Converting a C-130 Hercules into a Compound Helicopter: A Conceptual Design Study

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ABSTRACT

This study presents the performance and weight changes for a Compound C-130 as compared to the Baseline C-130H Hercules, using NDARC as the primary analysis tool. First, the C-130H was modeled within NDARC, from which performance at various conditions and a parametric weight statement were generated. Then, the C-130H NDARC file was modified to represent the Compound C-130, which was then put through the same performance analysis as the C-130H. A parametric weight statement was also calculated for the Compound C-130, which allowed for comparison to the C-130H.

As part of the modeling of the Compound C-130, a Rotor Design Spreadsheet was created that would allow the direct calculation of the weight of the main rotors being added. Using composite materials led to considerable weight savings for both the rotor system and the hub weights. These weight savings are reflected in the NDARC Technology Factors which were determined to be 0.71 and 0.5 for the rotor blades and the hub/hinge system, respectively. Such Technology Factors suggest that using composites for other components could drastically lighten the Operating Empty Weight of the aircraft.

The weight statements show the weights for each of the components on each aircraft. It is quite evident that the Compound C-130 has a higher Operating Empty Weight due to the addition of the two main rotors and a drive system to connect each engine group on the wing tips. Upon further analysis, the main weight driver is the drive system. While the main rotor/hub/hinge weight increase is to be expected, the weight increase due to the transmission drive and gear boxes are cause for concern. Unless a method can be found of reducing the weight of the drive system, the weight penalty makes the Compound a C-130 an inefficient aircraft in terms of payload/fuel capacity. Possible solutions are either offloading some of the power requirements through the drive system or using composite materials in the construction of the drive system.

The performance of the Compound C-130 versus the C-130H shows a clear need for more powerful engines than are currently present on the C-130H. This would also adversely affect the Operating Empty Weight since a larger power plant requires more weight. However, one advantage that the Compound C-130 presents is the ability to hover and operate at low speeds in Helicopter Mode. While the C-130H is unable to travel at speeds lower than its stall speed, the Compound C-130 is able to hover using the main rotors. Thus, the Compound C-130 is able to operate independent of runways, let alone the condition of the nearest runway. Ultimately, the Compound C-130 is an effective aircraft in theaters requiring VTOL aircraft due to geographical considerations in terms or performance. Unfortunately, the weight penalty associated with converting the C-130H to a Compound C-130 suggests that further work in the area of the drive systems is required.

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INTRODUCTION

Currently, the US Military and NASA are investigating the feasibility of a large Vertical Take Off and Landing (VTOL) aircraft that can provide both invaluable aid in the combat theater and significantly improve the civil transportation system. For example, the need to airlift personnel and materiel into a region without infrastructure, i.e. Afghanistan, poses a challenge to the US Military in its Global War on Terror. Without a paved runway, strategic and tactical airlift aircraft such as the C-5 Galaxy and C-17 Globemaster III are unable to land and are thus confined to airdrops. Thus, a need for runway independent aircraft appears.

Rotorcraft have become a clear choice for such missions when airlifts are needed for out-of-the-way places. With helicopters like the CH-47 Chinook and the UH-60 Black Hawk, the US Army has been struggling with missions in Afghanistan and Iraq where more people and equipment are needed farther from urban hubs. The CH-47 has a MTOW of 50,000 lbs while a runway dependent aircraft, like a C-130H Hercules has a MTOW of 155,000 lbs. This gap increases as aircraft such as the C-17 and C-5 are considered with MTOW of over 500,000 lbs and 700,000 lbs, respectively. However, the C-130H, C-17, and C-5 all require runways, limiting the airlift capacity of the United States Military. The current military requirement is based around a 28-ton, or 56,000 pound payload with VTOL heavy lift capability.

The civilian rotorcraft requirements have evolved into the Large Civil Tiltrotor (LCTR) concept, which has resulted in two designs, LCTR1 and LCTR2 (References 1 and 2). The LCTR1, using current airline passenger trends, was designed for a 120 passenger, 350 knot, 1200-nm range mission. For a payload of 26,400 pounds, the Mission Gross Weight was calculated to be 123,562 pounds. The LCTR2 was designed for a 90 passenger, 300 knot, 1000-nm range mission. This corresponded to a payload of 19,800 pounds and a Mission Gross Weight of 107,500 pounds.

One runway dependent aircraft that has a payload capacity similar to the military and civilian requirements is the C-130H Hercules. From Jane's All the Worlds Aircraft (Reference 4), the C-130H has the following characteristics.

Table 1. C-130H Specifications

Power plant	4 x Allison T56-A-16
Wing span	132 ft 7 in
Wing chord (mean)	13 ft 8.5 in
Length	97 ft 9 in
Operating Weight Empty	76,469 lb
Max Internal Fuel Weight	44,330 lb
Max Payload	49,818 lb
Max Normal Take Off Weight	155,000 lb
Take Off Run (Over 50 ft)	5,500 ft

While the C-130H has almost twice the payload capacity as the LCTR1 and LCTR2, the Maximum Normal Take Off Weight of the C-130H is similar to that of the LCTR1. The C-130H payload capacity's proximity to the military payload requirement suggested the Hercules as a good starting point for any design study concerned with the design of a heavy vertical lift aircraft.

STUDY OBJECTIVE

Studies regarding the conversion of the C-130H into various heavy vertical lift configurations are currently being undertaken and this paper presents a facet of the work being done. The current study concerns the conversion of the C-130H into two separate compound helicopter configurations. The first configuration examined was a single main rotor compound (SMRC). Analysis of the SMRC yielded drawbacks of the design, mainly due to the anti-torque required due to one main rotor. Thus a second configuration, a twin rotor compound (TWRC) was analyzed. The TWRC was modeled after the Russian Kamov Ka-22 with two main rotors, one located at each wing tip, and two forward thrust producing propellers.

APPROACH & GROUND RULES

The fundamental guideline of the study was to change the C-130H as little as possible. However, the addition of a rotor system for VTOL was still required. In order to design this new rotor system, as well as to take advantage of new developments in composite materials, a Rotor Design Spreadsheet was created in Excel. This allowed for rapid rotor blade conceptual design and allowed for quick spot checks on rotor power requirements and structural behavior. Once the rotor system had been validated by a series of physical constraints such as material and deflection limits, the NASA Design and Analysis of Rotorcraft code (NDARC), developed by Dr. Wayne Johnson at the Aeromechanics Branch of NASA Ames Research Center was used to analyze the design. NDARC design involved using parametric weight statements and power polars to characterize the design and provide performance metrics that could be compared to other designs.

METHODOLOGY

Overview

The basic requirement of the study was to keep as much of the Baseline C-130H Hercules design unchanged as possible. This meant that unless there was a pressing need to do so, systems such as the wing, the fuselage, the landing gear, and the empennage were kept constant. Weight empty values for these aircraft components were held constant. This approach minimized the impact of weight trend equation uncertainties The simplest configuration to study first was the SMRC, with the TWRC emerging as the preferable alternative from the deficiencies of the SMRC.

NDARC

NDARC is a Fortran 90 code written by Dr. Johnson that allows for the design and analysis of rotorcraft at the conceptual design level (Reference 4). The software can operate in either a design mode or a performance analysis mode. Given that the C-130H was taken as a baseline and that minimal changes were being put in place, the performance analysis mode was used to obtain the performance metrics of the original C-130H as well as the derived C-130 Compound.

Performance analysis was run using three main NDARC files, the NDARC job file, the rotorcraft description file, and the turboshaft engine description file. NDARC also contains the Army Aeroflightdynamics Directorate parametric weight models from 1982 and 2000 (AFDD82 and AFDD00, respectively). These models were used in conjunction with the rotorcraft description file to generate a parametric weight statement which was be used to determine useful load. (It is worth noting that these historical weight trend models offer at least a ± 5 to 10 percent latitude in component weights.)

The NDARC job file contains the flight conditions and constraints at which the rotorcraft performance is analyzed. The given flight conditions and constraints can be set to match a mission profile through variables such as trim, velocity, altitude, and temperature. The output contains a substantial amount of performance data ranging from power required to the amount of collective or cyclic that is needed to trim each rotor.

The rotorcraft description file contains over 900 separate values that describe the propulsive, aerodynamic, structural, and geometric aspects of a given rotorcraft (or airplane). These values are arranged in a modular format such that any number of rotors, fuselages, wings, and tails may be used. There is also a shortcut within the file formatting to copy various components for ease of use. Contained within the description file are Technology Factors, which are multiplying factors used to control various components of the parametric weight statement.

The turboshaft engine description file models rotorcraft engines using the Referred Parameter Turboshaft Engine Model. The RPTEM models the engine performance as a function of the operating conditions as opposed to going through a rubber engine sizing. This file is used along with the rotorcraft description file to provide the NDARC job file a performance model of the rotorcraft in terms of aerodynamics, propulsion, and weights.

Rotor Design Spreadsheet

A rotor blade design analysis methodology was developed during the investigation. This analysis computed steady stresses, blade deflection and blade weight among other key parameters – but only in hover. This analysis offers preliminary blade geometry and structural properties as inputs to more advanced aeroelastic tools. The analysis incorporated the following features.

Rotor design parameters were chosen based on previous designs as well as rational assumptions. Variables that were adjusted for the design study included number of rotors, rotor radius, number of blades per rotor, and solidity. Using these parameters, the root chord, tip chord, and blade area were all calculated. The blade was then split up into 101 stations with R/100 steps. This allowed for the calculation of structural properties, aerodynamic loading, and centrifugal loading at each station. Using a Forward Euler Method, the blade deflection was calculated by determining the behavior of the blade in response to the applied loadings.

At first a symmetric airfoil of a given thickness was picked as the airfoil for the entire blade span. The first chordwise one-third of the leading edge of the airfoil (0 to c/3) was modeled as a semi ellipse with a minor axis equal to the thickness and the semi major axis equal to c/3. The trailing edge (c/3 to c) of the airfoil was modeled as a triangle with the base equivalent to the airfoil thickness and tapering to a point. Figure 1 shows the airfoil structural geometry.

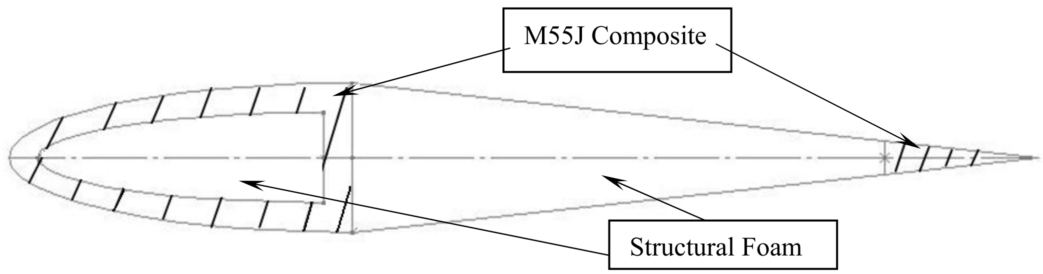

Figure 1. Airfoil used for aerodynamic and structural modeling.

The airfoil cross sectional material composition was modeled as a D-Spar plus a Trailing Edge wedge, both of carbon fiber composite and the rest of the structure filled in with structural foam. Using Moment of Inertia equations and geometry, the structural flapwise stiffness (EI) and mass distribution was computed as a function of the blade's length. For this design study, M55J carbon fiber composite and basic model making structural foam were chosen to model the structural properties that were used in the structural analysis of the airfoil section and the blade.

Once the structural properties of the blade section were calculated, the loading of the blade due to weight, centrifugal forces, and aerodynamic forces was applied in order to determine the deflection of the blades under full loading in hover. The aerodynamic loading was determined using blade element theory as described in Reference 5. While the model does not account for stall, it does provide a reasonable estimate of the two-dimensional lift along the radius. The effective angle of attack of the blade was based on the geometric angle of attack and the induced velocity at that radial station. The geometric angle of attack was defined through the twist of the blade which was set at 0^o for this design study, but can be varied within the Excel sheet.

These aerodynamic quantities were used to calculate the thrust produced by the blades for a given root collective angle. The root collective angle would then define the geometric angle of attack along the blade radius which would then be combined with the induced angle of attack to give the two-dimensional thrust coefficient at that station. In this manner, by changing the root collective angle, the thrust of the rotor system was also changed. This served as the primary method of controlling the thrust produced. Given a thrust requirement, the necessary root collective angle was calculated through Excel's internal Goal Seek.

Approximations for the natural frequencies of the blades were also applied in order to ensure that the harmonics were not on an n-per-rev frequency. The approximations are a result of the Energy Method outlined in Reference 6.

By using Excel to run the calculations, the blade structural and geometric properties could be changed in one sheet and all of the resulting properties and loadings would instantly adjust in another sheet. This allowed for "dynamic" design process because there was no need to wait for code to run after which the results needed to be analyzed. The changes could be seen almost immediately which allowed for a rapid turnaround time for the basic rotor system design.

The post processing of the blade properties and loading involved checking the blade design against five constraints and determining the power required. The five constraints were based on operating conditions, deflection limits, material stress limits, and blade natural frequencies. Once all five constraints were met, then the design point was considered valid and the power required was noted.

Part of the aerodynamic analysis included approximating the drag on each airfoil section. Using this approximation, a torque requirement was calculated which was used to determine the power required. The blade element theory power required was taken as a more accurate estimate of the power requirements for the given rotor system. This power estimate was used as a first approximation to engine size for the Compound C-130.

Rotor Design Results

The Rotor Design Spreadsheet used the M55J Composite properties listed in Table 2 as the basis for the redesigned Compound rotor. The new rotor system was design to static hover conditions at the 4,000 feet and 95^{o} F condition. The weight trends presented in NDARC use the blade natural frequency as a primary design factor, while the Rotor Design Spreadsheet emphasized the composite structural properties and blade deflection in the rotor blade design process. The natural frequencies are determined later in the design process as a constraint check.

Table 2. M55J Composite Material Properties

Density	102 lb/ft^3
Tensile Modulus	43,500,000 psi
Compressive Modulus	41,500,000 psi
Maximum Allowable Tension Stress	270,000 psi
Maximum Allowable Compression Stress	120,000 psi

NDARC blade weight equations returned the weight of one set of rotor blades as 6272.7 pounds for parameters listed in Table 3. Using similar parameters, the Rotor Design Spreadsheet calculated the one set of rotor blades' weight as 4454.8 pounds. This corresponds to a Technology Factor of 4454.8/6272.7 = 0.710. Such improvement is a result of the Rotor Design Spreadsheet design philosophy, i.e. placing the emphasis on the composite properties and deflection. Note that the second elastic flapwise frequency (4.04 per rev) at the 450 feet per second tip speed used in the slowed rotor compound appears virtually on an integer. (The second author considered this a quite acceptable result from the Rotor Design Spreadsheet, since, in his experience, this actually guarantees that this mode's natural frequency will be at least 0.25 per rev lower at the end of detailed design and shake test.)

Table 3. Blade Design Parameters

Vtip Hover	650 fps
Radius	62.5 ft
Taper	0.667
Average Chord	3.27 ft
Natural Frequency (For NDARC only)	1.19 per rev at 650 fps
Natural Frequency (For Forward Flight)	4.04 per rev at 450 fps
Air Density	0.0019196 slugs/ft3
CT/σ	0.15
Solidity	0.06
NDARC Blade Set Weight	6272.7 lb
Rotor Design Blade Set Weight	4454.8 lb

DISCUSSION

NDARC Model of C-130H

The Lockheed C-130H formed the reference aircraft for this study. As such, this aircraft was modeled in NDARC with nearly 900 input parameters. The parameter values were selected to give representative NDARC output for weight empty, aircraft power off drag coefficient versus lift coefficient, and aircraft forward flight performance. Each of these aircraft characteristics are discussed below.

Weight Empty

Jane's All The Worlds Aircraft for 1995–1996 (Reference 3) gives the C-130H operating weight empty as 76,469 pounds and a normal gross weight of 155,000 pounds. The operating weight empty includes the fixed useful load (about 1,400 pounds). Therefore, an NDARC weight empty somewhat below 80,000 pounds was considered sufficiently representative for this conceptual study.

NDARC uses a large array of component weight trend equations that are well documented in the NDARC Theory Manual. These equations, with suitable inputs created by the second author, yielded a reference weight empty of 77,461 pounds. NDARC's output provides weight empty approximately in MIL-STD-1374A Part 1 format. From this complete weight statement, Table 4 below gives the abbreviated weight statement used for this conceptual design study. The operating weight empty equals the sum of the baseline weight empty of (77,431 pounds) plus the fixed useful load (1,400 pounds) and is, therefore, 78,831 pounds. The design gross weight of 155,000 less the operating weight empty gives a useful load of 76,169 pounds. This useful load can be split between fuel and payload. Jane's for 1995-1996 gives the maximum internal fuel weight of 44,330 pounds which means the payload with maximum fuel is 31,869 pounds, assuming the NDARC derived weight empty.

