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CONCEPTUAL STUDY OF FOUR SUBSONIC VTOL PROPULSION SYSTEMS

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ABSTRACT

Typical ejector wing, remote fan-in-wing, remote lift/cruise fan, and lift plus lift/cruise propulsion concepts are parametrically studied on the basis of airplane weights (gross, empty, and propulsion) for three types of airplanes--a Carrier-Onboard Delivery/Search and Rescue airplane for the U.S. Navy, a military utility transport, and a business jet. None of the four systems led to airplanes substantially lighter than the others, and therefore no "best" system is selected.

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SUMMARY

Four VTOL propulsion concepts were compared parametrically for subsonic applications: (1) ejector wing, (2) remote lift fan-in-wing, (3) remote lift/cruise fans, and (4) lift jets plus lift/cruise turbofans. Representative weight and performance models were assumed for each propulsion system and three types of aircraft were selected for evaluation: (1) a Carrier-Onboard-Delivery/Search and Rescue (COD/SAR) airplane, (2) a utility transport (UT), and (3) a 6-passenger business jet (BJ). All airplanes were sized for vertical takeoff on a tropical day with a F/W of at least 1.1 (greater than 1.1 for engine-out capability) and, except for the remote lift/cruise-fan concept, all engines were optimized in by pass ratio and pressure ratio.

The COD/SAR airplanes would weigh (VTOGW) between 30 000 and 36 000 pounds when sized for a 1500 nautical mile COD range. They also would provide up to 47 minutes of on-station search time for a 300-mile-radius SAR mission that includes 10 minutes of hover time for rescue operations. A clear choice of a superior propulsion concept for the COD/SAR airplane did not evolve as a result of this study--all systems yield approximately the same weight and performance, certainly within the error tolerances inherent in this first-order study.

The utility transport VTOGW's also fell in a narrow band (35 000 to 40 000 lb. for 500 n. mi. flight radius) as did the business jets' (21400 to 25 600 lb for 1200 n. mi. range). Comparing empty weight and propulsion system weight also failed to reveal major differences except for the unlikely combination (noisy, high jet blast, too many engines) of a L+L/C business jet. Thus it appears that for all three subsonic applications a "best" propulsion system choice cannot be confidently predicted from airplane weight comparisons alone. Cost, reliability, serviceability, and so forth must be included in such a decision.

INTRODUCTION

Anticipating the eventual emergence of VTOL aircraft as useful vehicles, the Lewis Research Center has initiated a series of survey-type studies to identify promising VTOL propulsion concepts for a variety of applications. It is clearly desirable to identify attractive propulsion concepts at the outset of any VTOL program since the propulsion system is a long lead-time item requiring substantial amounts of research and development. It is important to know, for example, if the ejector wing concept is competitive with the lift/cruise, lift plus lift/cruise, and lift fan-in-wing concepts. Also required is the selection of the most appropriate engine cycle for each of these concepts. Results of some previous studies of this type are reported in references 1 to 3 for several military missions. These studies indicated that for supersonic fighter airplanes the ejector-wing concept is quite attractive in terms of low airplane gross weights and high performance provided the estimated thrust augmentation ratio (1.6) and low ejector system weight are actually achievable.

The present study is directed toward several subsonic applications where VTOL capability might prove especially desirable. First, the Navy is currently interested in a Carrier-Onboard-Delivery (COD) aircraft that could supply its aircraft carriers with needed supplies and personnel as a replacement for the relatively short range/small payload helicopters and S-2E Tracker now in use. Extending this capability for the proposed Sea Control Ships would naturally be useful but would require V/STOL aircraft. Adding VTOL capability to a COD aircraft also allows this aircraft to double as a search and rescue craft since it could presumably hover long enough to rescue a downed pilot. In this study, the COD/SAR airplanes are sized by the COD primary mission (1200 n. mi. baseline range, 5700 lb payload) but also evaluated for a 300-nautical-mile-radius SAR mission with 10 minutes of hover time alloted for the rescue task.

The second type of airplane is labeled a Utility Transport (UT) and is envisioned for such applications as a light assault military transport and a general purpose utility airplane for undeveloped countries. As such it is austerely appointed with provisions for 20 troops sitting on benches plus two attendants and 2 flight crew members. The UT has a baseline out-and-return radius of 500 nautical miles and a total payload of 5200 pounds.

The third type of airplane is a six-passenger business jet (BJ) with delux appointments, 2 stewardesses, and 2 flight crew members. While general private-ownership VTOL airplanes are rather difficult to envision from an economic standpoint, it is conceivable that the advantages such vehicles possess might create a market in the business jet segment. The ability to take off from one corporate installation and land at another without wasting time shuttling to and from airports would certainly be a major consideration to top level executives.

For each of these three types of airplanes, four different VTOL propulsion concepts were evaluated in terms of vertical takeoff gross weight VTOGW, overall weight empty, and propulsion system weight. This method of comparing various propulsion concepts is obviously quite crude and can only be expected to give order of magnitude results. Nonetheless, it usually provides enough information to indicate where more detailed study efforts should be concentrated.

The four propulsion systems examined are diagrammed in figure 1. The ejector system consists of a set of wing- and tail-mounted ejector flaps powered by the exhaust of wing-pylon-supported engines. These engines have a diverter valve that switches the exhaust flow from its normal horizontal direction to the ejector flap system whenever vertical flight is required. Secondary airflow is entrained by the primary gas flow and this produces thrust augmentation. The augmentation ratio ϕ (actual ejector vertical thrust/ideal thrust available by expansion of the ejector primary gas flow) is varied from 1.4 to 1.8, but 1.6 is selected as a baseline for most comparisons (ref. 4). All ejectors are interconnected by hot gas ducts for safety in the event of an engine failure during flight. The turbotip lift/cruise configuration (fig. 1(b)) is envisioned as a pair of J97-type gas generators mounted on the fuselage and connected to three LF 460-type tip-turbine-driven lift/cruise fans--two are mounted in nacelles at the wing-body junction and the third is inside the fuselage just aft of the cockpit. The two wing fans are fitted with hooded nozzles that permit thrust deflection from horizontal to vertical.

The remote lift fan-in-wing concept (fig. 1(c)) places a pair (or pairs) of lift fans in the wing and a fuselage fan behind the cockpit that are used only for vertical flight operation. Diverter valves in the wing-pylon-mounted cruise engines permit switching the engine exhaust flow from the cruise nozzle to the remote lift fans. As with the previous two concepts, interconnecting ducting is used for safety reasons. The lift plus lift/cruise concept (fig. 1(d)) consists of a pair of wing-mounted L/C engines and another pair of fore and aft fuselage-mounted direct-lift engines. Obtaining engine-out capability with the L+L/C concept takes more than just adding ductwork though, since all propulsion units are integral. In this case additional engines are required (4 L/C engines and 8 lift engines) so that symmetrical pairs may be shut down if either fails and still maintain thrust balance.

ASSUMPTIONS

Airplane Configurations and Missions

With three types of airplanes and four types of propulsion systems, it was not possible to make an in-depth study of each airframe/propulsion system combination. Instead, a quick scan of the most important variables was made that permitted reasonable selections of representative airframe/propulsion system configurations. Figure 2 illustrates how this was done for the COD airframe-geometry variables. An initial set of geometry variables was selected that yielded 1280 nautical miles of range for a 40 000-pound VTOGW airplane. The values of the initial choices are connected by the horizontal dashed line in the figure. Perturbations of each variable (denoted by open symbols) were made to obtain the set of sensitivity curves shown. These curves intersect at the initial choice point (1280 n.m.) and show that in some cases a maximum range occurs. For cases involving a maximum range, the baseline values (denoted by solid symbols) were selected on this basis. For the other cases, a value was selected that was judged to be representative on other grounds. For example, in the case of wing loading W/S a strong variation in range occurs that does not produce a maximum for reasonable values of W/S. Hence, a W/S value of 90 pounds per square foot was selected as a reasonable compromise between range and stall speed. Admittedly, this method of selecting baseline values is relatively crude; however, since only differences in airplane weight are sought, only representative values are required to generate valid trends.

A comprehensive listing of the baseline assumptions for both airplane geometry and mission variables is presented in table I. Figure 3 supplements table I with diagrams of the mission profiles and corresponding airplane configurations. The three types of aircraft were configured for their particular functions by adjusting the scaling of fuselage length, depth, and width as a function of gross weight. For example, the COD airplane's cabin was sized according to the overall cargo density (15 lb/ft^3) plus the usual crew accommodations. For the utility transport the cabin was sized to include a 6-foot-long clear area for rapid loading and unloading of troops. And for the business jet the cabin was sized with first-class passenger volume allowances plus space for work tables, lavatory, executive seats, trim, and other internal appointments. As another example, the utility transport was provided with self-sealing fuel tanks while the other airplanes were not.

