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DESIGN STUDY: A GLOBAL RANGE LARGE SUBSONIC MILITARY TRANSPORT

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Abstract

An aircraft design is presented to satisfy the proposal of the American Institute of Aeronautics and Astronautics/General Dynamics Corporation 1992/1993 Undergraduate Team Aircraft Design Competition. This requires that an aircraft, to be built in 2010, must be able to carry 800,000 lb of payload at a maneuver load factor of 2.5g. The primary mission consists of flying 6,500 NM and with full payload, land and offload payload, onload 120,000 lb, and return 6,500 NM all without refueling. Also required is the identification of emerging technologies crucial to the successful completion of the design. The Virginia Polytechnic Institute and State University Aerospace Engineering design team response, the C-28 Juggernaut, is a tri-surface design of a single fuselage of 355 ft length, main wing of 400 ft span, horizontal tail, vertical tail, and an all-moveable canard for trim stability, with a TOGW of 2,681,100 lb. The wheel track and LCN number of the Juggernaut enable it to operate from current military and international class civilian airfields. Four key areas of technology advancement were identified: materials (semicrystalline thermoplastics), aerodynamics (winglets, riblets, hybrid laminar flow control), propulsion (UHBR contrafans), and flight control (fly by light).

Introduction

The C-28 Juggernaut was designed in response to the American Institute of Aeronautics and Astronautics/General Dynamics Corporation Undergraduate Team Aircraft Design Competition, as an advanced solution for a global range transport aircraft for global mobility meeting or exceeding all the 1992/1993 AIAA/GD requirements in the Request For Proposal (RFP)[1].

The following characteristics are required by the RFP. The overall mission requires that the aircraft must be able to carry 800,000 lb of payload at a maneuver load factor of 2.5g. The primary mission consists of flying 6,500 NM without refueling and with full payload, land and offload payload, onload 120,000 lb, and return 6,500 NM without refueling, including all warm-up and taxi/idle times of 60 minutes and 15 minutes of reserve fuel. The secondary mission consists of flying 8,000 to 12,000 NM with 600,000 lb payload, landing and offloading payload, and returning 8,000 to 12,000 NM empty, without refueling. The aircraft's field performance includes an initial airfield critical field length ≤ 10,000 ft at sea level standard day conditions, and a mid point airfield critical field length ≤ 8,000 ft at 4,000 ft elevation and 95° F. Other considerations include meeting all appropriate Mil-Specs and FAR Part 25 regulations, considering the possibility of developing a commercial version, and minimizing both initial and operating costs. A cargo mix of six M1 tanks, three AH-1G attack helicopters, twenty 463L pallets at 10,000 lb each and two hundred passengers was defined. All of the requirements are to be meet by the year 2010 with deployment by 2015.

The design team has employed advanced technologies and has used proven design techniques to create a highly advanced, high capacity, cost effective transport aircraft. The C-28 Juggernaut is an extremely long range, heavy lift cargo aircraft designed to project United States military force overseas in the post 2010 time period, when U.S. bases on foreign soil and prepositioned equipment may not be available. The Juggernaut is an advanced tri-surface, six engine cargo aircraft with its all-flying canard surface positioned forward and above the in-plane wing and low horizontal tail. This layout permits efficient low drag flight over a wide CG range to accommodate a wide spectrum of cargo loadings. The effectiveness of the aircraft has been enhanced and costs have been diminished by focusing on four areas of enabling technologies: aerodynamics, controls, materials, and propulsion.

Composed mainly of advanced polymeric composite materials, it follows a conventional structural layout. Use of these materials and adhesives, in lieu of rivets and other fasteners, allows the TakeOff Gross Weight (TOGW) to be radically reduced from that expected for a conventional aluminum structure. In addition, use of thermoplastic resins allows the Juggernaut airframe to be recycled at the end of its service life, offering a cost savings through ease of maintenance and effective reuse of old airframes.

The six, Ultra High Bypass Ratio (UHBR) contra-rotating turbofan engines, are located below and ahead of the wing leading edge and below the canard induced wakes. The Juggernaut was designed to use existing conventional fossil fuels, and its wheel track is narrow enough to fit on current conventional runways. The 210'x32'x18' cargo bay permits the carriage of all U.S. military inventory helicopters without disassembly, and is loaded and unloaded through the forward and rear ends of the bay to facilitate quick turnarounds.

The main wing utilizes a natural laminar flow airfoil augmented by active laminar flow control on its leading edge to create a low drag boundary layer over a

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large portion of the wing chord length. The flight control surfaces, with the exception of the all-flying canard surface, follow traditional control philosophy with an elevator on the fixed horizontal tail and associated wing control surfaces. The latter are composed of high- and low-speed ailerons, upper surface spoilers/lift dumpers, and double slotted trailing edge flaps. A full span Krueger flap extends to form both a leading edge slot and a bug deflecting leading edge shield. These surfaces are segmented to function with wing structural deflections, and are controlled by an advanced fly-by-light flight control system.

Utilizing high technology, the Juggernaut is an affordable, effective heavy lift transport. It will be able to carry out its mission in the year 2015 and beyond.

Concept Exploration and Evaluation

The design of the Juggernaut began in October 1992 when each member of the design team developed an airplane concept that implemented the RFP mission. Each was evaluated on the basis of TOGW, overall size limitations (e.g., excessive wingspan, wheel track, etc.), range, payload, and operational feasibility.

The original eight concepts fell into three different categories (Figure 1). It was decided to group the best points of each type into a single configuration representative of each concept category. This led to the second generation of configurations, which included a flying wing, a conventional airplane, and a multi-fuselage multi-wing airplane (MFMW).

