Turbine Bypass Remote Augmentor Lift System for V/STOL Aircraft

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The study of a turbine bypass remote augmentor lift system for V/STOL aircraft was designed to identify the most promising turbine bypass engine cycle for combination with a remote augmentor lift system and to evaluate the merits of this combination relative to other V/STOL propulsion concepts. Three candidate TBE cycles selected for study were: 15%-bleed TBE with simple RALS, 30%-bleed TBE with simple RALS, and 15%-bleed TBE with a turbocompressor-RALS combination. Conventional turbofan-RALS and lift-plus-lift/cruise concepts provided bases for comparison. A preliminary design was developed for each propulsion concept and airplane configuration. All the aircraft were resized for equivalent capability using a supersonic deck-launched intercept mission, specified combat performance, and hover load capability. Fair comparisons could then be based on takeoff gross weight and life-cycle cost. The turbocompressor RALS design was chosen as the best TBE-powered concept based on TOGW, LCC, and alternate mission performance, as well as operational design considerations. Sizing and performance results, together with studies of variations of design ground rules and mission requirements, indicate that overall this TBE-RALS configuration was superior to the turbofan-RALS design and competitive with L + LC.

Nomenclature

ASuW	= antisurface warfare
CAP	= combat air patrol
CET	= combustor-exit total temperature
DLI	= deck-launched intercept
IOC	= initial operational capability
LCC	= life-cycle cost
L + LC	= lift-plus-lift/cruise
OPR	= overall pressure ratio
O&S	= operations and support
P_s	= specific excess power
RALS	= remote augmentor lift system
RCS	= reaction control system
RDT&E	= research, development, test, and engineering
TBE	= turbine bypass engine
TOGW	= takeoff gross weight
T/W	= thrust-to-weight ratio

Introduction

IN 1982 a study was conducted at the NASA Lewis Research Center to assess the feasibility of applying the turbine bypass engine (TBE) concept in combination with a remote augmentor lift system (RALS) to supersonic V/STOL aircraft.[1] Results of this study indicated that, from the standpoint of takeoff gross weight (TOGW), TBE-powered configurations were competitive with those powered by medium-bypass mixed-flow turbofans. It was also noted that the inherent simplicity of the TBE may result in a life-cycle cost (LCC) advantage over conventional turbofans. With this motivation, the present study was initiated with emphasis on airframe design and engine/airplane integration to verify the earlier results and quantify LCC comparisons.

Presented as Paper 85-3086 at AIAA/AHS/ASEE Aircraft Design Systems and Operations Meeting, Colorado Springs, CO, Oct. 14-16, 1985; received Nov. 11, 1985; revision received June 16, 1986.

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In the present study, one turbofan and three single-spool TBE cycles were selected for preliminary engine design. Each of these engine designs has been integrated into a high-performance V/STOL configuration in combination with a RALS (i.e., in combination with a forward combustor and nozzle for vertical thrust). The four configurations were sized to a supersonic deck-launched intercept (DLI) mission with specified point performance levels and then compared on the basis of TOGW and LCC. Comparisons were also made on the basis of performance for two alternate missions, namely, a fleet-air-defense combat-air-patrol (CAP) mission and an antisurface warfare (ASuW) mission. A fifth aircraft incorporating the lift-plus-lift/cruise (L + LC) concept was designed to serve as a baseline for comparison. This article summarizes the study results detailed in Ref. 2.

Engine Concept

The TBE concept was first suggested by Klees of Boeing and later studied by Franciscus[3] and Hunt[4] with application to supersonic cruise transports. A TBE is a mechanically simple variable-cycle turbojet with large compressor-discharge bleed capacity, shown schematically in combination with a RALS in Fig. 1. The bleed capacity provides variable flow area downstream of the compressor. When bleed ducts are open, bleed air is throttled and injected into the exhaust plenum. This feature offers advantages similar to those of a variable-geometry turbine without the attendant weight and cost: off-design compressor-turbine matching, high throttle ratio for good supersonic cruise, and reduced spillage and afterbody drag.

For a conventional turbojet with a fixed-geometry turbine, cycle efficiency and performance are optimum at very few flight conditions. Operating at part power requires reduced fuel flow, combustor-exit total temperature (CET), airflow, spool speed, and pressure ratio. Cycle efficiency is reduced and airflow-dependent drag increases. At subsonic maximum power, the airflow limit forces CET to be lower than maximum and, at supersonic maximum power, the CET limit forces airflow to be lower than maximum.

For a TBE, the bleed capacity adds a degree of freedom to engine operation so that compressor-turbine matching is maintained at cruise power settings, and airflow and CET limits are reached simultaneously at maximum power. The turbine is undersized relative to a conventional turbojet so that at zero bleed the TBE is an inherently high-throttle-ratio engine. At both subsonic and supersonic cruise conditions, the compressor and turbine are matched or nearly matched so that the compressor operates at maximum airflow, spool speed, and pressure ratio. TBE subsonic fuel consumption is slightly lower than that of the turbojet due to increased cycle efficiency. Supersonic fuel consumption is significantly less, as would be expected for a high-throttle-ratio engine, since more thrust is available in dry power. Also the relatively high airflow leads to reduced spillage and afterbody drag.

Simultaneously increasing bleed flow rate and combustor fuel flow rate maintains the effective flow area downstream of the compressor, allowing it to run at maximum speed and airflow. Airflow and speed are both maximized at subsonic maximum thrust conditions, in contrast to conventional turbojet operation. Therefore, increasing the bleed flow "augments" the thrust, even though the bleed flow must be throttled before being remixed with the turbine exhaust.