Table 4. NDARC Baseline C-130 Weight Empty Statement

Total Structures Group	**41,579**
Wing group	13,898
Rotor group	0
Empennage group	3,824
Fuselage group	15,708
Alighting gear group	5,262
Engine section/nacelle group	2,519
Air induction group	368
Total Propulsion Groups	**19,603**
Engine system group	6,753
Propeller install group	4,566
Fuel system	5,967
Drive system	2,316
Total Systems Groups	**16,250**
Flight controls	1,601
Auxiliary power	685
Instruments	539
Hydraulic	778
Electrical	2,428
Avionics	2,726
Furnishings & equipment	4,258
Environmental control	1,752
Anti-icing	787
Load & handling	696
Total Weight Empty	**77,431**

Aerodynamics

In order for NDARC to estimate basic aerodynamics of the C-130, detailed airframe geometry and component aerodynamic properties were provided by the second author. This geometry was based in part on more dimensioned 3-views derived from Figure 2. Aerodynamic properties of lift, drag and pitching moment as a function of angle of attack were created by the second author. The wing, fuselage, vertical tail, horizontal tail and nacelles were individually aerodynamically described for NDARC. Mach number effects were not considered. The Hamilton Standard 54H60 propeller geometry was provided to NDARC in rotorcraft format. Taken together, the airframe plus propeller input was sufficient for NDARC to perform a longitudinal trim at all speeds and altitudes under consideration in this conceptual design study.

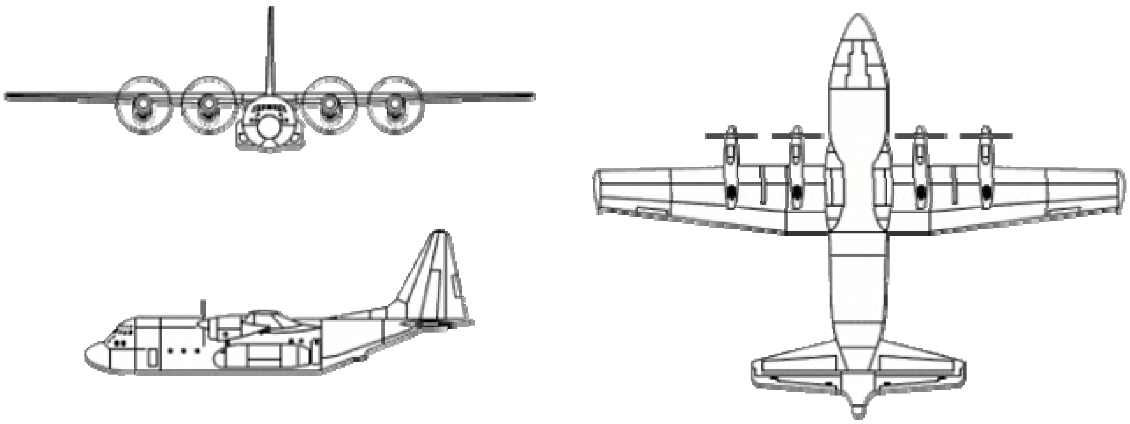

Figure 2. Typical 3-view of the C-130

The primary aircraft drag polar and lift to drag ratio of the Baseline C-130 as embedded in NDARC are illustrated with Figure 3. The aerodynamic properties include interference of the propeller – wing combination and wing – empennage interference.

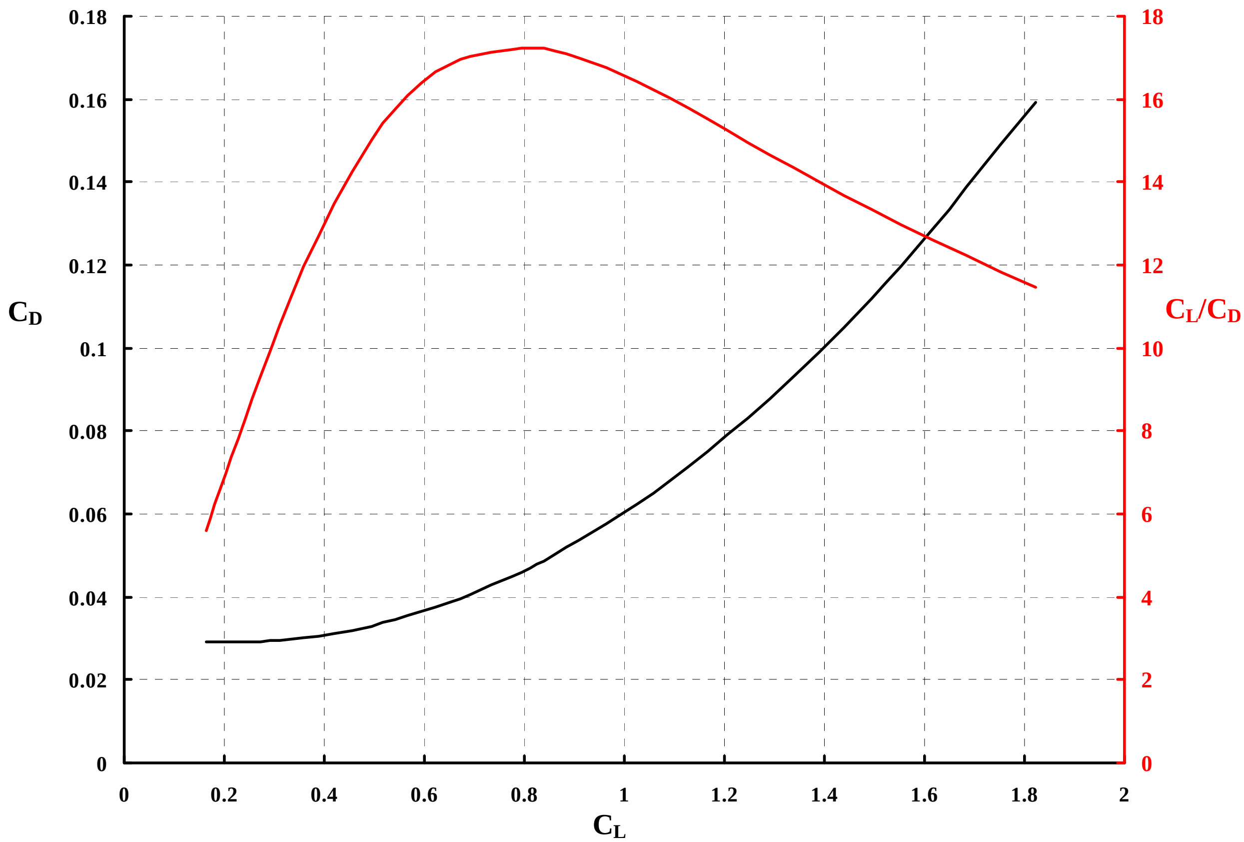

Figure 3. Baseline C-130 lift and drag characteristics embedded in NDARC. Computed at sea level standard with normal gross weight and normal center of gravity.

Performance

The Baseline C-130 performance can be expressed in several ways. For this conceptual study, the authors have used NDARC to examine engine power required and specific range, here defined as nautical miles per pound of fuel burned. Additionally, NDARC's mission analysis mode was used to obtain range. Finally, takeoff calculations were made with a program (independent from NDARC) constructed from first principals.

Power required and specific range for three altitude conditions are shown with Figure 4, 5 and 5. This performance was calculated by NDARC at the normal gross weight of 155,000 pounds and the normal center of gravity. The power required was calculated assuming 100 horsepower for accessories and a transmission efficiency of 0.95. After NDARC completes its trim solution, propeller thrust and collective pitch are known. The power to obtain that thrust is calculated by relatively simple blade element-momentum strip theory as used within the rotorcraft community.

Engine characteristics for the four Allison (now Rolls Royce) T56-A-16 were based on a military rated power at sea level standard of 4,591 shaft horsepower. In lieu of an actual engine performance deck for the T56 engine, NDARC's Gen4000 generalized performance deck for turboshaft engines was used. This NDARC capability provides power available variations with speed, altitude and temperature. The generalized performance deck also provides estimated engine residual jet thrust and this thrust acts as an apparent drag reduction to the aircraft. The fuel flow of the Gen4000 engine deck was increased 5 percent in accordance with Mil-C-5011A (paragraph 3.2.9), which accounts for "a service tolerance to allow for practical operations."

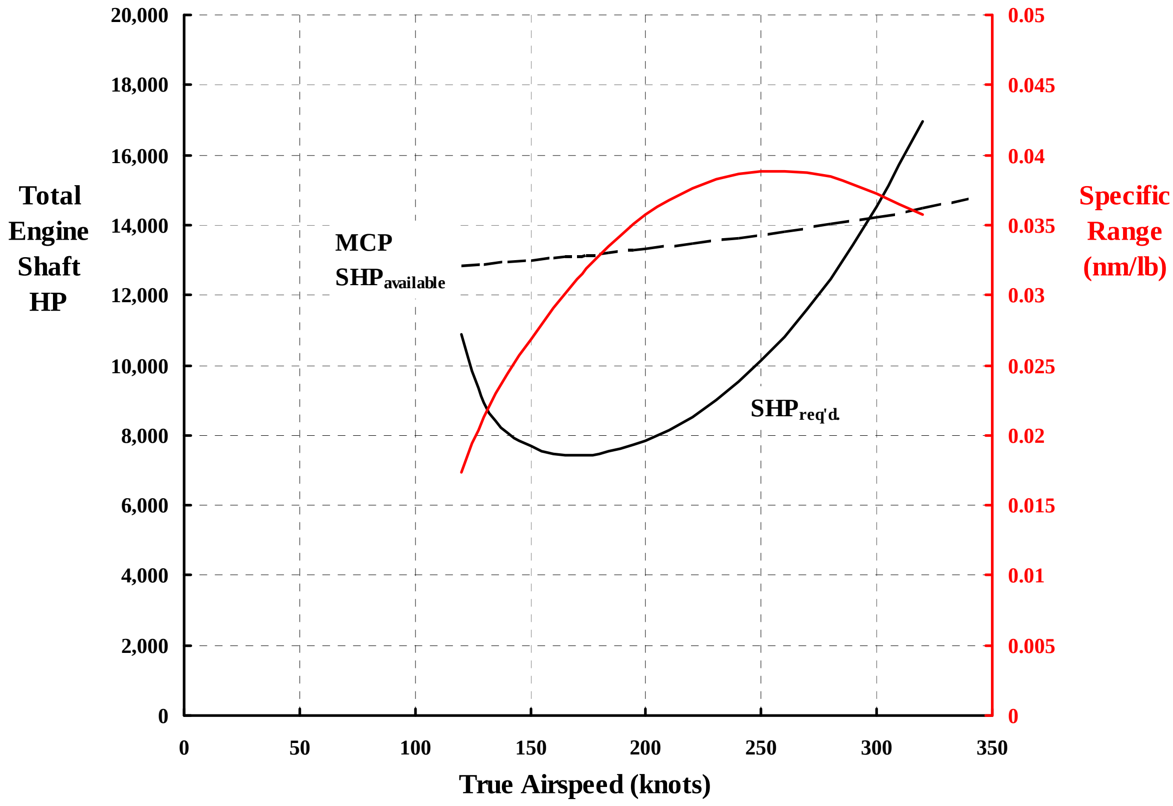

Figure 4. NDARC calculated Baseline C-130 performance at 4,000 ft, 95°F.

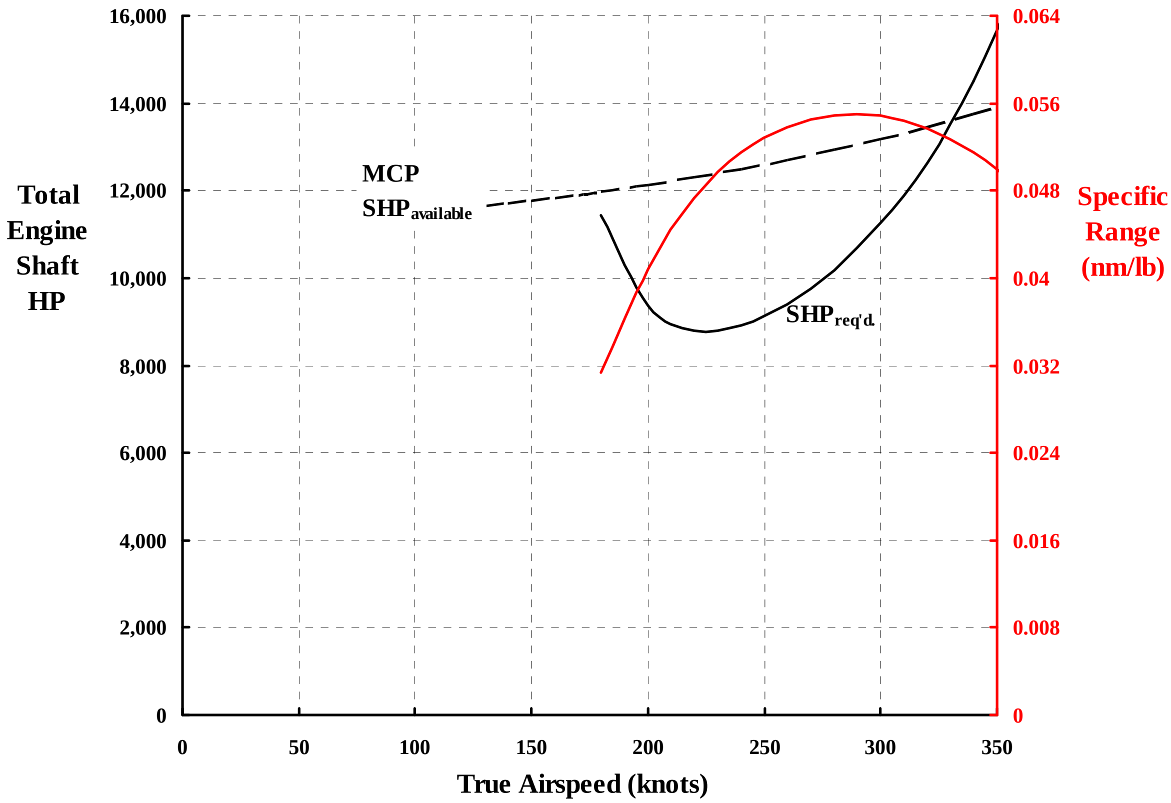

Figure 5. NDARC calculated Baseline C-130 performance at 20,000 ft, Std. Day.

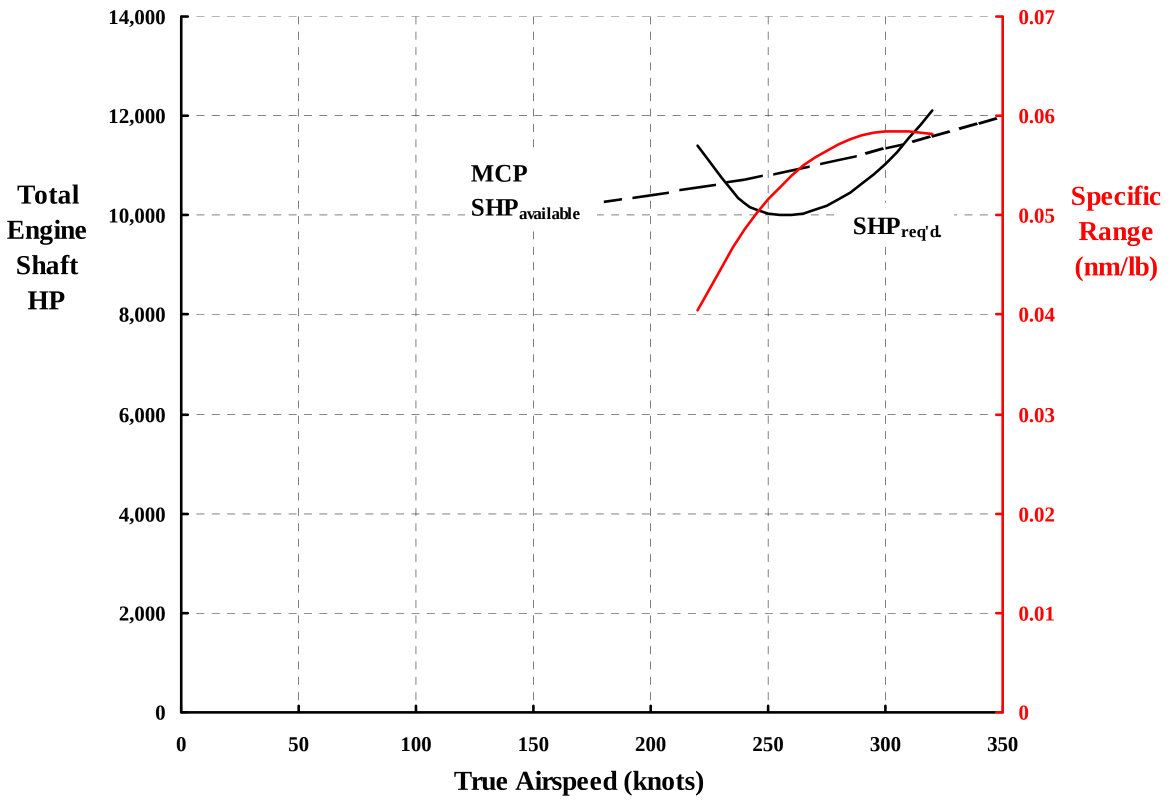

Figure 6. NDARC calculated Baseline C-130 performance at 25,000 ft, Std. Day.

