helicopter in terms of useful load lifted is

$$\frac{1 + K_3}{1 - K_2}$$

The airship hull alone could lift (with ballast/useful load interchange)

$$W_{UB} = \frac{B}{1 - K_1}$$

and the payoff factor for the airship is

$$\frac{1 + K_3}{K_2 + K_3}$$

But the big advantage for the airship is elimination of the requirement to interchange ballast for payload.

The design procedure using the simple relationships is to start with the useful load desired and compute H and B from the above equations using estimated values of K_1 and K_2 and a chosen value of K_3 consistent with the concept desired. Choose the helicopter rotor model and number required to produce the lift (H) and configure an airship hull of the size required to provide the buoyant lift (B). Make a preliminary design layout. Compute the resulting weight (weight fractions) and iterate the procedure.

Several practical considerations combine to make the design cycle less simple than the above. These considerations are described below.

First, weight fractions K_1 and K_2 must reflect the weight increments associated with marrying the helicopters to the airship hull. It doesn't matter whether this increment is put into K_1 or K_2 or split between the two. A logical split might be to increase K_2 sufficiently to provide the structure required to deliver the helicopter lift to the airship hull and let K_1 be increased enough to allow for internal hull strength requirements in excess of the normal airship requirements. In any event, these factors will be merely rough estimates at the initial design step to be refined by further iterations on the design.

Second, a decision must be made on whether to use the basic concept requiring no down thrust to keep the airship from rising in the lightweight condition or to use one of the alternates where the vehicle is designed to be heavy or light when empty. In essence, choose a value of K_3 .

Third, the question of whether to use complete helicopters or only the power and lift system must be addressed. Complete helicopters have the advantage of minimum modification so that these units are still flyable as individual units. A disadvantage is the installation of unnecessary dead weight. A compensating advantage is the provision of tail rotors that can be used for additional control forces.

The question of whether to use existing helicopter systems or to develop an entirely new system is heavily biased toward existing hardware by development cost considerations.

Fifth, the type of airship hull to use is a subject of choice and some trade-offs. Rigid, semirigid, and non-rigid are all candidates. For large vehicles, the rigid airship hull has the advantage in terms of providing outrigger support structure as an inherent feature of the hull structure. Increased strength in such structures can be provided with less weight penalty than would be required to provide the added strength in a separate and distinct structure.

Sixth, geometric arrangement will be an important consideration. On a rigid airship, hull minimum structural weight probably will result from mounting the helicopter lift systems near the equator. The problem of access to the rotors for inspection and maintenance might be alleviated by placing the rotors close to the ground. Hull bending moments for a vehicle designed to lift heavy unitary loads on a sling would be less demanding if the lift system were mounted near the center of the hull length. But precision control of the vehicle in hovering over the payload may require that the rotors be spread out as far as possible.

Seventh, the choice among existing helicopters will be biased toward those vehicles having "fly-by-wire" control systems. This feature will simplify the requirement to install a master control system to coordinate the actions of the multiple rotors.

In addition, provisions for safe operation in the event of loss of engine power or loss of buoyant lift will require among other things that excess lifting capacity be provided.

Heavy Lift Performance versus Gross Weight: Size Limitations and Scale Effects

Frank Piasecki has shown (Reference 19) that a vehicle of this type (called the Heli-Stat) can be designed to lift a 68,040-kg (75-ton) payload utilizing four CH-53D helicopters (complete) on an airship hull of 101,952 cu m (3,600,000 cu ft). From the layout, no crowding of rotors is in evidence. In fact, there would be plenty of room for four more helicopters.

What happens if the concept is expanded to a payload of 680,400 kg (750 tons)? If the same helicopters and the same weight fractions are used,

40 CH-53D's would be needed. The airship volume would increase by a factor of 10, but the hull length (of the same shape) would increase by a factor of 2.16. Finding enough room to mount 40 helicopters will be very difficult and will require several overlappings of the rotors.

This problem can be alleviated by using more powerful helicopters such as the CH-53E, which has a 50 percent more lift in a rotor of the same diameter, and by using an airship hull of higher fineness ratio. The higher fineness ratio will result in higher design bending moments and a higher structural weight fraction.

A vehicle consisting of 18 CH-53E lift systems mounted on a 566,400 cu m (20 million cubic foot) hull would provide a capability for lifting a payload of 453,600 kg (500 tons) with a comfortable margin for power loss considerations.

Take

$K_3 = 0$ requiring no thrust to hold down the machine.

Take

$K_1 = 0.50$ and $K_2 = 0.50$

If 45,360 kg (50 tons) of fuel is allowed, the useful load is 498,960 kg (1,100,000 lb). Therefore, the helicopter lift required is:

$H_{req'd} = 498,960 \text{ kg (1,100,000 lb)}$

Eighteen CH-53E's operating at normal gross weight provide:

$H = 555,206 \text{ kg (1,224,000 lb)}$

$B_{req'd} = \left(\frac{1,100,000}{1 + 0} \right) \left(\frac{0.5 - 0}{1 - 0.5} \right) = 498,960 \text{ kg (1,100,000 lb)}$

Volume required at 89 percent fullness is 566,400 cu m (20×10^6 cu ft)

Mounting 18 rotors at 24.384 m (80-ft) spacing on a cylindrical hull center section requires a center section length of 195.07 m (640 ft).

Increasing the hull diameter to provide an excess buoyancy equal to the maximum down thrust of the rotors might stretch the total payload load of this vehicle to 680,400 kg (750 tons).

It might be argued that the above example stretches the concept to ridiculous extremes. Further detailed study would be required to determine if it is actually feasible and whether there exists a need for a vehicle with this lifting capacity of sufficient economic importance to justify the cost.

