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Marrying Airframes and Engines in Ground Test Facilities: An Evolutionary Revolution

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Introduction

WHEN I was offered the honor of presenting this 58th AIAA Wright Brothers lecture, I was asked to address the role of ground test facilities in the integration process for airframes and jet engines. This topic is especially appropriate for this lecture series.

Wilbur and Orville Wright, for whom this lecture is named, were, by definition, the first successful practitioners of the art and science of airframe–engine integration for propeller-driven aircraft. History also confirms that the Wright Brothers utilized ground test facilities to support their airframe and engine integration process.[1] Further, although the Wright Brothers' engine was inferior to the engine of at least one unsuccessful competitor, their integration of the propulsion system (engine and propeller) and airframe was superior to that of their competitors. Their integration approach provided the winning edge in areas such as two propellers turning in opposite directions, pusher propeller configuration, substantially higher propeller efficiency, and chain drives to the remotely mounted propellers.[1,2]

Successful integration of airframes and engines has remained a major engineering and management challenge ever since the Wright Brothers' triumph in 1903. From a historical point of view, the last 50 years of aircraft development can be characterized as the jet propulsion era. The scope of this paper is restricted to the marriage of jet engines and airframes during this half-century period, with primary emphasis on turbine engines and a secondary emphasis on ramjet engines. By all measures the increases in aircraft capabilities during this period have been awesome. Aircraft parameters such as range, speed, altitude, payload, all-weather capability, maneuverability, durability, and reliability have all increased by large factors.

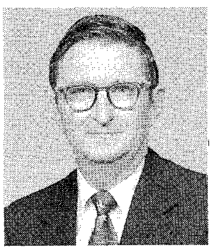
Many of these increases in aircraft capabilities have been enabled by advances in technology and engineering for aerodynamics, thermodynamics, structures, and materials. Another key enabler has been the large increases in net propulsive thrust and thermal and propulsive efficiencies available to the integrated airframe–engine combination. These improvements in propulsion system performance were made possible not only by increased net thrust per unit engine weight and decreased fuel burned per unit thrust, but also because of improvements in the airframe and engine control systems. In addition, improvements in the propulsion system tolerance of adverse weather, i.e., rain, snow, hail, and ice, supported some of the major advances in aircraft capability. Concurrent with these advances in integrated propulsion system capability, other mission-critical improvements in propulsion systems related to environmental factors such as smoke, chemical emissions, noise, and electromagnetic emissions have been developed and qualified.

Some of the evolutionary improvements in integrated airframe and engine characteristics were driven by engineering brilliance and vision. Perhaps a few of the improvements were simply the result of good luck. Certainly, many of the improvements were driven by the pain and agony of previous airframe–engine incompatibility surprises, as will be discussed in later sections.

Successful marriage of an airframe and jet engine is not just a simple handshake at two or three interfaces, but rather, it is a fully integrated, compatible partnership at dozens of interfaces. For purposes of this paper, these numerous interfaces have been organized into three areas related to the function of the airframe and engine combination as follows: 1) performance, 2) operability, and 3) durability/reliability.

There is a second class of airframe–engine interfaces related to the fit of the airframe and engine. Many mechanical, hydraulic, electrical, and electronic parts and connections must fit together as part of the successful marriage of airframes and engines. These fit interfaces and the ground test facilities that support integration are necessarily aircraft system-specific and are not included in this study. Such facilities include full-scale, high-fidelity mockups, computerized virtual mockups, and structural load and deflection rigs.

As important as airframe–engine integration is to the mission capability of aircraft, relatively few studies of the overall process are reported in the literature. Two of the earliest recorded efforts were directed at only one specific integration interface area, the compatibility of inlets and engines from a



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flow distortion viewpoint. The NACA Conference on Engine Stall and Surge was convened at the Lewis Flight Propulsion Laboratory in February 1955; shortly thereafter, the Industry-Government Meeting on Engine-Inlet Duct Compatibility was organized by the U.S. Air Force at Wright–Patterson AFB in June 1955 (Ref. 3). By far the most comprehensive work is the Proceedings of the Air Force Airframe-Propulsion Compatibility Symposium held more than 25 years ago.[4] A later comprehensive review for fighter aircraft only was published by Richey et al.[5] some 12 years ago. As important as ground test support is to the integration process, there is even less information in the archives. One early (1959) example is by NATO–AGARD.[6]

It is the purpose of this AIAA paper to provide a comprehensive assessment of the evolution of ground test support to the total airframe–engine integration process. Many earlier studies of test support to specific portions of this integrated process are reported in the literature, and a number of these are shown in the references. Ground test facilities have supported and continue to support the integration process for airframes and jet engines. The initial U.S. ground test facilities for airframe and engine integration testing became operational during the late 1940s. This study will track the evolution of ground test support to airframe–engine integration since that time.

Ground test capability as used herein is the sum total of the facility drive horsepower, test section size, specialized test equipment, test condition control, and test information acquisition, processing, storage, and retrieval. Key achievements in the evolution of ground test capability will be examined to provide a better understanding of the airframe–engine integration challenges that were successfully met during the past 45 years. A very important byproduct of this examination will be a more complete understanding of the current state of the art of the integration process. Specific examples will be cited that demonstrate the evolution of ground test capabilities that support the airframe–engine integration across broad families of requirements as follows: 1) aircraft size/mission: small unmanned, medium-sized manned fighter/attack, large strategic/logistic; 2) flight speed/altitude: subsonic, transonic, supersonic, sea level, high altitude; 3) aircraft operations: steady-state, straight and level, quasisteady aircraft operation with engine power transients, full transient operation with aircraft maneuver and engine power modulation; and 4) test configuration: subscale airframes with active inlets or exits, uninstalled bare engines, engines with simulated inlets and/or exits, propulsion systems with aircraft forebody, inlet system, engine bay, and engine exhaust system, and complete aircraft.

This accounting of improvements in ground testing support to the integration process for airframes and jet engines over the past half-century will be based largely on U.S. experience. However, insights gained from technical information exchange with members of the NATO alliance and, more recently, from technical information exchange with Russia will be included to permit a more global assessment of the airframe–engine integration process.

In any effort as intensive and extensive as the integration of airframe and jet engines, the equipment and physical assets are very important. Even more important are the energy and genius of the persons who provided leadership. I had the good fortune to be an active participant in the ground testing support to airframe and engine integration processes for more than 40 years. During this time it was my privilege to work with and be mentored by some of the key leaders of the industry, government, and academic teams who made this evolutionary revolution a reality. As opportunities arise, I will recognize these leaders.

In the following sections, an accounting of the many airframe and engine interfaces is provided first. Then, requirements for ground testing support to airframe–engine integration are outlined. Next, the timeline for acquisition of U.S. ground test capability with specific examples for each of the five different types of complementary test facilities is included. Next, a decade-by-decade assessment of the incremental growth of integration test capabilities is provided, along with identification of some of the key advances in analysis and interpretation tools for integration test results. Finally, some personal reflections are shared and pioneer personalities remembered.

Airframe-Engine Interfaces

Overview

The primary focus of this study is the marriage of turbofan and turbojet engines to airframes for manned aircraft. The full range of aircraft types, i.e., tactical, strategic, and transport for military applications and transport for civil applications is included. Each aircraft must be functional over the full range of atmospheric environmental conditions that may exist within the planned theater of operations. Most often today for military and civil aircraft alike, the planned theater is anywhere in the world. In addition, the conventional operational envelopes include altitude, airspeed, maneuverability, e.g., angle of attack, sideslip, roll, and payload. Further, additional internal and external environments are imposed by the engine on the airframe and vice versa. Most of these interfaces are within the engine bay or are external to the engine and within the inlet flowfield and the jet exhaust plume. These environments include thermal heating and cooling (conductive, convective, or radiative), acoustic excitation (aeromechanical), fuel and oil discharges, and electromagnetic emissions.

Effective integration of airframes and jet engines requires success in addressing every interface related to the function of the airframe and engine combination. These numerous interfaces will be organized into three areas related to mission effectiveness as follows: 1) performance–mission capable (can do the job); 2) operability–predictable response to pilot command (no surprises); and 3) durability/reliability–mission available (ready to go). Each of these interface areas is examined in more detail in the following sections. Although these interface areas are discussed separately in the following sections, it is very important to note that these areas are highly interactive. That is, performance levels affect operability margins, operability margins affect durability/reliability margins, and durability/reliability margins affect performance levels, etc. Thus, the airframe–engine integration process requires a simultaneous solution of a matrix with some 50 variables. In almost every case, an increase in performance or margin in one interface parameter will require a reduction (a tradeoff) in some other parameter. There is no free lunch in airframe–engine integration.

Airframe–Engine Performance Interfaces

An extensive, but not all-inclusive, roll-call of the airframe–engine interfaces that relate directly to the performance of an

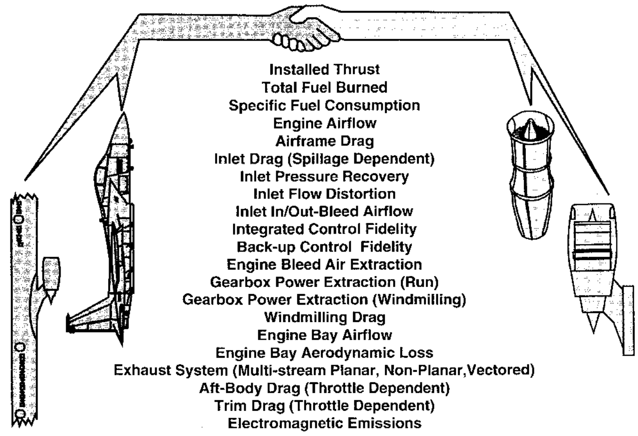


Fig. 1 Airframe–engine performance interfaces.

aircraft is shown in Fig. 1. Of these 21 performance interfaces, some are relatively independent and some are highly interactive, but all behave as continuous functions. Thus, the performance integration process, which ultimately becomes an optimization process, requires the solution of a very large multidimensional matrix when the numerous mission legs (e.g., takeoff, climb, cruise, maneuver, dash, and descent) and the numerous environmental conditions (e.g., standard day, polar day, tropical day, and adverse weather) are added in. This optimization process ensures that propulsion performance meets minimum aircraft requirements at all operating conditions.

Airframe–Engine Operability Interfaces

An extensive, but not all-inclusive, roll-call of the airframe–engine interfaces that relate directly to the operability of an aircraft is shown in Fig. 2. Of these 15 interfaces, some are relatively independent and some are highly interactive. However, unlike the performance interfaces, the operability interfaces behave generally in a discontinuous manner. That is, the interface provides threshold limits for the onset of some undesirable instability. The instabilities include inlet buzz, compressor surge, and combustion blowout, light-off, rumble, and screech. The operability integration process requires the simultaneous definition of the instability limits throughout the aircraft operational envelopes.

Airframe–Engine Durability/Reliability Interfaces

An extensive, but not all-inclusive, roll-call of the airframe–engine interfaces that relate directly to the durability and reliability of an aircraft is shown in Fig. 3. The terms durability and reliability are used jointly to challenge equally the engineering focus on durability and the statistical focus on reliability. The basic meaning is that each system element will not wear beyond usable limits, will not break or fail, and will adequately perform its design purpose within its defined success probability and design life. Most of the 16 interfaces shown are independent of each other; however, the cumulative damage to each system element induced at all interfaces ultimately controls its durability/reliability. Further, in a manner similar to the operability interfaces, the durability/reliability interfaces behave generally in a discontinuous manner and provide threshold limits for the onset of some unacceptable wear or structural damage such as crack initiation, crack propagation, creep, erosion, or corrosion. The durability/reliability integration process requires the summation of incremental parts life consumption over the universe of the aircraft operational usage.

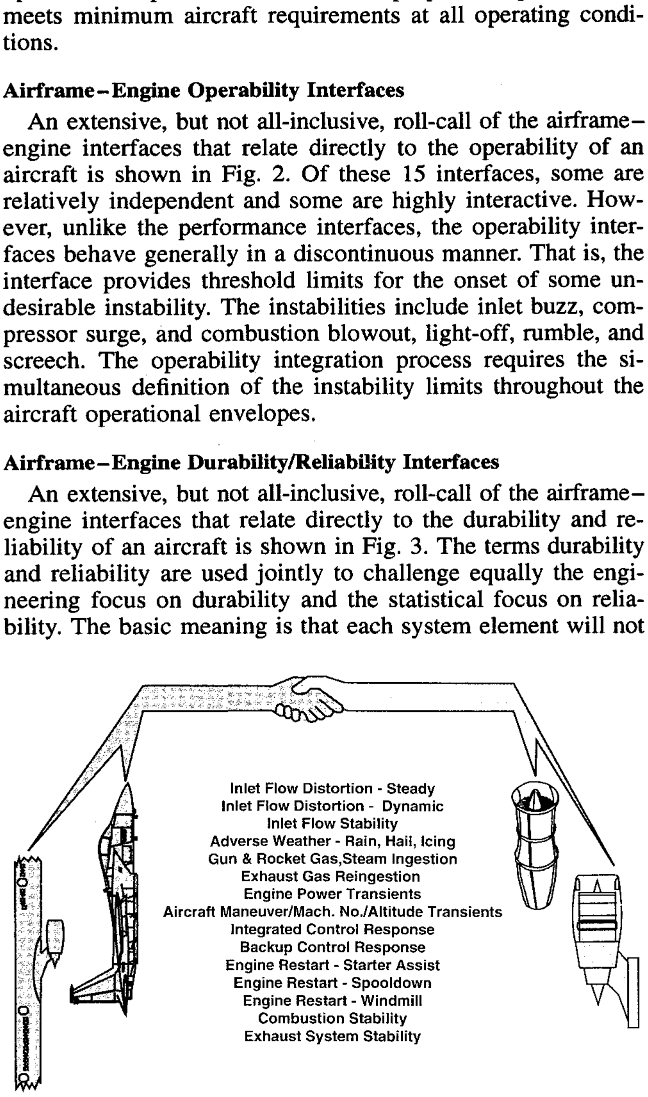


Fig. 2 Airframe–engine operability interfaces.

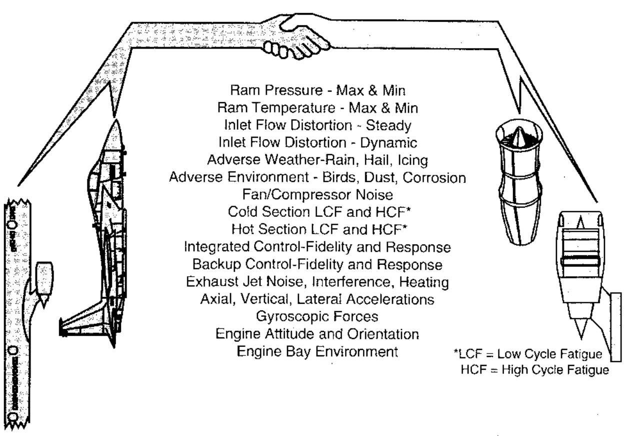


Fig. 3 Airframe–engine durability/reliability interfaces.

Required Ground Testing Support to Airframe–Engine Integration

Our Airframe–Engine Integration Heritage

The more things change, the more they stay the same. This old adage was never more true than for the support provided by ground test facilities to the marriage process for airframes and jet engines.

One of the best ways to communicate the many test requirements that must be addressed in the airframe–engine integration process is to use one or more specific systems as examples. The search for the best example of an airframe/engine/ground test facility combination identified several candidates. Options considered included a futuristic concept, a contemporary operational aircraft, and the documented experience of a now-retired aircraft. The example chosen is not one of these options, but rather an example taken from the earliest days of jet aircraft design and development in the U.S.

The example chosen meets the needs of this paper, and at the same time, affords the opportunity to enjoy and marvel at American engineering and scientific visions at their very best. The example chosen is the L-133 airframe and the L-1000 engine. This single-place interceptor aircraft, powered by two turbojet engines, was proposed by the Lockheed Aircraft Corporation during the 1940–1943 time period. This aircraft was never flown or even built, for that matter. One engine was designed, built, and tested during the 1944–1947 time period for the U.S. Army Air Forces. Unassembled parts for four additional engines were procured by the Army Air Forces during 1946 for delivery beginning in 1947 (Ref. 7).

This Lockheed L-133/L-1000 project was the first serious American work on a turbojet engine by a margin of at least a year.[8] The designer of the L-1000 and later the manager of the Lockheed project was Nathan C. Price. Before joining Lockheed, Price had designed and held patents for a number of steam-powered turboshaft engines for aircraft applications. Earlier, he had designed and flown lightweight reciprocating steam engines for aircraft.[8]

Toward the end of 1940, the Lockheed Corporation decided that the whole aircraft powerplant situation needed a fundamentally new attack if higher speeds and altitudes were to be attained. Price was set to work on the problem, and in six or eight months, he completed preliminary plans and analyses of a gas-turbine jet-propulsion engine. Additional personnel were then assigned to the project, and detailed layouts were made of both the L-1000 engine and the L-133 airframe, a single-seat interceptor intended to utilize the engine. The aims of the designers were high; the plane had a design speed of 625 mph (0.94 Mach) at 50,000-ft altitude.[8]

The L-133/L-1000 airframe–engine combination was certainly the first and probably the only time in the history of U.S. military jet aircraft that an airframe and engine were designed as an integral whole. In many respects the design was novel and proposed to use the jet principle not only for propulsion, but also for aircraft control by means of jets in the wingtips.[8] In addition, an active wing boundary-layer suction system driven directly by power takeoff shafts from the main engine gearbox was proposed. Also, engine shaft power was to be applied directly to the aircraft wheels during taxi and takeoff roll.[9] During 1941, Lockheed management decided to proceed with the development of both the airframe and the engine. These plans were discussed with various Army Air Corps officials in 1941 and were officially submitted to the Army in 1942 (Refs. 7 and 8).

Another unique feature of the Lockheed proposal was that resources for the ground test facilities required for development and integration of the engines and airframe were identified as part of the proposal.[7] The key role of ground test facilities in the development of turbine engines had been made visible by the difficulties being encountered at that very time by Northrup Aircraft, Inc. in the development of the first U.S. turboprop (the Turbodyne). No arrangement was made for provision of test facilities in the contract for this 2500 shaft horsepower turboprop engine. At that time there were no facilities capable of testing the compressor of a 2500-hp engine, other than the engine itself. Acquisition of required test capabilities led to program delays of at least 1 year during the first 4 years of work.[8]

L-1000 Engine/L-133 Aircraft and Ground Test Facilities

A brief review of the key features of the L-1000 turbine engine with reheat, the L-133 airframe, and the proposed ground test facilities (1940s style) will serve a double purpose. First, this review will demonstrate the requirements for airframe–engine integration. Second, this review will refresh awareness of an outstanding piece of U.S. aeropropulsion history. It is helpful to note that the L-1000 engine was redesignated as the XJ-37 in late 1945 or early 1946 to conform with the newly adopted standard for military engine designation.[7]

L-1000 (XJ-37) Turbojet Engine with Reheat

A photograph of the L-1000 (XJ-37) engine is shown in Fig. 4. The L-1000 (XJ-37) engine was designed to deliver a maximum takeoff thrust at sea-level conditions of 5000 lb. The design military thrust was 2390 lb at sea-level-static conditions.[10] The maximum o.d. at the compressor front frame was 25 in., the overall length was 123.5 in., and the engine weighed about 1500 lb, including accessories. Many of the details of the gas path components are shown in the engine cutaway drawing (Fig. 5). Some of the most interesting features of the components and their performance at rated power are as follows[9,10]:

1) *Compressors*: 32-stage axial flow, three spools; 4-stage low-pressure compressor (LPC); 12-stage intermediate-pressure compressor (IPC); and 16-stage high-pressure compressor (HPC). Design overall pressure ratio, 25 @ sea level–Mach numbers 0.73 and 43 @ 35,000 ft–Mach number 0.92; HPC direct drive from turbine; IPC driven by reduction gear set from HPC drive shaft; and LPC driven by variable speed fluid drive from IPC drive shaft.

2) *Compressor intercooler*: cylindrical, liquid-cooled, heat exchanger. Cooling temperature drop, 115°F @ sea level–Mach 0.73 and 58°F @ 35,000 ft–Mach 0.92.

3) *Primary combustion chamber*: annular configuration, rated discharge temperature, 1840°F.

4) *Turbine*: four-stage axial flow; single-spool; stage 1 reaction blading; stages 2–4 impulse blading; all blades hollow, pressure cast with tapered walls; rated turbine inlet temperature, 1840°F.

5) *Exhaust reheat*: fuel injection intraturbine at leading edge of third-stage turbine vanes. Tailpipe cooling–corrugated cooling liner.

6) *Exhaust nozzle*: fully modulating, variable-area, converging–diverging exhaust nozzle.

In addition, as will be discussed further in the L-133 aircraft section, the engine had six power takeoff shafts to meet both engine control and accessory requirements and airframe power requirements. These six accessory drive shafts were incorporated in the reduction gear set that powered the intermediate pressure compressor.

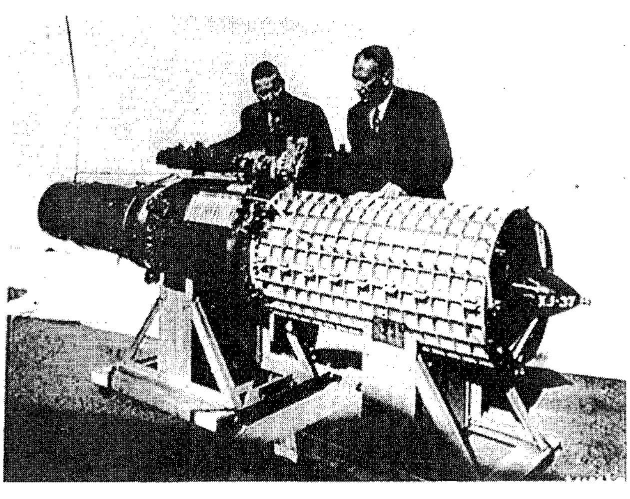


Fig. 4 L-1000 (XJ-37) turbojet engine with Nathan C. Price, engine designer and Hall L. Hibbard, Vice President and Chief Engineer, Lockheed Aircraft Corp. (Ref. 10).

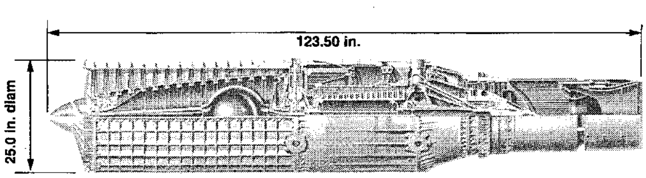


Fig. 5 Cross section of L-1000 (XJ-37) turbojet engine with reheat (Ref. 9).

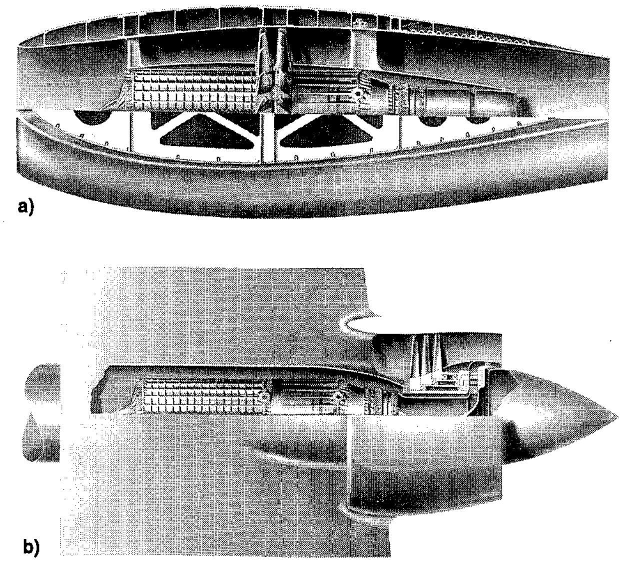


Fig. 6 L-1000 engine variants-ducted propeller (Ref. 9): a) gear-driven intube propeller (mid fan) and b) turbine-driven intube propeller (aft fan).

