# YC-15 Powerplant System Design and Development

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**Design and development work for the YC-15 powerplant system has been completed. Installation problems unique to the externally blown flap STOL concept were identified. Solutions to these problems influenced the nacelle design in terms of: 1) engine positioning relative to the wing and blown flap, 2) details of the inlet lip thickness, 3) exhaust nozzle design to reduce jet pressure and temperature imposed on the flap, and 4) the directed-flow thrust reverser enabling full-reverse power operation at zero-speed ground roll conditions. Development testing was conducted only in areas needing extrapolation of experience and included inlet model tests, externally blown flap wind-tunnel tests, and model and full-scale tests of daisy mixing exhausts in conjunction with large centerbody plugs. Engine ground tests with flight-nacelle hardware have demonstrated operational functions and structural integrity.**

## Introduction

THE YC-15 is one of two competing prototype developments for the concept of an advanced medium STOL transport (AMST). The prime technological feature, which distinguishes this specific STOL approach, is the use of the underwing externally blown flap (EBF) concept for propulsive lift augmentation.[1,2] Designs of the nacelle, pylon, engine inlet, exhaust nozzle, and thrust reverser were influenced by factors inherent in the EBF concept to assure reliable functioning under conditions peculiar to STOL flight and during operation on unimproved landing surfaces.

The powerplant system developed for the YC-15 aircraft is described in this paper, and related engineering design problems and solutions are discussed. New problems were posed for the powerplant designer due to the fact that the engine exhaust jet is brought into close contact with wing and flap structure to provide for augmented lift by utilization of jet momentum. These problems not only influenced engine installation design features, but were extended in the sense that considerable information regarding exhaust environmental conditions on the wing and flap was required in support of aerodynamic and stress analysis and structural design work.

## Powerplant Installation Description

The general arrangement of the YC-15 is shown in Fig. 1. Four pylon mounted engines are positioned to blow on large double segmented flaps for short takeoff and landing (STOL) capability. The engine is the Pratt & Whitney Aircraft (P&WA) JT8D-17 turbofan. This, the most recent growth version of the JT8D family, is rated at 16,000 lb of thrust. The bypass ratio is approximately one.

The pylon is arranged to position the exhaust nozzle ahead of the wing such that a large proportion of the jet reacts on each of two slotted flap segments, making for maximized thrust deflection and wing circulation. A beneficial aspect of the high and forward engine location is that a straight lower pylon spar was achieved, leading to simplified pylon tooling and assembly.

For cost saving and expediency, the cowl inlet lip is constructed of fiber glass. For the prototype no cowl anti-icing is provided. For production, a bleed-air anti-iced cowl lip would be provided. A thick bellmouthlike inlet lower lip is featured to prevent inlet-flow separation at high inlet air attack angles during high-lift modes of flight.

Engine access is provided by right- and left-hand cowl doors hinged from the pylon and extending the full length of the engine case. The aft portion of the doors serves to cover the reverser cascades in forward thrust operation. The propulsion nozzle is designed to reduce the severity of the engine exhaust environment on the wing flap. Reduction in peak values of pressure and temperature are achieved by a 10-lobed daisy nozzle in conjunction with a 30-in.-diam centerbody. Exhaust mixing with ambient air results in reducing peak temperatures in the exhaust plume to values consistent with capabilities for titanium flap construction. The thrust reverser is a translating cascade type, featuring a single moving assembly consisting of cascades, stiffening structure, and the daisy nozzle. It is defined as a directed-flow type, wherein reversed gases are blocked in escaping from lower portions of the reverser and are vectored upward from the sides of the reverser.

## Nacelle Positioning

Early in the development of the EBF concept, wind-tunnel tests were conducted to investigate effects of nacelle and exhaust positioning relative to the wing and flap. Great improvement in maximum lift coefficient was realized by positioning the fan exhaust plane ahead of the wing. This is due primarily to a favorable interference phenomenon, the entrained air around the nacelle effectively reducing the local angle of attack at the wing leading edge.