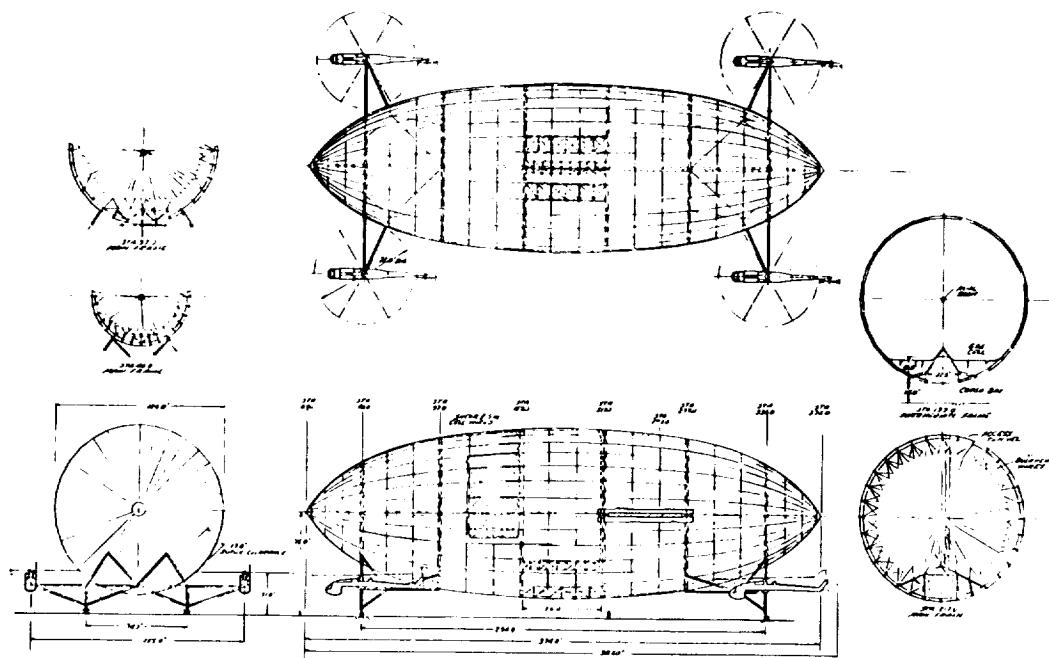
It seems clear, however, that the basic concept can be expanded to meet very large unitary payload requirements with minimal challenge to the state of the art. If a heavy lift vehicle is required with capacities much larger than the biggest current helicopters can provide, this concept would seem to be a viable approach to meeting such requirements.

The basic performance characteristics of the heavy-lift, short-haul airship/helicopter combination can be defined from these performance relationships if specific buoyant lift system and helicopter lift system characteristics are known. The estimated UL/EW performance for this general concept is estimated to remain approximately constant at a value of 1.0 up to gross weights of 907,200 kg (2×10^6 lb) and possibly beyond. The Piasecki Heli-Stat concept is representative of the design and performance characteristics of this vehicle class.

Goodyear Aerospace is currently in the process of a detailed design effort relative to the Heli-Stat, which Piasecki Aircraft Corporation is defining in detail under Navy contract. Goodyear is assisting in the definition of the LTA hull and helicopter support structure, mooring structure and technique, preparation of manufacturing cost information, and providing guidance as required from the overall LTA aspects of such a vehicle.

The Heli-Stat is a typical member of the baseline short-haul, heavy-lift vehicle concept. It combines a conventional rigid airship hull that offsets the total empty weight, fuel, and crew of the Heli-Stat. Four existing conventional helicopters are attached to the hull by means of a lightweight truss work; these helicopters provide the vehicle payload lifting and maneuvering capability.

Figure 52 is a preliminary general arrangement prepared by Goodyear for PAC of a 68,040-kg (75-ton) payload configuration that uses a 82,128 cu m (2,900,000-cu ft) helium-filled hull and four CH-54B helicopters. This vehicle's payload capability, which is 10 times that of a single CH-54B and twice that of the LTA hull alone, far exceeds that of hovering-type vehicles available or projected.



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		CONTR		GOODYEAR AEROSPACE CORP	
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XXX ± .010		MATERIAL		4 CH-54B'S	
ANGLES		CUSTOMER APPROVAL		DRAWING NO	
MATERIAL		CUSTOMER APPROVAL		75-259	
SEE CASE-9-A ROTOR DRAWING		SCALE		SHEET 1 OF 1	
INTERPRETATION STANDARDS					

Figure 52 - Preliminary General Arrangement of 68,040-kg
(75-Ton) Heli-Stat Heavy Lift Vehicle

Since the heavy lift mission is one of the unique missions isolated for application of a modern LTA vehicle, the Heli-Stat is of particular interest. The Heli-Stat offers a near-term, cost-effective, low-risk approach for assessing the utility of such a vehicle. In addition, such a vehicle would permit general design requirements, controllability requirements, and operating procedures to be assimilated so that refined heavy lift vehicles could be developed such as the configurations investigated during this study.

Alternate Figure of Merit for Conventional Airships

The statement of work specified productivity figure of merit (payload ton-miles per hour) led to the discovery of the significant potential of small semi-buoyant airships to achieve tremendous improvements in productivity; potentially

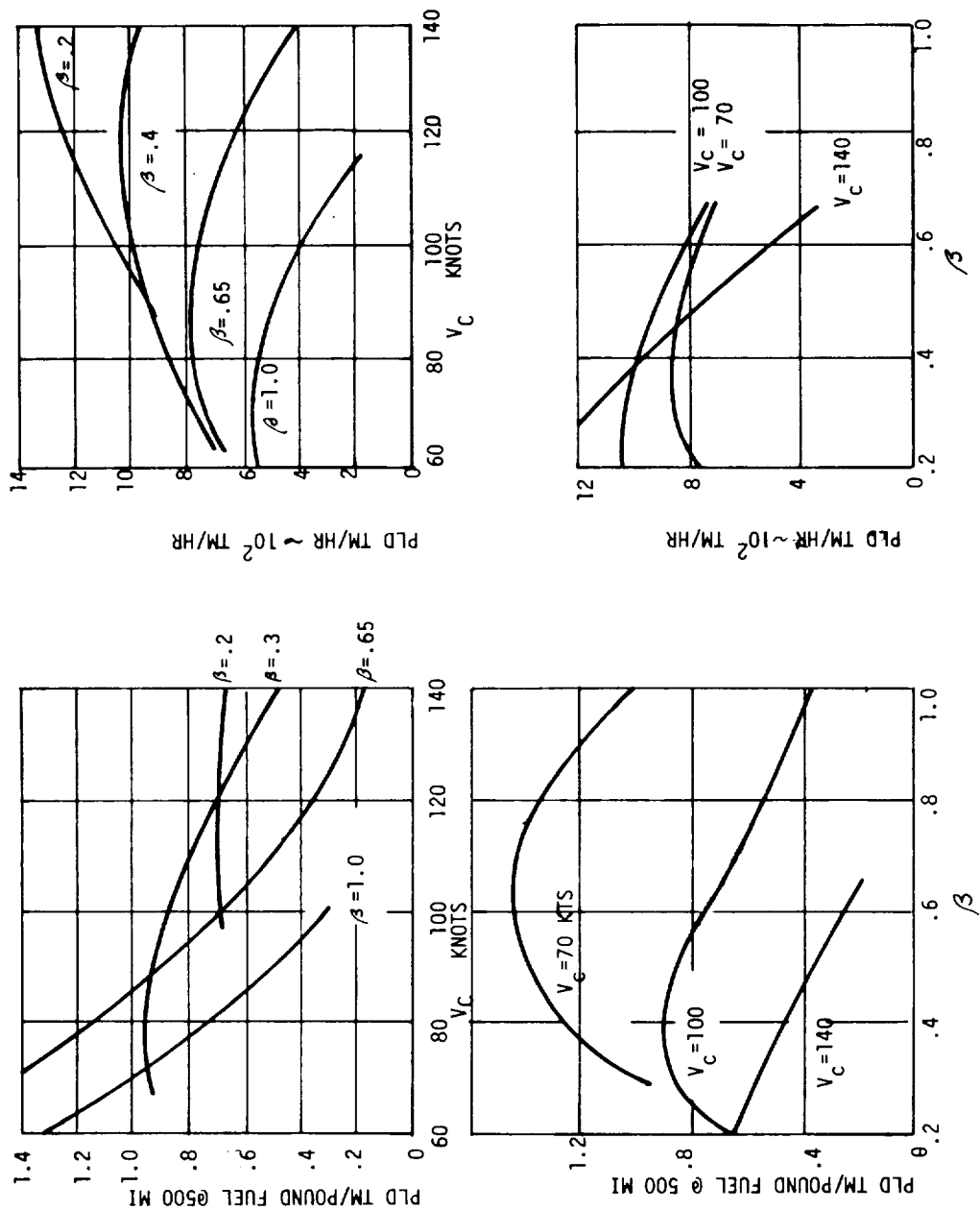
competitive with existing and proposed VTOL vehicles. However, it does not demonstrate the total potential and virtue of the airship for which productivity per se (which essentially demands speed) is often a secondary consideration to fuel efficiency, endurance, or range with a given payload. Many potential modern airship missions fall into such categories.

