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A SIMPLIFIED LIFE-CYCLE COST COMPARISON OF VARIOUS ENGINES FOR SMALL HELICOPTER USE

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Cleveland, Ohio
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and NASA - Lewis Research Center

ABSTRACT

A ten-year, life-cycle cost comparison is made of the following engines for small helicopter use: simple turboshaft ; regenerative turboshaft ; compression -ignition reciprocator ; spark - ignited rotary ; and spark - ignited reciprocator. Based on a simplified analysis and somewhat approximate data, the simple turboshaft engine apparently has the lowest costs for mission times up to just under 2 hours. At 2 hours and above, the regenerative turboshaft appears promising. The reciprocating and rotary engines are less attractive, requiring from 10 percent to 80 percent more aircraft to have the same total payload capability as a given number of turbine powered craft. A nomogram was developed for estimating total costs of engines not covered in this study.

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SUMMARY

A study was performed comparing various powerplants for possible use in Army utility helicopters. Engine types included the simple turboshaft, a regenerative turboshaft, a compression - ignition reciprocator (Diesel) , a spark - ignited rotary , and a spark - ignited reciprocator (Otto). Engine sizes examined were in the 500 - 2000 HP range. It was assumed that 1 HP of installed engine power could lift 8 lbs of gross weight. This, plus some assumed engine specific weights and fuel consumption rates allowed an aircraft weight breakdown to be determined for each engine type. Based on the payload fraction corresponding to each engine type, total numbers of aircraft were calculated that had the same payload carrying capability as 1000 turbine-powered aircraft. Using some rough estimates for airframe, engine, and engine overhaul costs, the final comparison was based on 10-year life-cycle costs of aircraft depreciation, flight crew, engine maintenance, and fuel. A sensitivity study was done with engine HP, mission duration, annual utilization rate, lift/HP ratio, and fuel price. A graphical technique was developed for estimating the life-cycle costs for engines not explicitly covered in the study.

The mission was to cruise for 1 hour at 100 knots and 4000 feet altitude, and land with 10 percent fuel remaining. For this 1 hour utility mission, no engine showed an advantage in life-cycle costs over the simple gas turbine. Due to their lower payload fraction, the reciprocating and rotary engines required 10 percent to 80 percent more aircraft than the simple turboshaft, thus eliminating their advantage in initial cost and specific fuel consumption (SFC). The regenerative turbine's fuel savings did not justify its higher weight and cost until mission time was increased to about 2 hours.

INTRODUCTION

The simple gas turbine engine can be characterized by low specific weight and high reliability, but compared to other current engines it is expensive and suffers from relatively high part - power fuel consumption. The cost of a helicopter turboshaft engine can sometimes amount to 20 percent of the acquisition cost of the vehicle. As the Army operates a large number of turbine - powered helicopters, a study was undertaken to examine and compare some alternative powerplants.

Engines included in the study were the turboshaft, a compression - ignition reciprocator (Diesel), a spark - ignited rotary, a spark - ignited reciprocator (Otto), and a regenerative turboshaft. The base or reference engine size was 1000 HP. This was perturbed over the range suitable for utility helicopters, 500 - 2000 HP. The study was done from the viewpoint of an operator who wants to be able to carry a certain total payload at any given time. The final comparison was then based on life - cycle aircraft depreciation, engine maintenance, and fuel costs for groups of aircraft with the same total carrying capacity of 1000 turbine - powered craft. In addition, a sensitivity study was done with mission duration, yearly utilization, engine size, and fuel costs. A nomogram was developed for estimating relative costs of any engine not explicitly covered in the study.

ANALYSIS

Mission

The mission was to cruise for 1 hour at 100 knots and 4000 feet altitude, and land with 10 percent fuel remaining. The engine power setting at cruise was taken to be 60 percent of maximum power.

Weight/Power Relation

Upon plotting some helicopter gross weight and installed power data from references 1 and 2 (see fig. 1), it appears that 1 HP (horsepower) can lift 5 to 8 lbs. This number is primarily a function of rotor characteristics, so for a specified engine size, aircraft gross weight is the same for all engine types. The higher of the two values shown on figure 1 (8 lb/HP) was chosen as representing more advanced technology. This parameter was later perturbed in the sensitivity study to show the effect of varying rotor system technology.

Aircraft Weight

Gross weight was divided into airframe, engine plus transmission, fuel, and payload weights. The assumed schedule of turboshaft engine weight with HP(*) is shown in figure 2, together with some data points from reference 2 for current turboshaft engines. Based on an optimum effectiveness of 65 percent , the regenerative engine was estimated as 40 percent heavier than the simple turboshaft (ref. 3). The current (1970) specific weight schedule for reciprocating, spark- ignited engines is plotted in figure 3 from engine data in reference 4. Also shown in this figure are two curves of air- and liquid- cooled engines from reference 5 (1944). Comparing the 1944 and 1970 curves of air- cooled engines, little improvement can be seen in specific weight over the HP range of interest. The schedule used for the study presumes a 20 percent improvement in the specific weight of the spark- ignited reciprocating engine. Specific weight data from references 6 and 7 for advanced military Diesels is plotted in figure 4. These engines contain a great deal of aluminum construction and incorporate features such as supercharging,after- cooling, and variable- compression ratio pistons. They represent the best of what is currently available in very high output (VHO) Diesels. It could be argued though, that since these

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* all references to engine power and SFC are based on NET power; i.e., less cooling and accessory drive requirements.

engines were designed for ground vehicle applications, specific weight was not as great a concern as it is for aircraft. To allow somewhat for this, the weight schedule for an aircraft type Diesel was obtained by adding 1 lb/HP to the VHO curve (for cooling system and generator) and then reducing the result by approximately one- third. The study diesel was assumed liquid - cooled. The rotary engine's specific weight is shown in figure 5, with some data points from references 8 and 9. It was assumed to be liquid - cooled, spark - ignited. The rotary's specific weight is roughly two- thirds that of a reciprocating engine's. It is assumed that liquid - cooled engine weights include coolant and radiator, and that all engines include the same accessories. A nomogram included in this report enables the reader to choose his own engine specific weight and recalulate some of the results. Transmission plus drive train weight is shown in figure 6, based on a specific weight of 0.55 lb/HP for the turboshaft case (ref. 10). The reciprocating and rotary engine transmissions would require fewer stages of reduction but because of the periodic nature of their output, heavier gear construction is likely. The first effect was thought to be dominant and these engines were allowed a lower transmission weight schedule (0.45 lb/HP)

Aircraft empty weight (including powerplant and fuel tanks) was estimated to be 52 percent of gross weight for the simple turbine case. Figure 7 shows the assumed schedule and some data points from reference 1. Airframe weights were adjusted to account for different fuel tank capacities and engine mounting. A fuel tank weight schedule (fig. 8) was derived from data in reference 3. Engine mounts were assumed to be 3 percent of the engine weight for a gas turbine. This was doubled for the rotary and reciprocating engines to account for the higher torque. The effect that fuel load and engine weight had on the basic airframe structure was ignored.

The study helicopter was assumed to have a constant - speed, variable - pitch rotor system. Fuel load was calculated for a 1 hour cruise. Since a helicopter derives added rotor lift from forward velocity , it can cruise at about 60 percent power (ref. 3). The part - power (60 percent power at 100 percent speed) SFC's are shown in figure 9. The gas turbine part power performance is at a level representing the best of what is currently available (ref. 11). (Ref. 11 is classified, but the information used in this study is unclassified). The regenerative turbine SFC was based on the improvement shown in reference 3 of a regenerative cycle over a simple cycle. This again is for optimum effectiveness of 65 percent. The rotary's SFC was estimated from data in references 8 and 9. The Diesel's part - power fuel consumption was based on data in reference 7. A fuel reserve allowance of 10 percent was included for all aircraft. Table I summarizes the assumptions and results of the weight calculations for the 1000 HP base case.