Additional increases in lift result from locating the nozzle high in relation to the wing such that the expanding exhaust

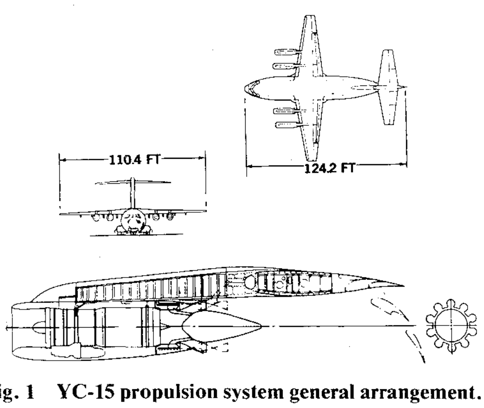

**Fig. 1 YC-15 propulsion system general arrangement.**

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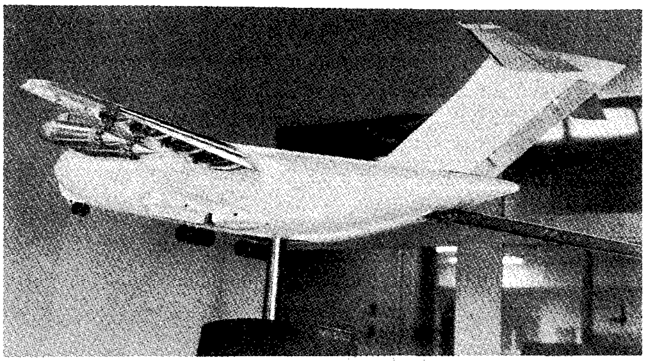

Fig. 2 YC-15 wind-tunnel mode.

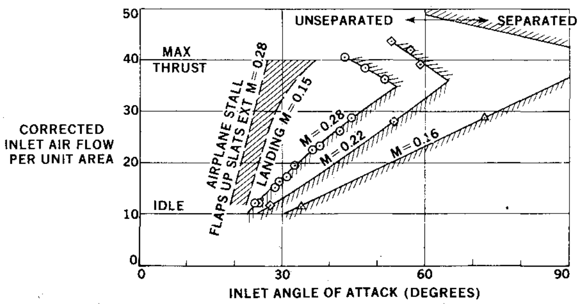


**Fig. 3 Inlet separation boundaries based on high Reynolds number wind tunnel test.**

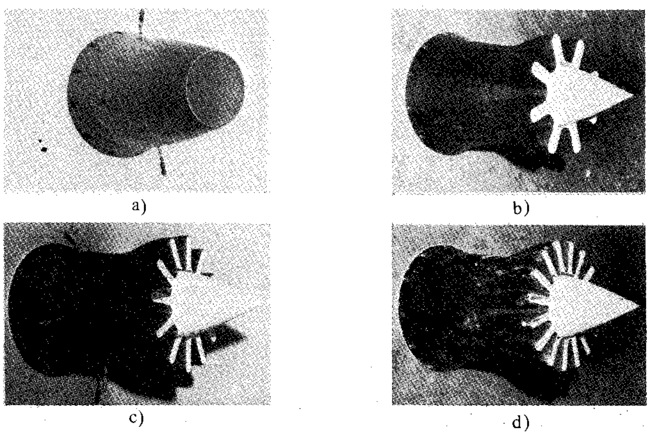


**Fig. 4 Mixing nozzle model configurations.**

plume flows over the upper flap segment. A large proportion of the jet passes through the flap slots and is turned on upper flap surfaces by coanda effect.[3] At higher flight speeds with the flap retracted the jet passes beneath the wing to avoid scrubbing losses at cruise. The wind-tunnel model of the YC-15, configured with simulated JT8D-17 nacelles complete with daisy mixer exhaust nozzles, is shown in Fig. 2.