Thus, it is worthwhile to consider the airship performance potential for alternative figures of merit and to briefly assess the impact of the specified FOM on the alternatives.

Fuel Efficiency Considerations

Figure 53 compares the performance of 18,144-kg (40,000-lb) vehicle as a function of β and V_C in terms of the two figures of merit: payload-ton miles per hour and payload ton-miles per pound of fuel both at 804.5 km (500-mi) range. The productivity FOM results have been previously discussed: the optimum β tends to zero, and V_C optimum tends to high values of approximately 82.22 m/s (160 knots). In terms of payload ton-miles per pound of fuel (TM/lb fuel), however, at any given velocity, the trend is to high β and low V_C as shown in Figure 53. Figure 54A further illustrates this trend and shows that, for any velocity below 71.94 m/s (140 knots), β optimum for maximum ton-miles per pound fuel to be much greater than β optimum for maximum payload ton-miles per hour.

Figure 54B is another way of illustrating the tradeoffs between ton-miles per hour and ton-miles per pound of fuel. For maximum fuel efficiency (TM/lb fuel), optimum vehicle performance would result from moving from left to right on the curve, i.e., reduce velocity at the expense of productivity. For maximum ton-miles per hour, maximum performance would result from moving from right to left on the curve and would trade fuel economy for productivity. The requirement to consider specific mission requirements and operating economics (with or without an energy efficiency constraint) is obvious from this illustration. The true performance optimum must be defined for a specific mission profile where the economic impact of vehicle operation is included in the optimization process.



NOTE: THESE FIGURES ARE PRESENTED PRIMARILY TO ILLUSTRATE TRENDS: THIS, ONLY THE CONVERSION FACTORS ARE PROVIDED: 1 TON MI/LB FUEL = 3218 Kg-Km/Kg FUEL, 1 TON MI/HR = 1460 Kg-Km/HR, 1 KNOT = .51389 m/s.

Figure 53 - Productivity and Fuel Efficiency Figure of Merit Variation as a Function of β

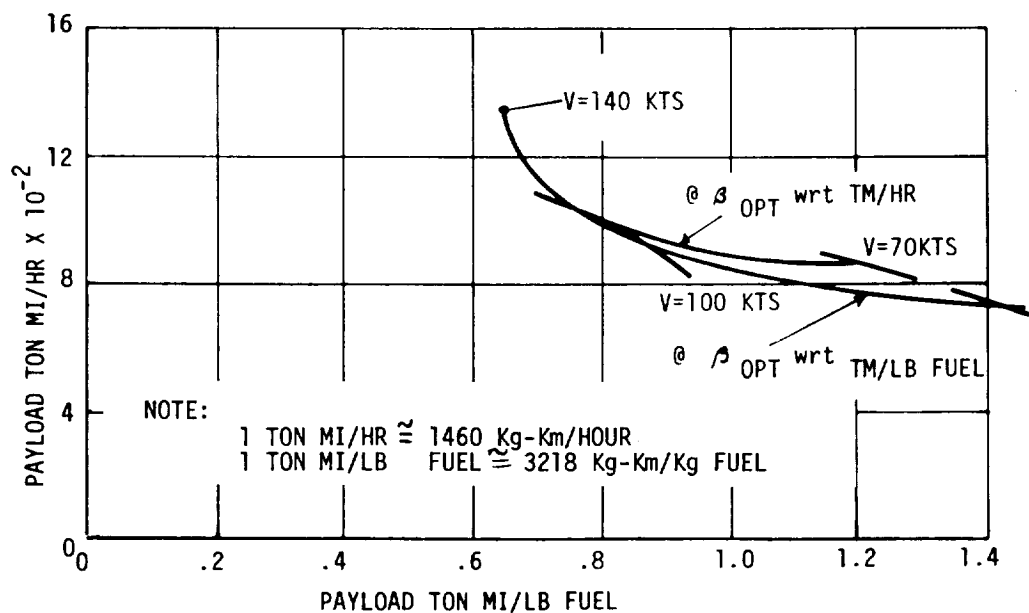
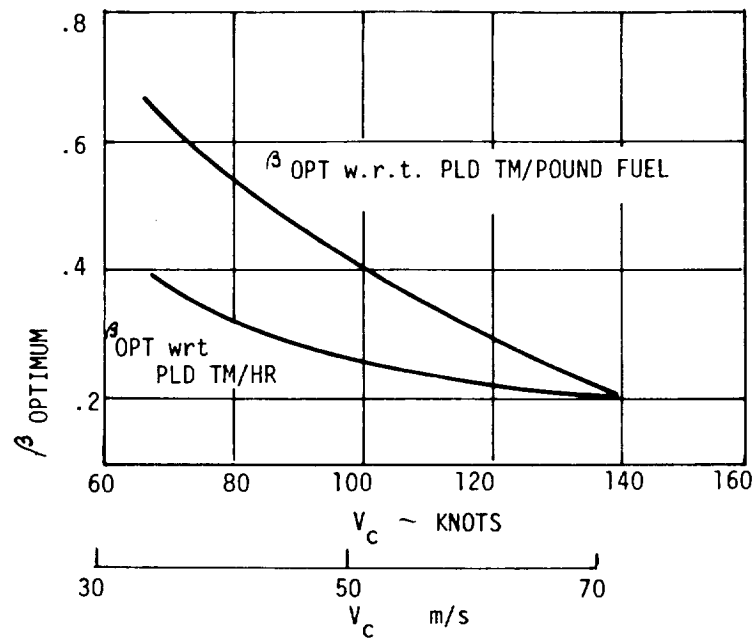


