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THE DEVELOPING TECHNOLOGY AND ECONOMICS OF LARGE HELICOPTERS

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The Developing Technology
and Economics of Large Helicopters

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ABSTRACT

This paper discusses the changing helicopter scene and the natural evolution to larger aircraft. Future needs for transport services are examined and some analogies with fixed wing transport development presented. Studies of the developing technologies enhancing the design of larger helicopters show that tandem helicopters offer the same efficiency advantages of size as do fixed wing airplanes and that there are no formidable reasons why the tandem helicopter cannot continue to grow in size.

The civil growth potential of the larger helicopters and their economics are discussed and their characteristics compared with other modes of transport. Projections of future market developments are presented showing that with proper market development, large tandem helicopters could thrive and multiply in the short haul transportation role.

INTRODUCTION

Forty years of helicopter developments have shown steady technological progress as evidenced by the helicopter's ever increasing size, speed, range, and operational efficiency. Developments in rotor aerodynamics and construction, efficient lightweight drive systems, shaft turbine propulsion systems, flight control systems, and avionics have been primarily responsible for today's explosive civil growth (as well as the earlier growth in military helicopter capabilities).

The early pioneers of rotary wing flight foresaw the promise of the helicopter, and even though (in their eyes) progress was very slow, in retrospect the helicopter followed a similar growth pattern to the fixed wing airplane albeit displaced in time by nearly forty years. The phasing of the invention/demonstration periods, followed by early piston engine production, then early turbine engine production, and finally a maturing business having a much expanded growth rate, appears typical of both, as seen in Figure 1.

Helicopter size growth (shown in Figure 2) has been primarily a record of achievements by single and tandem rotor helicopters (except for the very large Russian MIL-12 lateral twin). The Boeing Vertol Company and its predecessor organizations have been at the forefront of the tandem rotor developments since the early flights of the HRP Marine troop transports, through the H-21 series, the H-16 long-range rescue/transport, the CH-46 and CH-47 series, and the U.S. Army's 35 ton payload Heavy Lift Helicopter (HLH).

Future military and civil applications point to the desirability for further advances in size and capability, and studies of the 300,000 pound and up gross weight class have continued. However, the military markets for these aircraft appear to be small without sufficiently high priority. Therefore, continuation of the HLH development, as well as development of larger helicopters appears to be contingent on the increasingly rapid progress in the civil transport market. If the market development continues to follow the fixed wing pattern, there will be a need and an economical capability for these aircraft during the next two decades. The paper addresses the developing civil need, the technologies, the growth capability in tandem helicopters, and the economic potential of the large helicopters.