## High Angle-of-Attack Inlet Capability

The increased wing circulation due to a blown flap results in high angles of attack at the wing leading edge and the engine inlet. The critical condition for inlet lip separation exists during high angle-of-attack flight at high wing loading.

Some reduction in inlet angle of attack is afforded by positioning the nacelle far forward, where upsweep angles for airflow approaching the wing are less. Additional protection from lip separation is achieved by incorporation of thickened lip contours in the lower portion of the inlet.

Inlet separation boundaries were determined for inlets with 11, 18, and 25-% lower-lip thicknesses in large-scale wind-tunnel tests. Data for the 25%-thick inlet, which was selected for the YC-15, are shown in Fig. 3. The separation boundary consists of two regimes. At lower airflows, separation is caused by adverse pressure gradients and boundary-layer growth. At high airflows, separation results from high inlet Mach number and shocks at the higher angles of attack.

For reference, the engine inlet airflow characteristics with the aircraft operating at maximum lift are shown for conditions with slats extended and flaps up, and with slats extended and flaps in landing configuration. In all cases, operation is on the unseparated side of the inlet stall boundary with reduced but adequate margin at idle conditions.

## Daisy Exhaust Mixer

In 1972, numerous schemes for reducing peak values of jet velocity on the EBF for purposes of minimizing noise generated by flap scrubbing were evaluated. For AMST studies, additional interest existed in exhaust wake mixing to reduce temperatures imposed upon the flap for applications using low-bypass engines with relatively hot exhaust temperatures. From this work it was recognized that a mixer featuring diasy lobes arranged around a large centerbody would tend to maximize the amount of secondary ambient air between lobes available for mixing. Further, the boattail angles in valleys between lobes would be minimized. Finally, with an aerodynamic constraint that the nozzle exit plane must be ahead of the wing leading edge, use of the large centerbody would provide the shortest nozzle, hence allowing for a shorter pylon with the engine positioned closer to the wing.

Model tests were conducted to investigate performance and mixing characteristics of daisy exhaust mixers in conjunction with large centerbodies. Figure 4 shows typical mixing nozzles, which were tested in the Douglas Long Beach cold air facility. Key parameters which were evaluated included: number of lobes, lobe aspect ratio (lobe height to width ratio), and the height of the gap between the valley of the lobes and the centerbody. Conclusions from results of these tests were as follows:

a) Significant amounts of velocity decay can be achieved within 3-6 equivalent nozzle diameters downstream of the exhaust plane. Levels of velocity decay 40-50% are readily obtainable.

b) Increasing the number of lobes yields significantly increased velocity decay for axial locations close to the nozzle. The level of velocity decay further downstream is only slightly affected by lobe number.

c) The annular gap height is an important variable in controlling the exhaust wake velocity decay characteristics. Improved exhaust centerline velocity decays are achieved by decreasing the gap height.

d) Increasing lobe aspect ratio beyond about two yields small, if any, improvement in the velocity decay characteristics, with less effect seen as the number of lobes are increased.

e) Wake profile shapes can be tailored by changing the nozzle design variables. Flow velocities near the center portion of the wake can be most readily controlled by varying the annular gap height. The exhaust wake diameter can be tailored by varying the number of lobes and the aspect ratio of the individual lobe elements.

f) Thrust losses for the 8-, 12-, and 16-lobe nozzles tested were 3-5% relative to a reference conical nozzle.

During the YC-15 (AMSTP) proposal studies, it was considered that the P&WA TF33 engine might be a candidate engine for the prototype aircraft, provided that it could be operated with a common or mixed-flow nozzle for the fan and primary gas streams. Engine ground tests were conducted at Edwards Air Force Base to determine TF33 characteristics operating with a common nozzle, to evaluate performance and exhaust wake characteristics with several types of exhaust mixers, and to expand the data base for effects of exhaust pressure, temperature, acoustic loads, and forces being imposed upon a slotted externally blown flap.

