V/STOL SESSION INTRODUCTORY AND REVIEW PAPER

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INTRODUCTION

The title of this session - V/STOL - is a very broad one. Actually, however, the material to be presented does not cover all aspects of V/STOL aircraft in the broader sense, inasmuch as some of the other sessions also treat certain V/STOL areas. For example, the Rotary Wings Session covers helicopters and rotor-type V/STOL aircraft and the session on propulsion covers V/STOL fan and jet propulsion systems. This session is therefore restricted to propeller, fan, and jet V/STOL aircraft types and does not deal in detail with the propulsion system itself. Other V/STOL areas covered in other sessions include the V/STOL short-haul transportation system discussed by Professor Miller in his session on subsonic transports; and facilities and techniques for V/STOL testing which are covered in the session on facilities and techniques.

This session is organized on the basis of V/STOL propulsion type - that is, propeller, ducted fan, and turbojet types. In my review paper, I will touch briefly on some of the subjects which cut across the propulsion spectrum - subjects such as handling qualities, ground effects, and noise. First, I would like to cover a few basic points regarding V/STOL aircraft to prepare for the papers that follow. An appropriate starting point is definition of terms in order to avoid the confusion which has sometimes arisen in the use of the terms VTOL, STOL, and V/STOL. VTOL means vertical take-off and landing. STOL refers to short take-off and landing, where there is no VTOL capability, and some take-off and landing run is always required. The term V/STOL indicates the capability to perform either vertical or short take-offs and landings. An airplane of this type has VTOL capability but may operate much of the time as an STOL airplane for improved economy and a greater margin of safety in event of engine failure. Actually, the terms VTOL and V/STOL can be used interchangeably since all VTOL configurations currently under consideration can perform running take-offs and landings.

BASIC V/STOL CHARACTERISTICS

Some fundamental relationships between the lift and power required for conventional and V/STOL aircraft are illustrated in figure 1, taken from Reference 1. The lift, in percent of weight, and the power required for level flight are shown plotted against airspeed for both types of aircraft. On the lower plot, the solid line curve represents a typical variation of power required for a conventional airplane extending from the stalling speed to the top speed of the airplane. The top plot shows that for this speed range, the airplane is supported entirely by aerodynamic lift provided by the wing. On the other hand, for the V/STOL aircraft which can operate below conventional wing stalling speeds on down to hovering flight, the aerodynamic lift is gradually replaced by powered lift as hovering is approached. In this speed range where powered lift must be used - the so-called transition speed range - the power required for the V/STOL airplane, indicated by the dashed line, rises rapidly to a maximum for the hovering flight condition. The STOL, or short take-off and landing, aircraft only go part of the way up this power required curve - getting a modest reduction in stalling speed from a modest increase in power. This high power required in hovering flight is one of the basic characteristics of V/STOL aircraft. Three other basic and unique characteristics of V/STOL machines are the vertical slipstream for hovering flight, the inherent deficiencies in aerodynamic stability and control in hovering and low-speed flight, and the special provisions made for performing the conversion from the hovering to the cruise configuration. Now let us deal with these four characteristics in turn and consider some of the problems associated with each.

The following discussion may sound unduly pessimistic because it deals primarily with those factors which tend to limit progress on V/STOL aircraft and hence require special attention.

High Power Required

The high power required in hovering flight results in higher fuel consumption and greater noise. The magnitude of the increases depends upon the type of propulsion system, as illustrated in figures 2 and 3. Figure 2, taken from Reference 1, shows fuel consumption plotted against slipstream velocity for hovering and cruising flight for various types of V/STOL aircraft having the same gross weight. As we move from left to right on the plot - from the rotor to the propeller, ducted fan, and turbojet - we cover propulsion systems having progressivly smaller diameter slipstreams with greater slipstream velocities. Hovering fuel consumption is indicated by the hatched bands while the dashed lines represent the fuel consumption in cruise for the corresponding propulsion systems. It is apparent that the hovering fuel consumption is very high for these higher performance V/STOL types, particularly for the turbojet configurations. The significance of this characteristic in terms of operating procedures is that the hovering time of these aircraft must be kept to an absolute minimum, and it is not realistic to consider long periods of vertical climb or descent during take-off and landing operations.

In general, the noise associated with the various V/STOL propulsion systems varies in roughly the same manner as the power required and fuel consumption. That is, helicopters are generally the quietest and jet aircraft the noisiest, as shown in figure 3, taken from Reference 2. Here we have noise level in terms of the perceived noise level parameter, PNdB, plotted against disk loading for various V/STOL types. Some familiar noise levels are noted along the left-hand scale for purpose of orientation. The V/STOL noise levels shown are for an 80,000-pound airplane hovering 400 feet away from the observer. The point to be made from this figure is that the higher-disk loading V/STOL types are much noisier than the helicopter, which itself is noisy enough to be objectionable in some cases. Noise is therefore expected to be a major problem in the development of V/STOL transportation systems making use of close-in airports. In order to make V/STOL aircraft acceptable for such use, the aircraft will have to be designed from the beginning with minimum noise as a prime requirement even at the expense of aircraft performance and cost. It should also be possible to achieve some alleviation of the noise problem by using very steep approach and climbout flight profiles with the V/STOL machines.

Vertical Slipstream for Hovering

Now let us turn to the second basic V/STOL characteristic - the vertical slipstream required for hovering flight. As illustrated in figure 4, there can be important effects on the surroundings in the take-off and landing area as the high velocity vertical slipstreams impinge and flow outward in all directions. This slipstream impingement can cause serious surface erosion problems when the V/STOL aircraft is operating from unprepared sites. Some promising schemes for rapid site preparation for V/STOL operations are described in later papers in this session.

In addition to the effects of slipstream impingement on the surface, there are important effects on the aircraft itself as the slipstreams come together and recirculate about the airframe and propulsion system. Recirculation of dust and debris can cut down the pilot's visibility and cause damage to the airplane. Ingestion of foreign objects into the engine becomes a real problem for V/STOL aircraft operating over unprepared surfaces. In addition, rotors, propellers, and fans are exposed to the eroding effects of the sandblast produced by the recirculating slipstream. If it is not practical in a given situation to minimize such effects by some sort of site preparation, the best alternative solution is to use short take-off and landing runs in order that the dust and debris be blown backwards, away from the aircraft.

