$$a_{-1} \equiv C_0 = 22.0/3600 = 6.111 \times 10^{-3}\,\text{lb/s}$$

$$a_1 \equiv \tfrac{1}{2} C_1 C_{D_0} \rho S = \frac{(\tfrac{1}{2}) \times 0.623 \times 0.0154 \times 0.0004623}{3600} = 0.6160 \times 10^{-8}\,\text{lb-s/ft}^2 \tag{13}$$

Due to the relatively small value of a_1, it can be shown that R_s increases almost indefinitely with increasing V. However, use of Eqs. (4), (7), and (A1) results in the following expression for the maximum speed achievable with the thrust that is available:

$$V_{\max} = (1/\rho S)\{(T/C_{D_0}) + [(T/C_{D_0})^2 - (4KW^2/C_{D_0})]^{1/2}\} \tag{14}$$

Here, available $T = 234$ lb. This gives $V_{\max} = 779$ ft/s and Eq. (12) gives $R_s = 81{,}370$ ft/lb or 100.2 mi/gal (fuel weight = 6.5 lb/gal).

The airspeed (V_{md}) at which the drag is a minimum is given by [10,14]

$$V_{md} = (K/C_{D_0})^{1/4}(2W/\rho S)^{1/2} = 417.5\ \text{ft/s} \tag{15}$$

Thus, $V_{opt}/V_{md} = 779/418 = 1.864$, in contrast to $V_{opt}/V_{md} = (3)^{1/4} = 1.316$ obtained from classical theory (Appendix B type) by Hale and Steiger.[14] The present theory yields a higher optimum airspeed because the C predicted by Eq. (6) is actually lower at higher thrust levels, rather than constant as assumed in Appendix B. For example, at 45,000-ft altitude, when T is increased from 100 to 200 lb, C decreases from 0.843 to 0.733 lb/lb-h.

The optimum airspeed obtained here is 15.3% more than the aforementioned design cruise speed (400 knots). However, the design specifications were for 400 knots, suggesting that the wing area (S) may be disproportionately large. However, S was sized by the maximum permissible stall speed for single-engine aircraft, engine performance limited use above 45,000 ft, and structural limitations prevented use of a higher effective aspect ratio than 8.45 (with an Oswald efficiency factor of 0.8). A similar conclusion was recently reached by Holmes.[15]

Concluding Remarks

A closed-form equation for range at constant altitude was derived and applied to an example problem. It was shown in this example that the logarithmic-form equation given in Refs. 5-12 gave a range less than 2% higher than the accurate one, while the square-root-form equation (Refs. 2-4) gave a range only about 0.8% higher than the accurate one. The conventional endurance equations gave a value less than 2% higher.

Appendix A: Derivation 1

In Refs. 2-4, it was assumed that

$$\dot{W} = -CT; \quad V = (2W/\rho S C_L)^{1/2}; \quad T = (C_D/C_L)W \tag{A1}$$

where C is a constant.

Combining Eqs. (2), (3), and (A1) and assuming that altitude (and thus ρ), C, and $\sqrt{C_L}/C_D$ all remain constant (a physical impossibility), one obtains

$$R = -\sqrt{2}\int_{W_i}^{W_f} \frac{\sqrt{C_L}/C_D}{C\sqrt{\rho S}} \frac{dW}{\sqrt{W}} = \frac{2\sqrt{2}}{C\sqrt{\rho S}} \frac{\sqrt{C_L}}{C_D}(\sqrt{W_i} - \sqrt{W_f}) \tag{A2}$$

Combining Eqs. (5) and (A1), one obtains

$$E = -\int_{W_i}^{W_f} \frac{1}{C} \frac{C_L}{C_D} \frac{dW}{W} = \frac{1}{C} \frac{C_L}{C_D} \ln \frac{W_i}{W_f} \tag{A3}$$

Appendix B: Derivation 2

Substituting Eqs. (3), (4), and (A1) into Eq. (2) and assuming that C, L/D, and V all remain constant (a physical impossibility at constant altitude when W is changing), one obtains

$$R = -\int_{W_i}^{W_f} \frac{V}{C} \frac{L}{D} \frac{dW}{W} = \frac{V}{C} \frac{L}{D} \ln \frac{W_i}{W_f} = \frac{V}{C} \frac{C_L}{C_D} \ln \frac{W_i}{W_f} \tag{B1}$$

Since $V =$ const, the endurance is also given by Eq. (A3).

