Solving for V_{GE},

$$V_{GE} = \left\{ \frac{2}{\rho} \left[- C^2 \left(\frac{V^2 + W_\infty^2}{V^2 + W_{GE}^2} - 1 \right) P_{S_\infty} \right] + V^2 \right\}^{1/2}$$

For sea-level standard day conditions, $V = V_C$ and

$$V_{IGE} = \left\{ \frac{2}{\rho_0} \left[- C^2 \left(\frac{V_C^2 + W_\infty^2}{V_C^2 + W_{GE}^2} - 1 \right) P_0 \right] + V_C^2 \right\}^{1/2} + V_{P_\infty}$$

where V_{P_∞} is the flaps up static source correction out of ground effect. Experience has shown that indicated airspeed is nearly constant with altitude for altitudes from sea level to 10,000 ft. Therefore, indicated airspeed in ground effect will be nearly constant for low altitudes.

A similar equation may be developed for airplanes with flaps deflected by taking into account the change in induced drag due to flap deflection. The induced drag of wings with deflected partial-span flaps consists of three components:

$$C_{D_i} = (C_L^2/\pi Ae) + \text{“}v\text{”}C_L \Delta C_L + \text{“}w\text{”}(\Delta C_L)^2$$

where $\Delta C_L = (d\alpha/d\delta)\delta(dC_L/d\alpha)$ and indicates the two-dimensional increment of the lift coefficient in those wing parts that are equipped with flaps. Numerical values for "V" and "W" are presented in Ref. 2. An approximate equation for C_{D_i} may be found by assuming average values for the various constants involved.[1] Thus, assuming $d\alpha/d\delta = 0.5$ and $dC_L/d\alpha = 0.1$ the induced drag coefficient is found to be in the order of

$$C_{D_i} = (C_L^2/\pi Ae) + K_1 C_L \delta + K_2 \delta^2$$

where δ is in degrees.

For rectangular or tapered wings $K_2 \approx 2.3 \times 10^{-6}$ for flap-span ratios between 0.3 and 0.55. The K_1 factor (indicating a variation of the lift distribution along the span) is a function of the wing-plan form. Numerical values of K_1 may be obtained from Fig. 2. K_1 is positive for triangular wings (having zero taper ratio). This means that upon deflecting inboard flaps, the concentration of lift in the center part is increased. K_1 is negative for rectangular wings; their lift distribution is brought nearer the elliptical optimum by deflecting flaps.

We can now evaluate the constant of proportionality for the flaps down case. Downwash will be

$$(W_\infty)_{\text{FLAPS}} = W_\infty + K_1 \delta V + (K_2 \delta^2 V / C_L)$$

Therefore

$$\left(\frac{W_\infty}{W_{GE}} \right)^2_{\text{FLAPS}} = \left[\frac{W_\infty + K_1\delta V + K_2\delta^2 V/C_L}{W_{GE} + K_1\delta V + K_2\delta^2 V/C_L} \right]^2$$

The flaps down equation then becomes

$$(V_{GE})_{\text{FLAPS}} = \left\{ \frac{2}{\rho} \left[- \left(\frac{W_\infty + K_1\delta V + (K_2\delta^2 V/C_L)}{W_{GE} + K_1\delta V + (K_2\delta^2 V/C_L)} \right)^2 \times \left(\frac{V^2 + [W_\infty + K_1\delta V + (K_2\delta^2 V/C_L)]^2}{V^2 + [W_{GE} + K_1\delta V + (K_2\delta^2 V/C_L)]^2} - 1 \right) P_{S_\infty} \right] + V^2 \right\}^{1/2}$$

and for sea-level standard day conditions,

$$(V_{IGE})_{\text{FLAPS}} = \left\{ \frac{2}{\rho_0} \left[- \left(\frac{W_\infty + K_1\delta V_C + (K_2\delta^2 V_C/C_L)}{W_{GE} + K_1\delta V_C + (K_2\delta^2 V_C/C_L)} \right)^2 \times \left(\frac{V_C^2 + [W_\infty + K_1\delta V_C + (K_2\delta^2 V_C/C_L)]^2}{V_C^2 + [W_{GE} + K_1\delta V_C + (K_2\delta^2 V_C/C_L)]^2} - 1 \right) P_0 \right] + V_C^2 \right\}^{1/2} + (V_{P_\infty})_{\text{FLAPS}}$$

where V_{P_∞} is the flaps down static source correction out of ground effect. This indicated airspeed is also good for altitudes from sea level to 10,000 ft. The method presented here has been evaluated for representative aircraft of various types. The method correlates very well with flight test data. Figures 3a–3d are representative examples.