Number of Aircraft

The life of the aircraft was taken to be 10 years, with a utilization rate of 600 hours/year. Attrition rate, the rate at which aircraft are lost, was 5 per 100 000 flight hours. Maintenance float factors (the percentage of aircraft unavailable due to maintenance) were adjusted from the value used in reference 3 to reflect different mean times between unscheduled engine removals (MTBUR) and mean times between overhauls (MTBO). A simplifying assumption is made regarding the attrition aircraft. Although these aircraft losses would actually be spread out over the 10 year lifetime, they are treated according to reference 3, as if they all occurred on the day of delivery. The sum of attrition aircraft, maintenance float, and operational aircraft equals the total number of production aircraft. Total payload capability was based on the operational aircraft number. Table II summarizes the assumptions and results of the number of aircraft calculations for the 1000 HP base case.

Costs

Aircraft operating costs are generally made up of five components: flight crew, fuel, maintenance, depreciation, and insurance. Insurance, of course, does not apply to military aircraft. Life- cycle costs of depreciation, engine maintenance, flight crew, and fuel were considered. Assuming zero salvage value, lifetime depreciation equals initial cost.

The engine initial cost schedules are shown in figure 10. Turbine costs were based on some actual engine cost data and on curves from reference 12. The regenerative turbine's increased cost was based on reference 3. Of the internal combustion engines, the Diesel was taken to be the most expensive, and the Otto reciprocator, the least expensive. Little is known about costs of the rotary engine. Although it has fewer parts than a reciprocator, the housing is a complex shape and requires rather special surface treatment. Its cost schedule was chosen to be halfway between that of the Otto and Diesel engines'. An engine spares factor was included for all the engines (Table III). For the reciprocating and simple turbine engines, the spares factors were based on current Army experience. For the other engines, they are more or less speculative. The ratio of engine cost/ airframe cost for some current turbine - powered helicopters varied from 0.15 to 0.20 . A value of 0.15 was used in the study for the turbine- powered airframe with a lift capability of 8 lb/HP. The resulting $/lb figure was then applied to the other engines' airframes. Engine maintenance cost accounted for the scheduled overhauls based on the MTBO's in table II. Overhaul costs were taken to be 30 percent of initial cost for the simple and regenerative turbine, and 50 percent of the initial cost for the reciprocating and rotary engines.

Fuel costs assumed prices of 20¢/ gallon for JP fuel, 16¢/ gallon for diesel, and 27¢/ gallon for 100- Octane aviation gasoline. These prices are current, local industry figures for untaxed, bulk quantities.

From data in reference 3, flight crew costs were based on $39 200 per aircraft per year. The assumptions and results of the cost calculations are summarized in Table III for 1000 HP.

RESULTS AND DISCUSSION

Specific Engines

For the 1000 HP base case, figure 11 gives the weight breakdown of aircraft powered by each of the engine types. Airframe weight is essentially constant and only a relatively small amount of fuel is required. Thus approximately 4600 lb remain in every case to be divided between payload and engine + transmission weight. It is clear that payload (and hence number of aircraft) depends primarily on engine specific weight. Under the present assumptions, the turbine payload is 84 percent greater than the Diesel, 8 percent greater than the rotary, and 17 percent greater than the reciprocating Otto. Correspondingly, the Diesel requires 1848 aircraft, the rotary 1092 aircraft, and the Otto 1174 aircraft to equal the carrying capacity of 1000 simple turboshaft aircraft. The regenerative turbine doesn't achieve enough of a fuel saving in a 1 hour mission to offset the weight penalty associated with the regenerator.

The effect of engine size on the number of aircraft is shown in figure 12(a). This figure simply reflects the relative increase in engine specific weight with decreasing engine size for the different engine types. The corresponding cost results are presented in figure 12(b) where 10 year, life-cycle costs for depreciation (=initial cost), flight crew, engine maintenance, and fuel are compared for 500, 1000, and 2000 HP engines. The reciprocating engines' costs are from $150 million to $950 million above the simple gas turbines'. Their low initial cost per engine and the Diesels' low part-power SFC are not enough to make up for the larger number of aircraft required because of their low payload fraction. To just match the turbine costs, the 1000 HP Diesel would need to have a specific weight of 0.59 lb/HP. The rotary engine, also with low initial cost, but with a specific weight roughly two- thirds that of a reciprocating engine, seems to be the most promising competitor to the gas turbine.

The sensitivity of the results to mission duration, annual utilization, fuel price , and lift/HP are shown in the next four figures. As mission time increases, and the fuel fraction becomes larger, it might be expected that the engines with lower SFC (relative to the simple turbine) stand to gain, and those with higher SFC stand to lose. Figure 13 shows this happening in the case of the rotary, the Otto, and the regenerative turbine. The regenerative turbine for instance, begins to pay for itself at a mission time of just under 2 hours. The Diesel's behavior with increasing mission time doesn't follow this reasoning, however. To understand why, figure 11 should be recalled. For each engine type, a fixed portion of the gross weight is divided into fuel and payload. Each engine's fuel and payload fraction is fixed because engine + transmission weight does not vary with mission time. By expressing the payload as the difference between this fixed weight fraction and the mission fuel, and combining this with the fact that number of aircraft is inversely proportional to payload, a simple expression for relative number of aircraft can be obtained. Whether this expression produces an increasing or decreasing function with increasing mission time depends on two parameters - the total capacity for fuel (= fuel + payload fraction, where payload=0) as well as rate of fuel consumption. Put in simpler terms, it depends on how fast the payload fraction is shrinking as fuel displaces payload with increasing mission time. The Diesel's payload + fuel fraction is so low that even with its good SFC, its payload fraction decreases at a faster rate than the turbine's.

The effect of utilization rate is shown in figure 14. Total yearly payload will increase with utilization since the number of production turbine aircraft is always 1000. As utilization rate increases, two opposing effects come into play. Yearly maintenance and fuel costs per airplane rise, but the flight hourly attrition rate (i.e., 5 aircraft/ 100 000 flight hours) means fewer aircraft are left from the initial production number. In the case of total maintenance and fuel, the first effect is greater, and these costs, therefore, increase. Initial cost, unaffected by any flight hourly expense, remains constant. Crew costs see only the aircraft attrition effect, and therefore decrease. Figure 15 shows the effect of doubling the fuel cost. The engine that it affects the most is the rotary, whose fuel costs are already the highest. Aside from this, however, the overall comparison was not changed significantly. Figure 16 shows the effect of perturbing the lift/HP originally assumed. As lift/HP increases, the engine becomes a less significant part of the gross weight, and the effects of weight differences between engine types become less important. This trend can be seen in figure 16(a) where the difference in number of aircraft between the turbine and the other engine types decreases as lift/HP increases. The Diesel benefits the most from this effect since its engine is such a large part of the gross weight to begin with. The costs, figure 16(b), reflect the same trend. The relative standings, however, are unchanged.

To show the effect on life- cycle costs of tradeoffs between engine specific weight, cost, and SFC, table IV has been included. It gives ratios of Δ cost due to a 1 percent change in two of the variables. In the Diesel's case, for example, a 1 percent decrease in specific weight is equivalent to about a 5 percent decrease in SFC.

Parametric Engines

As other engine concepts arise, or technology advances occur or are predicted, the choice of an optimum engine type might possibly change. For instance, the effects of combining the Diesel's low SFC with the rotary engine's low weight and cost might be examined.