Acknowledgments

Helpful discussions with the following persons are gratefully acknowledged: Professors Karl H. Bergey and Maurice L. Rasmussen; graduate student Steven H. Findeiss, and senior Amir Saadat.

References

[1] Page, R. K., "Performance Calculations for Jet-Propelled Aircraft," *Journal of the Royal Aeronautical Society,* Vol. 51, 1947, pp. 440-450.

[2] Jonas, J., "Jet Airplane Range Considerations," *Journal of the Aeronautical Sciences,* Vol. 14, Feb. 1947, pp. 124-128.

[3] Perkins, C. D. and Hage, R.E., *Airplane Performance Stability and Control,* Wiley, New York, 1949, p. 192.

[4] Dommasch, D. O., Sherby, S. S., and Connolly, T. F., *Airplane Aerodynamics,* Pitman, New York, 1957, pp. 286-287.

[5] Ashkenas, I. L., "Range Performance of Turbojet Airplanes," *Journal of the Aeronautical Sciences,* Vol. 15, Feb. 1948, pp. 97-101.

[6] Bonney, E. A., *Engineering Supersonic Aerodynamics,* McGraw-Hill, New York, 1950, pp. 254-255.

[7] Corning, G., *Airplane Design,* published by the author, P.O. Box 14, College Park, Md. 20740, 1953, p. 2:36.

[8] Wood, K. D., *Technical Aerodynamics,* 3rd ed., McGraw-Hill, New York, 1955, Chap. 18.

[9] Küchemann, D. and Weber, J., "An Analysis of Some Performance Aspects of Various Types of Aircraft Designed to Fly Over Different Ranges at Different Speeds," *Progress in Aeronautical Sciences,* Vol. 9, Pergamon, Oxford, 1968, pp. 329-456.

[10] Nicholai, L. M., *Fundamentals of Aircraft Design,* METS, Inc., Xenia, Ohio, 1975, Chap. 3.

[11] Torenbeek, E., *Synthesis of Subsonic Airplane Design,* Delft University Press, Delft, the Netherlands, 1976, p. 157.

[12] Küchemann, D., *The Aerodynamic Design of Aircraft,* Pergamon, Oxford, 1978, pp. 6, 7.

[13] Hamlin, B. and Spenceley, F., "Comparison of Propeller and Reaction-Propelled Airplane Performance," *Journal of the Aeronautical Sciences,* Vol. 13, Aug. 1946, pp. 425-437.

[14] Hale, F. J. and Steiger, A. R., "Effects of Wind on Aircraft Cruise Performance" *Journal of Aircraft,* Vol. 16, June 1979, pp. 382-387.

[15] Holmes, B. J., "Aerodynamic Design Optimization of a Fuel-Efficient High-Performance Single-Engine Business Airplane," AIAA Paper 80-1846, Aug. 1980.

AIAA 80-1853R

RALS/VCE Turbine Inlet Temperature and Engine Complexity Optimization Study

William S. Willis*
General Electric Co., Cincinnati, Ohio

Background

STUDIES conducted by General Electric in the 1975-1979 time period had identified the variable cycle engine and remote augmented lift system (VCE/RALS) as a very at-

Presented as Paper 80-1853 at the AIAA Aircraft Systems and Technology Meeting, Anaheim, Calif., Aug. 4-6, 1980; submitted Sept. 9, 1980; revision received Jan. 26, 1981.

*Manager, Advanced Military Systems—Preliminary Design.

