

N76 11995

Chapter I
**GENERAL AVIATION
COMPONENTS**
INTRODUCTION

daVinci conceived it in his early sketches. Popov claimed to have done it first. Langley's effort disintegrated over the Potomac River. And on December 17, 1903, Orville Wright piloted man's first successful powered flight in a heavier-than-air vehicle; a flight which if undertaken today could be completed within the fuselage of a DC-10. His short 120 foot trip (0.023 of a passenger mile) marked the beginning of man's conquest of the sky, and the start of a multi-million dollar industry, which in 1974 alone resulted in 120 billion passenger-miles. It freed man from the earth and started him on his way to the moon in less than 66 years.

The aviation industry has had a tremendous influence on the American way of life: in time, in mobility, in technology, in weaving our social fabric. Much of its influence, nevertheless, remains highly misunderstood and unexplored. Although aviation has touched the lives of millions of people, most of their contact with it has been either through the use, or the image, of scheduled air carriers in operation around the world. Air carriers, however, represent only a small proportion of the total fleet of aircraft using the airspace, and serve only a small proportion of the landing facilities available around the country. Exclusive of the military, the other side of the civilian aviation coin is known as **General Aviation**, and is defined institutionally as incorporating all operating civilian aircraft other than the air carriers, which are certificated by the Civil Aeronautics Board.

Today there are approximately 3,000 aircraft being used by air carriers, while in excess of 130,000 make up the general aviation fleet. Of the 13,000 airports in the United States, only about 500 are served by air carriers in contrast to total use by general aviation vehicles. General aviation employs thousands of persons in this country in a wide variety of occupations, including aircraft crews, direct and indirect ground support personnel, and manufacturers.

General aviation is assuming an increasingly important role in the national transportation picture: in 1974 general aviation

aircraft flew 3.8 billion miles and carried 90 million people.¹

General aviation provides a wide variety of functions, varying from the actual transportation of people and goods through charter, cargo, mail, executive transport, and air taxi operations; to sports, recreational, and instructional activities. Between these two poles lie a range of industrial and community services such as aerial photography, stock-herding, fish-spotting, advertising, corpse-flying, logging, law enforcement, fire fighting, environmental management, health care delivery, banking, and emergency services.

Table I-1 shows the number of vehicle-miles and passenger-miles travelled by general aviation, in comparison to other modes of transport. Table I-II presents some basic general aviation statistics. These show that it includes 98 percent of all aircraft, 60 percent of the total number of vehicle miles and 7 percent of all passenger miles flown.

This report examines the relationship between general aviation and community development. The first chapter discusses general aviation and its components. Later chapters will examine the environment in which general aviation operates, the process of analyzing community aviation needs, and selected Virginia community aviation issues. The final chapter is a guidebook which will enable community decision-makers to determine whether or not a general aviation service is needed and how to go about satisfying such needs.

The major components of the general aviation system discussed in this chapter are (1) the vehicle, (2) the air support facilities, (3) airways and avionics, and (4) human factors. These components combine to produce the dynamic category of General Aviation; ever moving toward increased safety and efficiency.

THE VEHICLE
Introduction

The purpose of this section is to present an overview of selected aviation vehicles. The capabilities and performance of these vehicles are first presented, followed by a discussion of the aerodynamics, structures and materials, propulsion systems, noise, and configurations of fixed-wing aircraft. Finally the discussion focuses on the history, status, and future of attempts to provide vehicles capable of short-field operations. Inclusion of the final section is due to the importance of such capabilities in general aviation aircraft.

¹ "Non-Business Planes Carried 90 Million," Newport News Daily Press, July 25, 1975, p. 42

TABLE I-I
PASSENGER AND CARGO TRAFFIC BY TRANSPORTATION MODE — 1971
Domestic Only

	Cargo Ton-Miles x10 ⁶	Vehicle Miles x10 ⁶	Passenger Miles x10 ⁶
Air Carrier	3.457	2,081	110,718
Water	593,164	NA	4,100
Pipeline	444,000	NA	NA
Rail	746,000	482.4	6,908
Highway			
Truck	430,000	227,037	NA
Bus	55	3,414	25,500
General Aviation	NA	3,144	9,300
Auto	NA	954,155	2,082,582
Total	<u>2,216,676</u>	<u>1,190,313.4</u>	<u>2,239,108</u>

Note: NA may mean one of the following:

- 1) not available
- 2) not applicable
- 3) smaller than half the statistical unit used

Source: "Summary of National Transportation Statistics," DOT-TSC-OST-73-76, Washington, D.C., November, 1973.

TABLE I-II
1971 GENERAL AVIATION STATISTICS

General Aviation Category	Vehicle		Vehicle-miles		Hours Flown	
	Units	%	Units	%	Units	%
Business	33,314	25	1,130,000,000	36	7,100,000	29
Commercial	9,327	7	510,000,000	16	3,500,000	14
Instructional	19,750	13	650,000,000	21	6,400,000	26
Personal	68,475	52	794,000,000	25	7,200,000	29
Other	4,282	3	60,000,000	2	400,000	2
1. Total expenditures and revenues			\$2,206,000,000		21.4% of all air	
2. Passenger miles			9,300,000,000		7% of all air	
3. Number of fatalities			1,322		87% of all air	
4. Total number of vehicles			131,148		98% of all air	
5. Total vehicle-miles			3,144,000,000		60% of all air	

Source: "Summary of National Transportation Statistics," DOT-TSC-OST-73-76, Washington, D.C., November, 1973.

The airplane has been selected as the specific aircraft to be discussed because it has, since its invention, always been the dominant vehicle on the aviation scene, and there are no reliable indicators that its status will change. Other general aviation vehicles such as helicopters, balloons, airships, and gliders are discussed briefly. For definitions of these and other terms, see the Glossary (Appendix E).

Capabilities and Performance

The airplane is a specific type of flight vehicle or aircraft, propelled through the air by a powerplant which exerts its force preponderantly forward. It is sustained in the air by the forces created by differential pressures exerted on its exposed surfaces, mainly its fixed wings, due to its motion through the air.

