1993

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AIAA

https://hdl.handle.net/10945/71354

Aircraft Design at the Naval Postgraduate School: Tactical Waverider/Long-Range Cargo Aircraft

Conrad F. Newberry, P.E.,* David M. Dober,⁺ Peter J. Riester,⁺⁺
Robert B. Stoney,⁺⁺ Thomas A. Johnston,⁺⁺ and David R. Price⁺
Naval Postgraduate School

Abstract

The graduate program of the Department of Aeronautics and Astronautics at the Naval Postgraduate School uniquely supports a comprehensive design program in aircraft, spacecraft, missile, helicopter, and engine design. This paper is focused on four aircraft configuration designs proposed by AA 4273 Military Aircraft Design course team members. The AA 4273 course is, in turn, supported by a growing research program to enhance and further develop the methodology of aircraft design. This design effort has received considerable support from the NASA/USRA Advanced Design Program in Aeronautics. Specifically, two design solutions for a long-range, carrier based, tactical, wave-rider configured fighter/interceptor aircraft are reviewed herein, as are two solutions for a global range military transport. Both types of aircraft were developed as a graduate student team response to specific design RFPs.

Introduction

The Naval Postgraduate School (NPS) exists for the sole purpose of increasing the combat effectiveness of the U.S. Navy and Marine Corps. This purpose is achieved by providing military officers and defense officials with a quality education which supports the unique needs and interests of the Defense establishment. Although the NPS programs are developed for Navy and Marine Corps personnel, the student body consists of U.S. officers from all branches of military service, international students from allied countries and civilian employees of the United States Federal Government.[1] Eleven academic departments and four academic groups provide a wide spectrum of degree programs for about 1800 students. Nearly half of the students receive advance degrees in disciplines different from their undergraduate area of study.

The Department of Aeronautics and Astronautics offers the Degrees of Master of Science in Aeronautical Engineering, Master of Science in Astronautical Engineering, Master of Science in Engineering Science, Aeronautical and Astronautical Engineer, Doctor of Philosophy and Doctor of Engineering. Doctoral programs are available in the fields of gas dynamics, flight structures, flight dynamics, propulsion, aerospace physics and aerospace vehicle design.

There are approximately 180 students distributed across the aeronautics, astronautics and avionics curricula supported by the Department of Aeronautics and Astronautics. Departmental design requirements are supported by aircraft, missile, aircraft engine, helicopter, avionics and spacecraft design courses or course sequences. The aeronautical and avionics programs are accredited by the Accreditation Board for Engineering and Technology (ABET).

The aircraft design course, AA 4273 Military Aircraft Design, is a single, twelve-week quarter course offered twice a year (summer and winter quarters). The course enrollment typically supports two 7-10 member design teams. These design teams typically respond to a Request-for-Proposal (RFP), which specifies requirements for a military aircraft.

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*Professor of Aeronautics and Astronautics (also, Professor Emeritus; California State Polytechnic University, Pomona), Fellow AIAA.

⁺LT USN

⁺⁺LCDR USN

NASA/USRA Advanced Design Program

During the fall of 1984, the National Aeronautics and Space Administration (NASA) developed the Advanced Design Program (ADP) as a national pilot project initiative to encourage and nurture engineering design education in the universities and to supplement NASA's internal efforts in the advanced planning for space system design. In 1986 the ADP was expanded to include aeronautical design activities. The ADP is administered by the Universities Space Research Association (USRA), which consists of some 75 academic institutions, supported by grants from NASA Headquarters. Some 44 academic institutions are currently participating in this program. Of the 44 participants, twelve are pursuing aeronautical design initiatives, while the remainder are investigating space related design concepts.[2,3]

The senior author of this paper developed an undergraduate[4,5] ADP effort in the mid-to-late 1980s, and proposed to develop a graduate ADP effort at NPS during the most recent NASA/USRA ADP proposal period.[6] Based on a competitive selection in 1992, the Naval Postgraduate School was selected to participate in the NASA/USRA Advanced Design Program in order to pursue waverider design initiatives. These waverider design initiatives were concerned with the development of tactical, carrier compatible, military aircraft. Once these waverider initiatives received appropriate consideration, in any given year, other design topics could be addressed, if there was sufficient student interest and if class enrollment could support additional aircraft design teams.[6]

During the past year, student enrollment in AA 4273 Military Aircraft Design supported four design teams. Two teams elected to pursue waverider configurations and two elected to pursue subsonic, long-range, heavy-lift-capability configurations. The design teams were composed of either seven or eight members, depending upon the particular academic quarter. One waverider team (SABOT) was comprised of eight members, while the second (LONGBOW) was comprised of seven members. Similarly, one subsonic transport design team (DUMBO) was comprised of eight members, while the second team (HUGO) was comprised of seven members. The efforts of these four design teams are reported herein.

In the following discussion of these four aircraft designs, samples of the design effort will be presented herein. However, no effort will be made to compare the performance, life-cycle-cost or other parameters of any two similar aircraft. Instead, methodology and design results will be stressed.

Waveriders

Initially, waveriders were conceived as aerodynamic configurations that could be designed inversely to fit known flowfields. Nonweiler[7] proposed a wedge-based configuration similar to that shown in Fig. 1. Cone-based configurations may result in planforms similar to that shown in Fig. 2.[8] The XB-70 may well have been the first practical waverider configuration.[9]

The present National Security Strategy reflects resized Naval forces that can effectively support joint warfighting scenarios in the littoral regions of the planet. For the Navy, this new strategic direction represents a shift away from open-ocean warfighting on the sea, toward joint operations conducted from the sea.[10]

In keeping with this new warfighting direction, a hypothetical scenario was suggested by the senior author, wherein a carrier force was deployed sufficiently far at sea to preclude any land-based aircraft threat, yet able to support joint operations in the nearest littoral zone. The design question was whether or not a waverider configured aircraft could be developed as a plausible tactical aircraft capable of operating from such a carrier, yet able to provide significant support for joint operations in littoral zones of conflict.

One approach was to suggest that such an aircraft should have a large radius of operations, a high speed capability to traverse that radius and reach the littoral zone of conflict and then spend an acceptable residence time in the littoral zone, in order to provide sufficient support for joint operations. The vehicle should be able to carry acceptable quantities of ordinance and armament for that support as well as be able to provide adequate self-protection. Within this framework, the design team was free to refine and otherwise supplement these requirements.

The waverider Request-for-Proposal (RFP), to which the design teams responded, was developed by the senior author and consisted of few but stringent requirements. The specific waverider air superiority/fighter/interceptor requirements consisted of the following:

1. 1500 nm unrefueled range
2. Waverider planform
3. Cruise at $3 \leq M_\infty \leq 6$
   The cruise Mach number should be dependent upon a design team trade study
4. Carrier suitable
5. Major system considerations (not

necessarily in the order of importance)

a. Fuel fraction
b. Cost
c. Maintainability
d. Structures
e. Propulsion

6. 100 page final report.

There were two responses to these six requirements. The SABOT interceptor approximates the waverider planform, but is not a true waverider configuration. The LONGBOW configuration closely approximates a true waverider configuration.

SABOT

Fig. 3 presents a three-view of the SABOT aircraft. The trailing portion of the wing swings forward for low-speed flight. The aircraft has a length of 63.9 feet, a height of 14.2 feet and a span of 32.5 feet (swept forward wing position, 50.6 feet). Based upon a constraint analysis, the thrust-to-weight was determined to be T/W = 0.55 with a corresponding wing loading of W/S = 105 psf. The cruise configuration leading edge sweep angle was determined to be $\Lambda = 70$ degrees. The design team considered a maximum weight limit of 85,000 lb$_f$ for carrier suitability requirements. The maximum weight of the SABOT vehicle is 76,036 lb$_f$. Since this is somewhat less than the 85,000 lb$_f$ projected limit, there is some growth potential.[11]

Fig. 4 presents the SABOT weight statement. Weight relationships from the Nicolai[12] and Raymer[13] texts were used to generate these weight estimates. It should be noted that the fuel fraction is approximately 51% of the gross takeoff weight. The combined fuel and ordinance weight fraction is approximately 55%. The corresponding (large) c.g. travel varies from 23.8% to 83.5% of the mac.