Figure 54 - Comparison of Alternate Figures of Merit, Optimum β

Representative fuel efficiency for productivity optimized neutrally buoyant airships is presented in Figure 55 in terms of payload ton-miles per pound of fuel as a function of gross weight.

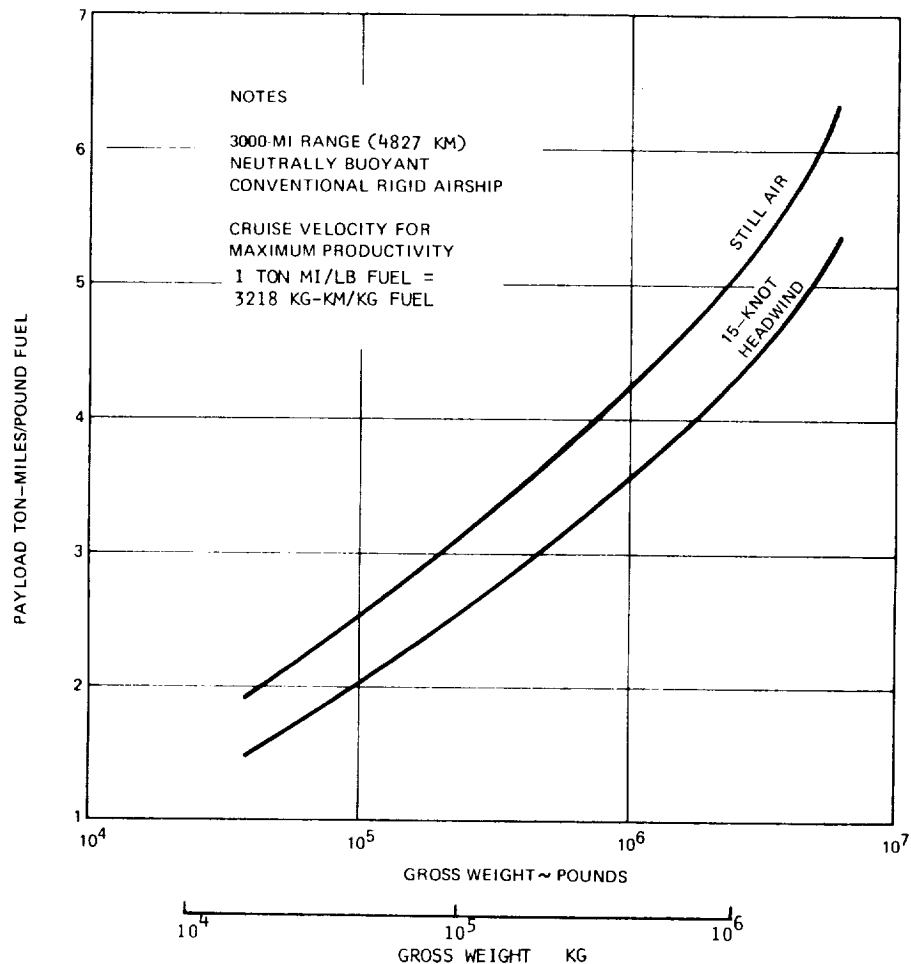


Figure 55 - Fuel Efficiency for Productivity Optimized Neutrally Buoyant Airships

Endurance Capability

One of the unique performance attributes of "pure" LTA vehicles is their extremely large endurance capability. This capability is unmatched by any other flight vehicle either in terms of total time on station, the product of payload and total time on station, and time on station per unit of fuel consumption.

This fundamental characteristic of conventional LTA vehicles was the basic reason for both their selection and outstanding performance in naval antisubmarine warfare applications during World War I and World War II.

As has been discussed in Reference I, a multitude of current day missions are of a platform or surveillance nature (environmental surveillance, law enforcement surveillance, border patrol, coastal surveillance). The applicable figure of merit for these missions is endurance or endurance per unit of fuel consumption. For such missions, LTA capability is unmatched by any other vehicle as shown in Figure 56.

Range Capability

Another unique performance attribute of LTA vehicles is the extremely large payload and long range capability. Many modern missions may require payload range performance capability in excess of that available by existing aviations systems with speeds in excess of those available by ocean-going surface vehicles. The unique range/payload capability of LTA vehicles is presented in Figure 57.

Comparison With Historical Results

Figure 58 compares the productivity of historical airships as defined in Task I with that of the current state-of-the art modern airships defined by the parametric analysis. The improved productivity can be traced primarily to the reduced empty weight resulting from the application of modern structures, propulsion, and materials technologies. A comparison of historical rigid airship EW and modern airships as investigated during the Phase I study is presented in Figure 59.