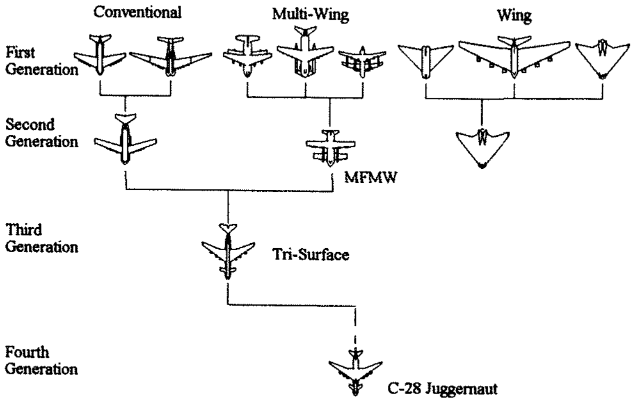

Figure 1 Concept Evolution

Several additional configuration types were studied, including the spanloader, slewed-wing and Wing In Ground Effect (WIGE). Each was rejected for inherent design reasons. The spanloader was abandoned primarily due to cargo loading difficulties. Engine placement on such an aircraft would also be difficult. The slewed-wing was abandoned due to its stability problems. The WIGE concept was abandoned because it was not capable of meeting the RFP requirement of landing at an airfield at a high altitude.

During the course of concept evaluation, a fourth configuration was proposed. This design was based on a tri-surface configuration, evolved from the conventional and multi-fuselage multi-wing designs. Those configurations which warranted further evaluation included the flying wing, multi-fuselage multi-wing, conventional configuration, and the tri-surface. These were compared according to their relative advantages and disadvantages (Table 1).

Table 1 Preliminary Concept Comparison

Aircraft	Advantages	Disadvantages
Flying Wing	Aerodynamically clean Low C_{Do} and high $(L/D)_{max}$ Long range capable	Sensitivity to CG location Buried engines High cost
Conventional	Simplicity Large CG range High span, high aspect ratio Long range capable Low cost	High wing weight Large wing structural deflections
MFMW	Two large wings Canard takes advantage of ground effect at takeoff High aspect ratio Long range capable	High drag due to wetted area Aerodynamic interference Possible asymmetric cargo loading High cost
Tri-Surface	Simplicity High aspect ratio Large CG range Long range capable Low cost	High wing weight Canard control system

One of the driving factors in the final concept selection was a preliminary sizing and cost estimate. As shown in Table 2, the MFMW and flying wing designs were prohibitively expensive. The conventional and tri-surface aircraft had competitive unit costs and showed promise as possible cost effective final configurations.

Table 2 Preliminary Cost Estimates

Aircraft	Unit Cost (1993 U.S. Dollars)	Cost/lb ($/lb)	Operating Cost/hr ($/hr)
Flying Wing	1,570,000,000	343	26,171
Conventional	816,000,000	194	23,522
MFMW	1,085,000,000	246	26,414
Tri-Surface	919,000,000	205	25,688

TOGW was chosen as the figure of merit for the basis of comparison as a Boeing study[2] demonstrated that it is only slightly affected by variations in other figures of merit and provides the best overall method of comparison. Table 3 shows a comparison of aircraft weight based on Roskam's[3] sizing method.

Table 3 Preliminary Sizing Data

Aircraft	TOGW (lb)
Flying Wing	4,570,000
Conventional	4,200,000
MFMW	4,400,000
Tri-Surface	4,480,000

Table 4 shows qualitative results of preliminary cost, performance, and aerodynamic comparisons of the four concepts. The MFMW concept was eliminated as it fell short of desired selection criteria in each of the three areas. Additionally, the conventional design lacked aerodynamic efficiency when compared to the flying wing and tri-surface, and was also abandoned.

Table 4 Preliminary Feasibility Comparison

	Flying Wing	Conventional	MFMW	Tri-Surface
Cost	High	Moderate	High	Moderate
TOGW	High	Moderate	Moderate	Moderate
Drag	Low	High	High	Moderate

The final decision to develop the tri-surface and not the flying wing was made on a basis of cost and operational feasibility. Both, it seemed, were capable of completing the mission successfully, since each was capable of meeting the range and payload requirements. However, the excessive production costs and loading limitations placed on the use of a flying wing as a cargo transport were deemed unacceptable. The decision was made to develop the C-28 Juggernaut as a tri-surface aircraft.

The finalized C-28 Juggernaut inboard profile design is presented in Figure 2. The fuselage was shaped so the pilot would have maximum visibility over the Juggernaut's nose and so the high position of the canard would limit the effects of downwash on the main wing. The main wing span is 400 ft. and is highly tapered with leading and trailing edge sweep in order to allow a high cruise Mach number. The all-flying canard is mounted high on a single through-fuselage pivoting axle. The entire exposed canard surface is moveable and has no inset control surfaces. The functions of the canard are trimming of the Juggernaut in flight, adding a pitching moment to ease takeoff rotation, and helping initiate maneuver rates. The empennage consists of a horizontal tail and a large vertical tail. The horizontal tail has standard elevators as primary pitch control surfaces. The vertical tail and rudder are designed to provide adequate control if one or more engines become inoperative.

The Juggernaut is supported by 96 main landing gear tires and 4 nose gear tires. The landing gear is capable of kneeling, for easy onloading and offloading of cargo, steering, ground maneuverability, and crosswind landings. The maximum overall load classification number of the Juggernaut at TOGW is 81.

Enclosing a total volume of over 120,000 cubic feet, the cargo bay of the C-28 Juggernaut has been designed to meet a recommended payload of six M-1 tanks, three AH-1G helicopters, and twenty 463L pallets. Two hundred the Juggernaut, as per the RFP. Though the recommended passengers are accommodated in the passenger section of payload mix exceeds the payload weight requirement stated by the RFP, the cargo bay was sized to the footprint (area) of the mix. This in turn will provide adequate space for any cargo mix.

The Juggernaut's cargo bay is accessible through two cargo bay doors located at either end of the aircraft, and eight exit doors (four on each side). The cargo bay door at the nose of the Juggernaut is of the visor type and swings up in front of the cockpit. The cargo bay door at the aft section is split, like that of the C-5 and C-17, so that one section lowers itself to form a ramp for cargo loading, and the other folds upward. Each cargo ramp forms a 14° angle with the static kneeling ground line to ease loading and unloading of cargo. The forward ramp is stowed in a vertical position and the aft ramp forms an integral part of the aft door.

The Juggernaut is powered by six UHBR contrafan engines mounted under the main wing in laminar flow cowlings. The engines are mounted so that there is more than seven feet between the underside of the engine cowling and the static kneeling ground line, providing adequate clearance for most ground vehicles and engine clearance at maximum landing load factor of -1.9g.

