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6.2 Installation Drag Considerations as Related to Turboprop and Turbofan Engines

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Introduction

Considerable effort is presently being expended by NASA, various universities, and industry to improve and develop technology in many areas directly applicable to general aviation aircraft design. One of these major areas is directed toward new airfoil designs for improved lift-to-drag-ratio characteristics for improved climb and cruise performance. Another is directed toward high-lift-device improvements that could open the door for increased wing loading design criteria, thus reducing wing area and cruise drag. The results of these programs will undoubtedly provide some significant aerodynamic improvements when the research and development work has been completed; however, the testing, proving, and optimization of most of these concepts are still in the early-to-moderate stage with respect to being introduced into production general aviation aircraft.

With this in mind, it would appear advantageous to approach the problem of improved aircraft performance and/or drag reduction along at least two parallel paths which consist of new technology development and identification of areas where potential improvement with existing technology could be attained. The latter would also tend to complement advanced technology.

One such area is the drag penalties associated with propulsion system installation. Typically, at representative cruise operating conditions, the total installed drag of a turbofan engine installation can effectively amount to between 10 and 15 percent of the total aircraft drag. Similarly, a turboprop engine installation can amount to between 20 and 40 percent of the total aircraft drag. As a starting point, some of the specific areas associated with straight jet and turboprop engine installations have been outlined where drag reductions and, thus, improved aircraft system performance can be obtained.

Discussion

Before the subject of drag reduction can be addressed, an accounting procedure for evaluating the propulsive effort must be defined. For the straight jet engine installation, this is a relatively simple procedure, as shown in Figure 1.

$$F_{N_e} = F_{N_{SPEC}} - \Sigma\,(\Delta F_N) - D_N - D_{ADD} - D_{MISC}$$

WHERE:

F_{N_e} = NET INSTALLED THRUST FOR PROPULSIVE EFFORT

$F_{N_{SPEC}}$ = SPECIFICATION NET THRUST (NO LOSSES, REFERENCE NOZZLES)

$\Sigma(\Delta F_N)$ = NET THRUST CORRECTION FOR RAM RECOVERY, BLEED, ACCESSORY LOAD, EXHAUST NOZZLE DEVIATION FROM REFERENCE

D_N = NACELLE DRAG (FRICTION AND PRESSURE)

D_{ADD} = ADDITIVE DRAG DUE TO FLOW PREDIFFUSION CORRECTED FOR LIP SUCTION

D_{MISC} = NET RAM DRAG OF SECONDARY FLOW SYSTEMS CORRECTED FOR EXITING MOMENTUM (COMPARTMENT VENTILATION, LEAKAGES, ETC.)

Figure 1. Propulsive Effort for Jet Installations

With the use of accounting procedures that have been accepted where drag is defined as the summation of forces acting on the outside of the stream tube bounding the flow that passes through the complete engine and thrust is defined as the summation of forces on the inside of the stream tube, the complexity of thrust and drag accounting becomes relatively simple.

Obviously, this same exact procedure cannot be applied to a propeller powered installation, since the stream tube or slip stream now has moved from the inside of the engine to the outside. However for a turboprop engine installation, an extension of the basic straight jet accounting procedure may be established as shown in Figure 2.

The purpose of defining an accounting procedure is twofold. First, it provides the means of completing a preliminary performance assessment of one engine installation with respect to another, which is an obvious requirement for aircraft performance analysis and trade-off studies; and secondly, it provides a method to identify areas of potential improvement. This procedure has apparently not been as fully utilized on propeller installations as straight jet installations. This is indicated by the lack of design guidelines and installation aerodynamic trade-off data. This may be attributed in part to the fact that propeller-powered aircraft engine installations come in many variations, whereas straight jet engine installations are fairly standard in terms of comparing one installation to another, independent of thrust or application.