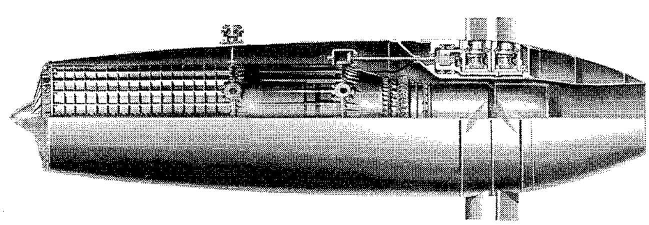


Fig. 7 L-1000 engine variants-unducted fan (Ref. 9).

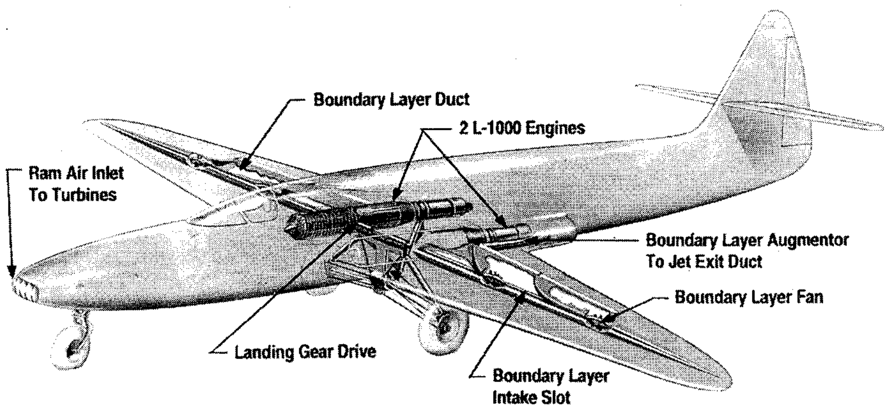


Fig. 8 L-133 jet-powered, single-place interceptor (Ref. 9).

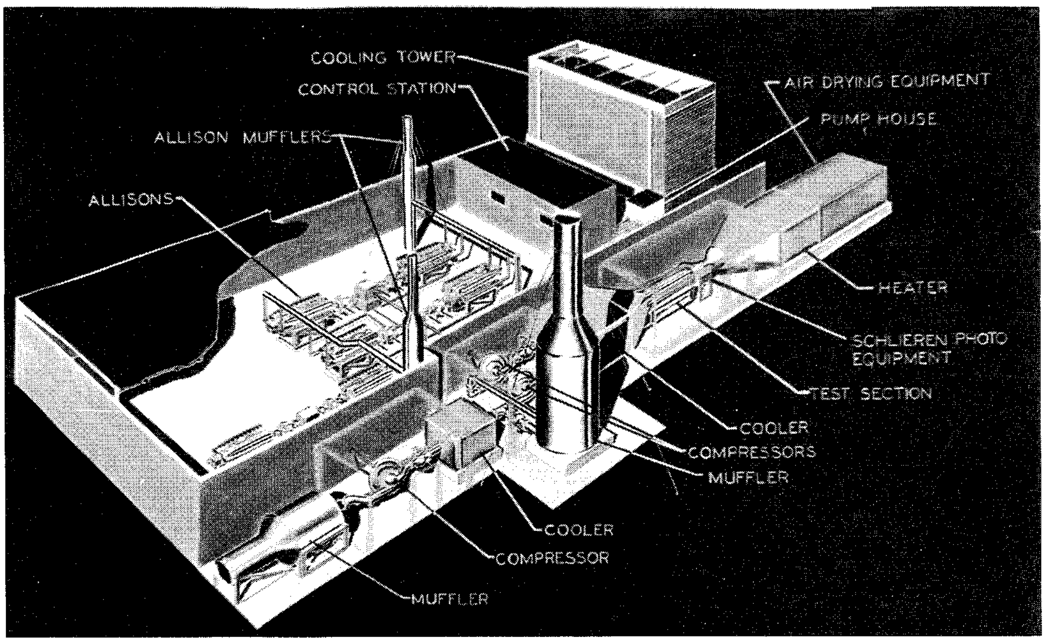


Fig. 9 L-1000 (XJ-37) air facility—Allison V-1710 power (Ref. 9).

L-1000 Engine Variants

Conceptual designs of a number of very interesting variants of the L-1000 turbojet engine were also prepared by Lockheed during this period. These variants are extremely interesting in the light of the actual evolution of the jet engine during the 1945–1995 period. Some of these variants are included here to reinforce the idea presented earlier that the more things change in the airframe–engine integration field, the more they stay the same.

Two versions of the L-1000 engine equipped with ducted propellers are shown in Fig. 6 (Ref. 9). A gear-driven intube propeller configuration is shown in Fig. 6a. This turbofan configuration included a ducted propeller located midway along the engine compressor. The shaft power to drive this propeller was derived from the engine turbine. This engine configuration is very similar to the prototype gear-driven forward fan turbofan (PLF1A) developed by AVCO-Lycoming during the mid-1960s. A turbine-driven intube propeller configuration is shown in Fig. 6b. This turbofan configuration included a ducted propeller located aft of the engine. This propeller was powered by a three-stage, counterrotating radial free turbine. Again, this engine configuration is very similar to the aft fan turbofan (TF37) developed by General Electric during the mid-1960s. One version of the L-1000 engine equipped with an unducted fan is shown in Fig. 7. These variable-pitch, counterrotating, unducted fan stages were gear-driven from the engine turbine.

L-133 Jet-Powered Single-Place Interceptor Aircraft

A conceptual drawing of the L-133 aircraft powered by two L-1000 engines is shown in Fig. 8 (Ref. 9). This arrangement of airframe and engines is very conventional by today's standards. As discussed earlier, this example contains all of the airframe–engine integration interfaces identified in Figs. 1–3 plus two additional interfaces as noted later, which affect the performance, operability, and durability/reliability of the aircraft system. It can be successfully argued that in the era before the advent of electronics and computers, the integration of the stick-and-pedal aircraft controls with the hydromechanical engine controls through the pilot/operator was a simpler process than today's fully integrated digital controls, but the integration challenge remains. On the other hand, the integration challenge of the engine-powered boundary-layer control system has been addressed only on research aircraft up to the present time. The airframe–engine integration challenge for direct drive of the landing gear wheels from the engine has yet to be addressed.

Ground Test Facilities for Integration Testing of L-1000 (XJ-37)

Conceptual designs of a number of ground test facilities required to support development and integration of the L-

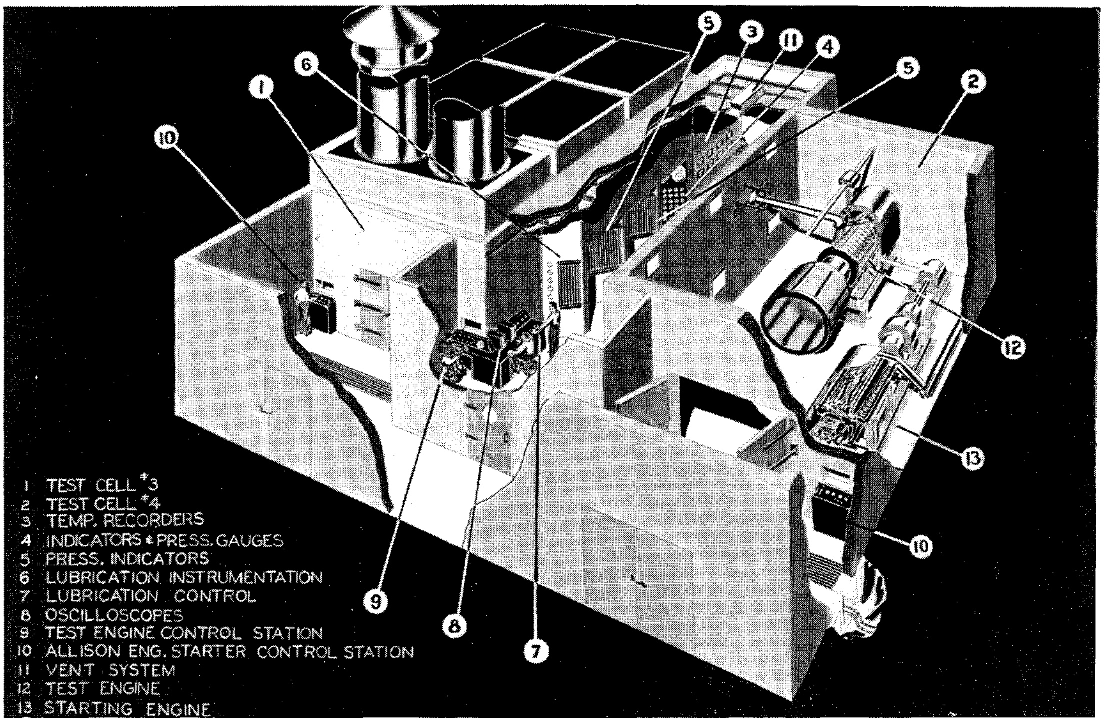


Fig. 10 L-1000 (XJ-37) test cells no. 3 and 4 (Ref. 9).

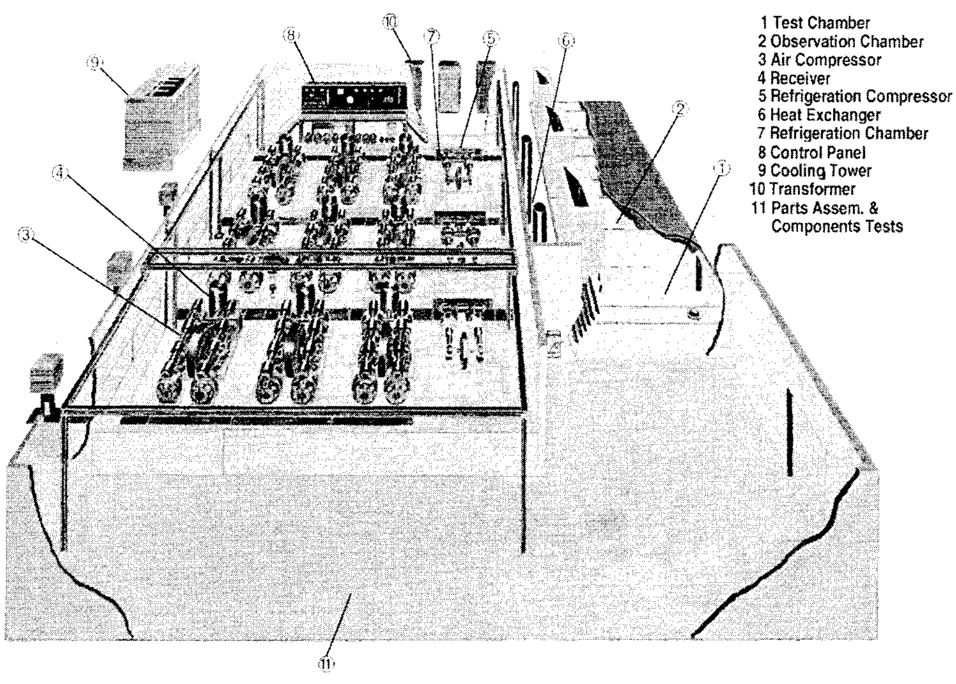


Fig. 11 L-1000 (XJ-37) engine test facility—electric power (Ref. 9).

1000 (XJ-37) were prepared during this period. Three examples of these test facilities are shown in Figs. 9–11. Please note that Figs. 9–11 were prepared by the Menasco Manufacturing Company. (Ref. 9). The Air Facility shown in Fig. 9 included a two-stage exhaust gas pumping system and a dried and heated atmospheric air supply to permit engine testing at simulated high-speed, low-altitude conditions. Note that the exhaust gas compressors are powered by banks of Allison V-1710 reciprocating aircraft engines. The engine test cells 3 and 4 shown in Fig. 10 would provide engine test capability at ambient ground-level conditions. An alternate engine test facility configuration that included provisions for refrigerated air supply and altitude exhaust is shown in Fig. 11. This pumping system is based on the use of electric drive motors and reciprocating compressors. This pumping system configuration is similar to that installed in the Altitude Wind Tunnel (AWT) at the NASA Lewis Research Center during this same time period.

At Lockheed's request, the U.S. Army Air Forces transferred the balance of the work remaining on the contract to Menasco on Nov. 3, 1945, but Lockheed retained contractual responsibility. As a part of this transfer, the entire staff at Lockheed attached to this project and the special facilities in use were transferred to Menasco.[7,10]

Current Airframe–Engine Integration Requirements/Approach

The roll call of current airframe–engine interfaces shown in Figs. 1–3, and the brief examination of the U.S. heritage of airframe–engine integration requirements confirm that the overall requirements for a successful marriage of jet engines with airframes have remained remarkably constant throughout the first 50 years of this industry. In addition, this historical perspective confirms that fully capable ground test facilities were viewed as an essential element in this process from the very beginning. In spite of this auspicious precedent, however, a number of times during the ensuing 50 years the commitment of national resources to provide test facilities has waned as shown by the evolution of U.S. airframe–engine integration test capabilities in the next section of this paper. Further, it is important to note that during this period some aircraft development programs elected not to utilize the then available ground test facilities to support airframe–engine integration. However, an accounting of ground test support to specific aircraft programs is beyond the scope of this work, and no details of individual programs are included.

While the big picture requirements have remained relatively constant for the past five decades, the details of the requirements have undergone massive changes. First, a most obvious area of change has been the expansion of the aircraft operational envelopes in all dimensions (altitude, speed, maneuvering attitudes and rates, payloads, and operating lifetimes of the hardware). Second, perhaps the most challenging change has been and is the drive toward increased accuracy in optimization of all integration parameters. Increased accuracy is required to reduce the design margins of performance, (e.g., thrust), operability (e.g., compressor surge margin), and durability/reliability (e.g., hot section life), which are necessarily allocated to cover process control and hardware variabilities. Operation of aeropropulsion systems closer and closer to the ideal simultaneous limits of performance, operability, and durability/reliability is essential to advancing the state of the art of military and civil aircraft. Third, in a totally different dimension, increases in airframe–engine integration requirements have been driven by advances in controls and information processing capability. It is clear that the designers of the L-133/L-1000 system could not foresee the availability of fully integrated, full-authority, digital control systems for both airframe and engine.

However, it is also fair to say that not once since the days of the L-133/L-1000 has the airframe–engine integration community been called upon to design and develop engine-powered landing gear to increase propulsive efficiency during takeoff roll. Similarly, although major strides have been made in applying active boundary-layer suction to improve aircraft lift and drag performance of experimental aircraft, the airframe–engine integration community has not yet been called on to design, develop, and certify (qualify) a boundary-layer control system for an operational aircraft.

Ground Test Capability for Airframe–Engine Integration

Overview

Examination of the timeline for the acquisition of ground test capability to support airframe–engine integration provides substantial insight into the evolution of the integration process. For purposes of this paper, this examination focuses on U.S. domestic capability, but includes some corroborating observations of foreign capabilities. This examination is restricted to altitude test facilities (simulated environmental facilities) and does not include ground test facilities that operate at local static atmospheric conditions. Suffice it to say that because of low capital investment and short construction lead times, the acquisition of static ground-level facilities has kept pace with the perceived needs during the jet engine era.

On the other hand, the acquisition of simulated environmental facilities for airframe–engine integration tests involves very large investments of capital and very long lead times. Thus, an evaluation of incremental increases in such test facilities provides understanding of the changes in the integration process. Such facilities include altitude engine test cells having freejet and/or direct-connect capabilities and aerodynamic, inlet-engine, jet effects, and propulsion wind tunnels. Freejet and inlet-engine test capability is defined here to mean test section size and capacity sufficient to test the complete, full-scale engine mated with a part of the airframe propulsion-related components (e.g., inlet, engine bay, and nacelle) immersed in a relatively small portion of the aircraft external flowfield. The larger capacity of propulsion wind tunnels permits testing of the complete full-scale airframe and propulsion system for small missiles in a nearly interference-free external flowfield.

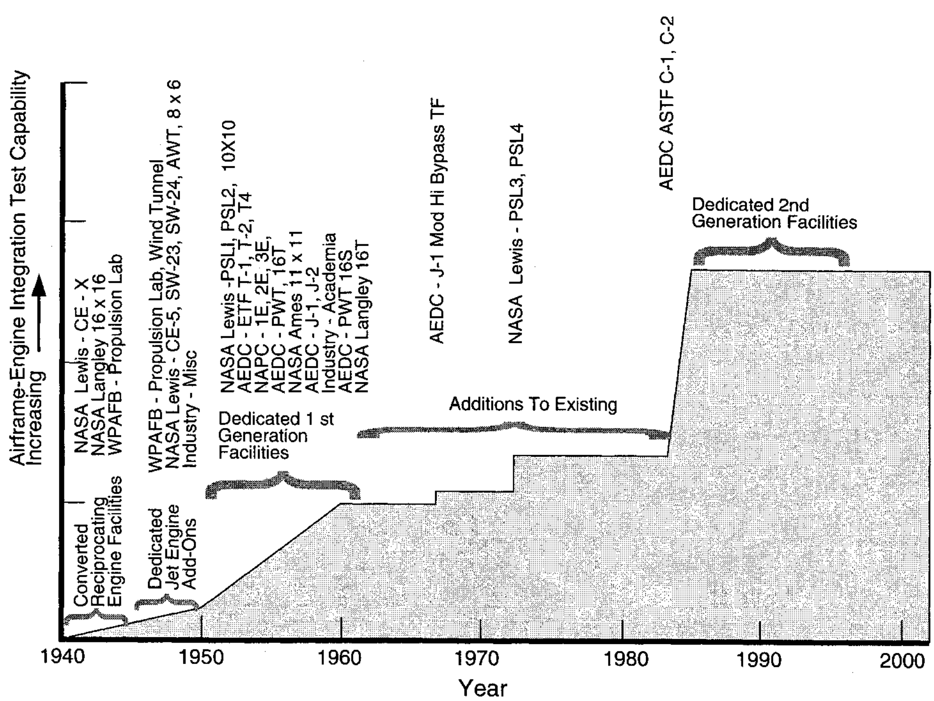


Fig. 12 Acquisition timeline: U.S. ground test facilities for airframe–engine integration.

Direct-connect test capability is defined here to mean test section size and capacity sufficient to test the complete full-scale engine directly connected to test fixtures that simulate some of the primary parameters of the propulsion system flows at the inlet and exhaust of the engine only. Frequently, the propulsion wind-tunnel inlet-engine, and freejet test articles are referred to as installed engines, and the direct-connect test articles are referred to as uninstalled engines.

The test capability timeline discussed next addresses only maximum capability examples to show the progression. Many contemporaneous examples having lower capabilities are omitted for the sake of brevity. These smaller units contribute in a major way to the total national test capability.

Ground Test Facility Acquisition Timeline

The timeline for acquisition of ground test facilities for airframe–engine integration testing is shown in Fig. 12. The initial environmental test facilities for jet propulsion in the U.S. were converted reciprocating engine facilities from the World War II period. During the late 1940s a number of dedicated jet engine add-on test units and the first propulsion wind tunnel were placed in operation at NASA Lewis.

The 1950s were a decade of rapid increase in U.S. airframe–engine integration test capabilities. Most of this increase was a direct result of the enactment of Public Law 81-415, Unitary Wind Tunnel Plan Act of 1949 and Air Engineering Development Center Act of 1949 by the U.S. Congress.

Primary advocates of this public law included H. H. Arnold, Theodore von Kármán, Jerome Hunsaker, George Lewis, Arthur Raymond, and Frank Wattendorf.[11] New, dedicated first-generation test facilities became operational at NASA and Department of Defense (U.S. Air Force and Navy) centers and at industrial and academic locations during the 1950s (Fig. 12) under provisions of these acts. The NASA facilities were located at the Ames, Langley, and Lewis laboratories, and the Air Force and Navy facilities were located at the Arnold Engineering Development Center (AEDC) and Naval Air Propulsion Center (NAPC), respectively. These facilities included all five categories of integration test capabilities, i.e., propulsion wind tunnels, inlet-engine wind tunnels, jet effects wind tunnels, altitude engine test cells, and aerodynamic wind tunnels.

The national airframe–engine integration test facilities remained basically constant from 1961 to 1985. Two notable increases were the addition of test capability for the new high-bypass turbofan engines at AEDC and the addition of PSL Cells 3 and 4 at Lewis. As will be shown later, however, these decades were periods of rapid increase in the development and application of new test capabilities within the existing test facilities.

A major increase in airframe–engine test capacity and capability was realized in 1986 when the Aeropropulsion Systems Test Facility (ASTF) was placed in operation at the AEDC. As a new second-generation test facility, the ASTF more than doubled the existing national engine test capacity.

At the present time, limited preliminary planning for future increases in integration test capabilility is underway. Detailed planning is in progress for the National Wind Tunnel Complex (NWTC). Currently, both of the tunnels included in the NWTC are configured as aerodynamic wind tunnels, and either or both of these tunnels would contribute significantly to the airframe–engine integration process. Some of the current planning is related to alternatives for increasing the test capacity of the ASTF.

Although this paper addresses the contribution of ground test facilities to the airframe–engine integration process, it is very appropriate to note as a concluding remark for this section that flight test aircraft have been and remain an important contributor to the integration process. Some aspects of the marriage of airframes and engines remain so complex that adequate duplication or simulation cannot be accomplished in ground test facilities using today's technology. One example of such complexity is the integration of the engine exhaust flows with the aircraft external flowfield and adjacent airframe structure. Such exhaust integration includes aerodynamic, thermal, and acoustic considerations. In such cases, a prototype or a preproduction aircraft remains the test facility of choice.

Ground Test Capabilities Timeline

Assessment of the airframe–engine integration test capabilities of the U.S. facilities listed in Fig. 12 is a relatively complex process because of the large number of variables involved. There are at least six major families of variables each having a broad range of options that must be considered (Table 1).

However, this assessment process is simplified by the fact that full-scale propulsion hardware (item 3 in Table 1) must be used for the majority of integration testing. Therefore, the complicated determination of appropriate subscale size limitations is avoided except for almost all aerodynamic wind-tunnel testing.

A meaningful assessment of the evolution of U.S. ground test capabilities for airframe–engine integration testing during the period from the 1940s to the 1990s is possible only when two assumptions can be reliably made. The first assumption is that the propulsion system size can be characterized by the largest airflow capacity of contemporaneous engines under development. The second assumption is that the test configuration can be defined as either the propulsion system or as the engine only. The propulsion system includes all or a portion of the airframe located near the engine air inlet, the engine, engine compartment, and all or a portion of the airframe located near the engine exhaust and is frequently referred to as an installed configuration. The engine only configuration consists of the basic engine supplemented with special test equipment that allows the engine to be directly connected to facility service systems including air supply, fuel, and exhaust collection and is frequently referred to as an uninstalled configuration.

