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AN ECONOMIC COMPARISON OF THREE HEAVY LIFT AIRBORNE SYSTEMS

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ABSTRACT: Current state of art trends indicate that a 50-ton payload helicopter could be built by the end of the decade. However, alternative aircraft that employ LTA principles are shown to be more economically attractive, both in terms of investment and operating costs for the ultra-heavy lift role. Costing methodology follows rationale developed by airframe manufacturers, and includes learning curve factors.

In this country, we have about a decade of experience with helicopters designed for the heavy lift role; at present, ten tons of payload can be transported from one random point to another and this capability has already made an impact in military operations, and the construction and logging industries, to name a few more notable applications. A wide variety of other uses have been found that, taken together, assure us that the heavy lift helicopter has become an acceptable, and in some cases a unique solution to some of our complex transportational requirements. But, as experience is gained, payload limitations are becoming rapidly apparent, and it is logical to look beyond the present in an effort to identify the options that exist in advancing current heavy lift technology.

This paper deals with the economics of heavy lift systems, but in a sense, it may be viewed as a technology assessment presented in an

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economic framework; economics and technology appear to be somewhat inseparable. It is also fair to point out that the subsequent text deals with direct economics of design, development, construction and operation of heavy lift systems, and makes no attempt to address the indirect economic benefits that will almost certainly accrue in a variety of future heavy lift applications; that aspect is left to other authors whose efforts, appearing concurrently with this one, will treat this subject in some depth.

For this study, we have chosen three such systems. The first is an extrapolation of current, or near-timeframe heavy lift helicopter technology to a fifty-ten payload machine. The second is the hybrid Aerc .ane as proposed by All American Engineering Corporation, also of fifty ton payload capacity. The last is a device that is an admixture of Lighter Than Air technology and existing helicopters, as proposed by Piasecki Aircraft. None of these systems exist, or are likely to in the next few years, even if work were to be begun at once on some or all of them. In economic forecasting, a "few years" may be an an unacceptably long time, considering present inflationary trends; nevertheless, conclusions reached on the basis of comparative costs should be relatively immune to this effect.

Baseline Lifting Capability

Mostly as a matter of convenience, but with some rationale, the payload to be held common to these three systems is established at fifty U.S. tons (100,000) lb). All American Engineering Company has effectively sized such a machine (F-1) and conducted a comprehensive design study during the course of their general feasibility efforts, and it thus seems appropriate to view this effort as a logical beginning for purposes of comparison. From a military standpoint, a fifty ton sling load is an all inclusive capability, except for the main battle tank and the heaviest mobile artillery pieces. In commercial applications, a fifty ton payload seems also to satisfy most requirements excepting large nuclear reactor components, and very large tree harvesting operations. Other baseline parameters will be developed subsequently, appropriate to the aircraft under consideration.

50-Ton Heavy Lift Helicopter Point Design

Since the best U.S. production helicopter to date has a design payload of 12.5 tons, it is necessary, before becoming greatly exercised about a 50-ton HLH, to establish that such a machine is technically feasible within the constraints imposed by near-time airframe and engine technology. It is to this end that the following assessment is made.

Much effort has gone towards the advancement of helicopter technology in the past thirty years or so, but remarkably few helicopters have been designed from the outset with the heavy lift role in mind; whatever else may be said, the Soviets have been completely dominant in this field (see Table I) although the first ultra-heavy lift helicopter appears to be the Hughes prototype YH-17 (1952) (called the Sky Crane[1]) which had a design gross weight (DGW) of 52,000 lb., and a lifting ability of 27,000 lb. Subsequently, in the U.S., we have developed helicopters having payloads in excess of 10 tons (the CH-53, 54 series) while in the USSR, the Mil-series designs, which started in 1957, appear to have peaked out as long ago as 1969, when the MI-12 set a world payload record by lifting 34.2 tons to an altitude of 2,000 meters. Present on-going efforts here are centered about the U.S. Army-sponsored Heavy Lift Helicopter, the Boeing-Vertol prototype presently under schedule to fly in 1975. This aircraft has a design payload of 22.5 tons and features a great deal of advanced materials applications as a means of keeping the structural weight fraction within bounds[2].