To facilitate the quick evaluation of these new or proposed concepts, figures 17 and 18 have been provided. These figures can be used to calculate the relative costs of 1000 HP engines not explicitly covered in this study. The base case parameters and mission and weight assumptions are built into these figures. Given an SFC and an engine + transmission specific weight, figure 17 will yield relative number of aircraft for constant total payload. The study engines are indicated on this plot. Given the SFC, cost of fuel, and an engine + maintenance cost ($/HP), the nomogram in figure 18 yields total cost per aircraft/ airframe cost. Multiplying this by the relative number of aircraft, making the approximation that airframe costs stay about constant for different engine types, and ratioing the results gives the relative total costs:

$$\frac{\left(\dfrac{\text{Total cost/ aircraft}}{\text{Airframe cost}}\right)_1 \left(\text{Rel. \# of aircraft}\right)_1}{\left(\dfrac{\text{Total cost/ aircraft}}{\text{Airframe cost}}\right)_2 \left(\text{Rel. \# of aircraft}\right)_2} = \frac{\text{Total Cost 1}}{\text{Total Cost 2}}$$

To illustrate the use of the nomogram, suppose a 1000 HP turbine and Otto reciprocating engine are to be compared. If the turbine burns JP4, its SFC is 0.52, and engine + maintenance cost* is \$132/HP, then figure 18 yields 1.815 as total/ airframe cost. Since the turbine is the reference, the relative number of aircraft is 1.0 . If the Otto engine burns aviation gas, has an sfc of 0.47, and the engine + maintenance cost is \$100/HP, the nomogram gives 1.80 for total/ airframe cost. From figure 17, the relative number of Otto- powered aircraft is 1.162 and therefore:

$$\frac{\text{(Total Cost) Otto}}{\text{(Total Cost) Turbine}} = \frac{(1.80)(1.162)}{(1.815)(1.00)} = 1.152$$

CONCLUDING REMARKS

Based on the assumptions of this preliminary study, the simple turboshaft engine appears to be the most suitable powerplant for an Army utility helicopter. The reciprocating engine's low initial cost cannot offset the effect that its poor payload fraction has on the total number of aircraft required. Unless the mission fuel fraction becomes large, or fuel price structure drastically changes, the Diesel's additional advantage of good SFC cannot offset its poor payload fraction. The rotary engine seems the most likely competitor to the gas turbine. The additional cost and weight of the regenerative turbine gives it the advantage over the other engines only when the mission time is increased to more than 2 hours.

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* Note: the engine + maintenance cost on scale D is arrived at by the following formula.

$$E{+}MC = IC(1.+SF+OC \times NO)$$

Where: E+MC = engine + maintenance cost , \$/HP
IC = initial cost of engine , \$/HP
SF = spares factor
OC = cost/overhaul as fraction of initial cost
NO = number of overhauls in 10 years

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TABLE I. SUMMARY OF ASSUMPTIONS & RESULTS FOR WEIGHT CALCULATIONS OF 1000 HP BASE CASE.

	1000 HP				
	TURBINE	DIESEL RECIP.	ROTARY	OTTO RECIP.	REGEN. TURB.
GROSS WT., LB.	8000	8000	8000	8000	8000
ENGINE WT., LB.	306	2000	600	900	420
TRANS. + DR. TR. WT., LB.	550	450	450	450	550
AIRFRAME WT., LB.	3310	3382	3353	3339	3262
SFC @ 60% POWER, LB/HP-HR	0.52	0.405	0.55	0.47	0.40
FUEL, LB.	343	267	363	313	264
PAYLOAD, LB.	3497	1901	3234	2998	3504

TABLE II. SUMMARY OF ASSUMPTIONS & RESULTS FOR NUMBER OF AIRCRAFT CALCULATIONS OF 1000 HP BASE CASE.

	1000 HP				
	TURBINE	DIESEL RECIP.	ROTARY	OTTO RECIP.	REGEN. TURB.
LIFE, YRS.	10	10	10	10	10
UTILIZATION, HRS/YR.	600	600	600	600	600
ATTRITION, PER 100000 HRS.	5	5	5	5	5
MTBUR, HRS.	1000	600	400	500	1000
MTBO, HRS.	1500	900	600	750	1200
MAINT. FLOAT FACTOR	11.5%	12.2%	12.9%	12.4%	11.75%
ATTRITION AIRCRAFT	212	390	229	247	212
MAINTENANCE FLOAT	81	159	99	103	81
OPERATIONAL AIRCRAFT	707	1300	764	824	705
CARRYING CAPACITY, LB.	2.47×10^6	2.47×10^6	2.47×10^6	2.47×10^6	2.47×10^6
PRODUCTION AIRCRAFT	1000	1849	1092	1174	998

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TABLE III. SUMMARY OF COST ASSUMPTIONS & RESULTS FOR 1000 HP BASE CASE.

	1000 HP				
	TURBINE	DIESEL RECIP.	ROTARY	OTTO RECIP.	REGEN. TURB.
ENGINE COST, $	60000	30000	25000	20000	84000
AIRFRAME COST, $ (INCL. TRANS.)	400000	408700	405200	403600	394100
ENGINE SPARES FACTOR	30%	50%	50%	50%	35%
ENG. OVERHAUL, % INIT. COST	30%	50%	50%	50%	30%
FUEL COST, ¢/GALLON	20.4	16.0	27.3	27.3	20.4
TOTAL FUEL COST, MILL $	46	53	83	77	36
TOTAL AIRCRAFT COST, MILL $	478	839	483	509	493
MAINT. COST, MILL $	43	131	97	65	70
FLIGHT CREW COST, MILL $	277	510	300	324	276
TOTAL COST, MILL $	844	1533	963	975	875

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TABLE IV. LIFE-CYCLE COST TRADEOFFS WITH CHANGES IN ENGINE SPECIFIC WEIGHT, COST, AND SFC.

	DIESEL RECIP.	ROTARY	OTTO RECIP.	REGEN. TURB.
$\frac{(\Delta COST)_{\Delta SFC=1\%}}{(\Delta COST)_{\Delta LB/HP=1\%}}$	.211	.892	.588	.671
$\frac{(\Delta COST)_{\Delta SFC=1\%}}{(\Delta COST)_{\Delta \$/HP=1\%}}$	.465	.508	.480	.296
$\frac{(\Delta COST)_{\Delta LB/HP=1\%}}{(\Delta COST)_{\Delta \$/HP=1\%}}$	2.206	.570	.816	.441

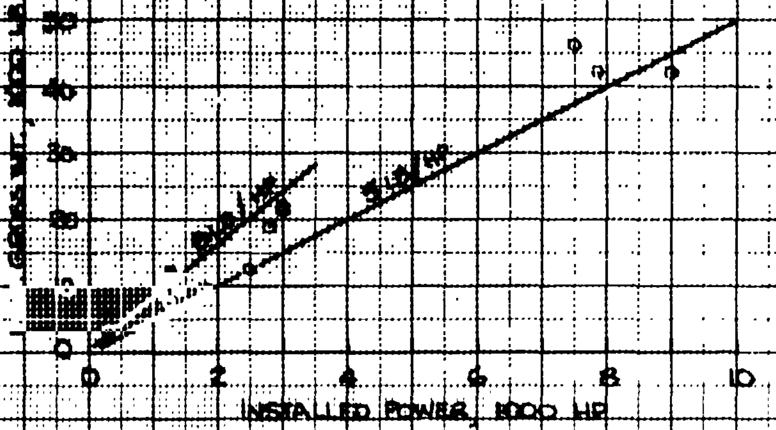


FIGURE 1 — HELICOPTER GROSS WEIGHT VS. INSTALLED POWER.

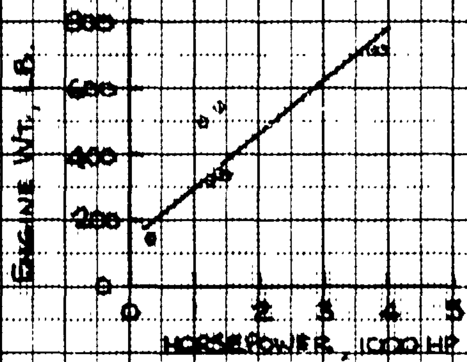


FIGURE 2 — TURBOSHAFT ENGINE WT.