Air-Intake Design Considerations

All turboprop and straight jet aircraft propulsion system installations have primary air intakes for directing airflow from the free stream into the engine. Most installations utilize secondary air intakes for providing cooling and ventilation airflows to various components and hot sections of the engine. The design considerations in terms of sizing, design-point selection, location, and shape can significantly affect the propulsive effort of the propulsion installation (net thrust, nacelle drag, and additive drag).

The design objective for most business jet intake systems is minimum length for weight and surface area considerations while maintaining a high drag-rise Mach number, low spillage drag characteristics, and high total pressure recovery with low flow distortion to the engine. With the advent of modern high-bypass-ratio turbofan engines (high flow per unit frontal area and increasing maximum diameters), this objective has become quite a challenge to the aerodynamicist. If the intake sizing is too large for the required engine airflow (low mass-flow ratio), flow spillage

$$THP_e = \eta_p \, [SHP_{SPEC} - \Sigma \, (\Delta \, SHP)] + [F_{N_{SPEC}} - \Sigma \, (\Delta F_N) - D_N - D_{ADD} - D_{COOL} - D_{MISC}] K$$

WHERE:

THP_e	= NET THRUST HORSEPOWER FOR PROPULSIVE EFFORT
η_p	= PROPELLER EFFICIENCY ADJUSTED FOR BLOCKAGE
SHP_{SPEC}	= SPECIFICATION SHAFT HORSEPOWER
$\Sigma \, (\Delta \, SHP)$	= SHAFT HORSEPOWER CORRECTION FOR BLEED, ACCESSORIES, EXHAUST NOZZLE DEVIATION FROM REFERENCE, AND INLET/EXHAUST DUCT LOSSES
$F_{N_{SPEC}}$	= SPECIFICATION NET THRUST WITH REFERENCE NOZZLE
$\Sigma \, (\Delta \, F_N)$	= NET THRUST CORRECTION FOR EXHAUST DEVIATION FROM REFERENCE (AREA, DISCHARGE ANGLE), BLEED, ACCESSORIES, AND INLET/EXHAUST DUCT LOSSES
D_N	= TOTAL DRAG ON NACELLE TO INCLUDE INFLUENCE OF PROPELLER SLIP STREAMS
D_{ADD}	= ADDITIVE DRAG OF PRIMARY AND SECONDARY AIR INTAKES (CORRECTED FOR LIP SUCTION)
D_{COOL}	= NET RAM DRAG OF SECONDARY AIR FLOWS (OIL COOLING, COMPARTMENT VENTILATION, ETC). FULL RAM DRAG OF EACH SYSTEM ADJUSTED FOR THRUST OF EXISTING MOMENTUM
D_{MISC}	= PARASITIC DRAG DUE TO PRIMARY AND SECONDARY AIR INTAKES AND EXHAUST NOZZLES, INTERFERENCE, LEAKAGE, ETC.
K	= CONVERSION FACTOR

NOTE: ALL DRAG COMPONENTS MUST BE CORRECTED FOR SLIPSTREAM EFFECTS.

Figure 2. Propulsive Effort for Turboprop Installations

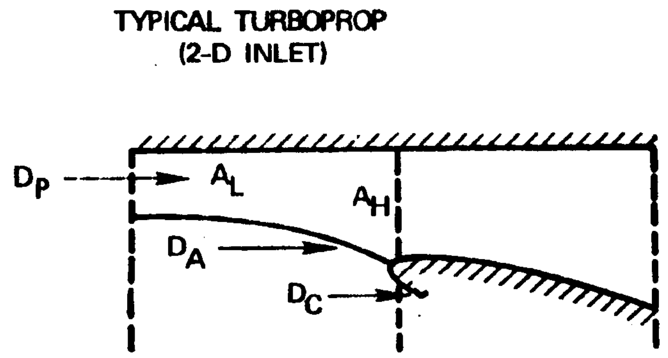
results which can lead to flow separation. If the forebody shape (fineness ratio) is not adequate, supersonic expansion can occur which may result in flow separation. If the inlet lip (from the highlight to the throat) and internal diffuser characteristics are not considered, excessive additive drag can result.