TABLE I

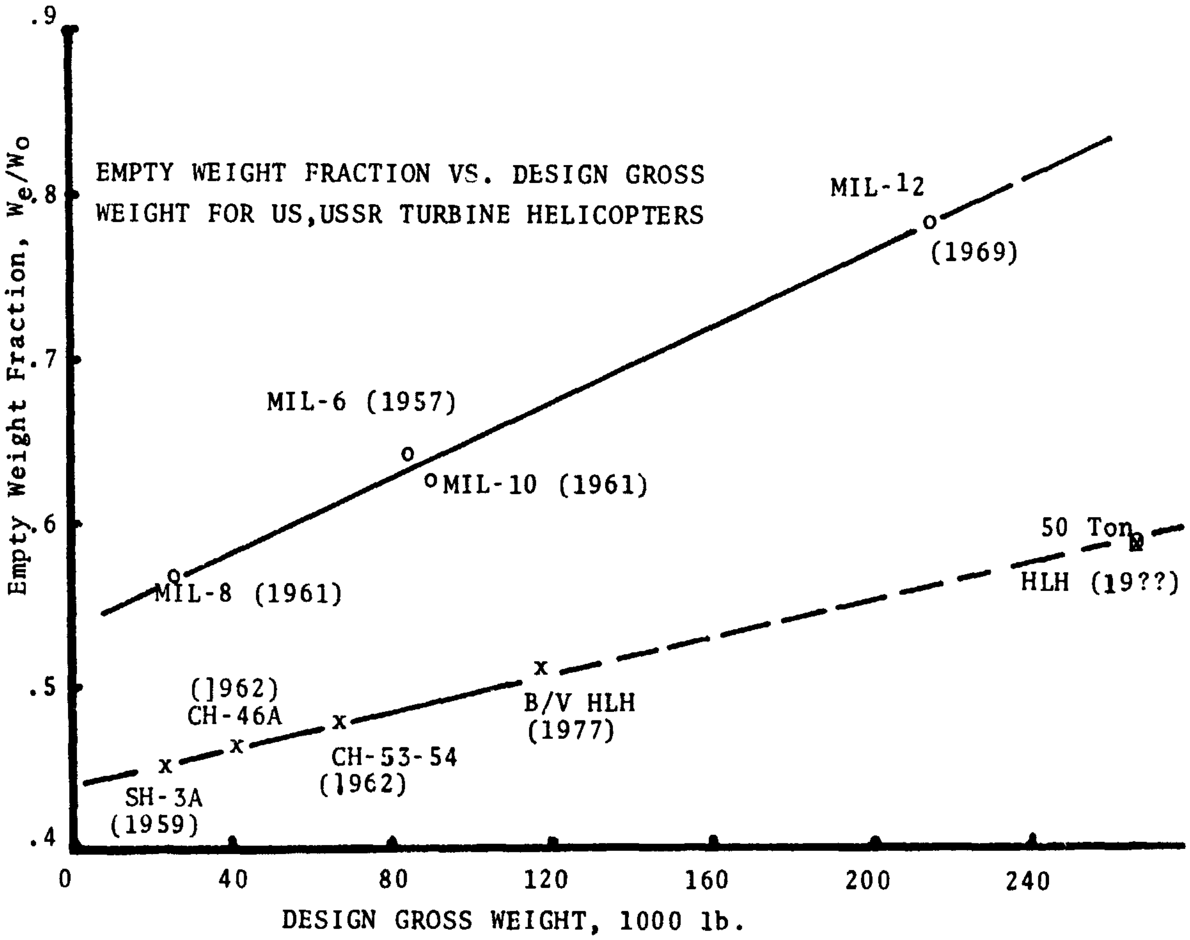
F.A.I. Heavy Lift Helicopter Records:
Greatest Payload Carried to 2,000 Meters

Date	Aircraft	Load
17 Dec 1955	YAK-24 (USSR)	4,000 Kg (8,818 lb.)
11 Oct 1956	HR2S-1 (USA)	6,010 Kg (13,249 lb.)
30 Oct 1957	Mil-6 (USSR)	12,004 Kg (26,464 lb.)
23 Sep 1961	Mil-10 (USSR)	15,103 Kg (33,296 lb.)
13 Sep 1962	Mil-6 (USSR)	20,117 Kg (44,350 lb.)
6 Aug 1969	Mil-12 (USSR)	40,205 Kg (88,636 lb.)