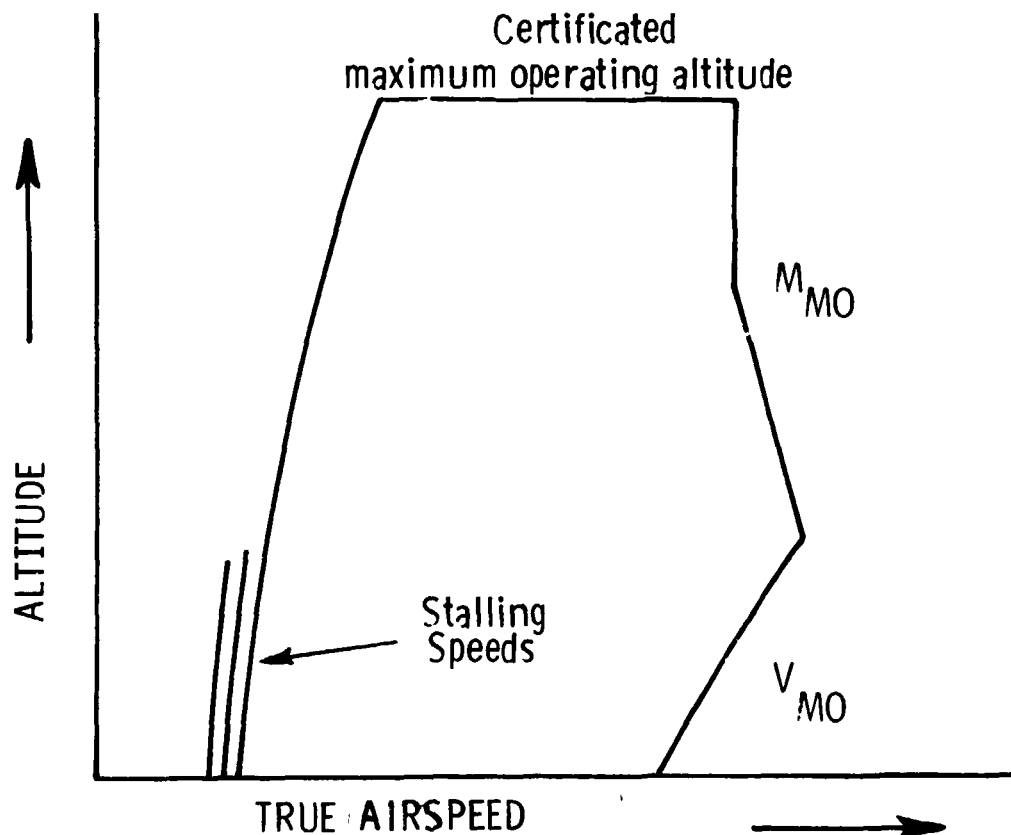
For purposes of considering its incorporation into an aviation system, the airplane can be considered as an imaginary box, the dimensions of which portray a volume of air around it which is forbidden to other aircraft; the airplane

is at its center. The dimensions of the box (actually a rectangular figure) are variable individually with phase of operation (e.g., operation in a terminal area). The important point is that the airplane interdicts a sizeable airspace and ground area, and this space may be, and sometimes is, the same for a small airplane as for a large one.

The airplane is a moderately constrained vehicle in terms of its freedom to move in various directions relative to its own plane of symmetry. In flight its broadest-band capabilities are in that plane, and are those of steady or nearly steady movement. These capabilities are known collectively as its **static performance**, consisting of climbs, cruise flight, and descents.

Straight and Level Flight

The straight and level unaccelerated flight capability of an airplane may be portrayed by a graph showing true airspeed (not groundspeed) against altitude. Figure 1-1 illustrates the "flight envelope." The curved line



CAPABILITIES: THE FLIGHT ENVELOPE
FIGURE 1-1

at the left represents the trend of **stalling speed**, the speed below which the airplane cannot be flown straight and level, because of insufficient aerodynamic lift. The long line is the stalling speed in "clean" (gear and high-lift devices retracted) configuration; the short lines give the stalling speeds for other configurations; takeoff, segmented climb, and landing.

The horizontal line at the top of the figure represents the maximum altitude for which the airplane is certificated. It may be well below the absolute ceiling of the airplane since reasons such as safety in event of a window blowout or oxygen requirements may govern the choice of the highest altitude for which certification is sought.

The crooked line on the right represents the highest speed or Mach number in normal flight for which the airplane is certificated. The symbol V_{mo} means "maximum operating velocity" and M_{mo} means "maximum operating Mach number." These speeds are usually very close to the top speeds the airplane can attain, and are set by a combination of structural and handling-qualities requirements.

Climb and Descent

Generally, an airplane does not climb without first pitching its nose up; at its maximum speed it has no climb capability at all. The maximum **rate** of climb is generally realized at an airspeed about 2/5 of the way between stalling speed and top speed.

The maximum **angle** of climb is important for takeoffs and for climbs which emergency conditions may necessitate performing near the ground. This can vary with size and type of aircraft, and with speed and flight configuration of a given type. Small, slow airplanes may have clean-configuration maximum climb angles of perhaps 14 degrees or so; the business jets may achieve 40-degree angles.

An airplane may be caused to descend without pitching by retarding the throttle (the throttle is said by some flight instructors to be the basic climb-and-descent control, though this is oversimplistic). Except in air-carrier operation this is not an important maneuver. A more popular descent technique is to establish some fixed vertical speed while retaining cruising airspeed (approximately). In the cockpit of practically all modern airplanes there is an instrument called a Vertical Speed Indicator, and a popular vertical speed for descents out of ground proximity is 500 feet per minute, a rate for which the apparent nose-down angle of the cabin is not disturbing to passengers, and

which is satisfactory for use in flight on airways. Emergency descents of 1,500 feet per minute or even more can be made with reasonable pitch angle changes and within acceptable limits of operation, though in unpressurized airplanes there is risk of damage to passengers' ears.

The "best approach" angle at which landing approaches may be performed is that representing a power-off (engines idling) glide at an airspeed about 30 percent above that for stall, with flaps fully extended and landing gear down. The angle may be anywhere from about 5 to 9 degrees. Steeper approaches may be made, but some pilots consider that safety levels are reduced at the higher angles. The "ILS landing approach" angle of 2.5 to 3 degrees is established by the angle that the glide slope beam of an instrument landing system transmitter makes with the ground. This shallow angle almost always requires that engine power or thrust be above idle setting, and this increases the degree of control the pilot has over the glide angle (since the throttle is a climb and descent control).

Other Changes of Flight Path

The airplane is an awkward machine to turn; it must be turned and banked simultaneously, much as a car requires banked curves on roads. A conventional airplane cannot move directly sideways at all except by **slipping**, during which altitude typically must be lost because the aerodynamic drag (rearward) force on the airplane increases, and the airplane must either slow down or descend or do both, as a consequence. The slipping maneuver was popular years ago as a means of steepening landing approach paths, but its capability is very limited. The advent of trailing edge flaps in about 1940 made it largely unnecessary, except as an aid in making crosswind landings. Recently interest has revived in improving the ability of the airplane to move sideways, this time as a means of making adjustments in the lateral position of the final approach path relative to a landing field runway. This ability can be important for instrument flight operations.