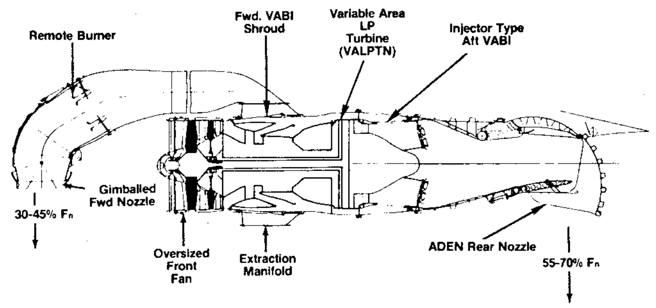

Fig. 1 VCE/RALS engine.

Table 1 Thrust-to-weight comparison

T4	SLS-90°F-VTO Base	−300°F	−600°F
Double bypass ratio VALPTN	E2 6.32	F2 5.82	G2 5.29
Single bypass ratio VALPTN	H2 6.49	J2 5.94	K2 5.40
Single bypass ratio fixed LPT	A2 6.61	B2 6.06	C2 5.50
Double bypass ratio fixed LPT	Q2 6.44		

tractive candidate for supersonic V/STOL aircraft. Figure 1 shows a cross section of this propulsion system.

The VCE concept was previously developed for mixed subsonic/supersonic applications, and its features have now been substantiated by engine test. The fan is split into two blocks, the forward two-stage block being driven by the low-pressure turbine, and the rear single-stage block by the high-pressure turbine. This arrangement balances the turbine energy to permit both the high- and low-pressure turbines to be single-stage designs. The forward fan block is oversized, such that for loiter operation the tip flow can bypass the rear block, effectively increasing bypass ratio and improving SFC. This double bypass mode of operation is accomplished by adjusting a translating-shroud, variable-area bypass injector (VABI). Further cycle flexibility is provided by a variable-area, low-pressure turbine nozzle (VALPTN). The engine is equipped with an aft VABI, a mixed-flow augmentor and an Augmented Deflector Exhaust Nozzle (ADEN) to permit both vertical and conventional operation.

The RALS concept adds a remote augmentor and vectorable exhaust nozzle located near the nose of the aircraft to provide a forward lift vector. This system is operated by ducting most of the bypass air forward through a remote augmentor, and exhausting it through a vectoring nozzle. The use of a round duct with modest Mach numbers provides a more uniform airflow and velocity profile entering the burner, facilitating the achievement of high burner efficiency and augmentation levels. The use of an air extraction manifold and translating valve on the engine allows the entire fan discharge flow to be directed aft to a mixed-flow augmentor in forward flight, reducing frontal area. The remote exhaust nozzle employed is a variable-area gimballed concept providing thrust vectoring from 15 deg forward of vertical to 30 deg aft with ±15 deg side vectoring capability. The side vectoring is useful in providing aircraft yaw control. Other nozzle concepts are also available to provide greater aft vectoring if needed for STOL takeoff operation.

The VCE/RALS compared very favorably with other propulsion concepts in the supersonic Deck Launched Intercept (DLI) mission ($Mo = 1.6$ maximum) which proved to size the aircraft and propulsion system. External fuel was added to accomplish the alternate subsonic missions, including Fighter Escort, Tactical Strike, Combat Air Patrol, Ferry, and Subsonic Surface Surveillance. Because all of the turbomachinery is available to provide forward thrust, the VCE/RALS produced much greater combat performance than systems carrying dedicated lift engines. It also proved to be more cost effective since only one engine type has to be developed, procured, and maintained in the life cycle of the system.