For a supersonic V/STOL aircraft, the bleed flow is available to supply a remote lift system for hover. Ducts for this air would be relatively small because the air would be at high pressure. This avoids the volume penalty associated with fan-air-supplied remote lift systems. Another feature of the TBE that is attractive for a supersonic V/STOL aircraft is that the high airflow of the TBE reduces the conflict in inlet capture area between hover and high-speed flight because the TBE uses nearly constant corrected airflow at maximum power for Mach numbers up to 2.0.

Design Guidelines

The design scenario is that of a high-performance naval V/STOL aircraft with a primary fleet-air-defense role and secondary ASuW role. Technology levels and equipment requirements consistent with airplane initial operational capability (IOC) in the year 2000 were assumed throughout the study.

The design mission is a fleet-air-defense DLI with a radius of 200 n.mi. and an outbound-dash Mach number of 1.8, as shown in Fig. 2. In addition, the following combat point performance constraints were imposed during sizing: 1) acceleration from Mach number of 0.8 to 1.6 in less than 80 s at 35,000 ft, 2) sustained turn load factor of 5.5 *g* at Mach number 0.65 and 10,000-ft altitude, and 3) 1-*g* specific excess power (P_s) of 850 ft/s at Mach number 0.9 and 10,000 ft.

Since it has become widely recognized that STOVL operation is most effective for V/STOL aircraft, that mode is incorporated in both the basic design mission and the alternate missions. The STOVL method maintains most of the basing flexibility of VTOL, while greatly increasing available range/payload performance. Each configuration is sized to have a minimum useful load during hover of 6000 lb (defined here as retained weapons, weapon suspension, and reserve fuel only). No engine-out-landing requirement is imposed. This requirement has been shown to negate the benefits of STOVL in preliminary designs by imposing oversized propulsion systems.[5] The STO requirement is defined as an unassisted 400-ft deck run at TOGW with no wind over deck, no sink over bow, and no ski jump.

All designs have a two-place cockpit. This ground rule does impact the configuration designs, especially those with remote lift systems aft of the cockpit. Since hover balance requirements dictate RALS (or lift-engine) placement, fuselage lengths may be longer than otherwise desired.

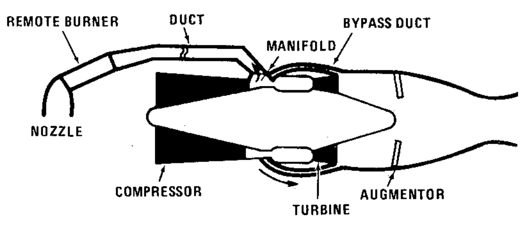

Fig. 1 TBE-RALS schematic.

Engine Cycle Selection

The initial task in the study was to select engine cycles for design and subsequent integration with airframes. The objective of this task was to choose three TBE cycles that offer a good compromise between integration for hover balance and up-and-away performance, and turbofan cycles to provide realistic and fair bases for comparison.

Maximum CET was initially identified as a cycle parameter to be investigated, but instead was fixed at 3000°F for all engines because performance for all of them benefits by increasing CET and because this level is considered a technology limit consistent with a year-2000 IOC. Only augmented engines were included in the study.

The most important cycle variable selection was found to be that of bypass-bleed capacity. This selection was essentially a trade between considerations of hover thrust balance and engine specific thrust. Past design experience shows that the best design integrations result when forward and aft vertical-thrust sources contribute nearly equally to hover lift. However, even for relatively large values of bypass-bleed capacity, thrust split values are considerably below the desired value of 1.0. On this basis, it was determined that a minimum bleed capacity of 15% of compressor airflow would be required for acceptable hover balance. This requires arranging the configuration such that the RALS nozzle is very far forward in the configuration and the main deflecting nozzle is very near the airplane c.g. In order to achieve more conventional airplane/engine integration, significantly higher amounts of bleed flow are required.

The cost of high bleed capacity is reduced specific thrust. Therefore, for a given thrust requirement, a high-bleed-

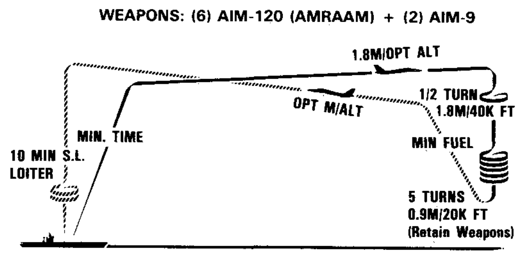

Fig. 2 Design-DLI mission.

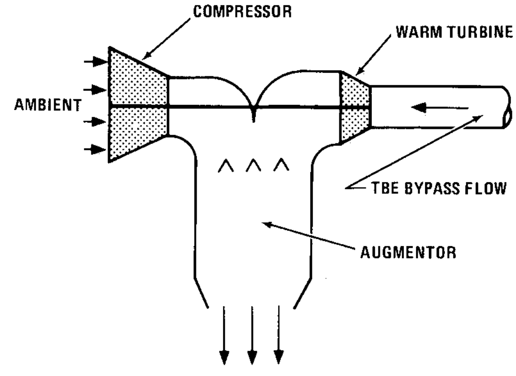

Fig. 3 Turbocompressor-RALS schematic.

Table 1 Selected TBE cycles

RALS type	Bypass bleed, %	OPR	CET, °F
Simple	15	18:1	3000
Turbocompressor	15	18:1	3000
Simple	30	15:1	3000

Table 2 Selected turbofan cycles

Lift system	Fan bypass ratio	OPR	CET, °F
Turbofan RALS	0.67	29.7:1	3000
L+LC	0.22	29:1	3000

capacity TBE requires a larger airflow size than a conventional engine. A 30%-bypass-bleed TBE has dimensions approximately 13% larger and weight 28% greater than a turbojet of equivalent thrust.