In turning flight, the measure is the radius of turn, a function both of speed and of bank angle. As a general rule, the radius of a turn may be decreased (the turn made tighter) by increasing the bank angle. At a given bank angle a slow airplane is able to turn tighter than a fast one, so the minimum turning radii of small airplanes are generally in the hundreds of feet, while those of fast airplanes such as fighters

are generally thousands of feet long. Power is required to make a level turn, in excess of that required to drive the airplane straight. Consequently, as the speed of an airplane is increased toward its top speed, its ability to turn gradually deteriorates until at top speed it cannot make level turns at all, but must slow down to do so. Passengers will begin to take notice, and some will be disturbed if turns are made with bank angles more than 30 to 45 degrees.

Historically, there has been a fairly close relationship between the size and the maximum speed of airplanes marketed successfully in the United States. The smaller airplanes have maximum speeds near 100 knots. As gross weight rises, maximum speed also rises, until at the top of the weight range for six-passenger single-engine airplanes (about 3,800 pounds) it is on the order of 200-220 knots. Larger piston-engine airplanes, the twins, are only a little faster than this, because of the unavailability of engines of more than about 350 horsepower. The turbine-powered twins use engines of 600 - 1,000 horsepower, and so are considerably faster than piston twins of comparable size, with maximum speeds on the order of 250 knots. This size-speed relationship has not changed much in recent years.

The turbofan and turbojet airplanes, whatever their weights, have maximum speed of 350-450 knots. The lack of size-dependence is due to the fact that the jet airplanes are limited by the effects of the compressibility of air on their ability economically to achieve high-speed flight. The speeds of the jet airplanes are well above those of propeller airplanes of any size, though military propeller airplanes during World War II were occasionally flown straight and level at speeds just above 430 knots, during development programs.

Little on the technological horizon has appeared to indicate that the above relationships will change much. New type piston engine development is moribund, the fuel economy of the Wankel engine is not outstanding, and there is a large region extending from about Mach 0.9 to about Mach 1.5 in which efficient airplanes are difficult to develop.

Takeoff and Landing

Airplanes can be built which will take off and land in any given distance, including zero. Takeoff and landing distances depend strongly on stalling speeds, but in general, power is required to fly slow, below a certain point, just as it is required to fly fast. This means that the available technology, as well as the market

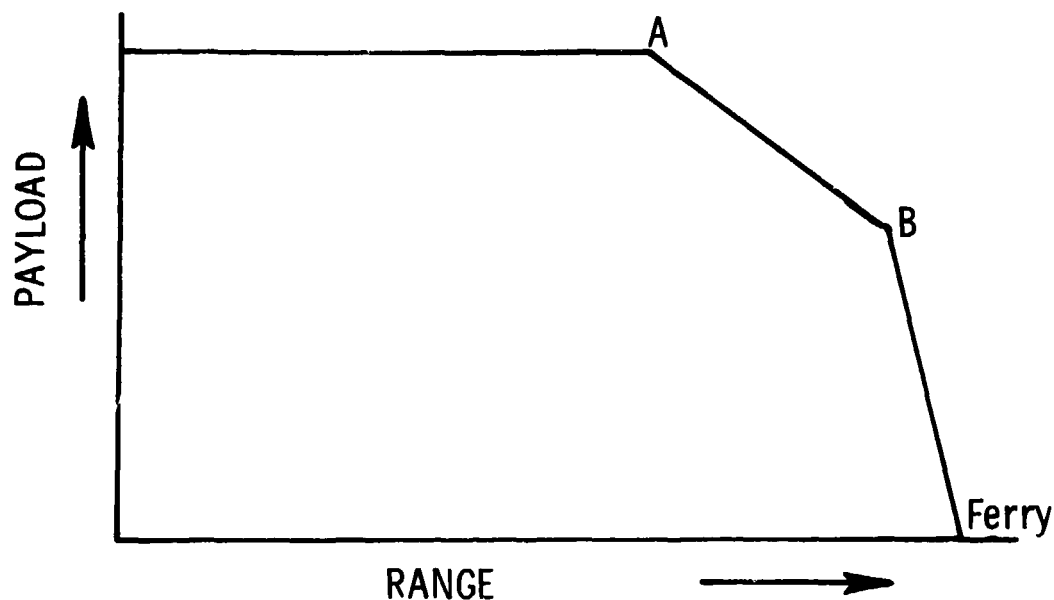
place, will establish whatever relationships exist between field performance and other design features.

Three identifiable technological levels have evolved into which marketed airplanes have been divided. (1) Conventional Takeoff and Landing (CTOL) technology is typified by simple flaps, such as appear on most general aviation airplanes. (2) Reduced Takeoff and Landing (RTOL) incorporates complex flaps and leading-edge high-lift devices called slots, slats, and Krügers, and perhaps a little powered lift. (3) Short Takeoff and Landing (STOL) airplanes use energy, in addition to that supplied to the main propulsive means (e.g., prop) to produce lift directly, through boundary layer control or lifting fans. Historically, STOL airplanes have not found a market except with the military. RTOL airplanes, such as the Boeing 727, are in operation, but the only small airplanes in the category have been isolated single examples because of the expense involved in adopting the technology.

Field performance data on specific airplanes are given elsewhere, but it is instructive to look at what corporate and utility airplane operators have considered to be adequate field length requirements. Two surveys of such operators made some years ago, indicate that all operators would be satisfied with 2,000-foot-or-shorter field performance, but field length requirements of 5,000 feet or longer would satisfy no one.

Range/Payload Tradeoffs

Most airplanes, except very small ones, are weight-limited in such a way that full passengers and full fuel cannot be loaded simultaneously without exceeding the maximum certificated gross weight. Figure 1-2 shows typical ranges for various types of aircraft starting with full fuel tanks. It also shows one of the informative ways in which range-payload information can be portrayed graphically. The empty airplane occupies a point at the origin of the graph, and either fuel or payload must be loaded first. If, for illustrative purposes, payload is considered to be loaded first, the lefthand end of the top horizontal line represents the airplane when loading is completed but fueling has not started; the airplane can thus go nowhere. As fueling proceeds, the capability of the airplane is indicated by points on the horizontal line. Finally enough fuel has been added that the airplane is at its maximum certificated weight, and fueling must stop whether the tanks are full or not (point A). If the tanks are filled before the payload is ad-



TYPICAL MAXIMUM RANGES (Nautical Miles)

General Aviation Aircraft

Light Airplanes 300-900

Business Jets 2,000-3,000

Airliners

Short-haul 1,500-2,500

Trunk and International 4,000-6,000

**RANGE — PAYLOAD TRADEOFFS
FIGURE 1-2**

ded, the airplane will be represented by points on the line between "Ferry" (the weight with no payload) and B (the point at which loading payload must stop because the airplane has again reached its certificated weight). Between A and B, fuel and payload must be traded to keep the gross weight constant.