A relatively high maximum T4 level was selected for the system, commensurate with the technology expected to be available in the 1990 time period. The primary advantage of a high T4 is in keeping the core size as small as practical, thereby providing a high thrust-to-weight ratio. Navy V/STOL requirements include rating the system on a 90°F day with maximum reaction control bleed and power extraction. Consequently the engine was flat-rated, and the high T4 operation was taken into account in the design duty cycle. A conventional standard day rating would be approximately 275°F lower in T4. Nevertheless, some concern was felt about the advanced T4 level, and about the relative complexity of the variable cycle engine. Accordingly, a study was conducted under contract to the Naval Air Propulsion Center, Trenton, N.J. to evaluate the system impact of reducing the design T4 level and removing some of the variable cycle features.

Approach

The approach taken for the study was the evaluation of a matrix of engines for aircraft takeoff gross weight (TOGW), performance, and Life Cycle Cost (LCC) with V/STOL B mission requirements. The matrix included reductions from the baseline engine in both T4 level and variable cycle features. Specifically, engines were defined with T4 levels 300 and 600°F lower than the baseline. The −600°F level is representative of today's operational military aircraft. Additional engines with differing levels of variable cycle complexity were also evaluated at the three T4 levels. It should be noted that the hot section design and material technology for all the engines was selected to be a consistent family. As a result, the acquisition costs calculated to determine LCC are probably higher than would be necessary for the lower T4 level engines. However, these costs are offset because the lower T4 level engines require less cooling flow with the same design/materials, which results in improved cycle performance.

TOGW and SFC effects were determined using aircraft sensitivity factors developed under a previous contract with McDonnell-Douglas. A 45/55% thrust split between the remote and main nozzles was used in the study to maintain the required aircraft balance and to avoid having to reconfigure the baseline aircraft. This constraint resulted in the need to maintain constant bypass ratio as T4 and fan pressure ratio were reduced. With constant overall pressure ratio (OPR), the core pressure ratio was found to be limited to about 7.8 by high-pressure turbine loading. It was therefore decided to hold core pressure ratio constant at 7.0, allowing OPR to fall as T4 was reduced.

All engines studied used mixed-flow augmentors constraining the mixing plane pressure balance to the range 1.3-1.4. The split fan concept was retained in all cases to balance turbine energy and to permit single-stage high- and low-pressure turbines to be used. Exhaust gas temperature from both the RALS and ADEN nozzles was held at a nominal 2800°F.

The Life Cycle Costs calculated in the study were intended to include only those elements which would be influenced by the engine. The study assumed a procurement of 2000 engines to support 825 aircraft. An average of 500 aircraft flying 300 h/yr for 15 yr with a typical V/STOL B mission mix was assumed. The individual cost elements for LCC included

Table 2 RALS trade study summary

T4	Base	−300°F	−600°F	
	E2	F2	G2	
TOGW (DLI)	34360	+5.5%	+13.3%	Double bypass ratio
Loiter time (SSS)	45 min.	+3.6	+5.7	VALPTN
LCC ($ million)	2098	+194	+529	
	H2	J2	K2	
TOGW (DLI)	−0.3%	+5.2%	+12.9%	Single bypass ratio
Loiter time (SSS)	−7.3	−2.6	+1.0	VALPTN
LCC ($ million)	−96	+93	+427	
	A2	B2	C2	
TOGW (DLI)	−1.1%	+4.3%	+12.2%	Single bypass ratio
Loiter time (SSS)	−5.7	−1.2	+1.4	
LCC ($ million)	−335	−124	+212	
	Q2			
TOGW (DLI)	−0.7%			Double bypass ratio
Loiter time (SSS)	−0.4			
LCC ($ million)	−206			

engine RDT&E, engine acquisition, flight test support, engine maintenance, engine Component Improvement Program, fuel, and aircraft procurement costs resulting from changes in TOGW.