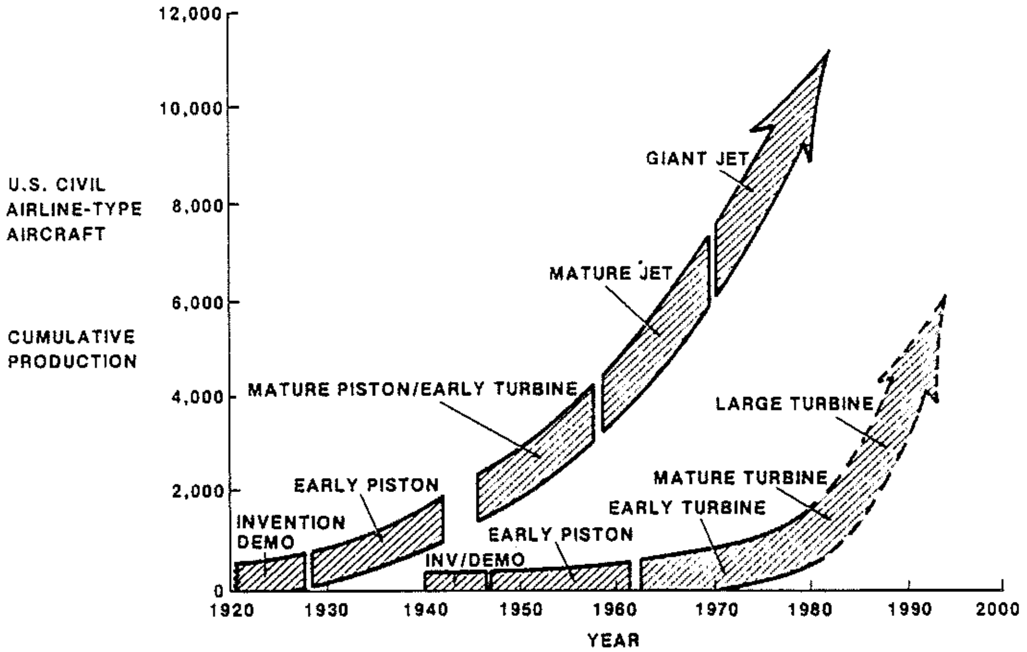


Figure 1. Historical Development

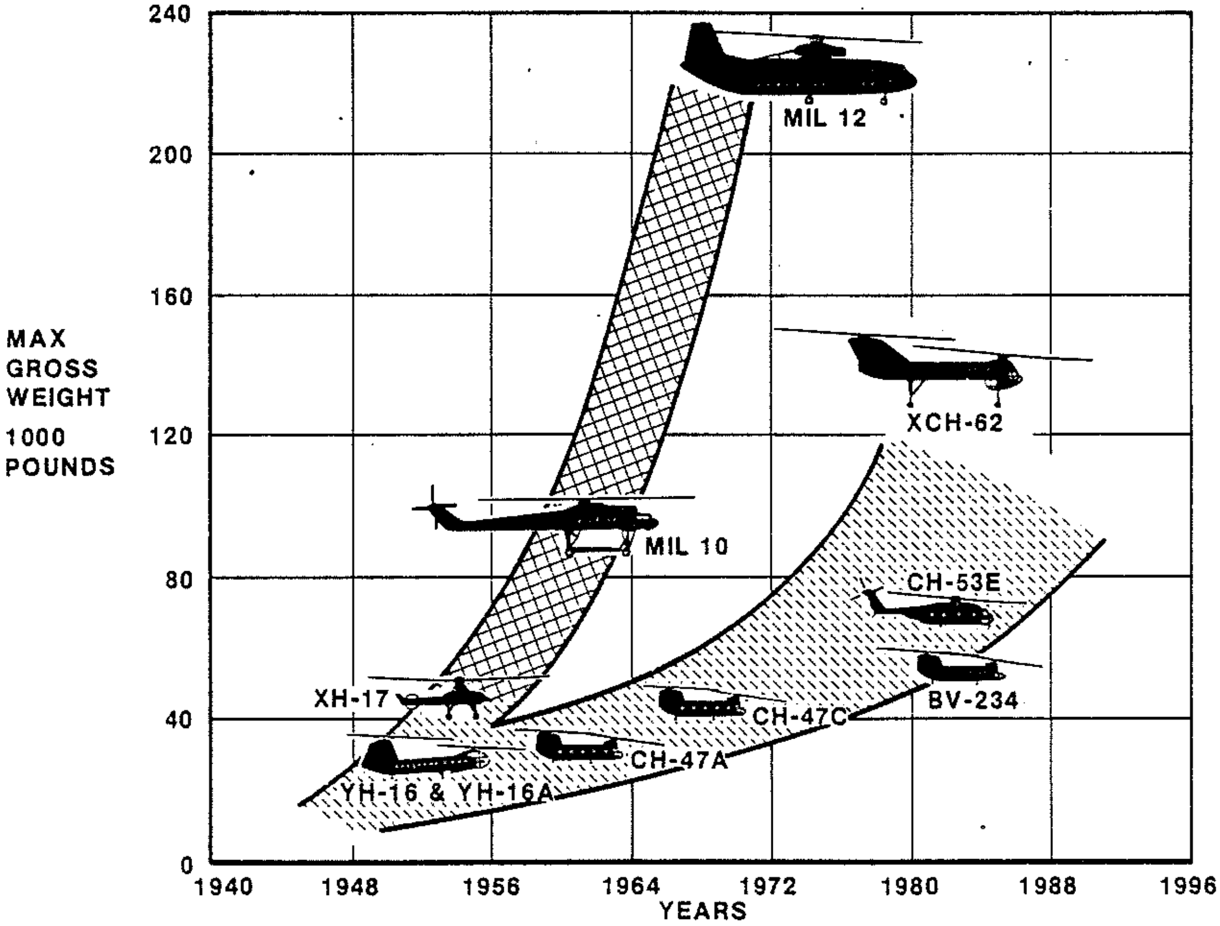


Figure 2. Helicopter Growth Trends

THE CHANGING HELICOPTER SCENE

In the late forties, civil helicopter operational experience began with the small piston engine aircraft available at that time. Although not capable of economical service on a scheduled airline basis, these operations led the way to further serious exploitation of the helicopter's potential. The first regular scheduled passenger helicopter service was initiated in June, 1950 between Cardiff and Liverpool by one of the predecessors of British Airways Helicopter — British European Airways. This, and other scheduled services, such as New York Airways, Sabena, Los Angeles Airways, Chicago Helicopter Airlines, etc., continued in one form or another for nearly twenty years — before most succumbed to the circumstances of the times (subsidy, losses, major airline apathy, manufacturer commitments to military programs, and in some cases, serious accidents). British Airways Helicopters has continued its operations using various helicopters up to the size of the S-61. However, it was clear even when the early turbine powered 25-passenger BV-107's and S-61's began their civil operations, that economical penetration of the short-haul market required even larger aircraft. Finally, BAH is about to initiate service with the 44-passenger Commercial Chinook in an airline-type operation, the North Sea oil rig support role.

The worldwide offshore oil explorations and support of the production oil rigs have already sparked an explosive growth rate in the smaller passenger transport roles. Here again, the pattern similarity to fixed wing is apparent. Figure 3 compares the seating capacity growth trends of both fixed wing and helicopters. The natural evolution to larger and larger aircraft is evident. It is hoped the helicopter can now, with the development of higher speeds and higher capacity, begin to be used in its fundamental role — that of short and medium-stage commercial air transport between city centers.

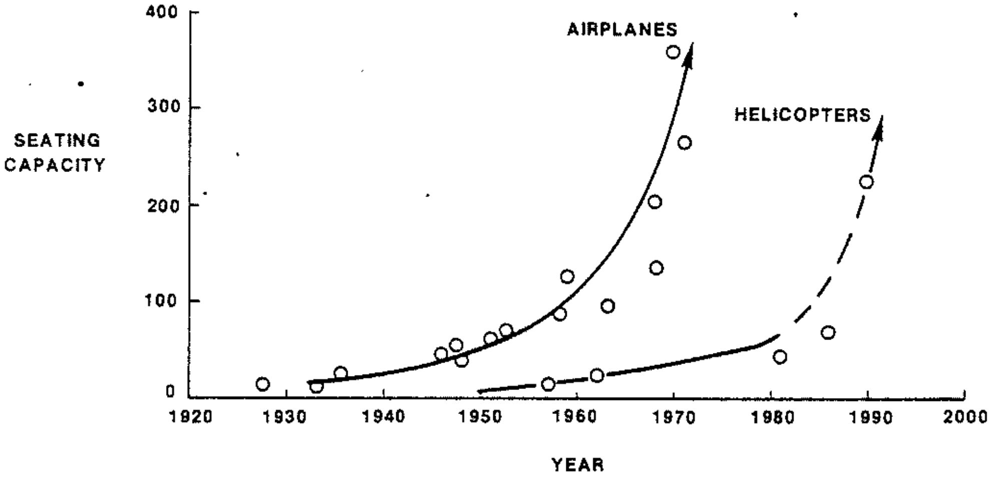


Figure 3. Seating Capacity Growth Trend

In the USA, deregulation of the airlines could provide the spark (and the business volume) to allow this dream to come true. Even before deregulation, the trend in airport congestion seemed to eventually force use of helicopters. Now since deregulation, the rapidly growing commuter activity has had a severe impact on hub cities and airport capacity is being strained to the breaking point. Creation of supplemental short-haul helicopter operations from the smaller cities to the hub cities could relieve this congestion without restricting growth and in addition, since probably only about 30-40 percent really want to go directly to the hub city airport, the downtown city-center traffic can be siphoned off to further reduce airport congestion and increase growth. Commuter passengers are showing that they value their time and are willing to pay enough to create this new capacity. As more and more passenger traffic is created, perhaps at the predicted growth rate of 15 percent per year, larger and more economical helicopters can be phased in and fill the needs of an ever-increasing number of city pairs for fast short-haul service.

TECHNOLOGY FOR GROWTH

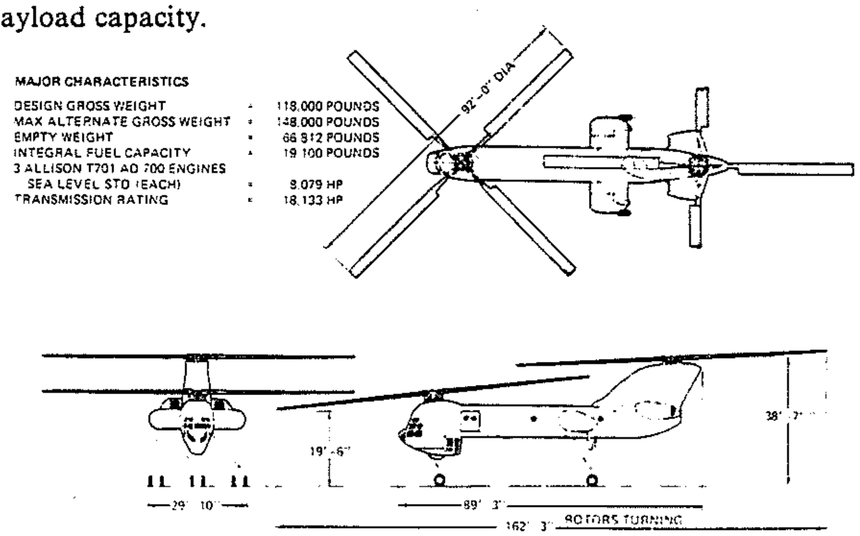
Throughout the history of the helicopter (and airplane), aside from speed, the primary thrust has been one of *ever-increasing* size since transportation economics benefit greatly from the resulting increased payload ratio, higher speeds, and longer ranges. Early attempts to develop quantum jumps in helicopter size were exemplified by the simple expedient of multiplying the number of lifting rotors — and the tandem helicopter, as well as lateral twins, trirotors, and quadrotors appeared on the scene. Of course, the apparent simplicity of adding rotors was afflicted with structural, dynamic, and complexity problems, and only the tandem multirotor helicopter has survived (along with the single lifting rotor plus tail rotor configuration) as the major type produced and operated in the world today.