The Fixed-Wing Aircraft Technologies

The history of the development of the airplane has been that of technological evolu-

tion, with the occasional addition of major jumps in innovation which nevertheless did not change the definitive outline of the airplane itself.

Aerodynamic Design

The general outline of the airplane as a set of wings with stabilizing and control surfaces was definitive from the start. There were other concepts, but these disappeared rapidly.

Two changes took place within a decade after the first flight, replacement of wing-warping by ailerons, and settlement on the conclu-

sion that the tail-surface of an airplane belonged behind it. Nothing basic has occurred since then in the area of general aerodynamic configuration of small subsonic airplanes.

Combat airplanes underwent evolutionary growth during World War I, with both sides producing airframes using about the same technology until the Germans introduced the first all-metal monoplane, near the end of the conflict. General acceptance of the monoplane waited until the appearance of aluminum in sufficient quantities, and of acceptable properties, made the aerodynamically superior internally braced monoplane technically feasible. In the meantime, during the decade of the twenties, the biplane and strut-braced monoplane lived side-by-side, with no singular advance in aerodynamic technology.

The next two significant improvements appeared almost simultaneously. The feasibility of the internally-braced monoplane resulted in higher wing loadings (thus higher stalling speeds) and in the increasing significance for drag of items which previously were of minor importance. Flaps and retractable landing gear appeared almost together, to make significant extensions to both ends of the speed range. The fighters of World War I could fly a little over twice as fast as their stalling speeds; by the 1930's "twice as fast" had become "over three times as fast."

At that point the major contributions to low subsonic aerodynamic art ceased. Since then there have been detail improvements—shaping refinements in ailerons, flaps, slats, air scoops, and so on.

General aviation includes high-subsonic airplanes, so the two most significant technical contributions to flight in the Mach-number range from 0.6 to 0.9 should be mentioned. The first of these was accidental. During the mid-thirties specially shaped families of airfoils were developed in an attempt to reduce wing skin-friction drag. Success in doing this was negligible for various reasons. Of interest, however, was the fact that the special airfoils had better high Mach characteristics than their predecessors. Maximum operating Mach number gains of more than 0.1, or about 15 percent, were possible. The second development, that of the swept wing, was German, and was not known to the United States until the collapse of Germany in 1945. High-subsonic airplane aerodynamic design coasted along on the strength of these two developments until the late 1950's, when Boeing commenced utilizing a further refined airfoil series and tailoring near the junc-

tions of wings and bodies, in accordance with the Whitcomb "transonic area rule."

Aerodynamically, the modern airplane is an extremely efficient device. Its propeller delivers thrust horsepower at an installed efficiency, typically, of over 85 percent. The "induced" drag which is an inherent theoretical penalty of the production of lift is exceeded by only about 10-15 percent in practice. The "parasite" drag which is the penalty for having a useful load that occupies space, is little more than that which would be experienced by a thin flat plate, equal in exposed area to that of the airplane's exposed skin, drawn through the air edgewise, at flight speed. This is approximately six times "cleaner" than a typical automobile (the above statements apply to "top-of-the-art" airplanes: unbraced-wing mono-planes with retractable gear).

On the low speed end of the flight envelope the airplane does not do so well. It cannot fly level at any speed below its "stalling" speed, which can be compared roughly with the cruising speed of an automobile. The safety implications of having to touch down no slower than this are obvious and efforts to improve the situation have been continual. The market place typically has called for speed and efficiency, however, and has accepted the risks of fast touchdowns.

Indeed, striving for very low stalling speeds can be more dangerous than not. The reason lies in the fact that the aerodynamic force that a control surface (e.g., rudder) can exert, is proportional to the square of the speed with which it moves through the air. So an airplane configured for low speed handling can be oversensitive at high speeds or one configured for high speeds too sluggish at low. Conventional general aviation airplanes of small-to-medium size are typically acceptable on both ends of the speed range. One of the ways in which power required for cruise flight can be reduced, however, is by reducing wing areas. The higher stalling speeds which result are undesirable, but can be lowered by increasing the maximum wing lift capability. Thus the energy crisis helps keep the pressure on for further development of high lift devices.

Airfoil Development

"Airfoil" refers to the shape and thickness of a cross-section of a wing. Three forward surges in airfoil development can be identified. First, the NACA low-speed programs of the 1920's and 1930's which resulted in the four and five-digit airfoil series (each digit of a designation such as 2412 gives the magnitude of an air-

**TABLE I-III
EXAMPLES OF AIRFOIL DEVELOPMENTS**

Airfoil	Maximum Lift Capability*	Remarks
NACA 24XX	1.47 - 1.7	4-digit series
NACA 230XX (1930's)	1.5 - 1.8	5-digit series
NACA 63-4XX	1.47 - 1.77	"Laminar-flow" airfoils
NACA 6716 (1974)	~ 2.0	4-digit airfoil with high-loaded trailing edge
GA(W)-1 (1973)	~ 2.1	"Low-speed super- critical" thick air- foil

*Defined as

$$\frac{\text{Lift}}{(\text{Dynamic pressure}) (\text{Area})}$$

foil shape parameter). The entire series used a type of thickness function based on only 2 airfoils: one designed by Col. Virginius E. Clark, and one very similar designed at Göttingen. The mathematical definitions of thickness functions and mean lines were systematized, but not on a theoretical physical base—they were arbitrary, as were the Clark and Göttingen airfoils that served as the point of departure.

Second, the so-called "laminar flow" series, which as it turned out offered more to high-Mach flight than to low. There were several families of these, of which the survivors are the so-called "6" and "6A" series. Airfoil contours were developed to match desired surface velocity distribution.

Third, various programs seeking further relief from high-subsonic-Mach number limitations of thick airfoils developed. The names connected with these programs are Sinnott and Percy in England, and Whitcomb in the United States.

Current work in the United States is of three kinds: (1) theoretical and experimental work on multi-element (flapped and slatted) airfoils; (2) theoretical and experimental work on high-lift basic airfoils, notable among which is the GA(W) airfoil series to which Whitcomb's name has literally become attached; and, (3) continued work on the "supercritical" classes of airfoils.

The gains being sought are relatively small, and the cost of obtaining them sometimes seems excessive. Table I-III illustrates the evolution of high-lift airfoil technology. The data are clouded by the fact that the later explorations have emphasized low test speeds.