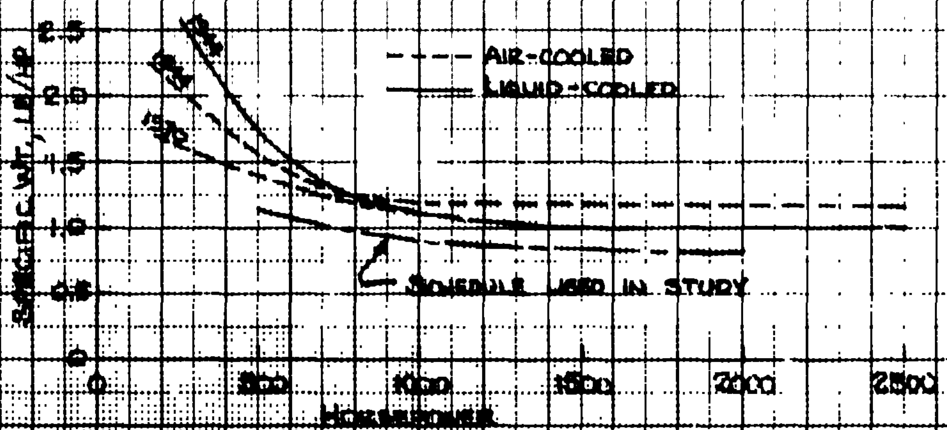


FIGURE 3 — OTTO RECIPROCATING ENGINE WEIGHT

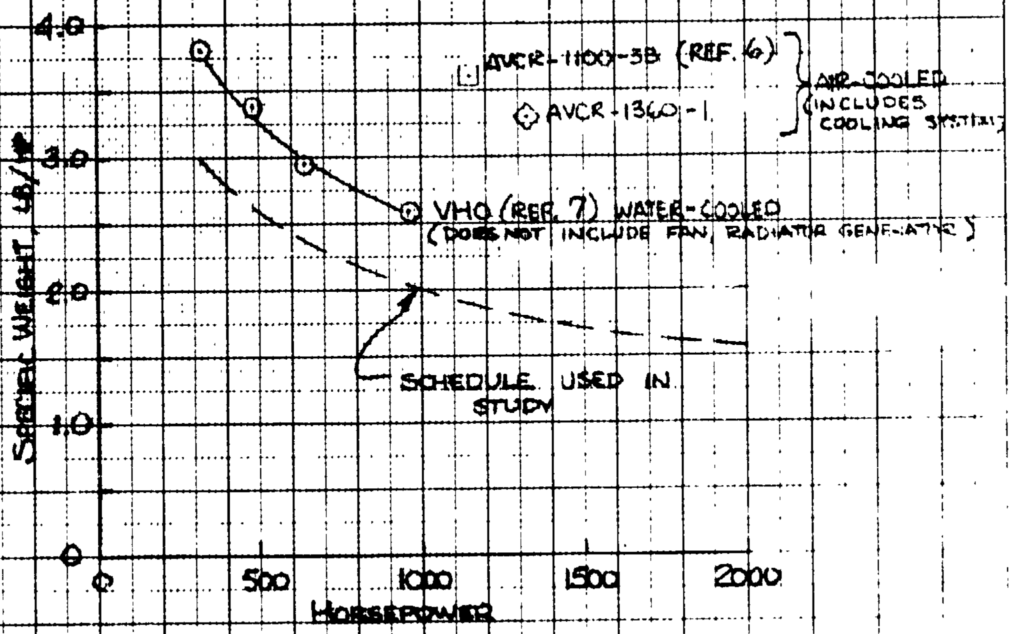


FIGURE 4. – DIESEL ENGINE SPECIFIC WEIGHT

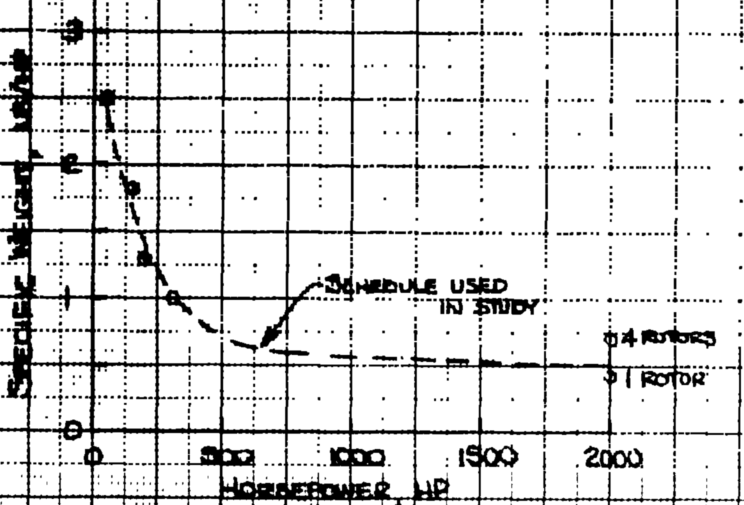


FIGURE 5 — ROTARY ENGINE WEIGHT

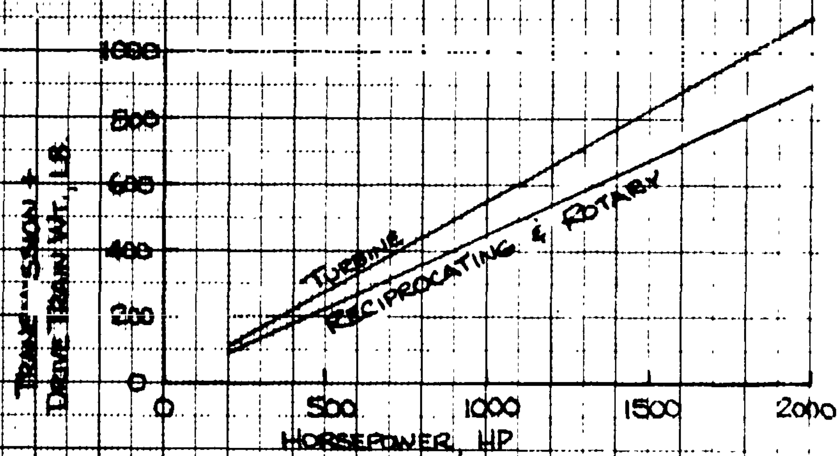


FIGURE 6. — TRANSMISSION AND DRIVE TRAIN WEIGHT

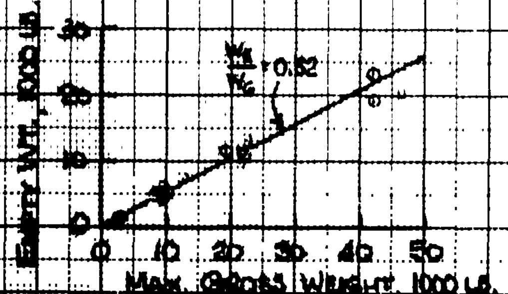


