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Naval Airship Program for Sizing and Performance (NAPSAP)

Jon W. Lancaster*
Lancaster Analytics, North Canton, Ohio
and
David B. Bailey†
U. S. Naval Air Development Center, Warminster, Pa.

This paper describes the Naval Airship Program for Sizing and Performance (NAPSAP) developed by the U. S. Naval Air Development Center (NADC) for preliminary design and performance evaluations of lighter-than-air vehicles. Program capabilities have been tailored to vehicle sizes and missions currently being investigated as a part of the joint U. S. Navy-U. S. Coast Guard Maritime Patrol Airship Study and NADC studies of anti-submarine warfare (ASW) mission concepts. The program has been designed to operate on a minimum of input data, but has the capability to evaluate the influence of over 40 key parameters. NAPSAP provides easy parametric analysis for several optional levels of detail. Once the design section of NAPSAP reports on a vehicle which meets the input requirements, this vehicle can then be evaluated against a specified mission profile with all key parameters monitored by mission time increments.

Introduction

IN 1974, an interagency workshop on lighter-than-air (LTA) technology was held in Monterey, California which produced a wide-ranging assessment of LTA vehicle technology, mission applications, operation and economics.[1] At about the same time, the Lighter-Than-Air Project Office was formed at the U. S. Naval Air Development Center in Warminster, Pa. In the ensuing years, the LTA Project Office has sponsored or participated in a broad range of vehicle concept and operational evaluations.

A primary conclusion of the various study efforts was that there is a broad spectrum of current and advanced naval missions for which LTA vehicles are particularly attractive.[2,3]

More recently, expansion of the U. S. Coast Guard's mission responsibilities[4] has necessitated the examination of alternative vehicle platforms to satisfy the mission requirements in the most cost-effective manner.[5,6] The NADC Lighter-Than-Air Project Office has provided technical management and analysis for the U. S. Coast Guard in the assessment of LTA vehicles for maritime patrol applications.[7]

One of the principal requirements which arose from the NADC study efforts was the need for an airship sizing and performance evaluation program that could perform rapid evaluations of the technical and operational feasibility of LTA vehicles. This requirement led to the NAPSAP program.

Program Application Overview

There are two major applications of the current NAPSAP program. The first (basic case) allows a vehicle to be sized in terms of a simplified set of input data and its performance to be evaluated in terms of payload as a function of range at the input design speed. The second major application allows the performance of the "basic case" vehicle to be evaluated over multisegment mission profiles, such as those described in Refs. 7 and 8. Several options may be exercised for parametric analyses and sensitivity studies of these two basic program applications.

NAPSAP can currently analyze two types of LTA vehicles: rigid airships of conventional, Zeppelin-type construction (e.g., wire-braced main frames, longitudinal girders with cruciform empennage; see Ref. 9, Appendix D); and nonrigid airships similar to the type most recently operated by the U. S. Navy. Either type of vehicle can be analyzed at a range of gross weights, including those greater than the total static lift (i.e., in a "heavy" condition).

The propulsion system may be sized for either a conventional takeoff using a ground run to develop aerodynamic lift or for vertical takeoff at maximum gross weight. Three

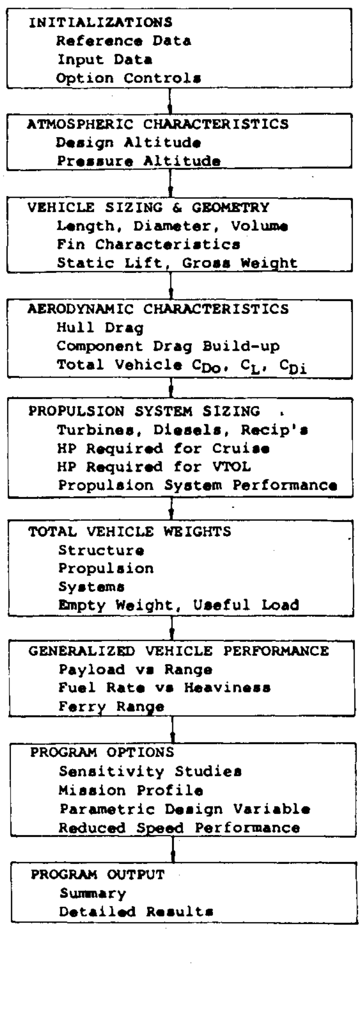

Fig. 1 Basic NAPSAP program top-level flowchart.