There has been much attention devoted to raising the maximum lift capabilities of airfoil sections. This has taken the forms of (1) devising basic sections with high maximum lifts, and (2) devising slat and flap configurations to apply to these sections to produce high maximum lifts in landing configurations (flap down, slat out).

Some of the recently-developed basic sections have had lower drag at high lift than have older sections of the same thickness ratio (thickness ratio is important because it indicates the depth of wing available for structure and tankage). A conventionally configured small airplane may be said to have "too much" wing for economical cruise, since the wing size is determined by the requirement for low stalling speeds. The benefit sought through use of the newer airfoil sections is in that they allow smaller wings than usual, since their maximum lift capability is high. In climb and at cruise, the small wing operates at higher lift per unit area, and the shift of maximum weight/drag ratios to higher lift values is therefore favorable to the new sections.

The classic approach to configuring multi-element wings for takeoff, approach, and landing has been to start with a given basic airfoil, lay in flap and slat elements that will fit inside the airfoil contour, and then explore what the settings of these elements should be for lift maximization. However, an airfoil designed for high lifting capability with no flap will not necessarily be exceptionally good when a flap system is added. This suggests that multi-element airfoil research might be directed toward finding airfoil sections and flap configurations that are best when the flaps are down.

Most of the multi-element airfoil developments of the past have been addressed to the landing configuration, where flap deflections are large and maximum lifts high. The most troublesome flight configuration remaining is that for climb, in particular the engine-out climbs of twin-engine airplanes. Federal Aviation Regulations acknowledge the importance of climb performance by prescribing minimum values of climb gradients or rates, but implicitly acknowledge that trouble exists by setting the minimum values very low.² Development of airfoil systems tailored for the climb regimes have received little attention.

Directions for Airfoil Research

With the advent of automatic computation, it became possible to conduct theoretical explorations of airfoil characteristics which previously had been too burdensome to undertake. The current analytical programs for single- and multi-element airfoil shaping are an example.^{3,4}

It would seem useful to apply such programs to the problem of developing airfoil and flap systems together rather than separately, with specific application to climb performance.

While these programs have merit, the following should be pointed out:

First, far cruder analyses, applied sensibly, have provided important indications of what should be done to make given modifications in airfoil characteristics.

Second, in one or two cases of note, sophisticated techniques have produced solutions for airfoil shapes which obviously were no good, but were carried through wind tunnel tests despite the clarity with which the low merits of the selections could be deduced from visual inspection of the airfoil contours.

Third, the omissions in the experimental data provided for families of existing NACA airfoils have been known to the industry for years. In some cases, filling in the data gaps and extending the ranges of parameters in directions whose utility could easily be perceived, would have provided section geometries which are only now being explored (an instance is the general correspondence between the characteristics of the NACA 6716 section, only recently tested,⁵ and those of the GA(W)-1 section⁶). In one notable case, that of the NACA 230XX airfoils, a family of sections with obviously superior high lift characteristics sat around for years, figuratively screaming for more inquiry into just why they were so good.

To many people there were good and sufficient reasons for the lack of attention to the data gaps — World War II, the postwar funding crunch, the advent of diverting work (supersonic flight, missiles, space programs). During those periods, understandably, relatively little work was done by NASA; general aviation manufacturers took occasion to point out the lack; the larger airplane companies such as Douglas and Boeing undertook to remedy the situation for their own benefit in their own facilities, and very little appeared in the public domain.

It is suggested that benefit to general aviation would result from a continuing, long-range program of subsonic aerodynamic research which would include:

- (1) increased financial support for NASA aeronautics research, to the extent that not only could NASA's own in-house and contractual research be augmented, but also close and continual technical monitoring could be maintained over the manner in which government funds in general use are spent for aeronautical research.
- (2) continuous liaison with universities and with general aviation manufacturers, using circuit-riders if necessary, to determine in what ways NASA or other government agencies can be

² Federal Aviation Regulations, Part 23, Par. 23.65 *et seq*

³ Hicks, Raymond M., *et al.*, "An Assessment of Airfoil Design by Numerical Optimization," NASA TM X-3092, July, 1974

⁴ Barger, Raymond L. and Brooks, Cuyler W. Jr., "A Streamline Curvature Method for Design of Supercritical and Subcritical Airfoils," NASA TN D-7770, September, 1974

⁵ Bingham, Gene J., "Low-speed Aerodynamic Characteristics of NACA 6716 and NACA 4416 Airfoils with 35-percent Chord Single Slotted Flaps," NASA TM X-2623, May, 1974

⁶ McGhee, Robert J., and Beasley, William D., "Low-Speed Aerodynamic Characteristics of a 17-Percent Thick Airfoil Section Designed for General Aviation Applications," NASA TN-D7428, December, 1973

responsive to their research needs. Coverage should not be limited to those of the public who have government contracts. A mechanism to ensure the responsiveness of the government agencies should be devised.

- (3) "gap-filling" experimental work. The everyday problems of the small or medium-sized airplane company are not those of pushing out the forefront of knowledge, but rather are those of obtaining detailed information on items basically already well within the state of present art—such items as airfoil characteristics, aerodynamics of fuselage irregularities, interference drag, engine cooling drag, propeller performance, excrescence drag, etc.
- (4) continued publication of compendia of data, of a high order of completeness, with periodic revisions and reissues.
- (5) revival of the pre-1958 NACA index system. The current STAR indexes are comprehensive, but need supplementing to increase the visibility of important NASA work. The old NACA index format was excellent in this regard, and far more usable than the STAR indexes.

Elements of this program exist; some have existed for a long time. The intent of the above suggestions is to express general concurrence with the decisions which have produced the present NASA general aviation aerodynamics programs, while citing areas in which additional funding seems desirable.

Structures and Materials

Structural development has been paced historically by materials availability. The best utilizable weight/strength ratios in the pre-World War I period were possessed by various woods (the use of weight/strength ratio is a vast oversimplification, which is why the word "utilizable" has been inserted). Wrought aluminum alloys were not available in temper states that allowed use in primary structure, though secondary structure could use it, and did during the war.

The necessity for building stiff structures

with low weights and low-strength materials dictated the use of wire-braced, thin-membered trusses: the bridge-type fuselage framework and the biplane wing cellule, which was essentially a repetition of the fuselage truss, disposed laterally and with its horizontal panels covered by secondary structure, the ribs and fabric envelopes. Some all-wood airplanes, their surfaces made of spruce plywood bonded with casein glues, appeared during the war and throughout the 1920's, but they did not account for a major market share. Wooden airliners were killed abruptly following the Knute Rockne crash; the Fokker transport in which he was killed was wooden-winged, and the crash was felt possibly due to the deterioration of the wing structure.

