complex depending upon the particular simulation requirements, aircraft configuration, etc. 3) Before considering the test program design, it is necessary to decide what extent of simulation is desired, and this is primarily a function of the design Mach number of the aircraft and the Mach number range of the tests. 4) After the extent of simulation has been decided upon, the development of a test program design can become a tradeoff between engine simulator cost, complexity and ducting requirements; available model support techniques; and the complexity of the test program design. 5) Test program design is strongly dependent on the particular aircraft configuration to be tested and for some configurations it may be impossible to find a test program design which provides complete propulsion system simulation.

References

[1] Pope, A. and Harper, J., *Low-Speed Wind Tunnel Testing*, Wiley, New York, 1966.

[2] Pope, A. and Goin, K., *High-Speed Wind Tunnel Testing*, Wiley, New York, 1965.

[3] Goddard, F. E., *High Speed Problems of Aircraft and Experimental Methods, Wind Tunnel Techniques*, Part 2, Princeton University Press, 1961.

[4] Nichols, M., "Aerodynamics of Airframe-Engine Integration of Supersonic Aircraft," TN D-3390, Aug. 1966, NASA.

[5] Swihart, J., Norton, H., and Schmeer, J., "Effect of Several Afterbody Modifications on the Drag of a Single-Engine Fighter Model with Hot-Jet Exhaust," Memo 10-29-58L, Dec. 1968, NASA.

[6] Berrier, B. L. and Wood, F., Jr., "Effect of Jet Velocity and Axial Location of Nozzle Exit on the Performance of a Twin-Jet Afterbody Model at Mach Numbers Up to 2.2," TN D-5393, Sept. 1969, NASA.

[7] Holdhusen, J., "Analysis and Demonstration Techniques for Installation Aerodynamics Effects on High By-Pass Turbofans," Paper No. 16, Sept. 1968, AGARD Conference Proceedings No. 34.

[8] Migdal, D. and Greathouse, W., "Optimizing Exhaust-Nozzle/Airframe Thrust Minus Drag," Paper 680294, April 1968, Society of Automotive Engineers;

JUNE 1971 J. AIRCRAFT VOL. 8, NO. 6

Optimizing the Propulsion/Lift System for Turbofan STOL Aircraft

H. T. Bowling*, C. H. Hurkamp†, and R. M. Thornton‡
Lockheed-Georgia Company, Marietta, Ga.

A methodology has been developed in which aircraft configurations are optimized and systems are compared with cost effectiveness included in the initial stages of analysis. This method is applied to a comparison of propulsive high-lift systems for a STOL configuration with high bypass ratio turbofan engines. Three basic propulsive lift systems are considered: 1) external blowing of the trailing edge flaps, 2) blowing from the interior of the wing at both the knee and trailing edge of the flap (jet flap concept) combined with thrust vectoring, and 3) blowing from the interior of the wing at the flap knee (BLC concept) combined with thrust vectoring. These systems are optimized for a fixed takeoff distance and then incorporated into a parametric mission-sizing computer program which recognizes the weight aspects of each system. The results of this program are costed and minimum cost configurations are selected and compared.

I. Introduction

THERE is now and will be a continuing need for cost effective STOL aircraft suitable for either cargo or passenger transportation. This need exists within the environs of both military and commercial operations. There have been successful STOL aircraft designed using turboprop propulsion combined with a deflected slipstream high-lift system. However, the development of an aircraft which integrates the thrust and economical fuel consumption characteristics of a high bypass ratio turbofan engine with an efficient high-lift system remains as a goal for the aircraft and propulsion industries. It is generally agreed that high bypass ratio turbofan engines must be considered for new STOL aircraft especially when high-thrust levels, high-altitude, and high-speed cruise are required. It is the primary purpose of this paper to present the results of a comparison of three STOL high-lift concepts which have been integrated with high bypass ratio turbofan engines. Transport aircraft configurations have been optimized using these concepts and will be compared along with significant characteristics of each system. This comparison should provide guidance for further study and direction for future research and development expenditures. None of these systems have been subjected to a highly detailed analysis and do not represent completely optimized concepts. Every effort has been made to make the comparison as consistent as possible.

In the highly competitive environment of both commercial and military markets it has become necessary to consider cost effectiveness even in very preliminary design studies. A secondary purpose of this paper is the discussion and demonstration of a study methodology which has been developed to integrate cost effectiveness into the early technical development of new airplane concepts.

Presented as Paper 69-1131 at the AIAA 6th Annual Meeting and Technical Display, Anaheim, Calif., October 20–24, 1969; submitted November 14, 1969; revision received September 24, 1970.

* Aircraft Development Engineer Specialist, Advanced Aerodynamics Division. Member AIAA.

† Research and Development Engineer, Advanced Concepts Department. Associate Fellow AIAA.

‡ Manager, Military Operations Research Department, Operations Research Division.