Fig. 5 illustrates the carrier approach and landing characteristics for the SABOT. As can be seen in Fig. 5, operations under no-wind conditions are limited to full flap landings at weights under 43,000 lb$_f$. The deck handling characteristics of the SABOT are in compliance with MIL-STD-805A.[14]

Fig. 6 illustrates the SABOT zero-lift drag coefficient variation with Mach number. USAF DATCOM[15] methodology was used to compute the subsonic, transonic and supersonic C_{D_0} values. Fig. 7 illustrates representative drag polars for the SABOT aircraft.

The propulsion system features a variable bypass turbofan engine with afterburner. Automatic controls vary the bypass ratio from 0 (turbojet), at high Mach numbers, to 1 at subsonic speeds. The maximum turbine inlet temperature was assumed to be 3200 °R.

The SABOT V-n diagram for sea level operation is shown in Fig. 8. This diagram is based on guidelines set forth in FAR Part 25[16] and in MIL-A-8861(ASL).[17] A similar diagram was developed for the SABOT at 50,000 feet of altitude. The gust load lines all fall within the operating envelope. Fig. 9 presents the flight envelope for the SABOT aircraft.

The SABOT flying qualities are compared with MIL-F- 8785C[18] class IV, level 1 requirements in Table I. As can be seen, the SABOT exceeded all requirements except for a small excursion in exceeding the maximum roll rate time constant (τ_{roll}). All stability derivatives were calculated by USAF DATCOM methodology. The waverider stability sensitivity, together with the large center-of-gravity travel, requires the utilization of a three-axis stability augmentation system.

Development, Test and Evaluation (DT&E) costs together with production costs were considered to result in a unit cost of $ 89.1 million (FY 2000 dollars) for the SABOT. This unit cost was based upon a 100 aircraft purchase, with a production rate of one SABOT per month and was based upon cost estimation methods provided by Nicolai[12]

Table II permits a comparison of the SABOT performance with the RFP requirements. It can be seen that the SABOT meets or exceeds the design goals set for the aircraft.

LONGBOW

The LONGBOW was essentially designed *to the same RFP specifications* as the SABOT. Fig. 10 presents a three-view of the LONGBOW aircraft. As with the SABOT, the LONGBOW features a swing-wing configuration for low-speed, subsonic flight. The LONGBOW has a 14 foot height, a length of 57 feet and a cruise configuration wing span of 57 feet (low speed span of 76 feet). The cruise configuration has an approximate leading edge sweep angle of 67 degrees.[19]

The constraint analysis for the LONGBOW is illustrated in Fig. 11, which indicates that the design point has a thrust-to-weight ratio of T/W = 0.55 and a corresponding wing loading of W/S = 120 psf. It should be noted that the maintainability and reliability constraint relationships are based upon historical data. This constraint analysis is consistent with the mission profile of the LONGBOW shown in Fig. 12.

Turbojet, turbojet with afterburner and ramjet engine cycles were considered for the primary propulsion system. The result of several studies by the design team suggested that the afterburning turbojet should be the cycle of choice. Accordingly, the ONX, OFFX computer programs of Mattingly[20] were used in the optimization of the cycle pressure ratio. Tsfc, specific thrust and aerodynamic heating trade studies resulted in the selection of $M_\infty = 3$ for the cruise portion of the mission.

A detailed static and dynamic stability analysis was conducted for the Mach 0.2 powered approach (configuration PA) and at the Mach 3 cruise (configuration CR). The USAF DATCOM[15] and Etkin[21] methodologies were used to compute the requisite stability derivatives. Stability augmentation was used as needed to ensure compliance with all of the stability requirements of MIL-F-8785C.[18]

Fig. 13 illustrates the results of the aerodynamic heating analysis. This analysis is based on a eleven element model of a typical section of the leading edge. Element 1 is the leading edge element, elements 1 and 2 comprise the leading edge heat sink. Elements 3,4,5,6,7 and 11 are skin temperatures near the leading edge. Elements 8 and 10 are spar caps and element 9 is a spar web. Element 20 is an isolated skin element six feet aft of the leading edge. The analysis suggests that the skin temperatures are acceptable for the materials selected for aircraft construction, without using an active cooling system. Painting the skin black typically reduced the titanium skin temperatures by some 35 degrees (°F).

The maximum structural loads on the wing were considered to be associated with a 6g, Mach 3 turn at 50,000 and 65,000 feet of altitude on a standard day. A finite element model was developed with MSC/PAL2 software. Stress levels were acceptable for this design condition. The swing-wing is fully swept aft at Mach numbers above $M_\infty = 0.8$. Thus, the swing-wing was designed for a maximum load factor of $n = 3$ at a Mach number of $M_\infty = 0.8$.

Based on the acquisition of 250 aircraft, the unit cost of the LONGBOW (DT&E and production) is estimated to be $ 46.9 million (FY 1993). Based on ten years of operation, the life-cycle-cost per unit is estimated to be $ 55.3 million.

Global Range Military Transport

The world is rapidly changing from one with two major military powers in which most countries were more or less aligned with one or the other of the so-called superpowers, to one with many downsized military powers. In this changing world environment, the United States can no longer count on the availability of worldwide operational bases that can be used by American forces responding to international crises. It is recognized that there is an increasing need to rapidly transport large numbers of both troops and equipment from the continental United States (CONUS) to potential crisis centers throughout the world. To respond to this perceived need, the national AIAA/McDonnell Douglas Corporation Graduate Student Team Aircraft Design Competition for 1992-93 addresses this global range military transport requirement.[22]

This design study was, as required, performed in two phases. Phase I was performed to formulate the mission performance specifications for range, speed and payload that will maximize the amount of material that can be transported in 72 hours (3 days). Phase II of the study was required to develop an optimum aircraft design capable of meeting the performance specifications developed in Phase I. The minimum designated unrefueled range requirement was 6,000 nm and the corresponding minimum designated payload was 400,000 lb$_f$ (at a 2.5g maneuver load factor). The mission specification for this heavy lift system is as follows:

1. Warm-up and taxi for 15 minutes
2. Takeoff and climb to best cruise altitude
3. Cruise at best cruise altitude and Mach number to the mission mid-point
4. Descend on course and land
5. Taxi/idle for 30 minutes, off-load full payload
6. Load 15% of full payload, takeoff and climb to best cruise altitude
7. Return at best cruise altitude and Mach number
8. Loiter 15 minutes (15 minutes reserve fuel)
9. Descend, land and taxi 10 minutes

The specifications further stipulated that the aircraft must be able to operate from existing domestic airbases and use existing airbases or sites of opportunity at the destination. Takeoff and landing rules (critical field length) were also required.

There were two NPS responses to these requirements. It should be noted that the competition requirements were not finalized until mid-to-late August of 1992 (midway through the course). The initial specified payload requirement was 800,000 lb$_f$, in contrast to the final payload requirement of a minimum of 400,000 lb$_f$. The DUMBO design responded to the 800,000 lb$_f$ payload requirement while the HUGO was designed for a payload of 450,000 lb$_f$.

UMBO

The solution space for the DUMBO design is shown in Fig. 14. The constant speed climb, takeoff and landing constraints tend to define the solution space. The point design thrust-to-weight ratio is T/W = 0.21 and the corresponding wing loading is W/S = 140 psf.[23]

Quality Function Deployment (QFD) was used to identify significant design related attributes of the DUMBO aircraft. One of the corresponding House Of Quality diagrams is shown in Table III. The 800,000 lb_f payload was considered the most important attribute of DUMBO. A plus sign indicates a strong positive relationship between the design (aircraft characteristics) parameters; a minus sign indicates a strong negative relationship. For example, the $M_{CRUISE} = 0.77$ customer requirement is shown as having a strong positive relationship with L/D.