Transition ducting and mixer nozzle hardware were constructed as shown in Fig. 5. Spare hardware was provided for exhaust arrangements configured as a double daisy, inner conical with outer daisy, and a double conical nozzle. Provisions for simulating the aforementioned increased gap height around the centerbody were made by trimming or scalloping the valleys of the outer daisy lobes around the centerbody.

A boilerplate section of a wing and double-slotted flap was fabricated and instrumented with microphones, strain gages, and thermocouples. For selected tests, the section was installed behind the engine in an inverted position such that the exhaust flow was deflected upward to avoid ground interference effects. Freejet exhaust wake velocity and temperature surveys were made with a specially constructed instrumentation rake, enabling measurements to be made at various axial locations.

Velocity reductions were in agreement with predictions from the scale model data. Even with a relatively low value of lobe aspect ratio, peak velocities near the flap station were reduced more than 40% from the nozzle exit plane values for either the double daisy or inner cone outer daisy nozzles. As expected, with the valleys of the outer daisy lobes scalloped to provide increased centerbody gap height, centerline peak velocities were increased.

Temperature data at an axial distance corresponding to the flap location are indicated in Fig. 6. The double daisy, by virtue of forced internal mixing of the fan and primary streams, provided the most reduction in centerline temperature in the vicinity of the flap; however, the inner cone outer daisy also provided a significant reduction. Scalloping of the double daisy increased temperature to about the level of the inner cone outer daisy. A following conclusion was that an inner cone outer daisy nozzle with increased gap height would provide adequate centerline temperature reduction, consistent with titanium flap structural materials, with no need for forced internal mixing with an inner daisy.

The foregoing work provided the technical background information for the daisy exhaust mixer design (Fig. 7) for the YC-15 exhaust nozzle. The centerbody diameter was selected to be slightly smaller than the inner diameter of the translating thrust reverser assembly to provide for rearward removal and installation of the assembly with the centerbody installed. This also negates the need for movable reverser blocker doors with the reverser deployed. From similar features in the TF33 mixer design it was concluded that the front of the centerbody could be terminated as a bluff radius without need for fairing into the turbine hub. A hole was provided in the centerbody nose so that it would always be pressurized from the exhaust and hence would not have to be designed to withstand negative pressure.

Only a modest amount of velocity decay was desired to distribute exhaust pressure on the flap to reduce locally high peak pressure values. Exhaust centerline temperature reduction to approximately 600°F was required at the flap station. It was concluded that 10 daisy lobes with an aspect ratio slightly greater than 1 would be adequate. The centerbody gap height of 1.85 in. was chosen. This is consistent with the gap height of the scalloped TF33 daisy.

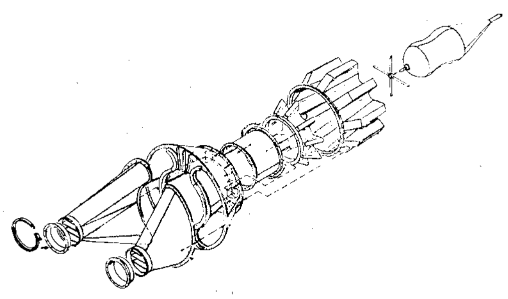

Fig. 5 Full-scale Daisy nozzle test hardware.

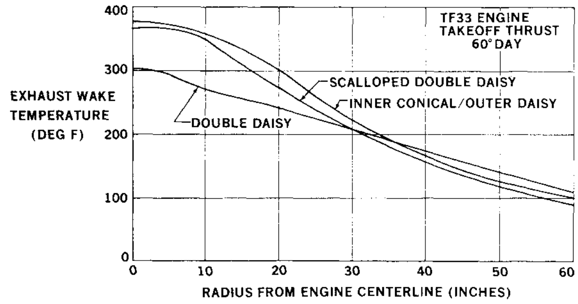


Fig. 6 Freejet exhaust temperature at flap.