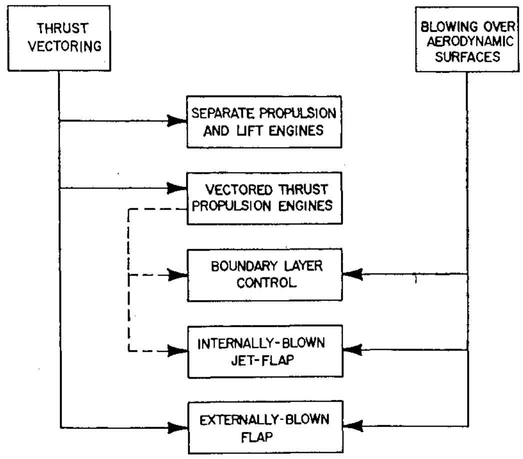

Fig. 1 Propulsion/lift systems for turbofan aircraft.

II. System Design

There are a number of alternatives for developing STOL performance such as low wing loading with conventional flap system, high-thrust to weight ratio, and exotic high-lift systems. Low wing loading is perhaps one of the most straightforward of the approaches but exacts penalties in speed, weight and ride comfort. A promising alternative is to incorporate an effective high lift system which utilizes the propulsion system as the source of energy. As shown in Fig. 1, combining the actions of the wing and power plant to achieve high lift can take several forms. All of these are based on thrust vectoring and blowing over aerodynamic surfaces, either singly or in combination. Some have achieved flight status, while others have not yet progressed beyond the wind tunnel and the drawing board. They include the types of system listed in the central column. The first two systems consider the pure vectored thrust approach differing only in the source and angularity of the thrust vectoring. Each system has its own advantages, i.e., the lift engine approach utilizes the lighter weight of pure lift engines. The last three systems depend heavily on blowing over aerodynamic surfaces. Boundary-layer control, particularly by blowing over trailing edge flaps, has been used extensively for lift augmentation. The internally blown jet flap represents an extension of BLC to higher energy levels. The externally blown flap provides the combined action of thrust vectoring and blowing.

In order to limit the scope of the investigation to the most promising systems which were determined to be both practical and within the present state-of-the-art, three systems were selected for comparison. They represent the BLC and Jet Flap Systems previously discussed combined with vectored thrust to take full advantage of the propulsion system in the attainment of high lift, and the Externally Blown Flap System. Although the takeoff condition was found to be critical for the determination of field length, attainment of the shortest possible landing distance was considered highly important. All of the candidate systems include the same type of highly effective thrust reverser, which is designed to minimize inlet contamination in the form of temperature rise at low, forward speeds.

Table 1 Design constraints

○ Payload	64,000 lb
○ Radius	250 nmile
○ Cruise speed	Mach 0.75
○ T.O. and landing over 50 ft obst.	1500 ft
○ T.O. and landing environment	2500 ft, 93.7°F
○ Airfield terrain	CBR 4 (200 passes)
○ Cargo compartment size	16 ft 8 in. width
	11 ft 8 in. height
	50 ft 0 in. length

The investigation presented in this paper is the result of a part of a continuing in-house study at Lockheed-Georgia to determine the optimum configuration for a military STOL cargo transport aircraft designed to perform short range STOL missions. Table 1 presents a table of the design constraints. These constraints are arbitrarily postulated for the purposes of this comparison and are based on operational analysis. Figure 2 shows the baseline aircraft design as configured for the Externally-Blown Flap System. A high wing position was selected for ease of cargo loading and minimization of lift losses due to ground effect. The four turbofan engines have a by-pass ratio of 6 and represent current state-of-the-art in the 40,000 to 60,000-lb thrust category. An upper limit of 68,000 lb of thrust was established from available propulsion information. The large fuselage cross-section was optimized for military cargo combinations, including large vehicles and double rows of pallets or containers. Moderate sweep and aspect ratio were selected from prior analysis, and the tee-tail arrangement from consideration of high downwash angles generated by the lift systems. The multiwheel landing gear reflects the need for flotation on soft terrain. Figure 3 presents a cross section of the wing and nacelle as designed for the Externally Blown Flap System. The engine is positioned close to the wing for efficient interaction with the double-slotted trailing-edge flap. The configuration shown here is the result of analyzing both earlier NASA tests and more recent tests in the Lockheed-Georgia V/STOL Wind Tunnel. Two features shown in this illustration are common to all three candidate systems. One is the Kruger type leading-edge flap, which provides a 10% extension of the wing chord, and the other is the thrust reverser. The latter provides a forward vector of the fan thrust, inclined at 30° upward from the horizontal, by opening a scoop-type door and simultaneously closing a blocker in the fan duct. All of the trailing-edge flap systems are full span and utilize 30% to 40% of the wing chord. This arrangement is not necessarily optimum but should provide a reasonable and consistent basis for this comparison. Figure 4 is a similar cross section which represents the combination of thrust deflection and blowing BLC. The thrust deflector is a hinged extension of the mixed flow duct, which at its horizontal setting discharges the entire flow through its rectangular nozzle. Any downward deflection angle opens up a passage for the flow of exhaust bleed into a spanwise duct for distributed blowing. The high location of the feeder duct assures the passage of a low-temperature fluid, consisting primarily of fan air. The flow quantity is governed by the area of the span-wise discharge slot and is limited by an amount sufficient to create

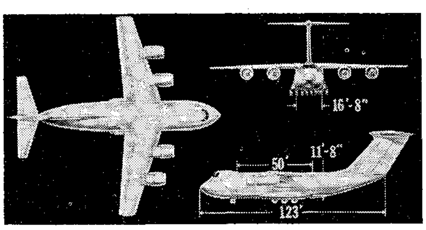

Fig. 2 Typical STOL intra-theater transport.