One approach to relieving this compromise between specific thrust and hover balance is to incorporate a "turbocompressor" mass-flow amplifier between a low-bleed TBE and RALS. A turbocompressor is a simple device that acts to increase remote thrust available from a low-bleed TBE. The concept is shown schematically in Fig. 3. Bypass flow drives a warm turbine, which in turn drives a compressor. The compressor draws in ambient air and compresses it so that exit pressures of the warm turbine and compressor are equal. Exit flows are then mixed before being burned by the RALS. Thrust is increased because, for a given level of turbine work, RALS mass flow is increased as exit velocity is reduced.

OPR selection was found not to have strong influence on either hover balance or high-speed performance. Values were selected for lowest cruise fuel consumption for given values of bleed capacity.

The TBE cycles selected for engine design and subsequent airplane/engine integration are given in Table 1. These selections give different configurations having distinct advantages and disadvantages, so that broad coverage of the range of design variables is achieved.

The engine cycles for the turbofan-RALS and L+LC configurations are shown in Table 2. The fan-bypass ratio for the turbofan-RALS concept was chosen to give the same installed thrust split as the 30%-bleed TBE simple RALS concept. The overall pressure ratio (OPR) was chosen for best cruise fuel consumption, and the CET was limited to 3000°F for consistency with technology levels. The cycle for the lift/cruise engine of the L+LC configuration was adapted from the Navy Advanced Technology Engine Studies[6] L+LC configuration.

Preliminary Engine Design

A major task in the study was preliminary design of engines corresponding to each of the cycle selections. This design work included design layouts for the 15%-bypass-bleed TBE, the 30%-bleed TBE, and the turbocompressor RALS unit, as well as performance and weights estimation for the TBEs and conventional turbofans. Design detail was of sufficient depth to define component materials and geometry, such as blade counts and blade/disk attachment arrangement.

Turbine Bypass Engines

A bypass flow level of 15% at sea level static, tropical day, is considered a minimum for practical hover balance, yet it is roughly twice the level studied in related efforts. This high level of bypass flow leads to some unique engine performance characteristics, which, once understood, were accommodated without undue performance or weight penalties.

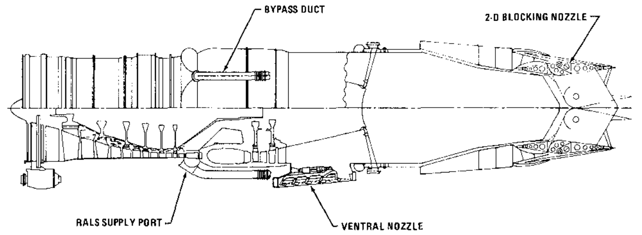

Fig. 4 15%-bleed TBE mechanical design.

One unique characteristic is constant airflow at maximum power up to a flight Mach number of 2.0. At this flight condition, the compressor inlet temperature is 242°F and, despite the reduction in bypass flow to a level of 6%, the turbine pressure ratio is increased 25% because the turbine continues to drive the compressor at its design pressure ratio. As a result, the Mach numbers in the turbine exit case and augmentor areas are quite high. A 6% turbine-bypass flow level was selected as a minimum, regardless of flight condition and power settings. Studies of lower bypass flows at typical subsonic cruise power settings indicate poorer thrust-specific fuel consumption due to the large pressure losses associated with high Mach numbers in the aft sections of the engine.

The mechanical arrangement of the engine is shown in Fig. 4. While the augmentor design is fairly conventional, the vectored-thrust requirements associated with STOVL operations have led to a rather unique set of exhaust nozzles. The two-dimensional convergent/divergent exhaust nozzle is configured such that it may be operated in either a partial-blocking or total-blocking mode. Part, or all, of the engine exhaust flow is diverted to a ventral nozzle located just aft of the turbine exhaust case and forward of the augmentor fuel system. This ventral nozzle provides an aft thrust vector location much closer to the aircraft c.g. Sea-level-static maximum T/W is 7.0.

Basic configuration of the 30%-bleed TBE (not shown) is quite similar to the 15%-bleed design. Minimum bypass bleed was set at 23% for this engine in order to avoid aft-end choking, which would result from further throttling at constant compressor match. Sea-level-static maximum T/W is 5.4. Much of the weight increase of the 30%-bleed engine over the 15%-bleed version may be attributed to the low engine pressure ratio due to the very high level of turbine bypass flow. This results in disproportionately large aft engine sections (augmentor and nozzle), which are particularly heavy due to the complexity of the blocker/ventral arrangement.

Turbocompressor RALS

The turbocompressor-RALS mechanical design is shown in Fig. 5. This device serves to increase the forward portion of the hover thrust to enable the aircraft to balance in hover with the RALS placed aft of the cockpit. At hover and STO conditions, turbine bypass flow bled from the engine compressor discharge location is ducted to a manifold and then through struts located downstream of the single-stage mixed-flow impeller before driving a two-stage axial-flow turbine, which in turn drives the impeller. The turbine expands the bleed flow to the impeller discharge pressure, and the two flows are mixed before entering a compact swirl-type augmentor and exiting through a variable-area convergent nozzle.