Because of the extreme duration of the mission specified by the RFP (approximately 29 hours round trip), the passenger section of the Juggernaut was designed to provide extreme comfort to its passengers, assuring that any troops will be battle-ready upon reaching their destination. The section is 105 ft. in length, 28.5 ft. wide, and 11 ft. tall, providing accommodations for 205 passengers and 5 attendants in three aisle, twelve-abreast seating (3x4). The aft-facing seats are sized and positioned to provide first-class comfort with a 40 inch pitch, and are arranged around three longitudinal aisles for ease of evacuation in the case of an emergency. All seats are fully reclinable to provide rest and sleep capability.

Access to the passenger area is by a staircase from the forward portion of the cargo bay, or directly into the section via jetway if one is available. A spiral staircase extends upward from the section to provide access to the cockpit, which is located above the passenger compartment.

The section has eight emergency exit doors, four on each side, any one of which may be used for normal passenger loading. Each door measures three feet in width by seven feet in height, exceeding the FAA Type I exit requirements. Four transverse aisles provide a clear route through which these doors may be accessed. The crew, consisting of a pilot, copilot, loadmaster, and five attendants, along with reserves for each position, have their own quarters forward of the area where passengers are seated.

The Juggernaut is designed for use by both military and civilian agencies. In addition to its military cargo mission, the Juggernaut's field performance and ability to operate from any conventional international airport make it a viable long range civilian cargo handling alternative. The Juggernaut can be modified to carry over 1,200 passengers (coach seating) by the addition of an interior plug inserted into the eighteen foot high, fully pressurized cargo bay. The cargo bay height would be divided into two sections, one ten feet high, the other seven feet high. The plug would be slid onto rails and occupy the upper ten feet of cargo bay height. The remaining seven feet of height encloses a 210'x32'x7' fully pressurized cargo bay for assorted cargo. The entire passenger section would be self-contained, with required interior seating and facilities installed to meet customer specifications. The civilian version would also have extra exit doors added to accommodate the extra passengers.

Performance

The calculation of performance characteristics for this type of aircraft necessitates the use of computer analysis tools. The first used by the design team for analysis was a simple sizing program based mainly on the Breguet range equations and additional data as presented by Roskam[3]. Later, to generate a detailed mission analysis, a program by Sidney Powers[4] was used. Table 5 shows that the Juggernaut meets or exceeds all standards put forward in the RFP.

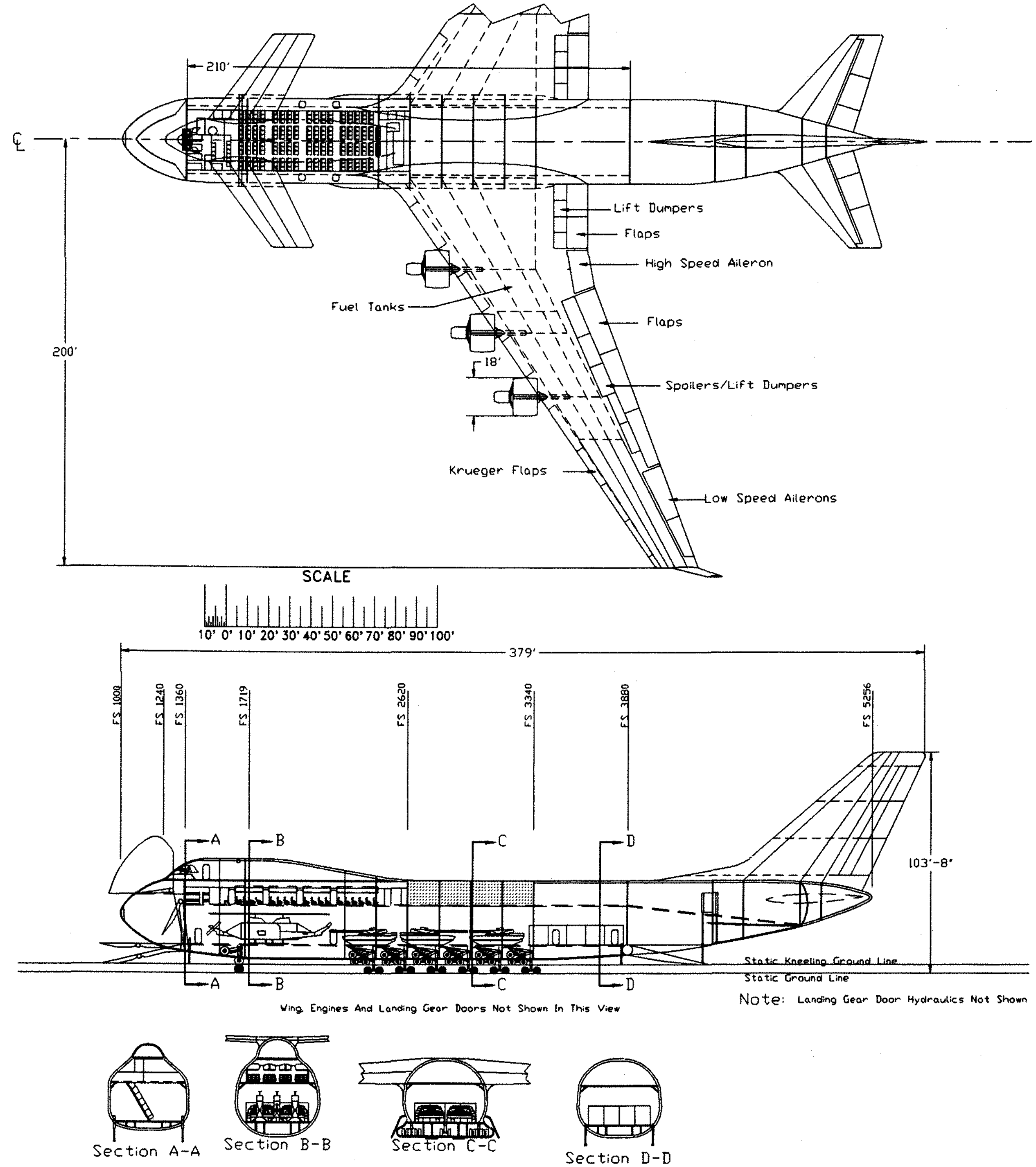

Figure 2 Inboard Profile C-28 Juggernaut

The primary and secondary mission profiles are fixed by the RFP. The aircraft climbs during the outbound cruise legs for both missions in order to maximize specific range. The return cruise legs are both flown at 45,000 ft. which was determined to be the maximum altitude at which pressurization could be maintained. The Juggernaut cruises at a Mach number of 0.8, giving a total mission time of 28.9 hr for the primary mission and 35.4 hr for the secondary mission.