Slipstream recirculation can also affect the performance of V/STOL aircraft in hovering and low-speed flight. These effects may take the form of changes in pressure on the airframe which can cause substantial changes in vertical lift or they may involve ingestion of hot gases into the engine which can seriously degrade engine thrust. Figure 5, taken from Reference 3, illustrates how the aerodynamic effect of the recirculating airflow can vary with aircraft configuration. For single slipstream configurations in hovering flight, the flow impinges on the ground and flows radially outward in all directions. This high-velocity outward flow of air entrains the stationary air above it to produce a reduction in pressure and a resulting suckdown effect. In the case of multiple slipstreams, the flows along the ground meet underneath the aircraft to produce an upward flow and buildup in pressure against the bottom of the airframe which results in an increase in vertical lift. Unfortunately, this upward flow is not very steady or symmetrical and hence can produce random upsetting moments which make most V/STOL aircraft more difficult to fly when hovering near the ground than when hovering out of ground effect. Moreover, in the case of jet aircraft with multiple slipstreams, the recirculation of hot exhaust gases into the engine inlets can be a very serious problem. Mr. M. N. Wood discusses this problem in his paper[4] and indicates means of alleviating it.

For STOL operation there can be a detrimental ground effect for some configurations as illustrated by the bottom sketch in figure 5. In this case, some of the slipstream moves forward after striking the ground and produces a recirculation which reduces wing lift. It is shown in Mr. K. R. Marsh's paper[5] that this recirculating flow is also quite turbulent and can lead to control problems for tilt-wing configurations flying at very low speeds near the ground.

Aerodynamic Stability and Control Deficiencies

Turning to the more general problem of stability and control deficiencies at low speeds, let us now consider the third item on our list of unique V/STOL characteristics. Figure 6, taken from Reference 1, shows typical variations of aerodynamic stability and control with airspeed for V/STOL aircraft from hovering through the transition to cruising flight. In this illustration we are assuming that the V/STOL airplane has satisfactory aerodynamic stability and control in cruising flight and at the upper end of the transition range represented by the end point of the curves. Since all these parameters vary with the dynamic pressure in the airstream, they drop off rapidly as the airspeed is decreased in the transition. There is no aerodynamic control effectiveness at all in hovering unless the control surface is in a high velocity slipstream. It is usually necessary, therefore, to provide an additional control system for V/STOL aircraft specially for the hovering and low-speed flight conditions. In hovering flight, all V/STOL aircraft have neutral static stability - that is, there is no stability of attitude. As for dynamic stability, jet V/STOL types are about neutrally stable in hovering but other V/STOL types usually have dynamic instability in the form of unstable pitching and rolling oscillations. This lack of static and dynamic stability does not prevent V/STOL aircraft from being flown under visual flight conditions, but it does lead to certain undesirable handling characteristics which must be improved by stability augmentation to insure satisfactory operation during instrument flight.

Provisions for Conversion

Now let us turn to the last unique V/STOL characteristic on our list - the special provisions made for performing the conversion from the hovering to the cruise configuration. Although there may appear to be numerous schemes for accomplishing this conversion or transition, actually only four fundamental principles are involved as indicated in figure 7, taken from Reference 6, which illustrates the family of V/STOL types formed by classifying the configurations on the basis of their propulsion type as well as their method of conversion. The four basic conversion schemes are aircraft-tilting, in which the machine merely tilts forward to fly forward; thrust-tilting in which only the thrust unit itself tilts, with the fuselage remaining essentially horizontal at all times; thrust-deflection, in which flaps or swiveling nozzles are used to redirect the slipstream or jet exhaust; and dual-propulsion, in which there are two different means of propulsion for hovering and forward flight.

THE V/STOL AIRCRAFT FAMILY

All V/STOL aircraft flown to date have incorporated one or more of these four basic conversion principles. When we consider the four different means of propulsion, together with these four conversion methods, we arrive at a family of 15 basic V/STOL types. Figure 7 can serve as an introduction to the other papers in this session if the size of the family is cut down a bit. First, of course, this session will not deal with the rotor types which have already been covered in a previous session. The aircraft-tilting category can also be disregarded since there is no serious consideration now being given to machines of this type except, of course, the helicopter. Mention should be made, however, of two airplanes of this type which were successfully flight tested back in the middle 1950's - the Convair XFY-1 propeller-powered tail-sitter and the Ryan X-13 jet design which performed vertical take-offs and landings by engaging a nose hook with a "clothesline" cable arrangement. Work on such configurations was discontinued when it became apparent that configurations in which the fuselage remains essentially horizontal would be far superior from operational considerations.

Now, by eliminating the rotor and aircraft-tilting configurations, we obtain in figure 8 the smaller V/STOL family which is to be the subject of this session. First, in the propeller category under thrust-tilting we have tilt-wing designs such as the Vertol VZ-2, the Ling-Temco-Vought XC-142, and the Canadair CL-84; and tilt-propeller designs such as Curtiss-Wright's X-100 and X-19. In the thrust-deflection category, only one V/STOL airplane has been flown - the Ryan VZ-3. Research has indicated that this deflected-slipstream principle is not well suited to VTOL operation because of the large thrust loss incurred in turning the slipstream through large angles. However, it has proved to be suited to STOL use where smaller slipstream turning angles are required. The Breguet 941 is a good example of an STOL airplane of this type. Actually, the deflected-slipstream principle is utilized in combination with the tilt-wing principle on airplanes such as the XC-142 and CL-84. These machines have large flaps which are programed to deflect downward as the wing tilts to perform the transition from hovering to cruising flight. This arrangement provides excellent STOL capability as shown in the paper by Mr. Marsh.[5]

The paper by M. O. McKinney[7] covers all three of the ducted fan types. Two tilt-duct configurations have been flown - first, the Doak VZ-4, which had a duct at each wing tip; and, more recently, the Bell X-22A, which is a tandem 4-duct configuration being tested as part of the U.S. Tri-Service V/STOL Program. In the ducted-fan, thrust-deflection category, no airplanes have yet been flown but two concepts which show some promise are being studied - one is Ling-Temco-Vought's ADAM or Air Deflection and Modulation design, and the other is a ducted-fan deflected-slipstream configuration which has been the subject of some exploratory research by NASA. The ducted-fan category which has received the most attention is the dual-propulsion type which is usually referred to as a fan-in-wing or lift-fan design. The G.E.-Ryan XV-5A research airplane is the only machine of this type to be flown to date but recent studies have shown promise for the use of lift fans in high-performance V/STOL military transports.