Conventional Turbofans

Design of the conventional turbofan engines for the turbofan-RALS and L+LC concepts was accomplished using a parametric engine program with technology levels consistent with those used for the TBE layouts. Weight adjustments were made to reflect the blocking/ventral V/STOL nozzle/augmentor for both engines and the fan-air collector-diverter for the turbofan-RALS engine.

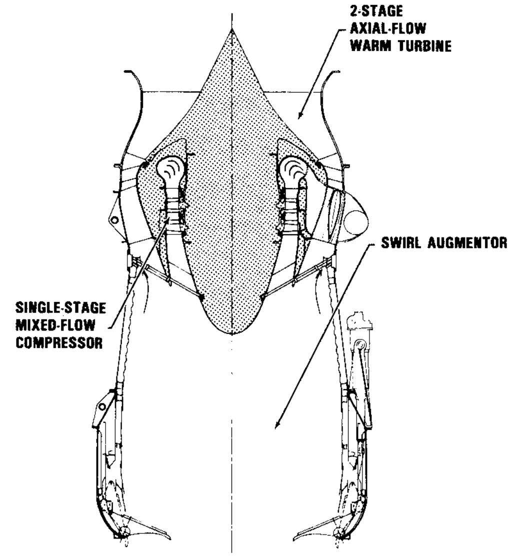

Fig. 5 Turbocompressor-RALS mechanical design.

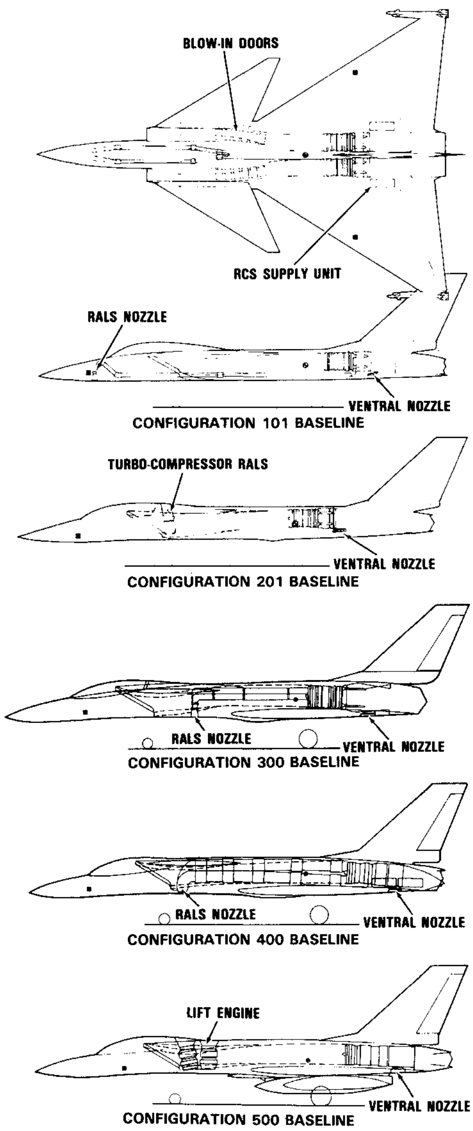

Fig. 6 Airplane/engine integration arrangements.

Airplane/Engine Integration

The majority of the study effort falls under the classification Airplane/Engine integration. In this task, methods of conceptual design were combined with design ground rules and engine designs to evaluate the propulsion concepts relative to each other.

The five configurations studied are designated as follows:

1) Configuration 101: 15%-bleed TBE, simple RALS.
2) Configuration 201: 15%-bleed TBE, turbocompressor RALS.
3) Configuration 300: 30%-bleed TBE, simple RALS.
4) Configuration 400: turbofan RALS.
5) Configuration 500: L + LC.

Figure 6 shows a sketch of the general arrangement of the Configuration 101 baseline, together with profile views of the other baselines.

In general, all the baseline designs are canard-delta arrangements. The delta wing planform was chosen as a good compromise for subsonic and supersonic performance. Its highly swept, highly tapered character provides low wave drag, while the large wing area provides good subsonic maneuverability. Delta wings also have large fuel capacity, and the diffuse wing carrythrough structure allows flexibility in integrating V/STOL propulsion systems. The canard arrangement places the wing aft, which is favorable for hover balance because it helps move the airplane c.g. closer to the aft ventral nozzle.

All the designs are twin-engine with side-mounted, fixed-ramp inlets and two-dimensional, blocking/ventral combination V/STOL nozzles. The forward edge of the inlet ramp is held behind the pilot's eye for good over-the-side visibility in hover. Blowin doors are used to increase inlet performance in hover and transition flight. Engine, lift system, and cockpit

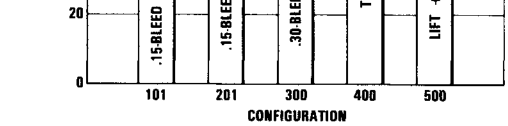

Fig. 7 Design-mission sizing results.

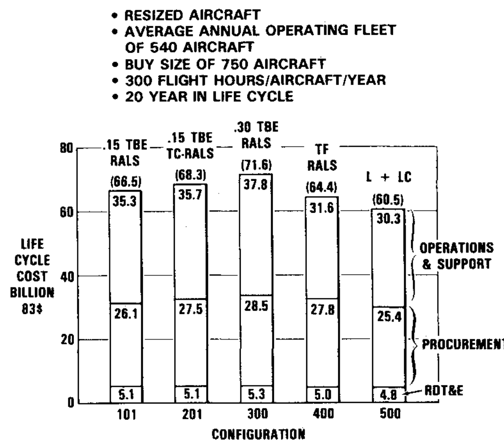

Fig. 8 LCC results.