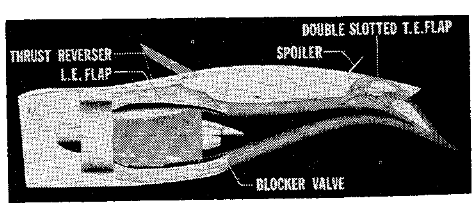

Fig. 3 External blown flap configuration.

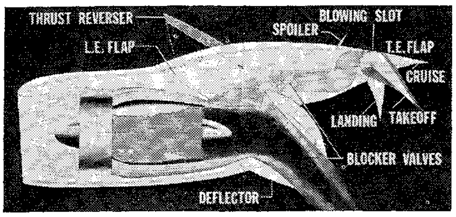

Fig. 4 BLC with thrust deflection.

flow attachment. The thrust reverser differs from that of the previous example in that the two blockers; one in the deflector and one in the feeder duct; permit all of the exhaust flow to become reversed.

Figure 5, representing the combination of thrust deflection with an internally-blown jet flap, is quite similar to the foregoing system and differs only in the quantity of exhaust bleed and the design configuration of the flap. Approximately 35% of the fan discharge is fed to the flap, limited to that amount only by the available duct area. The latter is created by the flap itself, the upper and lower elements of which separate progressively with flap deflection. An upper BLC slot is provided at the "knee" and a main jet slot near the trailing edge, located below a narrow auxiliary control flap. The auxiliary flap is used for both flight path angle and roll control by deflecting the main jet sheet.

Figure 6 shows the wing and nacelles of the foregoing system in planform to illustrate the flow patterns of the ducted fluid as shown by the arrows. Of particular interest is the fact that a cross duct is provided, connecting the right and left wings. This is accomplished by use of a flexible duct element between the flap and a fixed duct across the top of the fuselage. In the event of an engine shut down, the rolling moment due to asymmetrical deflected thrust can be counteracted by further opening the slot on the dead engine side, while closing it on the other side and thus equalizing the total lift vectors on each side. Differential slot opening can also be used to augment roll control. While the BLC system can function in a similar manner, it is not capable of providing the same magnitude of roll control.

III. Methodology

It is not practically feasible for one particular technical discipline (i.e., aerodynamics, propulsion, structures, design, etc.) to perform a meaningful analysis of a total aircraft design such as the one just described. In any successful study the talents of all these groups must be utilized in a systematic manner. The study methodology discussed here demonstrates how the various disciplines contribute to a preliminary comparison of candidate high lift systems for a STOL aircraft powered by turbofan engines. Figure 7 presents a block diagram which shows how the various study inputs are coordinated. Operations Analysis/Research provides the operational inputs to this study scheme to include such items as mission profile, payload/cargo compartment matching, and field length requirements. Preliminary design, aerodynamics, propulsion, and structures share in the

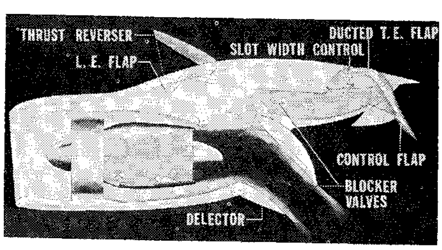

Fig. 5 Jet flap with thrust deflection.

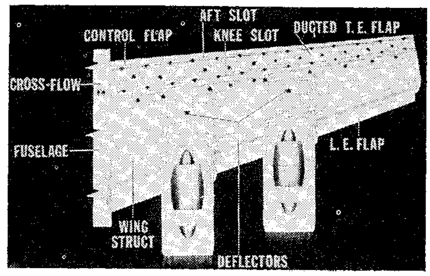

Fig. 6 Jet flap ducting system.

initial development of possible designs. There is a continuous interaction between these disciplines as noted by the dashed line on Fig. 7. This development work continues until sufficient confidence is achieved in a particular design for its inclusion as a candidate system. The aerodynamic, propulsion, and weight characteristics of each system are then input into parametric computer programs which size configurations to simultaneously satisfy the requirements of payload, mission profile and airport performance. Utilizing a rubberized engine concept permits a wide range of combinations of thrust and wing area all satisfying the requirements discussed previously. These combinations are then costed and the minimum cost is considered in final configuration selection.

IV. Aerodynamics

The lift, moment, and horizontal force characteristics (including power effects) of these systems have been estimated and correlated with a significant amount of data from various sources including tests conducted by Lockheed-Georgia. These characteristics are typical of each system but are not intended to represent the maximum that could be achieved by a complete optimization of such parameters as flap span, chord, engine location, etc.