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*President. Member AIAA.

†Aerospace Engineer, Lighter-Than-Air Project (605B). Member AIAA.

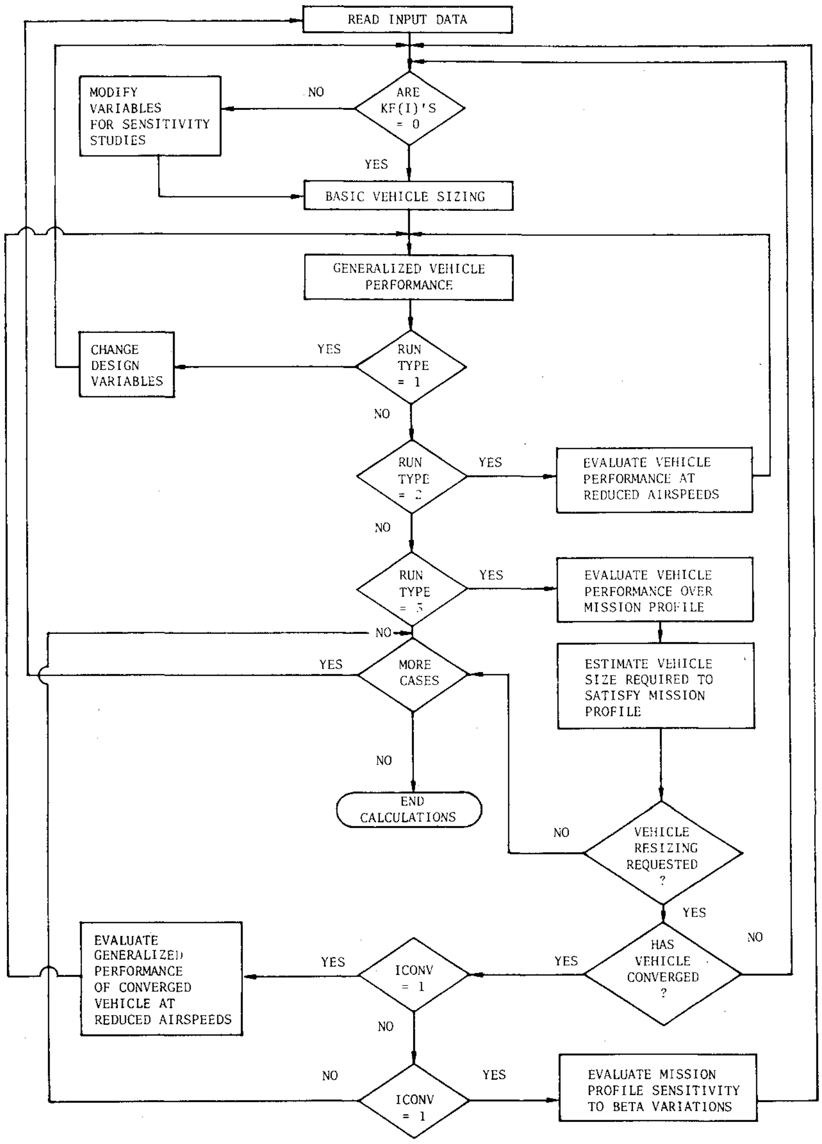

Fig. 2 NAPSAP program calculation options.

types of engine cycles may be utilized: gas turbines, diesels, or spark ignition reciprocating engines. Rotors or propellers may be analyzed on a point design basis by utilizing dedicated subroutines.