In the turbojet category, one example of a thrust-tilting configuration is the VJ-101, a design with tiltable engine pods at the wing tips, built by the German firm Entwicklungsring-Sud (EWR). This airplane also has special lift engines installed in the fuselage for vertical take-off and landing so it can also be considered a combination thrust-tilting and dual-propulsion type. There have been two highly successful jet V/STOL airplanes of the thrust-deflection type - the Bell X-14 research airplane and the Hawker P.1127 (Kestrel) which is the subject of Wing Commander D. M. Scrimgeour's paper[8] in this session.

The lift-engine types which make up the turbojet dual-propulsion category are generally considered to be promising but the airplanes of this type flown to date have not been very successful. These airplanes include the Short SC.1 and the two Dassault delta-wing configurations, the Balzac and the Mirage 3V. The jet V/STOL designs which have received the most attention in recent studies involve a combination of the thrust-deflection and dual-propulsion principles. That is, provisions are made to deflect the exhaust of the cruise engines downward, and then enough lift engines are used to provide the additional vertical lift for hovering.

During the last 10 years, all of these basic V/STOL types have been under study and 18 different V/STOL designs have been flight tested. Figure 9 shows a breakdown by country and propulsion type. All of the propeller designs but one and all the ducted fan designs flown have been built in the United States. European V/STOL effort has thus been concentrated on jet V/STOL with France, Germany, and Great Britain each having two different jet designs. A total of 42 aircraft of these 18 different designs has been flown.

V/STOL ACCIDENTS

One point of concern to many people has been the number of crashes of V/STOL aircraft in recent years. Figure 10 shows a breakdown of major accidents involving V/STOL experimental and research aircraft and also those involving the P.1127 aircraft in the operational evaluation squadron which Wing Commander Scrimgeour covers in his paper.[8] Of the 33 experimental and research aircraft flown to date, 15 have experienced major accidents in flight. It should be emphasized that most of these aircraft were one-or-two-of-a-kind machines used in exploratory research.

A more optimistic outlook on V/STOL accident potential is provided by the record of the P.1127 operational evaluation squadron. These 9 aircraft were built after considerable research and development flying had been carried out with early versions of the P.1127. It was possible, therefore, to eliminate or minimize a number of deficiencies before the squadron was put into operation to carry out the joint British-German-American trials in England in 1965 and the tri-service trials in the United States in 1966. As a result, an excellent safety record was achieved in these two operations which involved a total of about two thousand take-offs and landings from a wide variety of prepared and unprepared surfaces. Only two major accidents occurred in the trials - one in which a pilot attempted an STOL take-off with the brakes inadvertently locked, and the other in which a hard STOL landing was made in a pasture.

CONCLUDING REMARKS

To conclude this introduction, figure 11, taken from Reference 6, illustrates the basic trade-off between hovering capability and cruising speed for the various V/STOL types. Hovering capability in this case may be thought of in simple terms as hovering endurance which is inversely related to the power required for hovering or hovering fuel consumption. There is a general decrease in hovering capability and increase in cruising speed as we move from the rotor to the propeller, ducted fan, and turbojet types. Helicopters, of course, have the greatest hovering capability but are limited to rather low cruising speeds. In the session on Rotary Wings it was shown how the compound helicopter achieves higher speeds by unloading the rotor and using an additional means of propulsion for cruising flight. In the case of the so-called composite rotor aircraft, the speed limitations imposed by the rotating rotor can be completely eliminated by stopping and stowing the rotor in cruising flight. The propeller and ducted-fan configurations offer a compromise of moderate hovering capability combined with fairly high cruising speeds while the turbojet types have such limited hovering capability that their hovering time must be kept to a minimum. One point to be made from this figure is that the various V/STOL types afford a wide range of capabilities which could presumably satisfy a variety of mission requirements. It seems likely therefore that at least two or three V/STOL types, in addition to the helicopter, will eventually see widespread operational use.

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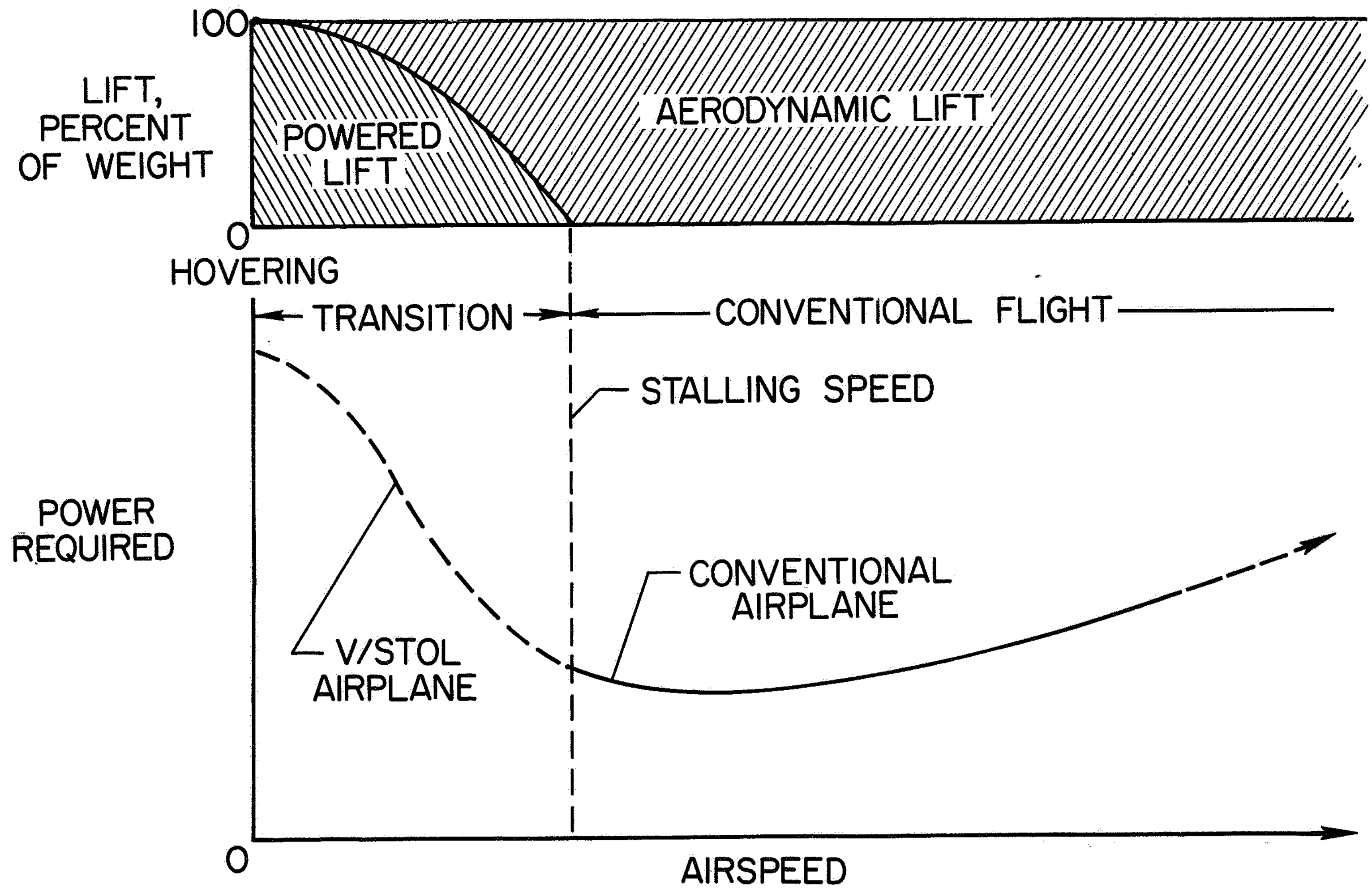