NDARC has the capability to calculate performance for any number of missions. The mission selected for this conceptual study was a range mission constructed with several segments. The segments approximated Mil-C-5011A. That is:

Segment 1. Starting, taxiing, takeoff at sea level standard day
Segment 2. Climb from sea level to 20,000 feet on a standard day
Segment 3. Cruise at 20,000 feet (standard day) at speed for best range
Segment 4. Descend to sea level standard
Segment 5. Loiter at sea level for 30 minutes
Segment 6. Land, taxi and park

In accordance with Table I of Mil-C-5011A, five percent of initial fuel was held in reserve. This reserve is over and above the 30 minutes of loitering called for with segment 5.

The preceding mission description was used to measure the NDARC model of the C-130 against published data. According to Jane's 1995-1996, the C-130H taking off at a gross weight of 155,000 pounds and with a payload of 40,000 pounds has a range of 1,945 nautical miles. The amount of fuel associated with this range is, from Jane's, the take off gross weight less the operating weight empty (76,469 pounds) less the payload (40,000 pounds), which amounts to 38,531 pounds. This amount of fuel is somewhat less than the quoted maximum internal fuel capacity of 44,330 pounds. NDARC was given the constraint of 38,531 pounds of fuel and returned a range of 2,000 nautical miles following the 6 segment. This agreement with Jane's quoted data satisfied the authors that an adequate baseline of the C-130 had been arrived at.

Additional studies of C-130 takeoff performance at sea level standard and at 4,000 foot on a 95^{o}F day were made. A time history program of takeoff was constructed in Microsoft's EXCEL format. Jane's 1995-1996 quotes a takeoff distance of 5,500 feet when a 50 foot obstacle is crossed, presumably for sea level standard. Jane notes that this is achieved at a gross weight of 155,000 pounds and (the authors assumed) from an asphalt runway located at sea level on a standard day. The analysis assumed a rolling coefficient of 0.025. Other assumptions with the time history calculation were:

a. The takeoff power of four engines was 4×4,591 hp less 100 hp for accessories for sea level standard day. On the hot day, the takeoff power was set at 3,170 hp less accessory power.
b. The static thrust of four propellers was 4×8,858 pounds for sea level standard, which is a forward thrust to gross weight ratio of 0.229. On the hot day, the propeller thrust reduced to 7,060 pounds per propeller.
c. The engine residual jet static thrust from four engines was 4×680 pounds and was not changed for the hot day.
d. Both propeller thrust and residual jet thrust decreased with forward speed while maintaining a constant takeoff power. Propeller thrust was calculated from simple blade element-momentum theory. This forward thrust behavior is illustrated with Figure 7.
e. The aircraft was assumed to operate at a lift coefficient of C_L = 1.95 with flaps deflected. A drag coefficient addition of 0.03 was added to the drag polar shown in

Figure 3 for flap deflection. The takeoff calculation was made holding $C_L = 1.95$ and $C_D = 0.209$ constant.

f. Numerical integration of F = ma equations in horizontal and vertical axes assumed a 0.25 second time step.

The calculated takeoff time history for the Baseline C-130 at sea level standard is shown with Figure 8. Note that with the selection of $C_L = 1.95$, the time history returned a takeoff distance over a 50 foot obstacle of 5,500 feet. This step calibrated the takeoff analysis. Because this conceptual study is aimed at satisfying U.S. Army takeoff conditions of 4,000 feet on a 95°F day, the authors used the calibrated analysis to examine the C-130 performance at this more demanding altitude/temperature condition. Figure 9 shows that the C-130 would need 11,500 feet to clear a 50 foot obstacle given a 155,000 pound takeoff gross weight on the Army hot day.

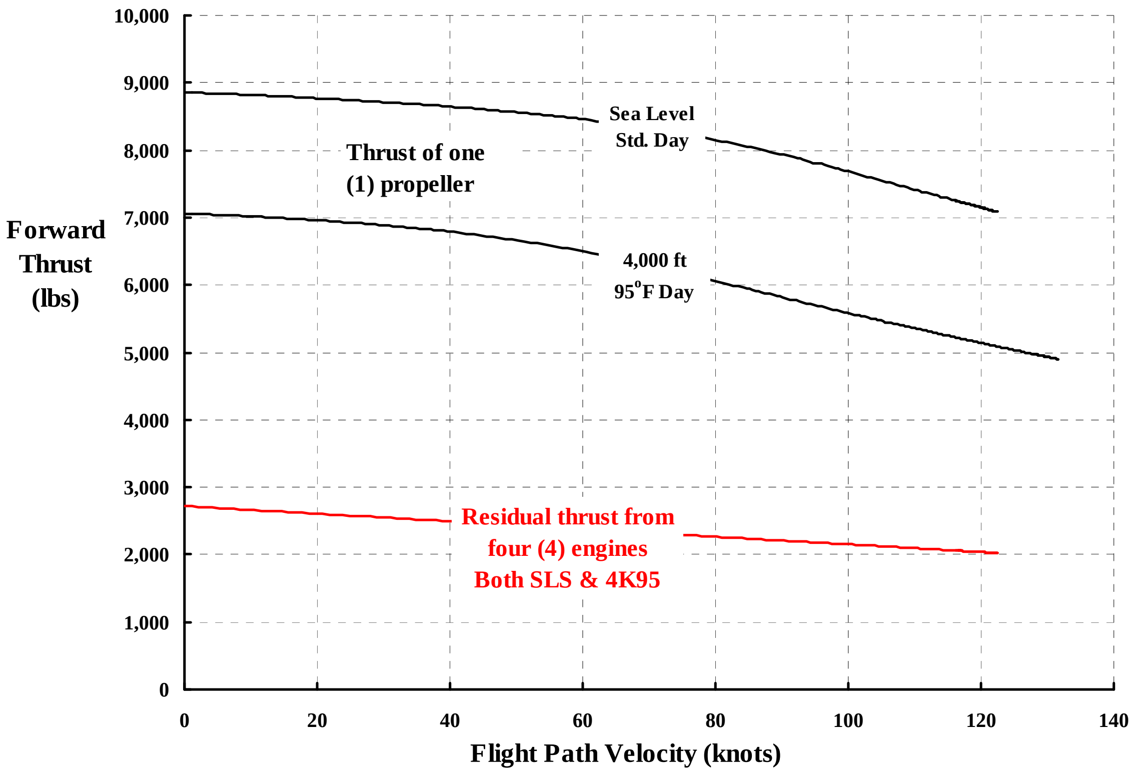

Figure 7. Thrusting forces at sea level standard day

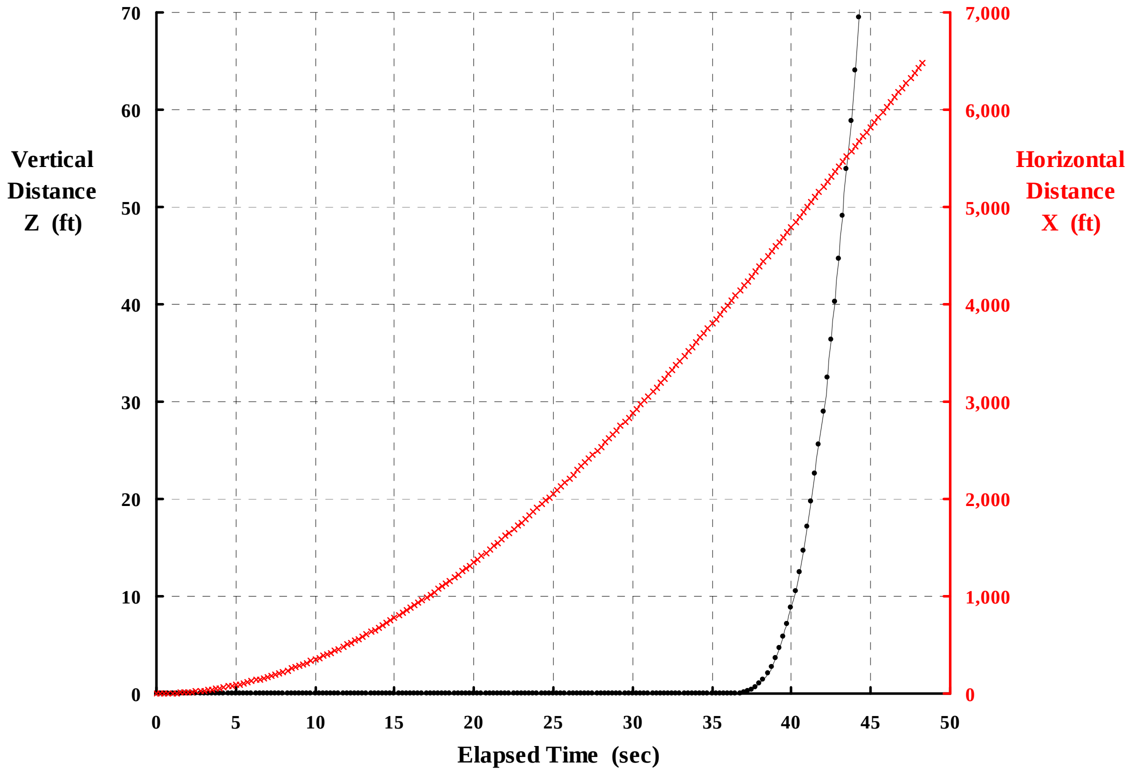

Figure 8. C-130 Takeoff time history for sea level standard day

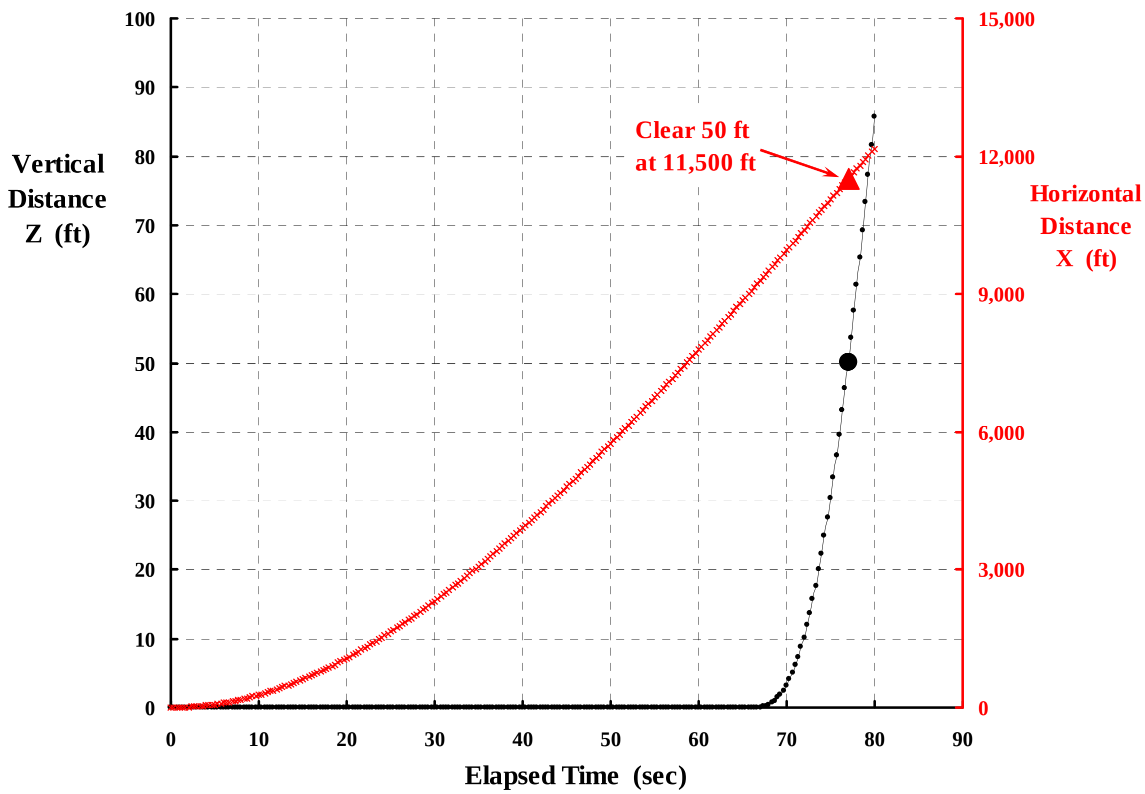

Figure 9. C-130 Takeoff time history for 4,000 feet, 95°F day

NDARC Model of Compound Conversion

Taken together, the weight, aerodynamic and performance of the C-130 baselined in NDARC encouraged the authors to seek a compound derivative of the C-130. As discussed earlier, a very large diameter, shaft driven, single main rotor with C-130 propellers for anti–torque was quickly discarded as a viable configurations. A Rotodyne approach using tip drive was also considered. This approach was not pursued because of two reasons. First, because of the rather daunting tip drive noise problems that the Rotodyne faced. (As discussed in Reference 7, the McDonnell XV-1 was another example where tip drive noise was a serious negative factor in going forward with the configuration.) The other reason was the second author's concern that high advance ratio rotor rpm control was best achieved by maintaining a direct engine to rotor shaft control.

With the above thoughts in mind, the authors chose to follow the Russian Kamov Ka-22 approach shown with Figures 10 and 11. Each wing tip of the C-130 would support a propulsion package. This package would contain two engines connected by a gear box. The gear box would have output up to the rotor, forward to the propeller and interconnected to its opposite box on the other wing tip. A rotor pylon would support a rotor and a nacelle which would house the engines and support the propeller. The propulsion package would be sized so that the configuration could hover with one engine out at 4,000 feet, 95^{o}F day at a takeoff gross weight of 155,000 pounds. Thus, the engines would be rated to an IRP with the lowest disc loading geometrically allowed. From the various 3-view drawings available, the authors concluded that two 62.5 foot diameter rotors could be tip mounted on pylons with adequate blade to blade and blade to airframe clearance. These large diameter rotors insured a low disc loading (GW/A) of 6.3 pounds per square foot and the lowest installed power for hovering takeoff on an Army hot day. Other top level specification data about this Compound C-130 configuration are given in Table 5 and the discussion which follows.

Table 5. Compound C-130 specifications

Power plant	4x7,840 hp
Wing span	132 ft 7 in
Wing chord (mean)	13 ft 8.5 in
Length	97 ft 9 in
Rotor Blade Radius	62.5 feet
Rotor Blade Taper	0.667
Number of Blades	4
Rotor Solidity	0.06
Hover C_T/σ	0.15
Disk Loading	6.3 lb/ft^2
Hover Tip Speed	650 ft/s
Compound Tip Speed	450 ft/s
Operating Weight Empty	122,330 lb
Max Normal Take Off Weight	155,000 lb
Max Payload + Fuel	32,670
Take Off Run (Over 50 ft)	0 ft

Figure 10. Kamov Ka-22

Weights

NDARC was configured with nearly 900 inputs to describe the Compound C-130 and the large array of component weight trend equations were again used. NDARC returned a weight empty of 120,930 pounds. This is considerably larger than the NDARC Baseline C-130 weight empty of 77,431 pounds shown with Table 4. The Compound C-130's abbreviated weight statement is given with Table 6, which is directly comparable to the Baseline C-130. The operating weight empty equals the sum of the baseline weight empty of (120,930 pounds) plus the fixed useful load (1,400 pounds) and is, therefore, 122,330 pounds. The design gross weight of 155,000 less the operating weight empty gives a useful load of 32,670 pounds, which is virtually one-half of the Baseline C-130's useful load. In most ways, this is not an encouraging result. The addition of the rotor group eats 13,090 pounds away from the Baseline C-130's useful load of 76,169 pounds. To power the rotor system takes another 24,264 pounds, the majority coming from the rotor drive system. A relatively minor systems group increase of 1,051 pound occurs because of additional rotor control system requirements. The net result is a *maximum of 32,670 pounds of fuels at zero payload*, whereas the NDARC Baseline C-130 can carry 39,060 pounds payload at the same fuel load.

In arriving at the rotor group weight given in Table 6, considerable credit for advanced design and materials was taken. The weights of the main rotor blades were modeled using the Rotor Design Spreadsheet. The spreadsheet modeled the blade using discrete steps along the radius as well as the structural properties of the Carbon Fiber Composite M55J and normal structural foam. NDARC calculated the actual blade weight at 6,272.7 pounds for 4 blades for one main rotor. The Rotor Design Spreadsheet determined that using the M55J and structural foam, the weight of 4 blades for a main rotor would be 4,454.8 pounds. This leads to an NDARC Technology Factor of 4,454/6,272 = 0.710.