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Impact of Air-Breathing Propulsion System Developments on Test Facilities

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Introduction

The past three or four years have shown a resurgence of interest in the further development of air-breathing propulsion systems. This resurgence has introduced rapid developments in flight propulsion as well as manufacturing and testing, thus causing an acute problem—test facility obsolescence. This note discusses the trends in subsonic, supersonic, and hypersonic propulsion and the problems related to developing test facilities for them.

Large Subsonic Engines

The continuing growth of commercial air travel, air-freight cargo, and military transport requirements are responsible for stimulating the improvement of large subsonic transport engines. Major advances are needed in lower total-noise levels, lower propulsive specific fuel consumptions, higher take-off and cruise thrusts, lower specific weights, and lower maintenance costs. The high-bypass-ratio turbofan engine has emerged as the best over-all compromise to meet these varying demands.

One of the major costs in providing development facilities is the simulation of the environmental atmosphere in which the engines must operate, both at sea level and altitude. Figure 1 shows the general trend of engine airflow requirements. The growth of this important facility parameter has been enormous and is due to the shift from straight turbojet engines to high-bypass-ratio turbofans. This type of engine, with still larger airflows, will play a prominent role in subsonic flight of the future.

There are two main reasons to expect that the growth in required airflow will continue. The first is the continued growth of required thrust. The second is the economic requirement for lower flight specific fuel consumption. To meet these requirements the designer has been forced to put the energy output of the core engine into larger and larger fan airflows, thus accounting for the major increase in required airflow which has taken place in recent years.

The basic problems encountered by the engine manufacturer in developing these fan engines are over-all noise level generated by the engine, engine life and reliability, and development of and the accurate determination of the required installed performance of the engine.

Much fundamental work is being done on the noise problem. Efforts are directed at both the origin of the noise and at

Presented as Paper 67-779 at the AIAA 4th Annual Meeting and Technical Display, Anaheim, Calif., October 23–27, 1967; submitted October 17, 1967; revision received March 18, 1968.

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methods to attenuate it. The solution requires the use of outdoor run-up stands, in which far-field sound measurements can be made, and a limited number of aircraft flyover tests. As such, this problem has little impact on major test facilities, except that more outdoor test stands are necessary.

Importance of engine life and over-all reliability have increased. These factors are commanding greater attention in the design and early development stages of engines. Many component and complete engine sea-level static test facilities have been designed for accelerated life testing in the early development cycle. Simulation of the entire mission of a propulsion system in a manner that would permit accelerated life testing would be invaluable toward this objective; however, the complexity and costs appear to be prohibitive. Some new ideas and economic evaluation studies of test facilities for these problems are needed.

Sea-level conditions impose more severe mechanical limitations of subsonic engines than do altitude operating conditions. The opposite is the case for aerodynamic limitations. It is imperative that some aerodynamic development work be done under simulated altitude conditions. If the engine design is such that the large bypass fan can be separated from the core engine, the aerodynamic development of the two components may be carried on to a point separately. In such cases, the altitude simulation facilities necessary to develop the core engine are smaller than those for the fan and generally will be within the capability of existing facilities.

Possibly, the fan could be developed in scale model size through its full-scale performance. If true, the justification for full-scale altitude simulation testing of the complete engine must be for the following reasons: 1) to verify the predication of altitude internal engine performance, based on full-scale sea-level tests of the complete engine, plus extrapolation of fan performance from sea level to altitude, based on scale model tests; 2) to uncover any unforeseen aerodynamic or mechanical effects, at altitude, upon the fan and engine system not detectable at sea level. Also, there is the question of the transition from sea-level static engine performance or expected altitude internal performance to actual altitude installed performance under flight conditions.