Figure 1.- Lift and power required for conventional and V/STOL aircraft.

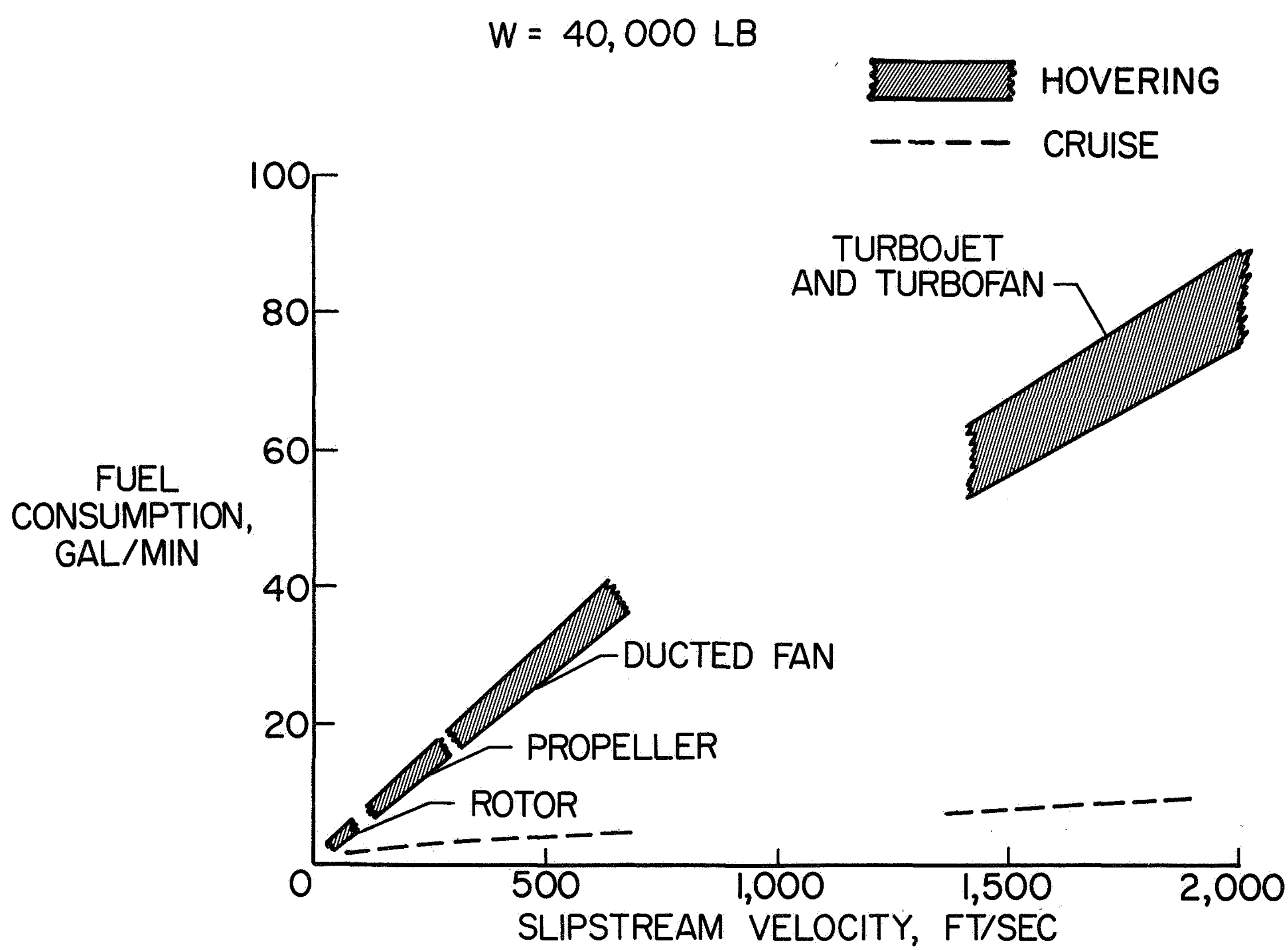

Figure 2.- Fuel consumption for various types of V/STOL aircraft.