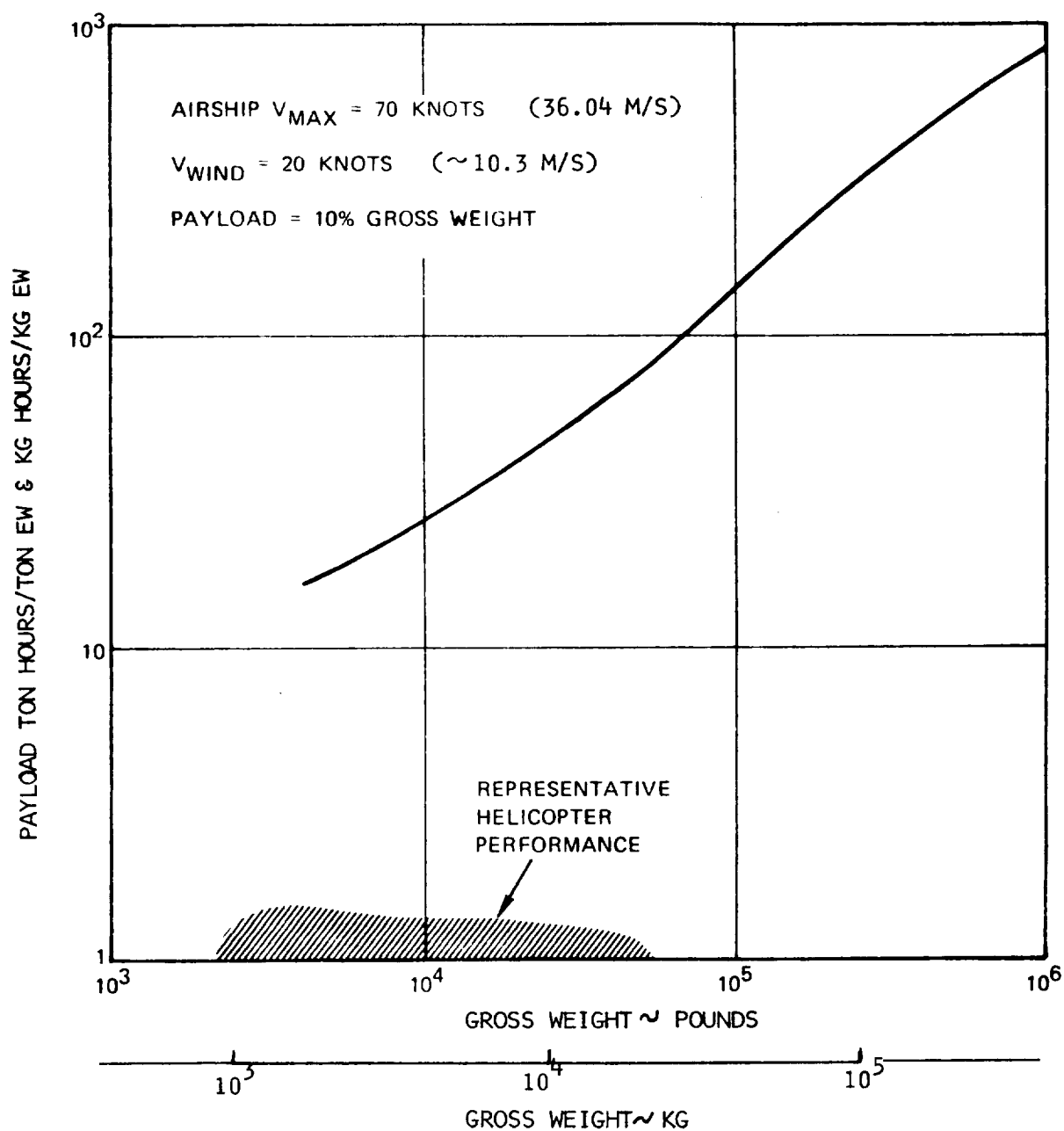


Figure 56 - Typical Endurance Capability of Neutrally Buoyant Airships

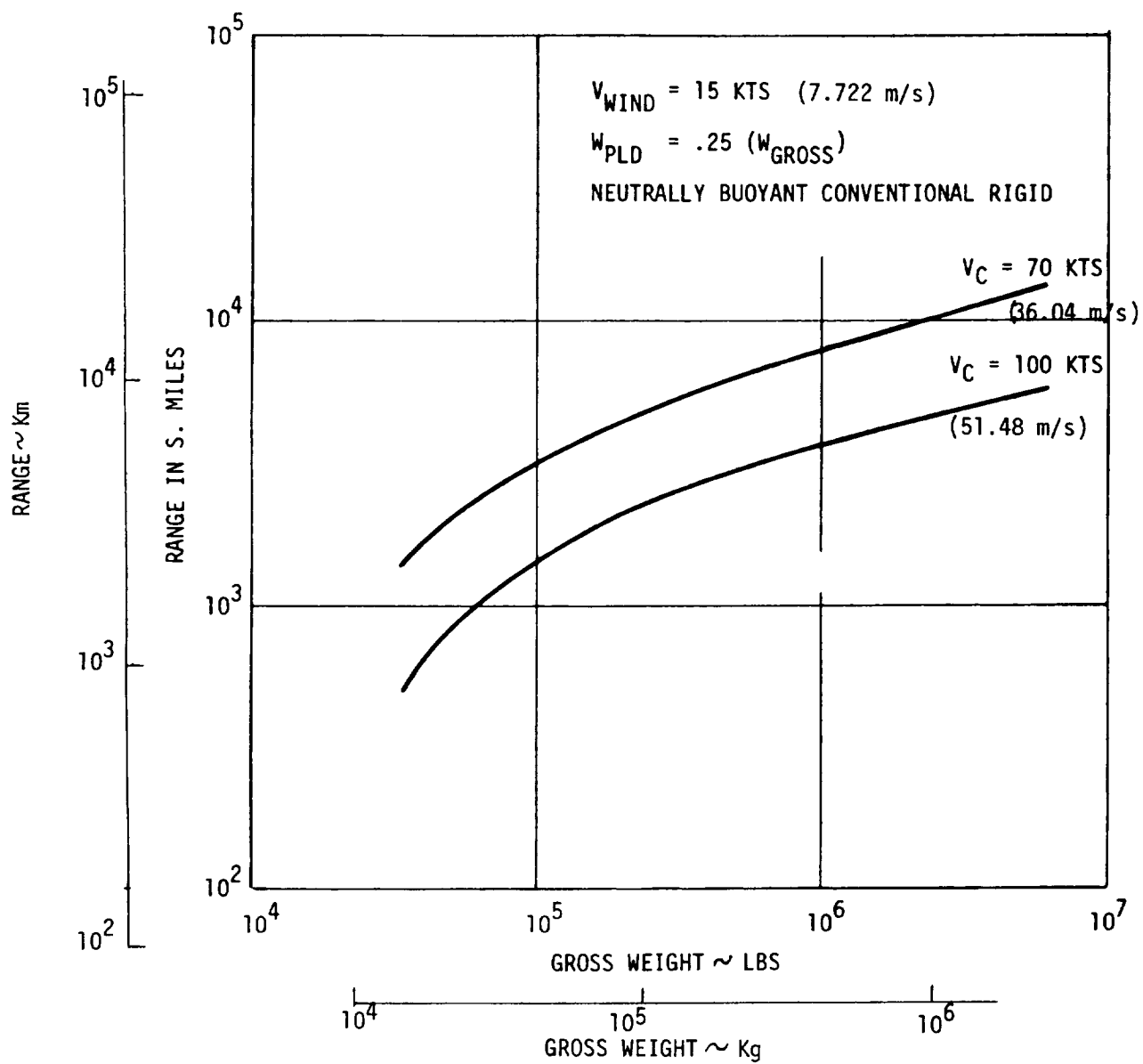


Figure 57 - Representative Payload-Range Capability of Conventional Neutrally Buoyant Airships