Other significant efforts to develop large helicopters were concentrated in the area of tip-drive rotor systems (in order to eliminate development of large geared drive systems). Although a major portion of available R&D money was devoted to those systems, solutions for major challenges in the area of momentum drag, noise, vibration, fuel consumption, and rotor system weights were never within reach and these concepts fell by the wayside. In the meantime, tremendous progress in weight reduction, increased power capability, efficiency, and reliability of the geared-drives for helicopters was made, resulting in a continuous growth in size and efficiency.

A major step in the direction of very large modern transport helicopters was taken with the initiation of the U.S. Army's Heavy Lift Helicopter Advanced Technology Components (HLH/ATC) program in the early seventies. Although the aircraft itself was not completed and flown, the research and development programs demonstrated the feasibility of efficient, large helicopter components and reduced the risk and cost of future large helicopter developments.

Fundamental to the feasibility of large helicopters are the propulsion system components — rotor, drive, and engines — and the influence of these components on the configuration layout, empty weight, and performance. In addition, the requirements for reliable and lightweight controls militate for the use of fly-by-wire systems. In the HLH/ATC program, design, fabrication, and testing of each of these systems resolved the issues associated with weight, power, and cost of large systems and hardware, and established a design and manufacturing technology base for future programs. These developments are summarized in Reference 1, and briefly noted here.

The HLH configuration, which established the basis for the ATC development, is shown in Figure 4. The arrangements included an aft facing loadmaster's station, a 14-foot ground clearance under the fuselage for taxiing over a container, and an internal cabin for support troops, as well as dual tandem hoist of 28-ton payload capacity.



MAJOR CHARACTERISTICS

DESIGN GROSS WEIGHT	-	118,000 POUNDS
MAX ALTERNATE GROSS WEIGHT	-	148,000 POUNDS
EMPTY WEIGHT	-	66 812 POUNDS
INTEGRAL FUEL CAPACITY	-	19 100 POUNDS
3 ALLISON T701 AD 700 ENGINES		
SEA LEVEL STD (EACH)	-	8,079 HP
TRANSMISSION RATING	-	18,133 HP

Figure 4. XCH-62A General Arrangement

The challenge in the design of large diameter rotors is the satisfaction of blade droop, coning, and inertia criteria without incurring significant weight penalties. In the XCH-62A HLH, the criteria are satisfied for the 92-foot rotor by development of a structurally efficient fiberglass rotor blade which was below the blade weight trend line. A titanium rotor hub and an elastomeric bearing for blade flap, lag, and pitch motions also contributed to meeting the weight objective. To meet flight safety and reduced operating cost objectives, the blade, hub, and upper controls were designed for 100 percent fail-safety employing redundant structure and failure detection design techniques. A new family of airfoils, especially tailored for helicopter rotor blade usage, gave improved performance. Whirl testing of the rotor demonstrated rotor system functional and structural integrity and a hover efficiency figure of merit of 0.767, exceeding the design objective of 0.751, and equivalent to a four-ton increase in payload for the HLH compared to the technology of then current rotor systems.

One of the overriding concerns in the development of large shaft driven helicopters has been the design of transmissions for the higher torques brought about by high power and aggravated by lower rotor rpm. The challenge is in both the design of lightweight efficient transmissions and the fabrication of the larger gears and cases. The size of the transmissions in the XCH-62A HLH configuration was reduced by virtue of the tandem rotor drive system arrangement shown in Figure 5. Still the requirement for HLH in terms of torque transmitted across a single spiral-bevel gear mesh exceeds that of any existing flight-weight transmission by about 2 to 1. In the design of the HLH gears, industry-wide aircraft gear design methods were employed, but problem areas unique to gear size were identified. It was found that the current AGMA design rating practices do not predict the magnitude of the bending stress as influenced by the tooth back up (rim thickness) material. The proportioning of tooth back up to tooth depth by current design practice was found to be inadequate for the HLH size gears resulting in excessive rim deflection and high root stresses. Testing in excess of 100 hours was accomplished on the initial designs of aft and combiner transmissions up to 70 percent of design rating or about 7,500 horsepower in a closed loop test stand, and in the dynamic system test rig shown in Figure 6 which included the 3-engines, combiner transmission, slant shaft, aft transmission, and rotor system. Further testing of the modified gears is now being initiated by NASA.