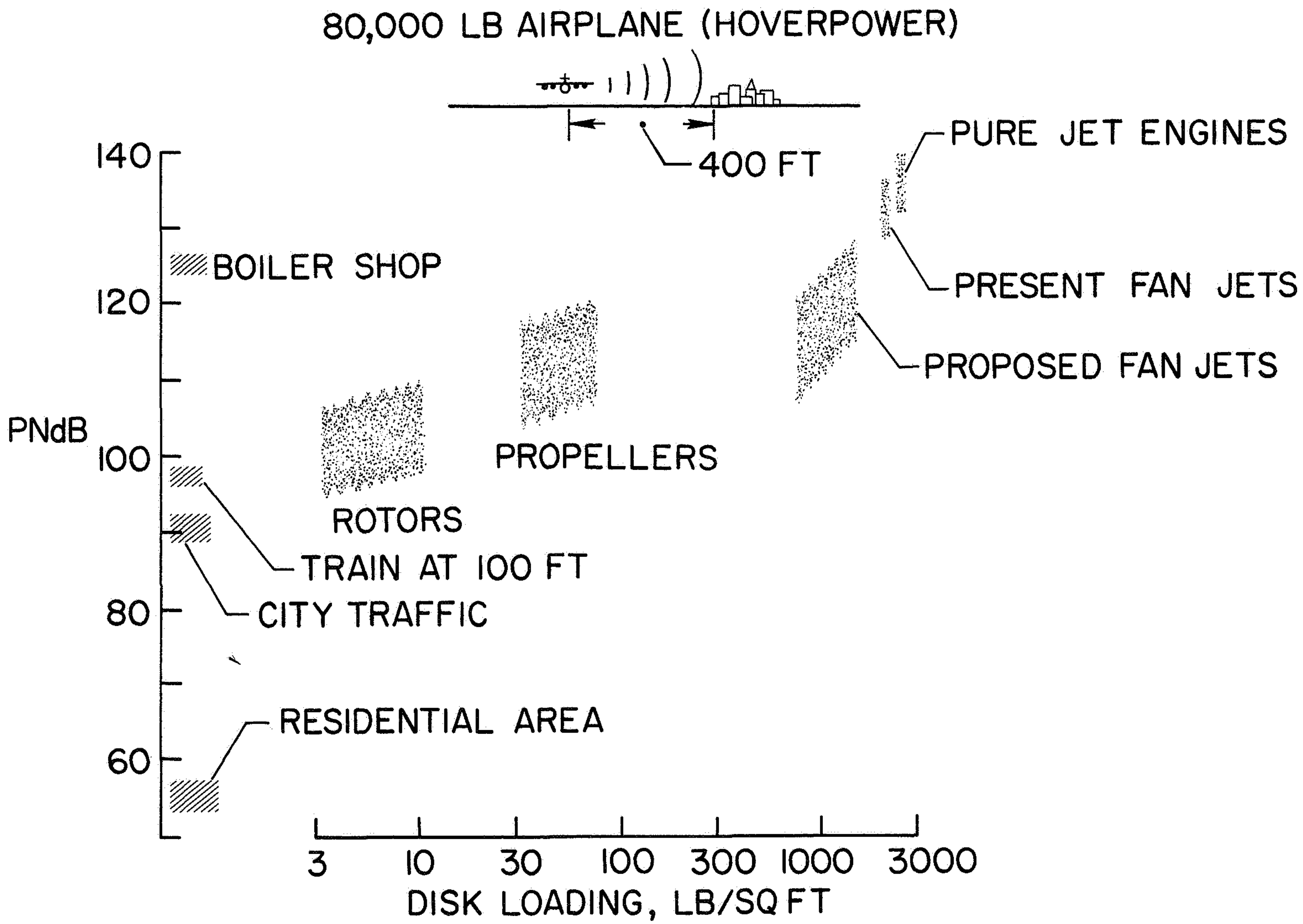

Figure 3.- Noise of V/STOL types.

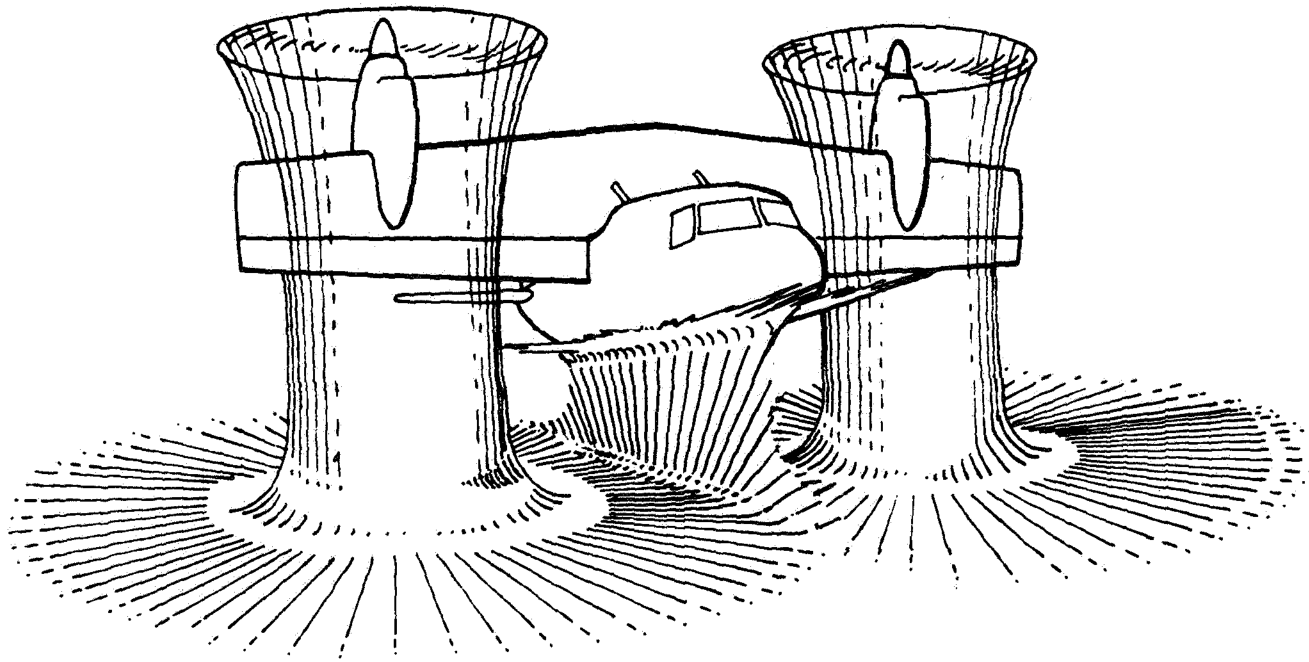

Figure 4.- Illustration of slipstream impingement and recirculation for V/STOL aircraft.