Externally Blown Flaps System (Double Slotted)

The lift (C_L) and horizontal force (C_X) characteristics of the system are expressed in Eqs. (1) and (2)

$$C_L = C_{L_0} + C_{L_\Gamma} + nC_T \sin(\alpha + \delta_f) - C_{L\text{trim}} \quad (1)$$

where C_{L_0} = power off lift coefficient; C_{L_Γ} = additional lift due to supercirculation; n = flow turning efficiency; C_T = thrust coefficient, T/qS; δ_f = flaps deflection; α = angle of attack.

$$C_X = nC_T \cos(\alpha + \delta_f) - [(C_{L_0} + C_{L_\Gamma})^2/ARe] - C_{D_0} - C_{D\text{trim}} \quad (2)$$

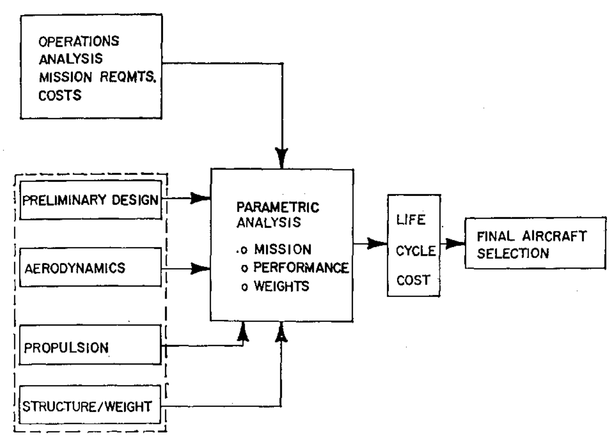

Fig. 7 Study methodology.

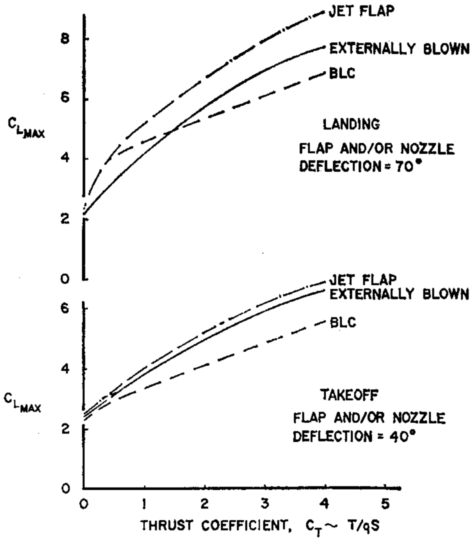

Fig. 8 Comparison of aerodynamic lift characteristics.

Boundary-Layer Control/Deflected Thrust System

The lift and horizontal force characteristics of this system are expressed in Eqs. (3) and (4). In this system which utilizes full span blowing at the knee of a simple slotted flap plus vectored thrust from quick acting nozzles, only the flow required for flow attachment is bled from the main propulsion engines.

$$C_L = C_{L_0} + C_{LC_\mu}{}^* + n_1(C_T - C_\mu{}^*)\sin(\alpha + \delta_v) - C_{L_{\text{trim}}} \quad (3)$$

where C_{L_0} = power-off lift coefficient; $C_{LC_\mu}{}^*$ = incremental lift due to flow attachment, $f(\delta_f)$; C_T = thrust coefficient, T/qS; $C_\mu{}^*$ = blowing coefficient required for flow attachment; δ_v = exhaust nozzle deflection angle; n_1 = exhaust nozzle turning efficiency.

$$C_X = n_1(C_T - C_\mu{}^*)\cos(\alpha + \delta_v) - [(C_{L_0} + C_{LC_\mu}{}^*)^2/ARe] - C_{D_0} - C_{D_{\text{trim}}} \quad (4)$$

Jet Flap/Deflected Thrust System

The lift and horizontal force characteristics of this system are expressed in Eqs. (5) and (6).

$$C_L = C_{L_0} + C_{L\Gamma} \text{ (based on } C_{T_1}) + n_1 C_{T_2}\sin(\alpha + \delta_v) - C_{L_{\text{trim}}} \quad (5)$$

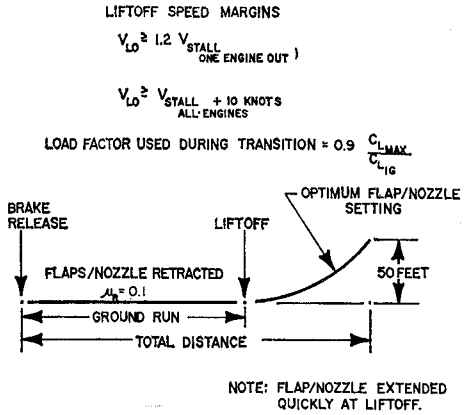

Fig. 10 Takeoff profile.

where $C_{T_1} = (0.35)(n_2)C_{T_{\text{total}}}$; n_2 = efficiency of jet flap system (system losses); $C_{T_2} = (0.65)C_{T_{\text{total}}}$.