FIGURE 7 — EMPTY WEIGHT OF TURBINE POWERED HELICOPTERS

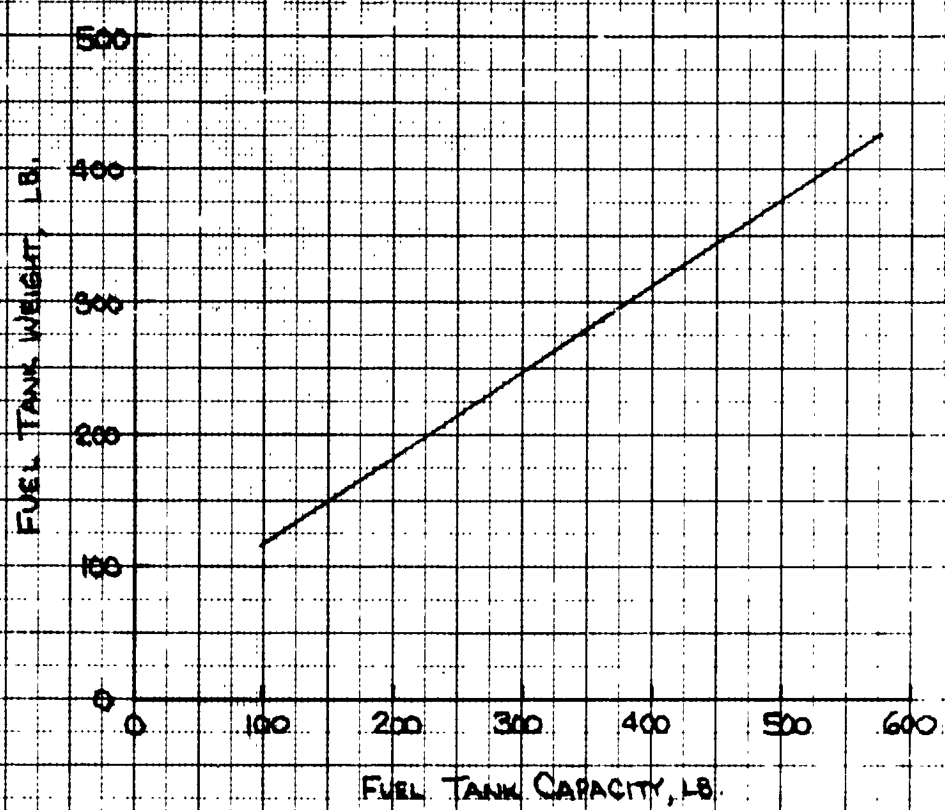


FIGURE 8. – FUEL TANK WEIGHT

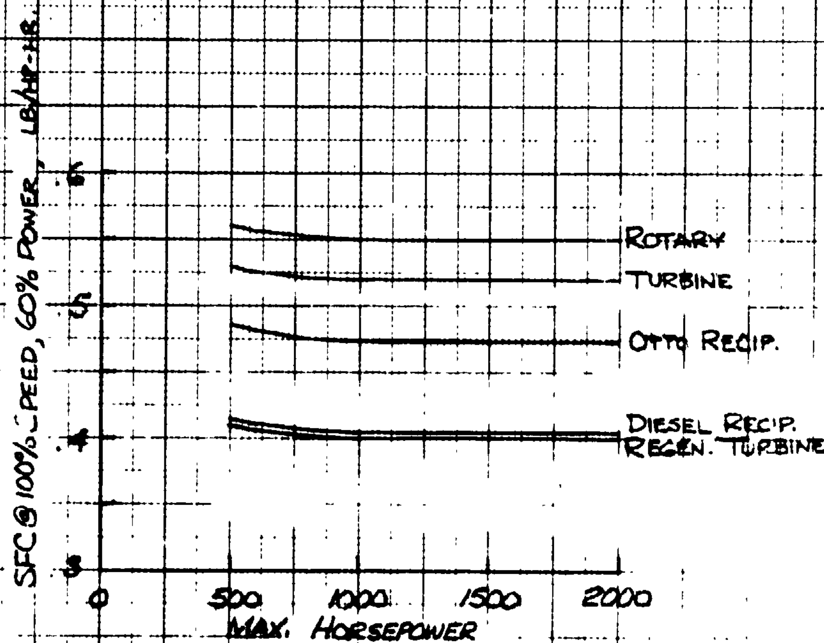


FIGURE 9. — PART POWER FUEL CONSUMPTION.

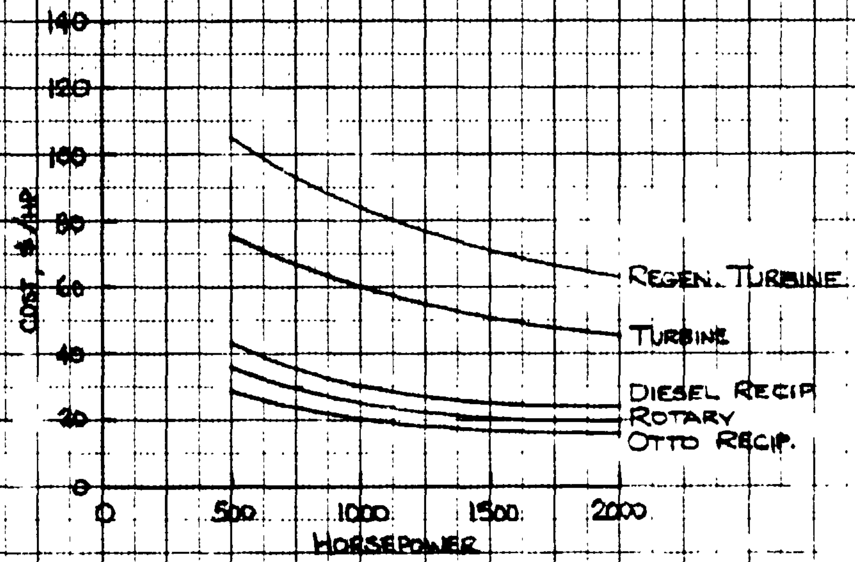


FIGURE 10. - INITIAL ENGINE COST

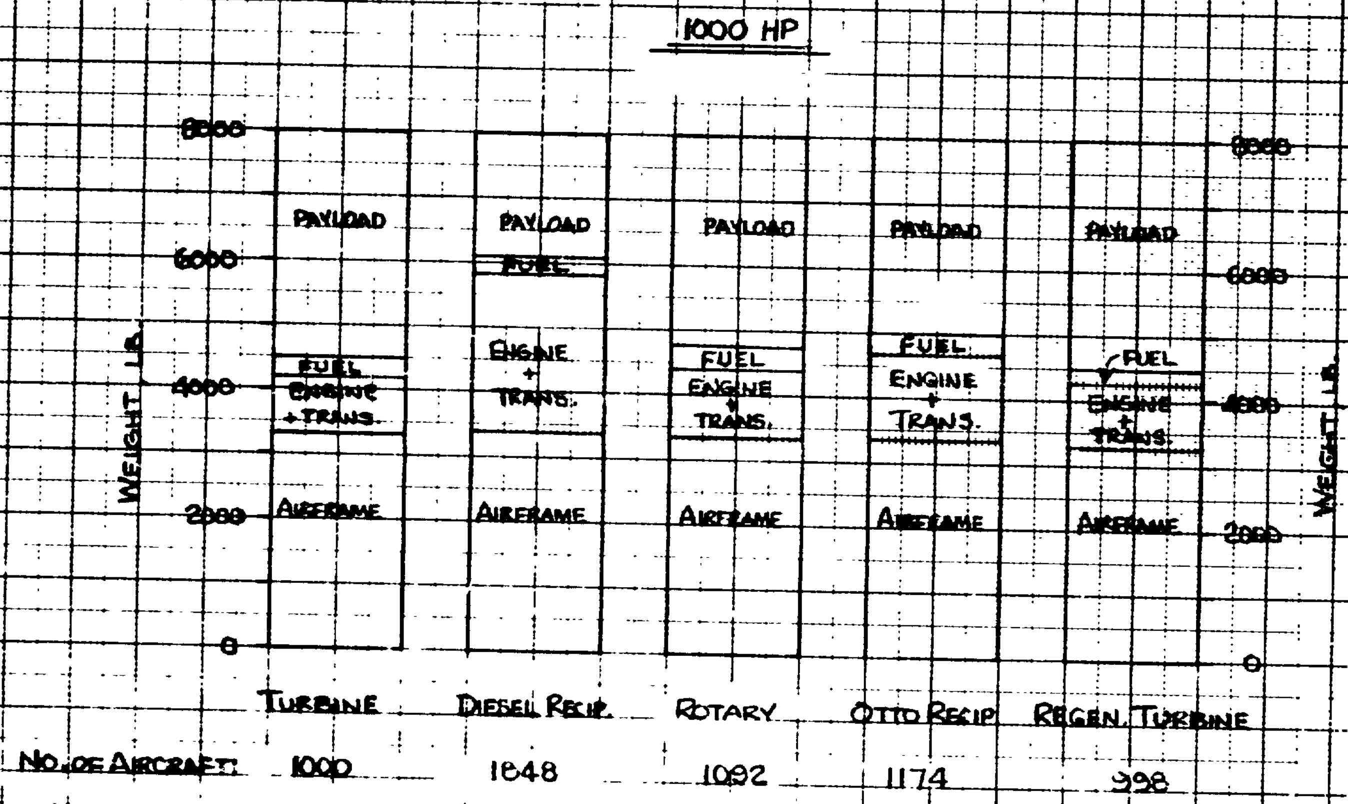


FIGURE 11. — WEIGHT BREAKDOWN FOR 1000 HP AIRCRAFT.