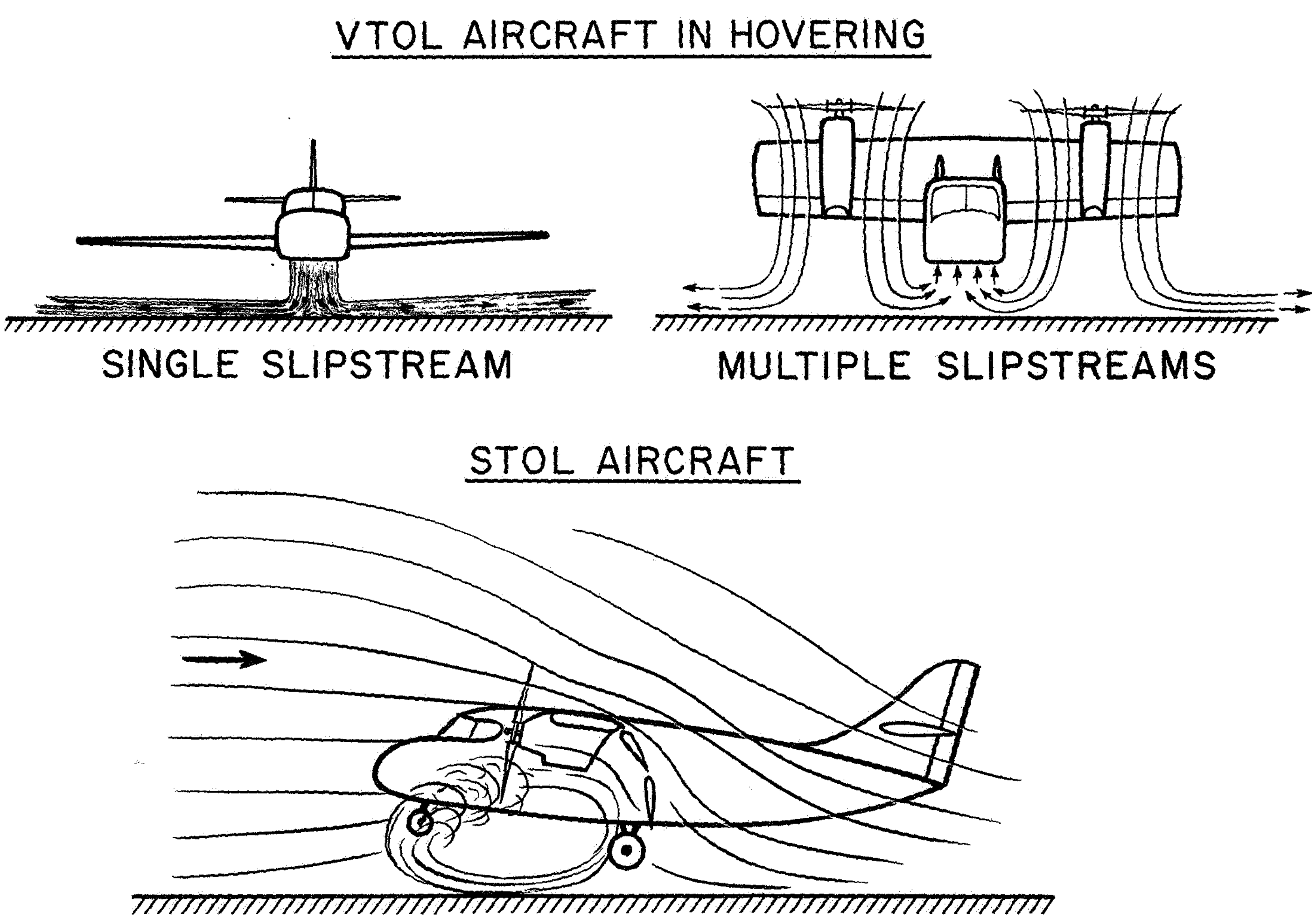

Figure 5.- Flows around V/STOL aircraft in ground effect.

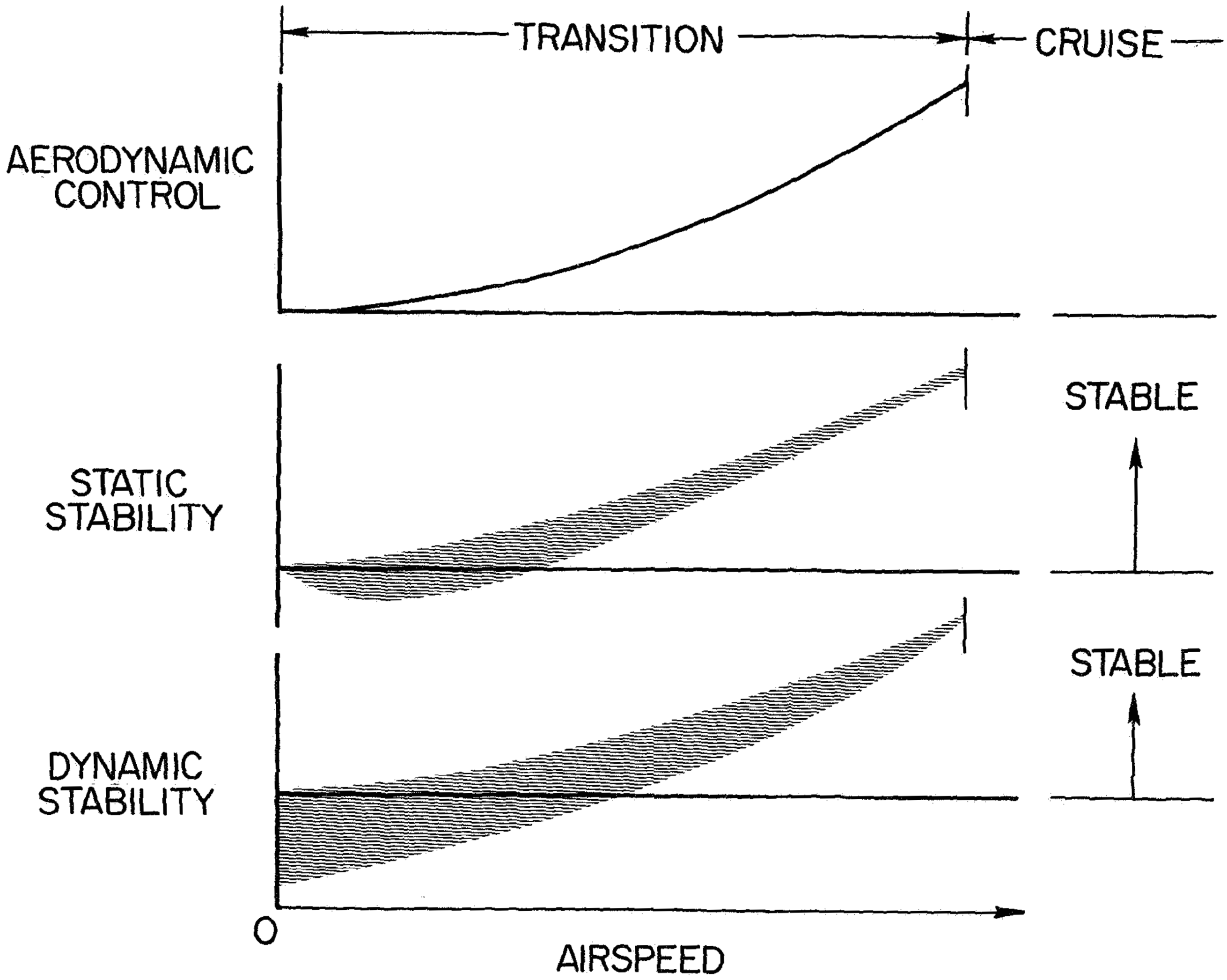

Figure 6.- Aerodynamic stability and control of V/STOL aircraft in hovering and transition flight.