$$C_X = n_1 C_{T_2}\cos(\alpha + \delta_v] - [(C_{L_0} + C_{L\Gamma})^2/ARe] - C_{D_0} - C_{D_{\text{trim}}} \quad (6)$$

Figure 8 presents a comparison of the trimmed aerodynamic lift characteristics of these three systems for typical takeoff and landing flap/nozzle settings. The trim effects incorporated in these data were calculated from moment data estimated in a consistent manner with the lift and drag data. These data show that the jet flap system develops higher maximum lift coefficients for a given thrust coefficient than the other systems. An additional comparison is presented in Fig. 9 where an aerodynamic/propulsive efficiency factor for each system is shown as a function of thrust coefficient. In this comparison recognition is given to the ability of each system to produce both lift and horizontal force. The actual efficiency factor is defined as the resultant aerodynamic force vector developed by power divided by the power input to the system. As shown, both the externally blown and jet flap systems are significantly more efficient in producing lift and thrust simultaneously than the BLC system.

Takeoff Performance

Generalized takeoff performance data have been computed and optimized using the aerodynamic data previously described. For this particular comparison a military type takeoff distance (total distance over a 50-ft obstacle) of 1500 ft was used consistent with the profile and speed margins shown in Fig. 10. Ground roll is minimized keeping the

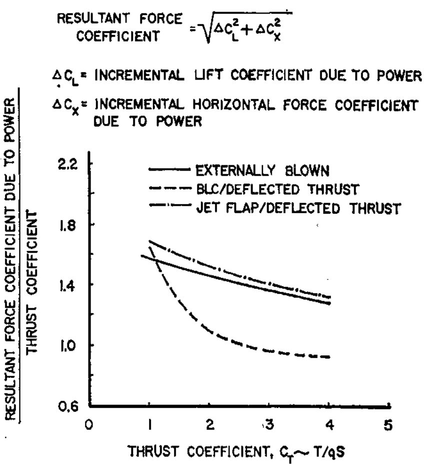

Fig. 9 Aerodynamic/propulsive efficiency.

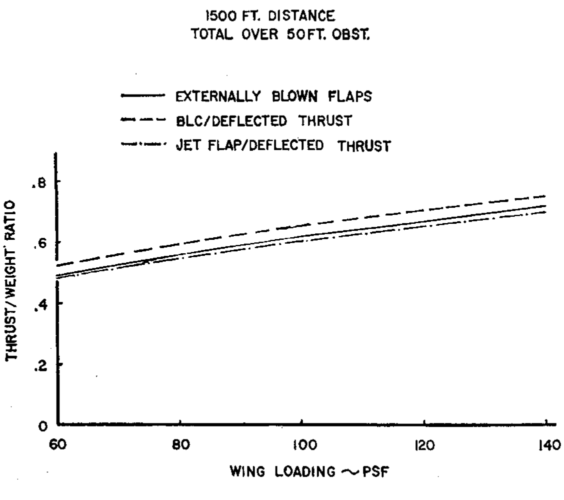

Fig. 11 Summary of takeoff requirements.

flaps retracted during the ground roll and then rapidly extending them at liftoff for the externally blown flap system. With the BLC system quick deflection of the thrust nozzles at liftoff is used and with the jet flap system, quick action of both flaps and nozzle are used. The results of these takeoff computations are presented in Fig. 11 where thrust/weight ratio is shown as a function of wing loading for each propulsive lift system. Each point on these curves represents an optimized combination of flap deflection and/or thrust nozzle deflection for minimum takeoff distance. This comparison reflects again the efficiency of these propulsive lift systems. As shown both the externally blown and jet flap system require a lower thrust/weight ratio than the BLC system. In turn, the jet flap system requires a slightly lower thrust/weight ratio than the externally blown flap system.

V. Configuration Sizing

The next step in the aircraft sizing process is the simultaneous consideration of both airport and cruise requirements of aircraft which employ these systems. The weight aspects of each system will significantly influence the size of each aircraft and parametric weight equations were developed for each concept. Empennage sizes were selected based on a brief analysis of stability and control power requirements.

Cruise matched configurations were developed as a function of wing loading and crusie power setting. From these configurations selected aricraft were chosen which also meet the 1500-ft airport requirement. This matching process is illustrated in Fig. 12 where T/W required and available is presented as a function of wing loading.

Figure 13 presents a summary of the characteristics of those aircraft (as a function of wing loading) which satisfy both cruise and takeoff requirements for all three systems. For this study a wing loading range of 60-140 psf was selected. Significant problems in obtaining acceptable levels of control power and ride qualities are encountered with very low wing loadings and very high wing loadings result in thrust levels in excess of practical consideration. In observing these results the expected trends of decreasing weight and increasing thrust with increasing wing loading are noted. Application of the externally blown flap system results in lower weights and thrust than either of the two internally blown systems. The jet flap system has higher weights but lower thrust requirements than the BLC system. Noted in this figure is the maximum available thrust restriction previously discussed. There are three major factors that influence these results: 1) The aerodynamic characteristics (as indicated by Fig. 11); 2) the weight of the wing and mechanical portion of the high lift system; and 3) the weight of the propulsion system and related control system. Because of loads and temperature effects the externally blown flap system has a