When these assumptions are applied, the timelines for integration test capabilities in altitude environments and special environments are obtained (Fig. 13). The evolution of the altitude environmental test capabilities is shown in Fig. 13a. These test capabilities are strong functions of engine airflow capacity, and therefore, the results are presented for turbojets,

Table 1 Variables affecting integration test capability

Family	Options
1. Integration areas	Performance, operability, and durability/reliability
2. Mission	Tactical, strategic, and transport
3. Propulsion parameters (thrust, airflow, and physical size)	Large, medium, and small
4. Test configuration	Complete air vehicle, complete propulsion subsystem, and engine only
5. Operational envelope	Altitude, Mach number, attitude, and adverse environments
6. Time scale	Steady state and transient

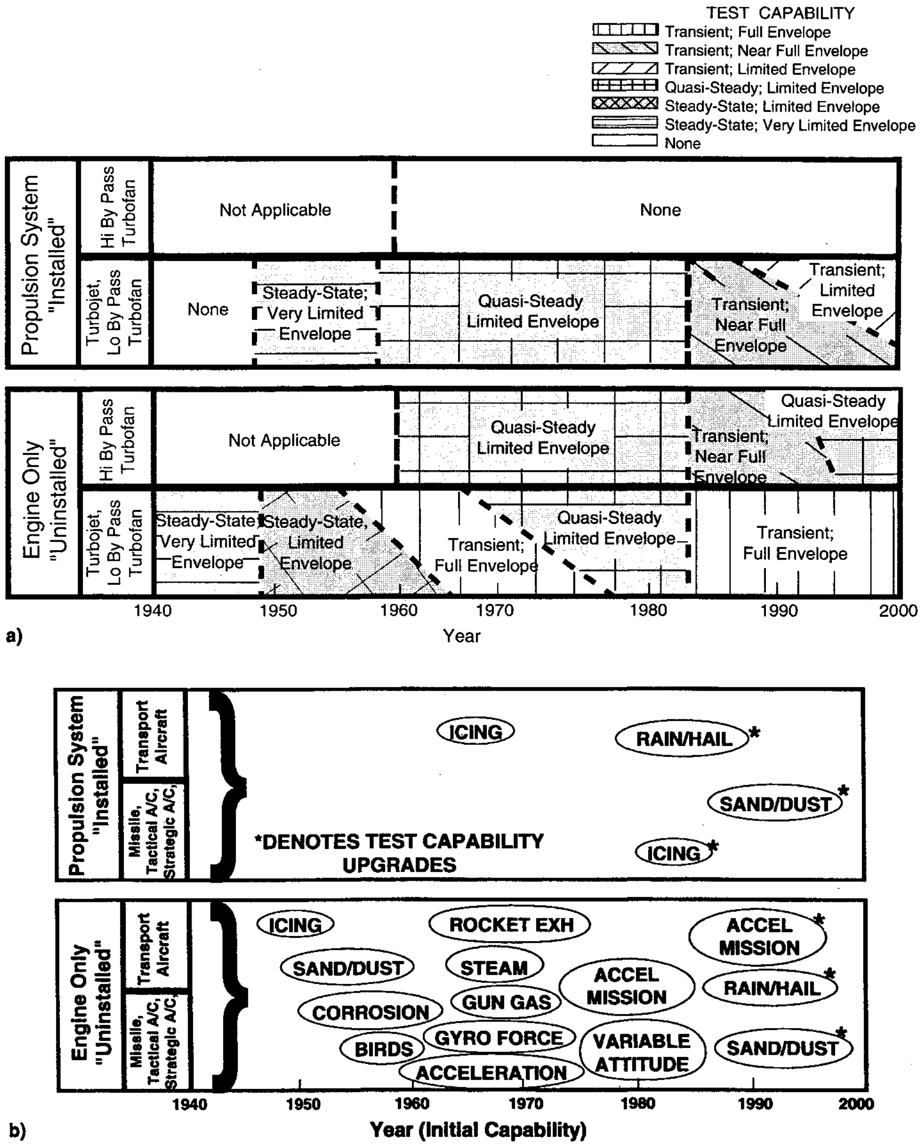


Fig. 13 Evolution of U.S. airframe–engine integration test capabilities: a) altitude environments and b) special environments (initial capability dates).

low-bypass turbofans and for high-bypass turbofans. Transient test capability over the full or near full system operational envelope represents an ideal level of test capability, and that level of capability has been available for several intervals during the jet propulsion era. These intervals are clustered in the late 1950s to early 1970s and the mid 1980s to mid 1990s when the Unitary Wind Tunnel Plan Act and Air Engineering Development Center Act had full force and effect. On the other hand, a very credible capability of transient, limited envelope or quasisteady, limited envelope has been available for much of the last three decades. At the present time, the integration test capabilities are decreasing as facility capacity remains essentially constant, and the airframe–engine integration test requirements continue to increase.

A sample of the initial capability dates for special environmental test capabilities is shown in Fig. 13b. The timeline for the acquisition of the capabilities in these environments is very approximate. Historically, there has been a proliferation of capability that tends to be program-specific, and it is very difficult to establish a timeline with high confidence.

Therefore, the sum of the capabilities of the ground test facilities listed on Fig. 12 meets most contemporary requirements for airframe–engine integration testing. A notable exception in the airframe performance area is the Reynolds number limitation (model size times density) for aerodynamic testing of large transport aircraft. This limitation is being addressed in the planning for the NWTC mentioned earlier in this section. It is also important to note that the airflow requirements of today's largest propulsion systems equal or exceed the maximum capacity of the altitude engine test cells, and so there is no capacity margin at this time.

Non-U.S. Test Facilities Comparisons

It is also very informative to compare the U.S. ground test capability for airframe–engine integration with the past and present capability of other nations. Substantial insight into the test capabilities of England and France has been gained through data exchange and alliances such as NATO's Advisory Group for Aerospace Research and Development (AGARD). Additionally, much information concerning the Russian test capabilities from the late 1930s until the end of the Cold War has only recently become available through data exchange and marketing. Many of the world's pioneer airframe–engine test facilities were constructed in Germany during the late 1930s and early 1940s. The capabilities of the German facilities were carefully documented before they were dismantled under terms of the Potsdam Agreement.[12]

Based on the information now available, it appears that the worldwide airframe–engine integration test capabilities have been relatively consistent during the period from the late 1930s to the mid-1990s, with three notable exceptions. First, the earliest test facilities were placed in operation in Germany and Russia during the 1939–1945 time period and had similar capacities. These initial facilities were very similar to the first U.S. test facilities that became operational during the late 1940s and early 1950s. Thus, in the World War II time period the German and Russian test capabilities held a 10- to 15-year lead over the U.S. Some of the earliest U.S. capabilities were derived from German facilities that were dismantled and relocated to the U.S. following the end of World War II. Second, the Russian propulsion facilities have generally maintained a few year's lead over U.S. facilities in terms of airflow capacity. Third, the English and French facilities have generally had a slightly smaller airflow capacity than contemporaneous U.S. facilities.

The specific airframe–engine integration test facilities considered in these comparisons are the following:

France:
- Centre d'Essais des Propulseurs (CEPr), Saclay
- Office National d'Etudes et de Recherches Aerospatiales (ONERA), Modane

Germany:
- Bayerische Moteren Werke (BMW), Munich-Oberwiesenfeld
- Luftfahrtforschungsanstalt Herman Goering (LFA), Volkenrode
- Luftfahrtforschungsanstalt (LFM), Munich
- Deutsche Versuchsanstalt für Luftfahrt (DVL), Berlin

Russia:
- Central Institute of Aviation Motors (CIAM), Moscow and Lytkarino
- Central Aerohydrodynamics Institute (TSAGI), Zhukovsky

United Kingdom:
- Defence Research Agency (formerly RAE), Bedford and Farnborough
- Defence Test and Evaluation Organisation (formerly NGTE), Pyestock

Evolving Test Support to Airframe–Engine Integration

Overview

A family of ground test facilities is required to support the successful integration of airframes and engines for flight operations. The two types of facilities, i.e., aerodynamic wind tunnels and altitude engine test cells that support the initial development of the airframe and engine independently, are depicted in Fig. 14. As system development proceeds toward first flight and later toward production qualification or certification, additional facilities are required that provide capabilities to test increasingly complex combinations of airframe and engine. For smaller systems these additional facilities include propulsion wind tunnels that can test the complete full-scale aircraft including the operational propulsion system (Fig. 14a). For larger systems, these additional facilities include inlet–engine wind tunnels, inlet–engine freejet test cells, jet effects wind tunnels, and exit freejet test cells (Fig. 14b).

An absolutely key element of the test concepts depicted in Fig. 14 is the successful superposition of the results from each of the parallel and serial steps in the process. Because it is not cost-effective or even possible in some cases to simulate or duplicate all boundary conditions simultaneously, the results from each step must be superimposed on the results from other steps to obtain complete results. The physical size and airflow capacity of available facilities control the extent of superposition required. This effect is demonstrated by comparing the process for systems that are small compared to available test facilities (Fig. 14a), and systems that are large compared to available test facilities (Fig. 14b). Specific examples of test installations for small and large systems are included in subsequent sections of this paper.

Each of the ground test installations depicted in Fig. 14 can support the airframe–engine integration process at some of the interfaces shown for performance, operability, and durability/reliability in Figs. 1–3. The specific airframe–engine interfaces supported are identified for each example. Specific examples of past and current test installations are shown in the following sections. These examples depict both the current state of the art and the evolution over the past five decades of ground test support to airframe–engine integration.

Aerodynamic Wind Tunnels

A relatively large number of aerodynamic wind tunnels that cover the full range of subsonic, transonic, and supersonic speeds up to Mach number 3 are currently in operation. Most of these tunnels can provide test support over the major portion of the aircraft attitude envelope (angles of attack, sideslip, and roll) for model sizes that are large enough to house required instrumentation and desired variable-geometry features. Available model size capability ranges from a scale factor of 1.0 (full-scale) for air-launched missiles down to scale factors of about 0.05 for large, subsonic transport aircraft. The maximum length Reynolds numbers that can be attained are substantially less than maximum full-scale flight Reynolds numbers. The tunnel flow qualities available range from highly uniform and quiet to somewhat nonuniform and noisy. Propulsion simulator capability is available in some of the tunnels.

The aerodynamic wind tunnel provides test support to the airframe–engine integration process at the interfaces listed in Fig. 15. A typical subscale airframe–engine inlet integration test installation is shown in Fig. 16. The model shown is a 0.176-scale model of the F/A-18 aircraft equipped with active air inlets, engine inlet airflow control and measurement systems, drag measurement systems, and a 40-probe steady-state and dynamic total pressure measurement array at the aerodynamic interface plane (AIP) located just upstream of the engine face. This test configuration permits definition of the steady-state and dynamic characteristics of the airframe, air intake, and engine interfaces shown in Fig. 15. This example is shown in the 16 by 16 ft supersonic Propulsion Wind Tunnel at the AEDC.

Altitude Engine Test Cells

Altitude engine test cells are comprised of three major subsystems as indicated in Fig. 14. These subsystems are 1) basic test unit, 2) inlet flow simulator, and 3) exhaust flow simulator. These subsystems contribute significantly to the overall engine test cell capability, and therefore, they are discussed separately in the sections that follow.

Basic Test Unit

Several altitude engine test cells that cover the full range of subsonic, transonic, and supersonic speeds up to Mach number 3 at pressure altitudes from sea level to about 80,000 ft are currently operational. A few of these test cells can provide true inlet total temperatures corresponding to standard, polar, and tropical atmospheres. The air supply and exhaust gas pumping capacities and the diameter and length of these test cells are sufficient to permit tests of full-scale turbojet and turbofan engines for aircraft ranging in size from small air-launched missiles to large, contemporary tactical and strategic aircraft and to very large transport aircraft.

Either the engine inlet (fan or compressor) is directly connected to the test facility air supply system, or the exhaust is directly connected to the exhaust gas pumping system. Thus, this test configuration is generally referred to as direct-connect.

The altitude engine test cell provides test support to the airframe–engine integration process at the interfaces listed in Fig. 17. A typical full-scale airframe–engine integration test installation from the early 1960s is shown in Fig. 18 (Ref. 13).

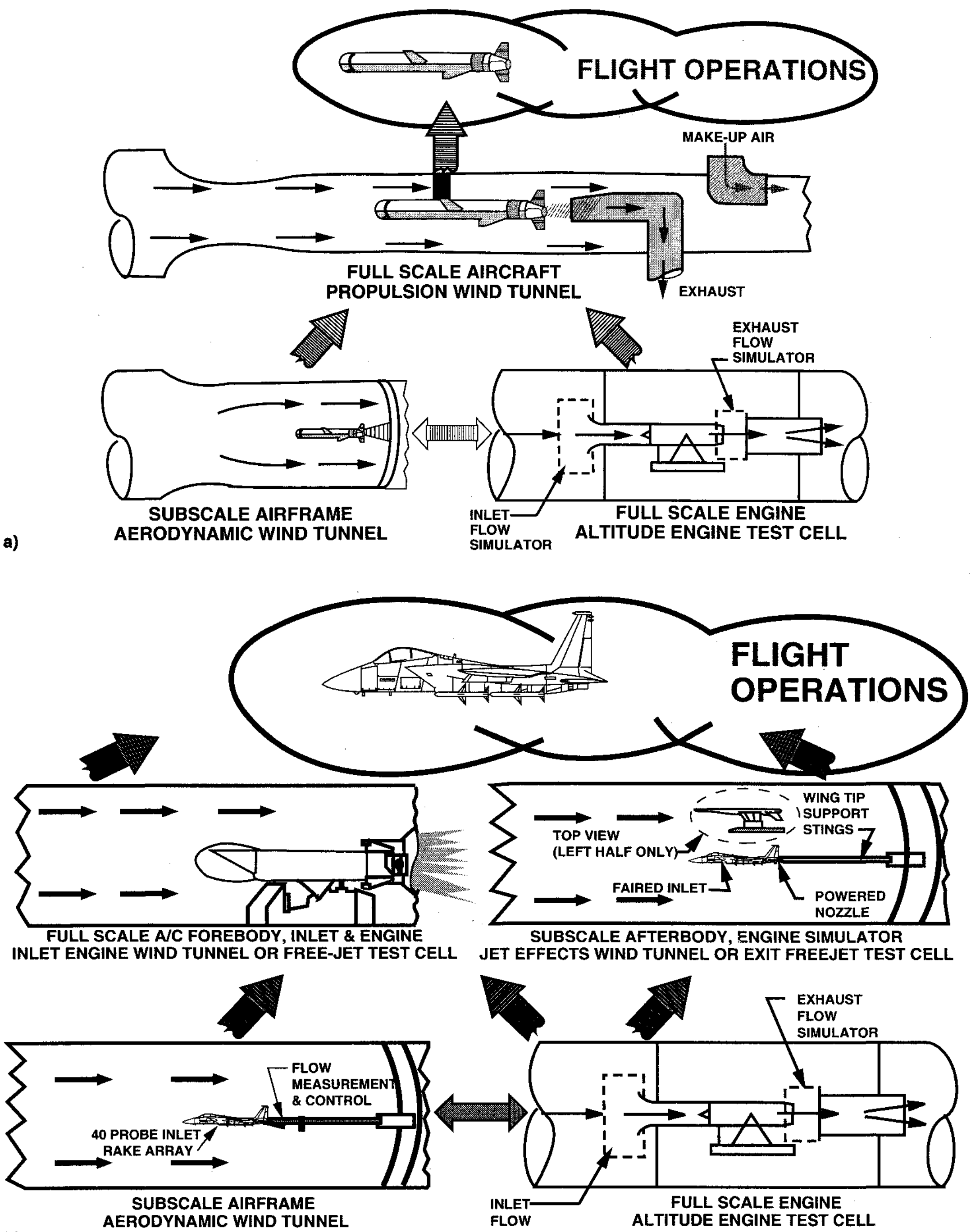
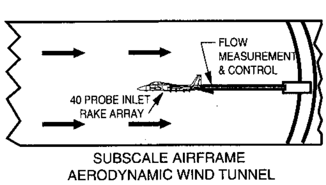


Fig. 14 Hierarchy of ground testing support to airframe–engine integration: a) smaller and b) larger systems (relative to ground test capacity).



INTERFACES

PERFORMANCE	OPERABILITY	DURABILITY/RELIABILITY
Airframe Drag	Inlet Flow Distortion - Steady	Inlet Flow Distortion - Steady
Inlet Drag (Spill Dependent)	Inlet Flow Distortion - Dynamic	Inlet Flow Distortion - Dynamic
Inlet Pressure Recovery	Inlet Flow Stability	
Inlet Flow Distortion		
Inlet In/Out - Bleed Airflow		

Fig. 15 Airframe–engine interfaces supported by aerodynamic wind tunnels.

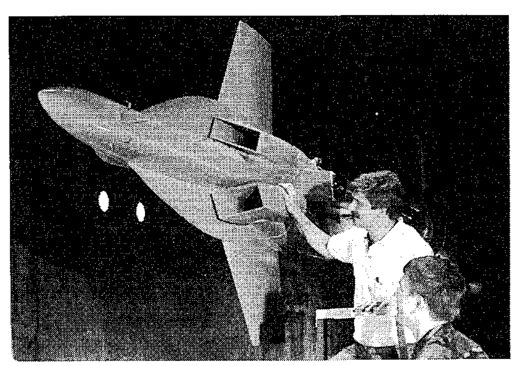
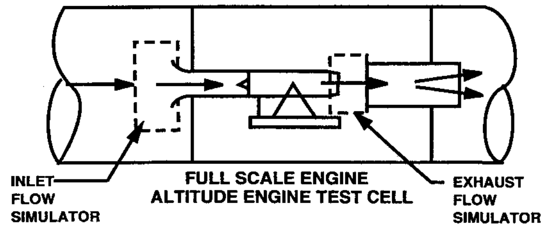


Fig. 16 Inlet integration test installation in aerodynamic wind tunnel (AEDC 16S, 1993).



INTERFACES

PERFORMANCE	OPERABILITY	DURABILITY/RELIABILITY
Installed Thrust	Inlet Flow Distortion-Steady	Ram Pressure-Max & Min
Total Fuel Burned	Inlet Flow Distortion-Dynamic	Ram Temperature-Max & Min
Specific Fuel Consumption	Adverse Weather-Rain, Hail, Icing	Inlet Flow Distortion-Steady
Engine Airflow	Gun & Rocket Gas, Steam Ingestion	Inlet Flow Distortion-Dynamic
Integrated Control Fidelity	Engine Power Transients	Adverse Weather-Rain, Hail, Icing
Backup Control Fidelity	A/C Maneuver/Altitude Transients	Adverse Environment -Birds, Dust
Engine Bleed Air Extraction	Integrated Control Response	Fan/Compressor Noise
Gearbox Power Extraction (Run)	Backup Control Response	Cold Section LCF and HCF*
Gearbox Power Extraction (Windmill)	Engine Restart-Starter Assist	Hot Section LCF and HCF*
Windmilling Drag	Engine Restart-Spooldown	Integrated Control-Fidelity and Response
Exhaust System (Multistream, etc.)	Engine Restart- Windmill	Backup Control-Fidelity and Response
Engine Bay Airflow	Exhaust System Stability	Exhaust Jet Noise
Engine Bay Aerodynamic Losses		Engine Bay Environment
Electromagnetic Emission		

*LCF = Low Cycle Fatigue
HCF = High Cycle Fatigue

Fig. 17 Airframe–engine interfaces supported by altitude engine test cells.

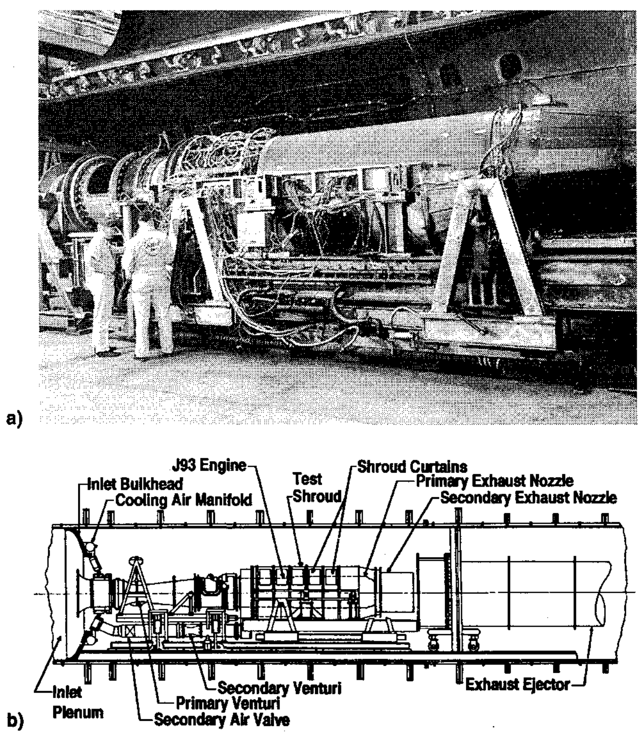


Fig. 18 Turbojet test installation in altitude engine test cell (AEDC J1, 1962): a) photograph and b) schematic.

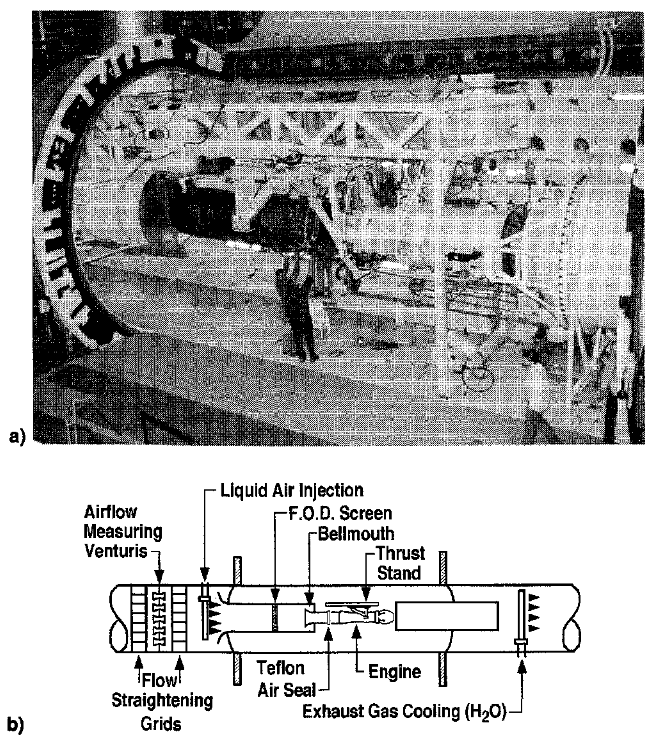


Fig. 19 Low-bypass turbofan test installation in altitude engine test cell (AEDC J-2, 1990): a) photograph and b) schematic.

The engine shown (Fig. 18a) is the J93 turbojet undergoing development for the B-70 aircraft. The schematic of this test installation (Fig. 18b) shows the relative size and location of the key components. This installation includes a simulated engine bay with bay cooling air discharged into the secondary air inlet of the ejector exhaust nozzle. This air supply system is configured to deliver a uniform (undistorted) total pressure profile to the compressor inlet. A typical full-scale airframe–engine integration test installation from the 1990s is shown in Fig. 19. The engine shown (Fig. 19a) is the F110 low-bypass turbofan undergoing component improvement tests for the F-16 aircraft. This installation does not contain any auxiliary airframe equipment items. Again, this air supply system is configured to deliver a uniform total pressure profile to the fan inlet. The schematic of this test installation (Fig. 19b) shows the relative size and location of the key components. These examples are shown in the 16- and 20-ft-diam J-cells of the Engine Test Facility at the AEDC.

The advent of the high-bypass turbofan engine in the 1960s imposed many new requirements on the altitude engine test cell configuration. Four of the most significant of these new requirements are 1) engine diameters more than twice as large, 2) engine airflow requirements more than four times as large at similar test conditions, 3) two independent exhaust systems separated by large axial spacing, and 4) exhaust nozzles operating at much lower pressure ratios and velocities that increase the probability of aerodynamic interference between the engine and the test cell.

A typical airframe–engine integration test installation for a high-bypass engine from the 1960s is shown in Fig. 20 (Ref. 14). The engine shown in Fig. 20a is the TF39 undergoing development for the C-5 aircraft. The schematic of this test installation (Fig. 20b) shows the relative size and location of the key components. Similarly, a test installation from the 1990s is shown in Fig. 21 (Ref. 15). The engine shown in Fig. 21a is the PW4084 undergoing development for the Boeing 777 aircraft. The schematic shows the relative size and location of key components (Fig. 21b). Both of these high-bypass engine installations include engine support pylons and pylon fairings. Both of the air supply systems are configured to deliver a uniform (undistorted) total pressure profile to the fan inlet.

In contrast to the aerodynamic wind-tunnel test installation configuration (Fig. 16), which has remained relatively constant over the past 3–4 decades, the altitude engine test cell installation configuration (Figs. 18–21) has several significant changes during this same period. A primary reason for this contrast is that the size and installation configuration of the subscale airframe test articles are tailored to match the wind tunnel, whereas the engine test cell is tailored to match the size and installation configuration of each full-scale engine. The evolution of the engine test cells is and has been driven by changes in configuration, size, and cycle of the evolving turbojet (zero bypass) and the low-bypass and high-bypass turbofan engines.