Lambda, conventional tail, canard, two wing and three wing configurations were considered for this aircraft. The final DUMBO configuration is shown in Fig. 15 with a span of 239 feet, length of 295 feet and a height of 64.5 feet.

The DUMBO configuration features a front loading raised cab visor nose; a canard; six unducted propfans mounted on the underside of the main wing comprise the propulsion system; a landing gear of six main struts and two nose struts; a flight crew of pilot, copilot, flight engineer, navigator and two load masters; and a primarily composite airframe. The weight estimates are based upon the statistical (historical) weight methodology provided by Nicolai.[12] The maximum gross weight of DUMBO is approximately 4,000,000 lb_f, with a fuel fraction of 0.425. The static margin is approximately 13.8% of the mac. The largest shift in the c.g. occurs when the required 60,000 payload drop is completed. However, the c.g. is always within acceptable limits.

Turbojet, turboprop, turbofan and unducted fan (UDF) engine cycles were considered for the DUMBO propulsion system. The mission requirements eliminated the turbojet and the turboprop. The UDF was selected for fuel savings and life-cycle-costs. The UDF core engine has a maximum pressure ratio of 45, sfc of 0.21 per hour and a compressor frontal area of 6.7 ft^2. To meet the thrust requirements of DUMBO, counter-rotating fans (10 blades per each of the two discs) with a 24.2 foot diameter were selected. At sea level takeoff conditions, the propfan will have a disc loading of 120 SHP/D^2 and a tip speed of 800 fps. For cruise conditions, a disc loading of 36 SHP/D^2 and a tip speed of 789 fps are optimal.

The DUMBO wing features an NASA SC(2)-0714 airfoil. Leading and trailing edge flaps are employed to achieve a $C_{L_{MAX}} = 3$. The wing lift curve slope is $C_{L_\alpha} = 5.51$/rad at $M_\infty = 0.5$. The wing aspect ratio is AR = 10 with a cruise lift-to-drag ratio of L/D = 21.

The DUMBO V-n diagram was determined to ensure compliance with MIL-A-8861B.[17] The maximum wing loading condition (3.75g at cornering speed) results in a wing shear of $4.3\text{x}10^6$ lb_f and a corresponding bending moment of $3.75\text{x}10^8$ ft-lb_f at the wing root. The corresponding wing shear and bending moment distributions are shown in Fig. 16.

On a standard day, the DUMBO can takeoff in 7833 feet (8767 feet on a hot day). The corresponding landing distances are 8798 feet on a standard day and 9396 feet on a hot day. The critical field length is estimated to be 8675 feet on a standard day and 9570 feet on a hot day.

The longitudinal dynamic characteristics of DUMBO are shown in Table IV. Stability augmentation about all three axes, using state variable feedback design techniques, is employed.

The main cargo deck of DUMBO is 200 feet long and 33 feet in width. At the center it is 15 feet high, tapering to a height of 10.5 feet at the sides. The upper cargo deck is 20 feet wide and 185 feet long. The entire upper deck can be rigged with jump seats for approximately 500 personnel. The DUMBO kill tree is shown in Fig. 17.

The cost analysis for DUMBO was computed using the methodology presented in Nicolai.[12] It was determined that only 13 aircraft would be required to meet the global airlift requirements; one test aircraft and twelve operational aircraft. Based on these assumptions, the unit cost of each DUMBO aircraft is $ 6.29 billion (FY 1992 dollars).

HUGO

The HUGO configuration was designed as a global mobility platform. The mission profile for HUGO is shown in Fig. 18.[24]

As with DUMBO, Quality Function Deployment (QFD) was used to identify significant design related attributes of the HUGO aircraft. The HUGO House of Quality for Product Characteristics is shown in Table IV. The significance of the plus and minus signs is the same as specified in the description of Table III above.

Table V shows a comparison of subsonic and supersonic aircraft delivery capability. Speed is shown to have little influence upon the total delivered payload quantity. The life-cycle-cost analysis shown in Table VI indicates that the subsonic, single fuselage HUGO concept has the lowest life-cycle-cost.

The HUGO constraint analysis is shown in Fig. 19, where the design point thrust-to-weight ratio is $T/W = 0.265$ and the corresponding wing loading is $W/S = 135$ psf. A three-view of HUGO is shown in Fig. 20.

The NASA SC(3)-0615 supercritical airfoil was chosen for the wing root section, while the NASA SC(3)-0609 section was chosen for the wing tip section. The wing thickness ratio versus the wing semispan is shown in Fig. 21. The extra thickness inside the 40% semispan break-point is used to balance M_{CRIT} across the span, to hold fuel and to match required bending moments.

The HUGO cargo bay loading configuration is shown in Fig. 22. Various civilian and military cargo payloads were investigated. It was found that civilian cargo container size dominated the selection of the cargo bay width, while the military cargo requirements dominated the cargo bay height selection.

The HUGO configuration has a gross takeoff weight of $W_{GTO} = 1.367$ million pounds, with a payload of 450,000 lb_f and a fuel load of $W_f = 500{,}000$ lb_f. The fuel fraction is $W_f/W_{GTO} = 0.366$. Cruise is at a Mach number of $M_\infty = 0.8$, at 35,000 feet on a standard day, with a corresponding $(L/D)_{MAX} = 17$.

The cargo bay is 160 feet in length, 13.5 feet in height and 35 feet in width. The wing span is 300 feet and the wing planform area is 10,080 ft^2, with a taper ratio of $\lambda = 0.38$ and an aspect ratio of $AR = 8.93$. The wing quarter chord is swept aft by 22.6 degrees.

The c.g. shift due to payload and fuel usage is shown in Fig. 23. The maximum c.g. travel is 23% of the mac (mac = 35.27 feet) and maintains a static margin of less than 15% of the mac. The cruise and ultimate wing shear and bending moment distributions are shown in Fig. 24 and 25, respectively.

Although several engine cycles were considered, as shown in Fig. 26, the AIAA ATF competition engine was selected for the HUGO. Six pylon mounted engines provide power for the HUGO aircraft.

The HUGO stability augmentation system (SAS) longitudinal and lateral stability characteristics are shown in Tables VII and VIII, respectively. The augmented Dutch-Roll response [roll/yaw rate (deg/sec) versus time] is shown in Fig. 26.

Life-cycle-cost (LCC) estimates were based on methods outlined by Nicolai[12] and Earles.[25] The results of the cost trade the aeronautical related design classes.

3. Four graduate student aircraft design configurations are summarized herein. Two solutions are proposed for the high-supersonic, carrier suitable, tactical waverider. Two solutions are also proposed for a 6,000 nm global range military transport.

4. The design classes also provide the impetus for considerable graduate level research in aircraft design methodology. An optimum $M_\infty = 6$ tactical, carrier suitable, waverider configuration was developed as part of this thesis effort. Water and wind tunnel models of this configuration will be tested in the near future to provide support for future tactical waverider design efforts.

Acknowledgements

The authors take this opportunity to thank Ms. A. Sherri McGee at NASA Headquarters for her constant support of the ADP and Messrs. Gary C. Hill and Jeffrey V. Bowles, of the NASA Ames Research Center, for their gracious willingness to provide time, suggestions, presentations and other support for the AA 4273 Military Aircraft Design class, in particular, and the NPS waverider design program, in general. In a similar manner, the authors take this opportunity to thank the USRA Advanced Design Program staff, particularly Mr. John R. Sevier, Dr. Vicki S. Johnson, Ms.Barbara A. Rumbaugh, Ms. Sue A. McCown and Ms. Cissy M. Novak for their constant concern and their untiring efforts to facilitate the administrative adventures of NPS participation in the ADP, and, in general, for their constant efforts to improve the ADP. The authors also thank Mr. Antonio M. Cricelli for his efforts to free them from their many entanglements with the various software and computer codes utilized in this project. Lastly, the authors thank all those graduate students in the AA 4273 Military Aircraft Design class who contributed to the completion of this paper.