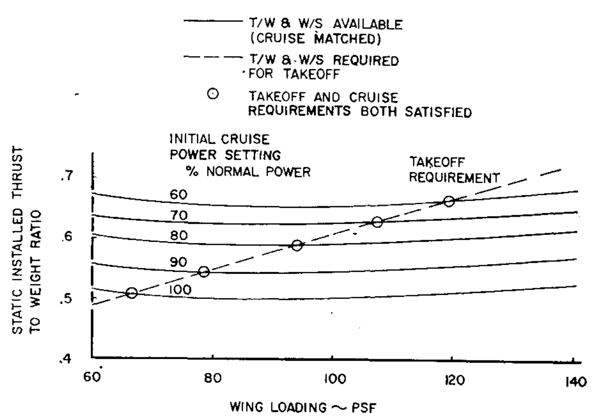

Fig. 12 Thrust/weight and wing loading.

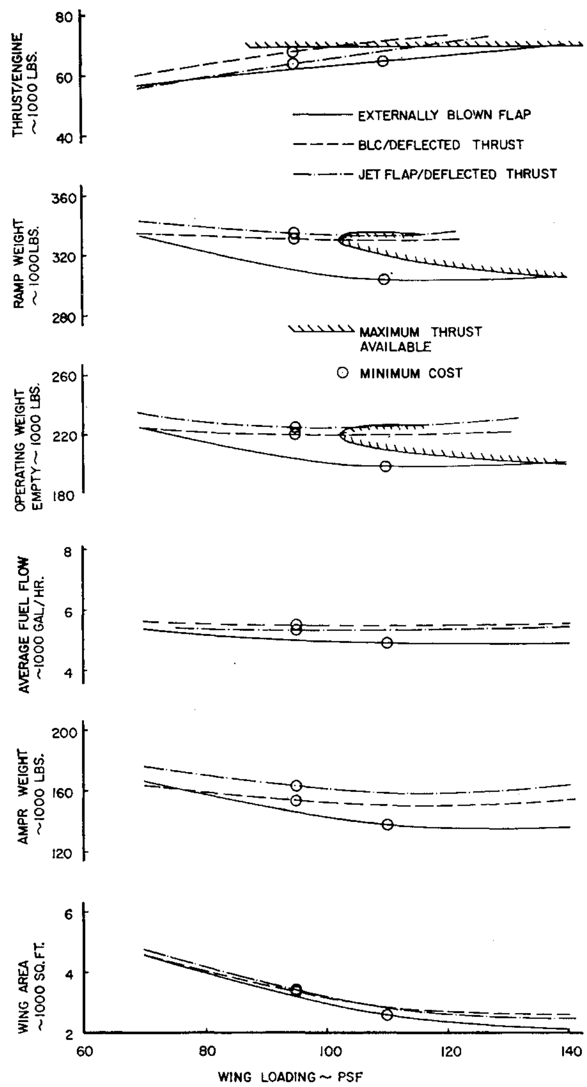

Fig. 13 Effect of wing loading.

higher wing weight/ft² of wing area. The jet flap wing is next heaviest followed by the lighter BLC wing. However, the higher wing weight of the externally blown flap is more than offset by lower propulsion system weights of the BLC and jet flap system offset the lower wing weights. The interrelationship of these factors essentially determine the results shown in Fig. 13. A configuration for each system must be selected from these data. However, in the methodology used in this study the final selection of a configuration for each propulsive lift system is made only after considering cost.

VI. Cost Effectiveness

All aircraft evaluated have the same design maximum payload, cargo compartment size, airport performance, and cruise speed. Inasmuch as each of the systems have equal capability, the effectiveness is the same excluding relatively small differences in reliability, maintainability, and survivability. Thus, the measure of cost effectiveness to be used in comparing these aircraft can then be taken as the life cycle cost for a fixed fleet size. The most cost effective design is the one with the lowest life cycle cost.

Life cycle cost as used in this study includes costs for Research, Development, Testing and Evaluation (RDT&E) plus Acquisition plus 10 years of Operating and Maintenance (O&M). The O&M costs shown in this paper are for 16 squadrons or 160 aircraft. The Acquisition costs are for

208 aircraft, or 30% more than the operational squadron level to account for command support, training and attrition aircraft. The life cycle costs represent total costs to the Government, including all support costs.

These costs were calculated using a computerized cost model in conjunction with a Value Engineering analysis of airframe manufacturing and tooling cost differences. The cost model incorporates Cost Estimating Relationships (CER's) taken from three sources: 1) a RAND study on airframe costs; 2) a cargo aircraft cost model developed by the Advanced Systems Cost Analysis Group within the Air Force Aeronautical Systems Division; 3) Lockheed experience on previous transport aircraft. The model has been validated for that portion of aircraft life cycle costs which includes airframe development plus production costs by comparing cost model results with Lockheed historical cost data on the C-130A and C-141A aircraft. The model results were lower than the actual costs on both aircraft, but by less than 10%. The STOL turbofan aircraft in this study depart significantly from the conventional construction methods and in distribution of weight among the various airframe components, therefore a modification in the model is required to properly account for this added complexity. To account for this a Value Engineering analysis was performed to determine "complexity" or "cost increase" factors to multiply times the basic code-generated costs.