Subsequently, wood for airliners was, in effect, regulated out of use, and the development of light-metal technology was thereby forced. Though unbraced-wooden-winged airplanes were built (Lockheed Vega, Fairchild PT-19), the development of light-metal technology probably was a major factor in promoting aerodynamic improvements starting with the unbraced (internally braced wing. One might almost say it forced the aerodynamic refinement, since duplicating wooden structural configurations typically leads to some weight increase, which must be offset by drag decrease if installed engine power is not to rise.

The 1930's were a period, then, of refinement in all-metal design, culminating in the great combat air fleets of World War II.

Immediate postwar developments included the introduction of "sandwich" materials (a double skin of very thin layers prevented from buckling due to in-plane compressive loads by a lightweight core of wood or metal honeycomb), but the impact of this technology on general aviation has not been felt until recently. The delay was due in part to the difficulty of inspecting sandwich structure bonding using nondestructive techniques, a difficulty not surmounted until a very few years ago.

The war production programs enabled some general aviation manufacturers to develop their all-metal technology at public expense. The result was that production of wooden, fabric-covered, general aviation airplanes rapidly subsided after the war until at present only a few minor types are being produced.

Sheet-metal technology of World War II level still dominates the civil airplane field. Early attempts to use plastics technology for

secondary structures resulted in saving neither weight nor cost. More recently a second cycle of attempts to use plastics technology was begun. One certificated civil airplane, the Windecker Eagle, uses plastics almost altogether for skin, but the extent of plastics use in its primary structure is apparently lower. Other manufacturers have acquired or are acquiring the capability to work major structural components in plastics.

Military structural research has concentrated most recently on the development of composite structure with mono-filament load-bearing members. This development has not yet reached the civil field.

Sail plane structure has reached a new plateau with the replacement of composite wood-and-fabric construction by conventional fiberglass/epoxy layups with foam filling. This enables glassy-smooth exterior skin-surfaces to be built fairly easily.

Perhaps the most active area of structures research—at least the most visible at the moment—is the analytical. The fairly simple sheet-metal structure of World War II could be stress-analyzed using closed-form methods. Very thick-walled structures such as landing gear forgings could not be well dealt with using such simple methods, however. The availability of digital computer time has resulted in an explosion of finite-element methods for the analysis of thick-walled structures of complex shape.

At the time of the disappearance of the wooden airliner, the technology of wooden airplane construction was fairly advanced. Throughout the years between then and 1941, wooden airplane development struggled along, and it is now the property of sport aviation and one commercial manufacturer. The state of the technology is practically the same as at the end of the last major wooden airplane production, the PT-19, left it.

It would appear that there is now reason for taking it up again. While the state of availability of the major civil aircraft structural materials of the present day—aluminum, magnesium, and titanium—is better than that of petroleum fuels, still the refinement of these materials to aircraft standards is energy intensive. In this regard wood is attractive—a renewable resource, potentially available in adequate supply to support small airframe production, and with small energy requirements to prepare it for aircraft use.

Larger airplanes will undoubtedly continue to be built of more exotic materials because of

the requirements for structural strength, efficiency, and low maintenance. Wood, however, continues to be an acceptable material for the construction of small airplanes. Fabric is a sort of natural companion of wood for this application, so along with the program of resumed development of wood construction technology which is suggested here, might well go one of fabric application development.

The bugbears of the past have been: (1) insidious, invisible deterioration of the mechanical properties of wood structures; (2) non-destructive inspection of woods; (3) rot and infestation; (4) deterioration of fabrics with exposure to sun (hence pigmented dopes replacing the clear dopes of the first two decades of aviation); (5) palatability to field creatures of cordage used in stitching; (6) resistance to action of aviation fuels and lubricants; and, (7) bonding materials and techniques.

Recent years have seen the introduction of synthetic aircraft cloths and long-life dopes, which it is hoped will give finished fabric airplane coverings lifetime durability. However, work toward improving the characteristics of aircraft covering using renewable resources may yet be in order. This same constraint should be considered for application to research in any of the other areas.

Propulsion

Propeller airplanes represent an overwhelming percentage of the general aviation fleet, so perhaps starting with the propeller itself is appropriate.

Someone has said that only a real genius could design a poor propeller. Operating at its design point a typical wooden fixed-pitch propeller of World War I vintage would show efficiencies in excess of 70 percent, and modern technology metal propellers can exceed 90 percent. Thus, aerodynamic refinements for design-condition operation yielded relatively small gains, the largest being experienced when aluminum technology permitted development of metal blades in the late 1920's.

The only major avenue of improvement, then, was in the area of off-design performance, and this problem was addressed in the early 1920's, with controllable-pitch and constant-engine-speed propellers finally achieving wide use by the mid 1930's. The propeller technology of general aviation today is largely the technology of that era, with detail refinements.

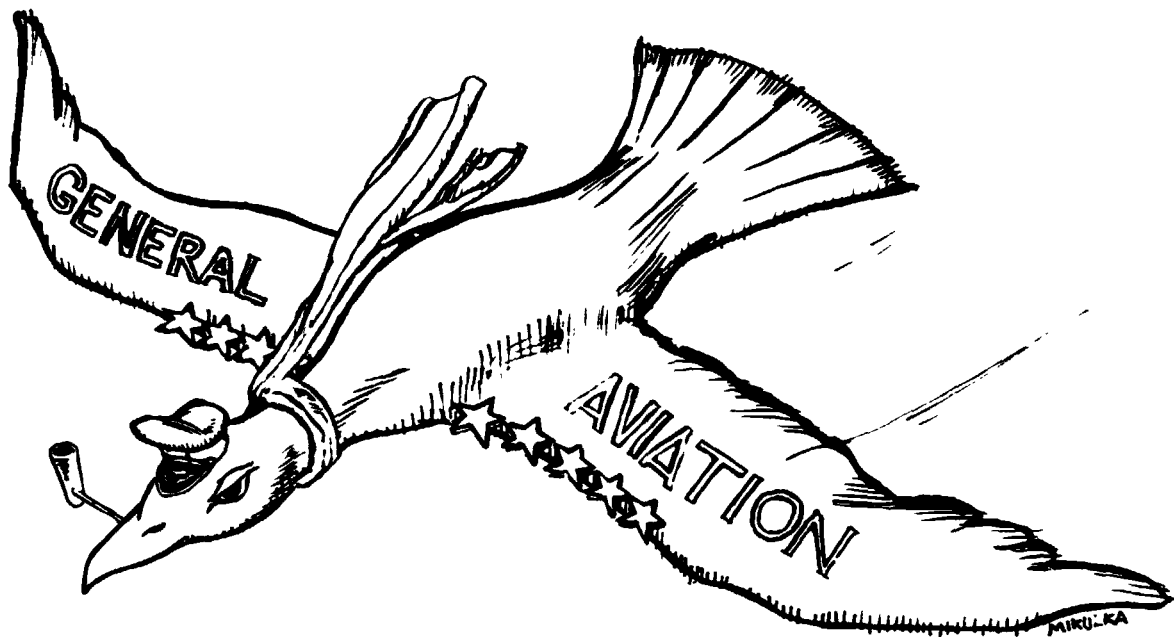
Practical piston engine development was along two lines—aircooled and liquid-cooled. Liquid-cooled engines are no longer used ex-

