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On-Wing Testing of Large Turbofan Engines

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16. Abstract

This report addresses the issue of on-wing testing of large turbofan engines used in transport aircraft. The expanded use of installed testing is addressed along with the factors pertinent to the decision of doing on-wing testing. The maintenance capabilities of the operator, environmental concerns, space requirements, and available instrumentation need to be considered carefully. Several aircraft and engine maintenance manuals were reviewed in relation to summarizing the original equipment manufacturer's requirements and precautions for on-wing testing. Asymmetric power limits, exhaust and inlet hazard areas, ice and snow, and cross/tail-wind restrictions are some of the areas of concern. The benefits and drawbacks are outlined along with proposed solutions to anticipated problems.

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PREFACE

This report was prepared by Galaxy Scientific Corporation under Contract No. DTFA03 89-C-00043 with the Federal Aviation Administration William J. Hughes Technical Center. Mr. Bruce Fenton of the William J. Hughes Technical Center was the Task Monitor for this project. Mr. Larry Butler of Galaxy Scientific Corporation was the Project Manager.

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LIST ACRONYMS AND ABBREVIATIONS

AMM	aircraft maintenance manual
EEC	electronic engine control
EICAS	Engine Indicating and Crew Alerting System
EPR	engine pressure ratio
MTBF	mean time between failure
N1	fan rotational speed
N2	core rotational speed
OAT	outside air temperature
OBCM	on-board condition monitoring
OEM	original equipment manufacturer
P&W	Pratt & Whitney
QEC	Quick Engine Change
rpm	revolutions per minute

EXECUTIVE SUMMARY

This report investigates the expanded use of performing on-wing engine testing for aircraft equipped with large turbofan engines. The motivation for such testing stems primarily from the need for aircraft operators to reduce their maintenance costs. The testing of large turbofan engines is of particular interest because of the additional equipment, resources, and special facilities required to support related maintenance activities, especially for the very large diameter (96 inches or greater) fans. Emphasis in the study was placed on the examination of the technical and environmental issues that influence the conduct of on-wing engine testing.

Many factors can affect the decision to perform on-wing testing. Some of these factors are of a technical nature, e.g., the maintenance capabilities of the operator or contracted maintenance organization and the availability of accurate instrumentation systems on the aircraft that will be tested. Other factors stem from environmental concerns and include safety issues associated with high-noise levels and hazard areas around the aircraft, as well as adverse weather conditions such as high winds, low temperatures, heavy rains, sleet, and snow.

Based on the above factors and on maintenance recommendations found in aircraft and engine maintenance manuals, several advantages and disadvantages associated with on-wing testing were identified. Some of the advantages include the elimination or reduction in the cost of engine test cell operation, reductions in maintenance, instrumentation, and personnel requirements. Several disadvantages also exist, such as the need for a large secure area where on-wing testing can be performed. This requirement is based on safety concerns related to where on-wing testing can be performed. Other disadvantages address technical issues, such as the need for aircraft restraint systems, limitations associated with takeoff power engine tests, and the requirement for accurate engine instrumentation systems.

The report contains recommendations that can be implemented to overcome on-wing testing limitations. Recommendations include using blast deflectors and noise suppression systems to reduce the test area requirements. Shelters can be used to minimize the effects of adverse wind conditions. New portable data acquisition systems are now available that can supplement engine data collected from the cockpit instrumentation system. These and other proposed factors contribute to making expanded use of on-wing engine testing of large turbofan engines a feasible option for airline operators.

1. INTRODUCTION.

The maintenance and testing divisions of airlines have been the subject of the cost control efforts of many worldwide and national airline operators, as depicted in several aviation-related articles [1 and 2]. In an era that has seen the continuous downsizing and restructuring of the commercial airline industry, the maintenance function has been perceived as a major target of cost control. The past few years have seen increased efforts on the part of the carriers to bring down their operating costs. They have done this partly by reorganizing their maintenance activities and setting up independent business units to concentrate on specific engines. Still, the average cost of engine maintenance comprises roughly over 30 percent of the total maintenance expenses of the major airlines [1], and the industry is looking for ways to reduce this amount.

The majority of air carriers currently perform some degree of on-wing engine testing, driven primarily by the nature of the engine repair being addressed. In cases where the engine must be removed for maintenance and testing, several steps must be carried out. These include removing the engines from the airframe, transportation to a maintenance shop, testing in an approved test cell, transportation back to the aircraft, and reinstallation. An alternate method would be to leave the engine installed, perform the necessary work on the components or the modules, and then do the testing installed. This procedure would ease maintenance requirements, especially for the larger turbofan engines that typically require additional resources and special facilities to support maintenance activities. Operators around the world who currently use aircraft equipped with large turbofan engines would benefit from this maintenance philosophy. This approach would also be useful for future aircraft that use large turbofan engines. A good example of this is the Boeing 777, which may be configured with either General Electric's GE90, Pratt&Whitney's (P&W) PW4084, or the Rolls-Royce Trent 800 engine.