The mission profiles shown in figure 3 are somewhat arbitrary since standard VTOL mission profiles have not yet evolved. Nevertheless, the baseline ranges, speeds, and altitudes are sufficiently representative to yield valid comparisons among the competing propulsion systems. In fact, range is varied parametrically in the study to determine if it significantly affects the results. The cruise speeds and altitudes were not varied but fixed at their selected values. The L/C fan propulsion system suffers a high thrust lapse rate and was therefore restricted to Mach 0.6 cruise instead of 0.7 for the COD/SAR and UT missions, and 0.8 for the BJ mission. The SAR alternative mission for the COD/SAR airplane is displayed as a dashed line in figure 3(a). The search time becomes a dependent variable because the COD/SAR airplane is sized for the COD mission.

The UT and BJ airplanes are assumed to require engine-out capability and are therefore provided with more engines and higher design F/W than the COD/SAR airplane to enable them to maintain thrust balance and F/W = 1.0 on a 90° F day. This degree of safety exerts a VTOGW penalty (shown later) but is regarded as necessary whenever passengers are carried.

Airframe Weight and Aerodynamics

Major airframe component weights such as wings, tails and fuselages were estimated with the statistical method of reference 5, and modified where necessary by semi-analytic corrections to account for VTOL propulsion. Statistical correlations were also used for the conventional subsystems such as surface controls, electronics, inlets, air-conditioning, and so forth. Since none of the statistical correlations include provisions for VTOL features, the following items were appended to the statistical estimates.

Ejector wing	Fan-in-wing	L/C fans	L+L/C
1. ejector flap system 2. additional power actuators and controls	1. wing fan cutout penalty 2. body fan cutout penalty 3. partial RCS	1. reaction control system (RCS)	1. reaction control system (RCS) 2. propulsion subsystem provisions for direct lift engines (DLE) 3. extra instruments and furnishings for DLE

In addition to these airframe differences there were, of course, propulsion system differences such as ductwork that will be noted in the next section.

The drag coefficients of all airframes were computed as a function of Mach number and airplane geometry using modeling techniques similar to those discussed in reference 6. In this technique the individual component drags are summed to give the total zero-lift drag. These individual drags are based on geometrical properties such as surface area, thickness, length, width, sweep angle, and so forth. The induced drag and compressibility drag rise terms are then added to the zero-lift drag to obtain the total drag.

Propulsion Systems

Except for the remote turbotip L/C fan configuration, all main propulsion engines were assumed to be two-spool mixed flow turbofans designed at the current level of technology (e.g., F401). Standard day performance data for these engines were generated with the GENENG computer program (ref. 7) assuming a 0.975 inlet pressure recovery and a maximum continuous turbine-rotor inlet temperature of 2650° R . The L/C fan performance data was obtained from reference 8 which implies the use of J97 turbojet gas generators connected to LF460 turbotip fans. In all cases, thrust directed vertically by hooded nozzles was decreased 3 percent from the calculated horizontal thrust values. An additional 10-percent thrust penalty was assumed for tropical day (90° F) engine sizing purposes. Reingestion, "suck-down", and control thrust allowances were assumed to be included in the $F/W \geq 1.1$ groundrule.

Bare engine weights and dimensions were calculated with the statistical correlation method of Gerend (ref. 9). Figure 4 shows how specific engine weight varies with bypass ratio and overall pressure ratio OPR using this model. Note especially how rapidly engine weight increases with pressure ratio. This trend has an important bearing on the selection of an optimum OPR for VTOL aircraft since the propulsion system weight fraction is relatively high. Other important assumptions and sources of data are listed in table II. Note that the L/C fan configuration was treated somewhat differently than the others in that the GENENG program was not used to estimate performance. Instead, existing J97-LF460 performance data for a fan pressure ratio of 1.2 were used. Also, the Gerend weight estimate for the L/C fan configuration was modified by a scale factor such that it would match the total system weight of J97-LF460 systems (ref. 8).

RESULTS

Carrier On-Board Delivery/Search and Rescue (COD/SAR) Airplane

The COD mission is the primary mission for the COD/SAR airplane and hence this mission sizes the aircraft. Figure 5 shows the effect of COD mission range on vertical takeoff gross weight VTOGW (on a 90° F day) for each of the four propulsion system types. The most important aspect of this figure is that none of the systems is substantially better or worse than the others. All curves lie in a relatively narrow band that extends from 30 000 to 36 000 pounds VTOGW at the 1500 nautical mile baseline range. If the airplane is designed for 2000 miles range, the band extends from 36 500 to 45 000 pounds. The lowest VTOGW configuration is the L+L/C. However, as will be seen later, the COD-sized L+L/C airplane has such poor SAR performance that it is advisable to resize it with a SAR mission--which increases its VTOGW considerably.

Of the remaining three propulsion concepts, the fan-in-wing with interburning is slightly better than the others. If interburning were not permitted the ejector wing would hold a slight edge. In any case, there is considerable uncertainty in the assumed state-of-the art connected with these systems and any of these curves could easily be shifted several band widths under different groundrules. The weight and augmentation ratio of the ejector wing system, for example, are quite controversial and the sensitivity of these results to these two variables will be shown later for the business jet. At the moment it is sufficient to note that none of these systems has a clear-cut advantage over the rest for this mission.

Cycle optimization. - Each of the points on figure 5 represents a system whose engine cycle has been optimized. An exception is the L/C fan system for which the J97-LF460 cycle was held fixed. On figure 6 the optimization of bypass ratio and overall pressure ratio is illustrated for the ejector wing, fan-in-wing, and L+L/C concepts. The discontinuity in the 0.77 bypass ratio curve for the ejector wing and fan-in-wing concepts is caused by a switch from Titanium to Rene' 41 material in the exhaust gas subsystem (divertor valves, ducting, ejectors, scrolls, etc.). This switch is caused by the higher turbine exhaust temperatures that accompany the lower engine compressor pressure ratios. Rene' 41 ductwork is also required by all of the turbojet points (the entire BPR = 0 curve). Titanium is adequate at all pressure ratios for the other turbofans shown (BPR = 1.5, 2.25). Note that this material change influences the selection of the ejector wing optimum engine cycle--had Rene' 41 been assumed for the entire BPR = 0.77 curve the optimum cycle would have been clearly one with BPR = 1.5 and OPR = 17. With the material change included, however, this cycle is slightly less optimum than the BPR = 0.77, OPR = 25 cycle. The latter cycle is very close to the F401 cycle and it may be concluded that the F401 cycle for a subsonic ejector-wing airplane is essentially optimum in terms of minimizing take-off gross weight. This cycle is also nearly optimum for the fan-in-wing concept. The L+L/C concept, though, would benefit most with a higher bypass ratio--a shallow optimum occurs at BPR = 3.5 and OPR = 20. The reduced sensitivity in the case of the L+L/C concept is due to the relatively smaller L/C engine required.

Turbine-inlet temperature. - The effect of raising the engine turbine inlet temperature 300° R while keeping BPR and OPR fixed at the F401 values is shown in figure 7. Results are given for retaining titanium as the ductwork material while raising the temperature and also for shifting to Rene' 41 ductwork as would actually be required in this case (the exhaust gas temperature is 1525° R at TIT = 2950° R). These results show that a boost in TIT would reduce VTOGW 1300-1700 pounds if it were still possible to use titanium ductwork. The shift to Rene' 41, however, would cause a savings of only 1000 pounds for the fan-in-wing and an increase of 1100 pounds for the ejector wing. The much larger penalty for using Rene' in the ejector wing case is caused by the comparatively large ejector duct gas flow (the fan-in-wing has a much larger augmentation ratio, 2.7 against 1.6, and therefore smaller engine). Thus, raising TIT for F401-type engines does not appear attractive in these applications. Of course at higher bypass ratios the shift to Rene' ductwork would take place at higher TIT due to their lower exhaust gas temperatures.

SAR hover time. - The alternative mission for the COD/SAR airplane is the Search and Rescue mission. Presumably a VTOL SAR airplane would hover during the rescue portion of this mission, hence good hover fuel economy is required to prevent excessive VTOGW. This is illustrated in figure 8 for an airplane sized by a 150 nautical mile radius SAR mission. Note that VTOGW increases rapidly with hover time--and especially so for the L+L/C concept since it has poor hover efficiency (the lift engines' sfc is 1.3 lb per hr/lb). The ejector wing and fan-in-wing curves are very close with the fan-in-wing concept becoming the better of the two at hover times in excess of 30 minutes. Such long hover times are probably not needed in the majority of downed pilot type rescue missions, however, and these missions might be more characteristic of antisubmarine warfare (ASW) missions than SAR missions.

The actual SAR mission selected as the COD/SAR airplane's alternative is one that has a 300 nautical mile radius, 10 minutes of hover time, vertical landing and takeoff, and 5700 pounds of payload. This leaves the search time (at Mach 0.3, sea level) free to vary. But since VTOGW is already specified by the COD mission, the search time is really a dependent variable and has the values shown below.