Inlet Flow Simulators

Major improvements in most capabilities of altitude engine test cells have evolved during the past 40 years. The largest changes have occurred in the inlet flow simulators employed to produce realistic flowfields at the engine inlet. During this time, several flow conditioning devices have been developed that can be installed in the air supply ducting immediately upstream of the engine to provide simulation of the total pressure, total temperature, and turbulence patterns of the airflow entering the engine. These devices include simple bellmouths that provide uniform inlet flows, and movable vanes, nonuniform density screens, random frequency distortion generators, discrete frequency distortion generators, planar pulse generators, and air–jet distortion generators that produce both steady-state and dynamic total pressure variations in the engine inlet flows. When required, additional features such as boundary-layer bleeds, flow accelerators, and flow diffusers that bypass small amounts of flows around the engine have been added to the inlet flow simulation device. These bypass configurations are generally referred to as semifreejet (or semidirect connect) installations. Similarly, devices such as rocket motors, gun charges, steam injectors, and gaseous hydrogen burners have been developed that produce steady-state and transient total temperature distortions in the inlet flow. These distortion generators are capable of reproducing with high fidelity the actual steady-state and time-variant conditions of the flow discharged from the aircraft air intake subsystem into the engine inlet. Selected specific configurations of these inlet flow simulators will be described in more detail in the remainder of this section.

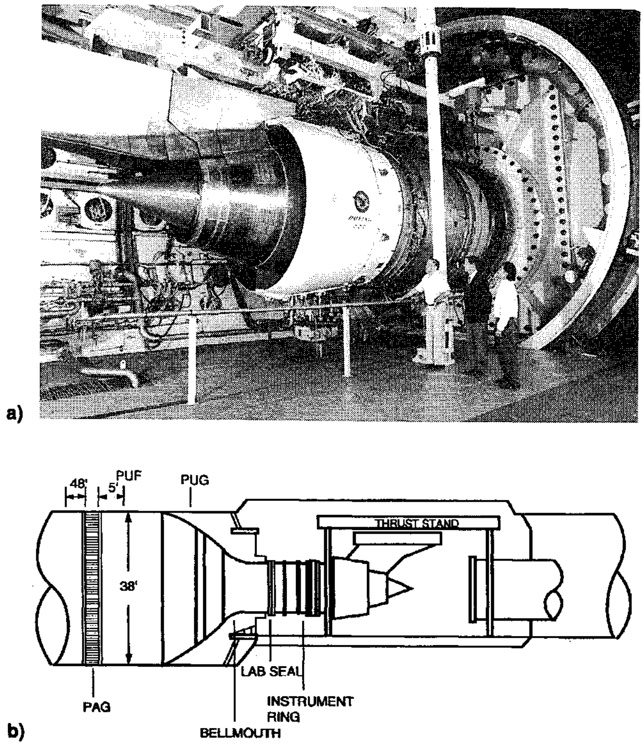


Fig. 21 Current high-bypass turbofan test installation in altitude engine test cell (AEDC C-2, 1992): a) photograph and b) schematic.

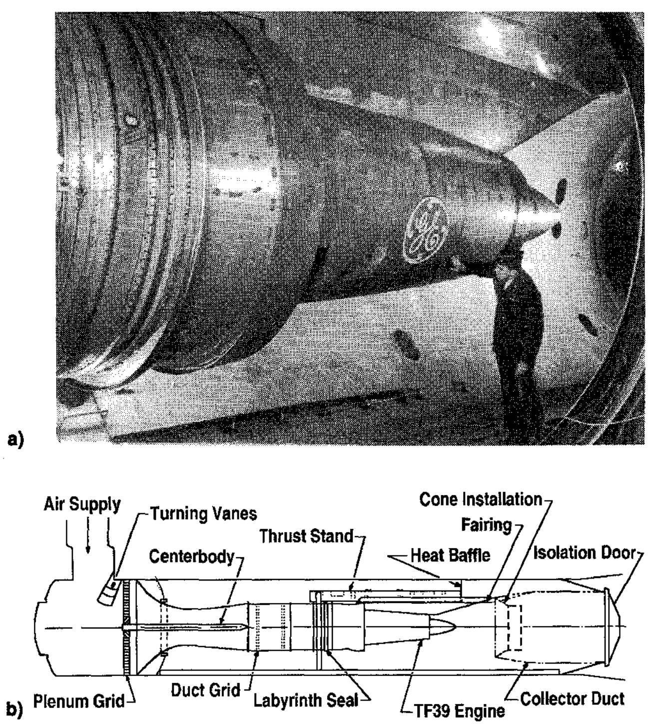


Fig. 20 Early high-bypass turbofan test installation in altitude engine test cell (AEDC J-1, 1967): a) photograph and b) schematic.

The original and most familiar engine inlet flow simulator is the bellmouth that delivers a nearly uniform total pressure to the engine inlet. However, research during the late 1940s at NASA Lewis and other locations showed that as aircraft flight speeds and/or maneuverability increased, the flowfield at the inlet–engine interface would become more and more nonuniform (distorted) at some flight conditions. At this time the flow distortions were defined as steady-state variations between local total pressure and the average total pressure. The magnitudes and shapes of the inlet distortion patterns were established from aerodynamic wind-tunnel tests as discussed earlier (Fig. 15).

In the early 1950s, the larger distortions were applicable to ramjet-powered aircraft because the design flight speeds were substantially higher than for turbojet-powered vehicles. Therefore, many of the early advances in test support for the airframe–engine integration at the inlet distortion and inlet stability interfaces were driven by requirements of ramjet-powered systems.

The most innovative device for simulation of inlet flow distortion in the mid 1950s was the variable vane configuration used during development testing of the Navaho missile/XRJ-47 ramjet engine configuration.[6] This device was developed for AEDC testing in conjunction with North American Aviation Corporation and Wright Aeronautical Division, Curtiss-Wright Corporation. This distortion generator, generally referred to as a ducted nozzle, consisted of 29 adjustable vanes (16 horizontal and 13 vertical) that were shaped to conform to the kidney-shaped area formed by the inlet centerbody and outer diffuser duct. These vanes were located a short distance upstream of the throat of the supersonic inlet (Figs. 22 and 23). During calibration and testing, the vane angular settings were adjusted in an iterative fashion until the steady-state Mach number profiles at the inlet–engine interface matched the specification profiles as determined from subscale inlet tests in wind tunnels. One example of the flow distortion capability of the ducted nozzle is shown in Fig. 24. The specification profile or target Mach number contours were based on wind-tunnel tests. The matching pattern produced by the ducted nozzle configuration compares favorably in both magnitude and shape with the specification pattern.

By late 1954, the inlet–engine interface had evolved into a major concern because of compressor stall problems on several advanced turbojet-powered aircraft. Most of these stalls were caused by inlet air pressure distribution (i.e., distortion).[3] During this mid-1950s period, arrays of nonuniform screen composed of different mesh and wire sizes were the distortion generator of choice for the levels of distortion required for testing of turbojet engines. A typical distortion screen configuration is shown in Fig. 25 (Ref. 16). Local total pressure variations at the inlet–engine interface up to a maximum of 25% of the average pressure level were controlled by selection of the density and number of overlapping screens.

Nonuniform screen arrays are still today a very viable choice for inlet distortion testing. The inherent advantages of screen arrays are simplicity, reliability, and repeatability. The disadvantages are lengthy lead time to design, construct, and tailor the pattern, inherent single design point operation, and lowered test productivity because of time required to change screen configurations.

Adequate definition of the radial and circumferential inlet total pressure profiles remains a challenge for distortion testing. Another advantage offered by nonuniform screen arrays is improved measurement of distortion profiles by incrementally rotating the screen through a series of angular positions in front of a fixed array of total pressure rakes. In this way, the effective spatial sampling capability of a given rake array can be multiplied severalfold. A family of rotatable inlet distortion screens is shown in Fig. 26 (Ref. 17).

A major reformation began in test support to airframe–engine integration at the inlet distortion interface when it was confirmed during the mid 1960s that steady-state simulation of inlet total pressure distortion was inadequate and that nonsteady (e.g., instantaneous) simulation was necessary.[18] Obviously, there is always some unsteadiness in the flow at the inlet–engine interface resulting from disturbances such as turbulence, separation, shock-wave–boundary-layer interactions, and vorticity. The sum of such disturbances causes the instan-

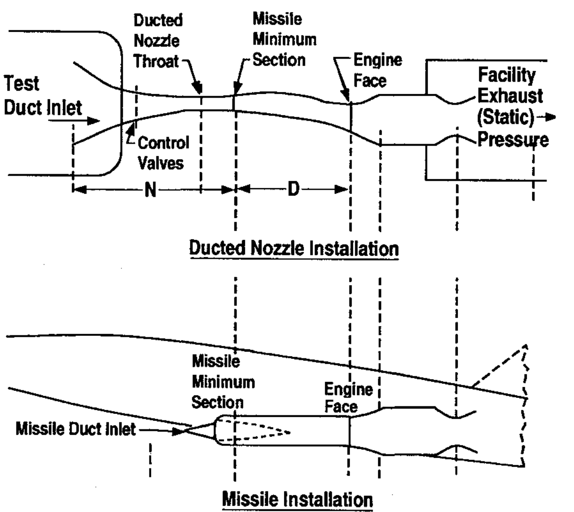


Fig. 22 Relationships of ducted nozzle installation to Navaho missile installation (Ref. 6).

Fig. 23 Adjustable vane assembly in ducted nozzle installation (Ref. 6).

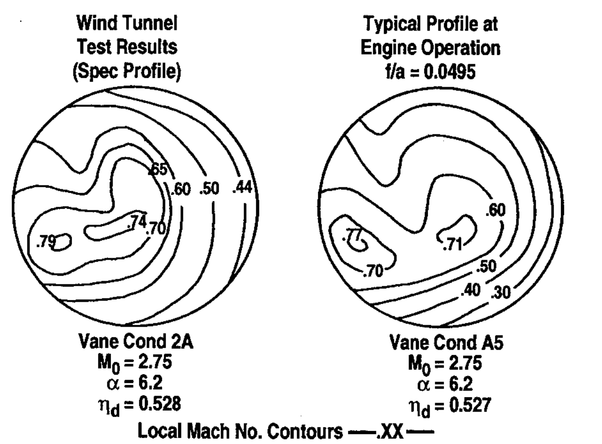


Fig. 24 Typical flow distortion capability of ducted nozzle installation (Ref. 6).

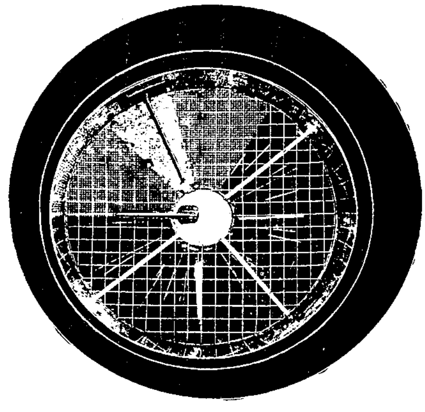


Fig. 25 Typical inlet distortion screen installation (Ref. 16).

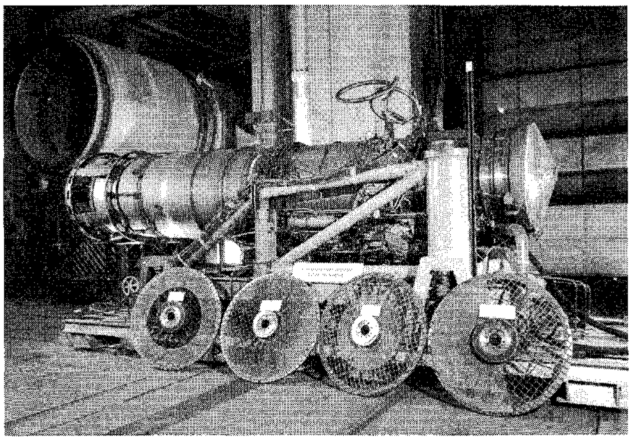


Fig. 26 Typical rotatable inlet distortion screens (Ref. 17).

taneous total pressure distortion to be different from the steady-state distortion. The key discovery was that if a distortion pattern persists long enough for all or most of the compressor blades or fan blades to pass through it, i.e., one engine revolution or less, then the engine will recognize that pattern as steady even though it may persist for only a few milliseconds.[18]

According to J. F. Montgomery[3] this important discovery had its beginning in the engine drift stalls, which were encountered during inlet–engine tests in 1961–1962. Under certain test conditions, these stalls would occur after random lengths of time at stabilized operating conditions. Further, these engine stalls were occurring randomly at both low and high steady-state distortions and on a nonrepeatable basis. The limited dynamic pressure measurements available suggested that fluctuating pressures (turbulence) at the inlet–engine interface might be the driving mechanism for these random stalls.[19]

Subsequently, work was initiated at AEDC to develop inlet flow simulators and other test equipment necessary to define the engine responses to the turbulence environment. This seminal work was led by W. F. Kimzey[20] and was eminently successful. Following this successful effort to develop a controllable random frequency turbulence generator, engine testing was initiated under Kimzey's leadership to define engine responses to turbulence.[21] This work by Kimzey is widely recognized[3,22,23] as the first ever correlation of the loss in compressor stall margin with increases in turbulence and demonstration of compressor stalls at steady-state distortion levels that were shown to be benign.

Simultaneous confirmation that compressor stall margin responds to instantaneous inlet pressure distortions that persist for approximately one engine revolution (a few milliseconds) and validation of ground test facility capabilities to measure engine responses to turbulence set in motion accelerated efforts on three fronts to improve the test support to airframe–engine integration at the inlet distortion interface. These efforts were 1) the definition of the scaling laws applicable to the time-dependent total pressure distortion measurements at the exit of subscale airframe inlets in wind tunnels; 2) improvements in the pressure measurement systems to extend the frequency range of flat response up to several hundred Hertz, reduce the uncertainty of measurement, and develop data compression and processing methods to manage the massive quantities of time-dependent data required; and 3) validation of new full-scale inlet flow simulators that would adequately reproduce in the engine test cell the instantaneous inlet distortion characteristics as measured during airframe inlet testing in wind tunnels.

These efforts were so successful that by the mid-1970s the wind-tunnel scaling laws (item 1 discussed previously) and the dynamic instrumentation and data processing capabilities (item 2) were available to characterize the instantaneous distortion characteristics of aircraft inlets in wind-tunnel testing.[24,25] A number of less complex inferential schemes based on combining local steady-state pressure measurements with statistical properties of local or average turbulence measurements were examined before the final approach of direct measurement of the local unsteady total pressure at many points in the inlet–engine interface plane was developed.

Concurrently, new inlet flow simulators with dynamic distortion capabilities for use in altitude engine test cells were developed and validated (item 3). These new simulators included capabilities such as 1) variable random frequency distortion generators,[26] 2) discrete frequency distortion generators,[27,28] 3) planar pulse distortion generators,[29,30] and 4) airjet distortion generators.[30–32]

The Airjet distortion generator was the last addition to this complement of inlet flow simulators. This concept was originated in the late 1960s and validated in 1976. The current dial-a-pattern configuration (Fig. 27) consists of a large number (e.g., 56) of high-speed airjets flowing counter to engine inlet flow. Each airjet is independently adjusted through an iterative closed-loop control system to minimize the rms deviation between the measured distortion pattern (40 probes) and a target pattern (40 local values) resident in the control computer. The airjet distortion generator will converge to a typical inlet distortion pattern with an rms deviation of less than 2% in less than 90 s.[25] On this basis, the airjet distortion generator offers substantial increases in test productivity over arrays of nonuniform screen wire because an hour or more is required to change screens. The level of turbulence (rms total pressure fluctuation) introduced by the airjets is higher than the turbulence behind nonuniform screens, i.e., screen average turbu-

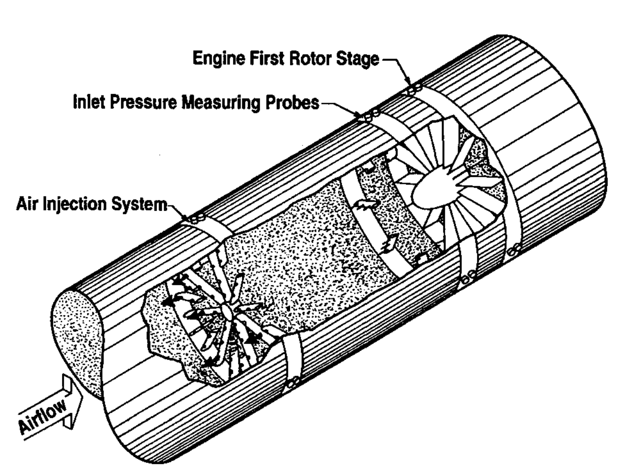


Fig. 27 Airjet distortion generator installation (Ref. 32).

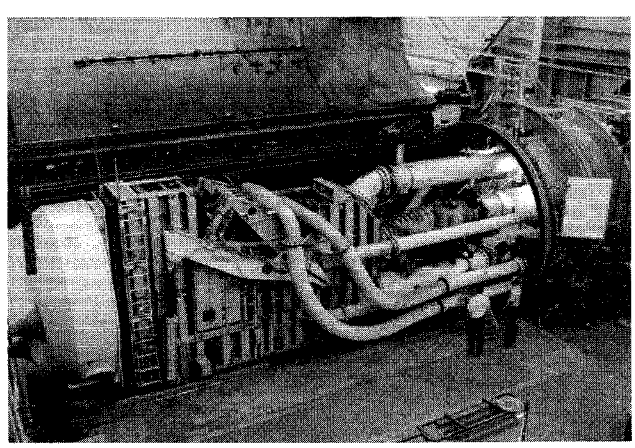


Fig. 28 F-15/F 100 Blue Max inlet simulator in altitude engine test cell (AEDC J-1, 1971).

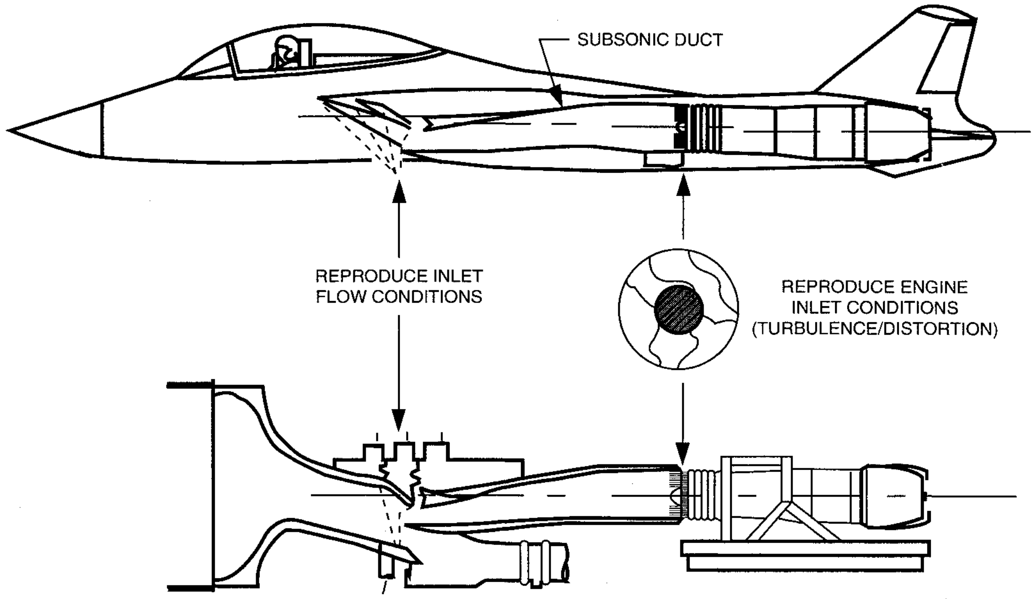


Fig. 29 Relationship of Blue Max inlet simulator to F-15 aircraft (Ref. 36).

lence is about 0.6% rms and airjet turbulence ranges from 0.6–1.8% and is dependent on pattern.[32]

In addition, work continued during this time period on refining techniques for use of nonuniform screens to produce inlet total pressure distortion. Two notable contributions were 1) enhancements of the design procedure for screens to produce specified complex distortion patterns,[33] and 2) characterization of the level of turbulence (rms total pressure fluctuation) introduced by screens.[32]

A state-of-the-art assessment of all of these validated testing techniques applicable to inlet flow simulators was published in 1973 (Ref. 34). This assessment also included new validated techniques to measure quantitatively the stall margin of fans and compressors when operating in a complete turbofan engine. Previous techniques had relied heavily on extrapolation of stall characteristics as determined in fan or compressor component test rigs. This assessment was updated in 1980 (Ref. 35).

During 1971, probably the highest fidelity inlet flow simulator of all time was placed in service to support F-15 aircraft development. This simulator was affectionately known as Blue Max because of its color and large size (Fig. 28). This unit was designed and constructed by Pratt and Whitney in conjunction with McDonnell Aircraft and AEDC specifically to support integration testing of the F-15 airframe and the F100 engine. The relationship of the Blue Max configuration to the F-15 aircraft configuration is shown in Fig. 29. This semidirect connect (or semifreejet) configuration duplicated the airframe inlet lines and configuration from the leading edge of inlet ramp 3 aft to the airframe–engine interface plane. The flowfields at the airframe–engine interface plane were established by simultaneous control of the Mach number and flow angle of the flow generator upstream of inlet ramp 3, the variable bleed and spill flows, and airflow trip doors on the simulator sidewalls and the upper front ramp and lower ramp.[36,37]

The most modern inlet pressure distortion simulator with variable geometry and transient capabilities was placed in service in 1990 at the Central Institute of Aviation Motors (CIAM) in Russia. This universal flow distortion generator provides the capabilities for real-time simulation of aircraft steady flight and maneuvering flight operations for a range of airframe inlet configurations and engine sizes.[38] The active elements of this inlet flow simulator are a pair of opposing tailored interceptor plates that are positioned in the engine inlet flow by hydraulically powered, computer-controlled actuators as shown in Fig. 30. This inlet flow simulator was first used for airframe–engine integration testing for the MIG31 airframe with the D-30F6 turbofan engine during 1990–1992, and later for the MIG29 airframe with the RD-33 turbofan engine during 1991 and 1992 (Ref. 39).

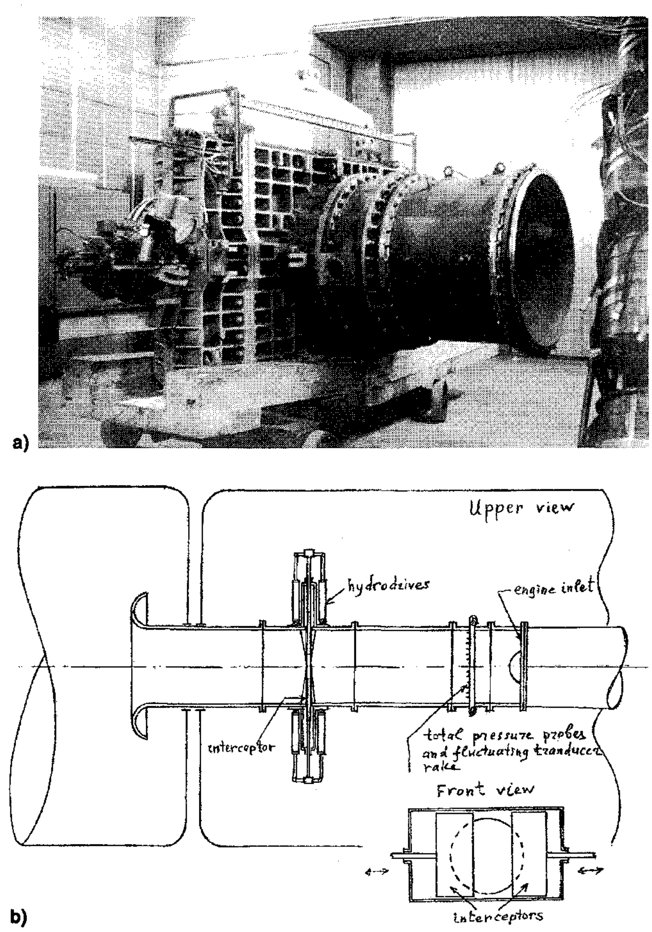


Fig. 30 Universal, real-time inlet flow simulator in altitude engine test cell (CIAM, Ts-4N, 1990) (Ref. 39): a) photograph and b) schematic.