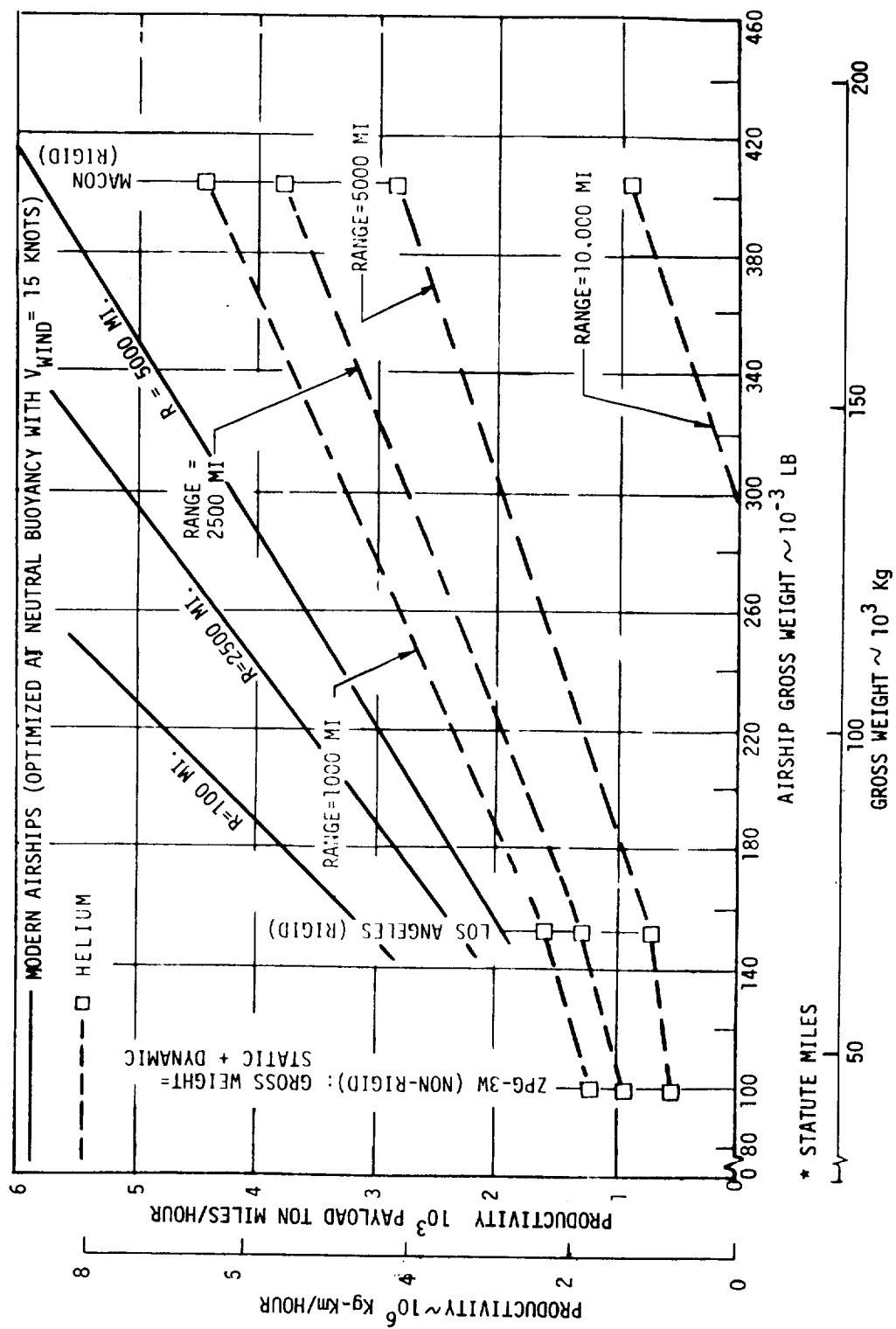


Figure 58 - Productivity of Historical versus Modern Airships

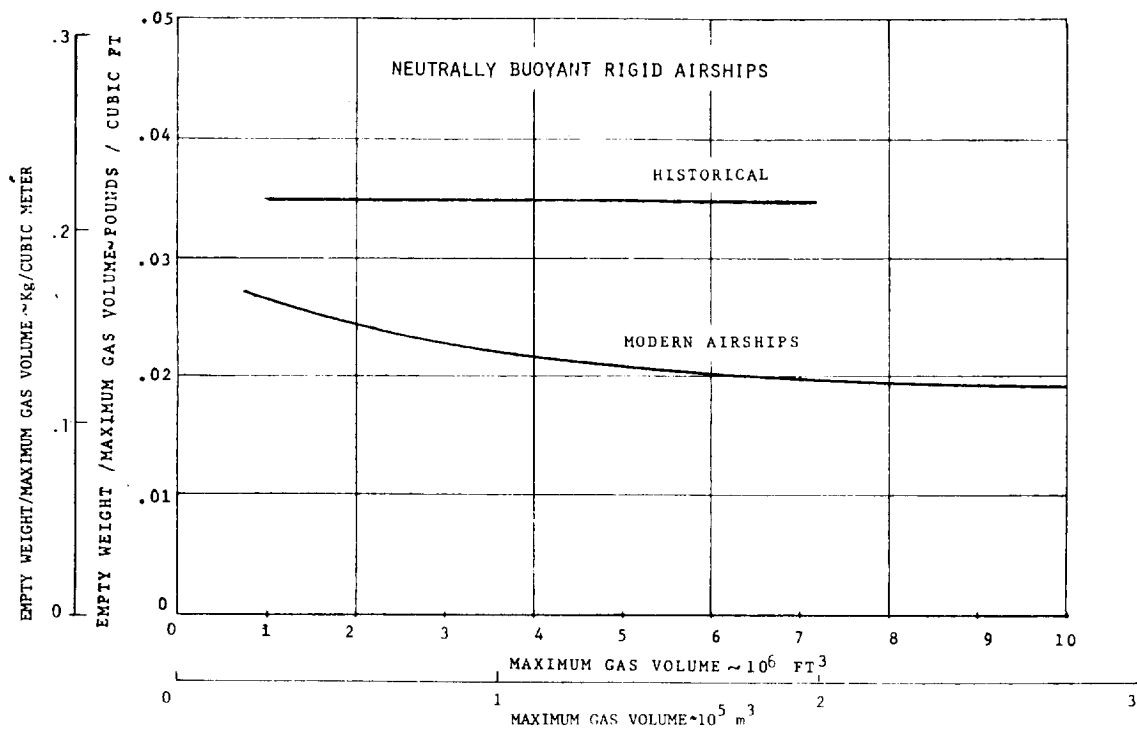


Figure 59 - EW of Historical Rigid Airships versus Modern Airships

PARAMETRIC ANALYSIS SUMMARY AND CONCLUSIONS

The parametric analysis was primarily concerned with determining the configuration characteristics that result in "optimized" productivity for MAV's. The criteria for the optimization study was payload ton-miles per hour and range. Three basic classes of MAV's were analyzed: conventional ellipsoidal airships, both neutrally buoyant and semibuoyant; lifting body hybrid airships; and short-haul, heavy-lift hybrid vehicles. By examination of the basic performance attributes of the three classes, the productivity figure of merit was judged to be applicable only to the first two classes of vehicles. The applicable figure of merit for the third class was defined as the useful load-to-empty weight ratio.