Basic Program Overview

The basic NAPSAP program methodology is illustrated in the top level flow chart of Fig. 1.

Input data are read in and program initializations are performed. The basic case vehicle evaluation requires only five input data cards. Vehicle input characteristics are used to size the vehicle and determine its overall physical and geometric characteristics. Vehicle sizing is based on an input value of volume or gross weight and static lift to gross weight ratio (beta), length to diameter ratio, prismatic coefficient, design altitude, and unit lift of the lifting gas at sea-level standard conditions.

The aerodynamic characteristics are calculated for zero angle of attack and the angle of attack required for cruise at maximum gross weight. Total vehicle drag coefficient at zero angle of attack is estimated on a simplified component buildup approach based on drag breakdown of prior Navy nonrigid airships. Induced drag is based on the expression used by previous Navy airship design methods. The drag at the input design conditions (gross weight, speed, and altitude) is used to determine the horsepower required for dash speed. If vertical takeoff (VTO) is required, the horsepower requirements for VTO at maximum gross weight are also calculated. The largest required horsepower sizes the propulsion system.

All propulsion calculations are based on "rubberized" engines (those sized for a conceptual mission and nonexisting production units) and conventional propellers that are tilted for vertical takeoff, landing, and hover. Propellers are sized by an approximation of Hamilton Standard propeller performance.[10] Propeller efficiency as a function of velocity is based on the data presented in Refs. 11 and 12 (separate subroutines have been developed for detailed point design analysis of rotors and propellers). Bare engine weight per horsepower and specific fuel consumption (SFC) as a function of horsepower are based on the data of Ref. 13. Fuel consumption for each engine cycle is corrected for airspeed, altitude, and throttle effects based on the data presented in Refs. 12 and 14.

Next, the vehicle weight characteristics are calculated. These include the nonpropulsive structure weight, the total propulsion system weight, the vehicle system weight, the total vehicle empty weight, and useful load.

Nonrigid airship weights are estimated by simplified weight estimating relationships (WER's) developed from an analysis of previous Navy weight reports and recent studies.[11,15] Rigid airship structural weight is based on the WER's utilized in the NASA Ames Research Center version of the Boeing

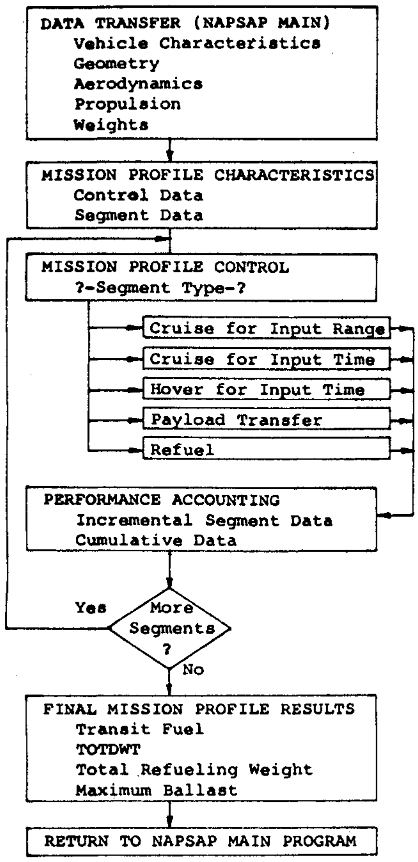

Fig. 3 Mission profile subroutine top-level flowchart.

CASCOMP program.[16] Disclosure of coefficients and constants is presently limited to only government agencies. Advanced state-of-the-art materials effects can be applied to the rigid airship WER's using, for example, the results presented in the Ref. 12 study (Appendix A). Propulsion system weights are based on the data of Refs. 12 and 16-18. System weights are based on a combination of prior vehicle actuals and generalized WER's from Ref. 16. The subsystem weights are summed to obtain the total vehicle empty weight, and the useful load is calculated.