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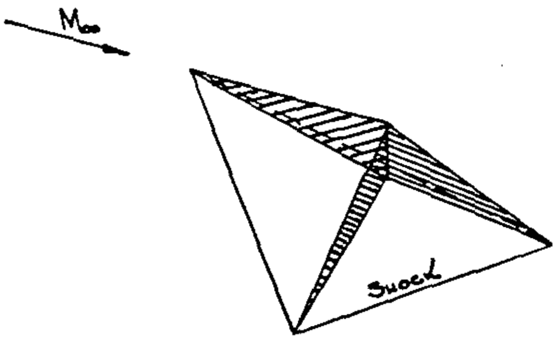


Figure 1
Wedge-Derived Waverider

Group Weights and Moments Statement

	weight (lb)	Centroid Location (ft) X	Y	Z	Ixx (slug-ft^2)
Structures Group					
Wing	8,617.33	30	0	2	35.49
Horizontal Tail	663.14	57	0	0	26.62
Vertical Tail	318.87	55	0	-5	396.61
Fuselage	8,898.11	29	0	-1	1,262.32
Arresting Gear	608.29	55	0	3	65.66
Catapult Gear	132.07	14	0	3	16.41
Main Landing Gear	1,589.46	48	0	4	405.10
Nose Gear	435.05	14	0	4	115.98
Inlet Ramps	834.05	37	0	1	936.53
Propulsion Group					
Engines	6,000.00	50	0	2	68,073.68
Engine Controls	48.79	40	0	-1	
Starting System	264.38	37	0	1	704.43
Fuel System	1,676.78	25	0	-2	8,020.30
Equipment Group					
Hydraulics and Flight Controls	2,006.71	38	0	-2	613.55
Electrical	572.74	20	0	0	22.99
Avionics	1,039.35	10	0	-2	305.75
Ejection seat	220.65	10	0	-2	88.87
Air conditioning ECS	230.58	25	0	-1	32.71
Total Empty Weight =	34,906.35				
Useful Load Group					
Pilot	230.00	10.00	0.00	-3.00	57.95
Fuel	39,000.00				
Ordnance	2,500.00	40.00	0.00	2.00	57.95
Takeoff Gross Weight					
Flight Design Gross Weight =	76,836.35				