Results

All of the engines were configured in a 200 lb/s airflow size, and then scaled to the takeoff thrust required by the aircraft. A small diameter and weight increase was noted as the T4 was reduced, but thrust fell off significantly. When the lower temperature engines were scaled up to the same thrust size as the baseline E2, the diameter and weight penalties became appreciable. This effect can be seen in Table 1, which shows the thrust-to-weight (F/W) comparison for all of the engines when scaled to the same installed net thrust for the 90°F, SLS, VTO condition. The engines in the first horizontal row (E2, F2, G2) are the baseline variable cycle design with double bypass (forward and aft VABI) and a VALPTN. F/W is seen to drop significantly as T4 is decreased. The engines in the second row (H2, J2, K2), which have a single bypass design (no forward VABI) show the same F/W vs T4 trend. The trend is continued with the A2, B2, C2 engines which have both the forward VABI and VALPTN removed. At a given T4, it can be seen that the elimination of the variable cycle features results in increased F/W as would be expected due to reduced engine weight. The Q2 engine, with both VABI's but no VALPTN, lies between the E2 and H2.

Table 2 summarizes the overall study results using three figures of merit; the required TOGW to complete the prime DLI mission, the loiter time available in the Subsonic Surveillance Mission, and the LCC for an assumed 15 yr USN V/STOL B program. The SSS mission proved to be the most demanding of the subsonic missions. The impact of T4 on aircraft TOGW is shown to be a 5.5% increase for −300°F, and a 13.3% increase for −600°F. Less than 1% of the increase is attributed to reduced OPR. The reduced temperature engines provide some improvement in subsonic loiter time, but the higher T4 levels provide a substantial payoff in aircraft size.

Data in the second row of Table 2 show the effect of removing the forward VABI. In the DLI mission, performance was affected only in the subsonic return leg where the engine could not be operated in the double bypass mode. Subsonic SFC increased about 2½%. The resultant increase in fuel weight offset the engine weight saving, so that an overall TOGW improvement of only 0.3% was realized. Since the double bypass feature breaks even in the DLI mission, and since it provides a distinct advantage in any alternate subsonic mission as indicated by the SSS loiter time, it was judged to be worth retaining. For these reasons, the Q2 engine with double bypass and without the VALPTN was investigated at the base T4 level. The results show that the Q2 is probably the optimum from a performance standpoint, with a 0.7% decrease in TOGW and only a 0.4 min loss in SSS mission loiter time.

The third row of engines shows the effects of removing the VALPTN feature and substituting conventional fixed area turbine vanes. LPT efficiency and thrust improved slightly with some saving in engine weight. These effects resulted in a TOGW benefit of 1.1% compared to the base engine. A reduction in dry subsonic thrust (35 K, Mach 0.8) of 2.9% also resulted, but did not affect the mission. Since the VCE/RALS far exceeds the combat performance (P_s and acceleration time) of competitive systems in the high subsonic operating arena, a fixed-area, low-pressure turbine may be desirable to simplify the system and reduce cost.

From the LCC results shown on Table 2, it is clear that reduced T4 levels significantly increase cost regardless of design configuration. However, the conclusions to be drawn regarding variable cycle complexity vs LCC are not so clear. The fixed-area single bypass A2 engine is seen to have the lowest cost. However, the double bypass Q2 has the next lowest LCC. The cost of fuel assumed in the study was $1/gal. As this cost is increased, the LCC delta between the A2 and Q2 would be reduced. In addition, a different aircraft configuration (SFC sensitivity), or increased subsonic vs supersonic mission time splits from the values used in the study, could also substantially reduce the LCC delta. It is therefore evident that a choice between single and double bypass configurations could be made only as a result of a detailed study of a specific aircraft and program.

Conclusions

The major conclusions of the study follow.

1) For maximum performance at the lowest LCC, the T4 level should be as high as practical consistent with available technology and life/service requirements.

2) The variable-area low-pressure turbine nozzle has value only in improving subsonic dry thrust where the VCE/RALS far exceeds V/STOL B requirements and should therefore not be incorporated in this application.

3) For the assumed V/STOL B program studied, the double bypass engine (Q2) showed the best performance, while the single bypass engine (A2) had the lowest Life Cycle Cost. A final selection would require a more detailed aircraft and program analysis.