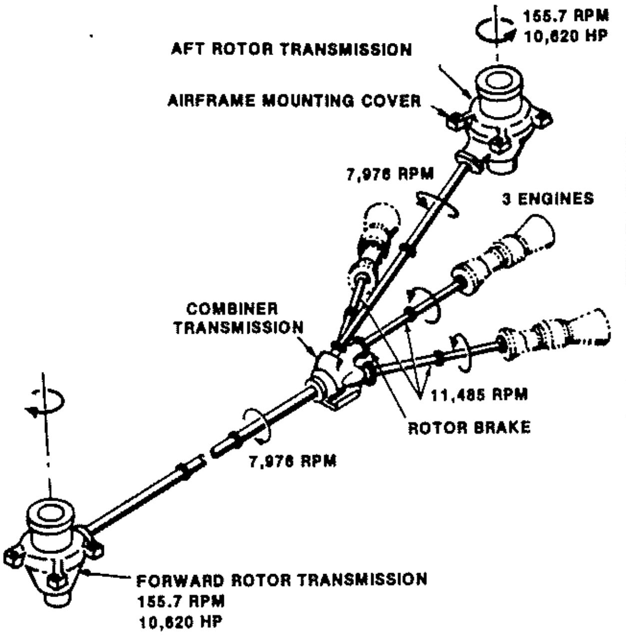


Figure 5. XCH-62A Drive System

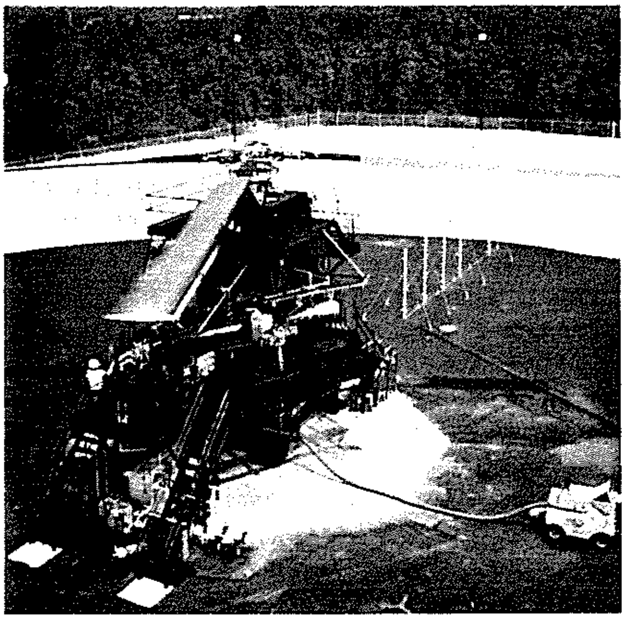


Figure 6. XCH-62A Drive System Test Rig

The objective of the HLH flight controls ATC program was the development of a fly-by-wire control system in which conventional mechanical control linkage is replaced by triple redundant wire runs. Design studies showed that flight safety could be increased 50 times through triple redundancy while realizing lower system weight and better maintainability through built-in test equipment. The fly-by-wire system was developed and flown on a modified CH-47 Chinook helicopter (Model 347), and major improvements in helicopter handling qualities were achieved with automatic stabilization and control augmentation made easier by the fly-by-wire system. The application of a fly-by-wire controls system in the ATC program was a first for helicopters, and when applied to future large helicopters, it will provide a significant reduction in weight and complexity over mechanical systems while providing exceptional stability and precision control necessary for passenger transport operations.

Design and construction of a prototype HLH flight vehicle was initiated about halfway through the ATC program to serve as a flying test bed for the ATC components. Designated the XCH-62A, the airframe was 95 percent complete at program termination. A comparison of the size of the XCH-62A with the CH-47 Chinook is shown in Figure 7. The airframe is of bonded honeycomb design, rather than conventional skin/stringer construction. This was the first aircraft to use bonded honeycomb construction for all primary airframe structure. This type of structure was selected because studies indicated that a large reduction in acquisition cost, due to reduced part count (23 percent), would be achieved. In addition, maintenance costs are expected to be reduced an estimated 65 percent for the HLH based on the operational history of honeycomb components to date. This reduction is a result of fewer parts, nonbuckling structure, minimized stress risers, and corrosion resistance. Composite panels, replacing the metal sandwich panels used on the XCH-62A, offer even further improvements.

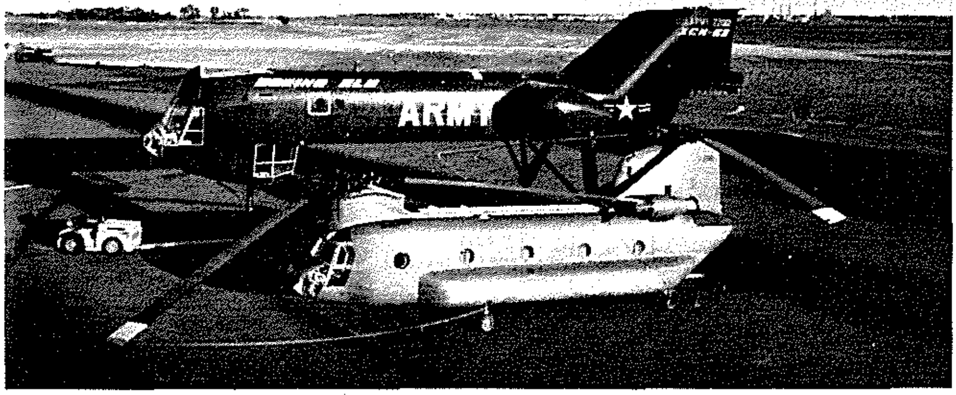


Figure 7. CH-47 and HLH Prototype

As a result of the ATC program, further evidence is available to establish the trend in useful load ratio resulting from advancing technology (Figure 8). It is apparent from this chart that an all-important element in this growth has been the developments in shaft turbine engine technology. Figure 9 illustrates the improvements in SFC resulting from size growth and advancing technology. The specially-developed (for HLH) 8,079 horsepower Allison XT-701 engines demonstrated fuel consumption about 25 percent lower in the cruise power regime than for current production engines.

Fortunately, technology never stands still. More recent improvements in helicopter technology will be available to the next generation aircraft. Even better airfoils and low drag rotor hubs have been developed. Fly-by-light is coming along and lighter weight and more reliable electrical, hydraulics and avionics systems will be available.

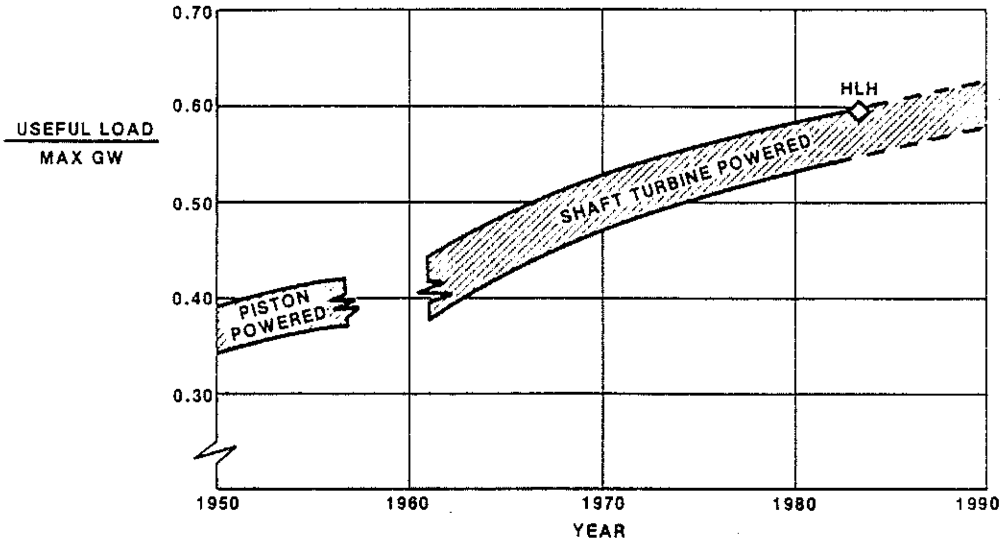


Figure 8. Advancing Technology Effects on Helicopter Useful Load Ratio

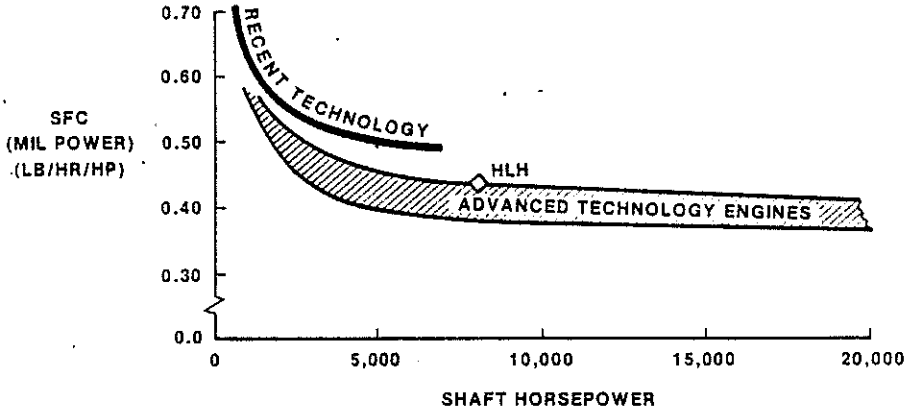


Figure 9. Specific Fuel Consumption Trends

HELICOPTER GROWTH POTENTIAL

Even though military operators have always had requirements for very large payload helicopters (for instance, a 26-ton payload requirement in the early fifties), issues of affordability have continually thwarted their attempts to develop the equipment. In recent years, the U.S. Navy and NASA have sponsored research and development investigations aimed at future missions for 75-ton payloads or more. Logging and forestry, construction, containership off-loading, and other lesser applications have been identified as potential civil missions for large aircraft. In addition, NASA has been working with the American Planning Association in examining short-haul air transport opportunities for rotorcraft (and fixed wing) (Reference 2).