It is in fact the growth of structural weight fraction which stands alone as a chief concern when contemplating large aircraft of any description. For baseline estimates, the square-cube law may be invoked. But in practice, this produces an overly-pessimistic picture since many aircraft components (e.g., flight instruments and avionics) do not scale up with aircraft size, and other major components such as engines have not historically followed this scaling law due to continuous improvements in state of art.

It is interesting, and as it turns out, highly instructive, therefore, to examine what sparse data exists on "scratch-built" heavy lift helicopters as a first attempt to determine the trend of empty weight fraction as a function of design gross weight.

F-2 summarizes this effort, revealing what appears to be a remarkably simple picture of structural weight growth for large helicopters. Two distinct trends are evident, one for the Soviet and the other for U.S. efforts. Study of these trends indicates some significant aspects. First, it can be seen that the Soviets gave high priority to the development of large helicopters as far back as twenty years ago. The Mil-6, which first flew in 1957, has a design gross weight of 93,000 lb. and a payload in excess of 30,000 lb., both figures roughly double the best U.S. effort to date. Then followed the Mil-8 and the Mil-10, which first flew in 1966. With this technological base, they were thus evidently encouraged in 1965 to begin the development of an ultra-large machine. This resulted in the Mil-12, which first flew in 1969, and, after a series of improvements, established the payload record mentioned above.



F-2

Of greater significance than its impressive size, however, is the indication that the Mil-12 is, or rather was, the largest helicopter payload configuration that could be developed within the constraint of their structural weight growth trend. To see this, it is only necessary to translate this trend into an approximate analytical expression, i.e.,

$$W_e/W_o = 0.54 + 0.10W_o/10^5$$

where W_e, W_o are the empty and design gross weights; and defining "payload" to include not only useful payload, but crew and fuel weights, then $W_p/W_o = 1-W_e/W_o$, and there results

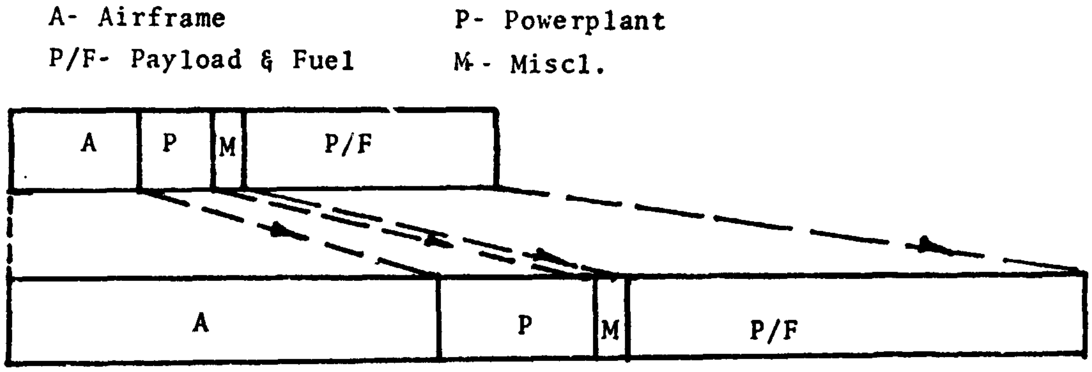
$$W_p = 0.46W_o - 0.10W_o^2/10^5$$

which shows that there is a value of W_o that will produce the maximum payload. This simple model predicts that payload to be 53,000 lb, corresponding to a design gross weight of 230,000 lb. This may be compared with data taken from Ref. 2, which lists the DGW for the Mil-12 at 213,000 lb. and a design payload of 55,000 lb. It is thus tentatively suggested that the Soviets had, in 1969, designed the ultimate load-lifting helicopter allowable within their technology. In keeping with their structural weight growth trend, a 50 ton payload helicopter would have been quite out of the question.