This report addresses the feasibility and concerns surrounding installed or on-wing testing and maintenance of turbofan engines. The report will focus primarily on large high-bypass turbofan engines, with maximum thrust ratings over 40,000 pounds and fan diameters of 85 inches and greater. Several of these engines are currently in use on commercial and military aircraft, and many new aircraft designs are being developed that will use such engines. Figure 1 presents thrust and size ratings of the most common turbofan engines in use today. As previously discussed, there is a benefit in avoiding frequent engine removal and reinstallation, especially for the larger engines. The technical feasibility of conducting installed testing was determined from engine and aircraft maintenance manuals (AMMs) [3 through 8], obtained from a variety of aircraft operators. The various detailed considerations of on-wing testing and the pertinent cautionary notes given in the AMMs are presented. Finally, the advantages and disadvantages are outlined along with possible solutions to the potential problems.

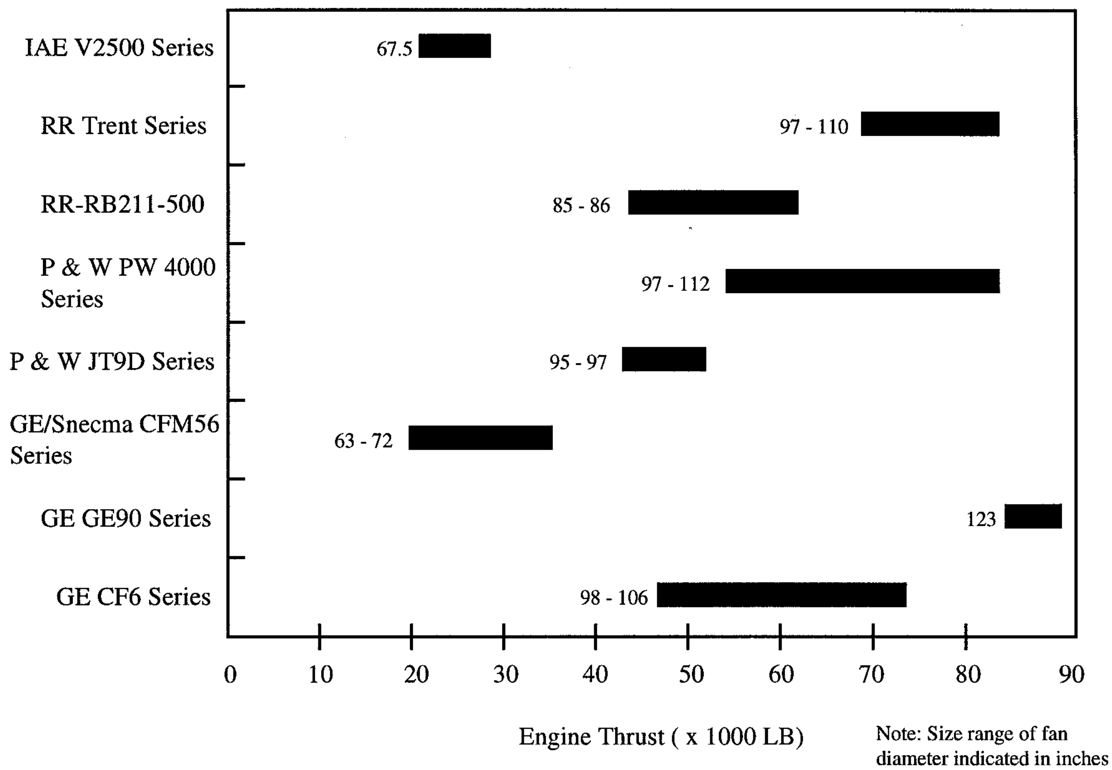


FIGURE 1. LARGE COMMERCIAL TURBOFAN ENGINES—THRUST AND SIZE

2. BACKGROUND.

The condition under which on-wing testing is warranted depends on the engine. The flow chart in figure 2 shows the conditions that lead up to the decision to perform on-wing testing. The decision will depend upon both the testing and repair criteria, which in turn are defined based on various factors outlined later.

A primary motivation for on-wing testing is the difficulty encountered in the handling and transport of fans and housings in excess of 96 inches in diameter. As the number of aircraft equipped with larger turbofan engines increases, so do the benefits of installed testing.