Up to now the NACA Series I profile has been used for most forebody air-intake designs; but at low mass flow ratios, excessive spillage drag can result due to the high local flow angle at the inlet lip or highlight. This is especially true of modern high-bypass-ratio turbofans used on general aviation aircraft where fixed-geometry air intakes are used predominantly. The air-intake throat is sized for good cruise diffuser performance, but the static takeoff conditions require generous highlight-to-throat-area-contraction ratios to preclude flow separation during static ground and crosswind operation. As a result, during some operating conditions (speed and engine power setting), extremely low mass flow ratios can result. While operating in these conditions the stagnation streamline can be located well within the air intake to the inside of the highlight, which will require the flow on the outside of the streamtube (spillage flow) to rapidly accelerate and expand around the highlight within the forward region of the cowl. If the flow separates, the effect of the suction pressure loss reduces the lip suction force and , thus, increases the additive drag in addition to the basic pressure drag of the nacelle. Some recent studies have suggested that the problems associated with low-mass-flow air-intake operation may be alleviated by incorporating forebody profile shapes similar to those being investigated for supercritical airfoils--the principle being that the suction pressure on the modified forebody shapes is retained well beyond the point where suction pressure collapse occurs on a Series 1 profile.

As shown in Figure 3, the reduction in additive drag from a NACA Series 1 forebody and a modified supercritical forebody is indicated as:

Mass Flow Ratio	C_D Spillage, Based on Frontal Area
0.6	-43%
0.4	-77%

With turboprop engine installations, the problems associated with air-intake design can become more of a challenge than that of straight jets. This can be attributed to propeller slipstream interaction effects, which complicate accurate local flow field definition. As a consequence, the air intakes on most propeller-powered aircraft are oversized to offset the uncertainties, thus resulting in high additive drags, increased surface areas, and propeller blockages. In addition to the basic



$D_T = D_P + D_A + D_C$

WHERE:

D_T = TOTAL AIR INTAKE DRAG
D_P = PARASITIC DRAG ON NACELLE
D_C = COWL DRAG (FRICTION)
D_A = ADDITIVE DRAG (CORRECTED FLOW FOR LIP SUCTION)
A_L/A_H = MASS FLOW RATIO $(\rho_H V_H/\rho_L V_L)$