Table 5 RFP Performance Requirements

	RFP	Juggernaut
Primary Mission Radius	6,500 NM	6,500 NM
Secondary Mission Radius	8,000-12,000 NM	8,000 NM
Initial Takeoff Distance	≤10,000 ft	9,324 ft
Midpoint Takeoff Distance	≤8,000 ft	2,768 ft
Midpoint Landing Distance	≤8,000 ft	6,716 ft
Final Landing Distance	≤10,000 ft	2,422 ft

A design point plot (Fig. 3) was made to determine the best thrust loading and wing loading conditions following the methods in reference 5. Inadmissible conditions occur on the lower side of each line except for the landing constraint, where the right side is inadmissible. The mission analysis yields the weights shown in Table 6. These figures include 15 minutes of reserve fuel and approximately 50,000 lb of trapped fuel.

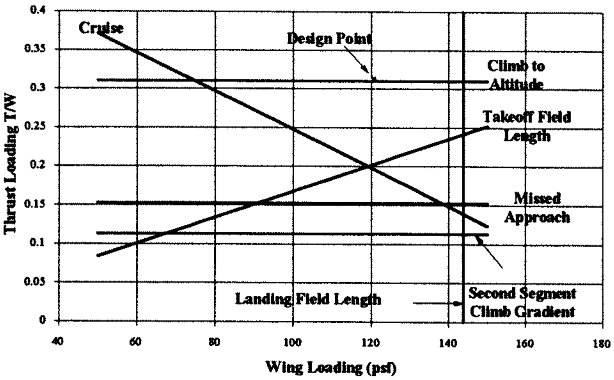

Figure 3 Design Point Graph

Table 6 Mission Weights (lb)

	Initial Takeoff	Midpoint Landing	Midpoint Takeoff	Final Landing
Primary Mission	2,681,100	1,929,764	1,226,447	858,451
Secondary Mission	2,671,100	1,789,699	1,166,395	735,196

Using a sizing program based on statistical methods presented by Roskam[3], the TOGW of the selected concept was predicted. The TOGW of the aircraft is most sensitive to changes in Thrust Specific Fuel Consumption (TSFC) and primary mission radius.

Field performance was determined using FAR Part 25 rules[5]. Both the initial and midpoint takeoff requirements specified in the RFP are met. Landing distances are also well within requirements. The Juggernaut was also designed to meet the second segment climb gradient with two engines out because it has more engines to fail than any other aircraft under FAR rules[6].

Aerodynamics

The NLF(1)-0414F was chosen as the airfoil section for the main wing. This section was designed for natural laminar flow and a high *L/D* ratio at speeds on the order of M=0.4. Experimental data for these conditions were found in reference 7. An inviscid transonic code, GRUMFOIL[8], was used to determine the properties of the section at the Juggernaut cruise conditions. Figure 4 is a plot of the pressure distribution of the NLF section at the Juggernaut's equivalent 2-D section and experimental results from reference 7. From this, it can be seen that the laminar flow properties of this section are retained at higher speeds.

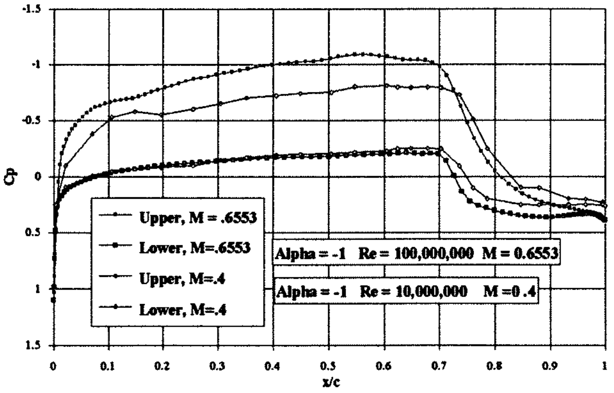

Figure 4 Pressure Distribution Over NLF Airfoil Section

Airfoil section selection was also performed for the other control surfaces. The resulting sections chosen are the NLF(1)-0414F at an incidence angle of 2° for the main wing, the 63-009 for the horizontal and vertical tail (-2° incidence angle for horizontal tail), and the 65-210 for the canard.

Estimates of C_{Do} for the Juggernaut were performed using FRICTION[9]. Results at takeoff and landing conditions as well as cruise are given in Table 7.

Table 7 C_{Do}

Mach #	Altitude (ft)	C_{Do}
0.1	0	0.01341
0.8	35,000	0.0111

Low C_{Do} numbers were calculated without any drag reduction schemes employed due to the decrease in skin friction coefficient with increasing Reynolds number (Re = 100 million for the Juggernaut cruise condition). *L/D* values were also calculated for the same conditions. $(L/D)_{max}$ of 21.4 occurs at the average cruise C_L of 0.55.

Several methods of reducing drag were investigated and included in the aircraft for later experimental verification. Hybrid laminar flow, riblets and winglets were studied. Theoretical skin friction drag reductions of 10 to

20% are expected using hybrid laminar flow[10,11], an estimated 4 to 8% turbulent skin friction drag reduction could be achieved with riblets, and an induced drag reduction of 1.5 to 2.5% has been shown on high aspect ratio wings using winglets.

As the true efficiencies of these devices can only be assessed through wind tunnel and flight testing, the drag reducing effects of these devices were not used to calculate the aerodynamic properties of the aircraft. A separate study was conducted using the FRICTION program to determine the theoretical drag reductions possible using 40% natural laminar flow on the wing and a turbulent skin friction reduction of 6% from use of riblets. The results at cruise are tabulated in Table 8.