In support of these activities, as well as exploration of the future potential of the helicopter in the civil passenger market, Boeing Vertol has continued studies of very large tandem helicopters to determine their growth potential, limitations, and economic viability. These studies have examined aircraft in the 300,000 pound and up gross weight class. Earlier studies (Reference 3) leading to the XCH-62A HLH procurement, had examined the 100,000—300,000 pound regime.

In the development of very large helicopters, the primary problems are those of ever-increasing transmission torque and larger rotor diameters which can result in state-of-the-art limitations on the payload size of the helicopters. These fundamental limitations, similar to the square-cube law so familiar in fixed wing development, are amenable to advancing technology improvements in materials, aerodynamics, and design techniques. Fortunately, the tandem rotor configuration, aside from its attractiveness in solving the antitorque requirements of lifting systems, has been primarily effective in allowing much smaller rotor diameters as well as reduced disc loadings (for lower installed power). Figure 10 reflects this general trend showing recent helicopter rotor diameters with respect to payload. Figure 11 defines the disc loading trends of these configurations and also projects the trend for very much larger aircraft. The single rotor trend shown here is as described in Reference 4 while the projected tandem rotor trend is based on Boeing studies. The extremely high disc loadings and the resulting diameters for the larger single rotor aircraft are necessary in order to control the blade coning angle (in this case the "constant coning angle assumption") and keep the blade droop angle within the configurational constraints.

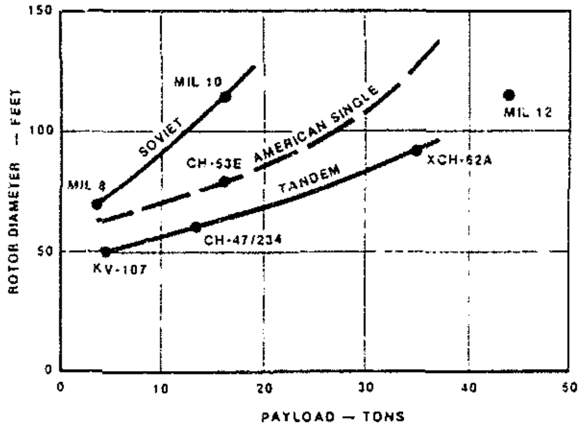


Figure 10. Rotor Diameter Trends

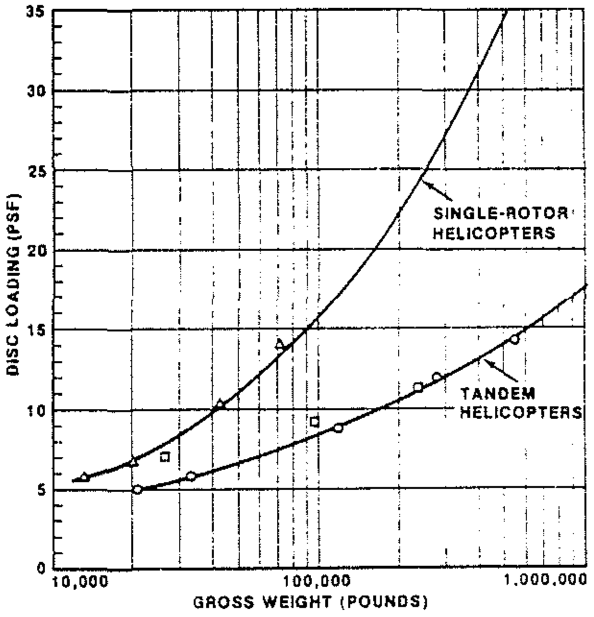


Figure 11. Helicopter Disc Loading Trends

Large coning angles must be avoided because of their adverse effect on blade coriolis forces which impact blade design loads and vibration levels. Large coning angles also reduce lift proportionately to the l-Cosine term. Blade coning angles of about 6 to 7 degrees (at design gross weight) have proven acceptable in past practice, and some small increase may possibly be handled. Coning angles are shown in Figure 12 for varying disc loading and nominal blade weight fractions. The trend illustrates that for very large helicopters (in excess of about 150,000 pounds) the tandem rotor configuration offers a low disc loading (low downwash and power) solution. While rotor blade tip weights are of some value, they are generally not desirable for their cascading effect on rotor weight as well as causing increased blade static deflection (droop). The static deflection, while at worst only a minor blade design structural problem, would increase with tip weights and have a severe effect on blade-to-fuselage or blade-to-ground clearances. Static droop limits of 3 to 5 degrees are typical since under dynamic conditions of start-up and shutdown in gusty weather, deflections several times larger can occur and blade-fuselage clearances are predicated on these conditions (as well as certain maneuver criteria).

While there have been great strides forward in transmission torque capacity over the years, perhaps the most limiting technical factor for very large helicopters is in the technology and manufacturing capability for large gearboxes. Since division of the power into a multirotor system reduces the design torque transmitted, the state-of-the-art in torque capacity will allow a near-doubling of gross weight for a dual transmission tandem system (Figure 13). Studies beyond the HLH drive system have shown the need for only evolutionary developments in the design and manufacture of larger gearboxes. Although planetary ring gear sizes are larger than present in-house quenching press capability, no special technical problems are foreseen for these operations or for ring gear grinding. The increased diameters do require modification and enlargement of today's fabrication tooling. Bevel gear sizes are within today's grinding capability and bearings are of today's standard. Of course, timely advances in materials and methods will contribute to further improvements.