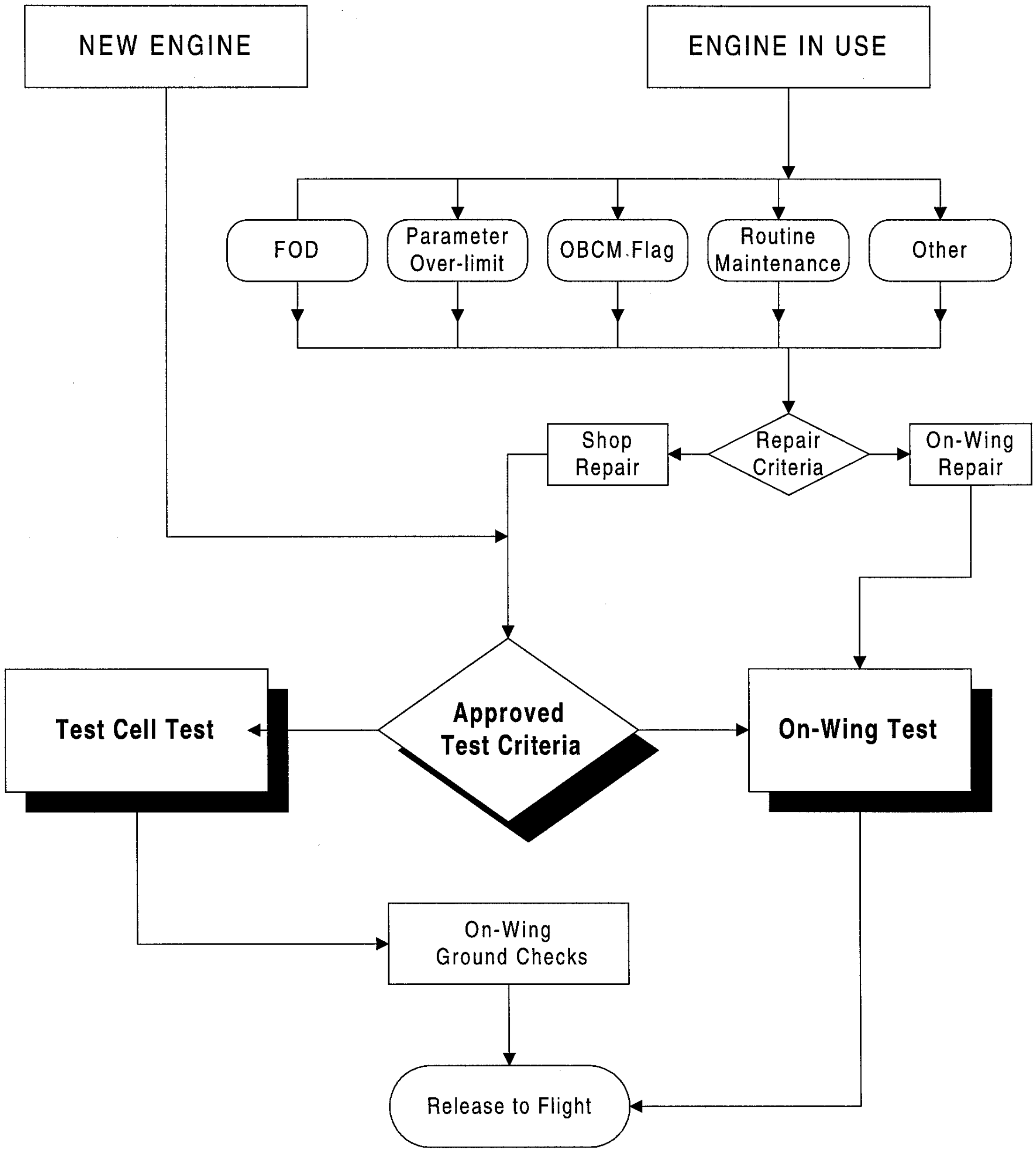


FIGURE 2. DECISION LEADING TO ON-WING ENGINE TESTING

3. CONSIDERATIONS CONCERNING ON-WING TESTING.

There are many factors to be considered in choosing on-wing testing: the size of the engine, the geographical location of the engines when testing is required, the proximity to a maintenance facility and trained personnel, and the availability of spare engines. The size of an engine is an important consideration because larger engines typically require special facilities and equipment to support engine maintenance. This includes test cells, hangar storage space, and handling equipment. The geographical location of the engines is also an important factor. If the aircraft is not at a facility that supports engine testing, the cost and time required to ship the engine to such a facility becomes prohibitively expensive. The availability of trained personnel also becomes an important issue for both the removal and repair of the engine and for the operation of the ground test facility. The availability of a spare engine or of a Quick Engine Change (QEC) flight-configured engine would also reduce an operator's willingness to perform on-wing testing.

Details of the aforementioned factors that would play a role in the final decision to perform on-wing testing include

a. Available maintenance capabilities.
b. Environmental factors associated with noise levels.
c. Hazard areas.
d. Weather conditions.
e. Instrumentation limitations.