The "generalized performance" is calculated for the vehicle sized above. This consists of calculating the payload as a function of range for the vehicle flying at the input (design) airspeed and altitude. Once neutral buoyancy is reached, the remainder of the evaluation assumes zero angle-of-attack flight. Buoyancy trim is maintained by collecting ballast by an unspecified means. Calculations proceed to the point where the total vehicle useful load has been consumed as fuel and fuel reserves.

The program calculations may be terminated at this point or any of the several program options may be exercised. These options include evaluation of the vehicle's mission profile performance, sensitivity studies via a perturbation factor option, parametric studies via the change design variable option, or evaluation of the basic vehicle generalized performance at cruise speeds below the design speed. These options are illustrated in Fig. 2.

Mission Profile Subroutine Overview

The mission profile subroutine (MISPFL) may have up to 100 segments, each defined by a set of performance characteristics which may include the following: airspeed, altitude, duration, range, expendables rate, auxiliary power requirements, tow drag, fuel weight to be picked up and payload to be picked up or off-loaded. A simplified overview of the mission profile subroutine is presented in Fig. 3. MISPFL currently has the capability to evaluate vehicle performance for five different types of segments: 1) cruise for a fixed range; 2) cruise for a fixed duration; 3) hover for a fixed duration; 4) pickup or off-load payload; and 5) refuel.

MISPFL calculates the following variables on a per segment and cumulative basis over the total mission: mission time, range, fuel consumed, fuel reserves, time on station, expendables weight, weight consumed for auxiliary power generation, ballast required, change in heaviness on the segment, the weight transferred on the segment. In addition, the program stores for output the initial and final values of each of the following variables on each segment: static lift to gross weight ratio (beta), heaviness in pounds, number of engines required, throttle setting per engine, fuel rate, total horsepower required, and ballast. A graphic output routine is under development which will allow any of the above variables to be plotted as a function of mission time, range flown, or by mission segment number.

The evaluation of a vehicle's capability to satisfy the input mission profile is analyzed in a "rubberized" fashion; that is, the vehicle never runs out of fuel. The MISPFL subroutine "flys" the vehicle over the input mission profile and keeps track of the total consumables weight (TOTDWT) required to satisfy the mission. TOTDWT is the main control variable in the mission profile evaluation and any iterations through MISPFL commanded by the main NAPSAP control program. This parameter is the sum of all fuel consumed, fuel reserves, expendables weight, weight consumed for auxiliary power generation, and any payload off-loaded minus any fuel picked up during the mission profile.

TOTDWT may be greater than or less than the total vehicle useful load. The value of TOTDWT is used to determine the actual payload for the input vehicle and to estimate the vehicle performance capability. Two different estimates are made based on the rubberized mission profile evaluation: 1) the actual vehicle volume required to satisfy the input mission profile, and 2) the time on station that the input vehicle could achieve at the specified range to station if each mission segment duration were scaled upward or downward. These performance estimates are useful in determining the performance capability of a vehicle sized for one mission in other mission applications.

Mission Profile Vehicle Resizing Option

One of the important features of the NAPSAP program is the capability to perform multiple iterations through the basic sizing program and the mission profile subroutine to determine the vehicle volume required to "exactly" satisfy an input mission profile (Fig. 2). The parameter TOTDWT is used as the control variable to determine whether the vehicle volume required is larger or smaller than the input vehicle. A new hull volume is defined and the entire sizing and performance reevaluated until vehicle size exactly matches the mission profile requirements.