The U.S. experience in heavy lift helicopter design shows a better structural weight fraction trend than the Soviets, probably because the early lack of comparably large shaft engines demanded that greater attention be given to detailed structural design. This has also had the effect of providing incentives to develop weight saving materials (e.g., composites) for secondary structural applications. In any event, whether this trend can be maintained (or better yet, reduced) for U.S. helicopters of arbitrary size is a question that cannot be answered at the present. Assuming that this trend were maintained, however, we find, by application of the above rationale, that the maximum payload is about 78.5 tons, at a DGW of 560,000 lb.

Thus, while we have not "proved" that there is an upper limit to a U.S. helicopter payload, we have, through this exercise, been encouraged to believe that a 50-ton payload helicopter is not a technical impossibility, at least according to current U.S. structural weight growth trends.

For present purposes, then, it is assumed that this trend well represents a technically feasible configuration in the 50 ton payload range, and, with a 10% payload allowance for fuel, sizes out nominally to be a 260,000 DGW helicopter having a payload (including fuel) of 110,000 lb. This gives a structural weight factor of 0.577. With this as a base, the 50 ton HLH sizes out fairly rapidly by using fixed component weight fractions and disk loadings for the Boeing Vertol HLH as a reference. Assuming a 22% rotor overlap, a 228' length emerges for a tandem rotor configuration, based on a 128' rotor diameter. This was determined[3] by assuming a rotor figure of merit of 0.78. A total of 30,000 SHP is required for this aircraft, allowing for a mechanical transmission efficiency of 0.95. Four engines of the Allison T701-AD-700 type, or its derivatives, should suffice. This engine is rated at 8,075 SHP, and is currently under development for the Boeing Vertol HLH. F-3 illustrates the composition of empty weight fraction for the two aircraft.



Weight Stretch Factors for 50 Ton HLH Based on Boeing/ Vertol XCH-64

F-3

The Aerocrane concept as proposed by All American Engineering Company is described elsewhere, but for completeness, a brief description is included here.

As shown in F-1, the Aerocrane consists of an aerostatic sphere that supports a set of equitorially mounted, cruciform wings. In operation, this assembly is rotated by wing-mounted engines and propellers. With this arrangement, aerodynamic lift is developed on the wings that adds to the aerostatic force so that lift can be controlled in the hovering mode. Control is directed from a non-rotating cab supported by the main structure. In the proposed fifty-ton version, the useful load divides in a roughly equal way between aerodynamic and aerostatic lift. In addition, all structural weight of the aircraft is supported by the aerostat, which has been sized for that purpose. Wing (or rotor) incidence is both cyclically and collectively controllable, so the aircraft hovers and translates in much the same fashion as a helicopter, except when the overall buoyancy of the system is positive; in this case forward flight is obtained by tilting the aircraft backwards, and using negative lift to propel the craft at constant altitude. For system parameters used in this study, the reader is referred to Ref. 4.

"Gargantua" (see F-4) is the name adopted by the Piasecki Aircraft Corporation to describe a heavy lift device that is engagingly simple; it places no demands on state of art, and could presumably be built almost immediately with relatively low technological risk. As can be seen, it consists of a large rigid airship hull built along the lines of the Akron/Macon design, except that all engines, controls and other subsystems have been transferred from the hull to four helicopters attached to the lifting envelope by two crossover, or "saddle" beams. In principle, the aerostatic lift of the hull compensates for the entire dead weight of the system, which includes the basic hull and saddle weights, and the fully-fueled helicopter weights as well. The total helicopter lift (equal to the DGW of the four helicopters) can then be used for lifting and propelling the system. In the configuration shown, this would amount to about 84 tons, corresponding to four CH-53D's.

As with the Aerocrane, a separate paper on this subject appears concurrently with this one, to which the reader is referred for additional details[5].

Cost of Gargantua - Since no rigid airships have been built for about 40 years, there is no relevant experience base whatever on which to draw in terms of unit airframe costs. The AKRON, having a gross weight of 460,000 lb., cost $5.3 million, about half of which went into tooling and hangaring costs, since her sister ship, the MACON, cost only about $2.6 million. During construction of these craft, vast amounts of hand labor were employed at rates that were cheap even by the standards of the era, since the depression was then in full swing. It seems fairly certain that this construction philosophy would not prove profitable, or perhaps even possible in the present age. A comprehensive study, performed by a task force of design engineers, manufacturing specialists, and costing experts, is probably required to determine the optimum capital investment in airframe fabrication machinery, as weighed against labor costs as can be foreseen in the 1980 timeframe. On the other hand, the traditional rigid airship structure is highly parts-redundant, suggesting that a diverse subcontracting approach that made use of the excess capacity of major airframe manufacturers might be a productive option. If this were done, a reasonable first estimate for unit airframe costs might be $10-$20/lb. (typical "low technology," i.e., light aircraft figures) the higher figure probably the more appropriate one initially, with costs tending toward the lower figure as experience was gained. This would put the cost of the basic Gargantua airship hull at somewhere between four and eight million dollars.