3.1 MAINTENANCE CAPABILITIES.

The maintenance capabilities of the aircraft operator may influence the decision whether or not to perform engine on-wing testing. If the operator does not possess the necessary resources and trained personnel to carry out on-wing testing, such as taxi-qualified crews, he may be required to remove the engine and have it shipped to a qualified maintenance facility. If it is normal practice for the operator to contract out his maintenance because of limited capabilities, it is to his advantage to ensure that the contractor possesses the necessary resources to carry out on-wing testing. In situations where the engine has reached an overhaul cycle, on-wing testing is typically not a viable option, thus, the engine is usually removed and shipped to an overhaul facility for repair and subsequent testing.

3.2 ENVIRONMENTAL FACTORS.

Operation of turbine engines results in extremely high noise levels, with decibel absolute (dBA) levels reaching well above 100 at full engine power (noise levels in the 120 to 140 dBA range cause pain). The composition of the exhaust gas stream noise is mainly in the low to midrange of frequencies. Typical values are in the 100- to 2000-hertz range. The inlet or fan noise levels can include fundamental noise bands in the higher ranges, namely in the 3000- to 9000-hertz bands, and can cause hearing loss in that range. At many airport facilities noise regulations and airport curfews exist that could severely impact the ability of maintenance personnel to carry out installed engine tests under these conditions.

According to the Department of Labor Occupational Noise Exposure Standard [9], hearing damage may result when exposed to noise levels at or above 90 dBA for longer than 8 hours. Therefore, personnel conducting the tests must be equipped with proper ear protection and all other personnel should be restricted from the surrounding area. Figure 3 [8] shows the noise signature of a single P&W JT9D-70 engine at three different power levels. From this chart, one can deduce that at maximum power setting, personnel not wearing hearing protection devices would have to be at a minimum of 600 feet away from the aircraft undergoing testing. This would not normally pose any problem for maintenance crews because they are generally required to wear the necessary hearing protection devices. However, special care must be taken to ensure that other personnel do not venture too close to the aircraft. This is generally the crew chief's or maintenance supervisor's responsibility.