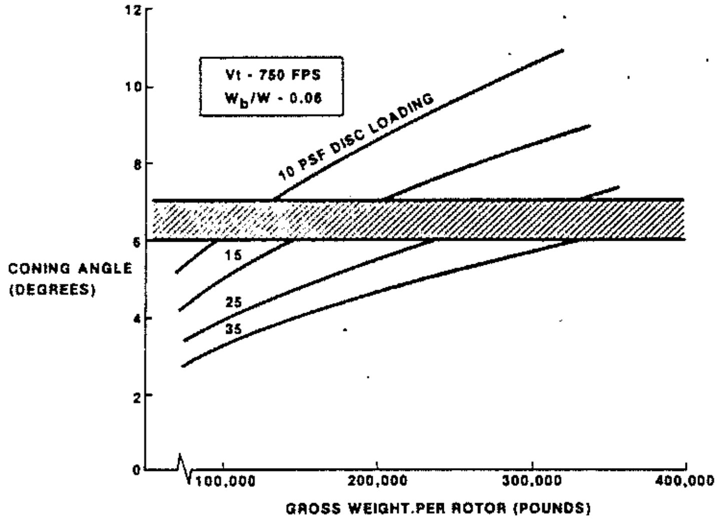


Figure 12. Coning Angle Trends

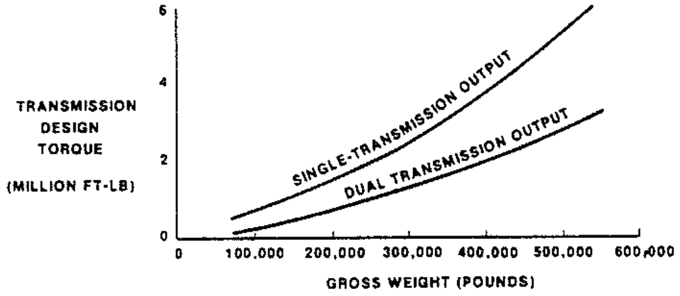


Figure 13. Transmission Design Torque Trends

CONFIGURATION ANALYSES

In order to define tandem helicopter growth potential, configuration development studies and parametric analyses have examined the layout of very large tandems, defined and studied the drive and power systems, structural arrangements and rotor systems, and calculated performance and weights parametrically over a wide range of sizes. Both passenger and external cargo missions were studied for their influence on layout and performance. It was found that, contrary to the general conclusions of Reference 4, tandem helicopters exhibit the same efficiency advantages of size as do fixed wing airplanes and within the range of gross weights studied, there are no formidable reasons why the tandem helicopter cannot continue to grow in size. With proper market development, large tandem helicopters could thrive and multiply in the short-haul transportation role.

Figures 14—17 summarize the parametric analyses. The empty weight trends shown in Figure 14 are similar to fixed wing with the upper band reflecting the inclusion of passenger accommodations while the lower band indicates the empty weight ratio for a typical utility external cargo mission. The effect of tandem helicopter size on power loading is shown in Figure 15 where, due to the relatively low disc loadings, it continuously reduces with size. Figure 16 illustrates the trend in fuel fraction for a 2.5 hour short-haul transport mission.

Combining these characteristic trends for large tandem helicopters in Figure 17, a continuous improvement with size is apparent for the critical parameter (payload fraction) similar to fixed wing. While these trends may vary with specific design requirements, in general, the message is pretty clear: large tandem helicopters provide a viable growth potential showing every efficiency advantage of size growth similar to fixed wing airplanes.

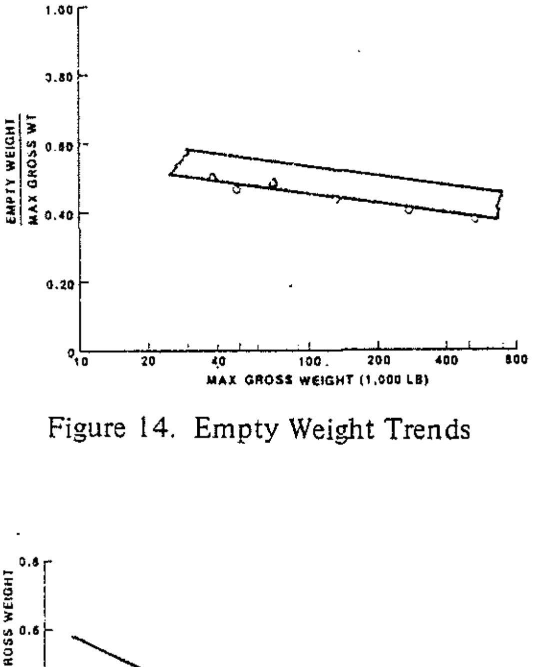


Figure 14. Empty Weight Trends

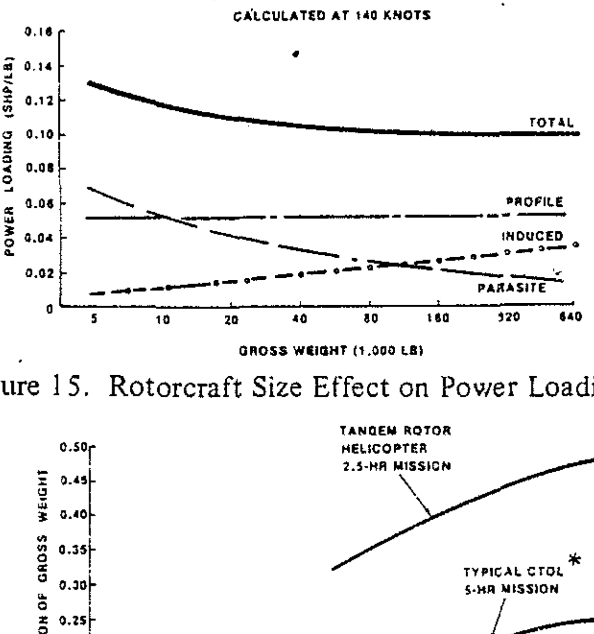
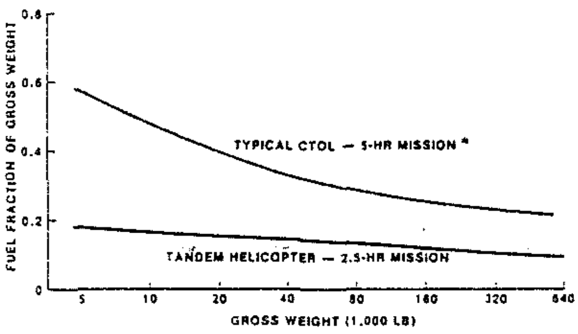
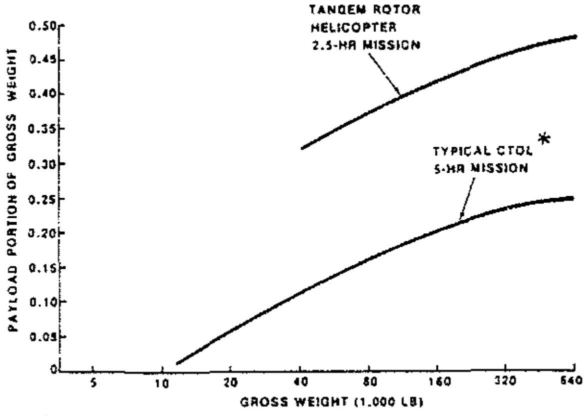


Figure 15. Rotorcraft Size Effect on Power Loading



* CTOL DATA FROM REFERENCE 4

Figure 16. Comparative Fuel Fraction



* CTOL DATA FROM REFERENCE 4

Figure 17. Comparative Payload Fraction

CIVIL HELICOPTER POTENTIAL

Since the tandem helicopter has the efficient growth potential to provide efficient transport aircraft for seating capacities of possibly 500 or more, similar to fixed wing, the real "Catch-22" is the ability to initially generate the short-haul passenger markets and then to successfully introduce properly sized helicopters on a timely basis as passenger growth and route expansion occur. Two efforts now proceeding are BAH's oil rig support operations (plus interest in development of scheduled airline services in the United Kingdom and cross-channel routes) and the expanded short-haul commuter operations in the USA. These will potentially generate passenger dependence on air service for short-haul routes and then, in the USA (because of commuter traffic congestion at the airports), require helicopter services as the market expands. Similar to fixed wing, favorable traffic growth patterns will imply a need for helicopters of larger and larger capacity.