Figure 4
SABOT Weight Statement

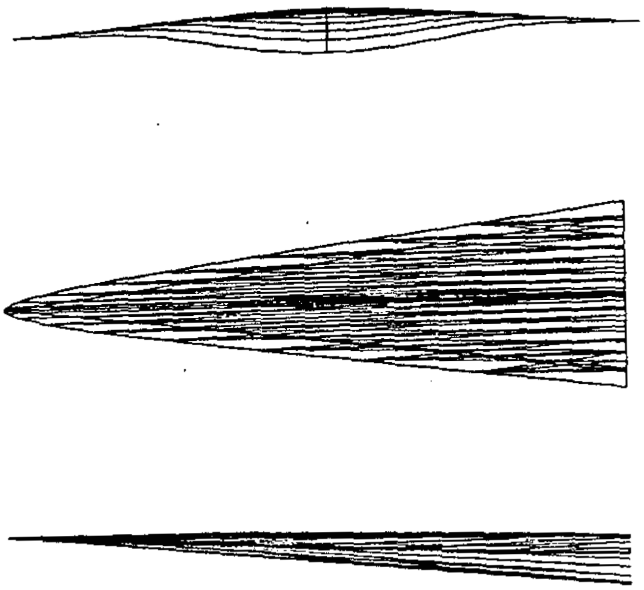


Figure 2
Cone-Derived Waverider

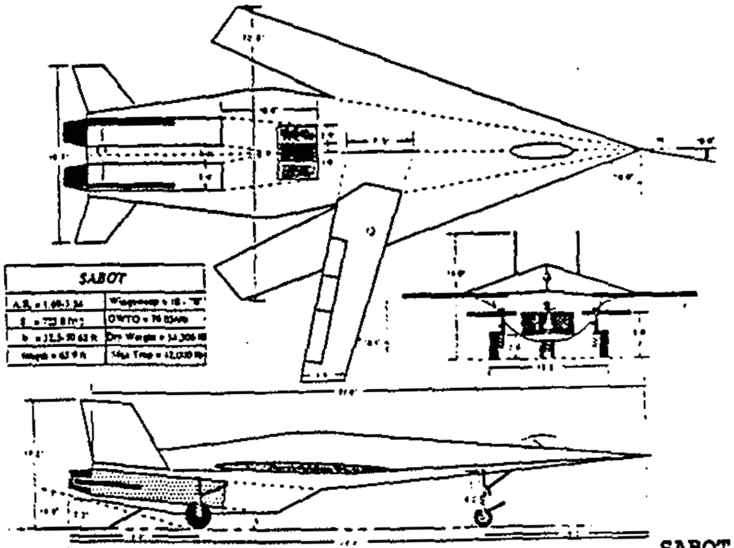


Figure 3
SABOT Aircraft

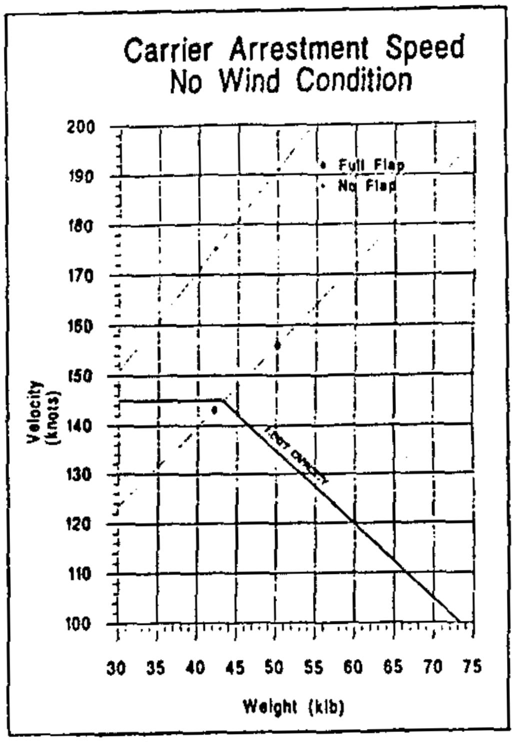


Figure 5
SABOT Carrier Approach and Arrestment Speeds

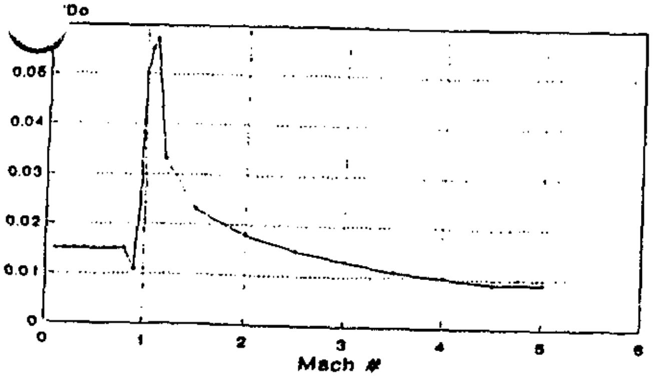


Figure 6
SABOT Zero-Lift Drag Coefficient Variation With Mach Number

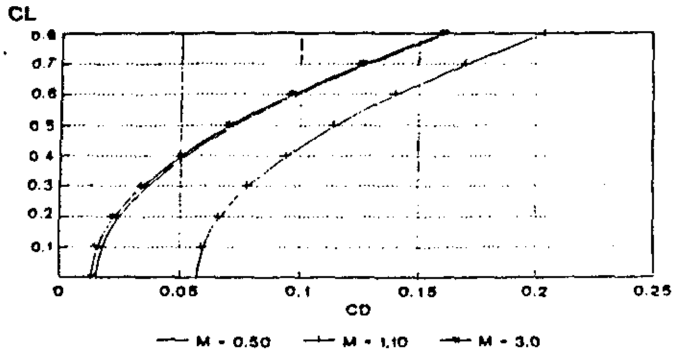


Figure 7
SABOT Drag Polars

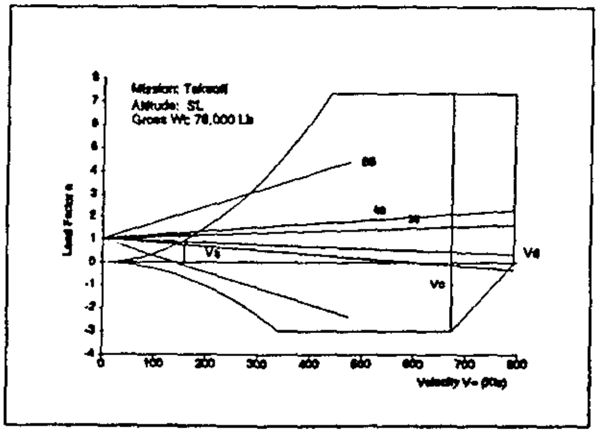


Figure 8
SABOT V-n Diagram

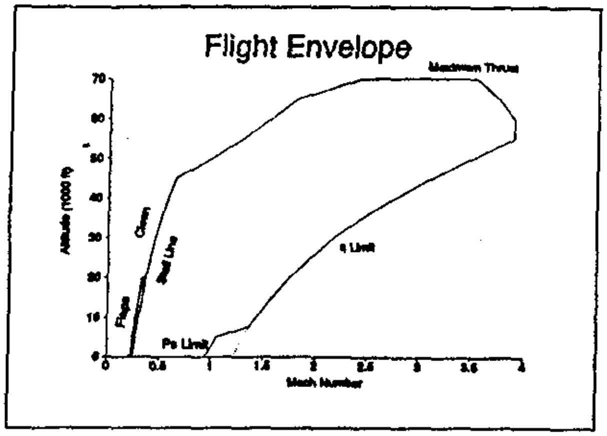


Figure 9
SABOT Flight Envelope

Flying Qualities	Sabot	MIL-F-8785C
Longitudinal-Short Period		
ω_{sp}	7.2143	n/a
ζ_{sp}	0.4043	$0.35<\zeta<1.3$
Longitudinal-Phugoid		
ω_p	0.6204	n/a
ζ_p	0.0621	> 0.04
Lateral-Dutch Roll		
ω_{dr}	3.5347	> 1.0
ζ_{dr}	0.1938	> 0.19
Lateral-Roll		
τ_{Roll}	2.0851	< 1.0
Lateral-Spiral		
τ_{Spiral}	21.142	> 20.0

Table I
SABOT Flying Qualities Summary

Specification	Required	Sabot
Minimum Radius	700 nm	762 nm
Dash Mach Number	<5	3
Missile Carriage (Internal/Conformal)	4	4
Cycle Time	1+00 (Min) 1+30 (Des)	1+00
Sustained Turn	2g or 4g	4g
Maximum Gross Weight	<85,000	76,036

Table II
SABOT Performance Comparison With RFP

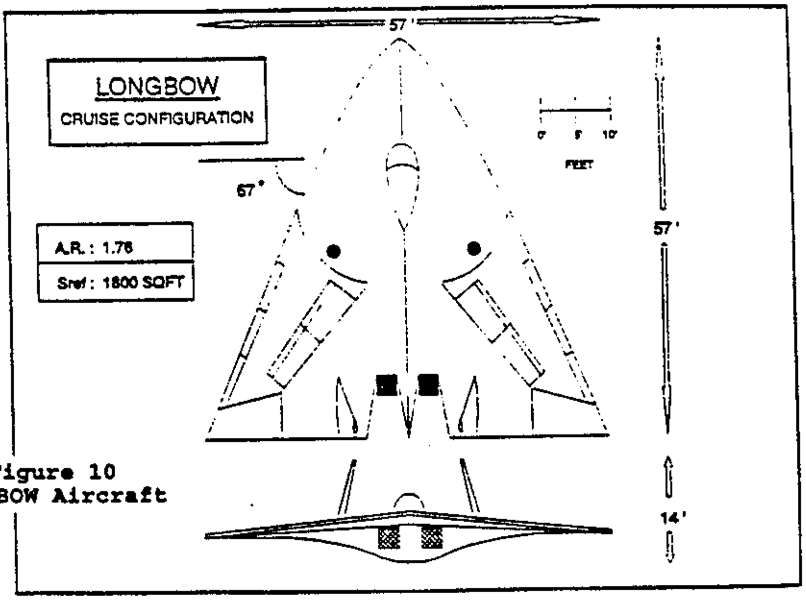


Figure 10
LONGBOW Aircraft

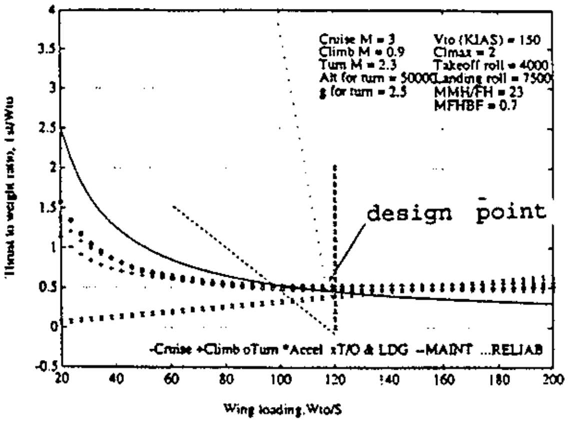


Figure 11
LONGBOW Design Solution Space

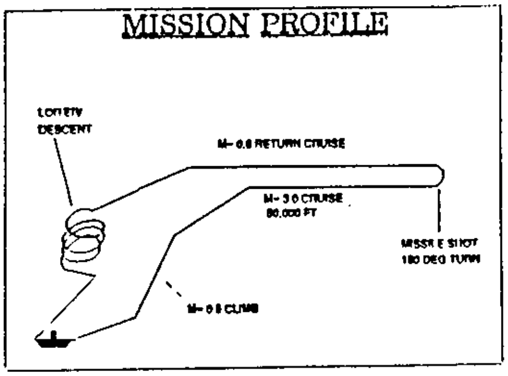


Figure 12
LONGBOW Mission Profile

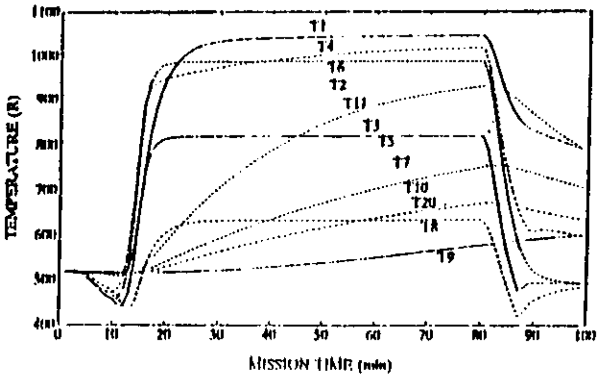
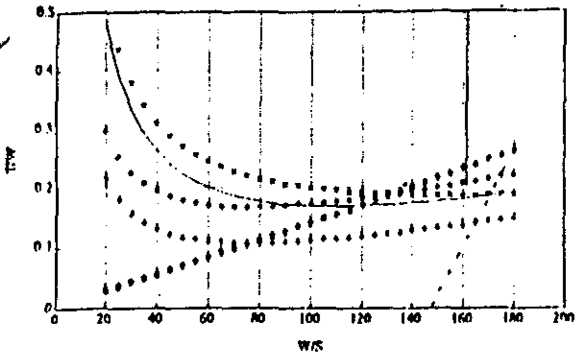
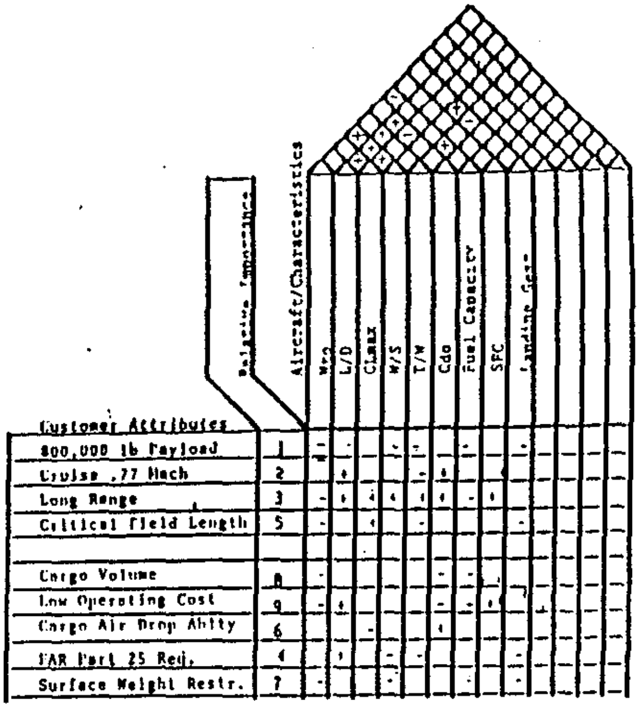