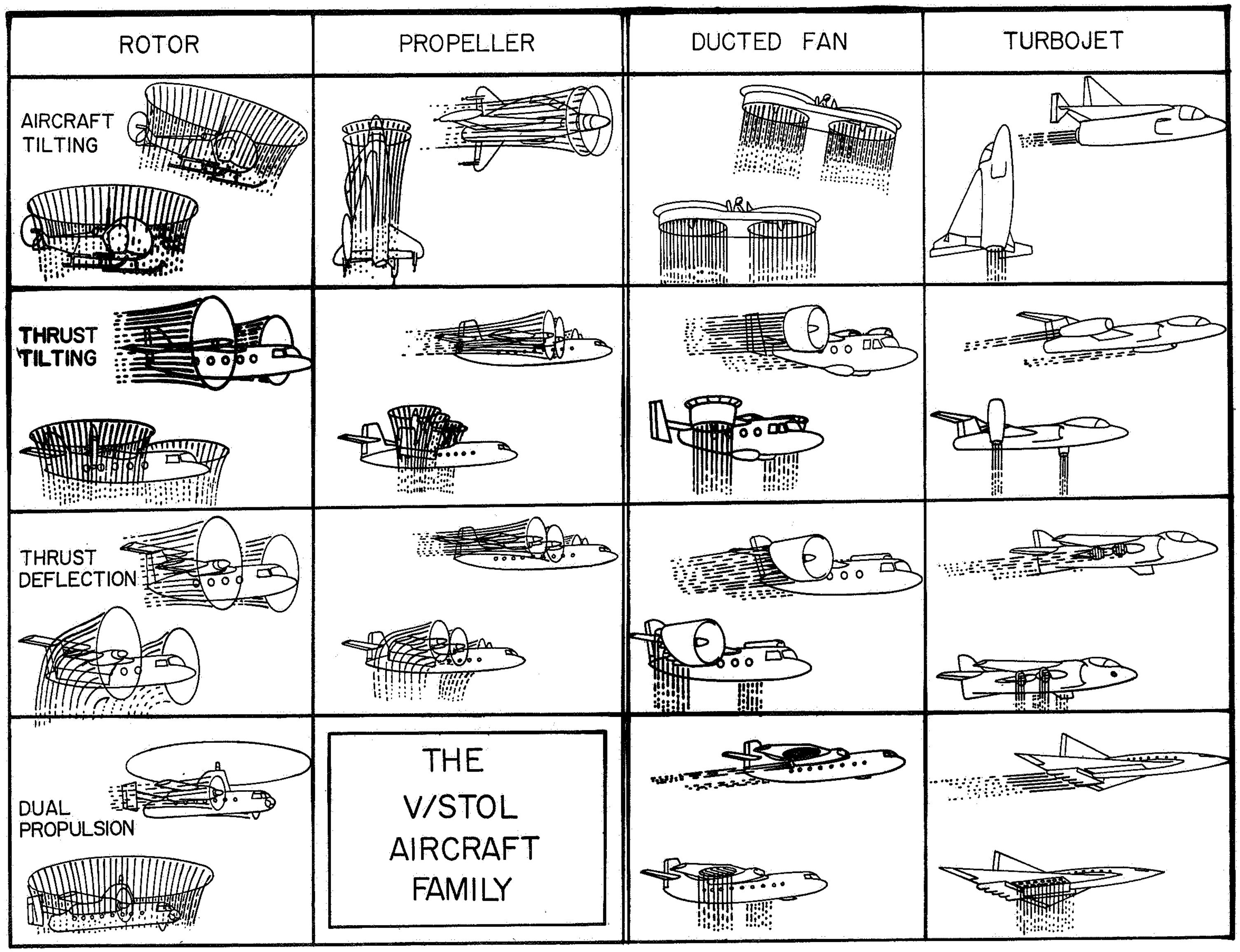

Figure 7.- V/STOL aircraft family.