Boeing Vertol studies of these helicopters have shown their passenger appeal and economic potential. For this illustration, the initial high density routes, shown in Figure 18, were investigated. The introduction of a helicopter cross-channel passenger service will prove attractive to the business travel segment requiring daily round-trip rapid transportation service between concentrated business centers such as the three routes considered here: London-Paris, London-Amsterdam, and London-Brussels. The major portion of that market will be composed of a share of the already existing fixed wing market, servicing those same city-pairs. Current estimates of this total market are about 4 million one-way passengers per year with an expected growth of nearly 4 percent annually. Analysis of this market indicates an attractive portion of that market for BV-234 Chinook variants.

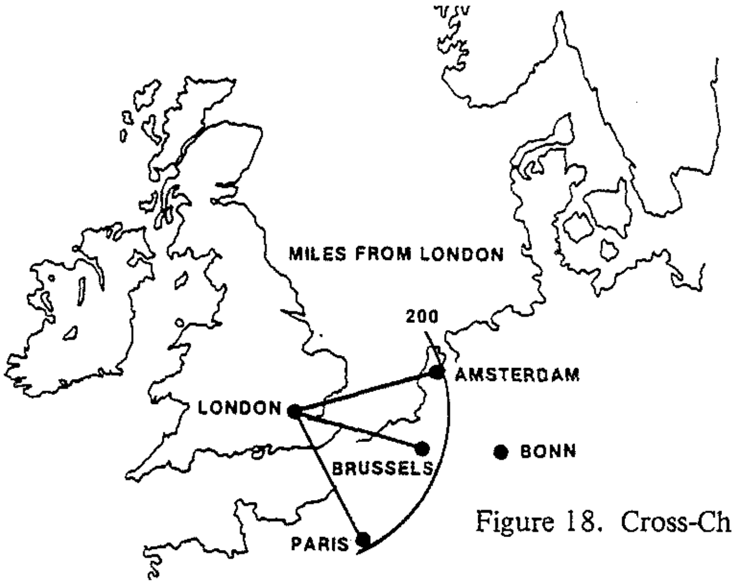


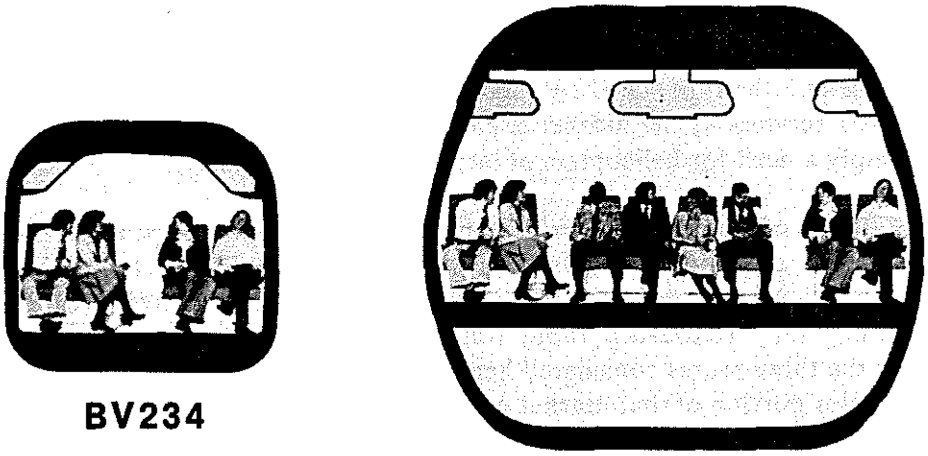
Figure 18. Cross-Channel Routes

Probably the most attractive consideration for the passenger is the time savings available (in addition to the elimination of long, traffic-snarled journeys to the airport) as shown in Table 1. For the business traveller, this can mean an additional 2.5 to 3.5 hours available during business hours without the aggravation of early-morning departures and late-night returns.

Table 1. Time Savings – Round Trip

	TOTAL TRIP TIME (HOURS)		TIME SAVINGS HOURS
	FIXED WING	HELICOPTER	
LONDON — PARIS	8.50	5.75	2.75
LONDON — AMSTERDAM	9.50	6.00	3.5
LONDON — BRUSSELS	8.20	5.70	2.5

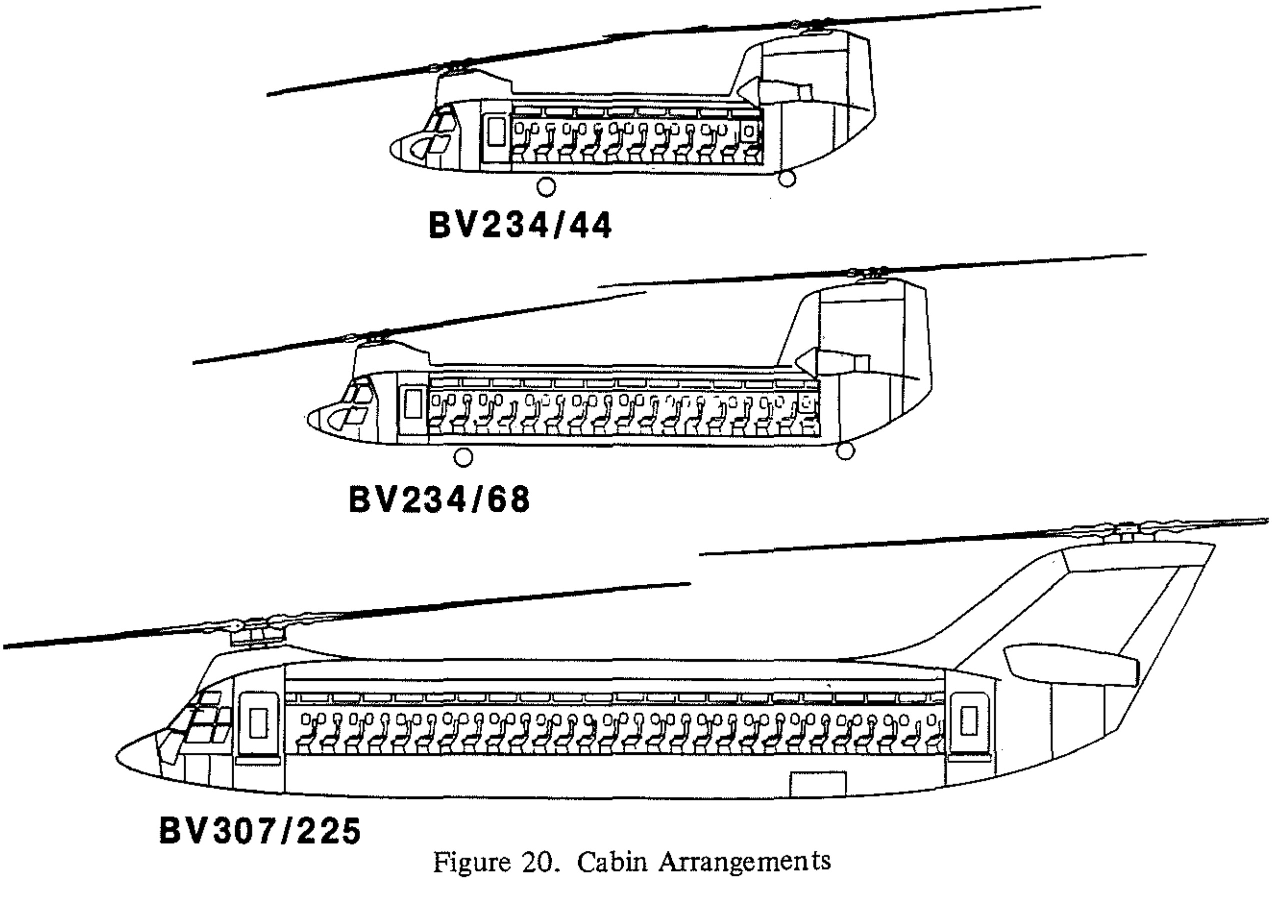
Passenger comfort features are a natural fallout from the tandem helicopter configuration providing spacious cabin arrangements as shown in Figures 19 and 20. Passenger appointments, head-room, seating, overhead racks, air-conditioning, lavatories, and galleys are of the familiar fixed wing quality and the larger HLH derivatives match the dual-aisle, wide-body airplane's appeal.