Table 8 FRICTION Drag Results

No Drag Reduction Schemes	Hybrid NLF		Riblets		Combined
C_{Do}	C_{Do}	% Change	C_{Do}	% Change	C_{Do}
0.0111	0.00914	17.7	0.0110	1	0.00913

Propulsion

An engine concept was defined assuming the use of advanced improvements in technology corresponding to what may be available for early twenty-first century engine design application. For long-range subsonic transports, high-bypass ratio turbofan engines are the design of choice. The required engine has a bypass ratio of 20 and an overall pressure ratio of 100, as noted by the AIAA engine data[12]. Turbine entry temperature will be as high as possible, in excess of 2200K, for a substantial reduction in TSFC as well as increased specific thrust, resulting in a smaller engine core design. The contrafan engine concept will be able to meet these requirements. The contrafan is projected to yield a 25% reduction in TSFC relative to today's commercial turbofan engine. An engine comparison chart is presented in Table 9.

Table 9 Engine Comparison Chart

	RB211-524D4	TRENT-884	Contrafan Engine Concept
OPR	33	35	100
Bypass Ratio	4.3	5.1	20
Thrust Rating	53,000 lb st.	86,500 lb st.	150,000 lb st.
At Cruise Conditions:	▨	▨	▨
Mach	0.85	0.83	0.80
Altitude	35,000 ft	35,000 ft	45,000 ft
TSFC (lbm/lbf-hr)	0.617	0.557	0.46
Thrust	11,230 lb	16,190 lb	26,550 lb
Bare Engine Weight	9,874 lb	9,855 lb	21,961 lb

The data from the AIAA engine deck was scaled in order to meet the takeoff and cruise thrust requirements of the Juggernaut. The engines were sized for cruise at Mach 0.8 at 45,000 ft for an uninstalled TSFC rating of 0.46 lb/lbf-hr as provided by the engine deck. The installed thrust requirement is 26,550 lb per engine at aircraft cruise. The contrafan could achieve a certification thrust rating of 150,000 lb, making it capable of producing the required takeoff thrust per engine of 138,600 lb.

For all aircraft performance calculations, an installed TSFC rating of 2% above the values provided by the AIAA engine deck was used. This TSFC penalty was arrived at as a result of the elimination of engine bleed air requirements for the provision of aircraft services.

Stability and Control

The tri-surface configuration of the Juggernaut makes it ideally suited for use as a transport due to its acceptance of large center-of-gravity excursions and because it allows the aircraft to fly at maximum efficiency for almost any cargo loading. In addition, its high wing and large vertical tail give the Juggernaut excellent lateral/directional characteristics, both at cruise and at extremely low speed. The Juggernaut meets or exceeds all applicable military specifications[13] for flight control and handling qualities for all flight regimes which it is expected to encounter. The Juggernaut is not only capable of completing its prescribed mission, but it is capable of doing it safely even in the most adverse conditions.

Figure 5 shows data generated using a linear optimization trim solution[14], which yields minimum trim drag for tri-surface airplanes. This graph was created using the geometry of the Juggernaut while neglecting flow interference effects.

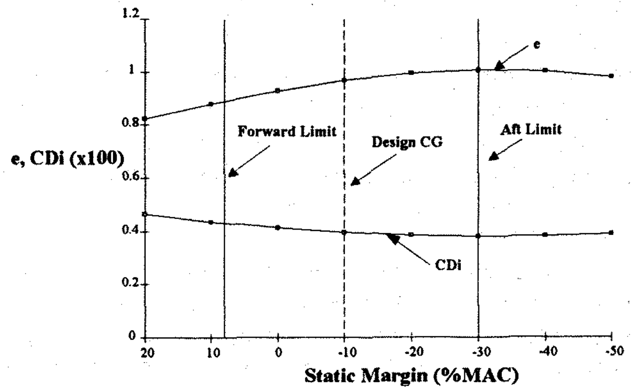

Figure 5 Span Efficiency and Drag vs. Static Margin

Figure 5 shows that the tri-surface configuration is affected very little by large movements in aircraft CG. The Oswald efficiency factor remains near 1, and the induced drag coefficient at cruise ($M = 0.8$, $C_L = 0.55$) remains near 0.0040 across a static margin change of almost 50 percent mean aerodynamic chord. This represents a change in CG location of almost 30 feet within the Juggernaut, or roughly the length of one of the main battle tanks it carries. This relationship demonstrates that, given enough control power, a tri-surface configuration can fly efficiently with *any* loading.

Due to the use of very lightweight materials in construction of the Juggernaut, the empty weight of the airplane is actually less than the weight of the payload it carries. This means that to maintain a large degree of static instability, the cargo would have to be centered aft of the aerodynamic center of the aircraft. Since the geometry of the airplane does not allow this, a compromise between efficiency and practical operation was reached.

The design static margin, for which the sizes of the canard and horizontal tail were chosen, is -10%. Additionally, a design CG range was established which placed the stability limits at 30% unstable and 8% stable.

The Juggernaut's longitudinal control system consists of an all-moving canard with 2,750 ft^2 of planform area and a low, fuselage mounted horizontal tail with 3,000 ft^2 of area. The canard is primarily used to trim the Juggernaut, and is not a primary control surface. The horizontal tail is responsible for primary pitch control, utilizing a standard elevator. All control surfaces are irreversibly connected to pilot input through an automatic flight control system.

The CG limits of the Juggernaut were selected on the basis of available control power. The forward limit is set by the requirement to rotate for takeoff at an altitude of 4,000 ft, the midpoint critical altitude prescribed by the RFP. The aft CG limit is set such that the feedback gain of elevator input per change in angle of attack (K_α) does not exceed 5 deg/deg.

Because the Juggernaut is longitudinally unstable, it requires control augmentation to satisfy the military specifications for open loop flight dynamics. While it is inherently well damped in phugoid oscillations, the Juggernaut employs both pitch rate (K_q) and angle of attack (K_α) feedback to generate acceptable short-period behavior. The Juggernaut exhibits Level 1 longitudinal flying qualities throughout its flight envelope, and behavior in category B and C maneuvers satisfies all minimum and maximum requirements for Level 1 handling stipulated by MIL-F-8785C[13].