*BASED ON DATA FROM AGARD-CP-124

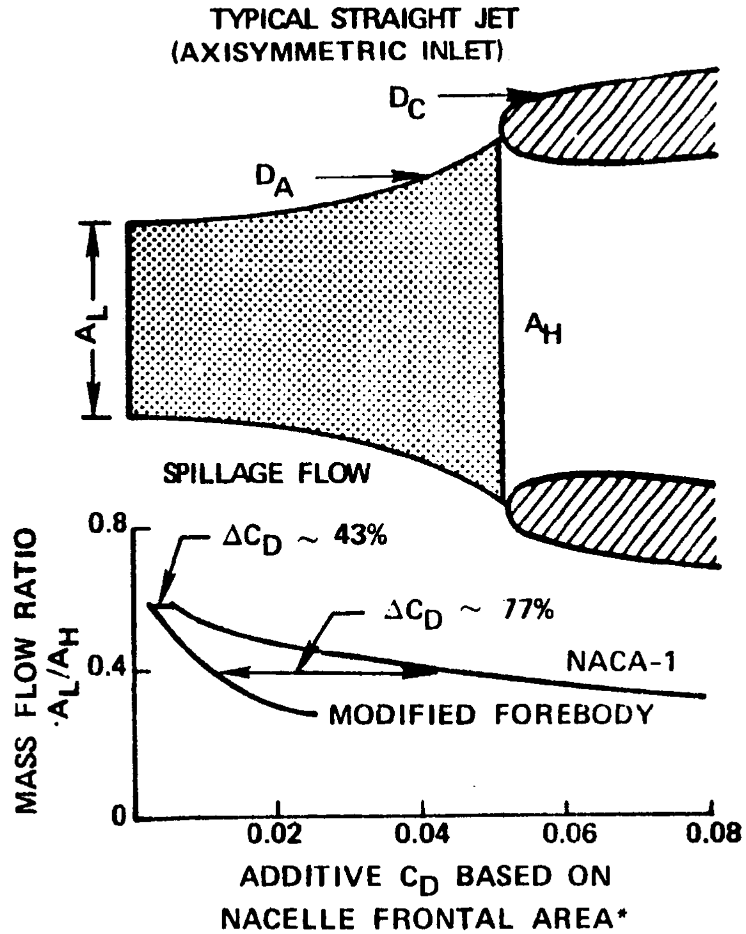


Figure 3. Air Intake Design Considerations

- SELECTION OF EXHAUST DUCT GEOMETRY IS BASED ON AIRCRAFT CONSTRAINTS, COST, AND PERFORMANCE

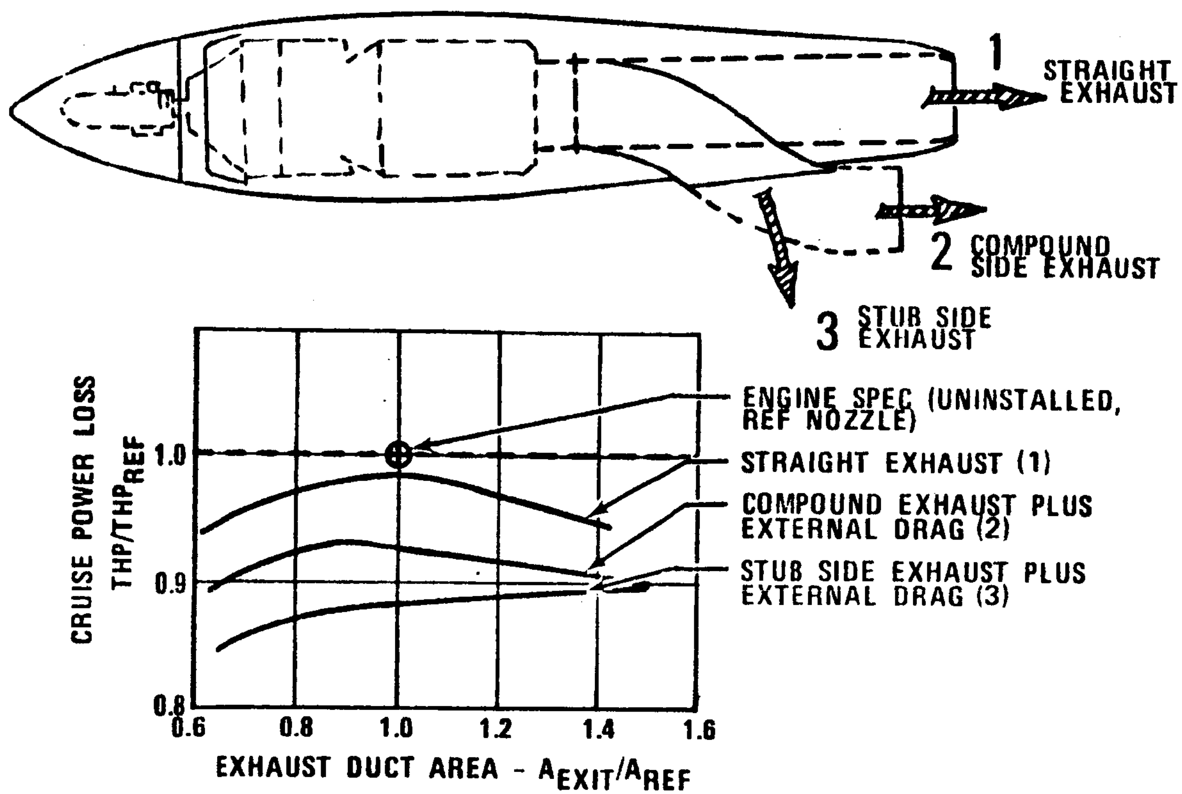


Figure 4. Turboprop Exhaust Arrangements

drags associated with the air intakes, the parasitic drag resulting from local flow separations on the nacelle due to prediffusion can be significant.