An example of the performance capability of the CIAM inlet flow simulator is shown in Fig. 31. The target values of local total pressure P_i^*, local total pressure fluctuations ε, three-dimensional time-averaged total pressure nonuniformity $\overline{\Delta\delta_c}$, and

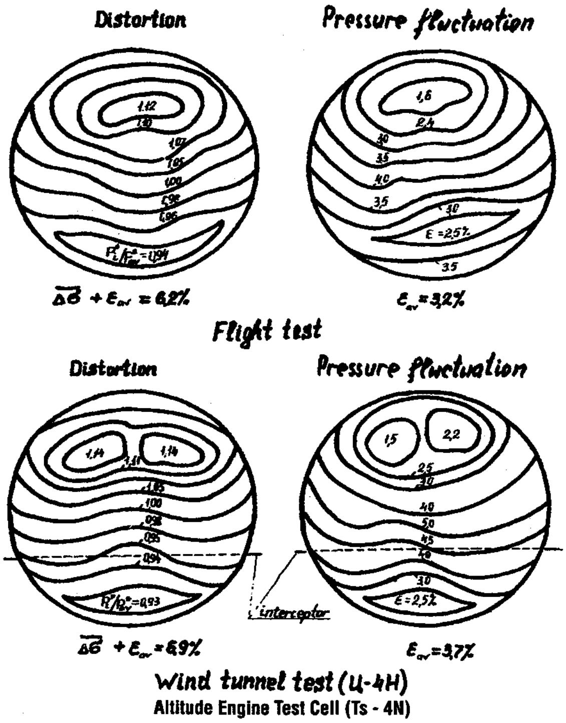


Fig. 31 Typical flow distortion capability of the CIAM inlet flow simulator (Ref. 39).

averaged random fluctuations of total pressure ε_{av} were obtained from aircraft flight tests. The matching patterns and average values of the distortion descriptors produced by the CIAM simulator in Test Cell Ts-4N compare favorably in both magnitude and shape with the steady-state distortion and pressure fluctuation values measured in flight.[39]

Inlet flow simulators with temperature distortion capability have also evolved during the past 40–45 years. These simulators have addressed a broad range of operational scenarios including catapult steam ingestion, gun gas ingestion, rocket gas ingestion, and exhaust gas reingestion. From the very beginning most of the temperature distortion simulators have been transient or dynamic devices because the real-life temperature distortions were clearly transient in nature.

The development of inlet temperature distortion simulators in the U.S. has been concentrated at NASA Lewis Research Center and at the Naval Air Propulsion Center. Devices used to provide the thermal input in test facilities have included direct steam injection, multiple gun charges, special-purpose rocket motors, and hydrogen–air burners. Hydrogen–air burners have also been used in Russia.[38]

The emphasis on development of test capabilities for total temperature distortion testing has been less intense and less focused than that for total pressure distortion testing, which was discussed in some detail earlier. As a result there appeared to be gaps and inconsistencies in the knowledge base for the temperature distortion case. On this basis the SAE technical committee S-16 on inlet flow distortion undertook a major effort beginning in the 1980s to collect and referee the diverse information available on engine–inlet temperature distortion. This SAE initiative was very successful and, in 1991, the results of this extensive study were published as an Aerospace Resource Document.[40] This reference work includes 55 archived references that span the period from the mid 1950s to the late 1980s, plus other contributions. Therefore, no specific examples of ground test support to airframe–engine integration at the inlet total temperature distortion interface are repeated in this paper.

Exhaust Flow Simulators

A wide range of flow conditioning devices has been developed and validated that can be installed at the engine exhaust nozzle(s) to ensure proper simulation of the exhaust jet flowfield(s) exiting the engine. These devices include conical and cylindrical diffusers, engine support pylons and fairings, independent secondary and tertiary air supplies for ejector nozzles, and exhaust gas collectors for vectoring and reversing exhaust nozzles.

Major advances in exhaust flow simulators were required to meet the requirements for testing of high bypass turbofans beginning in the mid 1960s. The configuration and cycle of these new engines simultaneously imposed four severe new requirements on exhaust flow simulators: 1) highly nonaxisymmetric exhaust nozzles for bypass flow, 2) large thrust and drag forces on core engine cowling immersed in bypass jet exhaust flow, 3) axial spacings of several feet between planes of core engine exhaust nozzle and bypass flow exhaust nozzle, and 4) relatively low pressure ratios across both the bypass and core engine exhaust nozzles. Each of these factors magnifies the undesirable aerodynamic interferences between the engine and the test cell and has the potential to increase the uncertainty of measured engine performance significantly. Exhaust flow simulators were developed on a timely basis to meet these new, stringent requirements. A typical configuration was shown in Fig. 21.

In the late 1980s, the requirements for testing of two-dimensional exhaust nozzles with thrust vectoring capability and, in some cases, in-flight thrust reversing capability again initiated major changes in the exhaust flow simulators. The initial generation of exhaust flow simulators for two-dimensional, vectoring, and reversing engine exhaust nozzles are complex, variable geometry mechanisms that are highly tailored to each specific engine configuration.[41]

Inlet–Engine Wind Tunnels/Freejet Test Cells

Only very few propulsion wind tunnels and freejet engine test cells with the capacity to test full-scale airframe intakes in combination with the full-scale engine and a substantial section of the aircraft forebody are in operation today. The available test units do cover much of the operational speed ranges of subsonic, transonic, and supersonic aircraft. In general, such wind-tunnel facilities are limited to small attitude ranges (angles of pitch and yaw). Available test capacity is limited to propulsion systems for tactical aircraft at transonic speeds. Somewhat larger propulsion units can be tested at supersonic and subsonic speeds.

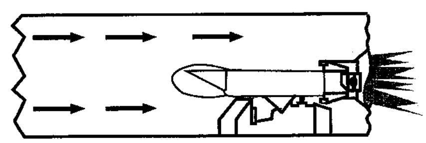
There are two major distinguishing differences between the inlet–engine wind tunnels and freejet test cells. First, the freejet test cells can provide true standard-day inlet temperatures at the engine inlet over most of the test envelope, whereas the wind tunnels provide true inlet temperatures at only a few conditions within the test envelope. Second, the wind tunnels are equipped with a closed-jet test section, whereas the test cells are equipped with an open-jet test section. The open-jet test section normally permits operation over larger ranges of pitch and yaw angles, but with on-design flow quality poorer than the wind tunnel.

The inlet–engine wind tunnels and freejet test cells provide test support to the airframe–engine integration process at the interfaces listed in Fig. 32. The wind-tunnel and freejet installations have evolved along separate but related paths and are discussed separately in the following sections. As discussed in the preceding section on Inlet Flow Simulators for engine test cells, many of the early advances in test support were driven by the requirements of ramjet-powered systems.

Inlet–Engine Wind Tunnels

One of the earliest wind-tunnel inlet–engine test installations supported the integration of the inlet and engine for a 16-in.-diam research ramjet propulsion system. Integration tests of this inlet–engine combination were conducted during the 1949–1950 time period in the 8 × 6 wind tunnel at the NASA Lewis Research Center.[42] The arrangement of the key components is shown in Fig. 33. This inlet–engine combination was tested over a Mach number range from 1.5 to 2.0 and an inlet angle-of-attack range from 0 to 10 deg. The tunnel static temperatures were significantly lower than standard atmosphere values at the higher Mach numbers.

The largest transonic and supersonic inlet–engine wind-tunnel installations for turbojet/turbofan engines are the Propulsion Wind Tunnels 16T and 16S at AEDC. These tunnels have supported inlet–engine integration testing for a number of tactical and strategic aircraft beginning in 1957. An early integration test installation included an axisymmetric inlet–engine combination that was strut mounted in an isolated nacelle for the B-58 (Fig. 34). More recent integration test installations have included highly integrated fuselage, air inlet, and wing configurations such as the F-15 aircraft forebody, inlet, and engine combination shown in Fig. 35.[43] The F-15 inlet–engine combination was tested over a range of subsonic, transonic, and supersonic Mach numbers from 0.6 to 2.20. The angle of attack ranged from −4 to +11 deg. The tunnel static temperatures were significantly higher than standard atmosphere values at subsonic and transonic speeds and significantly lower than standard at supersonic speeds.



PERFORMANCE	OPERABILITY	DURABILITY/RELIABILITY
Inlet Pressure Recovery	Inlet Flow Distortion-Steady	Inlet Flow Distortion-Steady
Inlet Flow Distortion	Inlet Flow Distortion-Dynamic	Inlet Flow Distortion-Dynamic
Inlet In/Out-Bleed Airflow	Inlet Flow Stability	Integrated Control-Fidelity and Response
Integrated Control System Fidelity	Engine Power Transients	Backup Control-Fidelity and Response
Backup Control System Fidelity	Aircraft Maneuver/Altitude Transients*	Engine Bay Environment
Engine Bay Airflow	Integrated Control Response	
Engine Bay Aero. Losses	Backup Control Response	

*FREEJET CONFIGURATION ONLY

Fig. 32 Airframe–engine interfaces supported by inlet–engine wind tunnels and inlet freejet test cells.

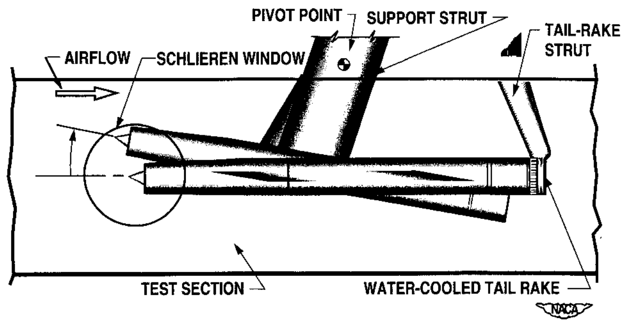


Fig. 33 Research ramjet (16 in.) propulsion system test installation in inlet–engine wind tunnel (NACA Lewis 8 × 6, 1950).

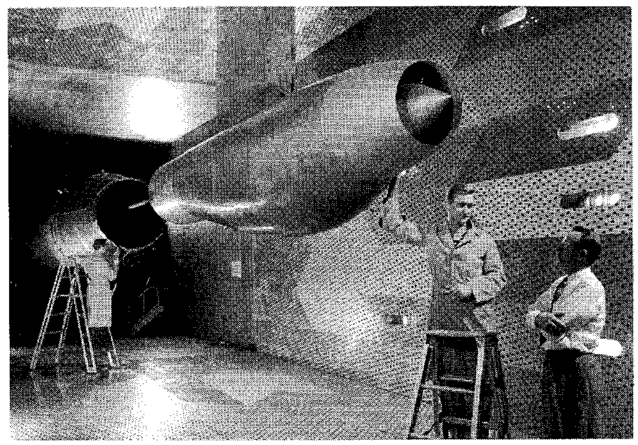


Fig. 34 B-58/J 79 propulsion system test installation in inlet–engine wind tunnel (AEDC 16T, 1958).

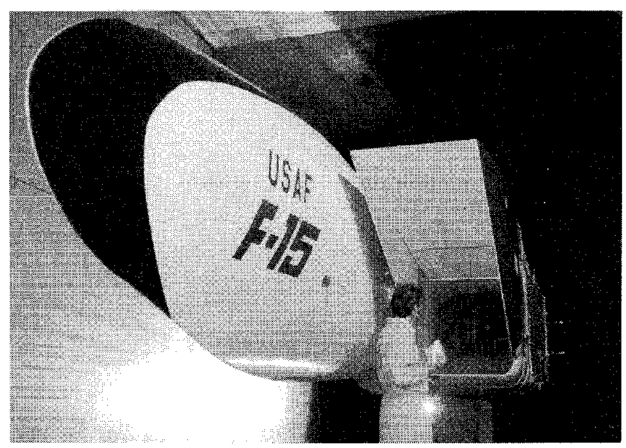


Fig. 35 F-15/F 100 turbofan propulsion system test installation in inlet–engine wind tunnel (AEDC 16S, 1972).

Inlet–Engine Freejet Test Cells

Two of the earliest inlet–engine freejet test installations were fixed Mach number and fixed angle-of-attack configurations. The earlier configuration provided Mach 3.0 test capability at 0-deg angle of attack for a 20-in.-diam research ramjet propulsion system (Fig. 36a).[44] The slightly later configuration provided a Mach 2.75 test capability at cruise angle of attack for the much larger XRJ47 engine with the additional complexity of a canted side-mounted nonaxisymmetric inlet cowl (Fig. 36b).[45] Note in both cases that highly tailored pressure recovery devices were required to provide an adequate range of test altitudes because the facility airflow capacities were

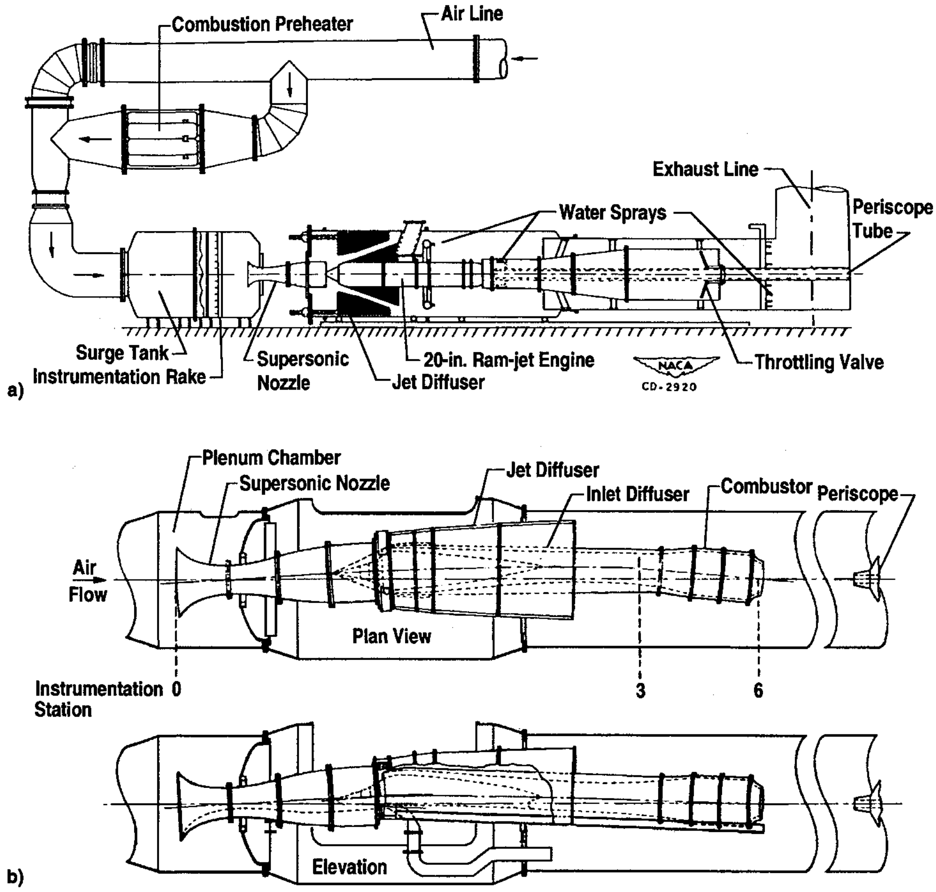


Fig. 36 Ramjet propulsion system test installation (supersonic, fixed Mach number, and angle of attack) in inlet–engine freejet test cells: a) research ramjet, 20 in. (NACA Lewis, ERB, CE-22, 1951) and b) Navaho/XRJ 47 (NACA Lewis, PSL2, 1953).

very marginal compared to the large airflow requirements of these freejet test installations.

By the mid 1950s the inlet–engine freejet test capabilities had progressed to the variable Mach number, variable angle-of-attack configuration shown in Fig. 37. The unique semi-flexible plate freejet nozzle provided a Mach number range from 2.0 to 2.7 and angle-of-pitch range from −17 to +20 deg.[46] In addition, the actuating forces required for the variable Mach number and variable pitch features of this nozzle were small enough that the actuation system provided rapid changes in flight speed (Mach number = 0.25/s) and flight attitude to simulate aircraft mission transients.[6]

A very large and advanced inlet–engine freejet test installation for turbojet/turbofan engines supported the integration of the air intake for the Concorde supersonic transport and the Olympus 593 engine during the late 1960s. Integration tests of this inlet–engine combination began in June 1967 in Cell 4 at the National Gas Turbine Establishment (NGTE) in Pyestock, England.[47] The arrangement of the key components is shown in Fig. 38. A photograph of the freejet nozzle and plenum is shown in Fig. 39. The test envelope for this configuration is as follows[48]:

Freejet test section area: 25 ft^2 (2.3 m^2)
Mach number: 1.75–2.3
Altitude: 45,000–85,000 ft
Pitch/yaw: 10 deg

Cell 4 at NGTE has also been fitted with a family of subsonic freejet nozzles. These nozzles provide subsonic test section areas ranging up to 18 ft^2 (1.7 m^2). The subsonic test sections have supported inlet–engine integration testing for a number of tactical aircraft programs.[48]

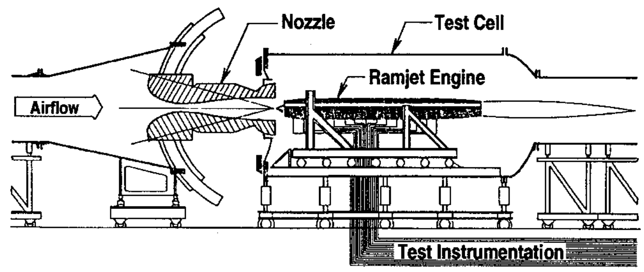
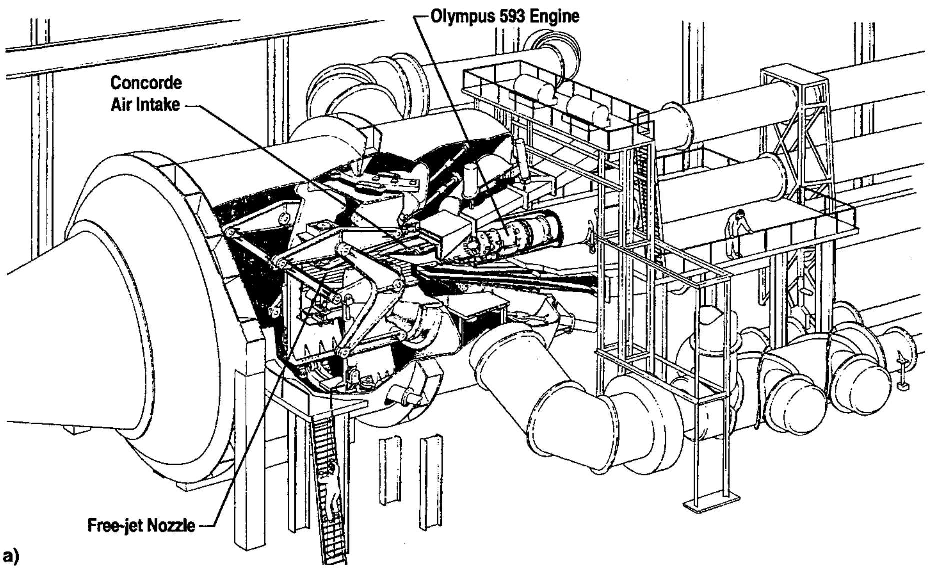


Fig. 37 Bomarc/RJ 43 test installation (supersonic, variable Mach number, and angle of attack) in inlet–engine freejet test cell (AEDC T4, 1954).

Major efforts to advance both the subsonic and supersonic inlet–engine freejet test capability were begun in 1978 and 1981, respectively, at AEDC. In 1987, a joint U.S. Air Force team assumed leadership of this effort. This team, composed of representatives from the Aeronautical Systems Division, Aero Propulsion Laboratory, Flight Dynamics Laboratory, and Arnold Center, directed experimental and analytical studies to upgrade and validate the state of the art for freejet testing of large tactical and strategic aircraft. This effort was, in particular, addressed to real-time (or near real-time) transient testing in terms of Mach number, altitude, angle of attack (pitch and yaw), and engine power settings.

This joint subsonic freejet effort was successfully completed in 1993 with the validation of new freejet capabilities for contemporary airframe–engine configurations.[49,50] This effort also included the construction, activation, and calibration of an advanced, large, subsonic freejet test section for the ASTF. The test envelope for this configuration is[51]



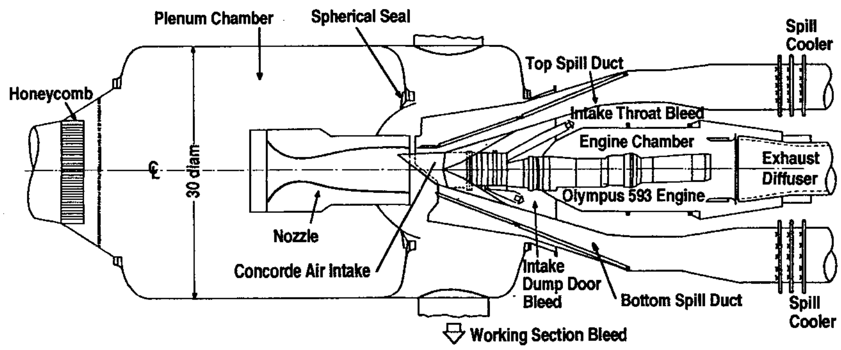


Fig. 38 Concorde/Olympus 593 test installation (supersonic, variable Mach number, and angle of attack) in inlet–engine freejet test cell (NGTE Cell 4, 1967): a) isometric, cutaway drawing and b) schematic.

Freejet test section area: 77 ft^2 (7.2 m^2)
Mach number: 0.3–0.9
Altitude: 15,000–80,000 ft
Pitch angle: −10 to +45 deg
Yaw angle: −10 to +10 deg

This new capability provides a real-time or a near real-time transient capability for Mach number, altitude, angle of attack, and engine power settings at true inlet temperatures. The nozzle inlet and plenum are shown in Fig. 40.

This joint supersonic freejet effort was also successfully completed in 1993 with the quantitative validation of freejet capabilities for contemporary airframe–engine configuration.[52] This effort also included the analysis and design of an advanced, large supersonic freejet test section for the ASTF. The design test envelope for this configuration is[53]

Freejet test section area: 55.3 ft^2 (5.1 m^2)
Mach number: subsonic to 3.0
Altitude: 30,000–80,000 ft (approximately)
Pitch angle: −10 to +20 deg
Yaw angle: −10 to +10 deg

The design capability includes a real-time or near real-time transient capability for Mach numbers above 1.5, altitude, angle of attack, and engine power settings at true inlet temperatures. The semiflexible wall supersonic nozzle configuration, including the location of the two throat jacks and trim jacks and pitch/yaw actuation cylinders, is shown in Fig. 41. This nozzle has not yet been constructed because the height-to-width ratio of the nozzle exit is dependent to some degree on the specific configuration of the airframe forebody and inlet cowl.

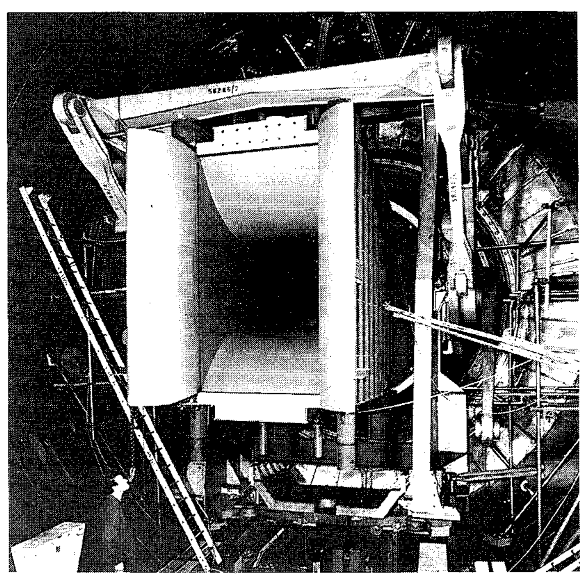


Fig. 39 Freejet nozzle and plenum for Concorde/Olympus 593 test installation (NGTE Cell 4, 1967).