Figure 12: Effect of Horsepower

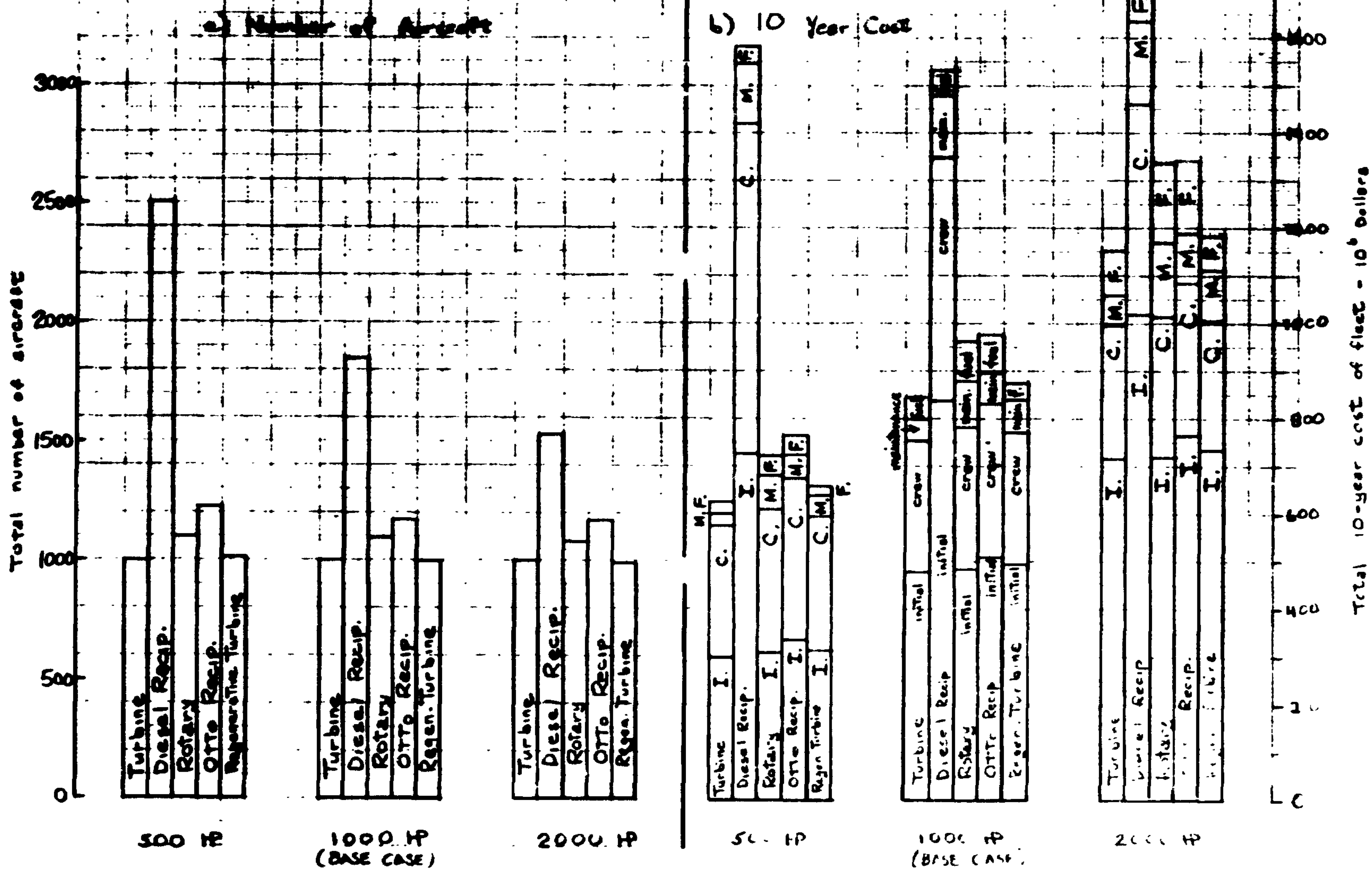


Figure 13 : Effect of Mission Time (1000 HP)