The bulk of the results are presented parametrically as a function of gross weight and range to enable synthesis of specific vehicle characteristics to satisfy mission requirements defined in the mission analysis task (Reference 1). The results encompass a gross weight range from 1360.8 kg to 2,721,600 kg (5000 to 6,000,000 lb) gross lift, heaviness ratios from 0.1 to 1.0, and ranges to 8045 km (5000 stat mi).

Neutrally buoyant airships employing a rather conservative (1975 state-of-art proven materials) update of materials and propulsion technology offer significant improvements in airship empty weight and performance. Successful adaptation of Kevlar fabric for non-rigid airship envelopes offers great potential for reduced vehicle empty weight and improved performance.

Application of propulsive lift for VTOL and aerodynamic lift for cruise flight can significantly improve the productivity of low to medium gross weight "conventional" ellipsoidal airships. For large gross weights, neutrally buoyant flight maximizes productivity for conventional ellipsoidal airships.

For the modified delta planform lifting body hybrid investigated, no optimum β was found, based on productivity, between the limits of 0.1 and 0.6. The trends that were observed can be summarized as follows:

1. At short ranges, productivity continuously improves as β is reduced from 0.6 to 0.1.
2. At larger ranges, two trends were observed that improve productivity. At all ranges, for β less than $\cong 0.3$ to 0.4, productivity improves as β is reduced to 0.1. At larger ranges, for β greater than $\cong 0.3$ to 0.4, productivity improves as β is increased to 0.6.

For all but very large ranges, the productivity of the $\beta = 0.1$ hybrid exceeds that of the $\beta = 0.6$ hybrid.

Depending on gross weight and range, semibuoyant lifting body hybrid vehicles can offer improved productivity relative to conventional neutrally buoyant airships, particularly at the very large gross weights. However, in comparison with commercial cargo aircraft at equal gross weight and range, their productivity is significantly lower. Furthermore, for the CTOL lifting body hybrid configuration investigated, the degree of partial buoyancy (β) for maximum productivity appears to converge to zero (no buoyancy) when the configuration characteristics and cruise velocity are allowed to vary as a function of β .

The optimized ellipsoidal airship productivity is compared with that of lifting body hybrid vehicles with β 's of 0.1 and 0.6 in Figures 60 and 61, respectively.

The third class of vehicles, the short-haul, heavy-lift concept, was evaluated in terms of the useful load-to-empty weight ratio as a function of gross weight. Results indicate this to be a very simple, potentially low-cost, near-term concept capable of maintaining UL/EW ratios of approximately 1.0 up to gross weights of 907,200 kg (2×10^6 lb) using existing helicopter componentry.

LIMITATIONS OF CURRENT STUDY

The most overriding limitation of the Phase I parametric study was the brief four-month time constraint. In such a short period and within the very limited budget constraints, it is simply not possible to address all of the important aspects or answer all questions relevant to the performance optimization of conventional airships, much less the universe of potential hybrid vehicles. Many assumptions and approximations have been made out of necessity. Alternate assumptions could have been used and possibly should be considered in future study efforts.

Despite these many limitations, the overall conclusions regarding the relationship between conventional airships and the modified delta planform lifting body vehicle are believed valid, particularly with respect to the trends for maximum productivity.