Example Mission Concept and Typical Results

Lighter-than-air vehicles offer many unique attributes for towed array missions.[2,11] The LTA vehicle is not in the water, thus vehicle noise does not affect towed array performance, and detectability by the enemy submarine is greatly minimized. An airship's performance envelope—essentially from zero-zero to 100 knots at 10,000 ft—make it ideally suited to sprint-drift-type ASW operations. These attributes, combined with the nonfatiguing crew environment, long time on station capability (days), and extremely low fuel consumption on station are a few of the key factors which led NADC to examine the performance of a conceptual airship towed array (ATA) mission.[8]

Table 1 Input characteristics

Type: nonrigid	Gas turbine propulsion
Hull volume = 1.5×10^6 ft^3	Three (3) engines
L/D = 4.75	Propellers
Design altitude = 5000 ft	Design speed = 90 knots

Table 3 ATA mission converged vehicle characteristics

Hull volume = 1.4163×10^6 ft^3	Total refueling = 68,129 lb
Installed hp = 2631 hp	Total mission time = 169.5 h
hp/engine = 877	Total time on station = 133 h
TOTDWT = 102,038 lb	

Table 2 Vehicle weight comparison

	ZPG-3W actual[19]	ZPG-X design[11]	NAPSAP vehicle estimate
Volume (ft^3)	1,516,000	1,516,000	1,500,000
Static lift (lb)	82,996	83,000	82,076
Gross weight (lb)	93,496	96,500	95,438
Structure weight (lb)	35,786	33,200	34,287
Propulsion system weight (lb)	10,524	12,350	10,641
Systems weight[a]	3,777	2,650	3,778
Empty weight[a]	50,087	48,200	48,706

[a] Both systems weight and empty weight are exclusive of instruments and navigation equipment, APU, and electrical equipment.

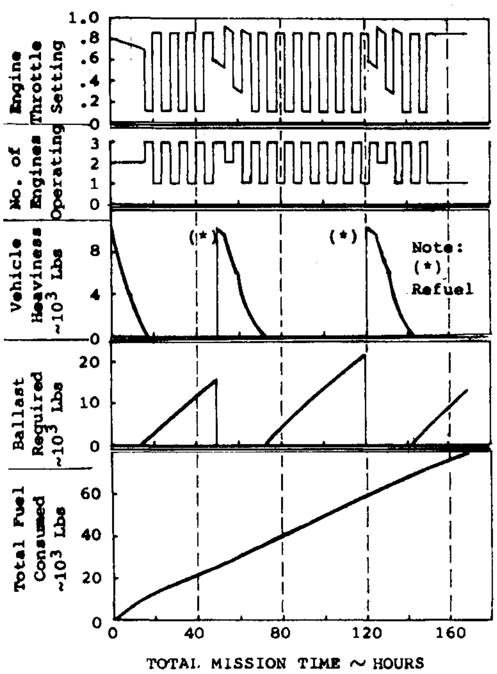

Fig. 4 Typical mission profile performance time histories.

This mission consists of the following (certain specified ranges and speeds are omitted):

1) Cruise to station at 60 knots.
2) Deploy array and tow for 4 h.
3) Retrieve array and sprint to new station.
4) Repeat segments 2 and 3 three times.
5) Refuel underway (0.5 h).
6) Repeat segments 2 and 3 nine times.
7) Refuel underway (0.5 h).
8) Repeat segments 2 and 3 three times.
9) Deploy array and tow for 4 h.
10) Return to shore-based station at 50 knots.

Total mission time = 169.5 h, total mission payload = 9828 lb.

The starting point for evaluation of this mission profile is identified in Table 1. The basic sizing portion of NAPSAP sizes the vehicle and estimates the generalized performance. The results of the initial iteration are listed in Table 2, along with a comparison of the actual weights of the ZPG-3W airship[19] and the recent study results of the ANVCE ZPG-X vehicle,[11] since their envelope volumes are identical.

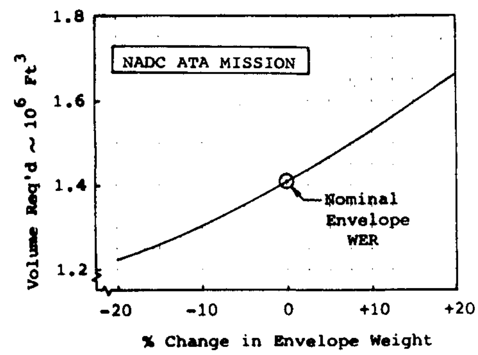

Fig. 5 ATA vehicle volume sensitivity to envelope group weight.