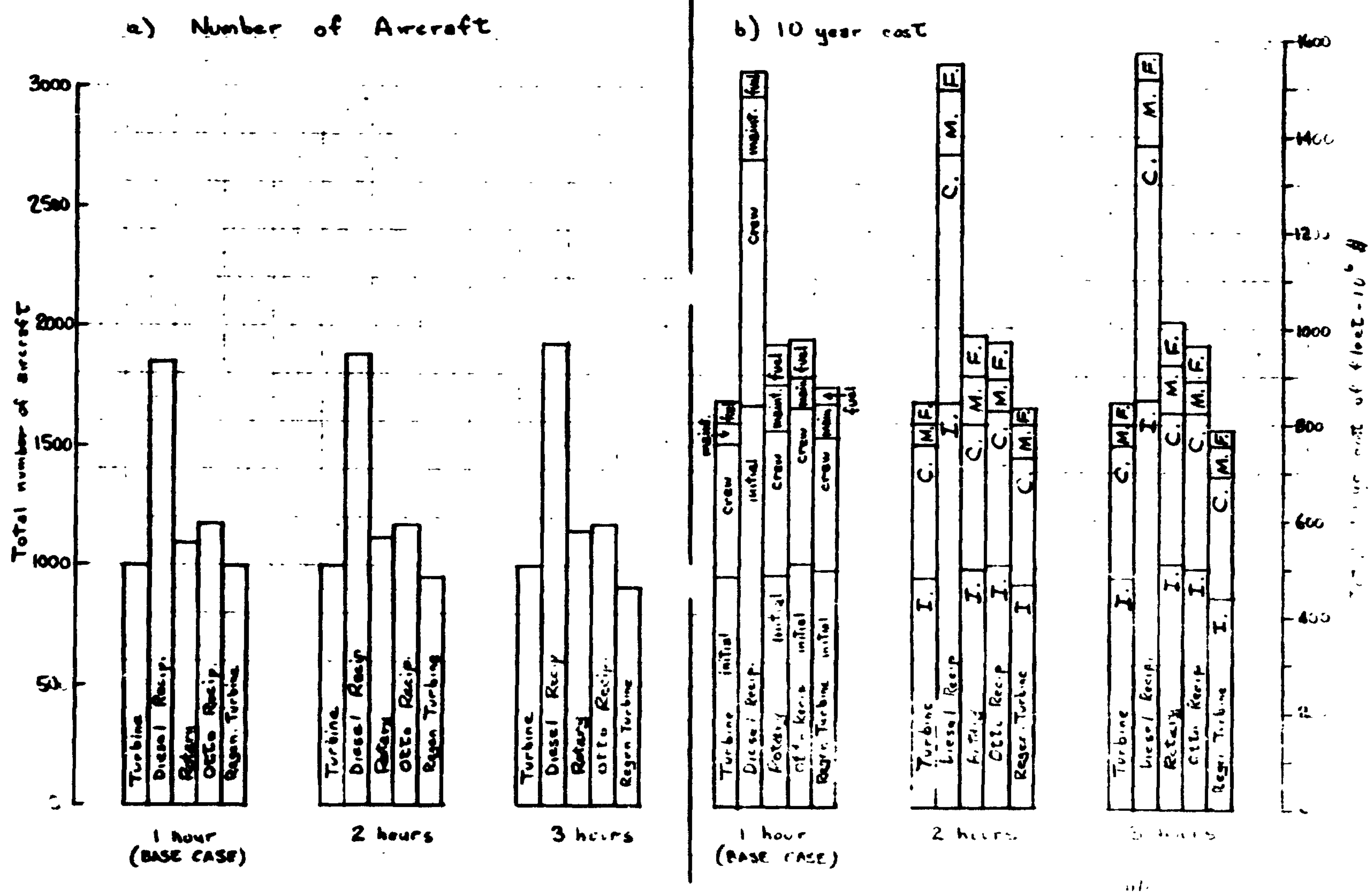


Figure 14: Effect of Utilization Rate

10 year cost as function of Utilization

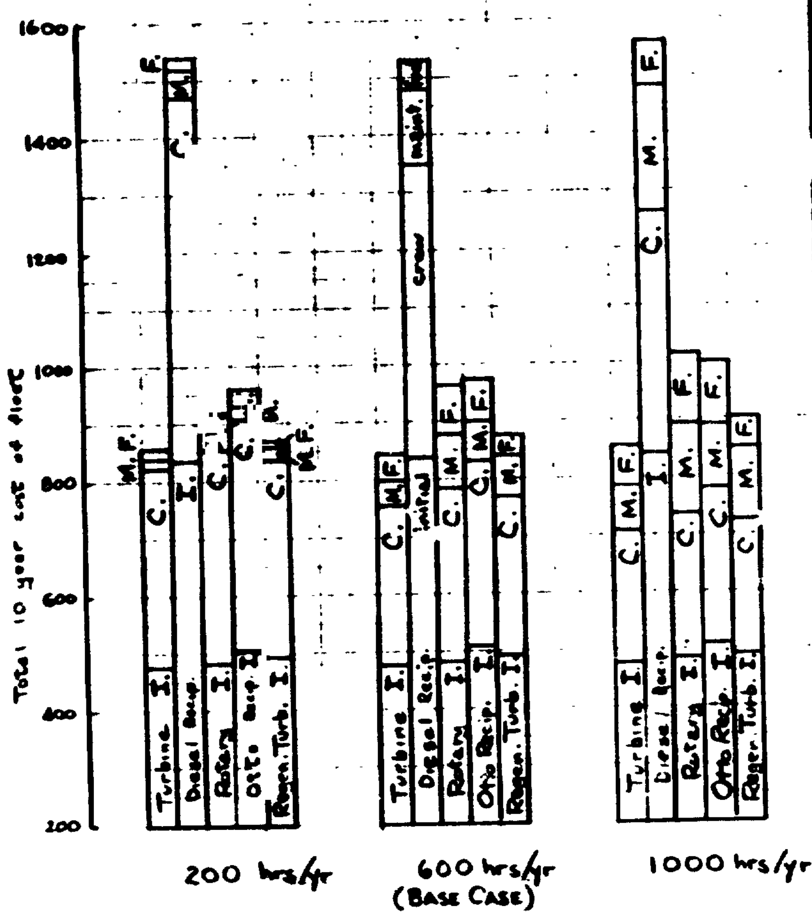


Figure 15: Effect of Fuel Cost

10 year cost as function of fuel cost.

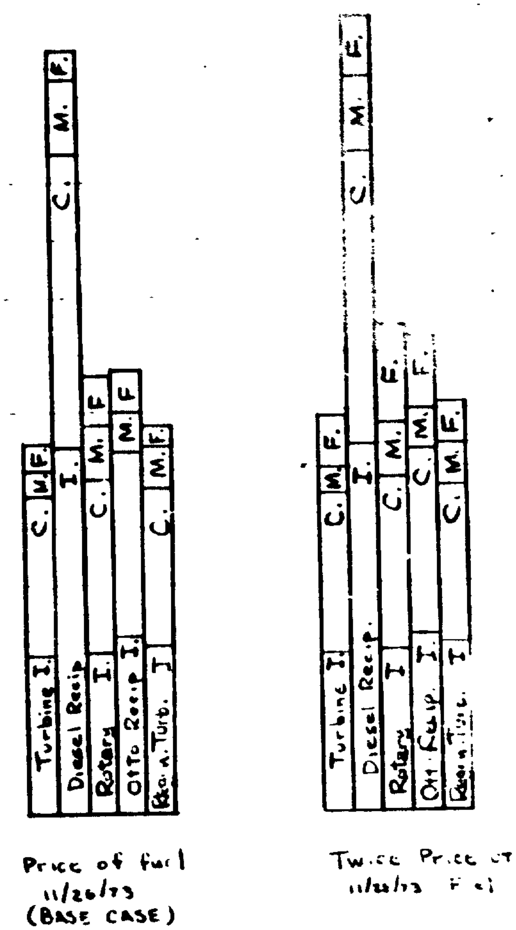
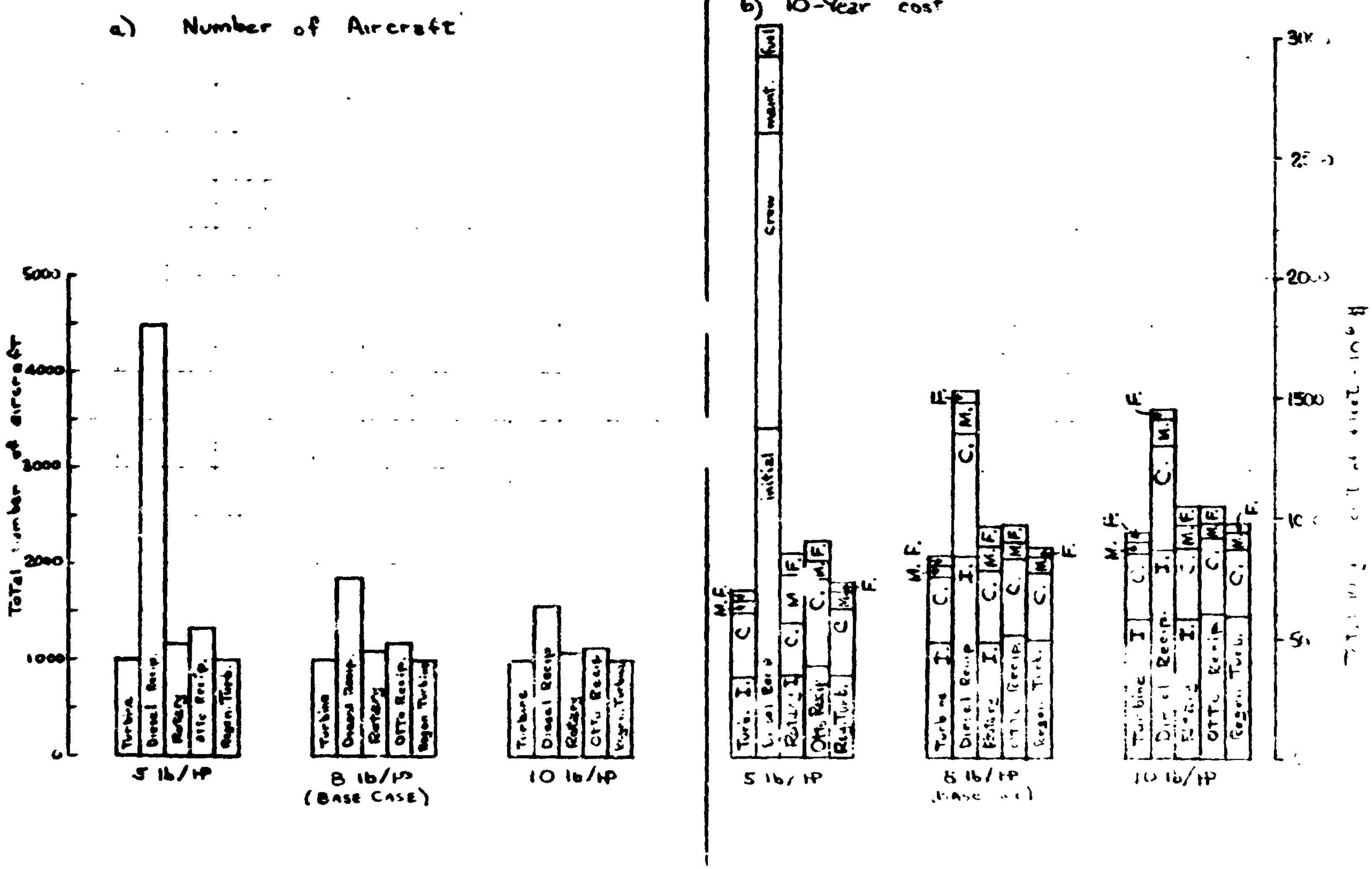