Figure 13
LONGBOW Transient Temperature Distribution Analysis



1) High Speed Cruise at M=0.77 & 35k ft ==> '__'
2) Constant Speed Climb at M=0.51 & 15k ft ==> 'x x'
3) Sustained 'g' Turn at 1.2g's & 20k ft ==> '+ +'
4) Level Accel Run at 30k ft ==> 'o o'
5) Takeoff Performance (Nicolai) ==> '* *'
6) Landing Performance (Nicolai) ==> '|'
7) Maintainability (MMH/FH=25) ==> '_ '

Figure 14
DUMBO Design Solution Space



Customer Attributes	Relative Importance	Wto	L/D	CLmax	W/S	T/W	Cdo	Fuel Capacity	SFC	Landing Gear				
800,000 lb Payload	1	-	-		-	-		-		-				
Cruise .77 Mach	2		+			-	+		+					
Long Range	3	-	+	+	+	+	+	-	+					
Critical Field Length	5	-		+		-				-				
Cargo Volume	8	-					-	-						
Low Operating Cost	9	-	+				-	-	+		+			
Cargo Air Drop Ability	6			-			+							
FAR Part 25 Req.	4		+		-	-				-				
Surface Weight Restr.	7	-			-			-		-				

Table III
DUMBO House of Quality of Customer Attributes

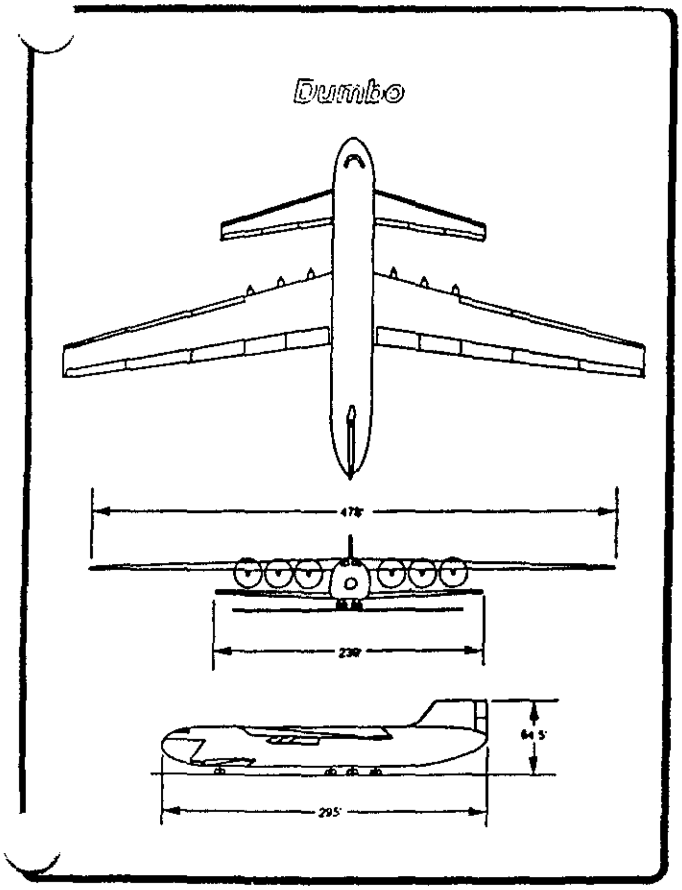


Figure 15
***DUMBO* Aircraft**

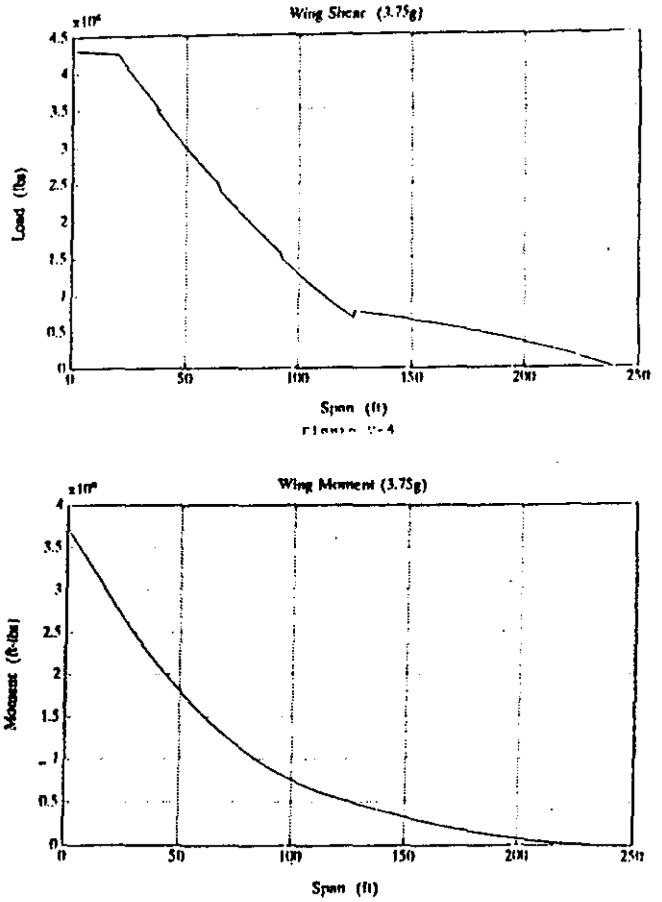


Figure 16
DUMBO Wing Shear and Bending Moment Distributions

	Mach = 0.2 Unaugmented	Mach = 0.2 Augmented	Mach = 0.77 Unaugmented	Mach = 0.77 Augmented
S.P. roots	-.351+.588i	-.9+.7i	-.435+1.179i	-.95+.7i
S.P. damping	.5125	.7894	.3465	.8051
S.P. nat. freq.	.6849	1.1402	1.2568	1.16
L.P. roots	-.012+.1912i	-.012+.19i	-.002+.0608i	-.004+.067i
L.P. damping	.0626	.0626	.0329	.0596
L.P. nat. freq.	.1916	.1916	.0608	.0671