Table 3 Design-mission sizing results

	Configuration				
Engine	101 0.15-bleed TBE	201 0.15-bleed TBE	300 0.30-bleed TBE	400 0.67 BPR turbofan	500 0.22 BPR turbofan
Lift system	Simple RALS	TC RALS	Simple RALS	RALS	L+LC
Sizing					
DLI-mission TOGW, lb	70,400	70,400	79,600	72,800	62,700
Wing: Area, ft^2	1,060	1,050	1,200	1,080	920
Aspect ratio	2.50	2.92	2.50	2.10	2.50
Thickness,%	5.0	5.4	5.2	4.2	4.4
Engine airflow, lb/s each	280	265	345	310	260
DLI-mission fuel, lb	22,700	22,900	27,400	26,000	21,200
Max TOGW for 400-ft STO, lb	91,300	86,800	93,300	89,700	77,300
Max hover useful load, lb	6,000[a]	9,400	11,800	6,000[a]	6,000[b]
Point performance					
P_s, ft/s, M 0.9, 10K ft	915	850[a]	850[a]	945	850[a]
Sustained g's, M 0.65, 10K ft	5.5[a]	5.5[a]	5.5[a]	5.5[a]	5.5[a]
Accel time, s, M 0.9-1.6, 36K ft	67	70	66	54	61
Overload DLI					
Radius, n.mi.	406	483	402	231	235

[a]Active sizing constraint. [b]Active constraint for lift engine sizing only.

locations are determined by the hover balance requirement. Typically, engines are located somewhat forward in the fuselage. This tends to move the airplane c.g. forward, but it moves the ventral nozzle even more, so that hover moment balance is satisfied. The engine tail pipe was allowed to stretch in order to locate the two-dimensional blocking nozzle at the aft end of the airplane. Cockpit and lift-system placement set minimum fuselage lengths.

The reaction control system (RCS) for each aircraft was sized to provide Level 1 flying qualities as specified in MIL Spec 83300 (Flying Qualities of Piloted V/STOL Airplanes). This was done using initial estimates of aircraft inertias. RCS airflow requirements were established based on satisfying Level 1 requirements during simultaneous abrupt application of pitch, roll, and yaw controls in the most critical combination.

The overall length, height, and span of each configuration was limited by the requirement that the aircraft be accommodated by aircraft carriers expected to be operational in the year-2000 time frame. Each baseline design can be rolled on and off elevators and transported between the hangar deck and flight deck without wing or vertical tail folding.

The configuration designs were made as consistent as possible, so that equitable performance comparisons could be made. Specific design advantages or disadvantages for each configuration are directly attributable to the characteristics of the particular propulsion system. Differences in RCS designs and static longitudinal stability levels are examples of this. For Configurations 201 and 300, sufficient thrust split for hover balance is maintained when RCS air is taken from the RALS supply. In the case of Configuration 101, marginal thrust split precludes taking air for the RCS, so an alternate air supply consisting of two gas generators, each driving a load compressor, had to be incorporated into the configuration. This system was also used in the turbofan RALS design (Configuration 400) because the RALS air supply (fan-discharge) pressure is too low for practical RCS use. The lift/cruise engine of Configuration 500 is sized by combat performance, so excess thrust is available in hover, and direct lift/cruise engine compressor bleed is used for reaction control. In addition, engine T/W and thrust split characteristics impact the c.g. envelopes differently in each design. As a consequence, Configurations 300 and 400 operate at static margins 3% of the mean aerodynamic chord more negative than those of the other three configurations. This results in lower maneuver trim drag for Configurations 300 and 400.

Design-Mission Sizing

Each baseline design was evaluated in terms of aerodynamic characteristics, weight and balance characteristics, and installed propulsion-system performance. These evaluations were expressed in terms of physically meaningful "level of excellence" parameters to facilitate scaling by the Conceptual Design Synthesis Procedure (CDSP). The CDSP is an interdisciplinary computer program used for efficient conceptual design evaluation and synthesis. The CDSP was used to scale configuration components (wing, fuselage, and engine) so that mission rules and performance requirements are exactly satisfied. Design variables, such as wing planform and thickness, were optimized to provide the lowest TOGW aircraft meeting all requirements. The optimized configuration result from the CDSP is referred to as the "resized" aircraft.

Sizing results for the five configurations are summarized in Fig. 7 and Table 3. It can be seen that the simple-RALS and turbocompressor-RALS concepts using the 15%-bleed TBE gave equal TOGW aircraft. Also they were considerably lighter than the 30%-bleed TBE simple-RALS design. The 15%-bleed TBE designs were lighter than the turbofan-RALS concept, but not as light as the L+LC concept.

Due to practical considerations of hover balance and pilot field of view, fuselage length was not allowed to decrease during optimization. Therefore, none of the five configurations have maximum density; that is, additional internal volume is available, so that greater mission radius is possible for each configuration by using the excess volume for fuel and relaxing combat performance requirements. Table 3 presents the capability of each resized design for such an overload DLI mission. Here it is evident that considerable excess capability exists for the TBE-powered aircraft, while relatively little exists for the turbofan-powered concepts. This fact must be considered when examining results and drawing conclusions.

The sizing results may be understood by examining relative propulsion-system fuel consumption and T/W characteristics, together with design variable trends in the configuration optimization. Propulsion-system T/W characteristics are most important at hover and P_s-requirement conditions because these conditions had the greatest influence on propulsion-system size. Table 4 presents propulsion-system T/W for these conditions.