The lateral/directional control system consists of a large vertical tail (3,100 ft^2) with a standard double-hinge-line rudder. The aircraft employs inboard high-speed ailerons and outboard low-speed ailerons for primary roll control, and outboard spoilers for additional lateral control power. The main wing has built-in anhedral to diminish the inherent stability in high wing aircraft such as the Juggernaut, thereby enhancing roll characteristics. The driving factor for the design of lateral/directional stability in the Juggernaut is the requirement that directional control be maintained in case of an inoperative engine, resulting in an asymmetric thrust configuration. These parameters were examined at the most critical flight condition: fully loaded, with an aft CG, flying at 150 mph at 4,000 ft., chosen to simulate landing at the midpoint field. As a result of this analysis, it was determined that the primary driver for rudder control power on the Juggernaut is the requirement to maintain controlled flight when the two most critical engines are simultaneously inoperative. Discussions with personnel at the Flight and Stability and Control Branch of the Flight Systems Division of the U.S. Air Force[15] have revealed that a safe return to landing must be executable in the event that two engines become inoperative. Though the aircraft would be statically stable with a much smaller vertical tail, the large thrust of the Juggernaut's advanced engines and the large wingspan combine to form such a large yawing moment that the tail size must be larger than that required for static stability. As designed, 20° of rudder deflection is required if one engine is inoperative, and 35° is needed if the two outboard engines on the same side of the aircraft become simultaneously inoperative. Both of these deflections are acceptable, since a double-hinge-line rudder is used.

Time-to-bank analyses were also performed to examine the adequacy of the Juggernaut's roll control power. The Juggernaut is capable of meeting Level 1 roll requirements through a bank angle change of 30°.

While the Juggernaut was designed to be statically stable in the lateral/directional sense, it does exhibit some inherent dynamic behavior in the dutch roll and spiral modes which require the use of the stability augmentation system to improve. By using roll- and yaw-dampers, the Juggernaut is able to compensate for its inherent dynamic instability. Using varying amounts of feedback, the Juggernaut exhibits Level 1 lateral/directional flying qualities throughout its flight envelope, for both category B and C maneuvers as compared to MIL-F-8785C requirements[13].

Materials

Determination of materials to be used in aircraft construction is the single most important task towards making an aircraft of this size possible. The correct material selection can lower the TOGW of an airplane significantly. Advanced composite construction can do more than just reduce the weight of an aircraft. Manufacturing cost and maintenance demands can be reduced by changing from a conventional aluminum surface to a composite one. These composites resist fatigue, may be easily fastened with adhesives, and reduce the number of routine checks required for safe operation of the aircraft[16].

The use of composites also help to reduce the impact of the Juggernaut on the environment. Thermoplastics have an almost infinite operational life because they can be recycled and reshaped. This means that at the end of the Juggernaut's service life, the majority of the parts can be reused or recycled. Thermoplastics such as ITX also do not emit toxic fumes during fabrication. Due to its light weight, the Juggernaut consumes less fuel and causes less pollution. Highly toxic substances such as beryllium, and systems such as nuclear power, were not considered for this aircraft in order to reduce the environmental impact.

The primary structure of the Juggernaut will be constructed of high performance graphite fiber reinforced semicrystalline thermoplastic in the form of a honeycomb sandwich. These polymeric composites, such as ICI IM8/ITX, are strong in longitudinal tension and compression, but somewhat fragile in shear. The frames, spars, longerons, bulkheads, and the majority of the skin are made of this material. The honeycomb sandwich structure is designed to transfer torsion and shear into tension and compression in the system.

The nose, nosecone radome, doors, door frames, floor supports, upper deck flooring, and other locations where impact resistance is essential are fitted with KEVLAR thermoplastic. KEVLAR/high performance graphite/thermoplastic hybrid is used for control surfaces. Due to its ductility, low density, and strong compressive strength, it was chosen to be employed in structural areas that have to support a great deal of compressive forces, and areas where ductility is essential.

Aluminum-lithium is used for the cargo deck floor. Aluminum-lithium's most important feature is the maintenance of its structural integrity when it is lightly scratched. Therefore, its use will reduce the frequency of required replacement due to wear.

Titanium superalloy RS-140, which is extremely impact resistant, is used for the landing gear, the leading edges of the wing and empennage.

Silicon carbide/ceramic composite and high temperature titanium composite are the primary materials for engine components due to their high strength and resistance to high temperatures.

The Juggernaut's surface will be coated with a silicone sealant to combat moisture absorption and to protect the thermoplastic from absorbing radiated heat at high altitudes. Nickel-coated graphite fibers are embedded into critical areas of the fuselage to provide electric shielding of electronic components.

Adhesives are used extensively in the Juggernaut. Thermoplastics such as the ITX may function both as a matrix to hold certain fibers and as an adhesive to glue panels together. Adhesives allow for the elimination of bolts and rivets, resulting in a 4% structural weight savings[17].

Structures

A description of the weight considerations of an aircraft as its size is increased is given by the Square-Cube Law[18]. This law states that as the linear dimensions of the craft are scaled up by a certain factor φ, the wing area will increase by φ^2 and the structural weight will grow by φ^3, assuming stress levels, material properties, and wing loading are held constant. Since lift is a function of wing area, the structural weight will eventually equal the available lift, and there will be no room for useful load. The limitations predicted by the Square-Cube Law can be averted by designing for higher wing loadings and using lighter, stronger materials. The design team has circumvented the limitations of the Square-Cube Law by the use of advanced materials. The structure is designed for the flight envelope shown in Figure 6. V_S the minimum speed with power off, is assumed to be 94% of the 1g stalling speed of 128 kts[18].