Propulsion system	VTOGW (from COD), lb	SAR search time, min
Ejector wing	34 000	47
Fan-in-wing	33 100	38
Lift/cruise fans	36 300	23
L+L/C	30 000	0

The lift/cruise fan concept yields the heaviest airplane yet allows only one-half the search duration as the ejector wing. The ejector wing and fan-in-wing are fairly comparable with the ejector wing holding a moderate advantage in search duration. Thus it may be concluded that under the assumed groundrules, the ejector-wing concept is the most attractive candidate for the COD/SAR airplane with the fan-in-wing concept a close second choice.

Note that the L+L/C search time shown in this table is zero. This is really not a fair comparison to make with the other system, however, since the low VTOGW is the prime reason it has such a poor showing rather than its poor hover efficiency (i.e., there is only 10 minutes of hover time devoted to rescue). Put another way, the L+L/C result shown above indicates that in this case the airplane should have been sized by the SAR mission rather than the COD mission. That this is so may be seen in the following table where the L+L/C airplane is sized by the SAR mission at search times corresponding to the previous results for the ejector wing and fan-in-wing.

Propulsion system	VTOGW, lb	COD range, N.M.	SAR search time, min
Ejector wing	34 000	1500	47
Fan-in-wing	33 100	1500	38
Lift/cruise fans	36 300	1500	23
L+L/C	30 000	1500	0
L+L/C	38 000	2130	38
L+L/C	38 900	2185	47

Viewed from this perspective, the L+L/C concept is still rather attractive. Comparing it with the ejector wing, for example, it is seen that for the identical SAR search duration of 47 minutes, the L+L/C airplane would weigh 15 percent more than the ejector wing but also be capable of 45 percent greater COD range. On the other hand, the very high levels of noise, temperature, and downwash velocity associated with lift jets are likely to be so severe as to rule out the L+L/C concept for rescue missions. And, of course, if the groundrule of 10 minutes hover time for rescue were increased to 15 or 20 minutes, then the L+L/C concept would no longer even offer attractive performance in comparison with the ejector wing and fan-in-wing concepts. Thus the L+L/C concept actually does not offer nearly as much potential for a COD/SAR airplane as the table indicates.

Utility Transport (UT) Airplane

Results for the utility transport and business jet airplanes are presented in an abbreviated manner in comparison with the COD/SAR results--emphasizing only the highlights and omitting the details of the engine cycle optimization. Figure 9 shows the tropical-day VTOGW results for the utility transport, both with and without engine-out capability to illustrate the penalty incurred for this safety feature. Again there is not a great deal of VTOGW spread amongst the four propulsion concepts. The L+L/C concept is the lightest at 31 500 pounds without engine-out capability, but this is only 5500 pounds less than the heaviest system (fan-in-wing). Adding engine-out capability does not change the relative ranking of these concepts, it simply adds 3000 to 4500 pounds to the VTOGW.

The airplanes without engine-out capability are sized on the basis of F/W = 1.1 on a tropical day (90° F) using four engines. With engine-out capability, the tropical day F/W ratio is increased to 1.33 so that if an engine fails during vertical takeoff the remaining three can provide a F/W ratio of 1.0 through the use of interconnecting ductwork. Since the L+L/C concept does not have such ductwork, the number of L/C engines for it was increased from 2 to 4 and the number of direct lift engines from 2 to 8. Since together the lift engines produce two-thirds of the total lift, twice as many lift engines were added to maintain equal engine sizes. If any of these engines fails, its symmetrical mate is also shut-down to maintain equilibrium. Because of the added number of engines, each engine pair produces one-sixth of the total lift and the tropical day F/W need only be increased from 1.1 to 1.165. The total number of engines (12) required, however, may very well be unacceptable from a cost standpoint. This number could be reduced to 8 if the lift engines were twice the size of the L/C engines--but then the F/W would have to be increased to 1.5 instead of 1.165. Either way, the L+L/C concept loses much of its attractiveness if engine-out capability is added.

Business Jet (BJ) Airplane

Engine-out capability is regarded as mandatory for the business jet; thus, except for the L+L/C concept (having 8 + 4 engines) all business jets were assumed to have four engines. Even this may not be sufficient redundancy for the fan systems, since either a lift fan or a L/C fan failure would be as disastrous as a core engine failure. Such considerations, while important in more detailed studies, are neglected here since only order of magnitude results are sought.

Figure 10 is presented to illustrate the effects of business jet range and two controversial ejector system parameters (augmentation ratio and weight). In part (a) of this figure it may be seen that the VTOGW for the baseline range of 1200 nautical miles varies between 20 000 and 26 000 pounds. The 1200 mile range is typical for a 1-stop transcontinental requirement. If 1800 miles were specified the VTOGW would increase about 30 percent. As before, the band of VTOGW is relatively narrow with the L+L/C concept appearing to be the lightest, yet almost certainly unacceptable because of its many engines (12), high noise, and high jet exhaust velocity. The ejector wing yields practically the same gross weight as the L+L/C, however, and would be preferred due to its relatively low noise and jet exhaust velocity, and relatively small number of engines (4). Note that if the ejector augmentation ratio ϕ were improved from the assumed value of 1.6 to 1.8 not much reduction in VTOGW results. Also, if ϕ decreased to 1.4 the VTOGW increases only 13 percent and is still slightly lighter than the fan-in-wing and L/C fan systems. Of course there really is not enough difference in VTOGW to judge one system superior to all the rest. Too many other criterions such as cost, noise, reliability, and jet blast have been ignored to make firm choices. What is evident is that the ejector-wing concept appears to be at least as attractive as its competitors on a first-look basis.

The effect of varing the ejector system ducting weight assumption is shown in figure 10(b). The baseline case is denoted by a circle at relative weight 1.0 and represents a 1200 mile range business jet with an augmentation ratio of 1.6. The optimum engine cycle is also noted at the baseline as BPR = 1.5, OPR = 15. The absolute ducting weight is 1194 pounds and is calculated with the aid of reference 13 (General Electric Co.) using the engine related inputs from GENENG (ref. 7). The duct weight includes all ductwork between the engines and the ejector, but not any ejector parts. The dashed curve shows how sharply VTOGW rises when a multiplying factor in the duct weight equations of reference 13 is increased above unity while retaining the same engine cycle. Actually, if the ducting were more than twice as heavy as estimated the engine cycle should be reoptimized in order to shrink the size of the ductwork. This approach is shown by the solid curve where the optimum cycle at 3-3/4 relative weight has shifted to BPR = 0.77, OPR = 27. This higher pressure/lower volume cycle leads to a more compact duct system and substantially lowers the penalty for higher specific weight.

Other duct weight estimates that have come to the authors' attention fall in the 0.7 to 2.0 relative weight range. Thus, the worst that may reasonably be expected is an increase from 21 500 to 26 000 pounds VTOGW, assuming the duct weight change occurs early enough in the design cycle to influence the airframe and engine design. Such an increase in gross weight would certainly detract from the ejector wing concept's apparent attractiveness presented so far--although it would not seriously affect its competitive position unless a simultaneous decrease in augmentation ratio to about 1.4 occurred. If both duct weight and augmentation ratio estimates prove to be quite optimistic then the ejector wing concept no longer would compete well with the fan-in-wing or L/C fan systems.

Airplane Sizing Summary

A summary of the overall results is presented in figure 11 with bar charts of the tropical day VTOGW, overall weight empty (OWE), propulsion system weight (PSW), and, for the COD/SAR airplanes, the search time permitted on a SAR mission. A logarithmic scale is used to emphasize the propulsion system weight differences (on a linear scale they become indistinguishable). Presumably there exists a relationship between cost and OWE and PSW so that weight comparisons give some indication of cost comparisons also. In-depth studies would be required, of course, to substantiate or refute this tentative presumption.

Generally, the weight differences among the four propulsion concepts are relatively small--making it difficult to select a "best" system. An exception to this observation is the low propulsion system weight of the L+L/C concept. The L+L/C propulsion weight for the UT and BJ aircraft, for example, is about one-half that of the fan-in-wing concept. However, as discussed previously, there are noise, jet blast, and engine number objections that would likely prevent the L+L/C configuration from being a serious contender in the BJ application. Assuming this to be so, the ejector wing OWE and PSW are somewhat lower than the others and this lends support to the earlier conclusion regarding its attractiveness on the basis of minimum VTOGW.

Results of sizing the L+L/C version of the COD/SAR airplane first on the COD and then on the SAR mission are shown as a pair of bars on the far right side of figure 11(a). To be competitive, SAR sizing is required for the L+L/C concept since otherwise no search time is available. Note also that even though the SAR-sized version appears attractive due to its low propulsion weight and high COD range, its VTOGW is highest and its severe lift jet downwash environment is likely to preclude its use as a rescue airplane.

Group weight statements for all baseline airplanes are presented in tables III to V. Additional airplane and engine information is supplied in tables VI to VIII.