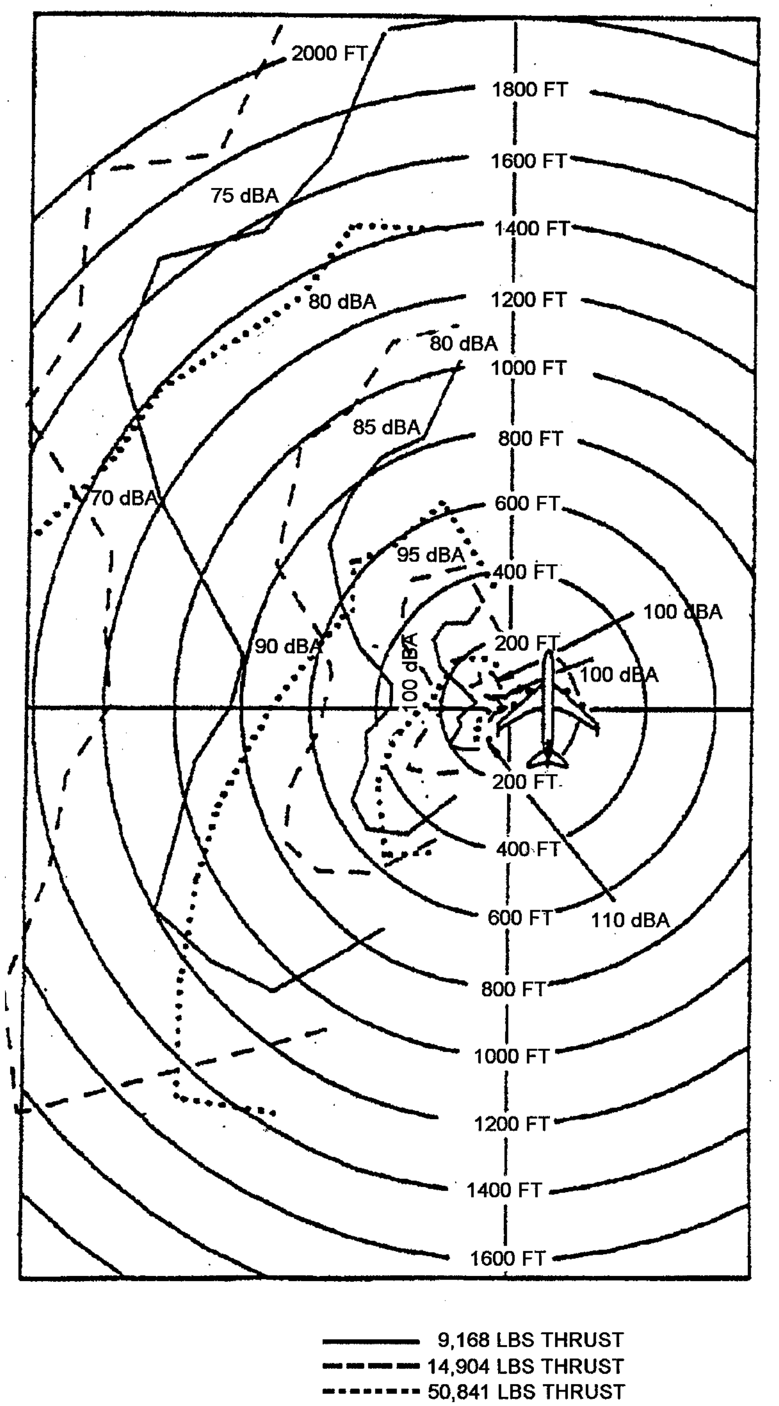


FIGURE 3. GROUND STATIC NOISE LEVEL dBA, SINGLE JT9D ENGINE

3.3 HAZARD AREAS.

High-bypass ratio turbofan engines pose threats to the safety of personnel in other ways. The exhaust gas stream area, even at low throttle settings, is strong and hot enough to cause serious injury. In addition, any structure or equipment that is not securely in place can also be damaged or destroyed. The zones of concern are illustrated in figure 4. The figure is a composite of the hazardous areas of engines producing takeoff thrust levels to 50,000 pounds and shows that a very large area around the aircraft is affected. Because exhaust gas velocities over 50 feet per second and temperatures in excess of 30°C can be experienced in these areas, it is important to make personnel aware of these hazardous zones.

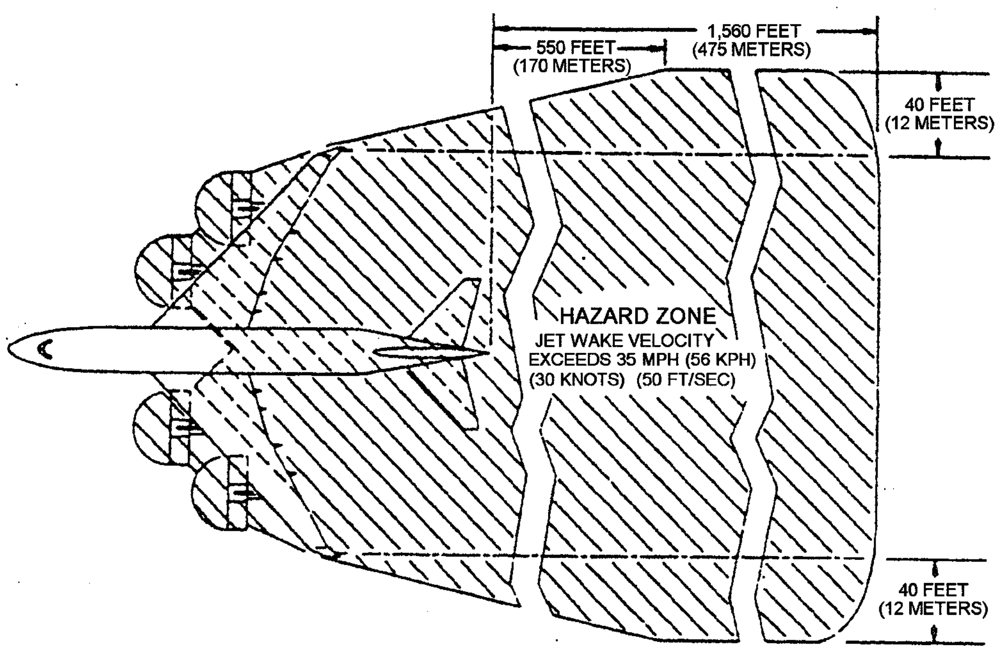


FIGURE 4. SCHEMATIC SHOWING HAZARD AREA DIMENSIONS

Care must also be taken to ensure that personnel, loose equipment, or other debris are not allowed in the inlet hazardous area. It was noted in reference 3 that even at ground idle power settings, a grown man can be lifted from his feet and drawn into the inlet of the engine. No inlet airspeed or engine thrust setting can be specified for when this will happen. Such an event would be dependent on a variety of factors such as the person's size, weight, posture (standing/crouching, etc.), position relative to the inlet, engine and inlet size, and inlet ground clearance. As shown for the exhaust gas hazard area, a composite hazard area for the inlet is shown in figure 5, for the engines of the same thrust levels. Figures 4 and 5 show that the area requirements for on-wing testing are large, going up to an area 1560 feet in length along the aircraft's axis and 280 feet in width along the wingspan. This corresponds to an area of over 10 acres.