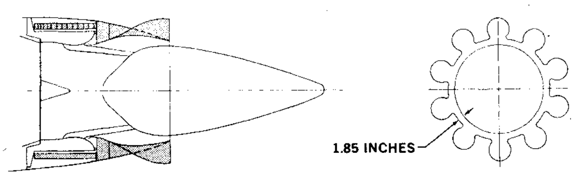


Fig. 7 YC-15 Daisy exhaust nozzle.

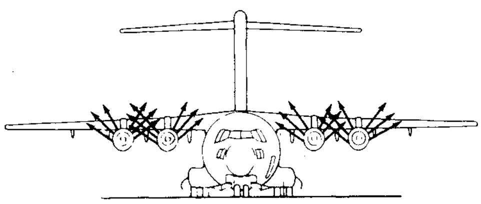

Fig. 8 Reverser flow vectoring.

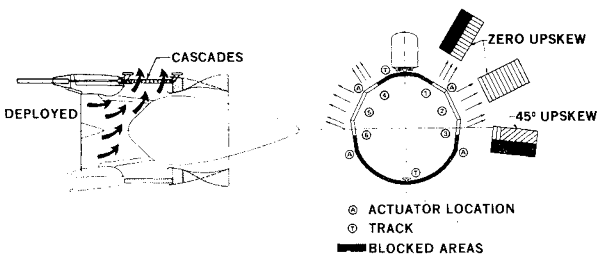


Fig. 9 Thrust reverser/Daisy exhaust assembly.

## Thrust Reverser

Early evaluation of thrust reverser design requirements for a military STOL aircraft indicated a need for operability at full reverse power, not only over the whole landing roll speed range but also for backward taxiing. Further more, this capability was required for operations on unpaved surfaces.

To fulfill these requirements, several factors which normally prevent damage-free, stable engine operation at low ground roll speeds had to be eliminated[4]: engine damage due to ground debris ingestion, engine instability due to self-ingestion, and instability due to cross engine ingestion. The upward-flow vectoring shown in Fig. 8 avoids blasting the ground surface with exhaust gas and hence eliminates the hazard of engine damage due to kickup of ground debris. This feature also prevents loss of pilot visibility when landing on wet or dusty runways.

Three features are provided to prevent engine closed-loop self-ingestion. First, as indicated in Fig. 9, the large arc in the lower area of the cascade section from which no reversed exhaust is emitted allows additional space for ambient ventilation air to get between the reversed plume and the engine nacelle. This reduces the tendency for low cowl surface pressures to occur, and thereby discourages flow attachment. Second, a technique called "flow compaction" is featured in