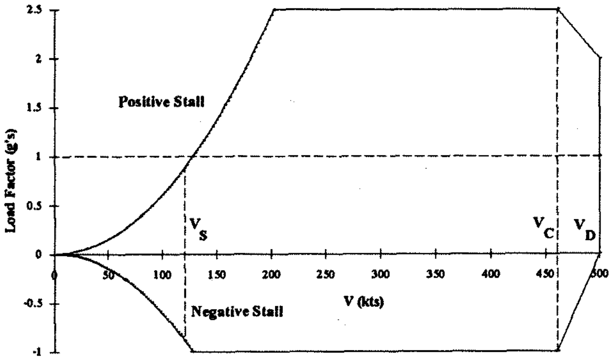

Figure 6 V-n Diagram

The wings of the Juggernaut are of the cantilever type. A good measure of the structural soundness of cantilever wings is the cantilever ratio. According to historical findings, this ratio should be below 25 to avoid structural failure of the wings[18]. The cantilever ratio of the Juggernaut is 21, which is a low enough value to ensure that no failures will take place during flight within the flight envelope and landing impact.

The wing structure was idealized by using an unswept, tapered box beam. In this model the beam was loaded with structure weight, engine weight, fuel weight, and lift at a certain load factor. Wing tip deflection was calculated by numerically integrating the following formula from Beer and Johnston[19]:

$$\delta_T = \int_0^{\frac{b/2}{\cos \Lambda_{0.5}}} \frac{zM(z)}{EI(z)} dz$$

The resulting deflections are shown in Table 10 for the aircraft at maximum TOGW for the in-flight and droop deflections, and at midpoint landing weight for the landing impact deflection.

Table 10 Wingtip Deflections

Flight Condition	Load Factor (*n*)	Deflection (ft)
Max. Maneuver Lift	2.5	17.1
Cruise	1	6.8
Static Wing Droop	0	-11.1
Landing Impact at midpt. landing weight	-1.9	-10.0

The fuel volume needed to perform the primary mission is 24,710 cubic ft.. This volume is accommodated in integral fuel tanks, located in the outboard wing box from the root to a spanwise position of 120 ft., corresponding to the outboard engine. The graphite structure is insulated from the fuel by a silicone coating.

The cylindrical axle holding the canard to the fuselage was sized at n=2.5 at maximum TOGW assuming the canard would take 4.5% of the total lift. The axle is made of titanium and has an outer diameter of 18 inches and an inner diameter of 13.6 inches.

The fuselage has thirteen major bulkheads and 79 frames located at four foot intervals. The bulkheads and frames were sized using the methods of Torenbeek[18] for a pressure difference encountered at an altitude of 45,000 ft., and are constructed of graphite honeycomb semicrystalline thermoplastic. The lateral width of the bulkheads is one foot and the width of the frames is six inches.

The fuselage skin is 0.5 inches thick and is built in an integral skin/stringer structure, with stringers spaced at 30 inches. The skin thickness was sized based on a hoop stress analysis.

Weights

After determining which components and materials were to be used for construction of the Juggernaut, the aircraft CG location and total structural weight were estimated.

The estimates of weight followed the rules outlined by MIL-STD-1374A[20]. To estimate the weight of the entire aircraft, the weight and the CG for each component in the aircraft were evaluated and the component location identified. The methods of both Roskam[21] and Torenbeek[18] were used to generate component weight estimates. The two results were then averaged to yield a preliminary weight estimate. These weights were estimated using today's technology with the assumption that aluminum and steel alloys are the primary construction materials. The TOGW estimated using these methods was 4,000,000 lb.. To yield an accurate estimate for the Juggernaut, a material efficiency factor (***K***) was used to multiply the values obtained with Torenbeek's and Roskam's empirical equations. The material efficiency equation was developed by the USAF. Young's modulus, Poisson's ratio and density are considered to obtain ***K*** factors[22]. The relation is:

$$K = \frac{\left[E/\left(1-\upsilon^2\right)\right]^{0.33}}{\rho}$$

A weight reduction program was carried out throughout the entire aircraft. The weights of secondary structures such as wing skins, frames, and longerons were reduced by about fifty percent. This was achieved by comparing aluminum's technology factor with that of the graphite polymer to be used. Instead of steel alloys, high performance graphite/semicrystalline thermoplastic honeycomb sandwich will be used for bulkhead construction because it is much more structurally efficient. This saves 70% of primary structural weight. After all weight estimates had been made, the aircraft's empty weight was estimated to be 671,100 lb and the fuel weight was estimated at 1,210,000 lb. Adding the 800,000 lb of payload, the TOGW was estimated to be 2,681,100 lb (Table 11). It is important to note that while the use of adhesives will possibly save 4% of structural weight, this savings was not considered in the weight estimate of the Juggernaut.

The advanced materials used in the Juggernaut result in a 30% structural weight savings over the use of conventional materials. By studying the overall structural weight as a function of specific material usage the effective structural technology factor of the overall aircraft may be determined empirically. The structural technology factor for transport planes is determined by the following equation[23]:

$$W_{empty} = 0.911(K_s)TOGW^{0.947}$$

The Juggernaut has a structural technology factor of 0.60. The C-5B has a technology factor of 0.75. This low factor is achieved with the use of advanced materials, and because as the payload increases, the factor tends to decrease.

Table 11 Overall Weights

	Primary Mission		Secondary Mission	
	Initial Estimate	Actual Weight	Initial Estimate	Actual Weight
Wfuel(lb)	2,260,000	1,210,000	2,350,000	1,400,000
Payload(lb)	800,000	800,000	600,000	600,000
Wempty(lb)	955,956	671,100	955,956	671,100
TOGW (lb)	4,015,956	2,681,100	3,905,956	2,671,100

Systems

Nine main system areas will be required for this aircraft. They are: the avionics, flight control, electrical, environmental control, hydraulic, fuel, anti-icing/defog, escape/fire suppression/lighting, and a defense system.

Components from contemporary 2010 aircraft will be adapted for use in this aircraft to save time and money. As such, present day comparator aircraft have been used extensively to assess the system requirements for the Juggernaut.

Program Costs

Careful consideration has been given to affordability risk and technology risk in the C-28 Juggernaut design. By focusing on enabling technologies for which research already exists, and by relying upon existing system components, cost and risk have been reduced.

To estimate these costs, several assumptions regarding the aircraft and its intended use must be made. The most important assumptions are discussed below.