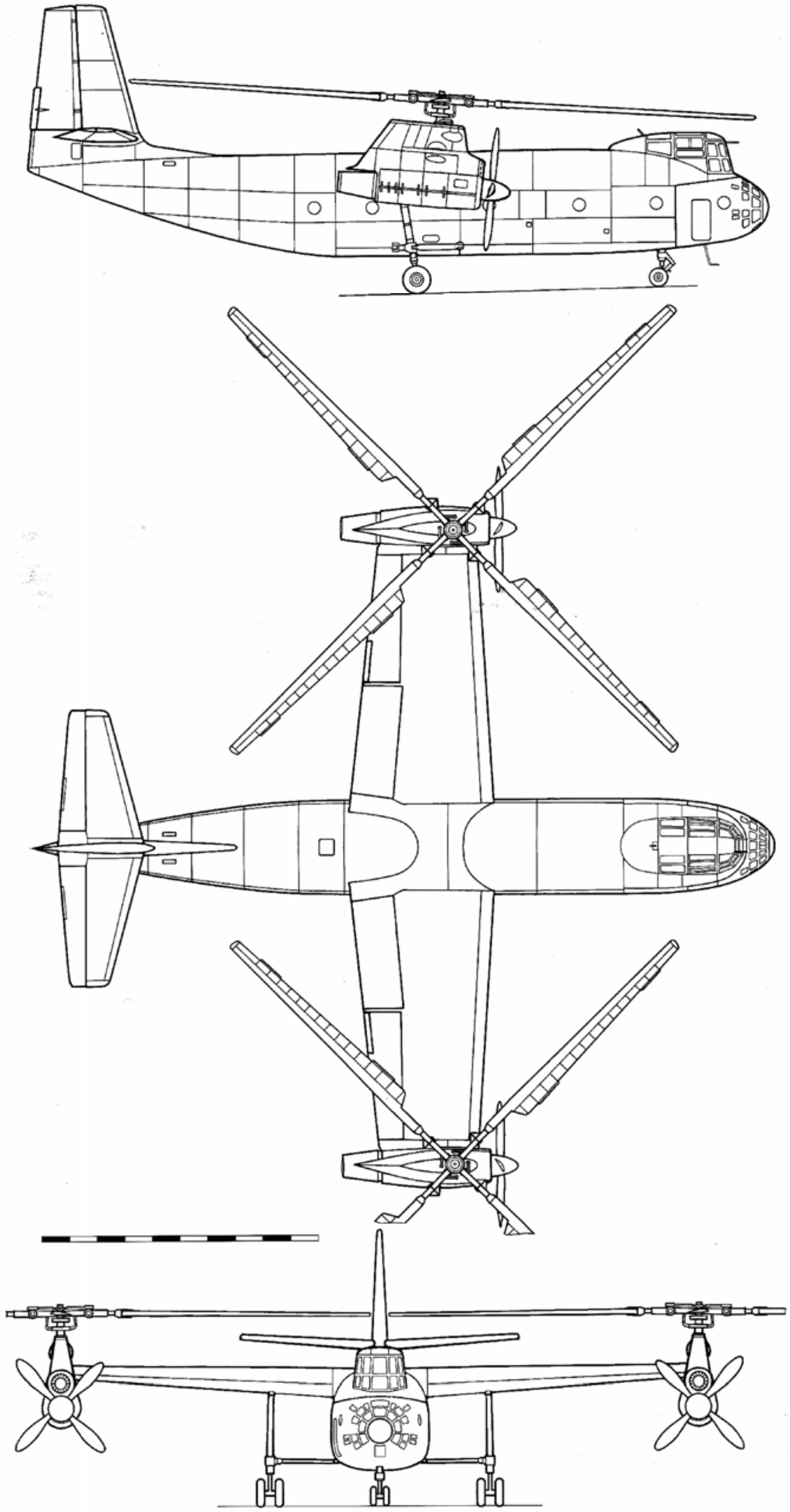

Figure 11. Kamov Ka-22

Table 6. Compound C-130 Weight Statement

Total Structures Group	**59,763**
Wing group	13,898
Rotor group	17,530
Empennage group	3,824
Fuselage group	15,708
Alighting gear group	5,262
Engine section/nacelle group	2,700
Air induction group	842
Total Propulsion Groups	**43,866**
Engine system group	10,642
Propeller install group	5,620
Fuel system	7,634
Drive system	19,970
Total Systems Groups	**17,301**
Flight controls	1,698
Auxiliary power	685
Instruments	539
Hydraulic	426
Electrical	2,428
Avionics	2,726
Furnishings & equipment	4,258
Environmental control	1,752
Anti-icing	2,093
Load & handling	696
Total Weight Empty	**120,930**

In addition to advanced designed blades, the authors chose to adopt the Lockheed AH-56 hub design for both its potential weight savings and drag reduction. This configuration, occasionally referred to as a "door hinge" is shown with Figure 12a and 12b. This type of hub was earlier developed by Bell Helicopter for its attack helicopter series. NDARC's estimate of the AH-56 hub weight was 1,014 pounds. The second author estimated the detailed part weight of one hub as provided with Table 7. The AH-56 fixed and movable hub parts together weigh 800 pounds and are made of titanium, which has a density of 281 pounds per cubic foot. The other parts are assumed to be made of steel. Assuming that the titanium parts can be designed using M55J high modulus graphite/epoxy having a density of about 100 pounds per cubic foot, a weight savings of about 500 pounds is possible. No weight savings with the steel parts is assumed.

Figure 12a. Lockheed AH-56 at Ft. Rucker (Courtesy Barry Lankinsmith, AFDD)

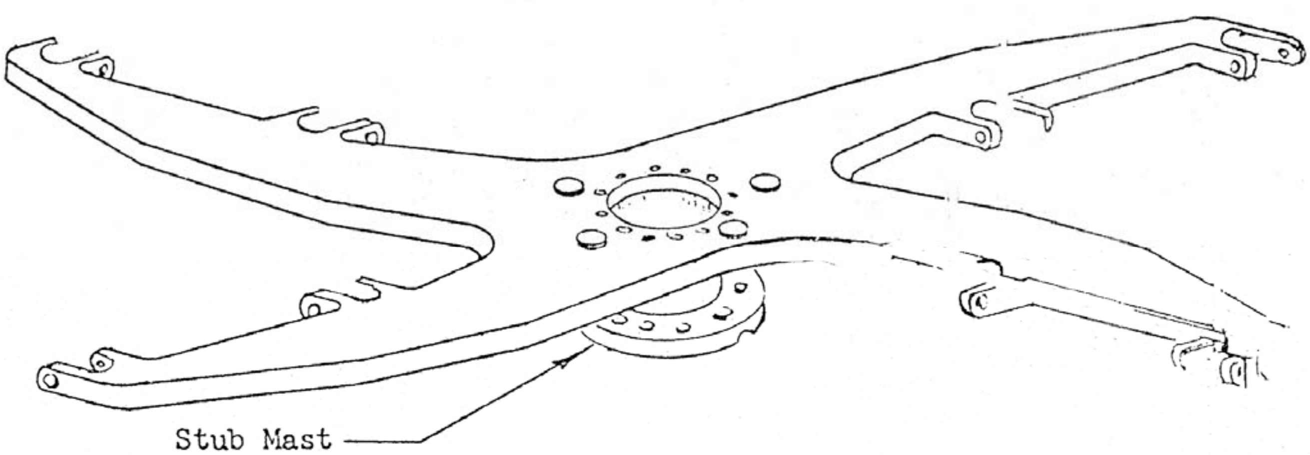

Figure 12b. Lockheed AH-56 fixed hub portion of the "door hinge."

Table 7. Compound C-130 Hub and Hinge Weight Statement

Component Weights for One Hub and Hinge	AH-56	AH-56 Advanced Materials	Compound C-130	Compound C-130 Advanced Materials
Fixed Hub	500	180	4,296	1,546
Movable Hub	300	110	2,578	928
Bearings & Attachments	30	30	258	114
Tension-torsion Strap & Attachments	100	100	859	859
Pitch Arms	40	40	344	344
Hub to Mast Attachment	20	20	172	172
Other	24	24	205	205
Total	**1,014**	**504**	**8,712**	**4,312**

The same logic can be applied to the Compound C-130 hub and hinge design. NDARC gives the Compound C-130 hub and hinge weight as 17,424 for two hubs and their hinges. Therefore, one hub and hinge assembly would be 8,712 pounds. This weight is estimated to breakdown as shown in the fourth column of Table 6. Changing from titanium to advanced graphite/epoxy should reduce hub and hinge assembly weight to 4,312 pounds has shown in the fifth column of Table 6. Therefore, two assemblies should weigh 8,624 pounds, a savings of 8,800 pounds. As an NDARC technology factor input, the authors used 8,624/17,424 ~ 0.5.

Within the propulsion group, the rotor drive system has been sized to a limit of 18,000 horsepower, which is the total power required to hover out of ground effect on an Army hot day at a gross weight of 155,000 pounds. The selected engine had a military rated power of 7,840 at sea level on a standard day, which insured that three engines operating at emergency rated power could maintain hover for one minute at the Army hot day design condition.

Closing on a positive note, the Baseline C-130 needs an 11,500 foot runway to takeoff at 155,000 takeoff gross weight on an Army hot day. The Compound C-130 can hover out of ground effect on three engines at the 4,000 foot, 95^{o}F day and at the same takeoff gross weight.

Aerodynamics

The aerodynamics of the hovering compound is a relatively straight forward analysis in the rotorcraft industry and will not be addressed in this paper. The aerodynamics during transition are also not discussed in view of the number of successful compound rotorcraft (i.e., Kamov Ka-22, Rotodyne and XV-1). Rather, it is the forward flight aerodynamics that is of greater interest to this concept study. And, in particular, rotor system (i.e., hub and blades) effects on the aircraft lift and drag polar is discussed in some detail below.

Consider first the NDARC Baseline C-130's lift – drag polar shown in Figure 13. Dispensing with a 1,745 square foot wing reference area, the baseline aerodynamics is shown in this figure as aircraft lift and drag divided by dynamic pressure (i.e., L/q versus D/q).

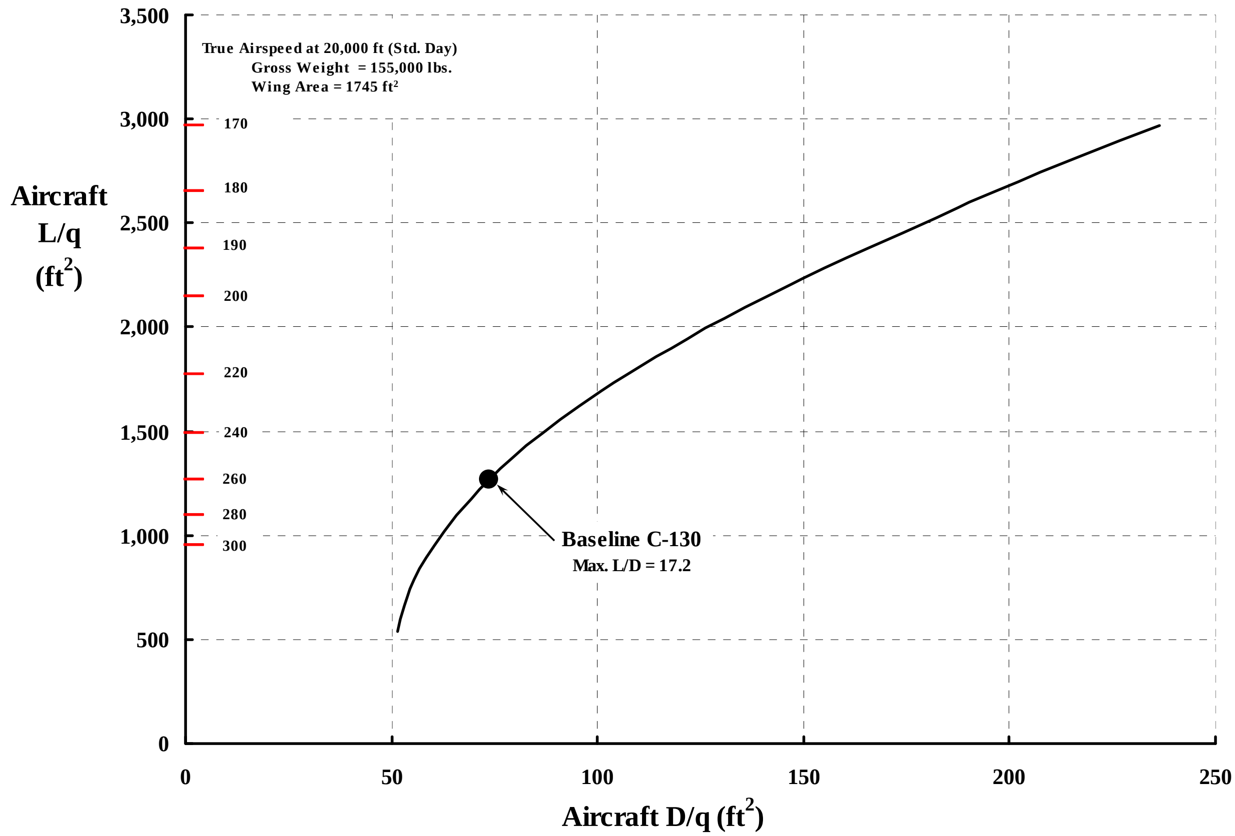

Figure 13. NDARC Baseline C-130 lift – drag polar.

The immediate question is how much drag (i.e., D/q) to add for two rotor hubs. Historical helicopter hub drag data, shown in Figure 14, as a function of normal takeoff gross weight suggests that today's rotorcraft industry can achieve a parasite hub drag of

$$\frac{D_{hub}}{q} = 0.85\left(\frac{GW}{1,000}\right)^{2/3}$$

The Sikorsky S-92 is a very recently developed helicopter and views of its hub and control system (Figure 15a and 15b) show that the frontal area is hardly streamlined. However, using this level of modern technology suggests that two hubs for the Compound C-130 would have a total D_{hubs}/q = 36.4 sq. ft. This is computed with the above equation using GW/2 = 77,500 pounds.

In the authors opinion, the hub developed as part of the Lockheed AH-56 compound helicopter program offered the opportunity for much lower hub drag. The AH-56 "door hinge" concept was shown with Figure 12a and 12b. The AH-56 low drag hub approach was complicated by the gyro control bar and system mounted above the hub, components which would not be used for the Compound C-130. The authors therefore estimated that with an AH-56 low frontal area approach, the hub drag would follow

$$\frac{D_{hub}}{q} = 0.28\left(\frac{GW}{1,000}\right)^{2/3}$$

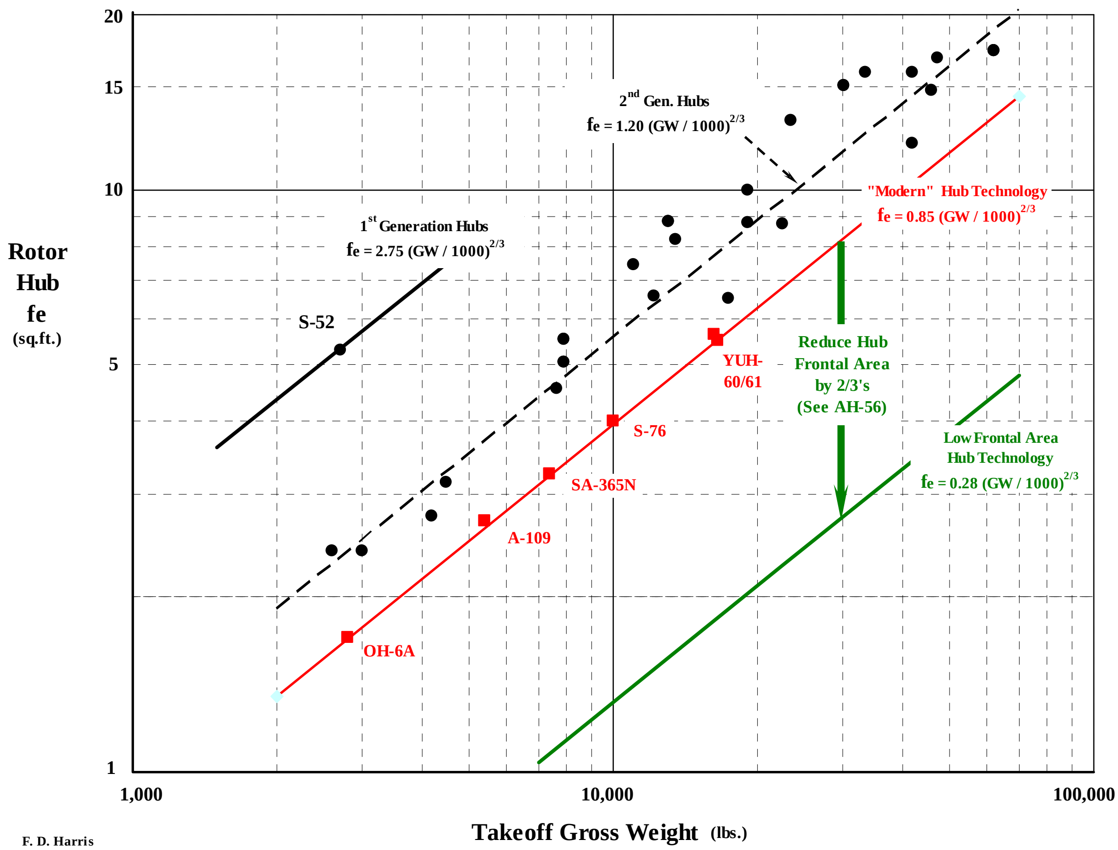

Figure 14. Baseline C-130

and therefore, the total hub drag would be $D_{hubs}/q = 12.0$ sq. ft. The impact of hub configuration and drag on the Baseline C-130 L/q versus D/q aerodynamics is more than substantial as Figure 16 shows. Without a low drag hub, the compound rotorcraft offers few aerodynamic advantages over other VTOL schemes.