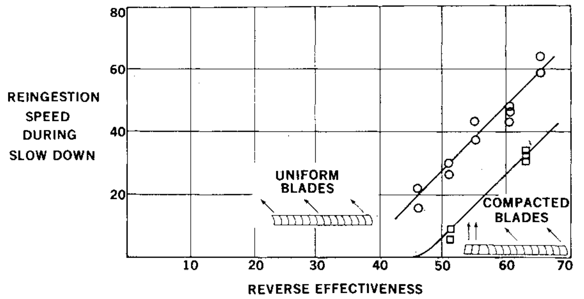


**Fig. 10 Reduction in self-ingestion speed by cascade flow compaction.**

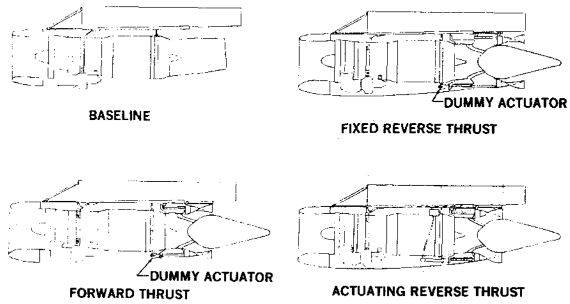


**Fig. 11 YC-15 nacelle test configurations.**

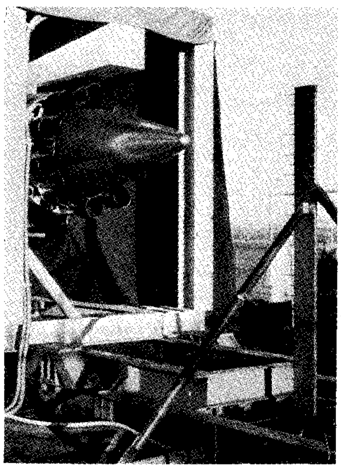

**Fig. 12 Exhaust wake survey rake.**

the cascade design wherein the forwardmost blades direct flow radially outward providing an "aerodynamic dam" to discourage flow attachment to the cowl. Model test results in Fig. 10 show that, for a given level of cascade effectiveness, lower self-ingestion speeds are attainable with flow compaction. Finally, a conservative low level of cascade effectiveness was selected to maximize the probability of successful results without need for test experimentation with high effectiveness blading. To avoid cross engine ingestion, features are incorporated to prevent reversed gases of one engine from entering the inlet of another. This is accomplished by upward vectoring of the flow from the cascades on the sides of each reverser as indicated in Fig. 9.

The single-unit translating assembly is supported vertically by a pylon mounted track. A small anti-sway lower track is incorporated to provide alignment between the translating assembly and the fixed-nozzle structure. All axial loads, both inertial and aerodynamic, are transmitted to the engine aft attach flange by four synchronized hydraulic actuators that are gimbal-mounted to support fittings. Since the cascades are predominantly arranged above the engine centerline, the effective point of reaction of the gas and track friction loads on the translating assembly is above the centerline. The point of reaction was calculated for both deploy and stow functions and the vertical positioning of the actuators was selected to minimize force unbalance between upper and lower actuators.

## Flight Nacelle Ground Testing

Engine and nacelle ground tests were conducted using a JT8D-15 engine which is functionally and physically similar to the JT8D-17, although rated at 15,500 lb of thrust rather than 16,000 lb. The test site was the Rohr facility at Brown Field, Calif. where an 18,000-lb rated thrust bed capable of force measurements in forward or reverse was utilized.

Primary purposes of the tests were to establish the compatibility of the engine with YC-15 inlet and exhaust systems, measure installed performance losses, develop the thrust reverser cascade arrangement, and culminate with a reverser actuation system cycling test. In addition, exhaust wake velocity and temperature profiles were to be measured behind the daisy mixing nozzle, and a wing flap structural panel specimen was installed behind the engine to evaluate exhaust velocity, temperature, and acoustic effects on proposed materials and types of flap-panel construction.

### Approach

The general approach for the nacelle testing was to configure the test installation sequentially in the four arrangements shown in Fig. 11. A performance baseline was first established utilizing a DC-9 inlet and exhaust nozzle. The YC-15 inlet and exhaust were installed and the exhaust area was adjusted to achieve proper engine match characteristics, followed by the forward thrust performance testing. During forward thrust testing, the exhaust wake surveys were made using the rake arrangement shown in Fig. 12. For the remainder of the test program, the structural flap panel specimen was installed as shown in Fig. 13. The reverser subsequently was fixed in the deployed position temporarily, using dummy actuators for trials with varied cascade and reverse-flow blocker arrangements. The YC-15 cowl doors were installed at this time to preclude blasting of engine case mounted equipment with reverse efflux. At no time during the program was an anti-ingestion baffle used between the reverser and engine inlet, since full reverse power capability at static conditions was a YC-15 requirement.

The final test arrangement was made by removing the dummy actuators and installing the YC-15 thrust reverser control and actuation system in preparation for the cycling tests.

### Results

During the initial tests with the daisy nozzle it was evident that the exhaust area was increasing an unacceptable amount at higher engine powers. This was attributed to stretching in the lower radii of the daisy lobes. An additional stiffening strap was incorporated across the bottom of each lobe and stretching was eliminated. Results of subsequent performance testing showed that thrust loss at takeoff power was approximately 2.0% relative to the DC-9 nozzle.