The Value Engineering study showed that these STOL aircraft differ significantly in construction cost from conventional aircraft in the wing trailing edge fixed structure and in control surfaces. These differences are primarily in the quantity of mechanism and the temperature environment in which the structure operates. The complexity factors for this study were derived by dividing the estimated production cost (considering the previous factors) by the estimated production cost the cost model would predict for a conventional aircraft of the same size. Tooling cost factors were estimated considering required construction methods. The derived factors are not universal, but should be reasonably accurate for a range of aircraft sizes near the point designs evaluated. The results of this Value Engineering Study were airframe manufacturing cost factors of 1.5–1.7 and tooling cost factors of 1.3–1.4.

For each of the propulsion/lift system concepts examined life cycle cost as a function of design wing loading was computed using the design characteristics shown in Fig. 13. Figure 14 presents the results of this study.

These cost curves are used to aid in the selection of the preferred point design among the several generated for each of the three propulsion/lift systems considered. The three driving factors in determining the shape of these curves are airframe weight, fuel consumption rate and engine thrust requirements (see Fig. 13). As wing loading increases, airframe weight decreases while engine size increases. While airframe and propulsion costs are not linearly related to weight and thrust, respectively, they do increase as these two parameters increase. The behavior of the fuel consumption rate vs wing loading curve depends on engine thrust requirements, and fuel costs are, of course, linearly related to consumption rate.

In Fig. 14, the cost curve for the externally blown flap system is minimum at approximately 110 lb/ft² while the jet flap/deflected thrust system cost is minimum at approximately 95 lb/ft.² However, the curve for the BLC/deflected thrust system does not show a well defined minimum within the wing loading range considered. The behavior of the externally blown flap and jet flap curves can be understood by referring to the plots of airframe AMPR weight, engine size and fuel consumption rate in Fig 13. For the externally blown flap system, the AMPR weight decreases in going from 90 to 120 lb/ft², while the engine size increases and the fuel consumption decreases slightly. When the costs driven by these three aircraft characteristics are combined, a minimum occurs at 110 lb/ft². For wing loadings greater than this the increase in propulsion costs combines with an increase in fuel costs to overcome a slight decrease in airframe costs. For wing loadings less than 90 lb/ft² the large increase in airframe costs is the controlling factor.

For the jet flap system a minimum cost occurs, but at a lower wing loading than for the externally blown flap system. Primarily, this is because the reduction in AMPR weight as wing loading increases is not as pronounced as for the externally blown flap.

The lack of a well defined minimum cost for the BLC system is because of the fact that the airframe weight does not decrease as rapidly with increasing wing loading is it does for the other two systems. This, in turn, increases engine thrust requirements. The net result of these changes is that life cycle cost for the BLC system is fairly insensitive to wing loading at a cost level slightly higher than the minimum costs of the other two systems.

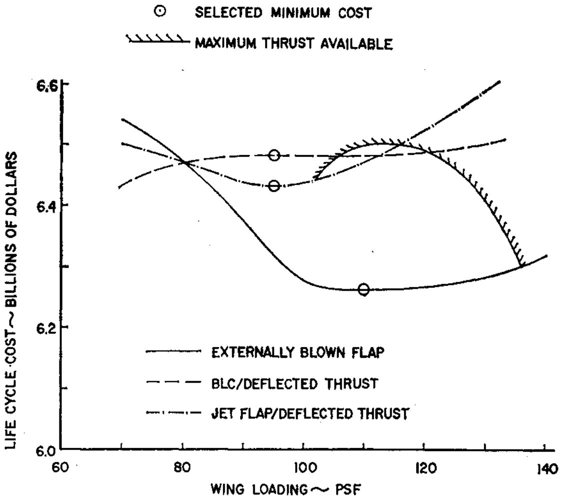

Fig. 14 Cost comparison.

VII. Selection and Conclusions

A configuration for each high-lift concept has been selected and significant characteristics of each configuration are presented on Table 2. Several criteria were considered in this selection process including stability, control, control power, ride qualities, and engine availability as well as cost. In this particular comparison, selection of minimum cost points represented a reasonable compromise with other criteria and minimum cost was used to make the final selection for each concept. A comparison of the major cost components for each configuration is presented in Fig. 15.