The first study objective was to identify the most promising of the TBE-powered configurations. It was found that advantages in integration for hover balance for the 30%-bleed design over the 15%-bleed designs are more than compensated for by the superior engine cycle performance of the lower-bleed TBE. Fuel flow rate at representative subsonic and supersonic 1-*g* conditions is considerably higher for Configuration 300 than for Configurations 101 or 201, even though Configuration 300 has lower drag due to lift, which is the result of greater longitudinal static instability obtained by this design. Configuration 300 has relatively low propulsion-system T/W (Table 4) at the P_s-requirement condition; that requirement became an active sizing constraint. At the hover condition, the large portion of air burned by the RALS contributes to fairly high T/W, which results in excess hover useful load capacity for this configuration (Table 3).

Since Configurations 101 and 201 (15%-bleed TBE with simple and turbocompressor RALS, respectively) have similar performance characteristics and the former suffers from the design drawbacks discussed earlier, the latter is identified as the most promising TBE-RALS concept. Nonetheless, it is of interest to examine and compare sizing trends for these two designs. Notice that hover useful load is an active sizing constraint for Configuration 101, so excess P_s performance is available. The opposite is true of the turbocompressor RALS concept, for which the P_s requirement is active and excess hover load capacity results. Since aerodynamic characteristics for the two baseline configurations are very similar and engine cycle performance is identical, the differences in sizing trends can be attributed entirely to propulsion-system T/W. Note that in Table 4, at the hover condition, the turbocompressor RALS design has higher T/W than the simple RALS design but, at the P_s-requirement condition, the opposite trend is seen.

The second and third study objectives were to evaluate merits of this best TBE concept relative to "conventional" turbofan-RALS (or fan-stream burning) and L + LC concepts. In this regard, the results on Fig. 7 are somewhat surprising in view of the anticipated advantages of the TBE: namely, good supersonic cycle performance, high engine airflow, and low volume penalties for RALS ducts. Comparison with the turbofan RALS was expected to favor particularly the TBE design since the relatively high fan bypass ratio required for hover balance is undesirable for good supersonic performance.

Design-mission TOGW for the turbofan-RALS concept is only 3.4% greater than that for the TBE concept, and the L + LC design TOGW is 10.9% lower. Supersonic cycle advantages of the TBE's over the conventional turbofans were realized. However, the optimization of the TBE configuration (Configuration 201) favored thicker higher-aspect-ratio wings for lower subsonic drag, while the optimization of the turbofan-RALS design favored thinner lower-aspect-ratio wings for low supersonic drag (Table 3). The result is that fuel flow rates are quite similar for both subsonic and supersonic flight conditions for the two configurations. These trends do not completely offset the cycle advantages of the TBE, but they do dilute the effects on TOGW. Similar wing sizing trends can be observed for the L + LC configuration, although they are not as extreme.

The benefits expected from the smaller RALS supply ducts of the TBE-powered configurations relative to the turbofan-RALS design are not realized in the design-mission sizing results because of the restriction on fuselage length. None of the aircraft have maximum density for the design mission, so extra duct volume is not a penalty. However, the duct volume benefits dramatically affect overload-DLI mission performance, as shown in Table 3. Even though Configuration 400 is a larger aircraft than Configuration 201, the latter is capable of more than twice the overload-DLI radius of the former.

The primary characteristic of the turbofan engines that makes the turbofan-RALS TOGW fairly close to the TBE-RALS, and also makes the L + LC design substantially lighter, is the T/W of the engines themselves at up-and-away conditions. Note that in Table 4, for the P_s-requirement condition, T/W's for the turbofan-powered designs are substantially greater than for the TBE-powered designs. T/W sensitivity studies confirmed that the TOGW difference between Configuration 201 and 500 is attributable to differences in propulsion-system T/W.

To recap the sizing results then, the 15%-bleed TBE with turbocompressor RALS concept is considered the most promising of TBE concepts, considering design-mission sizing, overload performance, and design aspects. Comparison of the TBE-RALS with turbofan-RALS designs shows lower TOGW and greatly superior overload performance for the TBE-RALS configuration. Comparison of the TBE-RALS with L + LC designs shows higher TOGW for the TBE-RALS design but equally superior overload mission performance. Generally, in comparing TBE-powered designs with turbofan-powered designs, cycle advantages of the TBE's at supersonic conditions are diluted by configuration optimization, and the T/W advantages of the turbofans tend to offset the TBE cycle advantages.

Life-Cycle Cost

LCC is a second figure of merit, after TOGW, for comparing the resized configurations. Cost estimates are sensitive not only to the aircraft size but also to the complexity and degree of advanced technology usage. Results of LCC analysis of the resized designs are summarized together with ground rules in Fig. 8. In general, it can be seen that RDT&E costs constitute a small portion of total LCC, so that total LCC is insensitive to changes in RDT&E. Procurement and O&S costs constitute the large majority of the costs, with O&S being somewhat greater than procurement.

Procurement cost results are most strongly influenced by aircraft empty weight and propulsion-system size and complexity. The cost of the turbocompressor units is evident in comparing procurement costs of resized Configurations 101 and 201. The procurement costs of resized Configurations 201 (TBE RALS) and 400 (turbofan RALS) are very close, even though the TOGW of Configuration 400 is higher than that of

Table 4 Propulsion-system T/W comparison

Configuration	Propulsion-system T/W[a] Hover condition (sea level static)	P_s condition (0.9 M, 10 K ft)
101-0.15 TBE simple RALS	3.97	5.18
201-0.15 TBE TC RALS	4.17	4.78
300-0.30 TBE simple RALS	4.17	4.72
400-Turbofan RALS	4.45	6.13
500-L + LC	4.75	6.04

[a] Includes lift system, RCS, auxiliary power unit, starting system, and engine controls.