Some results of the freejet exhaust wake temperature survey are given in Fig. 14. The temperature profiles are adjusted to represent the JT8D-17 at 70% thrust. For reference, the position of the structural flap panel specimen is shown. This position closely corresponds to that of the lower segment of the flap behind the outboard engines and is judged to represent the flap structure most susceptible to engine exhaust heating. For the conditions shown, maximum skin temperature adjusted from measured values was 528°F. For takeoff power with the flap still in landing position, maximum skin temperature adjusted from measured values was 602°F. In addition to the thermocouple installations on the titanium flap skin and inner structure, thermovision photos were obtained and analyzed to examine panel temperature distributions more thoroughly.

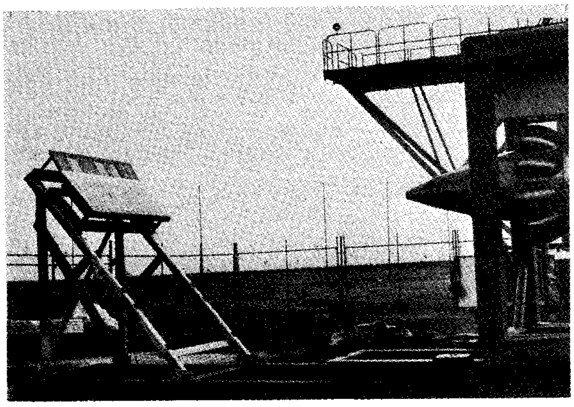

Fig. 13 Flap panel specimen.

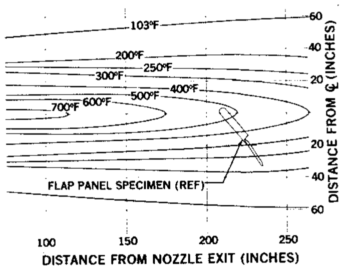


Fig. 14 Exhaust temperature JT8D-17, 70% thrust, 103° day.

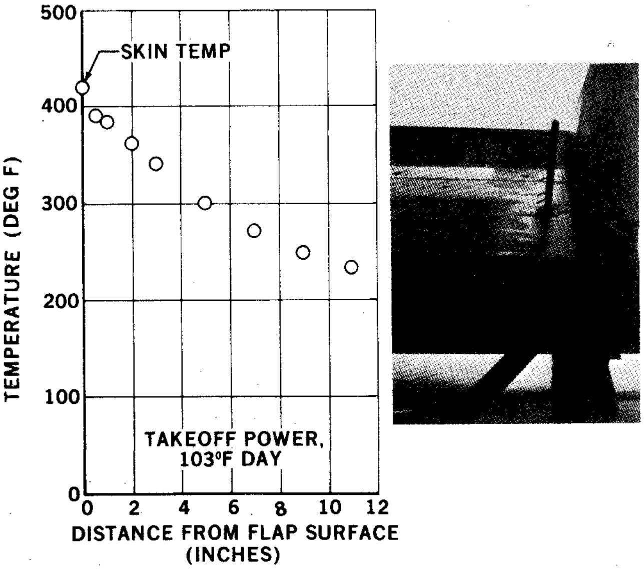


Fig. 15 Temperature of exhaust gas impinging on flap actuator fairing.

For selected tests, a simulated actuator hinge fairing was installed on the flap panel in conjunction with a rake, as shown in Fig. 15 to provide added information for predicting hinge fairing temperatures. Air temperatures as a function of height from the flap skin are shown as measured at takeoff power.