Jet Effects Wind Tunnels/Exit Freejet Test Cells

The preceding section has demonstrated many of the challenges to providing adequate test support to the aircraft inlet–engine integration process. Test support to the engine–aircraft aftbody integration process presents even more difficult challenges. Some of the primary challenges are 1) a very long interference-free flowfield; 2) adequate duplication or simulation of the engine exhaust jet(s), including velocity, Mach number, temperature, pressure ratio, turning angle, etc.; and 3) scaling of the test results that are dominated by difficult to scale viscous phenomena such as turbulence, separation, and mixing.

By definition, the engine–aftbody integration processes are located far aft of the leading edges of the fuselage and wings. Therefore, the test article, including exhaust plumes, must introduce low blockage in the tunnel flow if tunnel interference effects in the region of interest are to be maintained at acceptably low levels. Tunnel interference effects are exacerbated if aircraft attitudes other than straight and level are important. This low blockage requirement dictates relatively small test articles, even in the largest tunnels available, and provides very small internal volumes to house engine exhaust simulators. The small test article size also increases the range of scaling (extrapolation) of the test results. Only a few large aerodynamic wind tunnels that cover the full range of subsonic, transonic, and supersonic speeds and have support infrastructure for engine exhaust gas simulation are in operation.

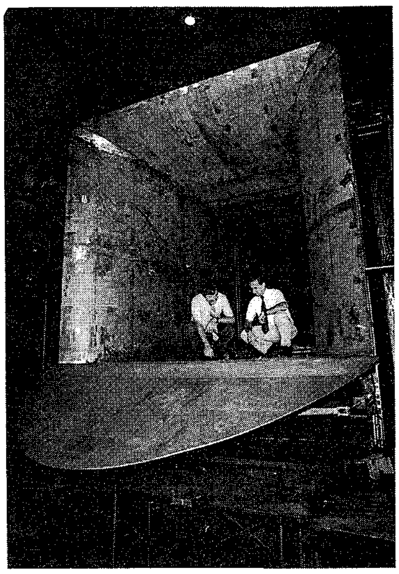


Fig. 40 Freejet nozzle and plenum for subsonic freejet test section (AEDC C-2, 1991).

The jet effects wind tunnels and the exit freejet test cells provide test support to the airframe–engine integration process at the interfaces listed in Fig. 42. A typical engine–aftbody integration test installation is shown in Fig. 43. The model shown is a 0.15-scale model of the F/A-18A aircraft equipped with wingtip model supports, faired-over air intakes, surface pressure measurements, and a warm air (150°F) exhaust gas simulator. This test configuration permits definition of the throttle-dependent drag forces associated with the jet exhaust interaction with the airframe aftbody and the external flow. This model was tested in the 16-ft transonic wind tunnel (PWT 16T) at AEDC.

The exit freejet test configuration provides a very specialized test capability to address engine–aftbody integration needs that require duplication of true freestream temperatures and real engine exhaust gas parameters. The primary advantage of this technique is that model sizes are large enough that full-

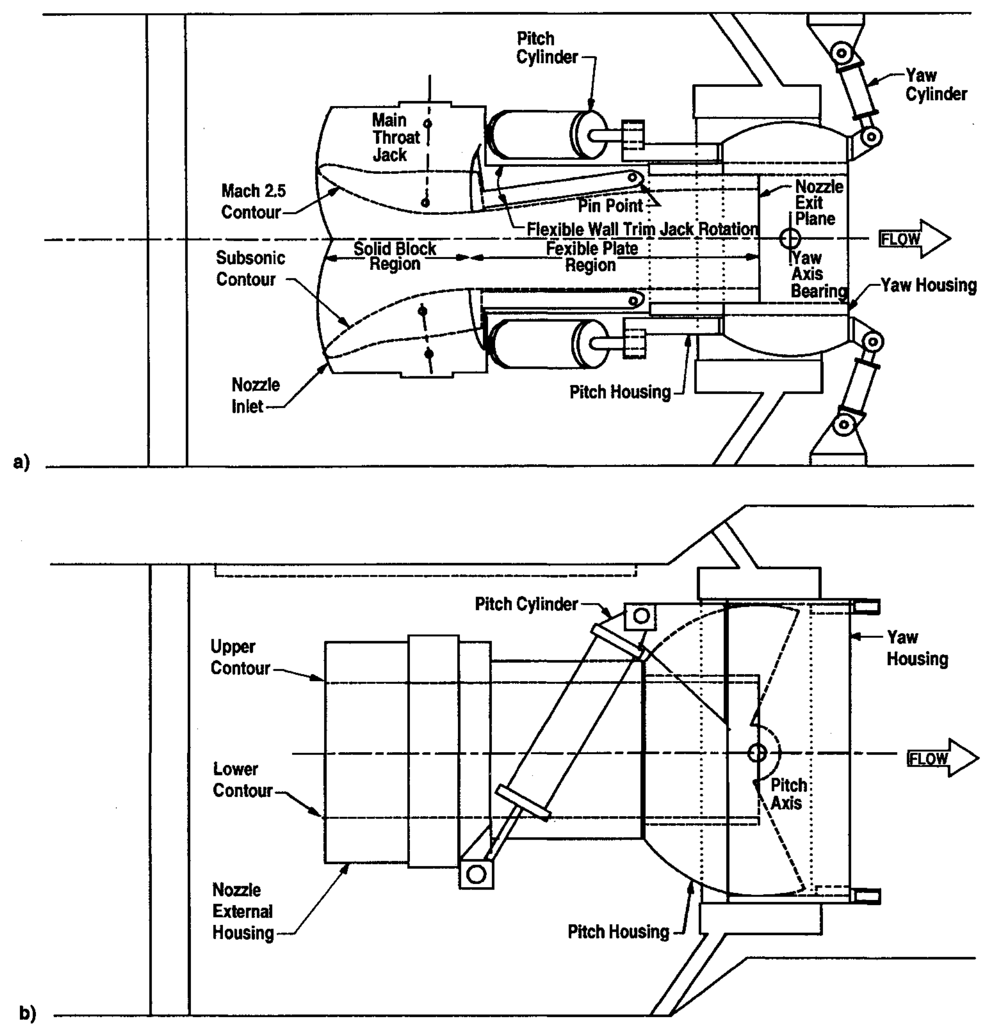
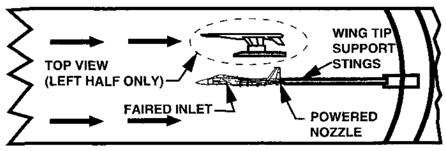


Fig. 41 Advanced supersonic freejet nozzle design (AEDC C-2, 1989): a) planview and b) elevation view.



INTERFACES

PERFORMANCE	OPERABILITY	DURABILITY/RELIABILITY
Aft - Body Drag (Throttle Dependent)	Exhaust System Stability	Exhaust Jet Interference
Exhaust System(Multi - Stream Planar, Non - Planar, Vectored)	Exhaust Gas Reingestion	Exhaust Jet Heating*
		Engine Bay Environment*
Trim Drag (Throttle Dependent)		

* Freejet Configuration Only

Fig. 42 Airframe–engine interfaces supported by engine jet effects wind tunnels and exit freejet test cells.

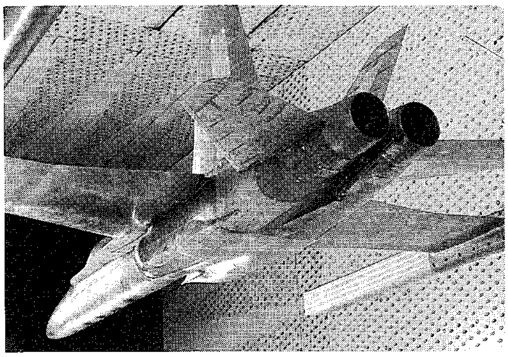
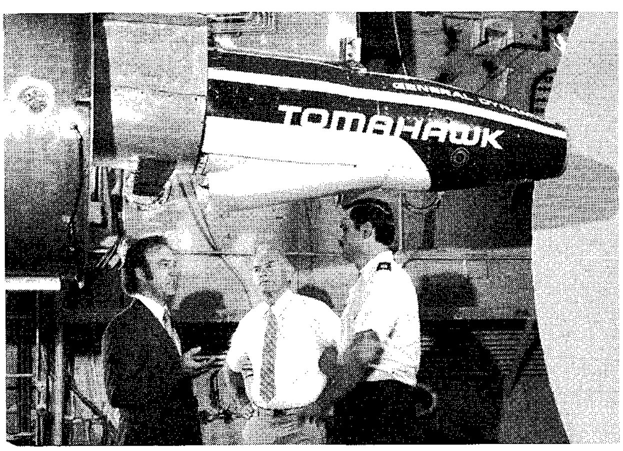


Fig. 43 Subscale airframe–engine test installation in jet effects wind tunnel (AEDC 16T, 1994).

a)


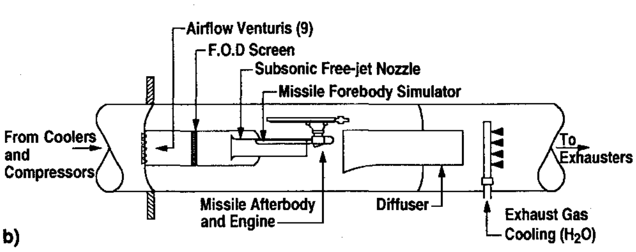
b)


Fig. 44 Full-scale afterbody-engine test installation in exit freejet test cell (AEDC J-1, 1989): a) photograph and b) schematic.

scale engines from tactical missiles can be installed. The primary disadvantages are that 1) model length is restricted to only a few diameters forward of the engine exhaust plane and 2) all testing is restricted to pitch and yaw angles of 0 deg only. A typical engine–aftbody integration freejet test installation is shown in Fig. 44. The model shown (Fig. 44a) is the aft 5.5 ft of the full-scale Tomahawk Cruise Missile equipped with an F-107 engine. The arrangement of the key components is shown in Fig. 44b. This configuration was tested in the ETF J-1 test cell at the AEDC.

Propulsion Wind Tunnels

Occasionally, the full-scale dimensions, flight speed, and configuration of a jet-powered missile are compatible with the capacity and capability of the largest propulsion wind tunnels that are currently operational. In these cases, the complete full-scale airframe, engine, and integrated control system can be tested over a significant part of the aircraft operational envelope (i.e., altitude, flight speed, and attitude) in the full-scale aircraft configuration shown in Fig. 14a. For this configuration, the propulsion wind tunnels can provide test support to almost all of the airframe–engine integration interfaces listed in Figs. 1–3. The primary exceptions are those interfaces related to special environments such as adverse weather, adverse environment, gun and rocket gas and steam ingestion, accelerations, and gyroscopic forces.

One shortfall of this method that must be carefully evaluated on a test-by-test basis is the lack of capability of large propulsion wind tunnels to duplicate standard and extreme atmosphere temperatures. This shortfall is most pronounced at subsonic high-altitude flight conditions (tunnel temperature high) and supersonic low-altitude flight conditions (tunnel temperature low) where the temperature mismatch can be 100°F or more. Additional engine testing at true inlet temperatures in altitude engine test cells can be utilized to overcome this shortfall.

Two examples of full-scale airframe–engine integration test installations are shown in Figs. 45 and 46. The Quail YGAM-72 missile powered by a J85 engine is shown in Fig. 45.[54] The Tomahawk Cruise Missile powered by an F-107 engine is shown in Fig. 46.[55] Both of these full-scale missiles were tested in the PWT 16T at AEDC.

Special Environmental Test Capabilities

The standard altitude flight environments that are simulated or duplicated in the several families of test facilities depicted in Fig. 14 comprise the vast majority of test support to the airframe–engine integration process. However, a large number of special environments forms a small but essential part of the overall ground test support to airframe–engine integration. These special environmental test capabilities support the airframe–engine integration process at the Operability and Durability/Reliability Interfaces listed in Figs. 2 and 3 as follows:

Adverse weather: rain, hail, icing
Adverse environment: birds, sand/dust, corrosion
Gun gas, rocket gas, and steam ingestion
Axial, vertical, and lateral accelerations
Gyroscopic forces
Engine attitude and orientation
Accelerated mission test

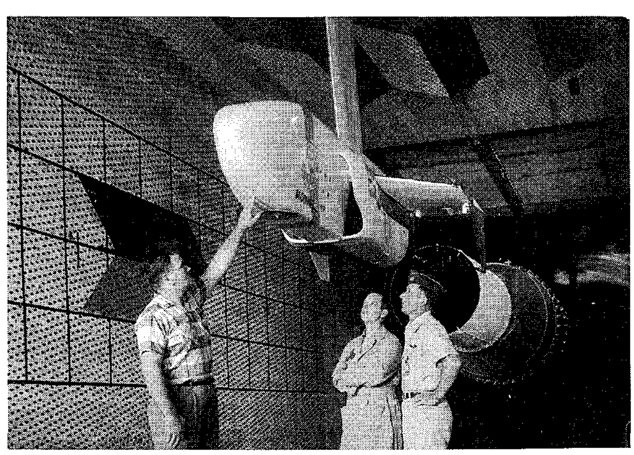


Fig. 45 Full-scale Quail YGAM-72 test installation in propulsion wind tunnel (AEDC 16T, 1959).

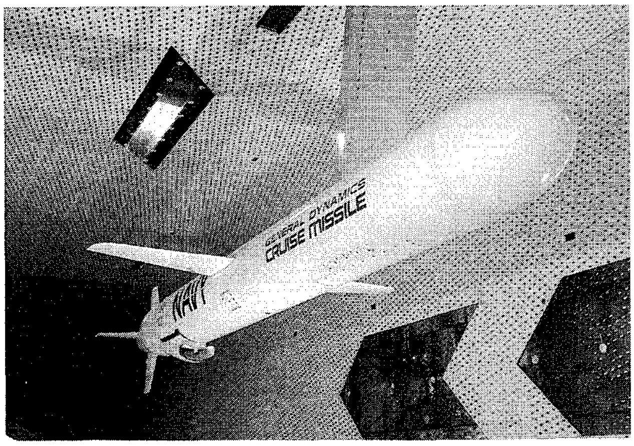


Fig. 46 Full-scale Tomahawk test installation in propulsion wind tunnel (AEDC 16T, 1975).

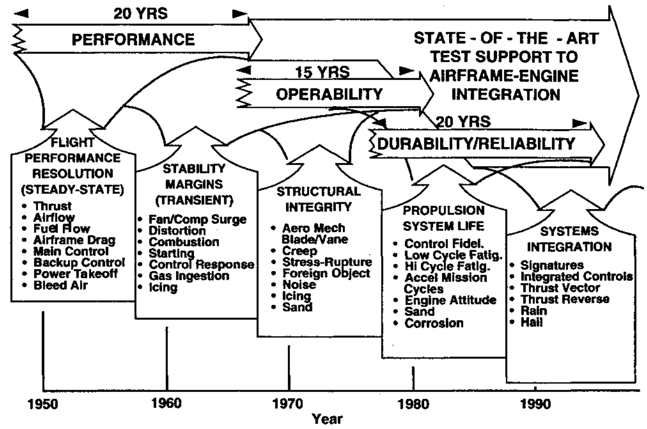


Fig. 47 Timeline: airframe–engine integration validated test capabilities (tactical, strategic, and transport aircraft).

An approximate timeline for the evolution of these special environmental capabilities is shown in Fig. 13b. Generally, several of these special environmental test capabilities are located at various industry-owned and government-owned sites. These special test capabilities generally require only modest capital investment, and the acquisition lead times are relatively short. These capabilities are usually acquired as an add-on effort to existing altitude or ground-level test facilities.

Intensive review and upgrades of special environmental test capabilities are underway in four areas because of recent civil and military aircraft operational experiences. These areas are 1) accelerated mission testing (AMT), 2) icing, 3) rain and hail, and 4) sand and dust. Specifically, the AMT test conditions, i.e., engine–inlet pressure and temperature, are being modified to include the effects on engine life of operation at inlet densities greater than standard sea-level density. The higher densities are the result of the inlet ram effect at higher flight speeds at lower altitudes. The AMT test profiles are being modified by the addition of these so-called RAM AMT cycles to the previously used sea-level-static test cycles as better understanding of actual engine operational usage is gained. In the area of icing, the knowledge base of natural icing phenomena and propulsion system response to icing environments is expanding.[56] Similarly, the statistical characterizations of worldwide rain and hail environments are being rapidly upgraded.[57] Both of these factors are requiring review of the test requirements and the availability of test capabilities to certify airframe–engine tolerance to adverse weather conditions. Finally, the results of extensive aircraft operations in sand and dust during Operation Desert Storm have been compiled on a multinational basis.[58] These results warrant a review of the test capabilities available to support certification of airframe–engine tolerance to this adverse environment.

Overall Perspective of Evolutionary Revolution

The periodic additions to the sizes and capacities of ground test facilities that support airframe–engine integration for jet-powered aircraft were chronicled for the period from the mid 1940s to the mid 1990s in the preceding sections of this paper. Incremental improvements in understanding the details of this integration process led to improvements in integration test capabilities during this same period. The sum of these evolutionary increases in facility capacity plus the increases in knowledge of how to apply this capacity to support the integration process has provided a cumulative total growth of revolutionary proportions in test support capability.

Examination of the ground test facility support capability with respect to the approximately 50 airframe–engine interfaces shown in Figs. 1–3 will provide insight into advances in the state of the art during the past five decades and will provide an assessment of the current state of the art. A timeline of these advances for tactical, strategic, and transport aircraft taken as a single group is shown in Fig. 47. This single grouping of these diverse types of aircraft may seem a little strained initially. However, from a test support viewpoint of the airframe–engine integration process, there is a strong commonality with one major exception. The exception was the introduction of the high-bypass turbofan engine during the latter half of the 1960s. This new engine cycle became the cycle of choice for most new subsonic transport aircraft and some subsonic tactical aircraft. The introduction of the high-bypass engine required revision and updating of some of the airframe–engine integration test support capabilities for the performance interfaces. The performance capabilities existing at that time had been tailored previously for low-bypass turbofans and turbojets (no bypass) only.

The order of maturity of ground test support capabilities for airframe–engine integration (Fig. 47) is very logical. There are, of course, substantial overlaps in the requirements for test capabilities to support airframe–engine integration at the performance, operability, and durability/reliability interfaces. However, as indicated in Fig. 47, there were times when each area of the interfaces was the dominant driver in the acquisition of mature test capabilities. The initial driver for the jet propulsion era was, by necessity, adequate performance, e.g., thrust minus drag and fuel burned, to perform a useful mission with a suitable payload. About 20 years were required to develop mature test capabilities for resolving flight performance of airframes and engines at each interface (Fig. 1), even though the parameters of interest were well-defined, well-known, continuous aerothermodynamic quantities.

Once useful performance levels were achieved, the emphasis naturally turned to enhancing the operability of the aircraft propulsion system. The mission planners and pilots required unrestricted access to the full speed, altitude, maneuver, and payload capabilities of the aircraft under all conditions. Some 15 years were devoted to developing test capabilities that permit quantitative assessment of the operability of the integrated airframe–engine system at each interface (Fig. 2). This development proceeded at a frustratingly slow pace because of the difficulties of first devising direct measures of operability and then developing test methods to quantify such measures. Even in hindsight, the success of these efforts is impressive because the limiting aerothermodynamic processes, e.g., stall, surge, and blowout, are discontinuous in nature, and it is difficult to measure the operating margins relative to each discontinuity. Such quantitative assessments replaced the much less reliable go/no-go assessments that had been used previously.

After the performance and operability goals were reached, the emphasis properly turned to control of the life-cycle costs of the integrated propulsion systems. The durability and reliability of the systems are major factors affecting both the initial cost and maintenance cost, and hence the affordability of each airframe–engine combination. About 20 years were devoted to developing test support capabilities that permit quantitative assessment of the structural margins and life limits of the propulsion system components at each interface shown in Fig. 3. This development also proceeded at a slow pace because of the difficulties of devising direct measures of durability. The limiting mechanical processes, e.g., crack initiation and crack propagation, are discontinuous in nature and operate within nonhomogeneous materials. Assessment of margins is made more difficult because each component retains artifacts of every production and operating event from the time of its manufacture. In a manner analogous to the stability margins and operability discussed previously, these quantitative structural margins and life limits replaced the fail/no-fail assessments used previously.

As indicated in Fig. 47, the sum of all of the evolutionary improvements in test support capabilities for airframe–engine integration over the past 50 years is today's state of the art. All of these validated test facilities and methods are available to support today's aircraft system acquisition process.

Three cautions should temper the enthusiasm for the strength of the current state of the art. First, even though improvements have been made in understanding the basic parameters that govern the airframe–engine integration process, significant portions of the process are still dependent on empiricism and scaling rules. Such dependencies always contain exposure to risks that the next configuration and/or next mission requirement will lie outside the bounds of applicability of the empiricism and/or scaling rules. Of course, these risks are exacerbated because the bounds of the current process are undefinable and unknowable until they are breached. The sum of these risks portends the possibility of a major airframe–engine incompatibility surprise. The airframe–engine integration process has previously produced many such surprises in all three interface areas, i.e., performance, operability, and durability/reliability. Second, new requirements for airframe–engine integration will likely require development of new test capabilities beyond what is available today. Some of these new systems integration challenges are listed in Fig. 47. Third, as has happened twice before, in 1950 and in 1975, the size and capacity of jet propulsion systems have reached and exceeded the maximum capacity of existing test facilities. Therefore, increased capacities for aerodynamic wind tunnels, altitude engine test cells, inlet–engine wind tunnels/freejet test cells, and jet effects wind tunnels/exit freejet test cells (Figs. 13 and 14b) must be acquired in the near future if even the present state of the art shown in Fig. 47 is to be sustained.

Enhanced Values of Airframe–Engine Integration Test Results

Overview

The acquisition of airframe–engine integration ground test facilities and test capabilities and the acquisition of quantities of test data are not the end of test support to the airframe–engine integration process. In reality, they are only the beginning, and this beginning is fraught with three large risks. The first risk is that the test data may not represent aircraft operational realities because of flawed simulation and/or inadequate knowledge of the real-world environmental conditions. The second risk is that there may be significant inaccuracies (uncertainties) in the measured quantitative results. The third risk is that the test data may be so voluminous that the most significant results are overlooked. Therefore, a necessary activity that complements the acquisition of test facility capacity and development of test capabilities has been, and continues to be, the acquisition of analysis and interpretation tools that adequately mitigate these three risks.

Several examples of specific key advances in analysis and interpretation methods are discussed in the following sections. Each example is an evolutionary step in the conversion of raw test data into validated test information that can be used for making accurate, action-oriented decisions on a timely basis during the aircraft–engine integration process.

Propulsion System Performance Resolution

Major improvements in resolving the installed performance of engines and propulsion systems were effected by the use of multiple, independent measurement methods for the key variables, e.g., thrust and airflow. The satisfactory closure of multiple independent values enhanced both the accuracy and reliability of the test results. Much of the impetus for these improvements is recounted in a study of aircraft performance and operational suitability problems by Montgomery.[59] Examples of the improved capabilities of multiple independent performance measuring methods for thrust are given in Refs. 60, 61 (Chap. 3), and 62. Earlier, much emphasis had been placed on improving the accuracy and repeatability of the basic engine airflow measurements because no national airflow calibration standards were available in the flow ranges of interest. Examples of improvements in airflow measurement are reported in Refs. 63 and 64.

In related efforts, significant advances in the measurement and accounting methods for airframe drag were realized. An example of current force accounting methods for airframes is contained in Ref. 61 (Chaps. 2, 4, and 5) and Ref. 65.