BV234

BV307

Figure 19. Cabin Arrangements



BV234/44

BV234/68

BV307/225

Figure 20. Cabin Arrangements

Table 2 summarizes the characteristics of a family of tandem helicopter passenger aircraft suitable for markets of the cross-channel type. Timing of the introduction of these aircraft could follow the schedule shown in Figure 21.

Table 2. Large Helicopter Characteristics

	UNITS	234/44	234/68	307/225
PASSENGERS		44	68	225
GROSS WEIGHT	POUNDS	47,000	51,500	127,990
EMPTY WEIGHT	POUNDS	24,279	29,287	70,890
ENGINES		(2) AL5512	(2)T64/T5A	(3)T701-AD-700
SHP (EACH)	SHP	4,075	5,000	8,079
RANGE	MI	635	345	300
CRUISE SPEED (99% BR)	MPH	150	160	170

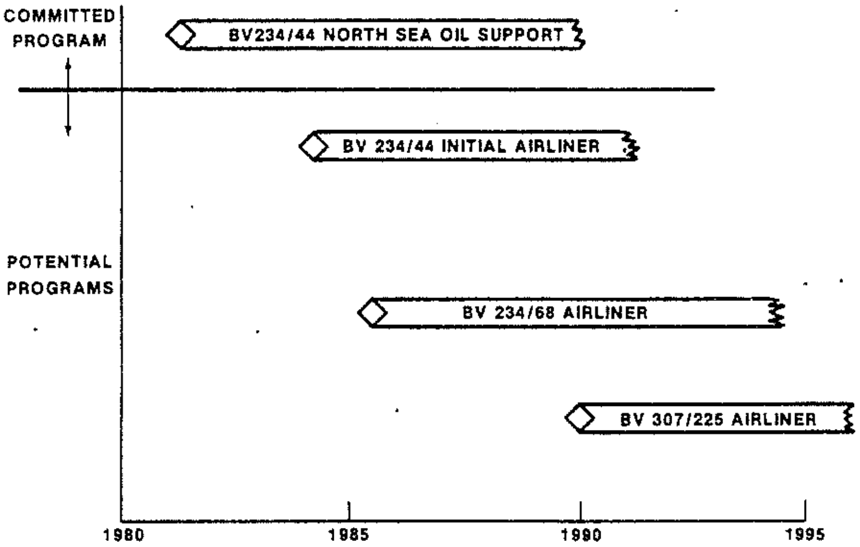


Figure 21. Timing of Helicopter Airliner Introductions

Direct operating cost estimates of this family of aircraft are shown in Figure 22 compared to current smaller (and older) helicopters. These values are comparable to existing fixed wing aircraft on short-haul routes (100—300 mile stages) and coupled with a potential for much-reduced terminal costs should lead to a healthy growth in helicopter passenger services.

Although the helicopter normally uses more fuel per passenger-mile than a fixed wing airplane, the reduced block time spent in terminal maneuvers, traffic delays, and alternate weather routing can make the larger helicopters more fuel efficient in the short-haul routes as shown in Figure 23.

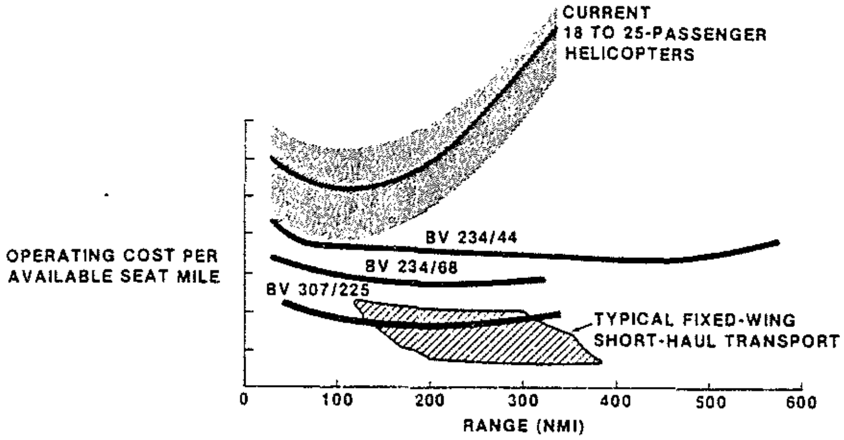


Figure 22. Comparative Direct Operating Cost

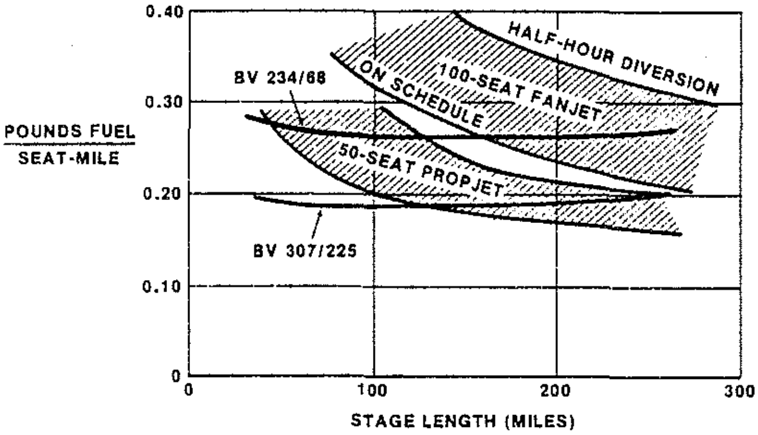


Figure 23. Fuel Usage Comparison

CONCLUSIONS

Studies of advanced tandem helicopters have shown that there are no fundamental reasons why the tandem helicopter cannot continue to grow in size and offer the same efficiency advantages of size as do fixed wing airplanes. The helicopter appears to be following step-by-step in the pattern established by the fixed wing passenger transportation systems, albeit separated by nearly forty years in time. With proper market development, large tandem helicopters could thrive and multiply in the shorthaul transportation role.

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