For the ATA mission utilizing three gas turbine engines, the iterations converged on a vehicle with a hull volume of 1.4163 million ft^3. Table 3 summarizes the results of the ATA mission profile vehicle resizing the converged vehicle performance. Following the convergence, NAPSAP sizes a vehicle at the converged volume and flys it over the mission profile. Figure 4 illustrates time histories of some of the key performance variables of a typical converged vehicle.

Other Program Options

The perturbation factor ($KF(i)$) option can be exercised with any other program option (see Fig. 2). This feature allows sensitivity studies to be made of the effects of several key design or performance variables. These include induced drag, total drag, propulsion efficiency, total propulsion weight, envelope weight, car weight, total nonpropulsive weight, and auxiliary gear weight. Growth for additional variables has been provided.

Figure 5 shows the effects of nonrigid envelope weight on the vehicle volume required to perform the airship towed array mission described above.

The parametric design variable option allows any one or more of the following input variables to be changed with a single input card: hull volume, gross weight, beta, design speed, design altitude, number of engines, and hull fineness ratio. The change is made to the basic case input data and the entire program is rerun. Multiple cases may be run with the single input card.

The off-design speed option allows the generalized performance of a vehicle sized for the input design speed to be evaluated at lower airspeeds. Typical results of a ZPG-3W-size vehicle sized for a 90-knot design speed at 5000 ft pressure altitude are presented in Fig. 6.

Table 4 Engine cycle effects on ATA mission vehicle size and fuel consumption

Engine type	Vehicle volume required, 10^6 ft^3	Installed horsepower	Total propulsion system, wt/hp	Total fuel + reserves	Total fuel picked up at sea
Gas turbine	1.416	2631	2.54	102,038	68,129
Diesel	1.492	2735	6.11	77,374	49,454
Reciprocating	1.051	2157	3.55	54,054	34,394

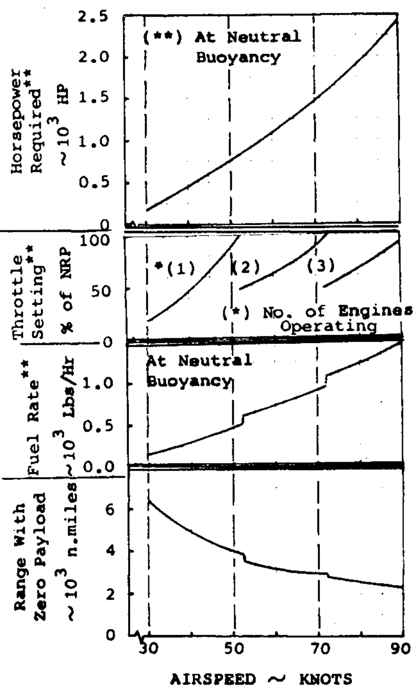

Fig. 6 Off-design speed performance evaluation results (1.5×10^6 ft^3, nonrigid).

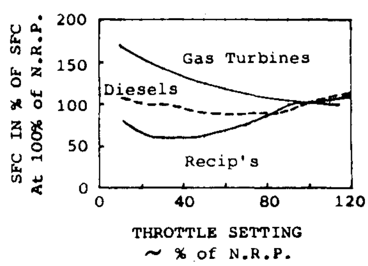

Fig. 7 Engine cycle SFC variation with throttle setting.