Propulsion System Stability Margin

A complete account of the stability-related problems in early U.S. Air Force jet aircraft was prepared by Montgomery.[3] He writes (pp. 5, 6),

> In the early years of jet-propelled military aircraft developments, a number of stability related factors arose in integrating engines and airframes. Early systems encountered various inlet-engine interface-related phenomena such as engine surge, flameout during armament firing, and inlet duct rumble ... Historical records show rather clearly that the inlet-engine interface evolved into a major problem in the early 1950's, with the advent of the "compressor stall problem" on several advanced Air Force weapons systems ...

This compressor stall problem as related to flow distortion at the airframe inlet–engine interface was the focus of several major advanced technology and system development initiatives by several industry and government (DoD and NASA) partnerships throughout the 1950s and 1960s. This compressor stall problem evolved naturally into a fan and compressor stall problem with the advent of the turbofan engine. The early approaches to understand and resolve the compressor stall problem were based on gross go/no-go definitions of the inlet distortion limits. This approach proved unreliable. During the 1955–1965 time period, the distortion limit concept was continually refined through the development of several empirical descriptors of distortion limits. These limit approaches continued to be unreliable.[3]

Finally, beginning at about 1965, major advances were realized in the characterization of quantitative compressor stability margin. At the same time development of the ground test techniques required to measure the margins and the margin utilization were underway.[3] A few years later, the goal of a quantitative definition of fan and compressor stability margins was realized.[24,25]

Uncertainty (Inaccuracy) of Test Results

An event in the nation's rocket and space program in 1965 set in motion a series of events that brought a major improvement in the airframe–engine integration process for jet aircraft. At that time, a Performance Standardization Working Group was organized under the cognizance of the Interagency Chemical Rocket Propulsion Group (ICRPG) to improve and recommend methodology suited to eventual adoption as national

CONTEMPORARY FIGHTER AIRCRAFT IN AERODYNAMIC WIND TUNNEL

	1970's				1990's			
MACH NO.	0.8	0.8	1.2	1.2	0.8	0.8	1.2	1.2
ATTITUDE	CRUISE	MANEUVER	CRUISE	MANEUVER	CRUISE	MANEUVER	CRUISE	MANEUVER
	U ADD-REF. 67		MEASUREMENT UNCERTAINTY ± UNITS OF MEASUREMENT				U RSS-REF. 67	
MACH NO.	0.0018	0.0018	0.002	0.002	0.0012	0.0012	0.0017	0.0017
DYNAMIC PRESS. PSF	2.5	2.5	2.5	2.5	0.8	0.8	0.5	0.5
DRAG COEFF.	0.0040	0.0070	0.0030	0.0060	0.0020	0.0050	0.0015	0.0035
LIFT COEFF.	0.0130	0.0130	0.0100	0.0100	0.0100	0.0100	0.0070	0.0070
ANGLE-OF ATTACK DEG	0.1	0.1	0.1	0.1	0.05	0.07	0.05	0.07

LOW BYPASS TURBOFAN ENGINE IN ALTITUDE TEST CELL

	1970's			1990's		
POWER	INTERMED	INTERMED	MAX	INTERMED	INTERMED	MAX
MACH NO.	0	0.9	2.2	0	0.9	2.2
ALTITUDE, FT	0	30K	40K	0	30K	40K
	U ADD-REF. 67		MEASUREMENT UNCERTAINTY ± PERCENT OF LEVEL		U ADD-REF. 67	
INLET PRESS.	0.4	0.4	0.4	0.1	0.2	0.1
INLET TEMP.	0.4	0.4	0.4	0.1	0.1	0.1
ENGINE SPEED	0.3	0.3	0.3	0.02	0.02	0.02
AIR FLOW	0.5	0.5	0.5	0.4	0.4	0.4
FUEL FLOW	1.0	1.0	1.0	0.7	0.7	0.7
THRUST	0.8	0.6	0.5	0.4	0.4	0.3

Fig. 48 Improvements in quality (reduced uncertainty) in test measurements, 1970s–1990s.

standards in a number of topic areas related to performance of liquid-propellant rocket engines. One of these topic areas was the estimation of the uncertainty (inaccuracy) of rocket test data. This effort was eminently successful, and in 1969 an uncertainty handbook was published.[66]

Before 1965, the pressing need for a methodology to determine the uncertainty of airframe–engine integration test data had been addressed, but several attempts to develop a methodology were unsuccessful. Buoyed by the success of the ICRPG effort, the AEDC entered into a contract with Pratt and Whitney Aircraft, developer of the ICRPG handbook, to develop a measurement uncertainty methodology for gas turbines. This seminal method tailored to the needs of airframe–engine integration was published in 1973 (Ref. 67). Using the Abernethy–Thompson method, the uncertainty, bias, and precision of performance data could be assessed with known confidence.

One of the greatest benefits of this uncertainty methodology has been the identification of the largest elemental precision and bias error terms for each measured parameter. Thus, for the past 20 years, it has been possible to target measurement improvement initiatives in those areas that offer the largest payoff in reducing the measurement uncertainties. The improvements in quality of measurement, i.e., reduced uncertainties, have been substantial, as shown in Fig. 48. The reductions in the uncertainties of pressure measurements and parameters (e.g., dynamic pressure) that are strongly dependent on measured pressures are very significant.

This original uncertainty methodology has been refined, expanded, and adopted by several national and international standards groups, including the American Society of Mechanical Engineers (ASME), Society of Automotive Engineers (SAE), American Institute of Aeronautics and Astronautics (AIAA), and International Standards Organization (ISO).[68] In addition, the methodology has been used extensively within the NATO Advisory Group for Aerospace Research and Development (AGARD).[69,70] The Abernethy–Thompson methodology also contributed substantially to the AGARD work related to aerodynamic data accuracy and quality in wind-tunnel testing related to airframe–engine integration.[71] Most recently, AGARD has provided a major addition by extending the method from steady-state measurements only to now include a first-generation method for transient measurements.[72]

Mathematical Models of Airframe–Engine Integration Processes

The lifetime of effective electronic computing capability very nearly coincides with the lifetime of the airframe–integration process for jet aircraft. Improvements in the capabilities of electronic computing hardware and software have contributed in a major way to the evolution of the airframe–engine integration process. Beginning in the 1950s, electronic computers provided limited cataloging of the large volume of integration test data only. These cataloging capabilities included indexing, compact storage, and timely retrieval of such data. During the 1960s and 1970s improvements in computing equipment and computational codes enabled development and utilization of cycle balancing mathematical models of steady-state engine performance.[73] In addition, computational fluid dynamic (CFD) models of one- and two-dimensional aerodynamic flows were available for computation of steady-state aerodynamic flowfields both internal and external to the airframe. These models permitted detailed analysis and interpretation of local steady flowfields and provided a means of validating experimental measurements of performance differences between two steady-state operating conditions.

Then, during the 1980s and 1990s the computing capabilities reached the levels required to support transient solution of engine performance at relatively low frequencies up to the order of the engine control response rates.[74] In addition, CFD models of steady three-dimensional internal and external aerodynamic flows could be solved.[75] A sample solution of the steady local stagnation pressure contours at the airframe inlet–engine interface plane and normalized pressure contours within the inlet duct and on adjacent external surfaces is shown in Fig. 49. Such CFD solutions permit the detailed analysis and interpretation of local steady flowfields and the validation of the effect of subtle design changes.

On-Line Near-Real-Time Information Processing

The effective integration of high-speed data acquisition systems and high throughput data processing computers now provides on-line, near-real-time, test information. This capability is a major factor in mitigating the third risk, that is, overlooking significant results as discussed in the Overview. Two contemporary examples demonstrate the current capabilities for computer-assisted screening of the massive quantities of digital information generated in current ground test facilities.

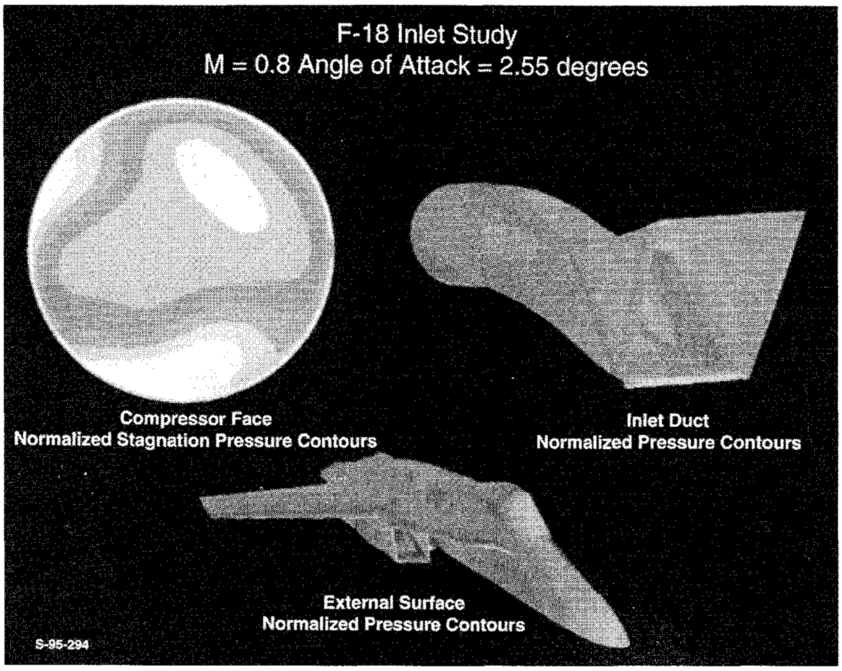


Fig. 49 CFD solution of engine inlet pressure distortion and inlet surface pressure distribution (1993).

First, since the mid 1970s, increasingly effective capabilities have been developed to compare many of the experimental data values with predicted values obtained from engine mathematical models on-line and in near-real time. In the early years, these comparisons were restricted to steady-state data only. Today, comparisons for both steady-state and transient data are available. With such on-line comparison capability, the probability of overlooking a significant new result in each data group is minimized because each experimental measurement that differs by more than a predetermined amount from the value predicted by the engine math model can be tagged by the computer. These tagged values, which total only a small fraction of the total data group, are available for detailed examination by test personnel. All of the other data values that lie within the predetermined limits are stored in memory for future use as needed.

As a second example, available array processors have made possible massive compression of dynamic inlet total pressure distortion data. A new Digital Distortion Analyzer has recently been placed in service at AEDC, which processes dynamic total pressure distortion data at the inlet–engine interface plane in near real-time.[76] This system can simultaneously digitize pressure data from up to 64 channels at rates up to 10,000 samples/channel/s. The system includes three array processors that process these pressure data to track the timewise behavior of programmable distortion parameters. High-level, i.e., Fortran 77, language coding capability is provided to allow quick, convenient entry of the desired computational algorithms. This system tracks and tags the maximum values of each inlet distortion parameter within a defined test data time window in less than three times real time. For example, a 60-s data point is processed in less than 180 s after data acquisition is completed.

The premier predecessor dynamic distortion processor was the off-line Dynamic Data Editing and Computing System (DYNADEC). This hybrid analog–digital computer was placed in operation in the Flight Dynamics Laboratory at Wright–Patterson AFB, prior to 1980.

Reflections and Personalities

I have intentionally withheld the most risky part of this lecture to this last section. It seems to me to be very important to provide some personal reflections regarding the evolution of ground test support to the airframe–engine integration process during the first half-century of the jet engine era. Further, I believe it is important to identify some of the key individuals who, by my own personal knowledge, were the movers and shakers in the airframe–engine integration process. These individuals provided much of the leadership and motive power for the evolutionary revolution just described.

By their very nature, almost all of the advances described herein were the results of large team efforts. However, it is equally obvious that there were individuals in key leadership roles. The risk of naming names is that certainly some very notable names will be omitted, and for those omissions, I apologize. The larger risk is that, if no individuals are named, then all will be omitted. Some of those remembered are deceased, some are no longer active participants in the airframe–engine integration field, and some are at their accustomed place, pulling their share of the load and more.

Reflections

Wartime Aeronautical Test Facilities in Germany

Any assessment of the evolution of ground test facilities in support of the development of jet-propelled aircraft has a natural milestone at the end of World War II. The airframe and jet engine test facilities that were discovered in Germany during the military occupation by Allied forces beginning in 1945 were a revelation. An excellent summary of the German facilities related to airframe–engine integration and many other aeronautical facilities was prepared by a group of Canadian scientists and engineers who visited the facilities in late 1945 (Ref. 12).

The assessment of the potential of these German facilities (many in operation and some under construction) by men of vision and brillance such as H. H. Arnold, Theodore von Kármán, and Frank Wattendorf led to the inescapable conclusion that the U.S. must mount an enormous national effort to reach parity and then surpass the existing German test capabilities. The essence of their collective vision was distilled in the report "Toward New Horizons."[77] This report is ample testimony to their remarkable ability to translate their observations and visions into a credible advocacy for aeronautical test facilities to meet a national need.

Public Law 81-415 Unitary Wind Tunnel Plan Act of 1949 and Air Engineering Development Center Act of 1949

The U.S. national resolve to meet the needs for aeronautical test facilities as defined in "Toward New Horizons" was implemented by the U.S. Congress through Public Law 81-415. This remarkable action had the immediate effect of providing premier U.S. facilities to support airframe–engine integration and other aeronautical disciplines during the decade of the 1950s.

These two powerful acts provided not only the initial 1950s surge in acquisition of test facilities, but also provided for timely upgrade of capabilities in future years. The provisions of these acts provided key support to the acquisition process for major national test facilities during the 1970s, namely, the ASTF at AEDC, the National Transonic Facility at NASA Langley, and the 80 by 120 ft Wind Tunnel at NASA Ames. These acts remain in effect today, and can serve to support the acquisition of future test facilities in the late 1990s and beyond, for example, the NWTC.

Turbofan Engines, Sunset Technology Circa 1970s

The early 1970s were a time of major national decisions related to the acquisition of three major new test facilities to support airframe–engine integration as discussed in the preceding section. I had the good fortune to be a member of the U.S. Air Force team assigned responsibility for the design and advocacy of the ASTF during this time period.

At the beginning of the decade, I was privileged to serve as the leader of the engineering team to prepare the final design criteria for the ASTF. The criteria that were completed during 1972 represented a consensus position of government agencies and industrial organizations engaged in the development and production of large jet engines.

After completion of the ASTF design criteria, I supported William H. Heiser and James G. Mitchell, successive chief scientists of AEDC, in the advocacy process to secure Congressional approval and funding for the acquisition of ASTF. The advocacy process required some four years of intensive interaction with Congressional and Executive agencies, Department of Defense organizations, NASA, and industry.

The good news is that the advocacy process was successful, and Congress approved and funded ASTF in 1977. This new national test capability became operational in 1984 as shown earlier (Fig. 12). However, two factors emerged during this advocacy process that are of concern for the present and future. First, there were individuals and groups who opposed ASTF on the basis that turbofan engines were a sunset technology, and thus, no additional engine developments were desired or even possible. The analogy drawn was to the sunset for large reciprocating aircraft engines in the late 1940s. It was not possible to respond to their request for proof on a technically credible basis that some radical new aircraft propulsion system breakthrough would not occur in the 1980s that would render the turbofan obsolete.

Secondly, there was significant opposition to ASTF on the basis that the physical size, thrust, and airflow capacity of turbofan engines would not continue to increase much beyond the contemporaneous values of 30,000–40,000 lb. These opponents agreed that there might be small increases in thrust, but nothing approaching the 75,000- to 100,000-lb thrust levels included in the ASTF requirements. Again, it was not possible to respond to their request for proof on a credible basis that future engines would be larger. Their key hypothesis was that future large aircraft would have at least four engines, and on this basis extrapolation of then-current growth trends in aircraft gross weight and engine power would not support the large increase in engine size.

Fortunately, there were a number of respected advisory groups, including the U.S. Air Force Scientific Advisory Board (SAB), that retained credibility with Congressional and Executive agencies. Inputs from these independent advisors formed the proof answers to the sunset and size questions. The vision and studied assessments by these groups were, in my opinion, the keystone of the successful advocacy of ASTF. It is axiomatic that one of the key elements in the Congressional approval of the Unitary Wind Tunnel Plan Act of 1949 and the Air Engineering Development Center Act of 1949 was the advice and counsel provided by the Army Air Forces Scientific Advisory Group (SAG) chaired by Theodore von Kármán. SAG was the predecessor organization to SAB of the 1970s and to the present day.

Leadership Personalities

In my view of the evolution of the airframe–engine integration world, three men emerge as dominant contributors in three separate but overlapping areas of expertise. These individuals and their areas of expertise are as follows:

1) Ernest C. (Cliff) Simpson—Aeropropulsion Systems: Advanced Technology and Full-Scale Development.

2) Bernhard H. (Doc) Goethert—Airframe–Engine Integration Ground Test Facilities: Design, Construction, and Operation.

3) Eugene E. (Gene) Covert—Airframe–Engine Integration: Basic Research and Resolution of Real-World Operational Difficulties.

Ernest C. (Cliff) Simpson

Certainly, when measured by almost all standards, Cliff Simpson (Fig. 50) emerges as the father of the airframe–engine integration process for the jet engine era. His achievements during his 38-yr career are well-chronicled in his memoirs, *The Last Great Act of Defiance*.[78] From his vantage point as Chief, Turbine Engine Division, Aero Propulsion Laboratory from 1960 to 1980, Simpson orchestrated many of the advances in the art and science of airframe–engine integration. Similarly, from 1942 to 1960, Cliff Simpson progressed through positions of increasing responsibility with the predecessor organizations, i.e., the Power Plant Laboratory and the Propulsion Laboratory, always leading and guiding jet engine development for his country. I find it very noteworthy that one of his earliest assignments was as Army Air Forces Project Engineer for the Lockheed L-1000 (XJ-37), which was cited earlier in this paper as the first jet engine designed in the U.S.

Some excerpts from his memoirs[78] show his deep sensitivity to successful airframe–engine integration right from the beginning.

> Our first effort at using turbine power, the P-59A, was by any technical parameter assessment a miserable show, but by more practical judgements the engineering community proved . . . you could fly an airplane with a gas turbine; . . . On the gross scale, it was clear we did not know how to match a turbine engine to an aircraft . . . (p. 34)

The P-59A was powered by two J31 engines, and of that Simpson writes: "The aircraft, as far as propulsion went, performed well when it performed, and although the fuel consumption was horrible, its life was far worse . . . The life (average) was seven and a half hours . . ." (p. 35). Simpson later writes,

Fig. 50 Photograph of Ernest C. (Cliff) Simpson.

"The P-80 was the first airplane that taught us a few points about inlet duct-engine compatibility. The inlet duct had to be redesigned to prevent "duct-rumble" . . . (p. 38). Of those early days of airframe–engine integration, Cliff Simpson also wrote, "Matching propulsion systems to an airplane is a hazardous occupation since the man who tells you how the aircraft will be used never knows and therefore you always end up with the wrong conclusion" (p. 38). These four brief comments attest to Simpson's innate understanding of airframe–engine integration as the simultaneous tradeoff of the three competing requirements for performance, operability, and durability/reliability.

Bernhard H. (Doc) Goethert

B. Goethert (Fig. 51) is a patriarch of test support to the airframe–engine integration process. He served as Department Chief of High-Speed Aerodynamics at the Deutsche Versuchsanstalt Luftfahrt (German Experimental Establishment for Aeronautics) in Berlin during World War II. In this position he spearheaded wind-tunnel testing for development of the world's first jet-powered combat airplanes.[79]

Goethert immigrated to the U.S. in 1945 and was assigned as a consultant for the U.S. Army Air Force test facilities at Wright Field in Dayton, Ohio. In 1949, he was appointed as Chief of the wind-tunnel test activities at Dayton. During this time he also made key contributions to the design of the new propulsion wind tunnels that were to be constructed at AEDC under the Air Engineering Development Center Act. For example, the Goethert concept was adopted for the porous test section walls of the transonic tunnel.[79]

In 1952, Goethert joined ARO, Inc., and became the Chief of the Propulsion Wind Tunnels at AEDC. The transonic tunnel (PWT 16T) was made operational in 1956 under his leadership. In that same year Goethert was reassigned as chief of the Engine Test Facility at AEDC.[80] In this new role he continued to expand his profound influence on ground test support to the airframe–engine integration process. His summaries of some of the engine testing highlights of the period are given in Ref. 6. Goethert's influence on test support again expanded in 1959 when he was elevated to Director of Engineering and assumed technical responsibility for the contract operation for all AEDC test facilities. Finally, his influence on the test support community was maximized while he served as Chief Scientist, U.S. Air Force Systems Command, during the years 1964–1966.

Eugene E. (Gene) Covert

Throughout the 1970s, 1980s, and 1990s, E. E. Covert (Fig. 52) has served as the master problem solver for the airframe–engine integration community. He has served the Massachusetts Institute of Technology continuously since 1952 in positions ranging from Research Engineer through Laboratory Director, Associate Professor, and Professor (1968 to present). In between teaching classes, Gene, in his roles as consultant and confidant, has worked closely with the Department of Defense, NASA, and the civil aviation sector to resolve performance, operability, and durability/reliability surprises on many U.S. aerospace systems. For example, he has assisted the U.S. Air Force in planning test programs in wind tunnels and propulsion test facilities to understand and resolve development and operational difficulties encountered at the airframe–engine interfaces in several U.S. military aircraft.

Fig. 51 Photograph of Bernhard H. (Doc) Goethert.

Fig. 52 Photograph of Eugene E. (Gene) Covert.

The hallmark of Covert's contributions has been and continues to be his rare and powerful combination of theoretical, analytical, and experimental skills. His multidimensional understanding enables him to be equally effective with the scientist in the basic research laboratory, with the crew chief in the engine bay of an aircraft on the flight line, and with all of the technology and engineering workstations in between. He recently rendered a great service to the airframe–engine integration community by serving as editor of an important new book on thrust and drag.[61] This work is serving to improve communications between the flight test and ground test communities that are involved in the performance integration of airframes and engines.

At the international level, Covert has been very active within NATO's AGARD, and served as Chairman of the Propulsion and Energetics Panel (PEP). In 1978, he originated the Uniform Engine Testing Program under the auspices of PEP. In this round-robin test program, two identical operational turbojet engines were tested in eight different test facilities in five of the NATO countries. The results of these tests[81] form a basis for improved understanding of measured engine performance as used in the airframe–engine integration process.

Some of the Rest of Us

In addition to the three dominant contributors just named, my active involvement in test support to the airframe–engine integration process also allowed me the privilege of working with many notable integration experts. By naming a few of these pioneers in the art and science of integration, I hope to stimulate the reader to remember others who contributed significantly to the evolutionary revolution of test support to the airframe–engine integration support during the past 50 years.

Airframe–Engine Integration

To provide some structure, I have grouped these contributors into the primary integration interface areas of performance, operability, and durability/reliability. The contributors listed in Table 2 represent government, industry, and academia, and it was my privilege to know and work with each contributor in all these groups at various times. I take this opportunity to salute each one for their contributions to the successful marriages of many airframes and engines. As with any strong marriage there have been enough good days to encourage us to new heights of accomplishment, and enough difficult days to help us remain appropriately humble. What has been accomplished was perhaps best described by Robert Naka in a speech some years ago to the Philosophical Society of Washington in Washington, DC as "The Graying of a Black Art–Aeropropulsion Test and Design."