The minimum drag of the rotors is another serious addition that reduces the aircraft's maximum lift to drag ratio and increases propeller required thrust. The study of rotor performance at high advance ratio (Reference 7) rather thoroughly examined this question. From that report's Appendix 11, the authors chose to express the rotor minimum drag to dynamic pressure ratio from minimum profile power theory as used in the energy method by the rotorcraft industry. From that theory,

$$\frac{D_{rotor}}{q} = \frac{2(\text{blade area})}{\mu^3} C_{Po}$$

where the profile power coefficient (C_{Po}) is obtained from

$$\frac{8}{\sigma C_{do}} C_{Po} = \sqrt{1+\mu^2}\left\{1 + \frac{5}{2}\mu^2 + \frac{3}{8}\mu^2\left[\frac{4+7\mu^2+4\mu^4}{\left(1+\mu^2\right)^2}\right] - \frac{9}{16}\frac{\mu^4}{\left(1+\mu^2\right)}\right\} + \frac{9}{16}\mu^4 \ln\left(\frac{1+\sqrt{1+\mu^2}}{\mu}\right)$$

The Compound C-130 has two 62.5 foot diameter rotors and the solidity of each rotor is $\sigma = 0.06$. Therefore, the blade area for two rotors is 1,472 square feet. Assuming the rotor blade is constructed from normal airfoils, a representative average airfoil drag coefficient would be $C_{do} = 0.009$. At an advance ratio of $\mu = V/V_t = 1$, the two rotors total $D_{rotor}/q = 23.4$ square feet. In fact, the rotor drag to dynamic pressure ratio benefits from advance ratios much greater than today's helicopter range of 0 to 0.4. This effect of advance ratio is shown with Figure 17. Of course, including compressibility effects would increase rotor blade D_{rotor}/q above the minimum describe by Figure 17.

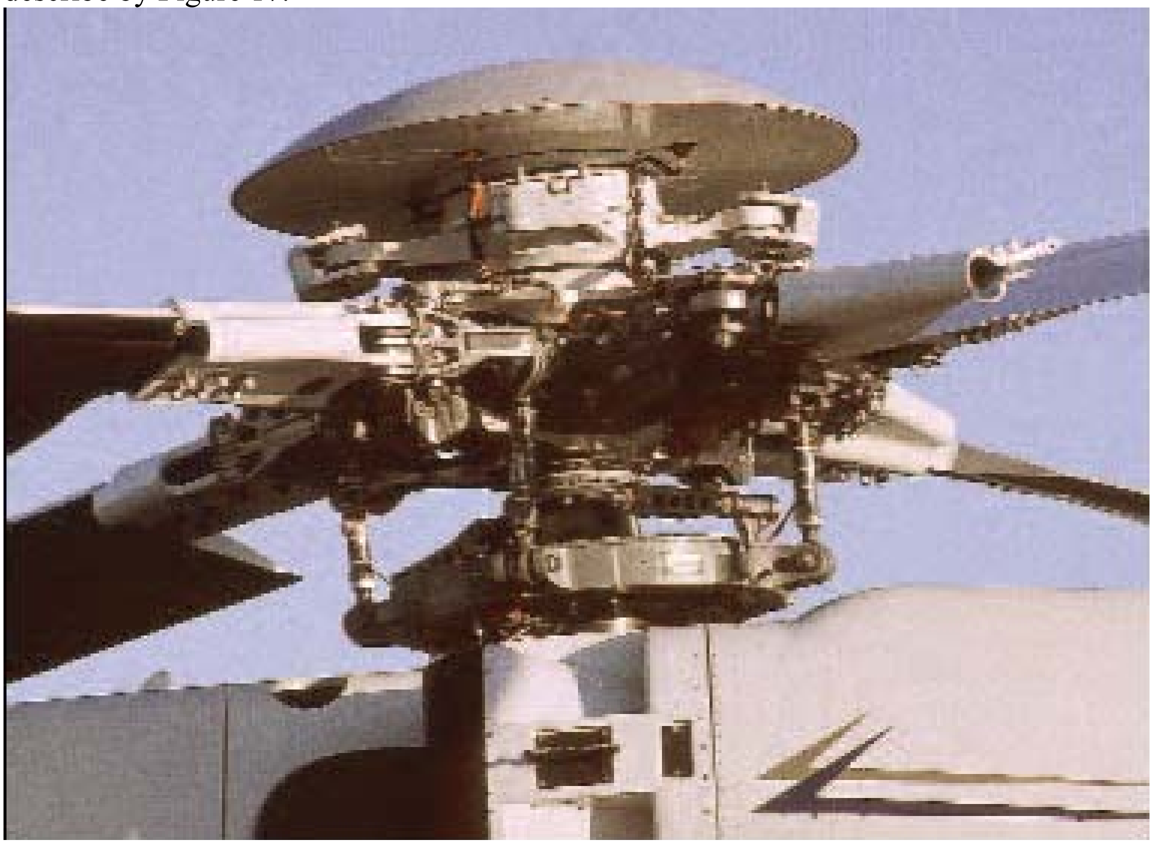

Figure 15a. Sikorsky S-92 hub and rotating controls in detail.

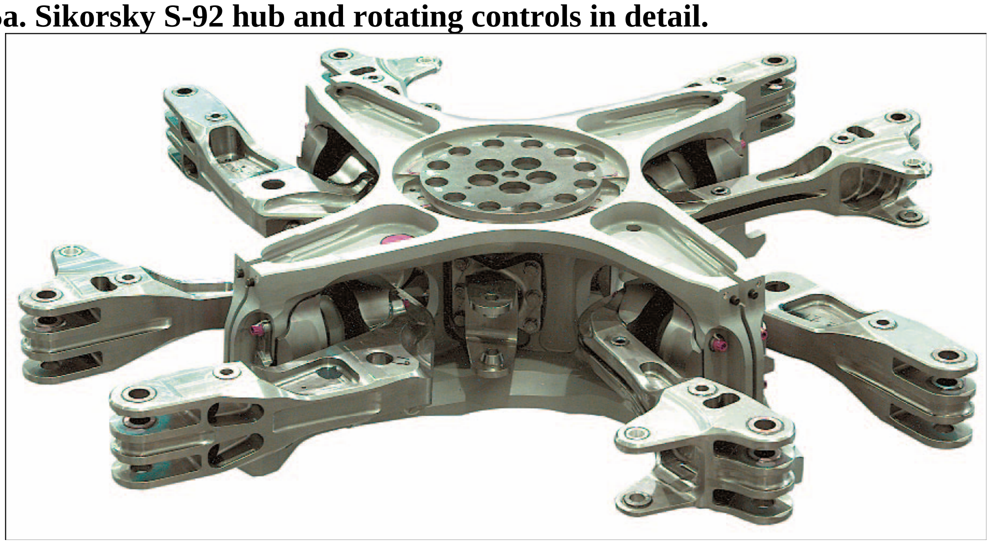

Figure 15b. Sikorsky S-92 basic hub.

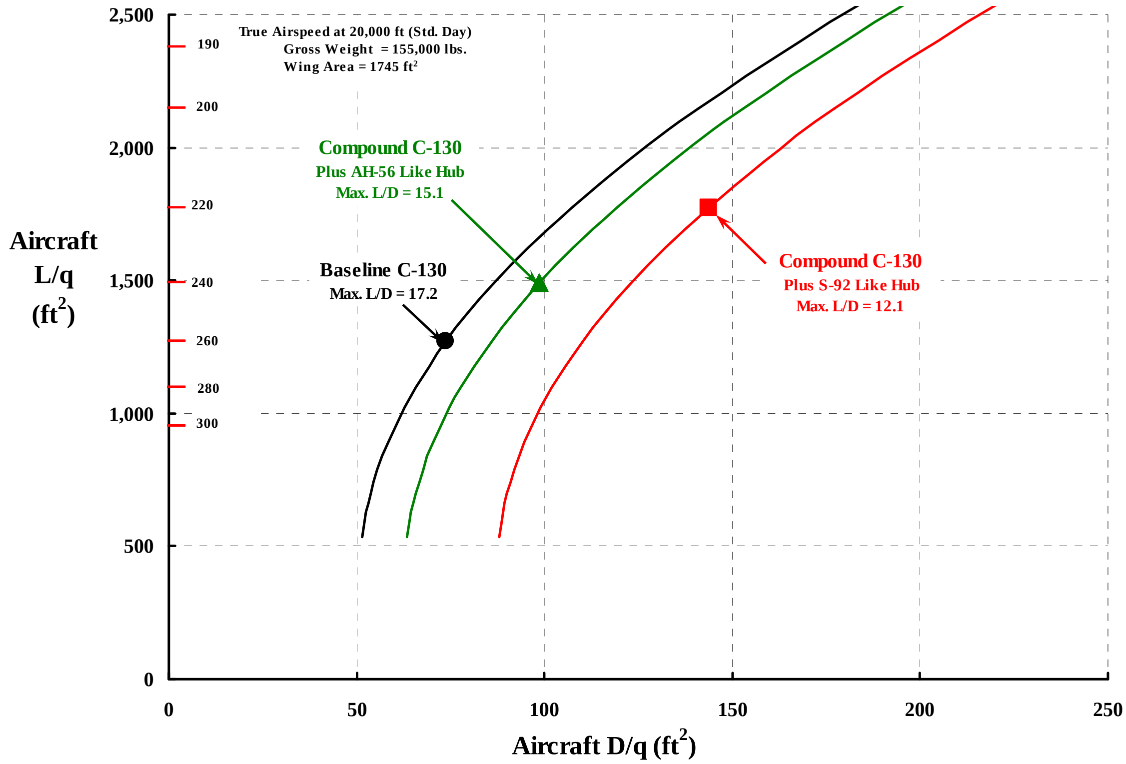

Figure 16. Impact of hub and hinge configuration and drag on Compound C-130 aerodynamics.

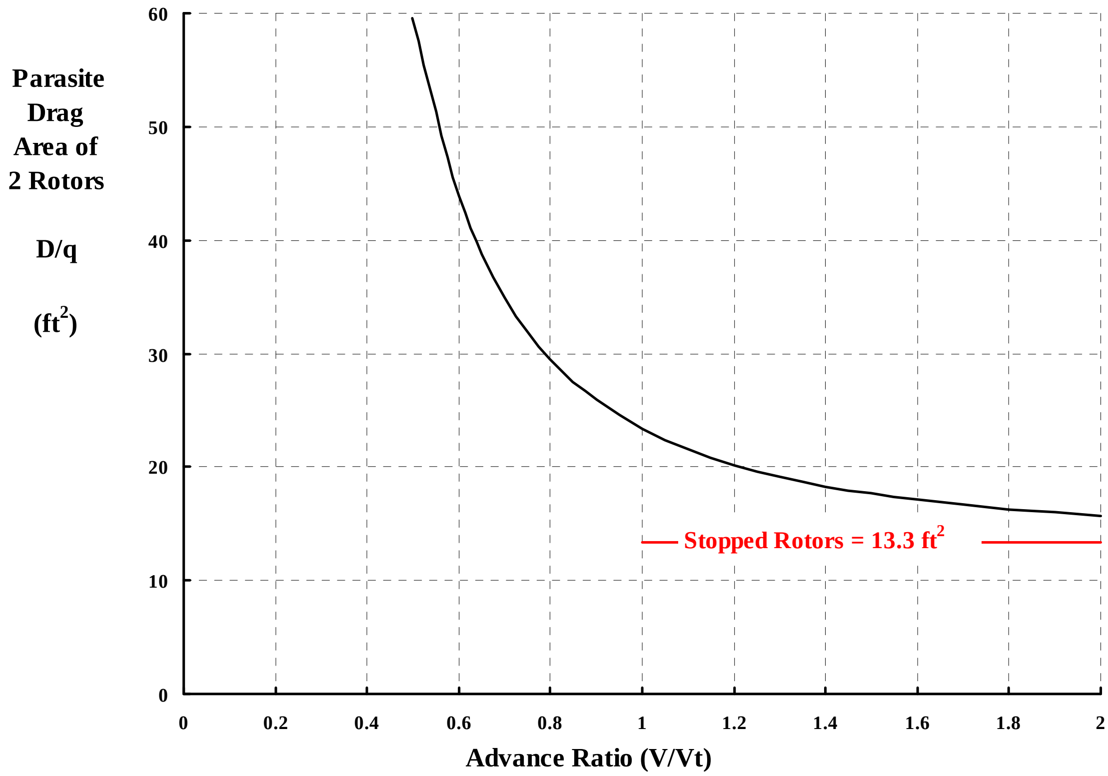

Figure 17. Compound C-130 rotor blade minimum drag (by energy method).

The rotor blade drag is added to the Baseline C-130 plus hub drag shown on Figure 16 with Figure 18. This result assumes that the low drag, AH-56 type hub is the choice. The drag polar is amplified with rotors operating at advance ratios of 0.5, 1.0, 1.5 and with the rotors stopped (i.e., $\mu = \infty$). The consequences of not slowing the rotor rpm in forward flight can be severe as Figure 18 shows.

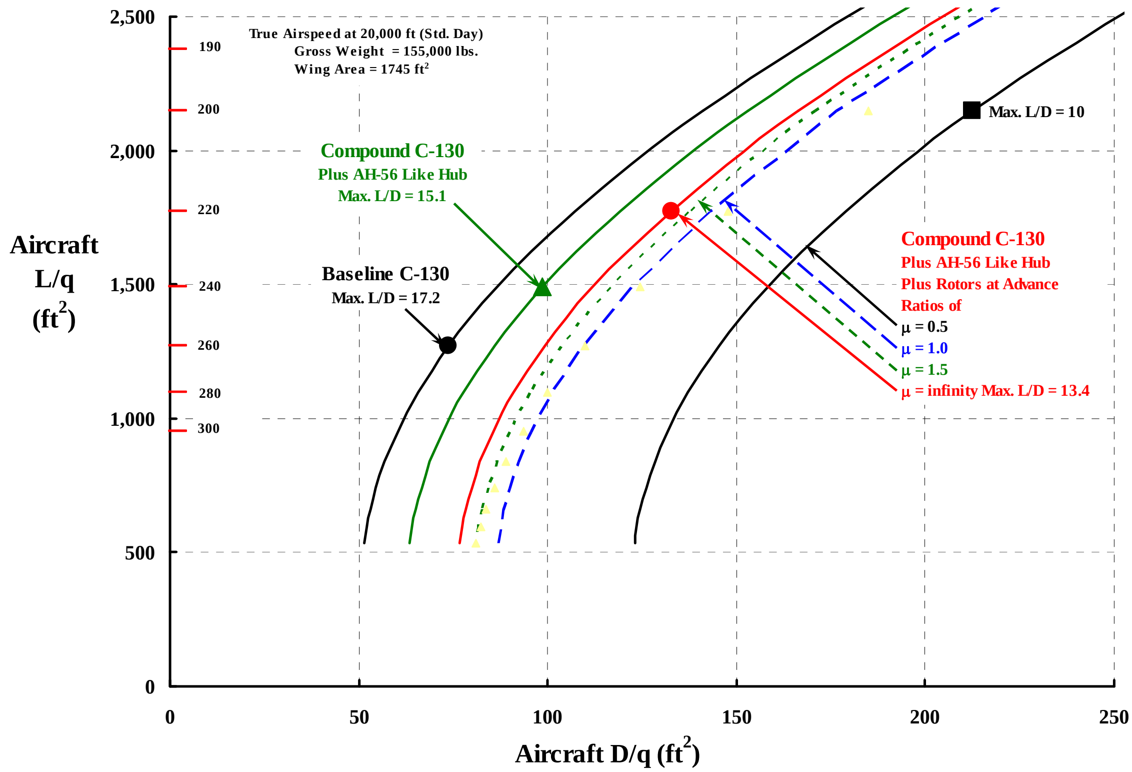

Figure 18. Baseline C-130 plus AH-56 type hub plus rotor blade minimum D/q at several advance ratios.