CONCLUDING REMARKS

It must be recognized that a quick-scan study of this nature cannot provide answers to many questions that effect propulsion system choices. In-depth studies of airframe/propulsion system integration are needed to accurately assess weight and performance penalties, and such penalties could easily shift the ranking displayed in this report. Nevertheless it appears that it would take sizable groundrule or weight modeling changes to alter the principal conclusions. The main conclusion centers on the relatively narrow range of VTOGW produced by the four propulsion concepts. None of the concepts was demonstrated to be far superior to the others and, on this basis, it would be premature to recommend one concept over the rest. Perhaps the most interesting result is that the ejector-wing concept holds promise in areas other than its current Navy fighter-interceptor role.

It would be helpful in future efforts to determine what impact optimizing the following would have: (1) the remote lift/cruise fan engine cycle and fan pressure ratio, (2) the remote fan-in-wing pressure ratio, and (3) the mission profile parameters such as cruise altitudes and speeds. These items were held fixed in the present study but it would be more equitable to allow them to vary with each design-point airplane.

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TABLE I. - AIRPLANE ASSUMPTIONS

		Ejector wing	L/C fans	Fan-in-wing	L+L/C
Wing loading, lb/ft^2	-COD	90	90	90	90
	-UT	90	90	90	90
	-BJ	90	90	90	90
Aspect ratio	-COD	4	8	4	4
	-UT	4	8	4	4
	-BJ	5	8	5	5
Taper ratio	-COD	0.35	0.35	0.35	0.35
	-UT	.35	.35	.35	.35
	-BJ	.35	.35	.35	.35
Leading edge sweep	-COD	30	30	30	30
	-UT	30	30	30	30
	-BJ	30	30	30	30
Thickness ratio, root/tip	-COD	0.14/0.12	0.14/0.12	0.14/0.12	0.14/0.12
	-UT	.14/0.12	.14/0.12	.14/0.12	.14/0.12
	-BJ	.11/0.11	.11/0.11	.11/0.11	.11/0.11
Body length/diameter	-COD	6	6	6	6
	-UT	6	6	6	6
	-BJ	8	8	8	8
Number of engines[a]	-COD	2	2	2	2+2
	-UT	4	4	4	8+4
	-BJ	4	4	4	8+4
F/W on 90° F day[b]	-COD	1.1	1.1	1.1	1.1
	-UT	1.33	1.33	1.33	1.16
	-BJ	1.33	1.33	1.33	1.16
Cruise Mach number[c]	-COD	0.7	0.6	0.7	0.7
	-UT	.7	.6	.7	.7
	-BJ	.8	.6	.8	.8
Cruise altitude, k ft	-COD	36	36	36	36
	-UT	36	36	36	36
	-BJ	36	36	36	36
Ultimate load factor	-COD	7	7	7	7
	-UT	4	4	4	4
	-BJ	4	4	4	4

TABLE I. - Continued. AIRPLANE ASSUMPTIONS

		Ejector wing	L/C fans	Fan-in-wing	L+L/C
Payload, lb	-COD	5700 (5000 lb cargo + 700 lb SAR avionics)			
	-UT	5200 (20 troops @240 lb ea + 2 attend. @200 lb ea)			
	-BJ	1840 (6 passengers @240 lb ea + 2 attend. @200 lb ea)			

[a]Number of engines operating during cruise and hold is one-half number of installed engines or 2, whichever is greater. UT and BJ have engine out capability, hence more installed engines. For L+L/C configurations, lift engines produce two-thirds of total lift.

[b]Higher F/W for UT and BJ due to engine out capability. If an engine fails, F/W decreases to 1.0.

[c]L/C fan Mach number lowered to 0.6 due to rapid thrust fall-off with Mach number.

TABLE II. - PROPULSION SYSTEM ASSUMPTIONS

	Ejector wing	L/C fans	Fan-in-wing	L+L/C
Engine performance[a]	ref. 7	ref. 8	ref. 7	ref. 7
Bare engine weight	ref. 9	0.63xref.9[b]	ref. 9	ref. 9
Remote gear box, lb	135	135	135	135
Diverter valve weight, lb[c]	150(Wa/265)	---	150(Wa/265)	---
Hooded nozzle weight, lb[c]	---	150(Wa/180)	---	150(Wa/180)
Remote fan weight	---	---	ref. 11,12	---
Duct system weight	ref. 13	---	ref. 13	---
Augmentation ratio[d]	1.6	---	---	---
Fan pressure ratio	---	1.4	1.2	---
Remote fan performance	---	---	ref. 10	---
Direct lift engine T/W,sfc[e]	---	---	---	16, 1.3
DLE thrust/total thrust	---	---	---	0.67

[a] For ref. 7 items, inlet pressure recovery assumed to be a 0.975 and maximum continuous turbine-rotor inlet temperature of 2650° R.

[b] Includes bare engine, L/C fans, and ducting. The 0.63 factor scales the ref. 9 estimate (assuming BPR = 7.9, OPR = 14, TIT = 2400° R) to the J97-LF460 combination.

[c] Wa is rated airflow, lb/s.

[d] Actual augmented thrust/ideal thrust of primary ejector gas.

[e] Includes accessories and hooded nozzle, ref. 14.

TABLE III. - WEIGHT STATEMENTS FOR BASELINE COD/SAR AIRPLANES (lb)

	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing	2094	1955	2786	1548
Body	3514	3428	3730	3284
H tail	549	282	515	259
V tail	268	261	466	237
Landing gear	1323	1299	1382	1215
Nacelles	386	224	660	254
Propulsion subsystems	908	825	894	806
Surface controls	1183	1074	1117	1027
Furnish, instr, a/c, misc	1428	1425	1474	1454
Reaction control system	0	608	1285	1054
Main engines	4274	2430	5998	1880
Lift engines	---	---	---	1520
Lift fans	---	2508	---	---
Ductwork	1125	511	---	---
Crew	400	400	400	400
Payload	5700	5700	5700	5700
Fuel	10210	9671	9005	8781
Tropical day VTOGW	34004	33078	36335	29915

TABLE IV. - WEIGHT STATEMENT FOR BASELINE UTILITY TRANSPORT (lb)

	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing	1972	1868	2282	2066
Body	3530	3834	3724	3735
H tail	582	253	419	387
V tail	225	246	388	354
Landing gear	1380	1466	1435	1349
Nacelles	251	170	676	153
Propulsion subsystems	1163	1196	1080	1114
Surface controls	964	864	838	830
Furnish, instr, a/c, misc	2923	2964	2948	3003
Reaction control system	0	777	1384	1688
Main engines	4184	3748	7657	2286
Lift engines	---	---	---	1890
Lift fans	---	3700	---	---
Ductwork	2184	776	---	---
Crew	400	400	400	400
Payload	5200	5200	5200	5200
Fuel	10287	11510	9111	9860
Tropical day VTOGW	36269	39766	38495	35037

TABLE V. - WEIGHT STATEMENT FOR BASELINE BUSINESS JET (lb)

	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing	1401	1394	1569	1103
Body	2182	2478	2523	2354
H tail	399	213	309	190
V tail	165	189	268	165
Landing gear	975	1071	1085	977
Nacelles	157	108	450	109
Propulsion subsystems	680	711	704	678
Surface controls	1102	1081	1088	1027
Furnish, instr, a/c, misc	2037	2055	2058	2113
Reaction control system	0	595	1049	1303
Main engines	2697	2654	5018	1608
Lift engines	---	---	---	1160
Lift fans	---	2293	---	---
Ductwork	1195	458	---	---
Crew	400	400	400	400
Payload	1840	1840	1840	1840
Fuel	5542	6628	6180	5928
Tropical day VTOGW	21442	24708	25210	21482

TABLE VI. - COD/SAR BASELINE AIRPLANE DATA (lb, ft, s)

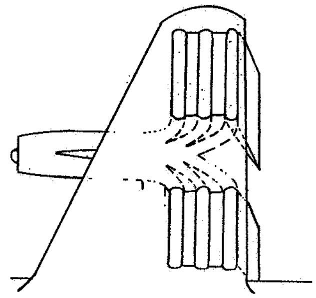
	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing planform area	378	368	404	332
Wing exposed area	285	277	331	258
Wing span	38.9	38.3	56.8	36.5
Wing root chord	14.4	14.2	10.5	13.5
Fuselage length	46.3	45.9	47.2	47.5
$(C_D)_{min}$	0.0190	0.0190	0.0195	0.0195
Main engine cycle, BPR/OPR	0.77/27	0.77/27	7.9/14	3.5/20
Main engine thrust, SLS	13348	7416	11373	6180
Main engine airflow	223	124	583	179
Lift engine thrust, SLS	---	---	---	12181

TABLE VII. - UTILITY TRANSPORT BASELINE AIRPLANE DATA (lb, ft, s)