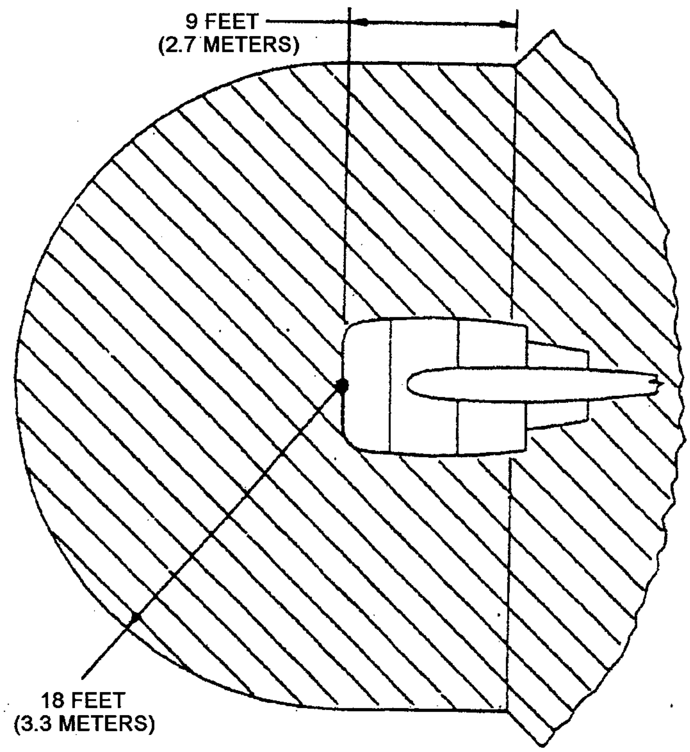


FIGURE 5. SCHEMATIC SHOWING INTAKE HAZARD AREA OF A LARGE TURBOFAN ENGINE

3.4 WEATHER CONDITIONS.

The existing weather also imposes certain restrictions on on-wing testing. It is not recommended, according to reference 5, to test engines during very cold weather when an anti-icing system is required. Heavy rains, sleet, hail, and snow may cause other restrictions. Each AMM will specify what limits apply. Aircraft and engine manuals [3 through 8] also include information on the maximum allowable wind speed for testing. The restrictions are usually stated in terms of the steady-state wind velocity that is permissible when blowing at various angles either into the inlet or into the engine tailpipe. The limits are designed so that the engine will perform at its design conditions, permitting the test data to be related to a known standard. If the wind speed exceeds the stated limits, especially if directed up the tailpipe, the engine can experience stall, surge, and over-temperature excursions. Care should be exercised to prevent this by continuous monitoring the wind velocity and direction. In addition to limits on the steady-state wind speeds, some manufacturers require that testing be terminated if wind gusts are above a certain specification. Detail wind speed restrictions are discussed in section 5.2.

3.5 INSTRUMENTATION.

The accuracy of instrumentation used to collect the engine parametric data is also a concern in performing on-wing testing and maintenance. In order for on-wing test data to provide the same level of confidence as test cell data, the instrumentation capabilities of the cockpit and test cell must be of comparable accuracy. Assuming that the instrumentation probes and transducers are the same for the two approaches, the only difference would be the range and accuracy of the display instrumentation used to collect the data during testing. It should be noted that during on-wing testing, portable ground-based instrumentation systems can also be used to supplement or reinforce data readings obtained from cockpit instrumentation. Systems exist that employ the same system designed for use in engine test cells. This will address the long-held skepticism about flight line ground-based test systems accuracies.

The latest avionics systems interface comprehensively with many aircraft subsystems including the engines, pneumatics, hydraulics, and electronics. Data generated by the engine sensors are processed by a central maintenance computer and then can either be displayed in the cockpit or used subsequently on the ground to isolate faults and perform maintenance. The system can be used to monitor all the engine parameters, such as speeds, temperatures, pressures, vibration levels, and fuel flow that can detect, isolate, and record engine system faults. Engine exceedances that occurred during the flight can also be recorded automatically or be requested by the crew. Engine data are displayed clearly on state-of-the-art cathode-ray tube displays located in the cockpit and the fault history can be stored to enhance line maintenance. Where aircraft are equipped with these state-of-the-art systems, overhaul and maintenance procedures already rely heavily on engine data collected from the aircraft's onboard condition monitoring (OBCM) instrumentation. This data can be used to determine if on-wing maintenance, repair, and test can be performed or if the engine must be removed and replaced. The presence of these onboard systems would prove to be of great benefit in the execution of on-wing engine testing, since the engine parametric data is readily available to maintenance personnel.

Table 1 shows some of the more common engine parameters measured during various engine testing procedures. Typical test cell and cockpit instrumentation range and accuracy are given to indicate general instrumentation requirements. Test cell data were obtained from reference 7, and cockpit data were obtained from a variety of vendor catalogs.