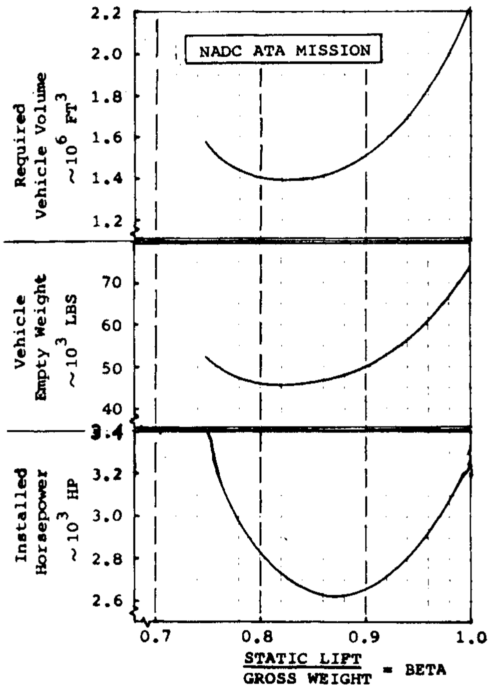

Fig. 8 ATA mission performance sensitivity to beta.

Other Program Capabilities and Sample Results

NAPSAP can analyze three different types of propulsion system cycles—gas turbines, diesels, and spark ignition reciprocating engines. Each engine type has its own characteristics in terms of performance variations with airspeed, altitude, and specific fuel consumption variation with throttle setting. All of these factors are important in complex mission profiles where much time is spent at low speeds. Table 4 summarizes the converged volumes and fuel requirements of vehicles utilizing each type of propulsion for the ATA mission. The payoff of the spark ignition reciprocating engine arises from its comparatively good performance at low throttle setting, as shown in Fig. 7. These results apply to the ATA mission only and are subject to revision pending further refinements of the basic data currently utilized by NAPSAP for each engine cycle. For example, upcoming inclusion of the lightweight diesel performance data of Ref. 20 will make the diesels more attractive due to the considerably lower engine weight density than that currently used from Ref. 13.

Effects of Heaviness

The vehicle volume sensitivity to takeoff heaviness (beta) is illustrated in Fig. 8 for the ATA mission. Each data point represents a "converged" vehicle volume required to exactly satisfy the ATA mission profile requirements. The "optimum" beta is a strongly mission-dependent variable. Missions which have the majority of time at high speeds will tend to "optimize" at low betas. Missions which have large percentages of time at low speed or hover tend to optimize at higher betas, depending on the range to station (hence, fuel consumed in transit).

Note that the optimum beta for the ATA mission is dependent on the criteria used. If minimum vehicle volume is the criterion, the optimum beta is about 0.825. If minimum installed horsepower is the criterion, the optimum beta is about 0.87. An obvious conclusion from the data of Fig. 8 is that cost (RDT&E, acquisition, and life-cycle operating costs) needs to be included as one criterion for selection of the optimum vehicle design characteristics. Continued escalation of fuel prices over the next decades will surely place a premium on fuel-efficient operation; hence, fuel consumption will undoubtedly also be one of the more important factors in the selection of preferred vehicle characteristics.

Summary and Conclusions

The Naval Airship Program for Sizing and Performance (NAPSAP) has been developed to assist the U. S. Navy's LTA Project Office at the Naval Air Development Center in their continued analysis of the technical and operational feasibility of modern LTA vehicles. NAPSAP can perform preliminary design and parametric performance analysis of rigid or nonrigid LTA vehicles in conventional takeoff or VTOL operations with various types of propulsion. Program analysis which may be selected include the following:

1) Point design vehicle sizing and performance evaluation at constant speed and altitude.

2) Performance evaluation of the point design vehicle at speeds below the design speed.

3) Parametric analysis of a point design vehicle sizing and performance as a function of the perturbation of key design or operational parameters.

4) Performance evaluation of a point design vehicle over complex mission profiles of up to 100 segments. Segments may consist of cruise, hover, payload pickup or off-load, and refueling, and may include the effects of mission-dependent expendables, auxiliary power, towing forces, and ballast requirements.

5) Multiple iterations of the vehicle sizing and mission profile performance evaluations to determine the minimum vehicle volume required to satisfy the input mission profile.

NAPSAP is a valuable analytical tool for preliminary design and parametric evaluation of the technical and operational feasibility of modern LTA vehicles. Continued development of the NAPSAP program is warranted as the credible technology base for modern LTA vehicles is extended.

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