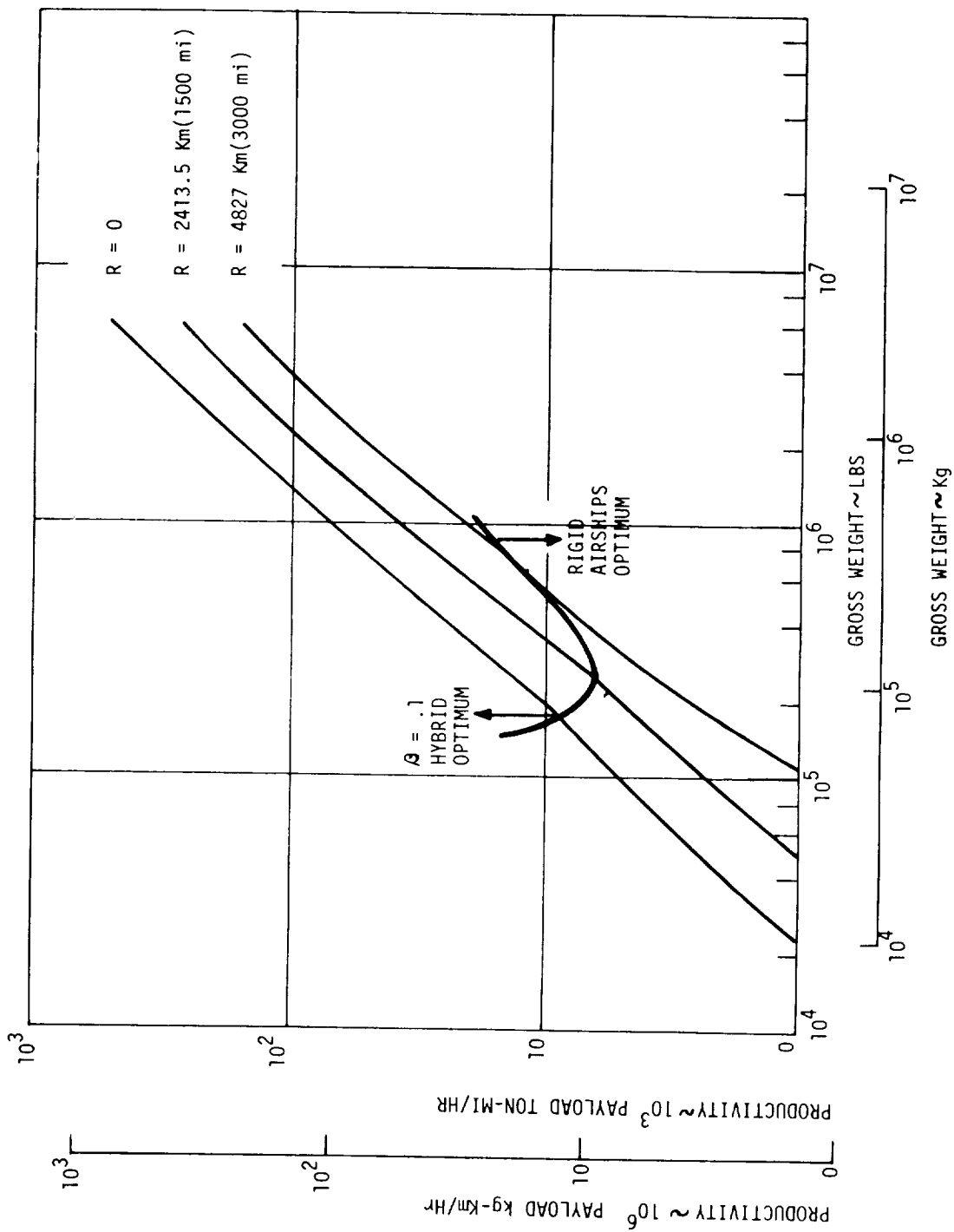


Figure 60 - Optimized Ellipsoidal Airship $\beta = 0.1$ Hybrid Productivity Comparison

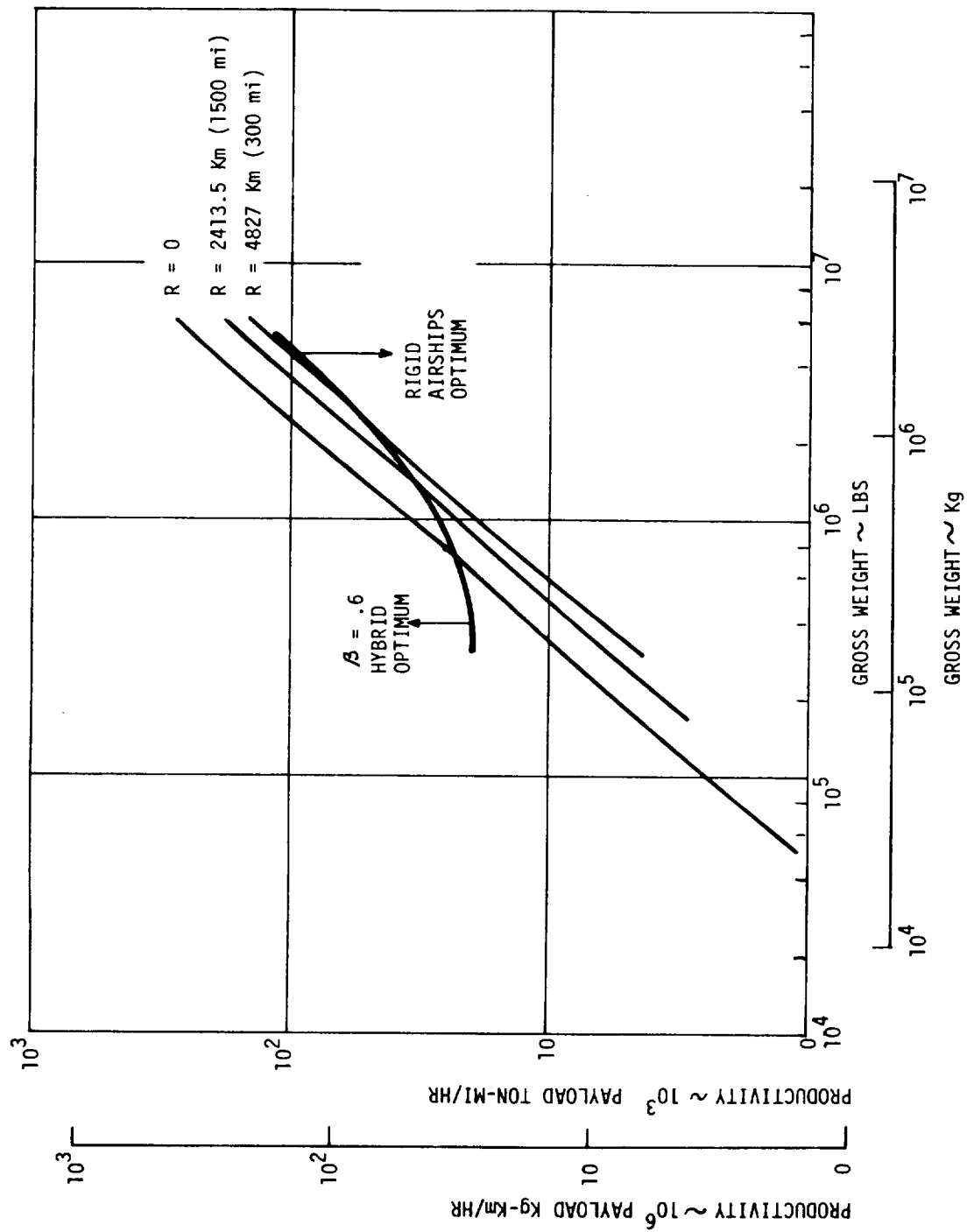


Figure 61 - Optimized Ellipsoidal Airship B = 0.6 Hybrid Productivity Comparison

Three particular assumptions could be further investigated during Phase II:

1. For the cruise performance evaluation, no lift component of propulsive thrust was assumed in determining the vehicle angle of attack required for a given heaviness. This could possibly make the results somewhat conservative (further improvements in productivity might be realized by combining propulsive and aerodynamic lift for cruise flight).
2. A more productive cruise velocity profile might be possible than the constant used in this study, possibly some function related to the degree of heaviness.
3. The detailed design and weight characteristics of the tilting proprotor need to be fully evaluated in Phase II.

All design options and secondary study variables introduced in the introductory sections of this volume were only briefly investigated in order to concentrate on the primary study variables. Many of the design options are so strongly dependent on the specific mission and economic factors that an assessment of their general applicability to modern airship concepts is not practical. Each design option has been briefly evaluated and the results included in Reference 2, Appendix H. These options include: vectored thrust, stern propulsion, boundary layer control, alternate engine cycles, artificial superheat, buoyancy management, and alternate lifting gases. A very limited sensitivity analysis was conducted near the completion of Phase I. This analysis included the effects of altitude and wind as well as several key design parameters. The results are also included in Reference 2, Appendix H.

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