Turboprop Exhaust-Duct Arrangement

Some turboprop engine installations offer options in the approach to designing the required exhaust duct and cooling systems. When these options exist, trade off studies in terms of aircraft constraints, cost, weight, and performance should be completed to assess the best configuration for the engine installation and, thus, the total aircraft system.

Figure 4 shows three possible exhaust-duct configurations that may be considered for a typical turboprop aircraft installation. As shown, the three configurations consist of a straight duct that has been designed to minimize internal pressure losses (no bends; minimum length), to provide maximum use of the jet thrust, and to minimize frontal area or blockage.

The second duct is a typical compromise that could be encountered on some installations. Like the straight exhaust, it has been designed to utilize the available jet thrust, but at the expense of additional internal pressure loss and external drag.

The third duct illustrates a configuration where the designer may consider minimizing external drag and frontal blockage at the expense of utilizing the engine exhaust jet energy.

To provide insight as to impact on propulsive effort of the three exhaust-duct configurations considered a simple performance assessment is shown that considers the relative effect of each configuration with respect to the power attainable with an uninstalled specification engine. The result obtained from this parametric analysis is unique for each exhaust-duct area considered with respect to internal pressure loss and external drag.

As expected, the straight duct configuration results in the smallest power loss (approximately 1.5 percent). The difference between the compound side exhaust (optimum area) and the straight duct (optimum area) is approximately 5.0 percent, which is attributable directly to external drag and internal pressure-loss effects on the engine. The optimum area stub side exhaust performance was estimated to be approximately 8 percent lower than the straight exhaust duct.

In terms of airplane drag, the difference between the optimum straight duct design and the stub side exhaust design represent 30 to 35 lbs drag differential at a typical cruise operating condition.

Turboprop Cooling Systems

As previously indicated for exhaust-duct trade-offs, turboprop engine cooling requirements (compartment ventilation and oil cooling) provide some design alternatives. Most systems use either full ram systems, which are dependent upon recovering kinetic energy from the propeller slipstream or free-stream velocity, or augmented systems using the kinetic energy of exhaust velocity to provide an eductor. Both systems have advantages and disadvantages.

At static or low-speed operating conditions, where the free-stream kinetic energy is low, eductor systems can provide the augmentation necessary to obtain the required cooling flows; however, the optimization of an eductor system requires a complete parametric analysis at the design point and off-design operating conditions to fully assess the interaction of the interrelated flows and the effect on propulsive effort. In comparison , full ram systems are simpler to analyze due to the elimination of the interacting flow fields. Improperly sized eductor systems can result in significant engine power loss and ram drag at normal cruise operating conditions.

As indicated previously, full ram systems are less risk to design than flow-augmentation systems. Proper designs can be obtained that result in minimum performance loss to the aircraft if proper design criteria are followed for air-intake sizing, internal diffuser design, and flow control employed for cruise operation where the cooling flow requirements are low.

Figure 5 shows the cruise power loss as a function of flow control area ratio for a full eductor cooling system and an isolated ram cooling system design. The points at 100 percent area ratio show the power loss if no flow control is used. As indicated, the power loss of the full ram system amounts to approximately 6 percent (oil cooler plus compartment ventilation), whereas the eductor system cruise power loss is only 2 to 2.5 percent. If the full ram-system flow control is implemented, the resulting power loss of the ram system can be reduced to approximately the same level as the eductor system. This is in direct contrast to the requirements for the flow-augmented eductor system. As shown on the figure, if flow control is imposed on the eductor system through a variable-area air intake or some internal device, the cruise power loss increases as the eductor flow is decreased. This is attributed to interacting effects of off-design eductor operation (higher pressure loss, incomplete mixing) being more pronounced on engine performance than the reduction in ram drag. These performance effects do not include the additional drags that may be encountered with each of the systems, such as additional wetted area, blockage, and nacelle interference drags with the full ram system.