TABLE 1. COMPARISON OF TEST CELL AND COCKPIT DISPLAY INSTRUMENTATION

Parameter	Operating Range	Accuracy	
		Test Cell	Cockpit
Fan Speed, N_1 (Analog)	0 - 5000 RPM	$\pm$0.5 %	$\pm$0.5 %
Fan Speed, N_1 (Digital)	0 - 5000 RPM	$\pm$2 RPM	$\pm$0.15 % RPM
Core Speed, N_2 (Analog)	0 - 11,000 RPM	$\pm$0.5 %	$\pm$0.5 %
Core Speed, N_2 (Digital)	0 - 11,000 RPM	$\pm$5 RPM	$\pm$0.15 % RPM
EGT	0 - 2000 °F	$\pm$5 °F	$\pm$3.6 °F
EPR	0 - 2	$\pm$0.04	$\pm$0.05
Fuel Flow	1,000 - 25,000 PPH	$\pm$0.5 %	$\pm$0.5 %
Fan Vibration	0 - 20 mils	$\pm$0.25 mils	$\pm$0.1 units
Core Vibration	0 - 20 mils	$\pm$0.25 mils	$\pm$0.1 units

Note: Accuracy measurements provided as a percentage of full-scale.

4. ON-WING TEST PROCEDURES.

The procedures for on-wing testing are as varied as the aircraft and engine combinations that allow the process. However, all have the same basic principles and guidelines. Whenever on-wing testing is contemplated, the organization performing the testing must have both the aircraft and engine manuals and should adhere to all the procedures and cautions listed in these manuals [3 through 8]. The manuals that were reviewed for this study are listed in table 2. The engine manufacturer and model are listed, along with the particular airframe it was mounted on, if applicable.

TABLE 2. AIRCRAFT MAINTENANCE MANUALS REVIEWED FOR THIS STUDY

Engine (Manufacturer/Model)	Airframe
GE/CF6-80C	Boeing 747-400
GE/CF6-80C	Airbus A300-600
P&W/PW4000	Boeing 767
P&W/JT9D	-
GE-Snecma/CFM 56	Airbus A320

4.1 TEST LIST.

Most manufacturers provide detailed procedures as a matter of course. Most manufacturers also provide a listing of the types of acceptance testing to be performed depending on the type of repair or replacement work done on the engine. For instance, Boeing provides a listing of 15 different specific tests required after a PW4000 series engine on a B767 aircraft undergoes some form of maintenance [6]. A copy of that listing is shown in table 3.

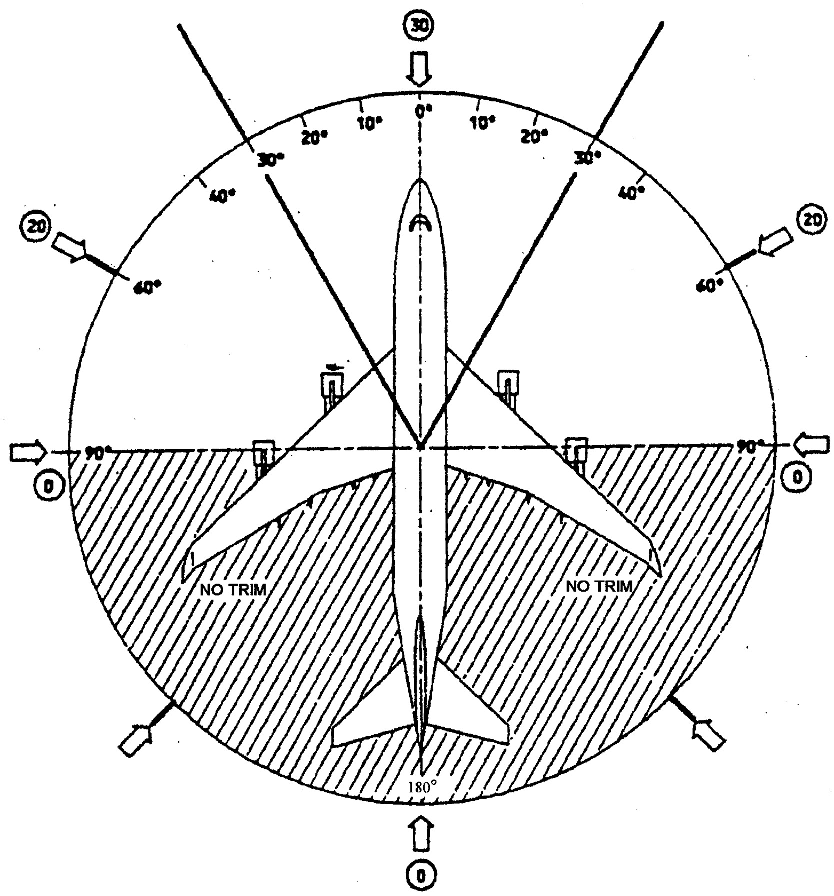
TABLE 3. POWER PLANT TEST LIST
(Adapted from AMM: Boeing 767/PW4000, reference 6)

Test Number	Test Title
1	Pneumatic Leak Test
2	Engine Motoring Test
3	Ground Test - Idle Power
4	Engine Power and Acceleration/Deceleration Test
5	Oil System Static Leak Test
6	Electronic Engine Control (EEC) Idle Test
7	EEC Static Test
8	Vibration Survey
9	Performance Test
10	Replacement Engine Test (Pretested)
11	Replacement Engine Test (Untested)
12	Engine Vacuum Test
13	Main Oil Pressure Test
14	PT2 System Leak Test
15	EEC Ground Test of Engine Control System

In addition to the listing by title, the manual also provides detailed step-by-step procedures for each of the listed tests. (It is in these detailed procedures that the various cautions, required test instrumentation and equipment, and the ranges and accuracy are stated.) Also included are the proper calculations to determine the engine's performance level. While this information noted is for the B-767/PWA4000 combination, all other aircraft model/engine model combinations examined for this study provide similar requirements and procedures.