cept for the World War II leftovers, and are not produced at all. Aircooled engines got a rather strange start with the "rotary" engine, whose crankshaft was rigidly fixed to the airframe, the pistons, cylinders, crankcase, and propeller all whirling around at prop speed, which was then (World War I) rather low. The rotary died a well-deserved sudden death after the war, its place taken by the aircooled radial.

The present horizontally-opposed configuration found in most general aviation airplanes dates back to the late 1920's; it and the prevalent "lightplane" highwing configuration started together at that time, and the family resemblance remains until now. Improvements since the 1920's have been in materials and

detail refinements, such as the introduction of fuel injection and turbo supercharging, both spinoffs from military aviation. Minor types and freaks have appeared now and then, such as the Guiberson diesel radial, the six-cylinder Curtiss radial (single-row radials have odd numbers of cylinders, so the Curtiss engine was in essence two three-cylinder radials with a common crankcase), and the Herrmann cam engine.

Propulsion research has produced many exotic configurations during the last twenty years—lift fans, tilting rotors, tilt-props, tilt-prop-tilt wings, tilting ducted fans, and so on. The main thrust has been toward development of VTOL types other than the helicopter. With a



single military exception, these devices have not been undertaken by any firm for production, although the present state of documentation seems fairly good. Much of the information has been condensed into a reference work by Dr. Barnes W. McCormick of Pennsylvania State University.⁷ Dr. McCormick has broadened the scope of his work to include powered boundary layer control, essentially a part of STOL technology which also has found, to date, only military applications.

Piston engine development has simply incorporated old military engine technology into civil engines, with one notable exception: Teledyne Continental has produced an engine with an altered internal power train and fairly sophisticated dynamic damping devices.

Dowty-RotoI has displayed a controllable-pitch piston engine/shrouded propeller combination in mockup form.

Turbine engine development in small sizes has utilized essentially military-funded technology for civil engines of fairly conventional form. Short-life turbine engines, based on drone-engine technology, have been proposed at various times as lift engines (axis vertical) for STOL or V/STOL airplanes, but none has been adopted for production. Turbine engine technology is very expensive to acquire, hence the lack of civil funding for advanced research.

No engine produced to date for aviation, except the diesel, has outshone the conventional gasoline piston engine from the standpoint of fuel economy. The shaft-gas-turbine engine is lighter and its overhaul times typically longer; through intensive development its fuel consumption has been hammered down to about the level of the wartime piston engine. Nevertheless, with little development since 1945 except what the civil engine manufacturers could afford, the fuel consumption of the gasoline piston engine is now, after thirty years, about as far superior to that of the turbine as it was when gas turbine development started, on a percentage basis.

As long as flight speeds are below about 325 knots, the propeller engine is superior to the only other two types in use, the turbofan and the turbojet. This superiority exists because of propeller, rather than engine, characteristics. The implication of this and the superior fuel economy of the basic piston engine is clear.

Noise

The general aviation airplane, taken by and

⁷ McCormick, Barnes W. *Aerodynamics of V/STOL Flight* (New York: Academic Press, 1967)

large, is a far less noisy device at the distances at which it is typically encountered than is a power lawnmower, a motorcycle or a "performance" car. Experience has shown, however, that the airplane's high visibility makes it vulnerable, and that noise levels at major airports generate an awareness of aircraft noise that "wipes off" on all airplanes. Also, an objectionable noise need not be "loud," or have any specific frequency content, to generate complaints. There is experience to indicate that many complaints about "noise" are generated simply by newness and unusualness. It all amounts to the fact that silencing airplanes is a response to a political fact of life, however artificially generated, which did not exist as such years ago, but which we now ignore at our peril.

Small piston engines are muffled, but not as effectively as automobile engines. There are two probable reasons: (1) a very significant proportion of the noise of an aircraft power plant is propeller noise—perhaps as much as 40 to 60 percent. The propeller noise therefore masks the exhaust noise at high prop speeds; and (2) weight is always critical, and the tendency is therefore to minimize the weight, as a percentage of the total, of items that do not contribute to safety of flight or to sales potential.

Propeller noise is predominantly due to air compressibility effects at the blade tips. To get rid of the noise, then, demands that either the propeller be slowed to a tip speed where these effects will disappear (usually below $M \cong 0.6$) or that blade profiles be reshaped. The "high-speed supercritical" airfoils proposed by Dr. Richard T. Whitcomb are designed for the specific purpose of delaying the onset of compressibility effects by approximately .05 - 0.10 Mach. Along with this benefit go increases in the loadings at which it is acceptable to drive the blades, from a power-required standpoint.

Low tip speeds dictate increases in propeller "solidity" (number and width of blades) to realize acceptable thrust power levels. Since thrust not only varies almost directly with solidity, but also with the square of propeller speed, ground and low-speed engine cooling becomes a problem with slow turning propellers, as was again demonstrated with the "spook" airplanes used in Vietnam.

Some persons have proposed use of shrouded propellers to diminish noise output. There is no present evidence to indicate that the complicated tradeoffs involved in shrouded propeller design will favor low-noise configurations of acceptable weight and efficiency. Indeed, the basic configuration generates noise

problems all its own at the low-loading end of the range of applicability. At the high end, the shrouded propeller becomes the secondary stage of the ducted fan engine. Here the trade-offs are considered vis-à-vis the turbojet engine, and are favorable to the fan because of its long shroud (not feasible at low loadings), which can be acoustically treated.

It is surprisingly little understood that small propeller airplanes can now be silenced almost to the level of the automobile at high speed cruise. Detail changes of configuration which must be made to do so include: (1) more effective exhaust muffling; (2) overwing routing of exhaust stacks; (3) slow turning, wind bladed propellers; and, (4) improvements in ground and low-speed cooling, perhaps with auxiliary blowers or a reversion to liquid cooling. But the job can be done within the limits of present technology. An inspection of the circumstances surrounding the addition of noise certification requirements to the Federal Aviation Regulations would seem to be in order, to determine whether, for any small airplane other than the business jets, a real need exists for the regulations.