- TURBOPROP INSTALLATIONS OFFER ALTERNATIVES FOR COOLING FLOW REQUIREMENTS SUCH AS FLOW CONTROLLED ISOLATED SYSTEMS VERSUS NO FLOW CONTROL VERSUS FULL EDUCTOR SYSTEMS FOR FLOW AUGMENTATION.

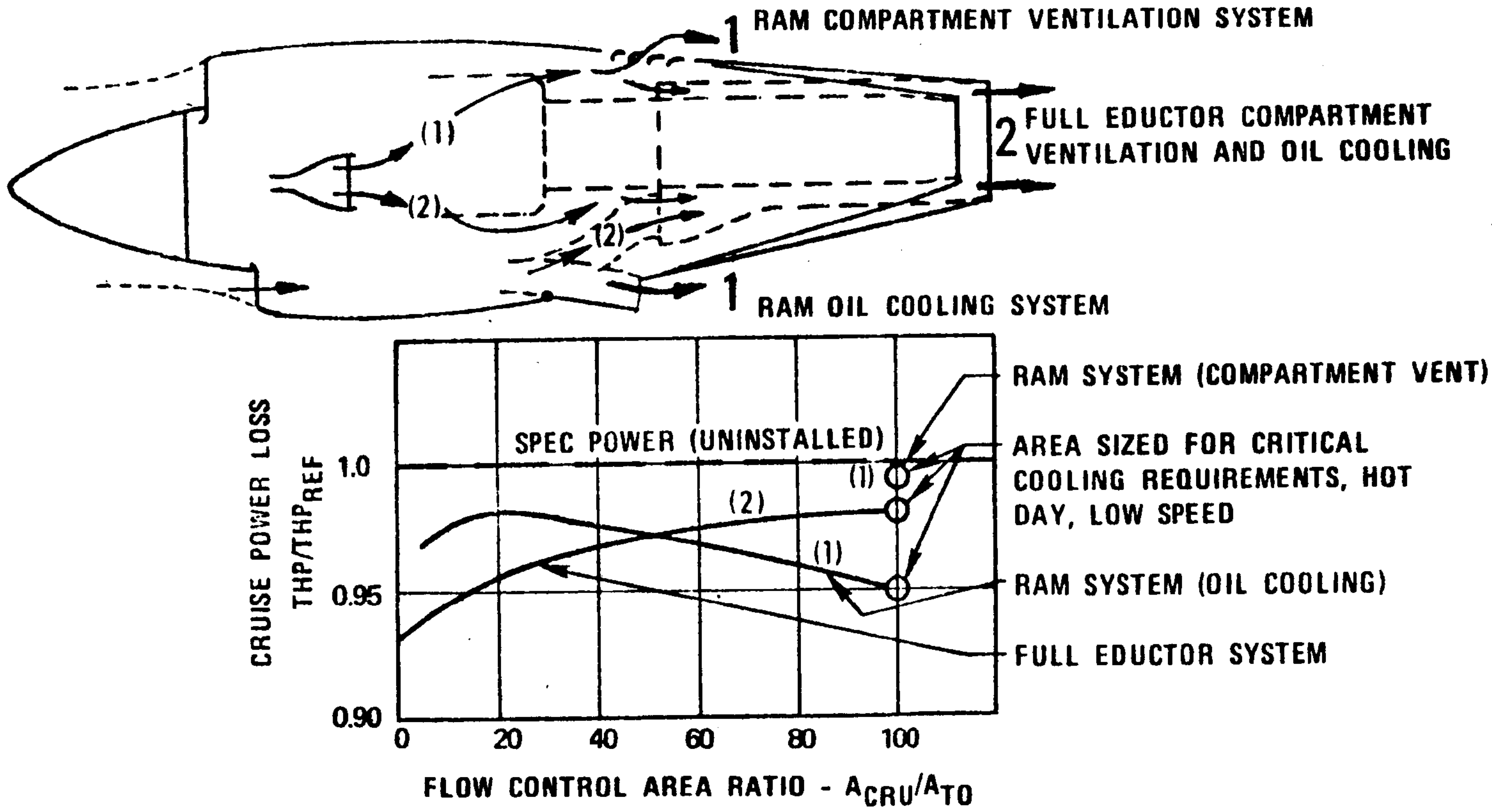


Figure 5. Turboprop Cooling System Arrangements

Proposed Programs for Drag Reduction

The performance penalties associated with the propulsion system installation can result in a significant percentage of the total effective aircraft drag. The specific areas associated with the engine installation where the major performance penalties are encountered should be identified and evaluated for potential improvements through improved design criteria.

Fundamental to improving design criteria is the definition of a propulsive effort thrust and drag accounting method that clearly identifies the interaction of the propulsion system and airframe. These procedures must be defined early in the preliminary phases of an aircraft program and maintained through flight test.

Through this approach of identification and accounting, a technical data base applicable to each component considered in assessing the effectiveness of the propulsive effort would be accumulated for defining improved design procedures. In addition, it would tend to reduce the uncertainties associated with evaluating preliminary aircraft performance.

Specific areas that suggest potential performance improvements on current and future general aviation aircraft are the design considerations used for air-intake sizing on all general aviation aircraft, and exhaust duct geometries and cooling system arrangements for propeller-powered aircraft. Studies have indicated that the power loss at typical turboprop aircraft cruise conditions can range from 16 percent (for a stub side exhaust duct, with no flow control installation) to between 2 and 3 percent (for a straight exhaust, full flow control system), thus suggesting a 13- to 14- percent improvement in system performance.