Accurate methods of determining the over-all installed flight performance of engines have not been available. Considerable testing is done at sea-level static conditions, and reasonably accurate measurements can be and are made during these tests. The problem is to determine the actual installed flight performance. Wind-tunnel tests, direct-connect altitude tests, and data extrapolated from sea-level tests

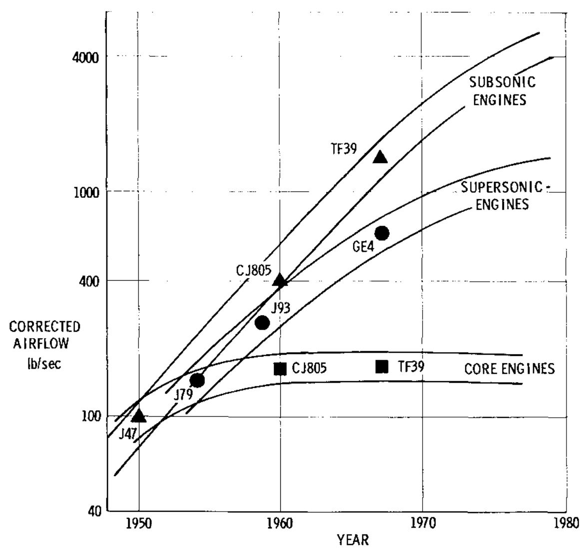

Fig. 1 Trends in correct airflow for subsonic, subsonic core, and supersonic engines.

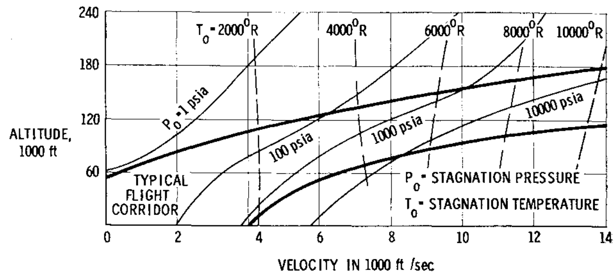

Fig. 2 Reservoir requirements for flight duplication.

along with flight tests are some of the methods used to define installed performance. Most data from these various approaches do not completely answer the question—what is the installed performance? The basic impact of the large subsonic fan engines, if they are to be tested as a complete system, is to make altitude test facilities extremely large and costly.

Supersonic Engines

The supersonic engines proposed for commercial and military aircraft are afterburning turbojets, dry turbojets, duct burning fans, and turbo-ramjets. Figure 1 also shows the trend of supersonic engine airflow. As in subsonic engines, this trend shows large growths in this governing test facility parameter. Because the engine thrust is directly related to airflow, Fig. 1 is also a trend in thrust level.

Subsonic engines, at altitude, operate at lower pressure and temperature levels than at sea-level static conditions. Engines in supersonic flight operate at inlet pressures and temperatures above sea-level static conditions. It is therefore mandatory that altitude environmental simulation facilities be provided which allow a substantial portion of the engine mechanical developmental testing to be done at actual altitude maximum operating conditions. This means that inlet air must be provided at pressures of 2 or more atm and at elevated temperatures.

Development of the inlets and exhaust nozzles pose major facilities problems beyond those of the gas generator. The interaction between the inlet and engine are so closely interwoven that it is desirable to evaluate both together under simulated flight conditions to assure their compatibility. Inlet generated distortion effects on engine performance, engine operation effects on inlet unstarts, and inlet unstart effects on engines are some of the recognized problems.

The simulation of the high-Mach-number operation of the combined inlet/engine system adds substantially to facilities requirements over that demanded for just the basic engine. Another major increase in required facilities results if simulation of the mechanical and aerodynamic operation of the exhaust nozzle is required. At Mach 2.7 the biggest single block of energy change occurs in the exhaust nozzle, the second biggest is in the inlet, and the smallest is in the actual engine itself. All three have an important influence on the over-all installed performance of the propulsion system.

As in the subsonic engines case, increasingly complex degrees of simulation of environment require more expensive test facilities. From component environment simulation through sea-level engine test, direct connect altitude test, propulsion wind-tunnel test, and finally flight test, various key development problems are solved. Large propulsion wind tunnels with dynamic capability would come closest to actual flight test; however, detailed technical and economic studies are necessary to provide realistic answers to the question of the proper economic balance between costs and risks for various levels of flight simulation.