Table 2 Comparison of selected configurations

	Externally blown flap	Jet flap deflected thrust	BLC deflected thrust
Gross weight, lb	303,800	333,400	330,700
Operating weight empty, lb	198,800	223,800	219,600
Thrust/Engine (S.L. std. day), lb	61,570	62,180	66,800
Wing area, ft²	2,680	3,370	3,380
T.O. wing loaded, lb/ft²	112	98	97
T.O. thrust/weight	0.65	0.60	0.65
C_{Lmax} at liftoff (pwr. on)	5.45	5.38	4.91
Liftoff speed, kts	98	91	97
Ground run, ft	870	860	930
Life cycle cost, million dollars	6,262	6,436	6,482
Thrust coef. at liftoff	2.3	2.2	2.0

Table 3 Comparison of three systems

Chracteristic	Externally blown flap	BLC/ thrust deflection	Jet flap/ thrust defl.
Life cycle cost	1	3	2
Handling qualities	3	2	1
Operational qualities			
Reliability	1	2	3
Maintainability	1	2	3
Associated engine development risk	1	3	2
Available test data	2	1	3

From this final comparison the Externally Blown Flap System is selected as most promising concept. This final system selection is the result of an over-all comparison of the three systems in several categories, with associated ratings in order of merit as shown on Table 3.

Life cycle cost comparisons show the Externally Blown Flap System with a cost approximately 2.5% lower than the Jet Flap System and 3.5% less than the BLC System. The number of unknowns and assumptions inherent in a cost analysis such as this lessens the importance of the absolute value of these cost results and the total spread between the absolute cost data is only 3.5%. However, this could represent a difference in 100–200 millions of dollars in relative cost and it is in this context that these data are most meaningful.

Handling qualities include stability and control characteristics, and the ranking is based on very limited test data and analysis. One-engine-out operation is the major consideration in this ranking and favors the Jet Flap System because of the cross-ducting feature, which enables the pilot to trim the aircraft laterally by differential adjustment of the blowing slot areas. This operation can be performed manually or made automatic by a pressure-sensing device. The control margin of the Jet Flap System, after trim, is considerably higher than that of the other two systems.

Operational qualities include reliability and maintainability. Here, the ranking is based on apparent complexity differences. Although the Externally-Blown Flap is ranked highest in both categories, the effect of engine exhaust impingement on the wing and flap structure is largely unknown. Even though heavily reinforced in the blast areas the structure will be subject to sonic and lower frequency fatigue cycles. The other two systems are faced with possible failure of the ducts and thrust deflectors. Short of operational experience, studies in much greater depth are required to achieve credible ranking.

Associated engine development risk is ranked in the reverse order of thrust required. Although an upper limit was established on the basis of engine manufacturer's proposals, the risk involved in developing a new engine is inversely related to the degree of thrust extrapolation required over that of the highest rated, present generation engines.

Finally, the matter of available test data must be considered. Since BLC systems have been extensively tested in flight and in the wind tunnel, the data credibility can be considered very good. Externally-Blown Flap configurations have been tested in the wind tunnels of NASA and aircraft manufacturers, but not, to our knowledge, in flight. Jet Flap Systems of various types have had extensive wind tunnel testing, but only limited flight evaluation. The Jet Flap System described in this paper has not been tested but appears to have very promising lift augmentation effects.

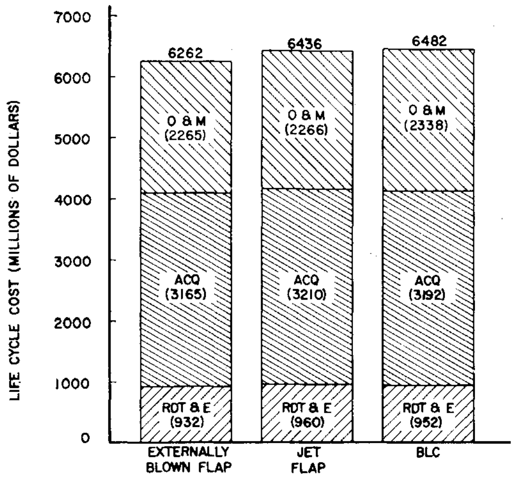

Fig. 15 Life cycle cost for selected designs.

Recommendation as to which system should be selected depends on the operational time frame. For operation in two to four years, the Externally-Blown Flap System would be a logical choice. Beyond this period, however, analysis and development testing in greater depth may well point to the Jet Flap System. We firmly recommend that further R&D effort be expended on all promising systems so that low cost, reliable and safe turbofan STOL aircraft can become operational.

VIII. Summary

A comparison has been made of three candidate high-lift systems designed for use with a turbofan powered STOL aircraft. In selecting a configuration for each concept and in the final comparison, consideration was given to the aerodynamics, propulsion, weight, and complexity aspects of each systems as well as cost. A specific study methodology was used in this comparison which introduces life cycle cost into the early phases of system development.

The results of this comparison indicate that for the application considered the Externally Blown Flap System is recommended. However, the results are not conclusive to the point that a final recommendation can be made and a considerable amount of study is required. In order to have a sound basis for this additional work, a significant amount of testing is required, especially with the Externally Blown and Jet Flap System. Operating margins, engine-out control, and control powers are but a few of the areas in which a detailed analysis is required before a definite conclusion can be reached between these systems.

The need for an efficient turbofan powered STOL aircraft justifies the additional study and testing indicated by the comparison. The development of an operational turbofan STOL transport which utilizes a well integrated propulsive high lift system must be considered as one of the real challenges to the airframe/propulsion industries.