Table IV
DUMBO Longitudinal Stability Characteristics

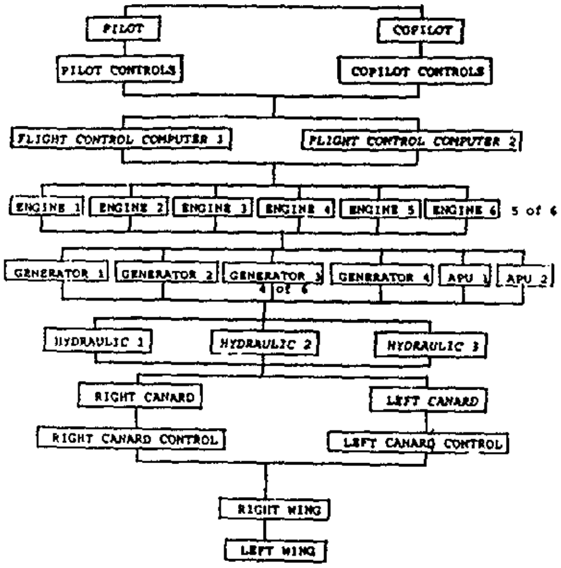


Figure 17
DUMBO Survivability Kill Tree

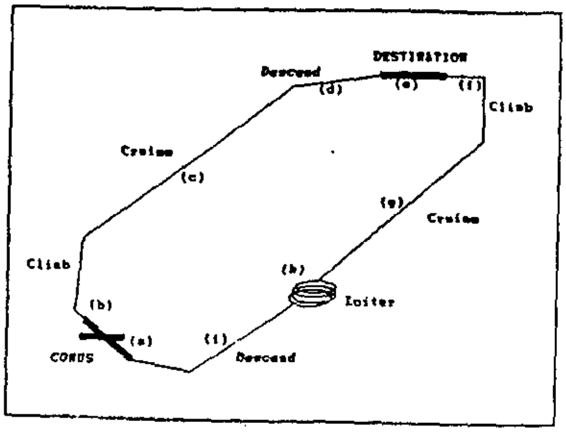


Figure 18
HUGO Mission Profile

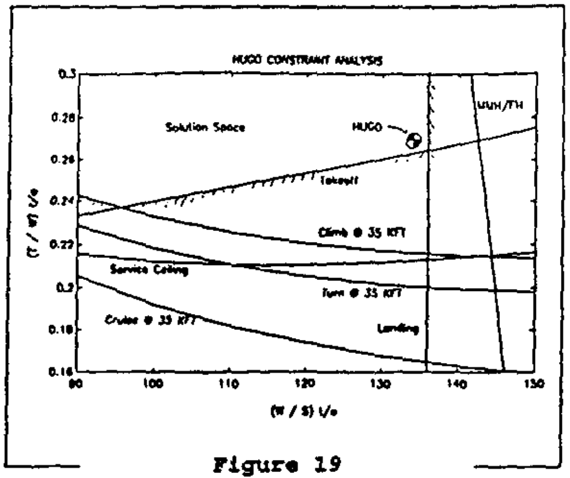


Figure 19
HUGO Design Solution Space

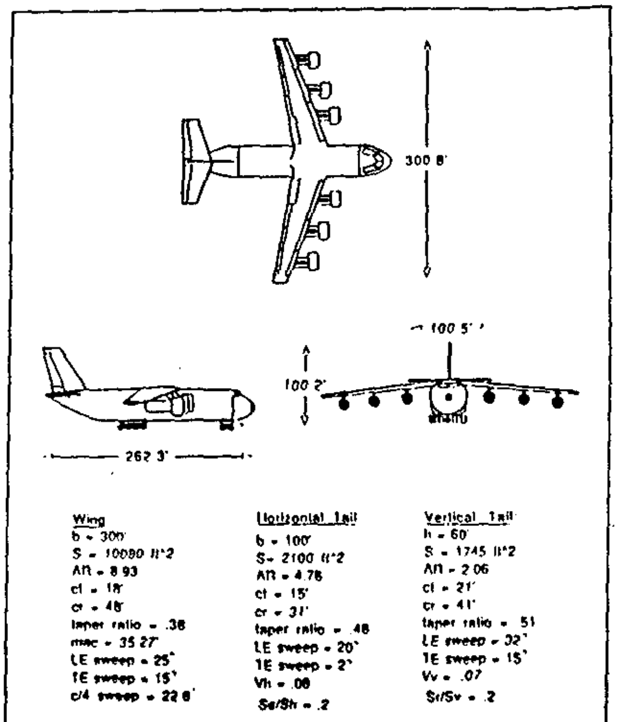
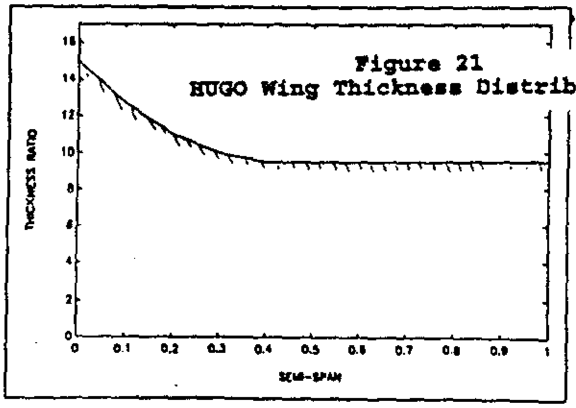