As for the helicopters, it may be supposed that surplus military aircraft (if they exist) would be used on a "proof of concept" prototype, but a serious commercial or military venture would surely require new aircraft, probably in the $3-8 million cost category, depending on the extent of modification required to existing designs, and whether they were intended to operate in the helicopter (as opposed to the completely captive) mode part of the time. Allowing for fail-safe interconnects, winching equipment and other auxiliary gear, initial production Gargantuas might cost as little as $20 million, and as much as $40 million, or thereabouts. Until the Gargantua proposal moves past the concept and into the preliminary design phase, more energetic attempts to pinpoint its development, production, and operating costs appear to be futile.

Costing Methodology

The remainder of this paper is concerned with the generation of estimates for the costs associated with the acquisition and operation of the remaining two aircraft.

In general, aircraft costing methodology follows an application of established trends based upon mission requirements, cost analyses of existing designs, historical trends, state of art potentials, and complexity factors. The actual process of generating total costs for a given configurational design then depends on the "order of estimate" appropriate to the study phase. To clarify, first order-estimates of acquisition costs can be obtained from relatively simple microscopic cost trends. Independent variables appropriate to this order are speed, range, payload, gross weight, installed horsepower, number of aircraft produced, and so forth. As the design evolves, individual components and subsystems begin to crystallize in terms of size and weight, and second-order estimating rationale can be applied (with liberal amounts of computer time) to provide a more refined estimate of total costs. Table II indicates an example of the informational detail necessary to proceed with this costing phase. In the terminal design phase, estimates become interwoven with reality (mostly as a result of prototype experience) and cost estimating is confined to design change practices.

In a paper of this scope, it is obviously not possible to develop cost figures much beyond the first order level of estimation, although an attempt has been made to apply second-order rationale for the Aerocrane and the 50-ton HLH where possible. The data base used for this study derives from studies conducted by several airframe manufacturers[6,7] for the U.S. Navy, but it necessary to point out that neither these data, nor the conclusions thus reached in the present study represent the official policies of the Department of the Navy.

TABLE II

Typical Second-Order Cost Estimating Factors
(shown for illustration only)

Component	Dollars Per Pound
1. MAIN ROTOR GROUP	81.3
2. WING GROUP	99.5
3. TAIL ROTOR	100.0
4. TAIL SURFACES	24.7
5. BODY GROUP	99.5
6. ALIGHTING GEAR	46.5
7. FLIGHT CONTROLS	115.0
8. PROPULSION GROUP	TREND
etc.	

Effect of Production Numbers on Manufacturing Costs - In proposing new aircraft, major airframe companies speak of a learning curve, or a price-quantity relationship that accounts for the fact that, during a production run, many cost-reducing factors will materialize that act to steadily decrease the unit aircraft cost. As an example, the first production aircraft (actually the tenth actual aircraft, allowing for preproduction prototypes) might cost $10 million, a figure that historical trends and other data might predict to be halved at the 100-aircraft mark. According to a linear-legarithmic relationship, this predicts that the tenth production aircraft should cost about $8 million, hence the term "80% learning curve" that would be cited in this instance. The production rate influences this figure significantly, mostly due to the effect of fixed costs that must be written off during production[8]; a half-rate might change this figure to 85%. But the important aspect to note here is the profound effect that production numbers have on average unit costs. With an 80% learning curve, the average cost is about 64% of the tenth aircraft cost, if 100 aircraft are produced; this figure further diminishes to 35% if the total production is increased to 1000. Another beneficial effect of production numbers is, of course, in the unit amortization of development costs.