The changes listed above do not come free. Each has its cost in weight or efficiency, small though it may be. Whether this cost will be tolerable as fuel supplies grow scarcer cannot be predicted, but it is worth considering whether significant amounts of funds should be spent on developing improvements which may in a very few years have to be discarded as the last few percentage points of efficiency are sought.

Basic Configuration

As pointed out previously, no definitive changes in airplane configuration have taken place since about World War I. That war also generated the basic conventional twin, with wing-mounted tractor-type powerplants, a type which survives and is popular today.

The conventional light twin represents the first step up in performance from the heavy single, largely due to the fact that there are no engines on the market today in the 600 horsepower class except the Pratt and Whitney PT-6 turbine and the R-1340. Neither of these engines is suitable for other than specialized single-engine applications, the turbine because of its cost, the R-1340 because of its limited availability. The twins, with their modern opposed engines, fill the gap.

The conventional twin as a type, unfortunately, has one bad characteristic, which renders it among the most potentially dangerous

machines in the air. This characteristic is the difficulty of "cleaning it up" after a single engine failure. The pilot must sort out which engine failed, shut it down, at the same time counteracting the roll and yaw occasioned by the shutdown, then rapidly retract the gear and raise the flaps if they are extended. The difficulty of doing this is emphasized by the fact that a large proportion of fatal accidents to twin-engined airplanes in which engine stoppage played a part is sustained in training for engine failure emergencies.

Attempts have been made to circumvent the trouble by designing airplanes with "centerline thrust," e.g., the "push-pull" Cessna 337. Such airplanes have their own problems, notably those of detecting when an aft engine failure has occurred, and of providing adequate ground cooling for the aft engine. The concept remains attractive, however, as a remedy for the basic problem, and if the conventional twin cannot be rendered more tractable by the application of advanced technology, the centerline thrust twin should be taken in hand and developed to the extent that it possesses less serious problems of its own than are possessed by the conventional type.

The Advanced Technology Light Twin (ATLIT). For several years a group under Dr. David Kohlman and Dr. Jan Roskam has been working at the University of Kansas in the area of the improvement of cruise and low speed performance of small airplanes. The general approach is to adopt high-lift airfoil technology to maintain low stalling speeds while improving cruise performance (range) and gust response by reducing wing area about 30 percent to cut skin-friction-type parasite drag. Spoiler ailerons are adopted to maintain good roll performance at low speed.

At present this NASA-contracted program has modified a Piper airplane, an "ATLIT," for further experimental work. Their first airplane was a single-engined Cessna.

Robertson Aircraft. While the aerodynamic gains sought by the ATLIT project are worth achieving, quite a bit can be done toward improvement of low-speed performance alone by adopting less drastic measures. For many years the Robertson Aircraft Company has specialized in modifying conventional production airplanes for this purpose. The modifications consist of sophisticated flap systems, drooped-wing leading edges, vortex generators, and lately full-span flaps and spoilers. Robertson's emphasis has been on keeping modification costs low and doing as little as

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possible that will affect the structural integrity of the basic airplane.

Short Field Aircraft

"Short-field Aircraft" is a catchall term under which can be lumped all aircraft which use advanced technology to achieve shorter than ordinary takeoff and landing distances. The term embraces short takeoff (STOL), reduced takeoff (RTOL), and vertical-or-short takeoff (V/STOL) types of machines.

RTOL and STOL

There have been two definitions associated with each of the names Reduced Takeoff and Landing (RTOL) and Short Takeoff and Landing (STOL), and much confusion has existed because this fact was not appreciated. The confusion existed because, while Conventional Takeoff and Landing (CTOL) airplane technology and its associated performance were represented by existing types of airplanes, as was Vertical/Short Takeoff and Landing (V/STOL) by the performance of the helicopter, no hardware and no steady performance targets existed for STOL. During the early years in the development of STOL technology, the typical argument was over what single fixed takeoff and landing distances should be striven for through the application of the technology. One of the early "definitions" of STOL was "500 feet over a 50 foot obstacle." It was surprisingly long in coming out that there were actually two entities to define separately.

The first was **STOL technology**, the aggregation of technical developments that would enable the design of an airplane with field length requirements substantially less than those of a CTOL airplane, of the **same payload, range, and speed**.

The second was **STOL airplane**, and to its definition no fixed field performance requirement could be attached except arbitrarily. The field performance of successful airplanes designed to a given state of the art is size dependent as shown in Figure 1-3. A STOL airplane, then, is an airplane which utilized STOL technology effectively to produce some percentage improvement in performance, no matter how short or long its field requirement is.

Potential users, however, insist on thinking in dimensional terms so here is a sample run-

down of the various field length performance targets advocated throughout the years, with a little information on each:

- (1) 1952: 500 feet; this was the point of departure for many discussions among commercial manufacturers, the Army, and the Office of Naval Research. In 1953, the Cessna Aircraft Company actually produced an airplane capable of taking off and landing over a 50-foot obstacle in 450 feet. The airplane was a heavily-modified L-19A. The "improvement" over CTOL was approximately 25 percent.
- (2) 1959: 1,200-2,000 feet, developed in part by technical studies growing from ONR/Army-sponsored research performed at the University of Wichita. The aircraft associated with these field lengths were transports in the 30,000 - 60,000 pound class. At this same time, Lockheed Aircraft started development of a "BLC-130" with comparable performance.
- (3) 1968: 1,000 feet. The FAA marked off 1,000-foot sections of runway at Washington National, Friendship, and LaGuardia airports and designated these as "STOL" strips. An airline using Dornier "Sky Servant" heavy twins (7,700 pounds) used these strips. Though this airline operated only for a while, it provided information on the feasibility of introducing STOL airplanes into the mix of traffic at a heavily-used airport.
- (4) 1970: 2,000 feet. This was a relaxation of the 1,000-foot "requirement" above. Surveys of the larger commuter operators at that time indicated that they would have been content with about 3,500-foot field performance.
- (5) 1975: 3,000-4,000 feet. This length is associated with medium weight transport category airplanes (146,000-206,000 pounds) in a NASA-funded set of short-haul systems studies by Douglas, Lockheed, Boeing, and others. Advanced hi-lift technology and materials were necessary at these

* Stalter, J. L., and Watson, Robert K., Jr., "Experimental Investigation of a Means of Obtaining Independent Control of Lift and Drag in Landing Approach," University of Wichita Engineering Report UWER-315-5, Contract DA 44-177-TC-356, U.S. Army Transportation Research Command, April, 1959