The baseline directed-flow cascade arrangement selected from the fixed position reverser testing is shown in Fig. 9. The upper two open boxes, locations 1, 2, 4, and 5 on each side, direct flow radially outward and forward. By having the blades skewed 45 deg, the lower open boxes in locations 3 and 6 direct flow forward and upward from the horizontal. Measured reverse force for this configuration was 35% of forward thrust force at maximum continuous power. Analysis shows that, by redesigning and retooling for a production version of the thrust reverser, 40% effectiveness would be

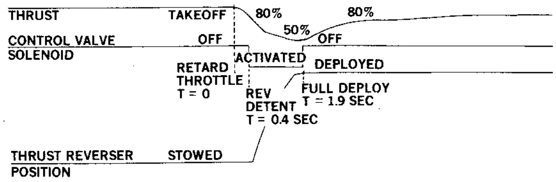


Fig. 16 Data trace reverser deployment.

achieved by reducing the amount of leakage allowed around the centerbody. In addition, further improvement could be achieved with increased cascade blade forward turn ng angles. The latter, however, would require added ground testing to assure avoidance of closed-loop ingestion.

Alternate cascade schemes were tested with varied degrees of upskew on the sides of the reverser. The most severely skewed arrangement had 30 deg of upskew in location 2 and 60 deg in location 3. It is anticipated that, if fuselage heating should occur during testing of the prototype aircraft, added upskew may be required on the inboard side of the inboard engines. Normally, ambient cooling air effects and short duration of reverse operation during landing prevent fuselage skin overheating. On the YC-15, however, requirements to taxi backward, and to leave engines operating in reverse for rapid aircraft loading in advanced combat areas, may necessitate complete avoidance of fuselage impingement by reverser efflux. Spare cascades will be made available during flight testing for this eventuality.

A data trace of system parameters during a typical rejected takeoff deployment of the reverser is illustrated in Fig. 16. Complete deployment of the reverser was accomplished in 1.5 sec from initiation of the deployment signal. A total of 250 reverse thrust operations was made during the functional cycling tests. Of these, 35 were rejected takeoff cycles. Thrust was stabilized at forward takeoff for 30 sec. Hand lever motions for thrust reduction reverser deployment, and reverse thrust application were made as rapidly as possible and reverse thrust was maintained at maximum continuous for 30 sec prior to return to the stow position and idle power.

The remaining 215 cycles represented normal landing operations. Forward thrust was stabilized at 70% for 30 sec. The reverser was deployed and reverse power was applied for 30 sec before stowing. In 130 of these cycles maximum continuous thrust was used as the reverse power setting.

## Conclusions

In the early design stages of the YC-15 STOL aircraft, factors influencing the design of the powerplant installation were identified which were uniquely related to the use of the EBF powered lift concept. To insure proper flow to the engine during high lift flight with locally steep upwash flow angles related to increased wing circulation, the nacelle inlet was positioned well forward of the wing where upwash angle is reduced. Additionally, generous thickness was provided in lower inlet lip contours to provide resistance to separation. The pylon was configured to position the exhaust exit high and forwardly for proper exhaust impingement on the blown slotted flap and for local enhancement of freestream flow over the wing leading edge during STOL flight.

In addition to proper positioning of the exhaust relative to the wing and blown flap, requirements evolved for reduction in jet temperature at the flap. The selected solution was derived from model and full-scale testing of daisy mixer exhaust nozzles featuring daisy-type lobes arranged around a large centerbody in such a manner as to maximize the space available between lobes for ambient air mixing. Full-scale testing of the YC-15 flight nacelle hardware indicated that maximum temperature anticipated with the flap fully down would be limited to 600°F. Performance testing showed takeoff thrust loss to be 2% greater than for a reference conical nozzle.

Design requirements for the thrust reverser included need for ability to operate at full reverse power over the whole ground roll speed range, to taxi backward, and to have these capabilities on unpaved surfaces. The solution evolved around a "directed flow" concept wherein the cascade blading was used to divert reversed gas selectively away from the ground and from adjacent engine inlets. Engine ground tests were completed in June 1974. They have demonstrated operational functions and structural integrity.

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