The key to arriving at a minimum drag, maximum propulsive effort engine installation on any aircraft system is the interface between the airframe and engine manufacturers. The concept of "teaming" has been an accepted practice, to a limited degree, among the larger airframe and engine manufacturers for some time. However, within the last few years, the realization of the true significance of the concept in terms of achieving the best performing aircraft system (airframe/engine intergration) with minimum cost and program delays has been acknowledged.

From the general aviation point of view, the concept of teaming should be even more significant, since a large percentage of general aviation airaraft evolve through engine retrofits for performance improvements. In order to obtain the full aircraft performance potential, the general aviation airframe and engine manufacturer must understand each others sytems in terms of constraints, performance, penalties, and trade-offs.

The proposed programs for drag reduction are summarized on Figure 6.

- IDENTIFY AREAS ON CURRENT AIRCRAFT DESIGNS WHERE POTENTIAL PERFORMANCE IMPROVEMENTS CAN BE OBTAINED
- ESTABLISH DETAIL THRUST AND DRAG ACCOUNTING PROCEDURES FOR ASSESSING AIRCRAFT PERFORMANCE
- DEVELOP A DATA BASE FOR ESTABLISHING DESIGN CRITERIA RELEVANT TO GENERAL AVIATION AIRCRAFT
- INVESTIGATE MODIFIED PROFILES FOR AIR INTAKE NACELLE DESIGNS TO REDUCE ADDITIVE DRAG ASSOCIATED WITH INLET/ENGINE MATCHING
- REVIEW AND UTILIZE CORRECT AIR INTAKE SIZING CRITERIA ON TURBO-PROP APPLICATIONS TO REDUCE PROPELLER BLOCKAGE, WETTED AREA, AND NACELLE INTERFERENCE DRAGS
- REVIEW EXHAUST DUCT AND COOLING SYSTEM DESIGNS AND DEVELOP VALID ANALYTICAL/PRELIMINARY DESIGN TOOLS FOR TOTAL SYSTEM ASSESSMENTS
- IMPLEMENT AN INTEGRATED PROPULSION SYSTEM APPROACH TO GENERAL AVIATION AIRCRAFT DESIGN (TEAM EFFORT OF ENGINE AND AIR FRAME COMPANIES)

Figure 6. Proposed Programs for Drag Reduction