Hypersonic Engines

Hypersonic engines[1–3] are those operating above Mach 5. Many studies have been conducted on "aircraft" with air-breathing propulsion systems that fly from Mach 5 to near orbital velocities. Two of the most interesting applications for such systems are the hypersonic transport and recoverable space boosters. Figure 2 shows the approximate flight corridor in which these systems would operate.

Hypersonic transports have been considered with cruise Mach numbers from 6 to 12. Propulsion systems for this vehicle seem at this time to fall into three categories. Propulsion for Mach 6 cruise vehicles are generally of the turbo-ramjet variety. "Tandem" or "wrap-around" turbo-ramjets appear attractive. In this Mach number range, liquid methane is an attractive fuel. Size studies of this system vary, but corrected airflows per engine of between 500 and 1000 lb/sec seem inevitable. For Mach 12 cruise vehicles, two propulsion systems are being considered: turbo-ramjets as aforementioned for takeoff, climb, and acceleration to Mach 6 to 8, after which they are shut down and scramjet engines take over, and turbojets for takeoff, climb, and acceleration to Mach 3.5, after which they are shut down and convertible ram-scramjet engines take over. The convertible ram-scramjet engines would change from subsonic burning to supersonic burning at around Mach 7. This system appears most attractive in current studies. Physical size of the turbojet engines again fall into the 500 and 1000 lb/sec class.

Size estimates for the convertible ram-scramjet engines vary because of vehicle size, acceleration, flight altitude, and configuration. Single engine or reasonable sector air flows at the cruise condition should fall between 50 to 200 lb of air per second. The fuel for these systems is liquid hydrogen because of its heat sink and cooling capabilities. Propulsion systems for recoverable space boosters will, in all probability, be based on similar propulsion system combinations.

Development and evaluation of these advanced propulsion systems demands new and larger test facilities. Direct-connect testing can serve many of the requirements, but thrust measurement and inlet compatibility will require some freejet or wind-tunnel testing. The transition from turbojet to ramjet must be developed and demonstrated. Figure 2 shows that facilities for this testing will have stagnation temperature requirements of up to 4000°R and stagnation pressures approaching 1000 psia. For 500–1000 lb/sec sized engines, these requirements dictate enormous air supply and heater capacities, when approached in the conventional manner. It is important to have test operational times of at least 15 min per run, so that the system reliability and life can be demonstrated. The convertible ram-scramjet portion of the propulsion package will have to be evaluated either by the freejet or modified direct-connect† techniques. Figure 2 shows clearly the severity of the conditions. For example, cruise at Mach 12 (13,200 fps at 150,000 ft) results in stagnation temperatures of 9000°R and stagnation pressures of at least 10,000 psia. These conditions when coupled with an engine or a sector of an engine size of the range mentioned lead to truly gigantic arc-heated freejet test facilities. Arc-heater input powers of up to 1000 Mw and air supplies with pressure capabilities need to have operational times in excess of 15 min. These parameters indicate a demand for new techniques in the design of test facilities. Mechanical acceleration or magnetohydrodynamic acceleration are two techniques that do not involve complete aerodynamic acceleration and its accompanying high stagnation pressures and temperatures. These parameters also indicate that large liquid methane and liquid hydrogen storage facilities will be necessary. Considerable research and concept ingenuity must be exercised on the ground-test facility problem in order to minimize costs.

The impact of air-breathing propulsion development on ground-test facilities is threefold: size, cost, and design. It seems clear that both subsonic and supersonic engines will continue to grow in size. Without question some altitude simulation facilities are required to develop the supersonic engine mechanically. Aerodynamic development and verification of internal and in-flight performance of both types must be analyzed for the best economic balance between costs and risks, compared to various levels of flight simulation. Hypersonic engines, on the other hand, require very large pebble bed and/or arc-heated freejet facilities with high pressure capability or new techniques in the design of test facilities. The solution is a continued planning effort, looking at all new developments and creating preliminary designs that consider all the tradeoffs and economics.

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† Modified direct connect is a freejet test of combustion system with inlet involving only a portion of the flight compression.