In view of these simple facts, the authors somewhat arbitrarily chose to operate the Compound C-130 rotor system at a tip speed of 450 feet per second in the compound mode. This choice removed compressibility losses for the aircraft operating at 20,000 feet on a standard day. Also, this is a reduction from 650 feet per second selected for hovering and helicopter mode flight, a selection favoring low noise in hover. The use of a constant forward flight tip speed means that advance ratio varies with true airspeed and this changes the lift – drag polar. The effect is summarized with Figure 19. Note that using a tip speed of 450 feet per second reduces the maximum lift to drag ratio from 13.4 for a stopped rotor (Figure 18) to 12 for the Compound C-130 under concept study in this paper.

The authors viewed the Compound C-130 as needing an advanced propeller and drew upon the NASA Advanced Turboprop Project (Reference 8) for the forward propulsion system. This NASA project led to flight hardware as shown with Figures 20 and 21. A 16.5 foot diameter propeller having a solidity of 0.29 was selected for NDARC analysis. In hover this Compound C-130 propeller operated at 721 feet per second tip speed and aircraft yaw control would be obtained from differential pitch. In forward flight, the propellers would operate at reduced tip speed of 500 feet per second, the same slowed speed ratio as the main rotors.

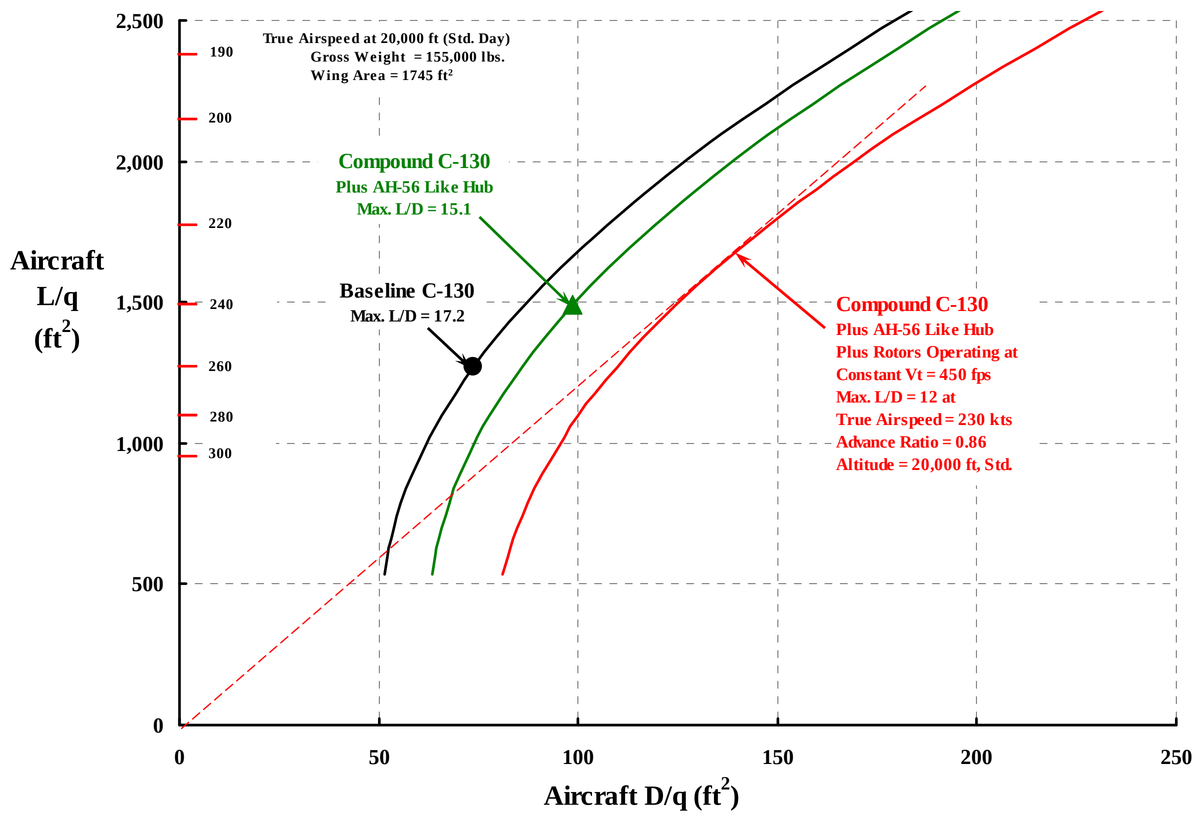

Figure 19. Baseline C-130 plus AH-56 type hub plus rotor blade minimum D/q at constant V_{tip} = 450 fps.

Figure 20. NASA Advanced Turboprop Project single rotation assembly on PTA aircraft

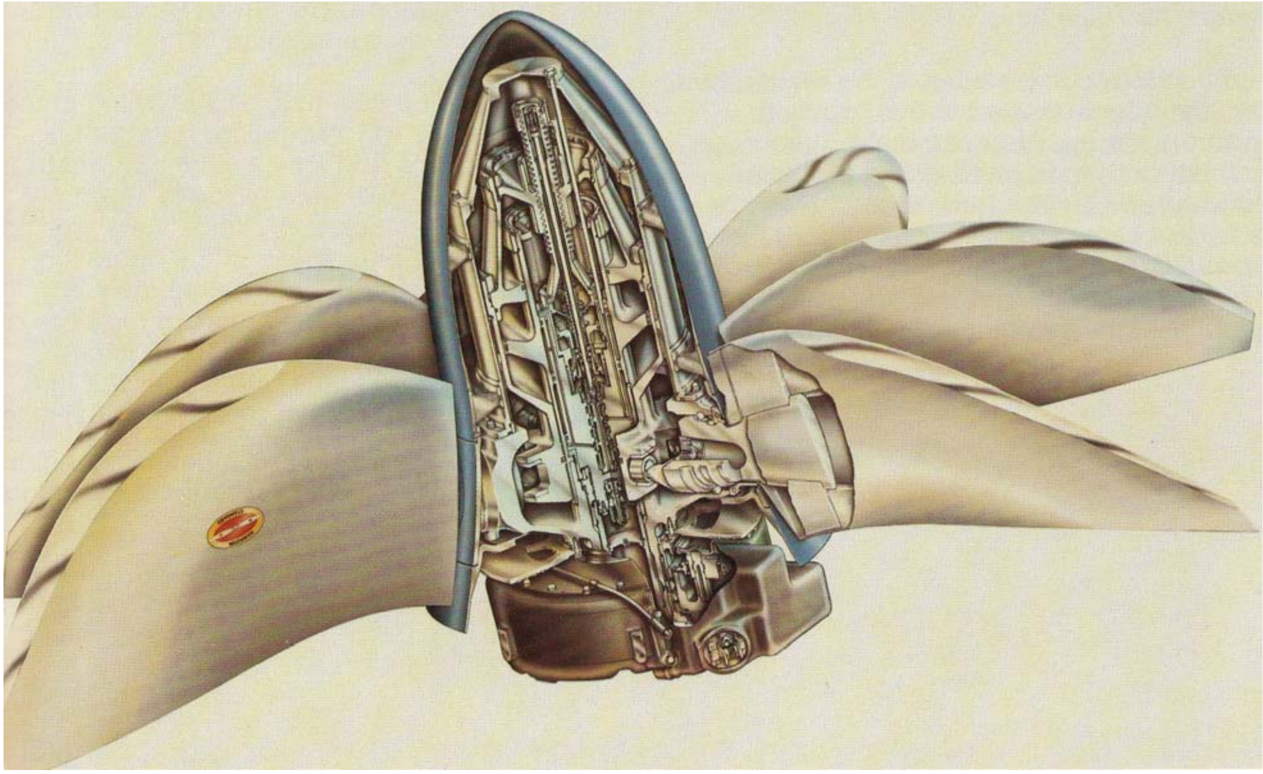

Figure 21. Blade feathering assembly for advanced propeller.

Performance

NDARC was used to study the trim and performance of the Compound C-130. With respect to trim, it is helpful to re-study the Russian Ka-22 side view (Figure 22) in detail. It is immediately seen that the propeller thrust is inclined downward from the fuselage reference line (about 5 degrees). Furthermore, the rotor shaft appears to follow the propeller rotational angle because the rotor shaft looks perpendicular to the propeller thrust vector. The inference to the authors is that the aircraft was setup to cruise with the fuselage flying at a positive 5 degree nose up angle of attack. Given this presumption, the rotor shaft would operate in cruise at virtually zero angle of attack. This assumption was incorporated into the Compound C-130 concept study. The additional constraint imposed was that rotor cyclic pitch would trim the rotor tip path normal to the shaft for all conditions. This constraint minimizes fatigue stresses on the rotor system components.

The primary effect on trim examined during this study was increasing the lift of two rotors from zero to 40 percent of the 155,000 pounds gross weight. Two true airspeeds – 175 and 275 knots (advance ratios of 0.66 and 1.03 respectively) – with the aircraft operating at 20,000 feet on a standard day were studied. Several parameters of interest are illustrated with Figures 23a thru 23e, with a brief summary as follows.

1. Power required is relatively unaffected by rotor lift over a wide range in lift centered around about $L_{rotors}/GW = 0.2$.

2. Fuselage angle of attack is reduced by increasing rotor lift. It is likely that cruise attitude can be improved by varying rotor shaft incidence, but this design aspect has been left to the preliminary design phase.

3. The collective pitch required to obtain lift can be substantial. Furthermore, there is a control reversal that occurs in going from an advance ratio of 0.66 (175 knots) to 1.03 (275 knots). This control system complication is well predicted by NDARC and is further discussed in Reference 9. The figure shows that for the assumed shaft incidence, a fixed collective pitch of -5 degrees for the untwisted rotor blades would be a reasonable choice. (This early version of NDARC experienced some trim searching problems in the intermediate speed range because it searches for the collective pitch required to obtain the desired rotor lift. When the change of rotor lift with collective pitch is near zero, this early version of NDARC cannot reach a conclusion, which compromises some output.)

4. The cyclic feathering required to trim the rotor tip path plane normal to the rotor shaft and virtually zero out blade once per rev flapping is very sensitive to rotor lift. The cyclic feathering interacts with collective pitch and reflects the control reversal associated with high advance ratio operation.

5. The effect of rotor trim and lift on rotor power required can be substantial. The rotor is obviously capable of adding and subtracting energy depending on trim. This situation implies that some means of controlling rotor speed is an inherent requirement for compounding. The authors chose to maintain a positive drive shaft connection so that the energy could flow back and forth without serious concerns about rotor over speeding – or stopping.

This study of trim suggests that rotors carrying somewhere between 0.15 and 0.20 of the gross weight would be feasible. Particularly because the blade collective and cyclic feathering is relatively low in this range of rotor lift for the 20,000 foot, standard day design cruise condition

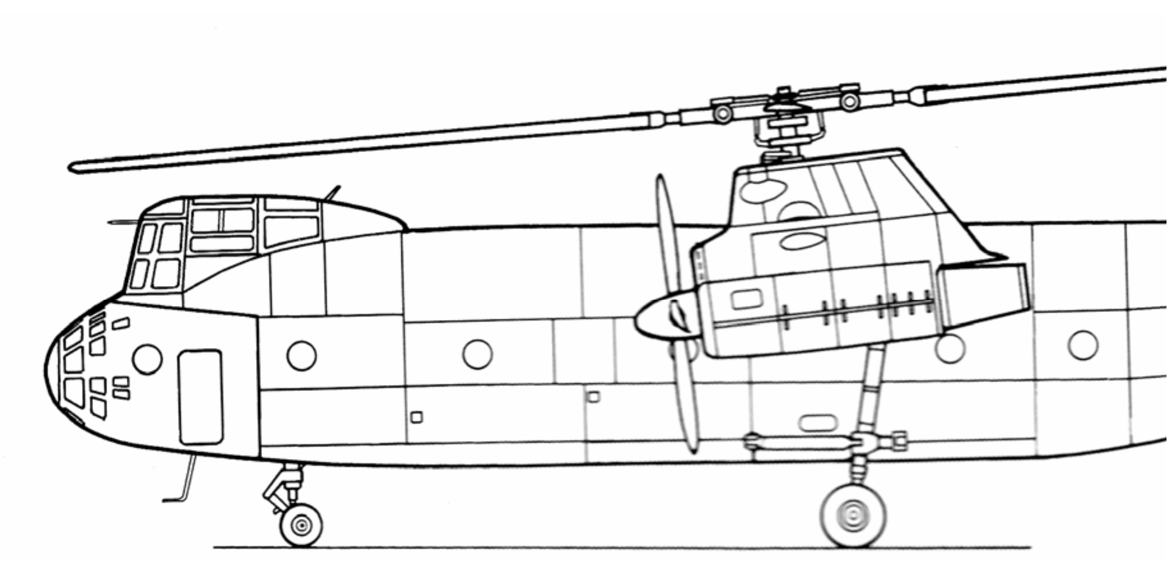

Figure 22. Ka-22 profile view showing angle between propeller thrust line and fuselage reference line.

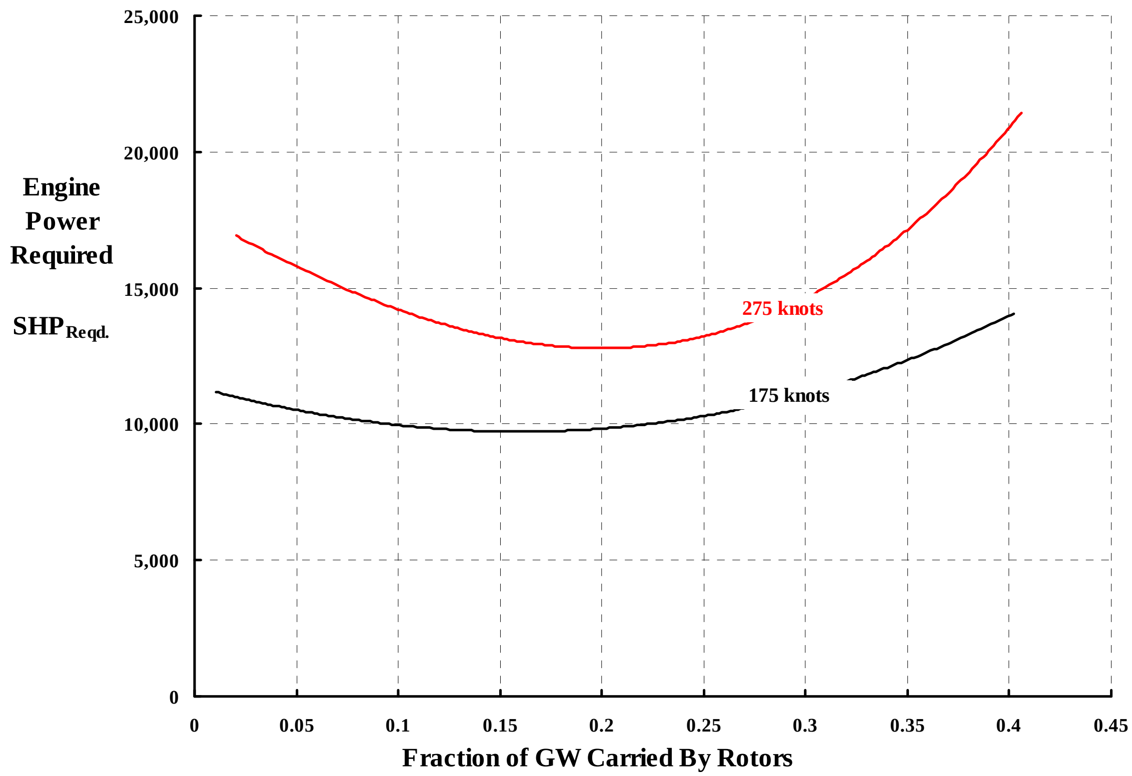

Figure 23a. Effect of rotor lift on power required.