Production rate: 0.7143/month
Quantity test aircraft: 5 (3 flight test, 2 ground test)
Quantity built: 80
Service life: 30 years
Flight hours (per annum): 1,200 hrs
Peace time loss rate: 0.1/yr
Profit from RDTE and ACQ stages: 10%
Cost to finance RDTE and ACQ stages: 15%

A production run of 80 aircraft is recommended to minimize unit cost and maximize mission carrying potential. Initial estimates of the recommended number of aircraft required were determined by observing the trend of decreasing cost with increasing number of aircraft built. This analysis demonstrated that aircraft unit costs under $700 million apiece could be achieved after the production of 75 aircraft. This number was used for all the initial cost estimates.

Life cycle cost (LCC) estimates were calculated from Roskam's[24] statistical methods. As defined by Roskam, the total life cycle of an aircraft program has four phases: research, development, testing and evaluation (RDTE); acquisition (ACQ); operations (OPR); and disposal (DISP).

The results of the Juggernaut cost estimate are summarized below. Comparison parameters such as aircraft unit cost, cost per pound TOGW, and operating cost per hour reveal the soundness of the design strategy, and the affordability of the overall concept (Table 12).

LCC Estimate for C-28 Juggernaut (1993 U.S. Dollars)
Unit cost: $591 million
Projected operating cost/hr: $14,800
LCC Factors:
RDTE Phase: $11 billion
ACQ Phase: $36.3 billion
Military OPR Phase: $38.3 billion
DISP Phase: $865 million
LCC of C-28 Juggernaut Program: $86.5 billion

Table 12 Production Cost per Pound

	Juggernaut	C-17	C-5A
Cost/lb (TOGW)	$220.50	$306.90	$187.50

Reliance upon existing research and conventional practices has made the Juggernaut an affordable airplane. With its relatively high cost effectiveness it can carry out its mission well into the twenty-first century.

Manufacturing

Several different methods will be used to manufacture the Juggernaut. Pultrusion is a proven and rapid method of producing components of constant cross section and will be used to produce keels, longerons and stringers. Automated lay-up will be used to manufacture wing skins, frames, passenger/flight deck flooring, spars, engine nacelles, and the outer panels of bulkheads. Matched die molding will be used to produce all metal components including titanium leading edges, landing gear components, aluminum-lithium cargo decking, and wing ribs.

The wing skin is fabricated in several pieces using automated lay-up so that a large autoclave will not be required. The parts will then be joined together to form the wing surface. Since the matrix for the wing skin is a thermoplastic material, the matrix itself will serve as the adhesive to glue parts together.

The spars will be manufactured in several steps. Two C-channels will be fabricated by lay-up and then joined back to back to form an I-beam, completing the spar shape. The C-channels will be adhered in overlapping sections, in a staggered fashion, so that joints and resin-rich sections will not coincide in the final I-beam. Several I-beam spars will be butted end to end to create the full-length spar. Cross patches of graphite reinforced thermoplastic will be added to the joints to strengthen them. The canard and tail surfaces will be manufactured using the same method.

Filament winding is used to fabricate the nose section, tail section, and fuselage skin. The fuselage skin will be constructed in three sections. Each section will be filament wound to a minimal thickness adequate to maintain the fuselage shape. This cylindrical fuselage shape will then be cut into a left and right half.

Three jigs are set up to hold the bulkheads in position for assembly. Fuselage frames and stringers are adhered to the skin shells. The flight deck and passenger deck are also added at this time to the front section to aid in preliminary systems installation. The two halves of each section are then joined, adhered with their own thermoplastic matrix and then filament wound again to give required structural support.

Main fuselage keels and longerons are attached later. Cross patches of graphite reinforced thermoplastic will cover the joints to ensure structural integrity. Once the fuselage structure is joined, the cargo bay floor and major systems are added. The main and nose landing gear are also added during this phase of construction, as are the nose visor and back loading ramp doors.

Silicone protectant is applied to all subassemblies including spars, longerons, bulkheads, shells and control surfaces before assembly to ensure uniform coverage.

The final assembly station is where the wings, horizontal tail and canard are added. Engines are mounted and avionics are installed and checked for proper function.

The vertical tail and final systems installation and tests are performed outside the hangar prior to flight testing. Also, a final protective coating of silicone with color pigments matching the customer's desired color scheme is applied. At least twenty hours of flight testing will be completed by manufacturer and customer test pilots prior to final customer delivery.

Two main developments will be required in composite technology before the Juggernaut can become a reality. Progress in non-destructive evaluation and total quality management of composite manufacturing facilities must be made to ensure safe, quality manufacturing. At present, no single definitive method exists that can completely determine flaws in composite materials.

Conclusions

The next century will see the need for a long range, heavy lift cargo aircraft. While the Soviet Union has disintegrated, the world is still full of regional conflicts that may require the rapid delivery of a large U.S. military force. The Juggernaut is designed to provide the airlift capabilities necessary to accomplish this mission without reliance on equipment prepositioned at bases in foreign countries. It is also perfectly suited for delivering humanitarian aid and for evacuation of areas devastated by war or natural disaster.

In addition, high-capacity passenger aircraft will be needed to serve the Pacific Rim and other areas of the world which are experiencing an explosive increase in demand for civil aviation. The Juggernaut has been designed to be able to operate from international airports and meets all applicable FAR certification standards, so conversion for use as an airliner will be easy to accomplish.

The design team has presented the C-28 Juggernaut in response to the 1992/1993 AIAA/GD Undergraduate Team Aircraft Design Competition RFP. The Juggernaut embodies the design philosophy of striving for effectiveness, efficiency, technology, and economy in aircraft design. Technological advances have been limited to the areas of material development, propulsion, aerodynamics, and flight controls, in order to decrease cost while increasing the Juggernaut's operational capabilities. It has been shown that the Juggernaut is capable of meeting or surpassing all RFP requirements.

The C-28 Juggernaut is the ideal solution to the problem of rapid global mobility. It is a technologically sound, cost-effective, high-technology transport capable of handling the large passenger and cargo demands that will exist in the twenty-first century.

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