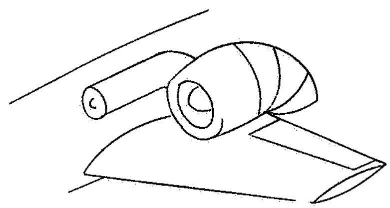
	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing planform area	402	441	428	389
Wing exposed area	315	343	359	339
Wing span	40.1	42.0	58.5	55.8
Wing root chord	14.9	15.6	10.8	10.3
Fuselage length	52.9	54.3	53.8	58.9
$(C_D)_{min}$	0.0194	0.0192	0.0198	0.0202
Main engine cycle, BPR/OPR	1.5/15	0.77/27	7.9/14	3.5/15
Main engine thrust, SLS	8768	5390	5827	3839
Main engine airflow	174	90	299	110
Lift engine thrust, SLS	---	---	---	3784

TABLE VIII. - BUSINESS JET BASELINE AIRPLANE DATA (lb, ft, s)

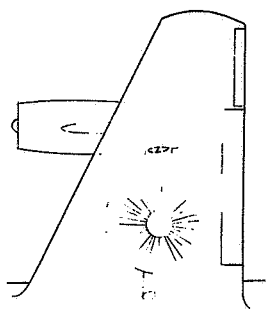
	Ejector wing	Fan-in-wing	L/C fans	L+L/C
Wing planform area	238	275	280	239
Wing exposed area	193	220	236	199
Wing span	34.5	37.0	47.3	34.5
Wing root chord	10.2	11.0	8.8	10.2
Fuselage length	48.9	50.8	51.1	53.8
$(C_D)_{min}$	0.0200	0.0195	0.0199	0.0206
Main engine cycle, BPR/OPR	1.5/15	0.77/27	7.9/14	3.5/15
Main engine thrust, SLS	5183	3144	3816	2354
Main engine airflow	103	52.6	195	67.2
Lift engine thrust, SLS	---	---	---	2320



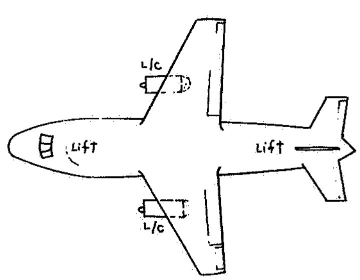
a) EJECTOR WING



b) Turbotip Lift/CRUISE FAN



c) FAN IN WING



d) [illegible] T/CRUISE

FIGURE 1 [illegible] SYSTEMS

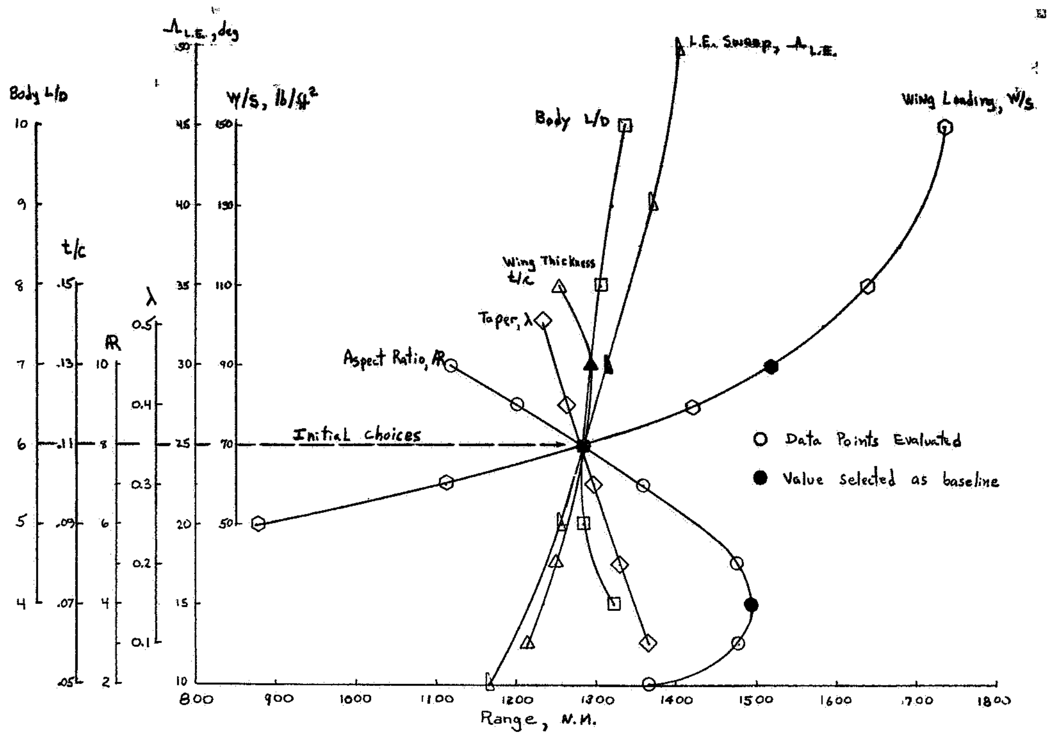
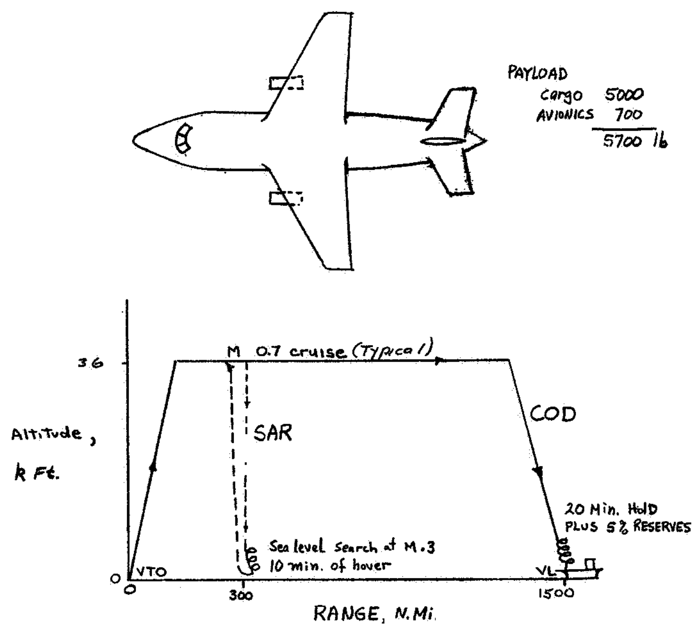


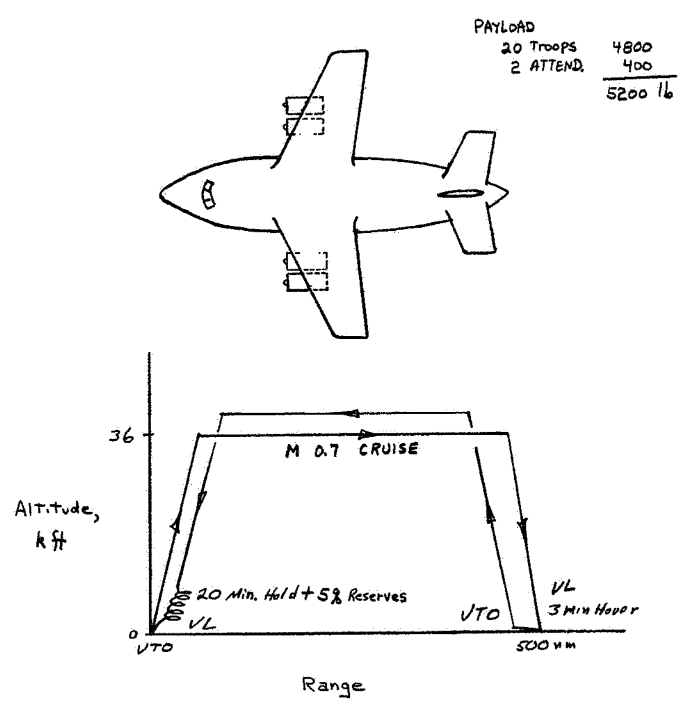
Figure 2 Selection of Airplane Geometry for COD Mission Airplane. VTOGW = 40000 lb.