Figure 20
HUGO Aircraft

Figure 21
HUGO Wing Thickness Distribution



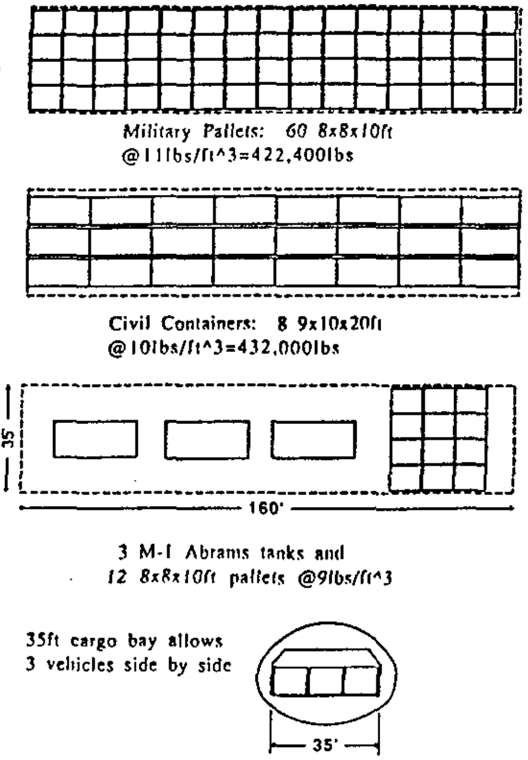


Figure 22
HUGO Cargo Bay Loading Configuration

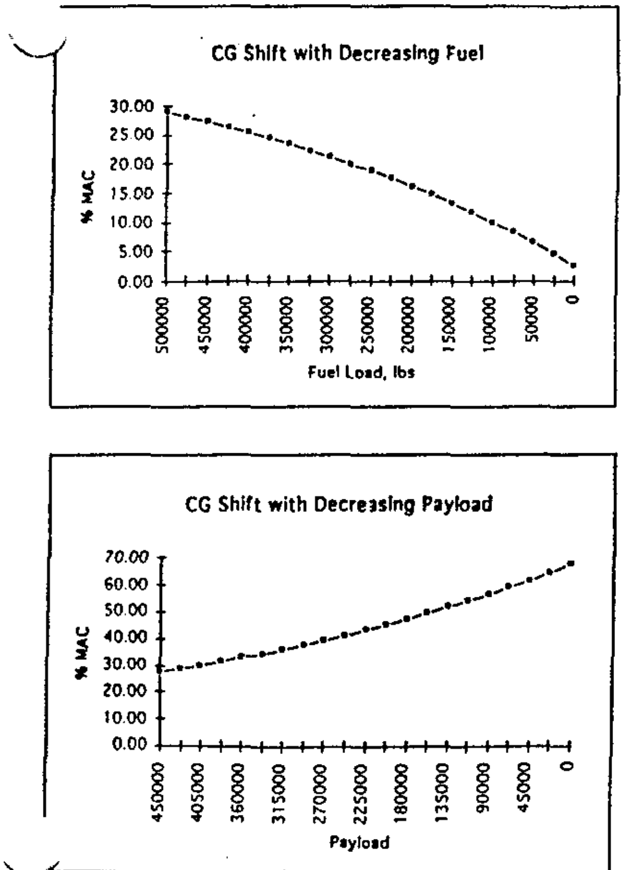


Figure 23
HUGO Center-of-Gravity Shift

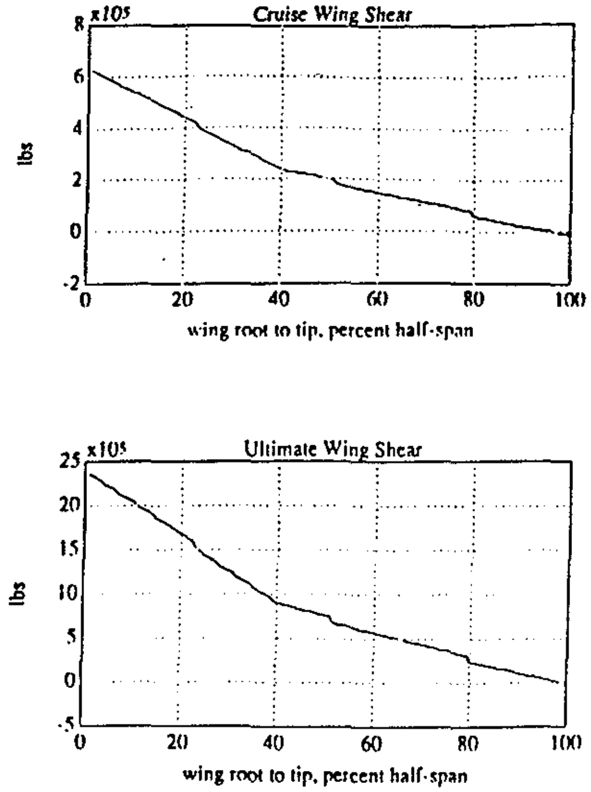


Figure 24
HUGO Wing Shear Distributions

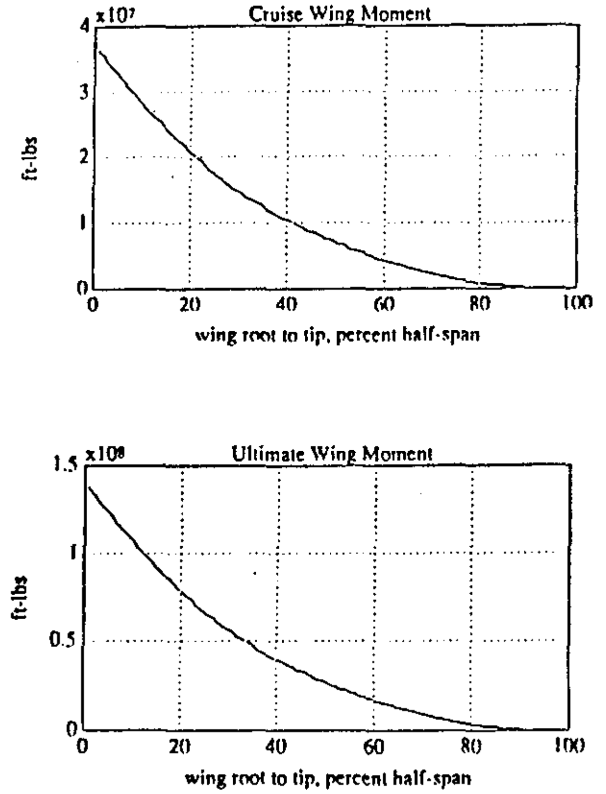


Figure 25
HUGO Wing Bending Moment Distributions

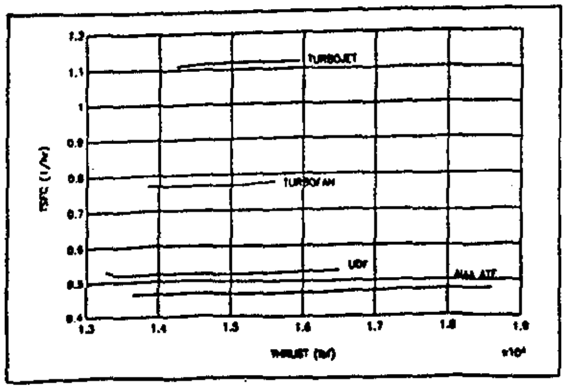


Figure 26
Engine Cycle Trade Study for HUGO

Concept Design	Cruise Time (HRs)	Trip Time (HRs)	MIN # REQ A/C	MIN # Buy	Ave Trips/ A/C	Total # Trips	Total Tons moved
SUBSONIC (331 kips @ M = .6 @ 35 Kft, TSFC=.61)	9.07	22.81	46	58	2.7	125	28,125
SUBSONIC (446 kips @ M = .8 @ 35 Kft, TSFC=.67)	6.72	18.11	37	46	3.5	130	29,250
SUPERSONIC (1419 kips @ M = 2.5 @ 60 Kft, TSFC = 1.0)	2.5	9.67	20	25	6.9	138	31,050

Table V
Effect of HUGO Speed Capability on Payload Delivery Capability

	MACH =.2	MACH = .8	MIL-F-8785C
Short Period Roots	-.401±.226i	-.405±1.051i	Negative
Short Period Damping	.870	.360	.35-1.30
Short Period Natural Frequency	.461	1.126	NA
Phugoid Roots	-.039±.181i	-.009±.069i	Negative
Phugoid Damping	.213	.134	> .04
Phugoid Natural Frequency	.185	.069	NA

Table VII
HUGO Augmented Longitudinal Stability Comparison

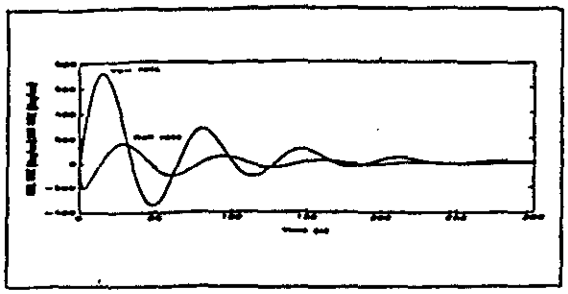


Figure 27
HUGO Augmented Dutch-Roll Response

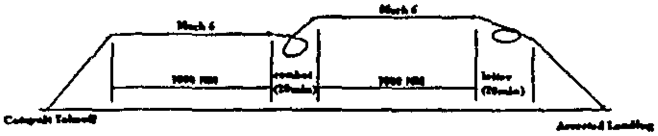


Figure 28
Hypersonic Waverider Mission Profile

	SUBSONIC TWIN FUSELAGE	SUBSONIC SINGLE FUSELAGE	SUPERSONIC LOW AR HIGH SWEEP
Airframe	1280	1067	4889
Development	502	419	2826
Flight Test A/C	2414	2012	10060
Flight Test Operations	236	197	985
Total DT&E	4434	3696	18760
Engine & Avionics	1316	1197	598
Manufacturing	3348	3044	3285
Material	663	603	663
Engineering	1926	1751	1926
Tooling	1905	1732	1905
QA	595	541	595
Total Production	9784	8871	8972
Fuel	261	234	371
Maintenance	25	22	32
Crew	15	15	11
One Year O&M Total	301	272	414
20 Year O&M Total	6020	5420	8280
Total LCC	$ 20,300	$ 18,000	$ 36,000

Table VI
Life Cycle Cost Trade Study for HUGO
(Millions 1993 Dollars)

	MACH = .2	MACH = .8	MIL-F-8785C
Dutch Roll Roots	-.0202±.097	-.0118±.2921	Negative
Dutch Roll Damping	.2041	.0405	Minimum .08
Dutch Roll Natural Frequency	.0988	.2918	
Roll Root	-.8977	-1.223	Negative
Roll Natural Frequency	.898	1.223	
Roll Mode Time Constant	1.114	.818	Maximum of 1.4
Spiral Response Roots	-.0091	-.0439	NA
Spiral Natural Frequency	.0091	.0439	
Minimum Time to Double Amplitude	76	15.8	Minimum of 12

Table VIII
HUGO Augmented Lateral Stability Comparison