Since it is difficult to envision heavy lift aircraft of whatever description being produced in numbers greater than several hundred, the basis for estimating production costs has been set at runs of one hundred and two hundred aircraft, in an attempt to illustrate this effect. In so doing, we have assumed an 80% learning curve. Current trends indicate this figure to be on the low side.

Development Costs - Airframe manufacturers' data[6] and a study of current trends indicate a development cost of $380M (1973 dollars) for the 50-ton HLH. This assumes the use of developed engines and avionics. For purposes of comparison, a separate study (1971) performed under U.S. Army contract estimated development costs for a 24-ton HLH at $535M, which included $90M for engine development, $60M for a new rotor test facility, and $30M for avionics development. Therefore, our figure appears to be the correct order of magnitude. For the Aerocrane, a figure of $163M has been developed, which includes allowances for developmental problems in engine installation, and the design and development of propellers that will be required to match engine performance with the low speed environment. This figure is considerably in excess of that predicted by All American Engineering.

Flyaway and Investment Costs - For this study, the flyaway cost is taken as 110% of the production cost, which includes net profit and marketing costs, such as ferrying and crew training. To this is added another 20% which, to the order of accuracy sought here, represents the initial spares allocation, which is comprised of 50% of the basic engine cost, and 25% of the basic airframe and equipment costs. Both the Aerocrane and the HLH appear to be well represented by this approximation.

Table III summarizes the total acquisition costs for the two aircraft, as a function of production run.

TABLE III

Acquisition Costs vs Production Run, 80% Learning Curve, 1973 M$

	Aerocrane (100/200 A/C)	50-Ton HLH
R&D	163/163	378/378
Mfg Cost (tot.)	364.3/614.3	1570/2648
Unit Cost	5.27/3.89	19.46/15.13
Flyaway Cost[1]	5.80/4.28	21.41/16.64
Invest. Cost[2]	6.85/5.06	25.30/19.67

1. Flyaway Cost = 110% Unit Cost
2. Invest. Cost = 130% Unit Cost

Operating Costs - In developing operating costs, the following rationale was employed: a) Specific fuel consumption is taken nominally to be 0.5 lb-fuel/HP-hr, and fuel costs $150/per ton. b) Maintenance hours per flight hour (both scheduled and unscheduled) is estimated to be 7 hrs for the HLH vs 5 hrs for the Aerocrane, diminishing linearly to 3 hrs after two years of operational experience, and costs $8 per hour. c) Crew costs are $90 per hour, which includes overhead. d) Non-productive flight time (e.g., ferrying, training) represents 20% of total utilization. e) Hangaring and insurance costs are not included. f) Initial cost includes 20% for spares, which are replenished annually at a rate of 3% of the original flyaway price. g) True interest rate on the debt is 5% after allowances are made for depreciation and interest tax deductions. With these assumptions, the following average annual operating costs were developed (Table IV) based on 10 years life cycle.

TABLE IV

Average 10 yr Hourly Operating Costs for 600/1200 flight hours per year (1973 dollars, 1974 fuel prices)

Prod. run/Aircraft	Aerocrane	50-Ton HLH
100	$1805/1385	4605/3065
200	1580/1270	3920/2720

Conclusions: In this paper, the attempt has been to combine reasonable technological projections with representative, current costing rationale as a means of determining, to first order, the costs associated with heavy lift capability. While the exactitude of numbers developed in a study of this scope is always open to question, it is felt that they are of the correct order of magnitude, and almost certainly of correct relative magnitude in the comparisons that have been made. In all phases of development, manufacture, and operation, the Aerocrane emerges as considerably more cost effective than the 50-Ton HLH, underscoring the savings that might be expected in a heavy lift device, where part of the lift is gotten for free, so to speak. Costs, like weight, have a way of "snowballing" in advanced, state of art aircraft, which the 50-ton machine represents. Part of this escalation derives from obvious physical causes, such as the necessity to develop better materials, to keep empty weight fractions within bounds. Somewhat less obviously, there is a "cost-risk" spiral that has become ever-increasingly a dominating cost element in new aircraft development; whether this can be avoided in the development of LTA technology would make an interesting study in itself.

As remarked earlier, lack of details argued against the comparable cost analysis of Gargantua, and it is hoped that this paper will be useful for comparative purposes, when this information is forthcoming.

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