E-7599



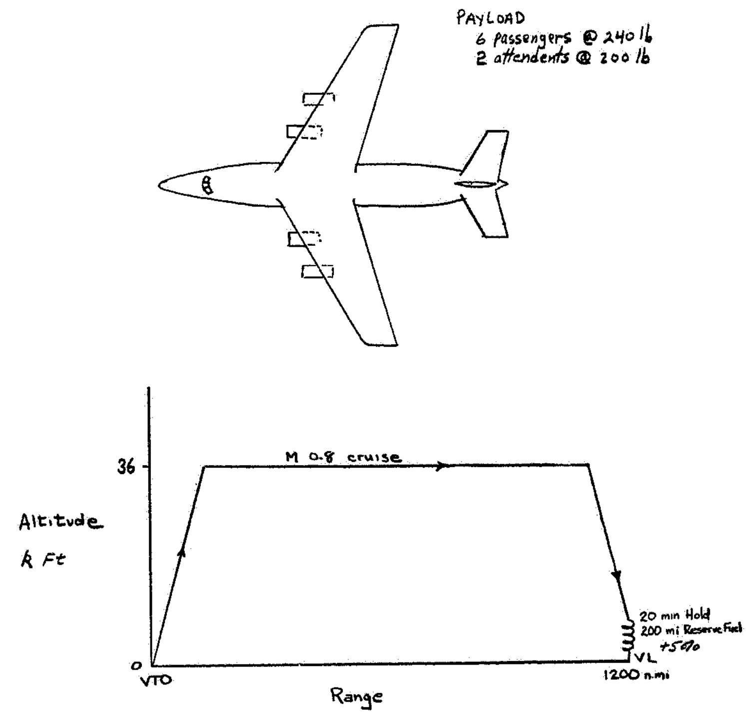
a) CARRIER ON-BOARD DELIVERY (COD) AND SEARCH AND RESCUE (SAR)

FIGURE 3 - MISSION PROFILES AND AIRPLANE CONFIGURATIONS



b) UTILITY TRANSPORT (UT)

FIGURE 3 (cont.) - MISSION PROFILES AND AIRPLANE CONFIGURATIONS



c) BUSINESS JET (BJ)

FIGURE 3 (concl.) - MISSION PROFILES AND AIRPLANE CONFIGURATIONS

5/9/73 LWF E-7599

5/9/73 LWF E-7599

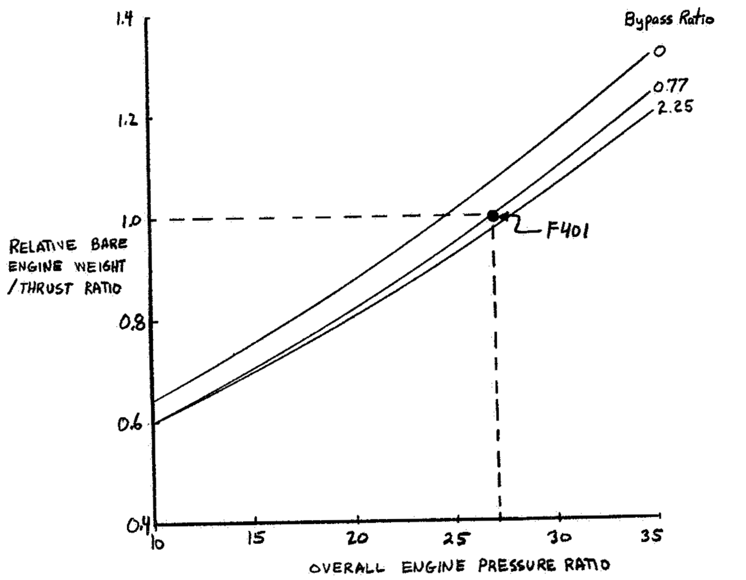


FIGURE 4.- BARE ENGINE WEIGHT PER GEREND (ref. 9) USING Thrust/AIRFLOW FROM GENENG (ref. 7).

E 1599

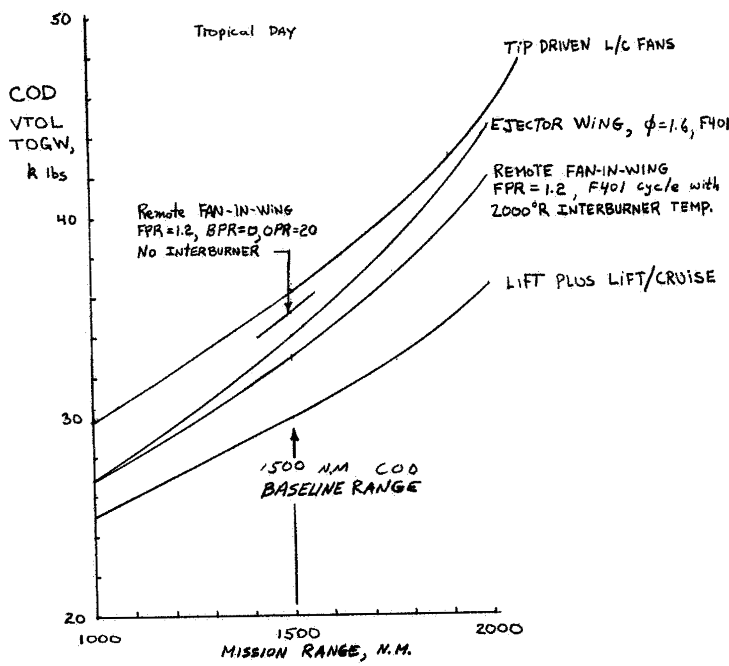
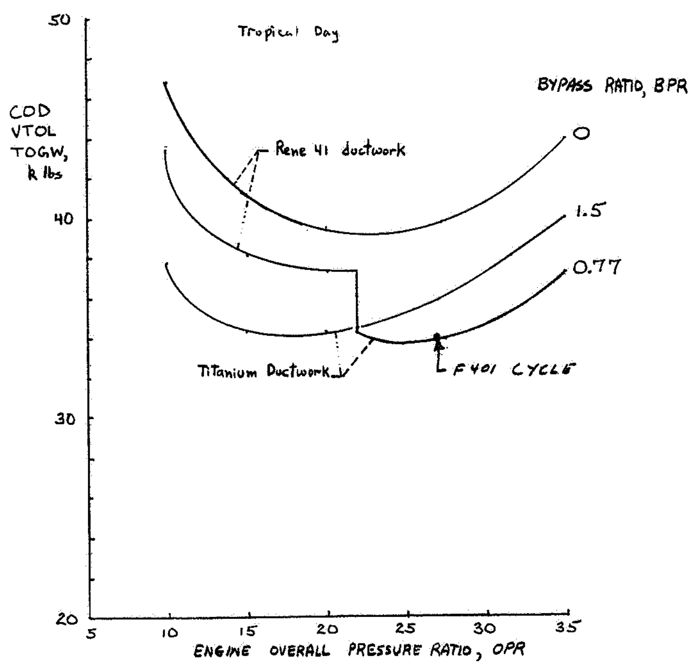


Figure 5 - Effect of Mission Range FOR COD MISSION.



(a) EJECTOR WING, $\phi = 1.6$

FIGURE 6 - EFFECT OF ENGINE CYCLE COD MISSION, RANGE, 1500 N.M.

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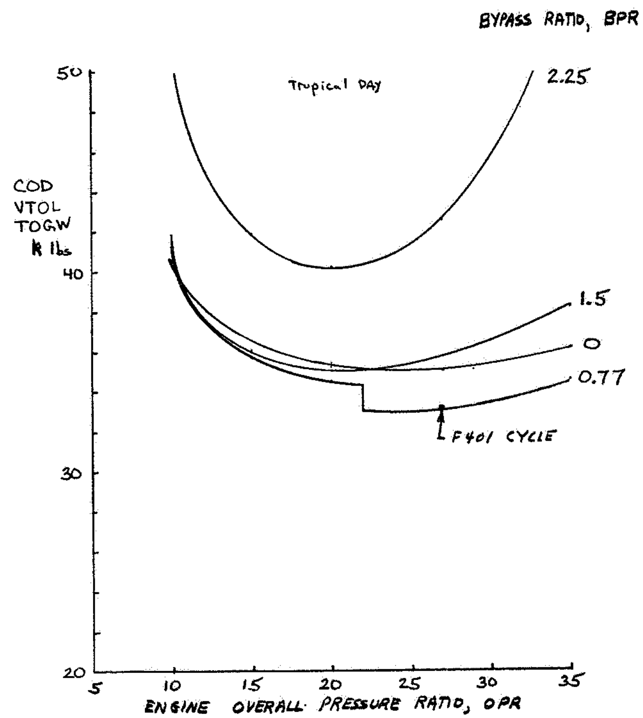

(b) FAN-IN WING, FAN PR = 1.2, INTERBURNER TEMP, 2000°R

FIGURE 6 (cont.).- EFFECT OF ENGINE CYCLE COD MISSION; RANGE 1500 N.M.

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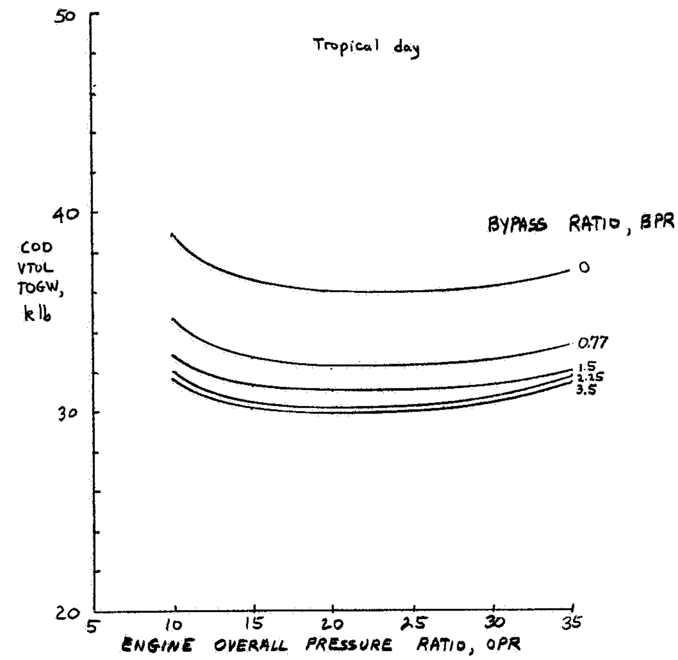

(c) L + L/C

FIGURE 6 (cont.) - EFFECT OF ENGINE CYCLE COD MISSION, RANGE, 1500 N.M.