Measurement Uncertainty

A most important byproduct of the 1965 initiative by the Interagency Chemical Rocket Propulsion Group in Measure-

Table 2 Pioneers[a] in test support to airframe–engine integration

Performance	Operability	Durability/reliability
Eric Abell, ASD	Bob Anderson, NAPC	Joe Batka, APL
A. Butch Atkinson, NAVAIR	Dave Bowditch, NASA Lewis	William Cowie, ASD
Bill Chew, Calspan	Doug Bowers, FDL	Zeke Gershon, APL
Frank Csavina, ASD	Bill Braithwaite, NASA Lewis	William H. Heiser, APL/AEDC
James Day, ASD	Brian Brimelow, APL, GE	Jack Horan, NAVAIR
Ben Edwards, Sverdrup	Ivan Bush, APL	Ed Horn, ASD
Ted Garretson, AEDC	Pike Farr, McDonnell	Troy King, ASD
Tom Kennedy, Calspan	John Hartin, Sverdrup	Ed Koepnick, ASD
Jack Kerrebrock, MIT	William F. Kimzey, Sverdrup	Robert Mahorter, NAPC
Pete Lauer, Calspan	James Korn, Allison	James W. Mar, MIT
Glen Lazalier, Sverdrup	Gus Lampard, Boeing	Larry Parsons, ML
Bruce T. Lundin, NASA Lewis	Cary McMiller, Rockwell	Walter Reiman, ML
Gene Manganiello, NASA Lewis	Gary Plourde, P&W	Wayne Tall, APL
Roy J. Matz, Sverdrup	Cal Porcher, GD	Charles Tiffany, ASD, Boeing
J. Frank Montgomery, APL	Fred Rall, ASD	Al Varani, AEL
Bruce Reese, Purdue	Keith Richey, FDL	Ron Williams, ML
Marvin Schmidt, APL	Howard Schumacher, APL	
Roy Smelt, Lockheed	Bill Steenken, GE	
Dan Snyder, NAPC	Jack Tate, Sverdrup	
H. E. Wolff, Sverdrup		

[a]Listed alphabetically organization pro tem.

ment Uncertainty (described earlier) was my opportunity to meet and work with Robert B. Abernethy of Pratt and Whitney Aircraft. Our new relationship, plus the enthusiastic support of Cliff Simpson, created the opportunity for Abernethy and his collaborator, J. W. Thompson of Sverdrup Technology, to create their seminal work in measurement uncertainty.[67] Their pioneering approach changed forever our understanding and knowledge of the complex experimental measurements that are foundation stones in the airframe–engine integration process.

Conclusions

1) Many evolutionary improvements in the roles of ground test facilities in the integration process for airframes and jet engines have been made during the nearly 50 years from the late 1940s to mid 1990s. During this period, the growth in test facility capacity and test capabilities has generally been adequate to support the minimum requirements leading to the successful marriage of contemporaneous airframes and engines both in the U.S. and various other nations.

2) The sum of these evolutionary improvements represents a revolutionary change in the airframe–engine integration process. Today's state of the art includes validated test support capabilities for some 50 airframe–engine interfaces related to the performance, operability, and durability/reliability of modern jet aircraft.

3) It is altogether appropriate that the AIAA Wright Brothers Lectureship should, from time to time, address the relationships of test support and airframe–engine integration. History recognizes the skillful use of wind tunnels and pioneering approaches to airframe–engine integration as two major factors in the Wright Brothers' invention of the airplane. Their manned powered flight breakthrough was enabled by propeller efficiencies almost twice as large as competing designs, two pusher propellers turning in opposite directions with chain drives, and a functional aircraft control system.

4) The basic thread woven through all of the improvements in test support to the airframe–engine integration process is the drive toward quantitative measurement of the interface parameters under realistic environmental conditions, plus a quantitative assessment of the uncertainty of each measurement relative to the true in-flight environment. The drive toward quantitative understanding of integrated performance was well-defined and focused from the beginning. The desired parameters, e.g., thrust, drag, and fuel burned, were straightforward, continuous, aerothermodynamic quantities. The drive toward quantitative understanding of integrated operability was far more difficult because no direct measures had been defined for this family of discontinuous, aerothermodynamic processes. Therefore, the concepts of quantitative margins, e.g., compressor stall margin, engine surge margin, and combustion stability margin, had to be devised first. Then, test facilities and test methods were developed to quantify these margins. The drive toward quantitative understanding of integrated durability/reliability was yet more difficult because it too is a discontinuous process, and in addition, the working mediums are nonhomogeneous solids with a memory of and a scar from every single previous production and operating event. Therefore, the concept of quantitative life tracking, e.g., production flaw sizes, stress cycle counting, and flaw propagation rates, had to be devised. Then, test facilities and test methods were developed to quantify and track the life-consuming processes.

5) The diameter and airflow capacity of jet propulsion systems have increased dramatically over the past five decades. Nearly concurrently, increases in capacity and capabilities of ground test facilities have been acquired. Today, once again, the largest and most powerful airframe–engine combinations in design or under development equal or exceed the capacities of the largest existing facilities. Therefore, a new generation of expanded test facilities is required to maintain the historical level of test support to the airframe–engine integration process.

6) In spite of all of the improvements cited in this assessment, significant portions of the current state of the art for the airframe–engine integration process are still dependent on empiricism and scaling rules. Such dependencies always contain exposure to risks that the next configuration and/or next mission requirement will lie outside the bounds of applicability of the empiricism and/or scaling rules. These risks portend the possibility of a major negative surprise. The airframe–engine integration process has produced many such surprises in its history. For example, in the operability area, it was initially believed that only the magnitude of the inlet total pressure distortion affected propulsion system stability. What a surprise it was, early on, to discover that the shape of the distortion pattern was just as significant or even more so. A much larger surprise came several years later when it was discovered that a distortion pattern that persists for only a few milliseconds (instantaneous) reduced the system stability margin as much as a steady-state pattern that persisted for minutes. In the durability/reliability area, it was a surprise to discover, very early, that minor partial thermal cycles consume significant portions of low-cycle fatigue life. Other surprises came later when it was discovered that inlet air density affects the high cycle fatigue life of the turbomachinery blading, or very recently when

it was confirmed that inlet air temperature and pressure affect overall durability/reliability.

7) The sum of these various conclusions reaffirms what Cliff Simpson learned many years ago, "Matching propulsion systems to an airplane is a hazardous occupation." We can take pride in the progress in the airframe–integration process that has been realized, but we must be appropriately humble and realize that there are still substantial risks in the contemporary empirical methods. These risks can be minimized only if we exercise due vigilance whenever excursions beyond the bounds of current aerothermodynamic and structural design practices are called for.

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References

[1]Culick, F. E. C., "The Origins of the First Powered, Man-Carrying Airplane," *Scientific American*, July 1979, pp. 86–100.

[2]Lippincott, H. H., "Propulsion Systems of the Wright Brothers," *The Wright Flyer: An Engineering Perspective*, edited by H. S. Wolko, National Air and Space Museum, Smithsonian Inst., Washington, DC, 1987, p. 80.

[3]Montgomery, J. F., III, "The Need for Air Force Engine Stability Margin Testing for Inlet-Engine Interface Definition," Air Force Aero Propulsion Lab., AFAPL-TR-71-84, Wright–Patterson AFB, OH, Dec. 1971.

[4]*Proceedings of the Air Force Airframe-Propulsion Compatibility Symposium*, Air Force Aero Propulsion Lab. and Flight Dynamics Lab., AFAPL-TR-69-103, Wright–Patterson AFB, OH, June 1970.

[5]Richey, G. K., Surber, L. E., and Berrier, B. L., "Airframe-Propulsion Integration for Fighter Aircraft," AIAA Paper 83-0084, Jan. 1983.

[6]Manganiello, E. J., Goethert, B. H., Hensel, R. W., Matt, H. K., and Pierre, M., "Part I—Engine Test Facilities," *Advanced Aero Engine Testing*, edited by A. W. Morley and J. Fabri, AGARDograph No. 37, Pergamon, 1959.

[7]"Case History of L-1000 (XJ37-1) Jet Propulsion Engine," Historical Division Intelligence, T-2, Air Materiel Command, U.S. Army Air Forces, Wright Field, OH, June 1946.

[8]Schlaifer, R., "Aircraft Gas Turbines in the United States," *Development of Aircraft Engines*, Harvard Univ., Boston, MA, 1950, pp. 447–450.

[9]Hiebert, D. M., "L-1000 (XJ-37) Jet Propulsion Engine Project Records," Arnold Engineering Development Center, AEDC History Office, Arnold AFB, TN, 1952.

[10]St. Peter, J., "Chapter-Nathan Price and the Lockheed L-1000," *A Tradition of Excellence—The Evolution of the Aircraft Gas Turbine Engine in the United States*, American Society of Mechanical Engineers, New York, 1995.

[11]Wattendorf, F. L., "A Chronology of the Background and Early History of the Arnold Engineering Development Center 1938–1949," AFSC Historical Publication, History Office, Arnold Engineering Development Center, Arnold AFB, TN, 1986.

[12]Green, J. J., Hiscocks, R. D., and Orr, J. L., "Wartime Aeronautical Research and Development in Germany," *The Engineering Journal*, Engineering Inst. of Canada, Montreal, PQ, Oct. 1948 (Part I); Nov. 1948 (Part II); Dec. 1948 (Part III); Jan. 1949 (Part IV).

[13]Kimzey, W. F., "Determination of Sea-Level and Altitude Vibration Characteristics of a YJ93-GE-3 Turbojet Engine in an Altitude Test Cell," Arnold Engineering Development Center, AEDC-TDR-64-194, Arnold AFB, TN, Oct. 1964.

[14]German, J. A., and Gall, E. S., "General Electric TF39 Engine (S/N 441-006/3) Performance Obtained During Development Testing in the Propulsion Engine Test Cell (J-1)," Arnold Engineering Development Center, AEDC-TR-69-3, Arnold AFB, TN, March 1969.

[15]Roberts, J. H., Guidone, J. A., Mancuso, B., Babilon, J., and McIllveen, M., "Engine Testing at Simulated Altitude Conditions," AIAA Paper 93-2452, June 1993.

[16]Smith, R. E., Jr., Wolff, H. E., and Scobey, W. P., "Effects of Inlet-Air-Flow Distortion on the Steady-State Performance of the XJ79-GE-1 Turbojet Engine at Several Reynolds Number Indices," Arnold Engineering Development Center, AEDC-TR-56-12, Arnold AFB, TN, Jan. 1957.

[17]Christenson, R. J., and Parker, J. R., "Evaluation of a Rotating Screen System for Producing Total Pressure Distortion at the Inlet of Turbojet Engines," Arnold Engineering Development Center, AEDC-TR-69-171, Arnold AFB, TN, Oct. 1969.

[18]Tear, R. E., "Approaches to Determine and Evaluate the Stability of Propulsion Systems," Air Force Aero Propulsion Lab., AFAPL-TR-67-75, Wright–Patterson AFB, OH, Feb. 1968.

[19]Sicking, T. E., "YJ93-SB70 Inlet Compatibility Test in the Propulsion Wind Tunnel at AEDC," General Electric, Technical Information Series R63FPD78, Feb. 1963.

[20]Kimzey, W. F., "An Investigation and Calibration of a Device for the Generation of Turbulent Flow at the Inlet of a Turbojet Engine," Arnold Engineering Development Center, AEDC-TR-65-195, Arnold AFB, TN, Oct. 1965.

[21]Kimzey, W. F., "An Investigation of the Effects of Shock-Induced Turbulent Inflow on a YJ93-GE-3 Turbojet Engine," Arnold Engineering Development Center, AEDC-TR-66-198, Arnold AFB, TN, Nov. 1966.

[22]Brimelow, B., Collins, T. P., and Pfefferkorn, G. A., "Engine Testing in a Dynamic Environment," AIAA Paper 74-1198, Oct. 1974.

[23]Bowditch, D. N., and Coltrin, R. E., "A Survey of Inlet/Engine Distortion Compatibility (Invited Paper)," AIAA Paper 83-1166, June 1983.

[24]"Gas Turbine Engine Inlet Flow Distortion Guidelines," Society of Automotive Engineers, SAE-ARP 1420, March 1978.

[25]"Inlet Total-Pressure-Distortion Considerations for Gas-Turbine Engines," Society of Automotive Engineers, SAE-AIR 1419, May 1983.

[26]Parker, J. R., Lazalier, G. R., and Rakowski, W. J., "Effects of Time Variant Inlet Distortion on Compressor Stability Characteristics of an Augmented Turbofan Engine at Reynolds Number Indices 0.6, 0.3, and 0.15," Arnold Engineering Development Center, AEDC-TR-71-150, Arnold AFB, TN, July 1971.

[27]Lazalier, G. R., and Parker, J. R., "Performance of a Prototype Discrete Frequency Total Pressure Fluctuation Generator for Jet Engine Inlet Compatibility Investigation," Arnold Engineering Development Center, AEDC-TR-69-139, Arnold AFB, TN, Oct. 1969.

[28]Korn, J. A., and McKain, T. F., "Exploratory Research into Turbofan Stability Performance," Air Force Aero Propulsion Laboratory, AFAPL TR-73-96, Wright–Patterson AFB, OH, Nov. 1973.

[29]Kutschenreuter, P. H., Jr., Collins, T. P., and Vier, W. F., III, "The P^3G-A New Dynamic Distortion Generator," AIAA Paper 73-1317, Nov. 1973.

[30]Braithwaite, W. M., Dicus, J. H., and Moss, J. E., Jr., "Evaluation with a Turbofan Engine of Airjets as a Steady-State Inlet Flow Distortion Device," NASA Lewis Research Center, NASA-TM-X-1955, Cleveland, OH, Jan. 1970.

[31]Overall, B. W., and Harper, R. E., "The Airjet Distortion Generator System: A New Tool for Aircraft Turbine Engine Testing," AIAA Paper 77-993, July 1977.

[32]McIllveen, M. W., "Further Test Results with the Airjet Distortion Generator System: A New Tool for Aircraft Turbine Engine Testing," AIAA Paper 79-1185, June 1979.

[33]Overall, B. W., "A Procedure for the Design of Complex Distortion Screen Patterns for Producing Specified Steady-State Total Pressure Profiles at the Inlet of Turbine Engines," Arnold Engineering Development Center, AEDC-TR-72-10, Arnold AFB, TN, Jan. 1972.

[34]Tate, J. T., and Smith, R. E., Jr., "Normalized Testing Techniques to Determine Turbine Engine Stability Margins," Arnold Engineering Development Center, AEDC-TR-71-249, Arnold AFB, TN, Jan. 1973.

[35]Tate, J. T., "Inlet-Engine Compatibility Testing Techniques in Ground Test Facilities," *Turbine Engine Testing*, NATO Advisory Group for Aerospace Research and Development, CP-293, AGARD, Paris, France, 1980 (Paper 21).

[36]Kimzey, W. F., Williams, V. O., and Gall, E. S., "Aerodynamic

Calibration and Shakedown Testing of the Full-Scale F-15 Aircraft Inlet Simulator," Arnold Engineering Development Center, AEDC-TR-72-147, Arnold AFB, TN, April 1973.

[37]Kimzey, W. F., and Ellis, S. H., "Supersonic Inlet Simulator—A Tool for Simulation of Realistic Engine Entry Flow Conditions," National Aerospace Engineering and Manufacturing Meeting, Society of Automotive Engineers, Paper 740824, Oct. 1974.

[38]Ogorodnikov, D. A., "Real-Time Simulation of Maneuverable Aircraft Flight Conditions on Altitude Test Cell," AIAA Paper 93-1845, June 1993.

[39]Sosunov, V., private communication, Sverdrup Technology, Inc., Arnold Engineering Development Center, Arnold AFB, TN, June 1995.

[40]"A Current Assessment of the Inlet/Engine Temperature Distortion Problem," Society of Automotive Engineers, SAE-ARD50015, Jan. 1991.

[41]Kimzey, W. F., Jones, R. B., and Lazalier, G. R., "A New Technique for Test Assessment of Advanced-Technology Turbine-Engine Propulsion Systems in the New Aeropropulsion Systems Test Facility (ASTF)," AIAA Paper 87-1789, June 1987.

[42]Perchonok, E., Wilcox, F., and Pennington, D., "Effect of Angle of Attack and Exit Nozzle Design on the Performance of a 16-Inch Ram Jet at Mach Numbers from 1.5 to 2.0," NASA Lewis Research Center, NACA-RM E51G26, Cleveland, OH, Oct. 1951.

[43]McDill, H. F., Lauer, R. F., Jr., and Jacocks, J. L., "Results of the Full-Scale F-15 Inlet/Engine Compatibility Test at Subsonic and Supersonic Mach Numbers," Arnold Engineering Development Center, AEDC-TR-72-149, Arnold AFB, TN, Oct. 1972.

[44]Trout, A. M., and Wentworth, C. B., "Free-Jet Altitude Investigation of a 20-Inch Ram-Jet Combustor with a Rich Inner Zone of Combustion for Improved Low-Temperature-Ratio Operation," NASA Lewis Research Center, NACA-RME 52L26, Cleveland, OH, May 1953.

[45]McAulay, J. E., and Smith, I. D., "Preliminary Results from Free-Jet Test of a 48-Inch-Diameter Ram-Jet Combustor with Three Different Flameholder Configurations," NASA Lewis Research Center, NACA-RM E56K26, Cleveland, OH, Aug. 1961.

[46]Sola, J. M., Nelius, M. A., and Moore, F. G., "Preliminary Flight Rating Tests of the Marquardt YRJ43-MA-7 Model MA 20YS-1 Ramjet Engine at AEDC," Arnold Engineering Development Center, AEDC-TR-59-7, Arnold AFB, TN, May 1959.

[47]Ashwood, P. F., "The Design and Development of a Large Supersonic Free-Jet Test Cell," *The Aeronautical Journal*, Vol. 74, No. 711, 1970, pp. 205–212.

[48]Ashwood, P. F., "Free-Jet Testing of Powerplants for Aircraft and Missiles," *Turbine Engine Testing*, NATO Advisory Group for Aerospace Research and Development, CP-293, AGARD, Paris, France, 1980 (Paper 20).

[49]Beale, D. K., and Zelenak, M., "Development and Validation of a Freejet Technique for Inlet-Engine Compatibility Testing," AIAA Paper 92-3921, July 1992.

[50]Beale, D. K., Kelly, P. G., and Lacasse, J. E. P., "Subscale Validation of a Freejet Inlet-Engine Test Capability," AIAA Paper 93-2179, June 1993.

[51]Maywald, P. V., "C-2 Subsonic Freejet Development and Demonstration," AIAA Paper 93-2180, June 1993.

[52]Beale, D. K., and Kelly, P. G., "Validation of Freejet Inlet-Engine Compatibility Assessment Technique for Fighter Aircraft, F-15 Configuration Results—Part I, Subsonic and Part II, Supersonic," Arnold Engineering Development Center, AEDC-TR-93-9, Arnold AFB, TN, Nov. 1993.

[53]Duesterhaus, D. A., and Maywald, P. V., "Free-Jet Test Capability for the Aeropropulsion Systems Test Facility," AIAA Paper 89-2537, July 1989.

[54]Tuthill, C. M., Galigher, L. L., and Prunty, C. C., "YGAM-72 Stall Investigation (J85-GE-3 Engine)," Arnold Engineering Development Center, AEDC-TN-60-137, Arnold AFB, TN, Aug. 1960.

[55]Lauer, R. F., Jr., "Captive Flight Tests of the Navy Tomahawk Cruise Missile in the AEDC 16-ft Transonic Wind Tunnel," Arnold Engineering Development Center, AEDC-TR-76-179, Arnold AFB, TN, Dec. 1976.

[56]*Low Temperature Environment Operations of Turboengines (Design and User's Problems)*, NATO Advisory Group for Aerospace Research and Development, CP-480, AGARD, Paris, France, May 1991.

[57]"Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines," NATO Advisory Group for Aerospace Research and Development, AGARD-AR-332, Paris, France, 1995.

[58]*Erosion, Corrosion and Foreign Object Damage Effects in Gas Turbines*, NATO Advisory Group for Aerospace Research and Development, CP-558, AGARD, Paris, France, 1994.

[59]Montgomery, J. F., "Engine Altitude Test Procedure," Air Force Aero Propulsion Lab., APTP-TM-69-20, Wright–Patterson AFB, OH, 1969.

[60]Smith, R. E., Jr., and Wehofer, S., "Measurement of Engine Thrust in Altitude Ground Test Facilities," AIAA Paper 82-0572, March 1982.

[61]*Thrust and Drag: Its Prediction and Verification*, edited by E. E. Covert, Vol. 98, Progress in Astronautics and Aeronautics, AIAA, New York, 1985.

[62]Kimzey, W. F., and Rakowski, W. J., "Preparatory Studies for Qualification of the TF39 Turbofan Engine in the Propulsion Engine Cell (J-1)," Arnold Engineering Development Center, AEDC-TR-69-85, Arnold AFB, TN, July 1969.

[63]Smith, R. E., Jr., and Matz, R. J., "A Theoretical Method of Determining Discharge Coefficients for Venturis Operating at Critical Flow Conditions," *Journal of Basic Engineering*, Vol. 84, Series D, No. 4, 1962, pp. 434–446.

[64]Smith, R. E., Jr., and Wolff, H. E., "Accurate Measurement of Airflow Rate During Tests of Air-Breathing Propulsion Systems," Arnold Engineering Development Center, AEDC-TR-68-22, Arnold AFB, TN, March 1968.

[65]"In-Flight Thrust Determination," Society of Automotive Engineers, SAE-AIR 1703, Nov. 1985.

[66]Abernethy, R. B., Colbert, D. L., and Powell, B. D., "ICRPG Handbook for Estimating Uncertainty in Measurements Made with Liquid-Propellant Rocket Engine Systems," Chemical Propulsion Information Agency, CPIA 180, April 1969.

[67]Abernethy, R. B., et al., and Thompson, J. W., Jr., "Handbook-Uncertainty in Gas Turbine Measurements," Arnold Engineering Development Center, AEDC-TR-73-5, Arnold AFB, TN, Feb. 1973.

[68]Abernethy, R. B., and Ringhiser, B., "The History and Statistical Development of the New ASME-SAE-AIAA-ISO Measurement Uncertainty Methodology," AIAA Paper 85-1403, July 1985.

[69]"Measurement Uncertainty Within the Uniform Engine Test Programme," NATO Advisory Group for Aerospace Research and Development, AGARD-AG-307, Paris, France, May 1989.

[70]"Recommended Practices for Measurements of Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components," NATO Advisory Group for Aerospace Research and Development, AGARD-AR-245, June 1990.

[71]Laster, M. L., "Technical Evaluation Report of the Symposium on Aerodynamic Data Accuracy and Quality: Requirements and Capabilities in Wind Tunnel Testing," NATO Advisory Group for Aerospace Research and Development, AGARD-AR-254, Paris, France, July 1988.

[72]"Guide to the Measurement of the Transient Performance of Aircraft Turbine Engines and Components," NATO Advisory Group for Aerospace Research and Development, AGARD-AR-320, Paris, France, March 1994.

[73]Fishbach, L. H., "Computer Simulation of Engine Systems," AIAA Paper 80-0051, Jan. 1980.

[74]Chappell, M. A., and McLaughlin, P. W., "Approach to Modeling Continuous Turbine Engine Operation from Startup to Shutdown," *Journal of Propulsion and Power*, Vol. 9, No. 3, 1993, pp. 466–471.

[75]Nichols, R. H., "Calculation of the Flow in a Circular S-Duct Inlet," AIAA Paper 91-0174, Jan. 1991.

[76]Morton, W. K., and Lazalier, G. R., "On-Line Distortion Analysis System for Inlet-Engine Testing," International Gas Turbine and Aeroengine Congress, American Society of Mechanical Engineers Paper 91-GT-166, June 1991.

[77]AAF Scientific Advisory Group, "Toward New Horizons," U.S. Army Air Forces, Washington, DC, Dec. 1945.

[78]"The Last Great Act of Defiance: The Memoirs of Ernest C. Simpson, Aero Propulsion Pioneer," edited by J. J. St. Peter, Aero Propulsion Lab., and Special Staff Office, Wright–Patterson AFB, OH, June 1987.

[79]Payne, W., *Web to the Stars—A History of the University of Tennessee Space Institute*, Kendall/Hunt Publishing, Dubuque, IA, 1992.

[80]Franzwa, G. M., *Legacy, The Sverdrup Story*, Sverdrup Corp. in cooperation with Patrice Press, 1979.

[81]"The Uniform Engine Test Programme," NATO Advisory Group for Aerospace Research and Development, AGARD-AR-248, Paris, France, Feb. 1990.