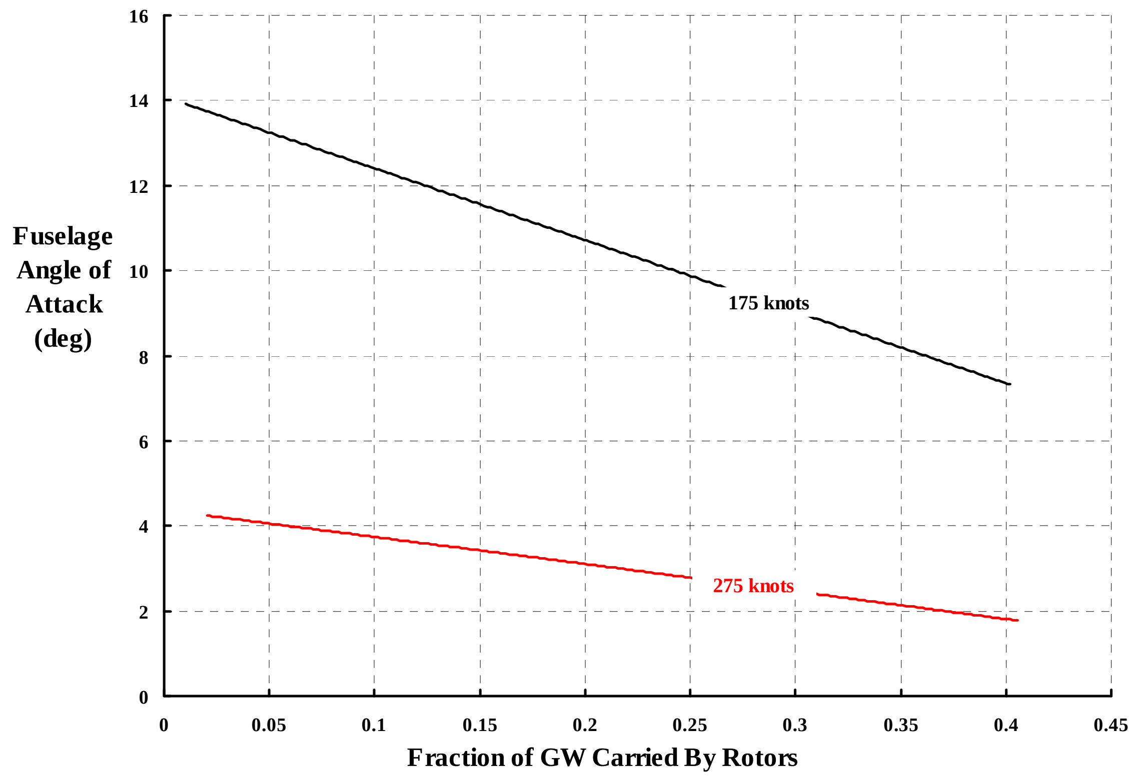

Figure 23b. Effect of rotor lift on fuselage angle of attack.

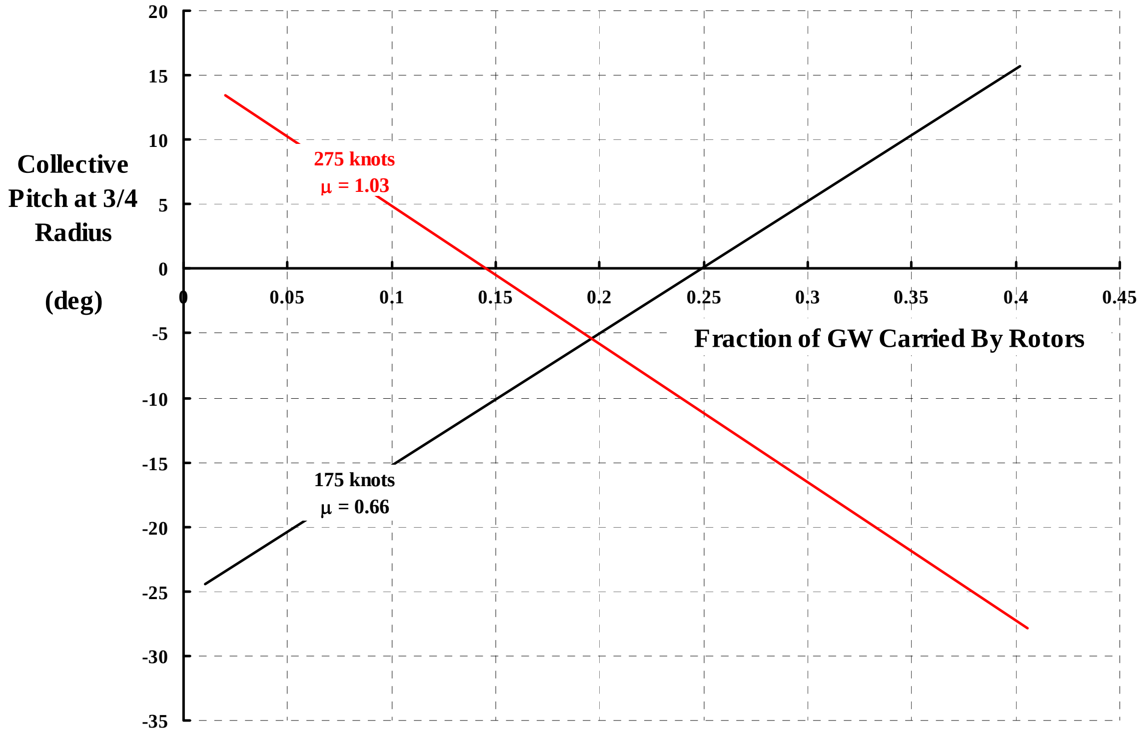

Figure 23c. Collective pitch required to obtain rotor lift.

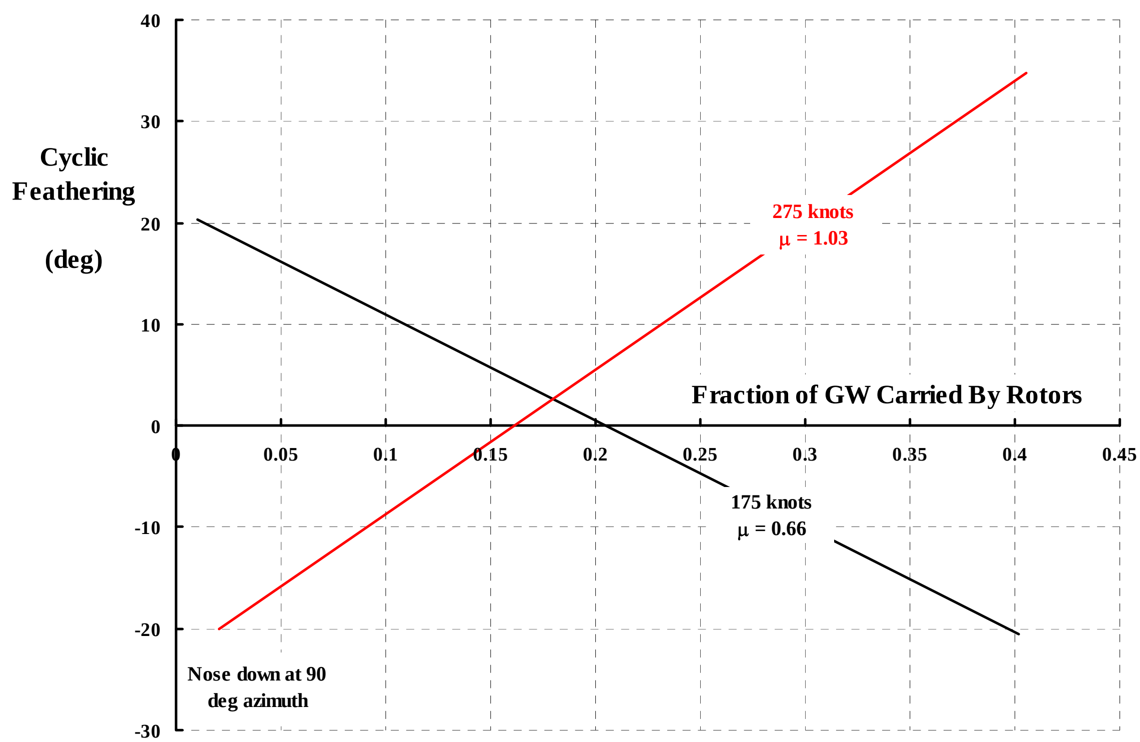

Figure 23d. Cyclic pitch required to trim rotor tip path plane normal to rotor shaft.

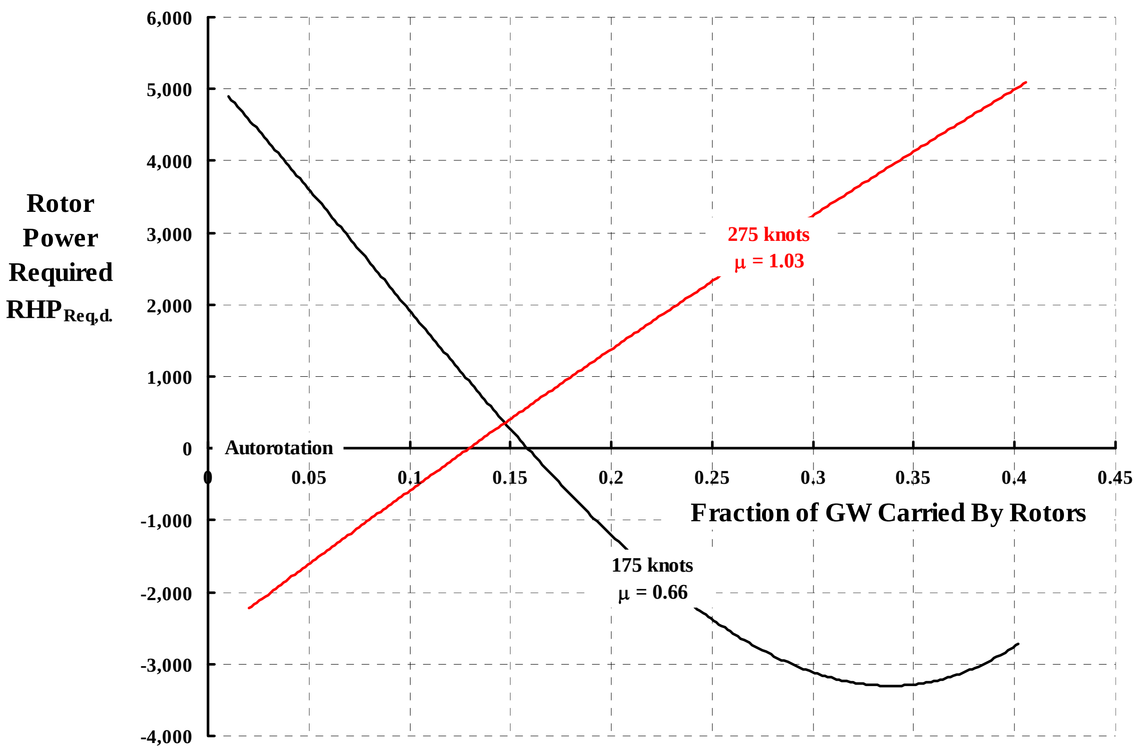

Figure 23e. Rotor power required as affected by rotor trim and lift.

Based on Figures 23a to 23e, the authors concluded that the compound C-130 should operate at all forward flight conditions with minimum blade feathering and with the rotor tip path plane normal to the rotor shaft. (Rotor shaft incidence variations other than zero degrees were not examined in this concept study.) Operating with minimum feathering would maintain the lowest fatigue stresses in the rotor system components. Application of NDARC showed that rotor lift as a fraction of gross weight would vary somewhat with flight condition and power required would not be an absolute minimum at off design conditions. Emphasizing fatigue stresses over performance appeared prudent to the authors.

The Compound C-130 performance at 20,000 feet on a standard day with the aircraft at 155,000 gross weight is provided with Figure 24. The performance from takeoff, through transition and up to maximum cruise speed is provided with Figure 25. The design condition is 4,000 feet on a 95°F day with a takeoff gross weight of 155,000 pounds. The authors envision the Compound C-130 drive system having no clutches, so at takeoff the propellers are at zero thrust and at a tip speed of 721 feet per second. The main rotors were set to operate at 650 feet per second and sized to a design C_T/σ of 0.15. NDARC computed performance in the speed range from hover to 100 knots true airspeed with the compound flying as a helicopter. Between 100 and 150 knots, the transition is initiated by bringing on propeller thrust and reducing each rotor's propulsive force. The rotors were set in NDARC to provide the majority of lift until the 150 knot point is reached to avoid any wing stalling. The transition is completed by reducing engine speed from 100 percent to 70 percent, which reduces both propeller and rotor speeds. In the compound mode, NDARC found minimum blade feathering with the tip path plane normal to the shaft and with the rotors carrying 0.12 of the 155,000 pound gross weight.

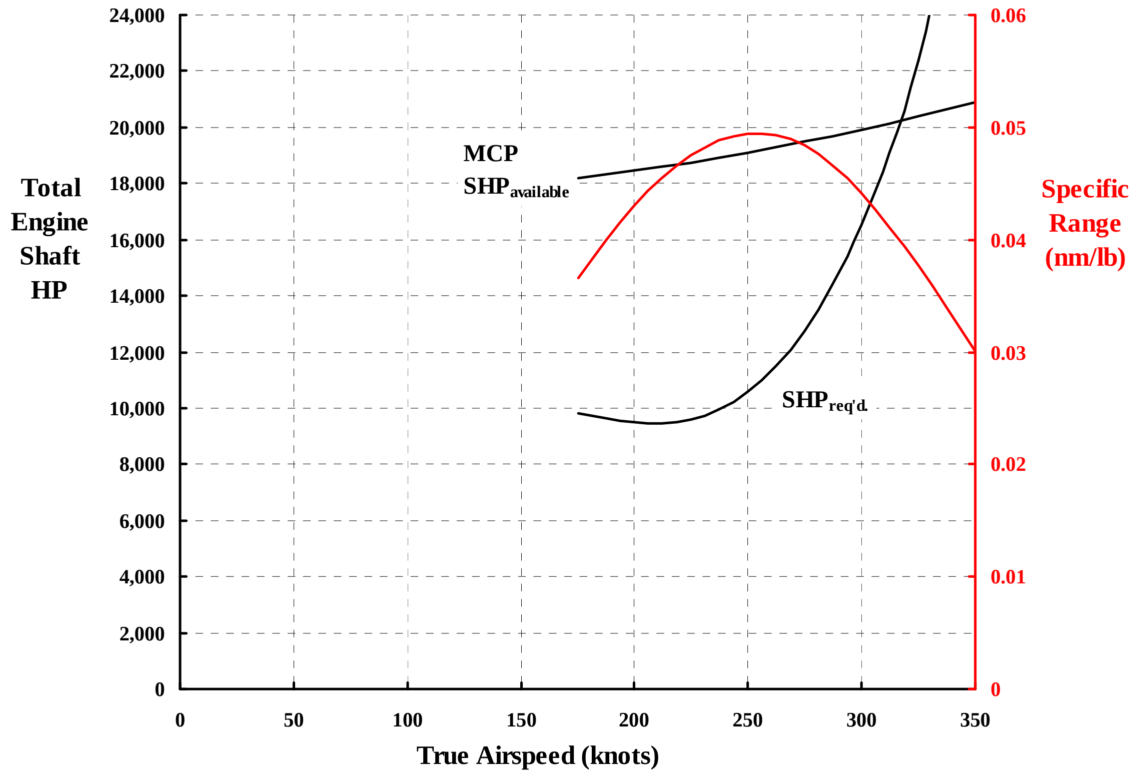

Figure 24. Performance at 20,000 feet on a standard day, gross weight of 155,000 lbs.

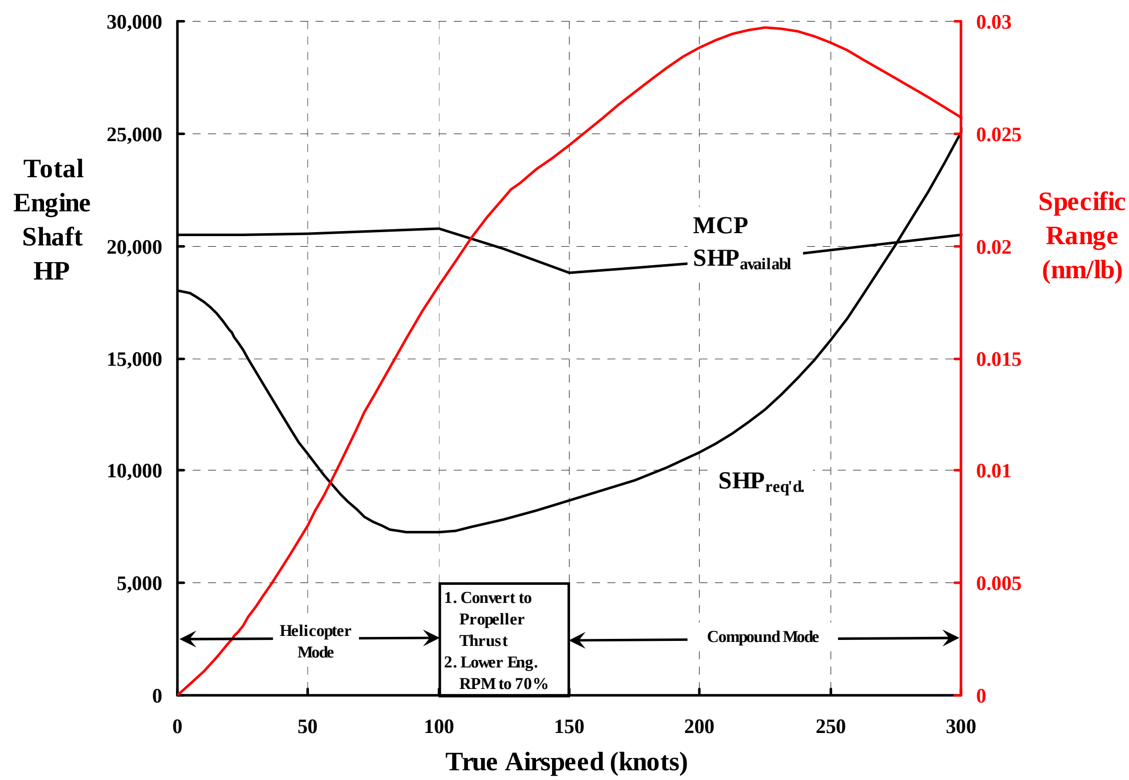

Figure 25. Performance at 4,000 feet on a 95°F day, gross weight of 155,000 lbs.