E 7599

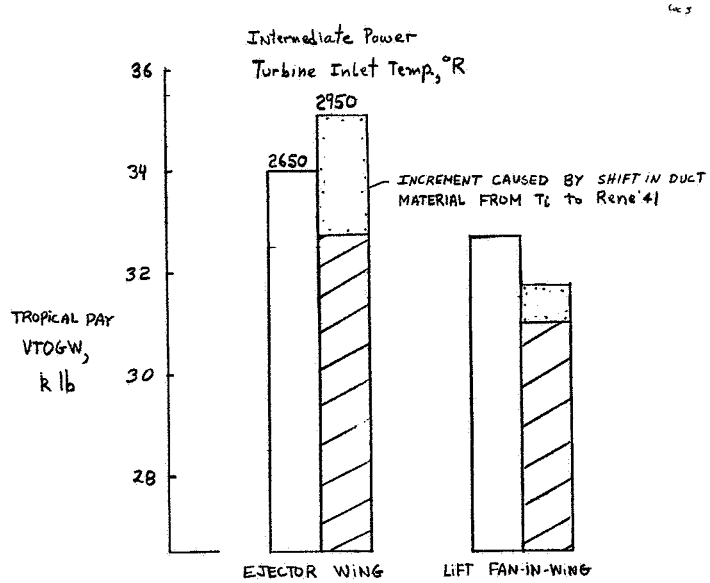

FIGURE 7. - EFFECT OF TURBINE INLET TEMPERATURE COD MISSION, RANGE 1500 N.M., BPR, 0.77, OPR, 27

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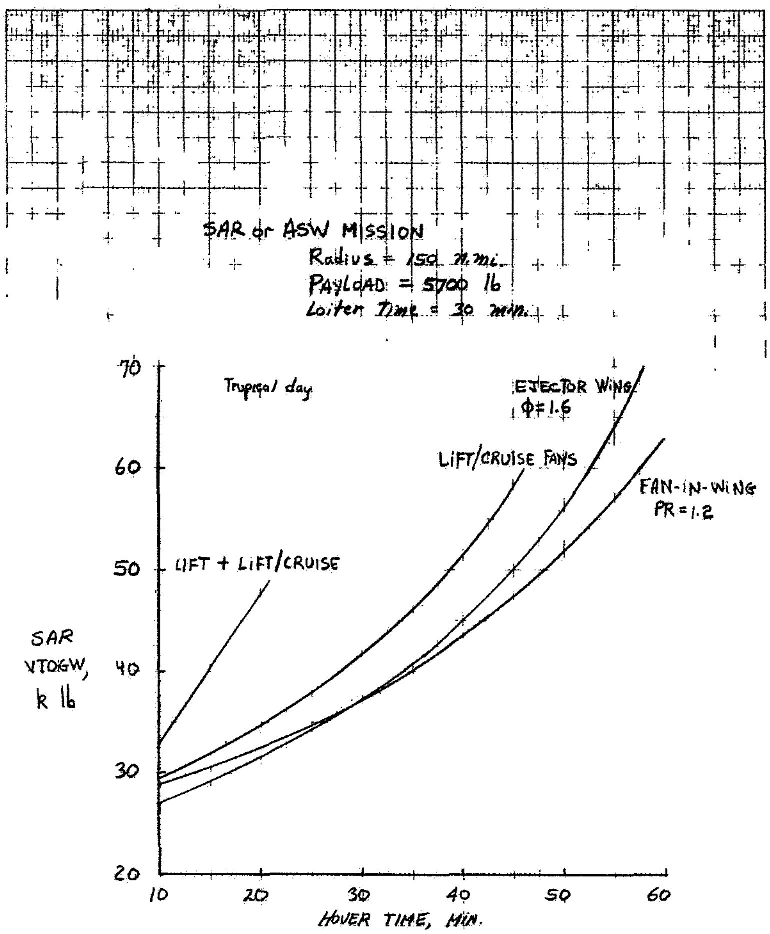

FIGURE 8.- EFFECT OF HOVER TIME REQUIRED ON VTOGW

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5-14-73

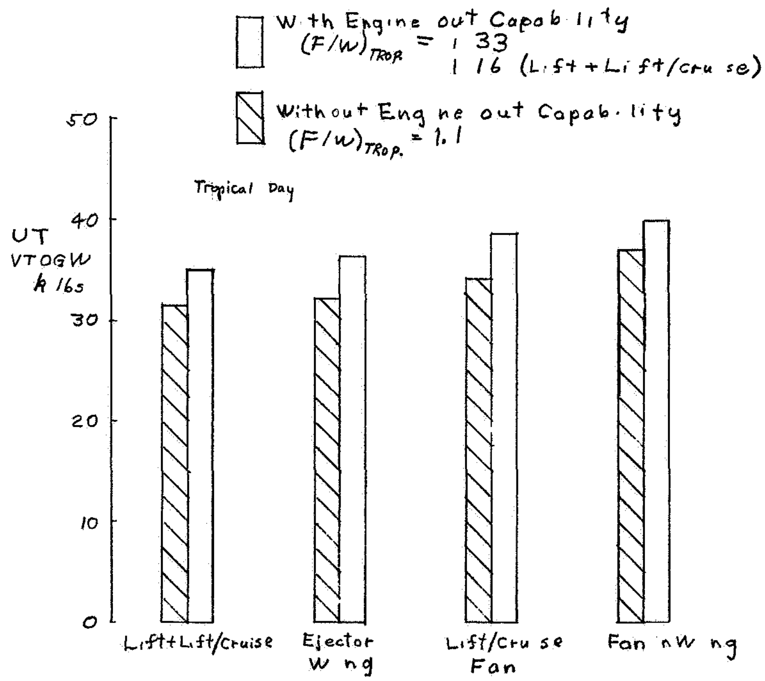

Figure 9.- Effect of Engine-Out-Capability on VTOGW for Utility Transport

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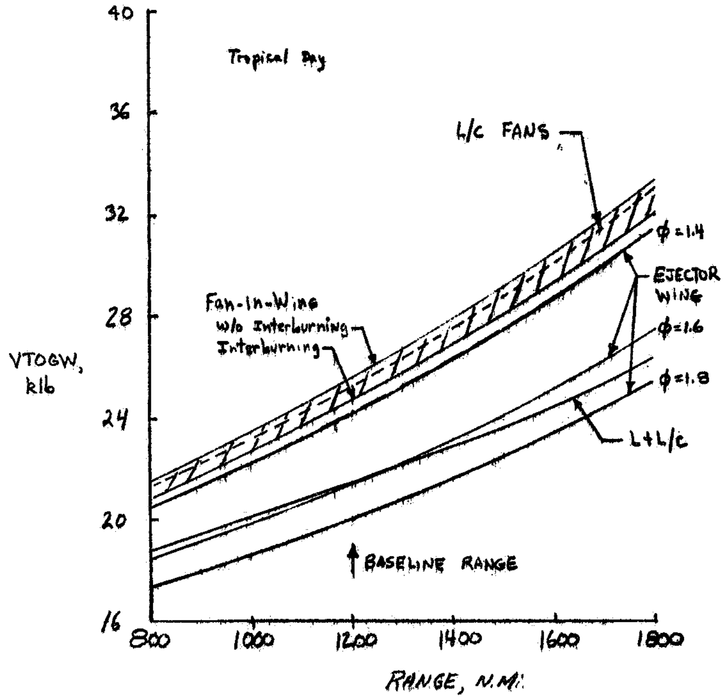
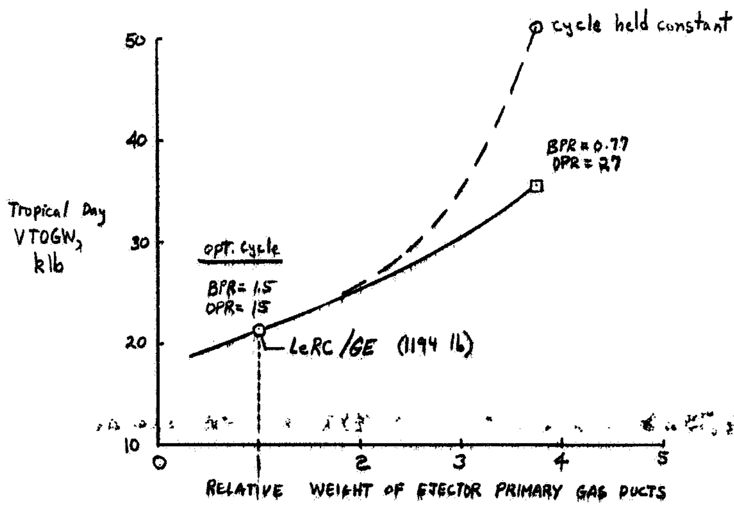
5 23, 73