Configuration 201. The empty weights of these configurations, however, are quite close (Table 3). Also the addition of the turbocompressor offsets the simplicity advantage of the single-spool TBE. Note that the small size of the L + LC Configuration 500 overcomes the considerable added complexity of the lift-engine system.

The most notable trend in operations and support (O&S) costs is that of significantly lower fuel consumption for the conventional-engine-powered configurations than for the TBE-powered designs. Fuel consumption is based on a realistic generalized peacetime mission mix composed of air-to-surface training, air-to-air training, and administration and test segments. Air-to-surfce training includes equal-time portions of cruise at optimum Mach number and altitude and military power combat at 0.85 Mach number and 200 ft of altitude. Air-to-air training includes equal-time portions of optimum cruise, optimum loiter, maximum-power combat at 1.8 Mach number and 40,000 ft and military-power combat at 0.9 Mach number and 20,000 ft. Administration and test includes only cruise flight. Since the mission mix favors the good subsonic efficiency of the conventional engines, their relatively low O&S costs are reasonable.

Potential for Design Refinement

Imposition of minimum fuselage length as a sizing constraint was based on specific identifiable design considerations. However, the result of nonmaximum density for the resized configurations obscures or, at least complicates, interpretation of sizing results. In comparing results for the 15%-bleed-TBE turbocompressor-RALS design with L + LC, for instance, it was found that the L + LC design has lower design-mission TOGW and LCC. However, the TBE-RALS design has much greater overload mission capability. Therefore, identifying either as the "best" design is somewhat subjective.

It is likely that some reduction in fuselage length is feasible for some or all of the resized designs but probably not enough to obtain maximum-density for the TBE-powered configurations. Determination of the extent of feasible length reductions would require additional iterations of the conceptual design cycle. Since this is beyond the level of effort of the present study, a cursory investigation was made to determine the potential for design refinement and the possible effects on relative sizing results. This was done by simply resizing and optimizing the designs of interest, using the CDSP with the fuselage length constraint removed.

Figure 9 presents TOGW and LCC results for Configurations 201, 400, and 500. Note that the TBE-RALS design exhibits significant reductions in TOGW and LCC compared to fixed-fuselage-length results of Figs. 8 and 9. However, in the case of the turbofan-powered configurations, little change is seen from the previous results. These trends are consistent with the overload mission results for the fixed-length designs given in Table 3; that is, large excess fuel capacity for Configuration 201 indicated significant potential for improvement, while the turbofan-powered fixed-fuselage-length designs have little excess capability because they have nearly maximum density.

Therefore, relative TOGW and LCC results between the three concepts are quite dependent on the issue of fuselage length. In this maximum-density case, the TBE-RALS design is shown to be competitive with the L + LC design, in terms of TOGW, and clearly superior to the turbofan-RALS configuration. Procurement cost shows the same trend, but O&S costs are still greater for the TBE-RALS design, owing to the relatively poor subsonic efficiency of the TBE.

It should be reiterated that these results illustrate potential for improved integration only. They show that the TBE-RALS designs may benefit significantly from reduced fuselage length, but it is not known what portion of this potential can be realized while still satisfying hover balance and pilot over-the-side visibility requirements. On the other hand, these results indicate that the baseline fuselage length is near optimum for the turbofan-powered designs, and little benefit should be expected from integration refinement.

Sensitivity to Performance Requirements

Before drawing general conclusions from a conceptual design study such as the present investigation, it is important to determine if changes in design ground rules and objectives change relative results. Therefore, a brief study was undertaken in which the best TBE-RALS configuration and the turbofan-RALS and L + LC designs were resized (with fixed fuselage length) to systematically varying mission and combat performance requirements.

Figure 10 presents results from the requirements-sensitivity study. The left portion of the figure shows the sensitivity of TOGW to DLI-mission radius with the basic combat performance requirements imposed (labeled "TS-169 Goal"). Note that the relative results are insensitive to mission radius. Sensitivity to mission radius with relaxed combat performance requirements (labeled "TS-169 Threshold") is shown in the right-hand portion of the figure. Again, the relative sizing results are insensitive to mission radius. However, note that the relative results are quite sensitive to the combat requirements. Relaxing the combat requirements has little influence on TOGW for the turbofan-powered concepts because hover useful load is an active sizing constraint, so even TS-169 Goal P_s and acceleration requirements are exceeded. On the other hand, the TBE-RALS design is sized by the TS-169 Goal P_s requirement, so relaxing the combat requirements does significantly reduce TOGW.

From these results it may be inferred that stringent combat requirements and/or relaxed hover requirement favor the turbofan-powered concepts over TBE RALS. Also, stringent hover requirement and/or relaxed combat requirements favor the TBE RALS.

The sensitivity studies indicate that the TBE RALS is consistently more promising than conventional turbofan RALS. However, when comparing TBE RALS with L + LC, care must be taken in defining ground rules and requirements because the selection of a "best" concept is highly dependent on these definitions. It is easily seen, for instance, that a ground rule of single-place cockpits (which would make a shorter fuselage feasible), together with increased hover load requirement and reduced P_s requirement, may result in lower TOGW for the TBE RALS than for the L + LC.