CONFIGURATION COMPARISONS

The brief summary comparison of the weights, aerodynamics, and performance is presented in Table 8 while the more detailed performance at both the Army hot day and cruise altitude conditions are shown in Figure 26, 27 and Figure 28

Table 8. Summary Comparison

Parameter	NDARC C-130H	Compound C-130	Factors
Weights (lbs)			
Structures Group	41,579	59,763	Add Blades at 8,906 And Hub & Hinges at 8,624
Propulsion Group	19,603	43,866	Add Drive System at 17,564, Bigger Engines at 3,676, Larger Props at 1,054, Increased Fuel Flow at 1,667, Other at 302
Systems Group	16,250	17,301	Rotor controls
Weight Empty	**77,431**	**120,930**	**Delta of 43,500 for VTOL**
Fixed Useful Load	1,400	1,400	
Useful Load	76,169	32,670	Weight Empty Growth
Normal Gross Weight	155,000	155,000	Design Constraint
Aerodynamics			
Maximum L/D	17.2	12.0	Add Hubs L/D Down to 15.1 Add Blades L/D Down to 12.0
Performance at Normal GW			
Engine MRP (shp)	4 at 4,591	4 at 7,840	Hover on 3 engines at ERP at
Take Off (Over 50 ft) (ft)	11,500	0	4,000 feet, 95°F day
Max. Cruise Speed at 20,000 ft. Std. (kts)	330	320	Engines at Max. Cont. Power
Long Range Cruise Speed, 20,000 ft. Std (kts)	300	280	Loss of 4.7 in Maximum L/D
Specific Range (nm./lb)	0.056	0.049	Higher Fuel Flow & $SHP_{req,d.}$

At the Army hot day takeoff condition (Fig. 26), the Compound C-130 requires more power than the NDARC Baseline C-130 at speeds above 150 knots. This power required increase is a result of the added drag due to the main rotors and the hubs, as described in the drag build-up. Figure 27 shows that comparable cruise speeds are obtained because of the increased power available required for engines sized for VTOL. Figure 28 shows the substantial decrease in specific range when converting from a C-130 to a Compound C-130.

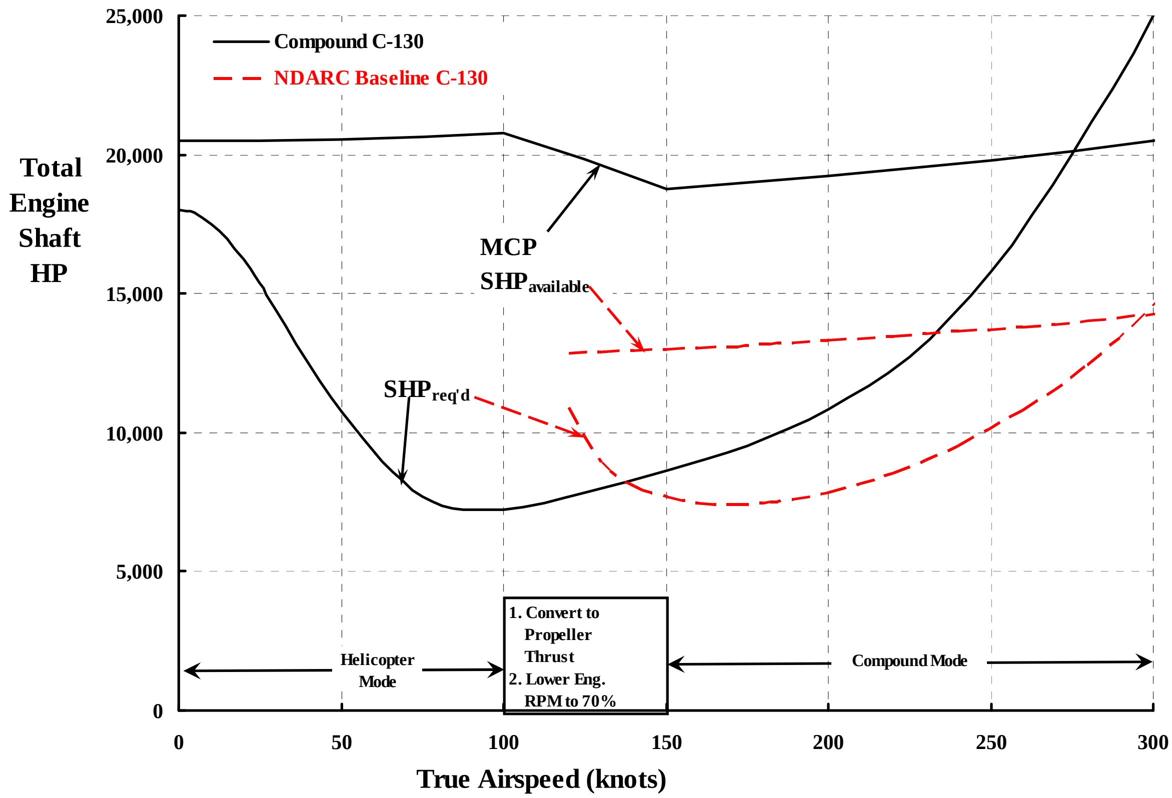

Figure 26. Power Comparison at 4,000 feet, 95°F Day.

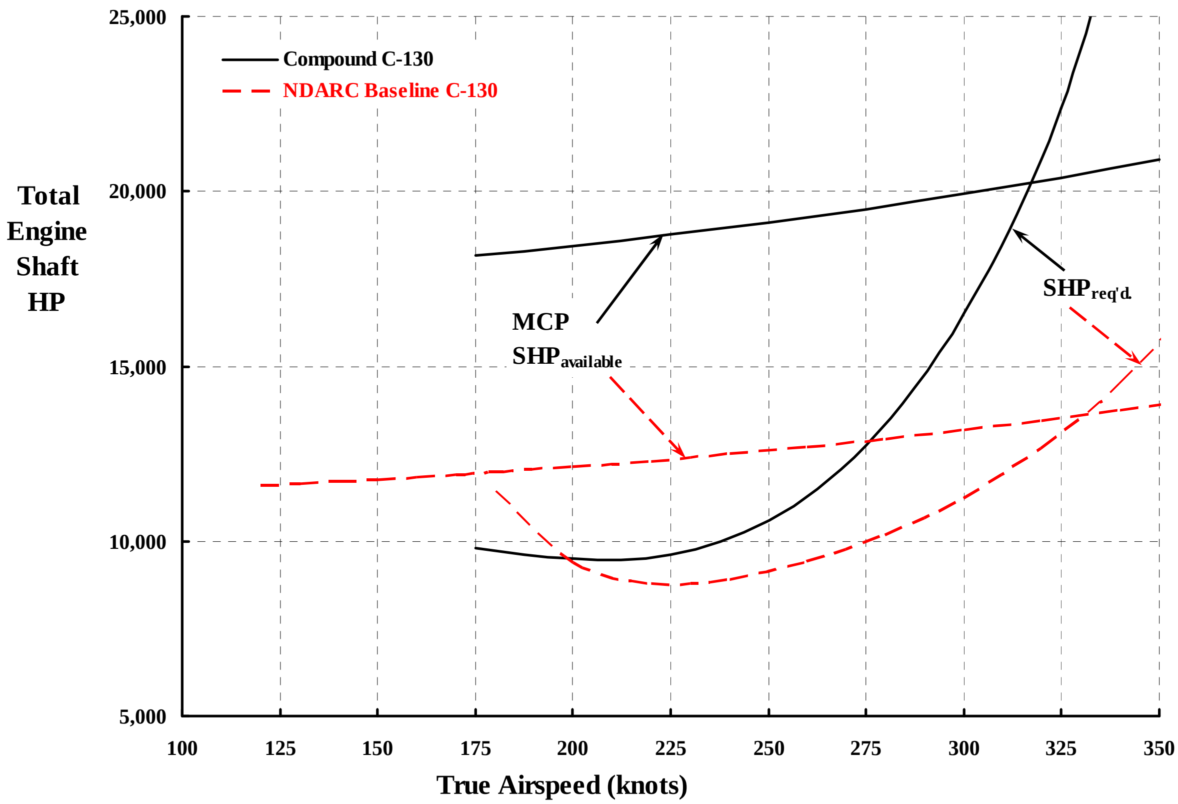

Figure 27. Power Comparison at 20,000 feet, Std. Day.

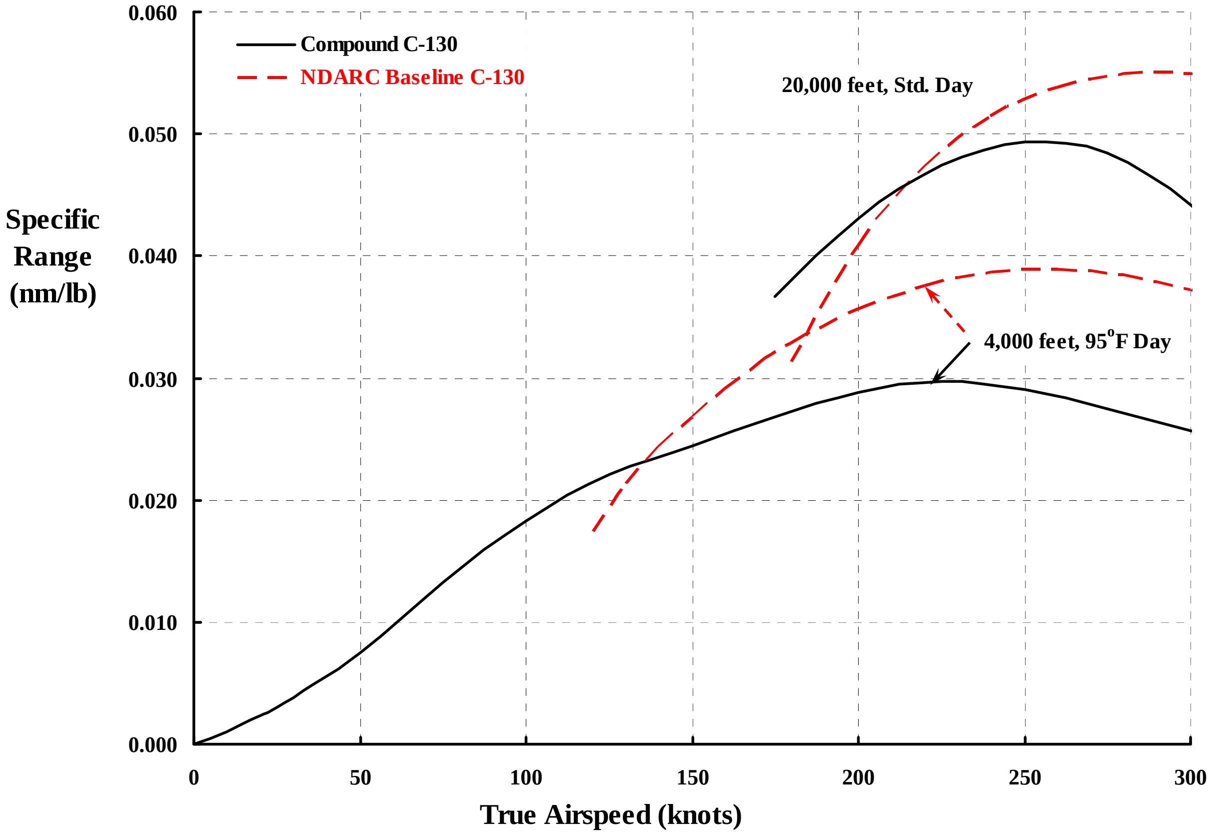

Figure 28. Specific Range Comparison.

CONCLUSIONS

Several conclusions have emerged from this concept study of what can be obtained if a conventional takeoff C-130 airplane is converted into a compound "helicopter":

1. The converted aircraft is more aptly called a compound airplane since it is derived from a very efficient airplane rather than a relatively inefficient helicopter.

2. Advanced, high modulus graphite composites ($E = 43{,}500{,}000$ psi, $\rho = 102$ lb/ft^2) offer an opportunity to reduce rotor blade weight by 30 percent relative to historical blade weight trends. The reduction comes about by designing for stiffness and deflection as opposed to designing for blade frequency placement. This approach places the second elastic flap frequency in the 3 to 4 per rev range versus the historical 2 to 3 per rev range.

3. The Lockheed AH-56A rotor hub is a most attractive starting point for edgewise flying rotors needing hub drag reduction. Because of its "door hinge" arrangement of small diameter feathering bearings, a low frontal area can be obtained with a stiff inplane, hingeless rotor system.

4. The U.S. Air Force Lockheed C-130 offers an airframe quite suitable to large scale compound airplane demonstration.

5. As an airplane, the C-130 power and propeller thrust available are well match to its aerodynamic efficiency (a maximum L/D of about 17 at an L/q of about 1,300 ft^2). However, the relatively low installed power offers poor takeoff performance at 4,000 feet on a 95^o day with a 155,000 lb normal takeoff gross weight. On this U.S. Army hot day and at normal gross weight, the C-130 requires an 11,500 foot runway (preferably concrete or asphalt) to clear a 50 foot obstacle.

6. Conversion of a C-130 to a twin rotored compound airplane (aka Russian Kamov Ka-22) increases the C-130 weight empty from 77,431 lbs to 120,930 lbs, which is a very significant reduction in useful load given a normal gross weight of 155,000 lbs. However, this compound airplane will takeoff and land vertically – even with one of its 4 engines inoperative.

7. Because of the installed, sea level standard day, military rated power increase (4 x 7,680 versus 4 x 4,591 hp), this compound airplane has comparable maximum cruise speeds to the Baseline C-130. However, this compound airplane's specific range is reduced about 15 percent principally because the aircraft's maximum L/D is reduced from 17 to 12; a decrease created by hub and rotor blade drag.

8. The NASA Ames developed NDARC program is a very powerful tool now available for many other concept studies

ACKNOWLEDGEMENT

The authors are deeply indebted to Wayne Johnson. First for the development of NDARC which made this concept study possible. Second, for his help and guidance in applying this very advanced tool.

REFERENCES

1. Johnson, W., Yamauchi, G. K., and Watts, M.E.: NASA Heavy Lift Rotorcraft Systems Investigation. NASA/TP-2005-213467. NASA Ames Research Center, Moffett Field, CA, 2005

2. Acree, C. W., Yeo, H., and Sinsay, J. D.: Performance Optimization of the NASA Large Civil Tiltrotor. NASA/TM-2008-215359. NASA Ames Research Center, Moffett Field, CA, 2008.

3. Taylor, J. W. R. (editor): Jane's All the World's Aircraft 1995-1996. Macdonald and Jane's, London, UK, 1995.

4. Johnson, W.: NDARC NASA Design and Analysis of Rotorcraft, Theory, Release 1.0, NASA Ames Research Center, Moffett Field, CA, 2009.

5. Gessow, A; and Myers, G. C.: Aerodynamics of the Helicopter. Frederick Ungar Publishing Co., New York, NY, 1983.

6. Johnson, W.: Helicopter Theory, Princeton University Press, Princeton, NJ, 1980.

7. Harris, F. D.: An Overview of Autogyros and The McDonnell XV-1 Convertiplane. NASA/CR-2003-212799. NASA Ames Research Center, Moffett Field, CA, 2003.

8. Hager, R. D., Vrabel, D.: Advanced Turboprop Project. NASA/SP-495. NASA Glenn Research Center, Cleveland, OH, 1988.

9. Harris, F. D.: Rotor Performance at High Advance Ratio: Theory versus Test. NASA/CR-2008-215370. NASA Ames Research Center, Moffett Field, CA, 2008.