VTOL 6 PASSENGER BUSINESS JET
2 CREW
2 ATTENDANTS
4 ENGINES
200 N.MI + 20 MIN. Hold + 5% Reserves
(F/W) TROP DAY = 1.33 (1 engine, out capability)
1.16 (L+L/c only)



(a) Augmentation Ratio

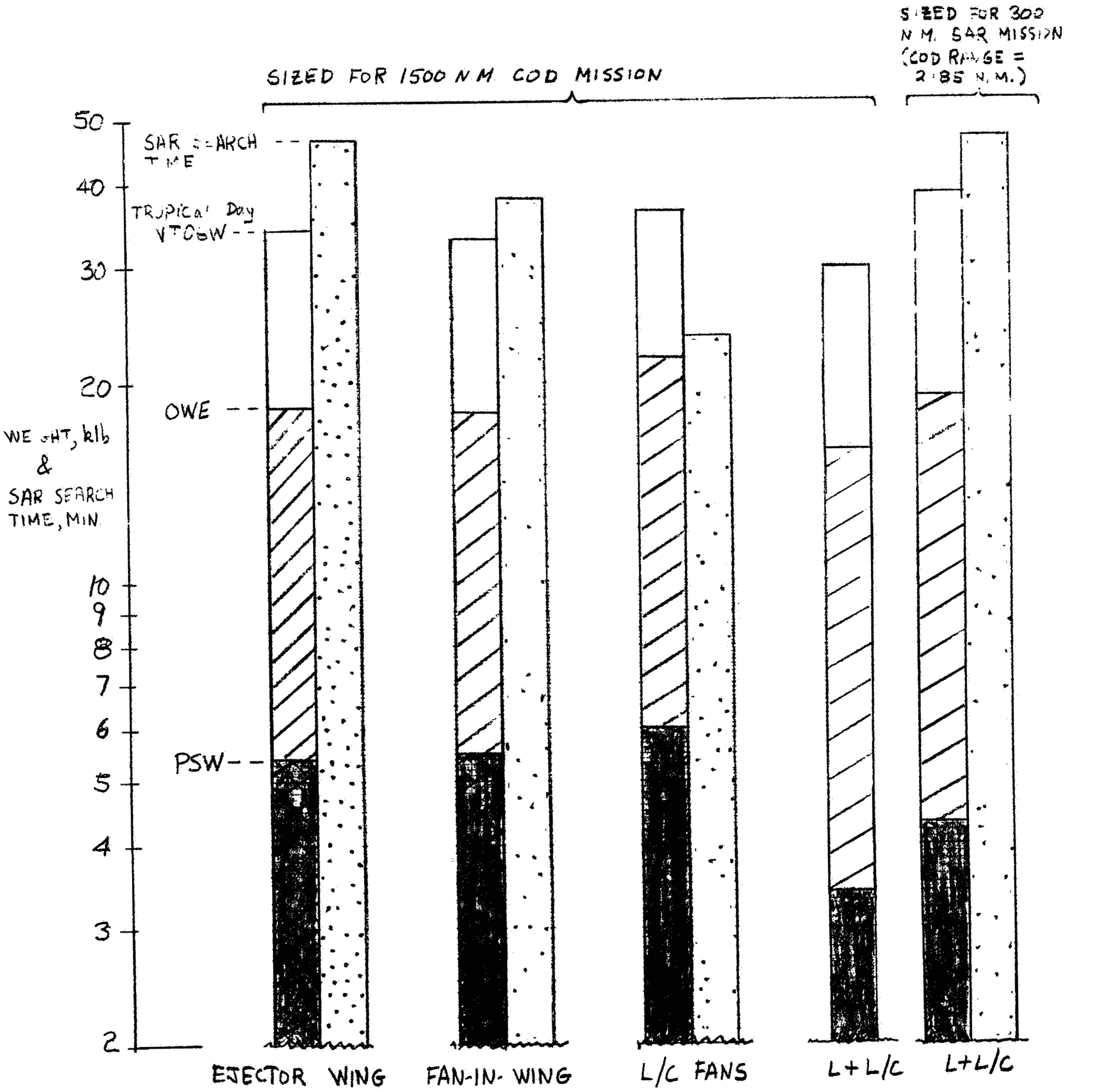
Business Jet - RANGE = 1200 n.mi, φ = 1.6



(b) Duct Weight

FIGURE 10 - EFFECT OF EJECTOR SYSTEM PARAMETERS ON VTOGW FOR 6-PASSENGER BUSINESS JET.

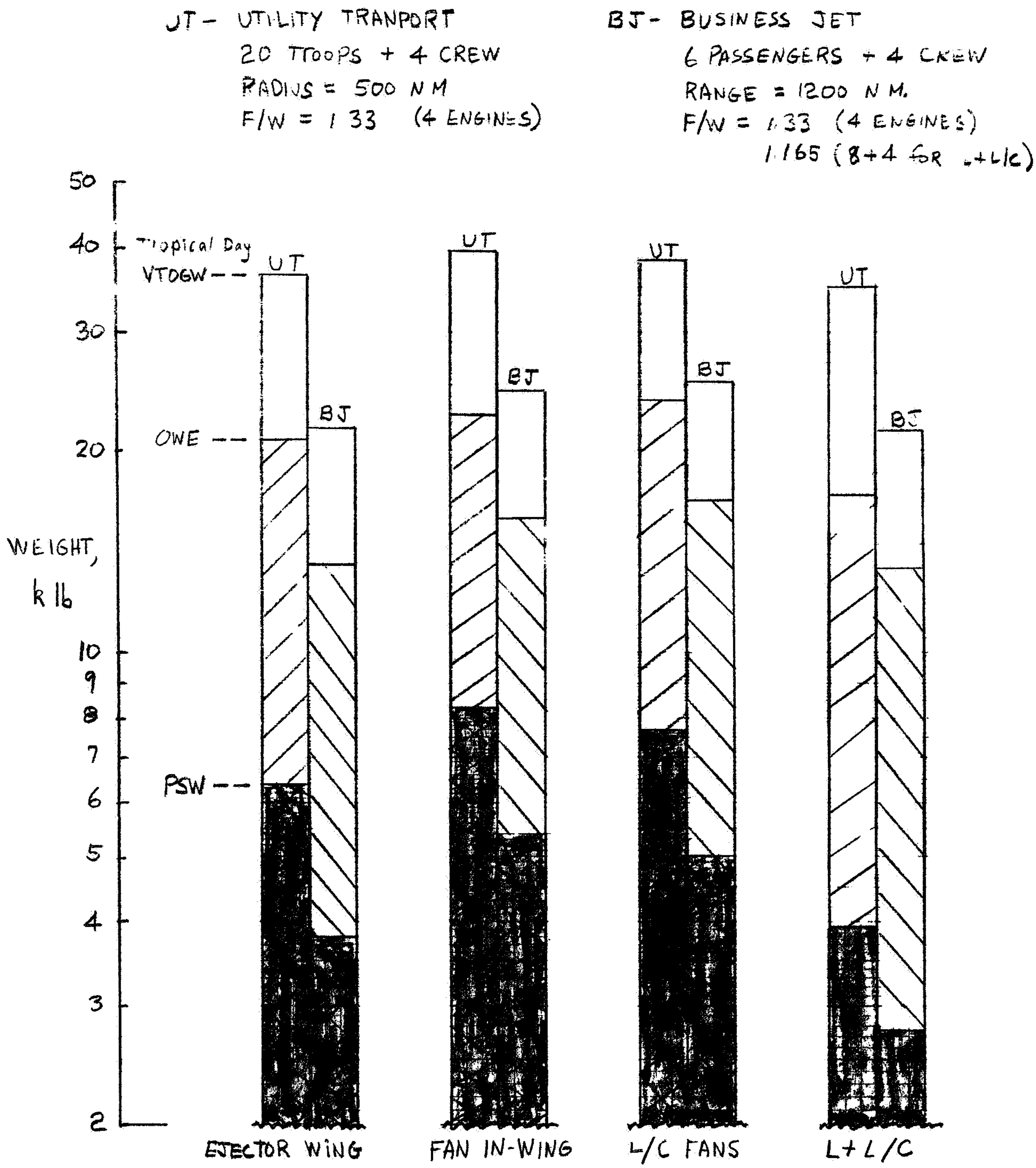
E-1599
5-5-73



(a) COD/SAR AIRPLANE

FIGURE 11 - AIRPLANE SIZING SUMMARY PAYLOAD, 5700 lb.; SAR RESCUE HOVER TIME, 10 MIN.

E7E33
5-31-73



(b) Utility transport and business jet

FIGURE 11.- AIRPLANE SIZING SUMMARY.

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