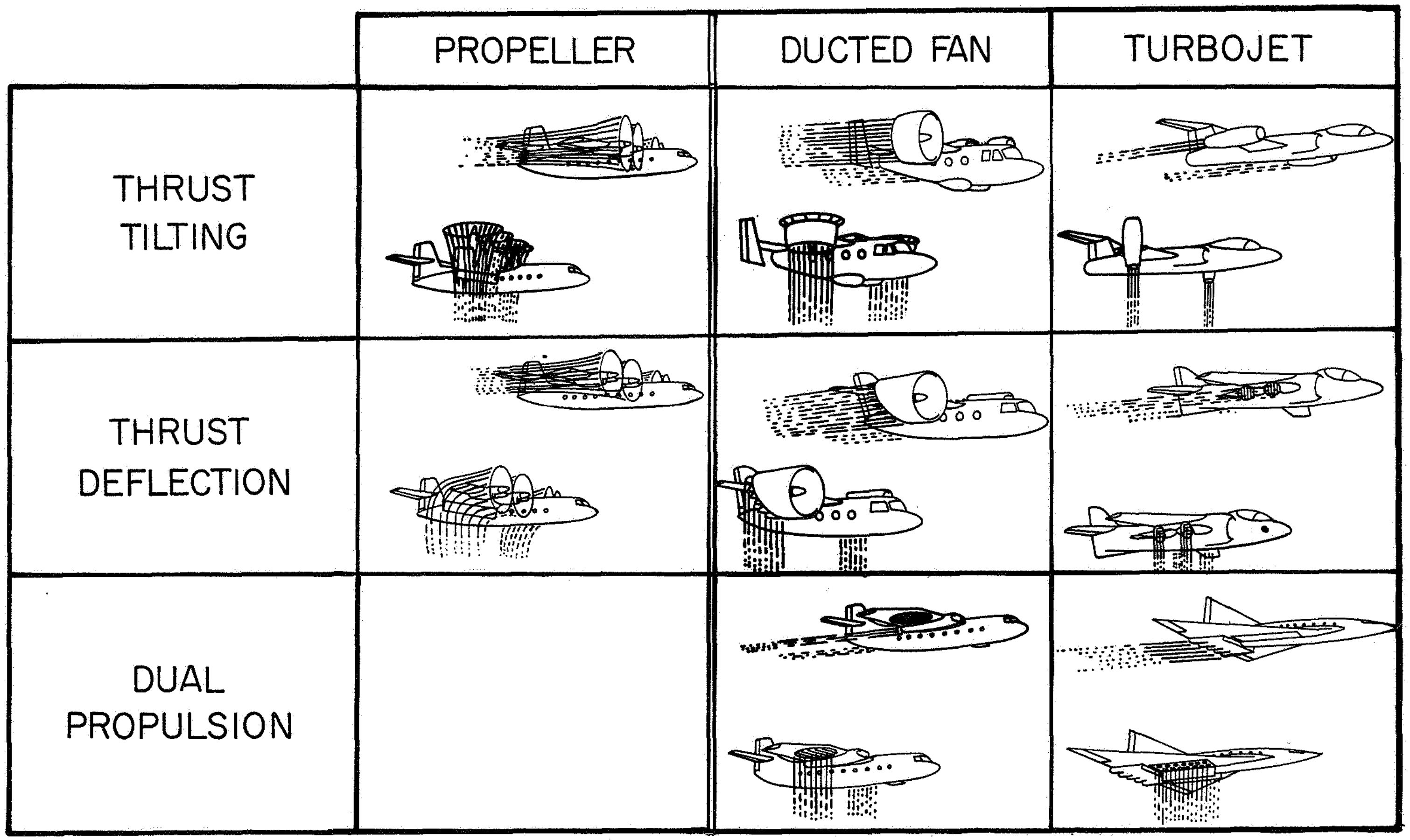

Figure 8.- Configurations covered in V/STOL session.

COUNTRY	PROPELLER	DUCTED FAN	TURBOJET
CANADA	1		
FRANCE			2
GERMANY			2
GREAT BRITAIN			2
UNITED STATES	5	3	3
TOTAL	6	3	9

Figure 9.- V/STOL aircraft designs flown to date (excluding aircraft-tilting types).

EXPERIMENTAL AND RESEARCH AIRCRAFT

V/STOL TYPE	AIRCRAFT FLOWN	ACCIDENTS
PROPELLER	11	5
DUCTED FAN	5	3
TURBOJET	17	7
TOTAL	33	15

OPERATIONAL EVALUATION SQUADRON

V/STOL TYPE	AIRCRAFT FLOWN	ACCIDENTS
TURBOJET (P.1127)	9	2

Figure 10.- V/STOL accidents.

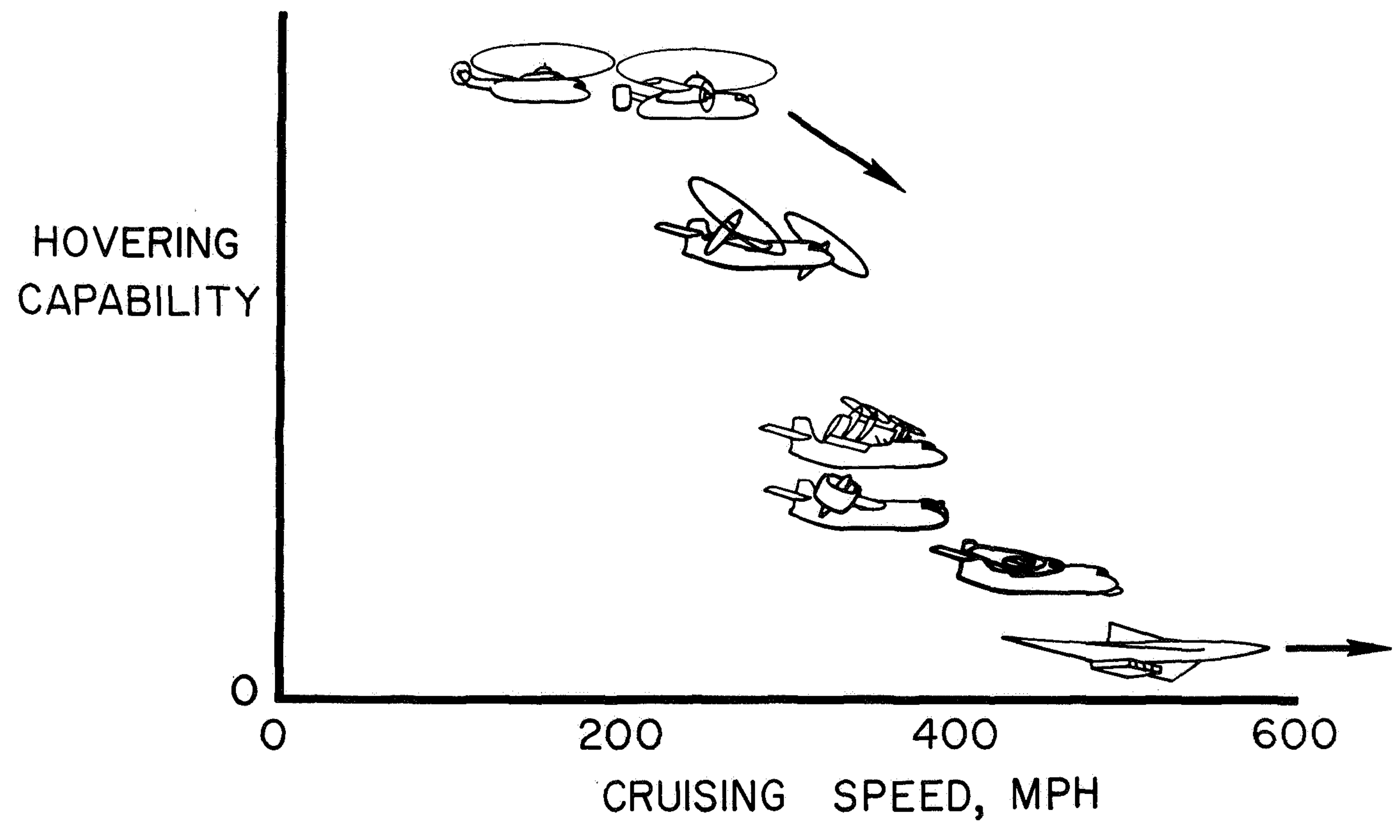

Figure 11.- V/STOL hover-cruise trade-off.

NASA-Langley, 1967