Alternate Mission Performance

Performance calculated for two alternate missions provides additional means of comparison between the five airplane/engine systems. The missions were selected for relevancy in the year-2000 time period. The ASuW mission profile was designed to attack an enemy fleet or ground target with standoff air-to-surface weapons. The mission is entirely subsonic, with a 100-n.mi., low-level, high-speed penetration. The second alternate mission examined was a CAP for fleet air

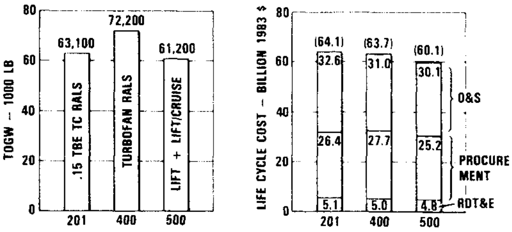

Fig. 9 TOGW and LCC for maximum-density configurations.

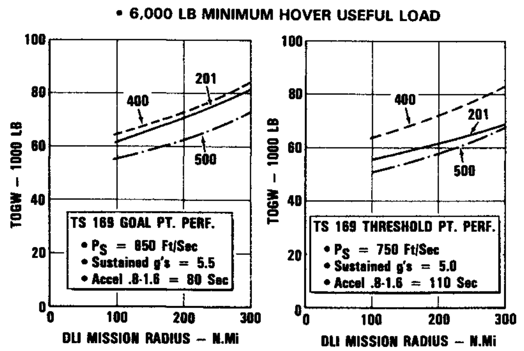

Fig. 10 Sensitivity of TOGW to mission and combat performance requirements.

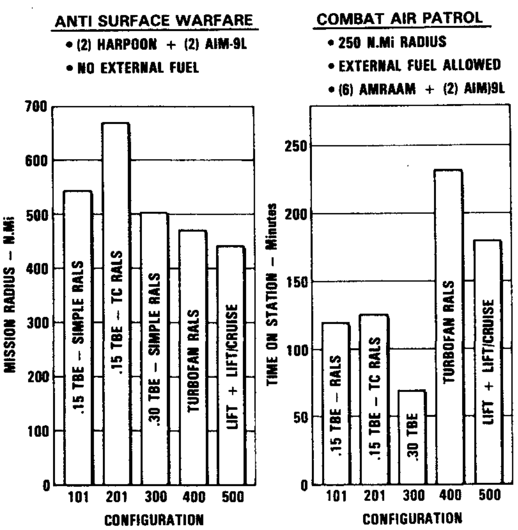

Fig. 11 Alternate mission performance.

defense. It was designed to counter threats of standoff weapons launched against the fleet from aerial platforms by destroying the platforms. The CAP acts as a first-tier defense against the threat for which the design DLI serves as the second tier. The projected weapons consist of long-range air-to-air missiles with capabilities greater than the AIM-54 Phoenix but with size and weight similar to the AIM-120 AMRAAM. Although weapons are retained in the mission, external fuel tanks are dropped when empty.

Alternate missions results for the resized configurations are given in Fig. 11. Extra internal fuel volume was filled with fuel (and tankage), as in the overload DLI, for each configuration. ASuW mission results with two missiles indicate that Configuration 201 (TBE with turbocompressor RALS) has excellent radius capability significantly greater than that of other TBE-powered or conventional-engine-powered designs. Advantage over the TBE configurations may be traced primarily to better subsonic-cruise fuel consumption. Additional fuel capacity resulting from the design-mission sizing rules account for the advantage over the conventionally powered designs.

CAP performance results are also given in Fig. 11, with as much external fuel added as possible while still meeting takeoff and landing requirements. When external fuel tanks are added, the superior loiter performance of both turbofan-powered designs becomes dramatically apparent. Note that the 400-ft STO requirement limits the amount of external fuel that can be carried by Configurations 201 and 300. The higher-bypass turbofan of the turbofan-RALS design clearly gives superior performance for CAP mission.

Conclusions

The first study objective was to identify the most promising engine cycle and/or configuration for the TBE-RALS application. Results indicate that the combination of a relatively low-bleed-capacity (15%) TBE with a turbocompressor RALS yields the best compromise between up-and-away mission performance and hover thrust balance considerations. Also the turbocompressor-RALS configuration gives superior performance for alternate missions.

The second task was to make comparisons between the best TBE-RALS design and "conventional" turbofan-RALS (fan-stream-burning) design. This comparison shows that the turbofan-RALS concept yields a slightly larger (3% greater) TOGW but lower-cost (6% lower LCC) design. Sizing results are insensitive to design-mission radius, but relaxing combat performance requirements results in considerably higher TOGW for the turbofan-RALS design than for the TBE RALS. The TBE-RALS concept gives clearly superior performance for the overload DLI and ASuW missions, while the turbofan-RALS configuration gives superior CAP-mission performance. Overall, the TBE-RALS concept is considered more promising than the turbofan RALS.

Comparison with the L+LC concept was the third major study objective. In the design-mission sizing results, the L+LC design shows lower TOGW (by 11%) and LCC (also by 11%) relative to the best TBE-RALS configuration. Sizing to relaxed requirements gives TOGW for the TBE-RALS design competitive with L+LC. As with the turbofan-RALS concept, the L+LC design has considerably less capability on the overload-DLI and ASuW missions but clearly greater CAP-mission performance. Although TOGW and LCC results for the L+LC design are somewhat more promising than for the TBE-RALS designs, these results appear dependent on sizing requirements and ground rules.

Acknowledgments

This work was done under contract to the NASA Lewis Research Center under the direction of NASA program manager Leo C. Franciscus. Propulsion-system design and performance data were provided under a subcontract agreement with Pratt & Whitney Aircraft Government Products Division. The Pratt & Whitney program manager was Jere G. Osmer.

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