Figure 16: Effect of Lift / HP



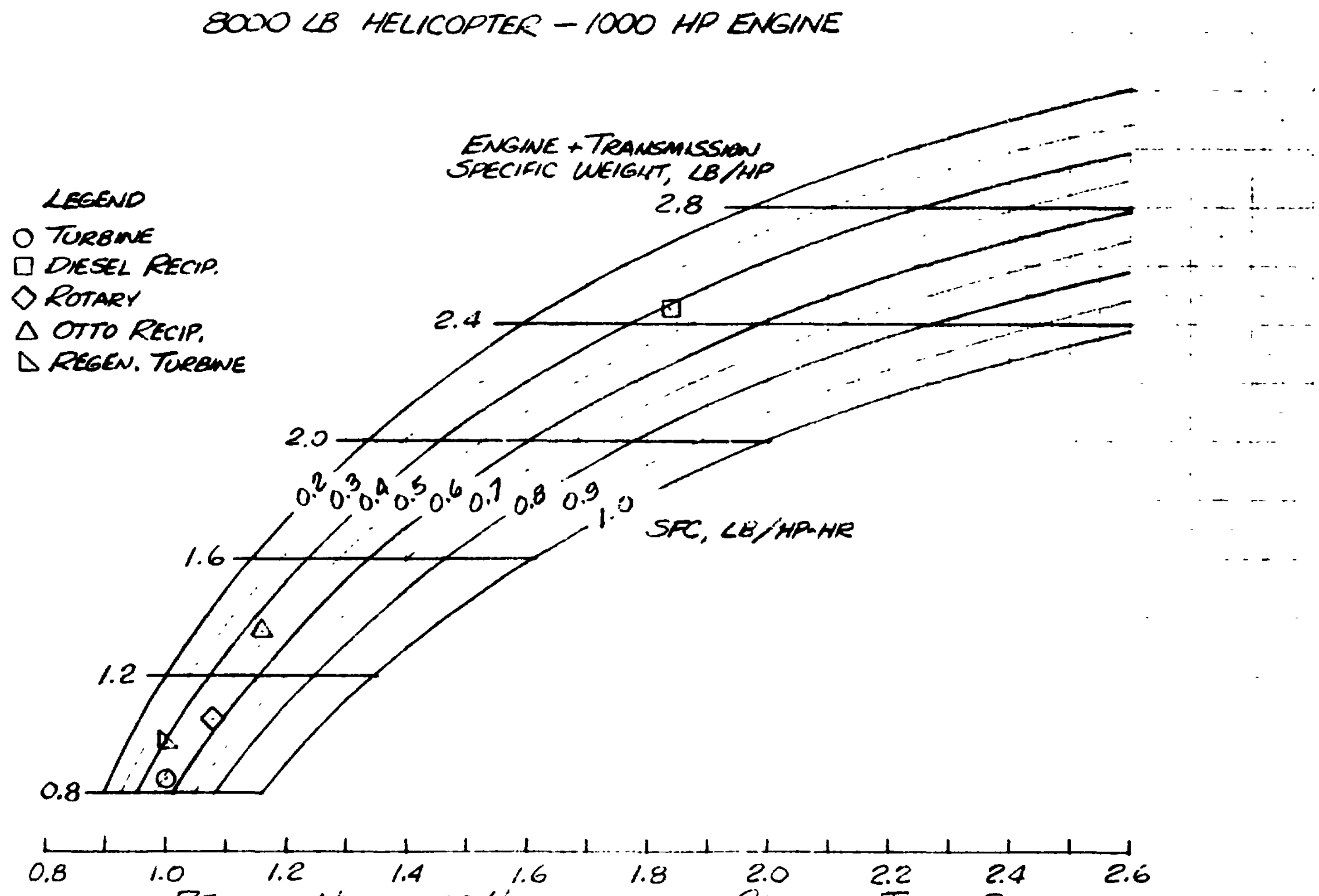


FIG. 17. – EFFECT OF SFC AND ENGINE WEIGHT ON RELATIVE NUMBER OF HELICOPTERS (1000 HP)

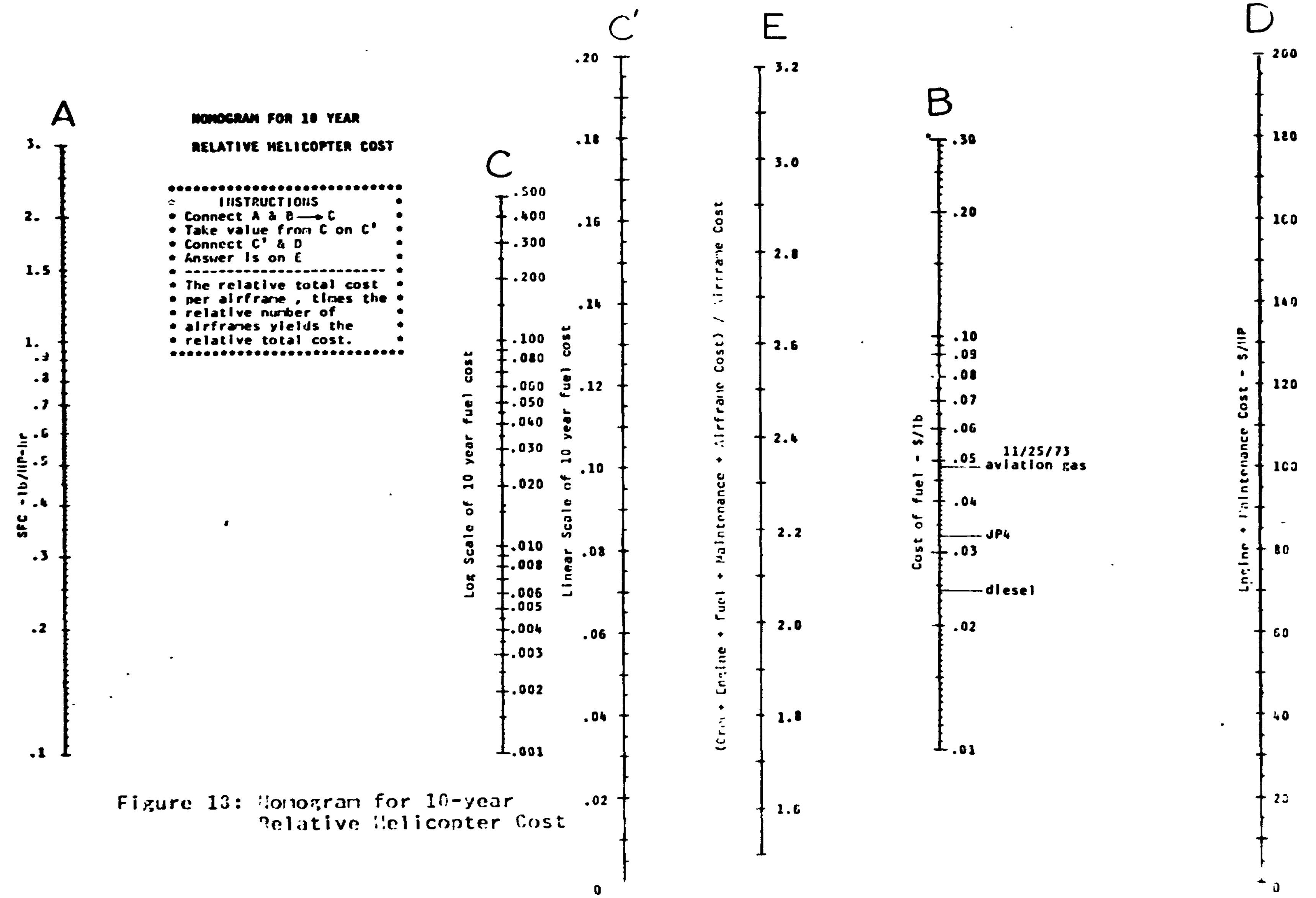


Figure 13: Nomogram for 10-year Relative Helicopter Cost