4.2 WIND RESTRICTIONS.

As section 4 states, the restrictions imposed on wind conditions under which testing can be performed can be quite severe. Examples of wind direction and speed limits can be seen in figures 6 and 7 for a four- and two-engine configuration, respectively. The limits placed on the magnitude of the tail winds are the most restrictive. For the B767/PW4000 combination [6] for example, a maximum headwind of 30 knots is permissible while no tailwind is permitted (0 knots).



Maximum Wind Speed in Knots

FIGURE 6. MAXIMUM PERMISSIBLE WIND SPEED AND ORIENTATION FOR A FOUR-ENGINE AIRFRAME

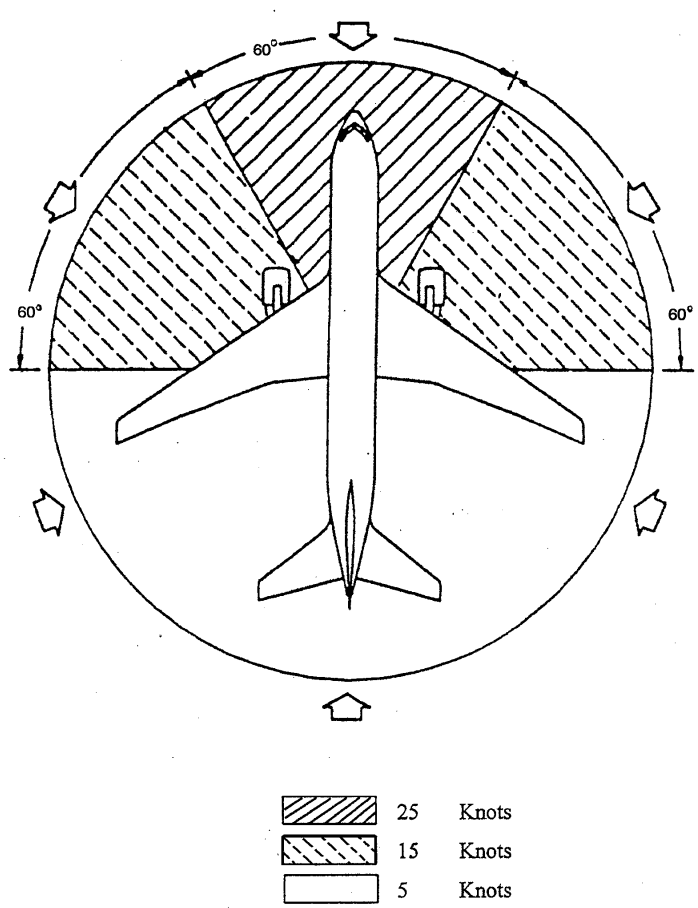


FIGURE 7. MAXIMUM PERMISSIBLE WIND SPEED AND ORIENTATION FOR A TWIN-ENGINE AIRFRAME

For the CFM 56/A320 combination [3], the extent of danger to the engine depends on the power level at which tests are performed. For example, the maximum permissible tailwinds are 5 to 10 knots, 2 to 5 knots, and 0 to 2 knots for testing at power levels of 70%, 85%, and 90% fan rotational speed (N1) respectively. During starting and at idle or low-power settings, wind speeds above these limits can cause excessive exhaust gas temperatures and fan/engine compressor stalls. Also at power settings where N is greater than 90 percent, fan blade tip stall can occur and will manifest itself by rapidly increasing N excursions, excessive airplane vibration, and a pulsating blowtorch type of sound [3].

It is also probable that similar restrictions apply for other aircraft and engine combinations. The allowable limits are provided in each aircraft AMM and should be followed when performing on-wing engine tests in windy conditions.

4.3 INSTRUMENTATION.

Based on a review of several manuals [3 through 8], the instrumentation used in test cell testing exceeds the basic requirements needed to verify engine performance (i.e., compressor discharge pressure, bleed valve position, and oil/bearing temperatures are frequently measured during test cell testing but not normally during on-wing testing). In most cases, it was found that the aircraft cockpit instrumentation system provides enough instruments with the necessary degree of accuracy to support on-wing testing. Several manuals describe the necessary systems and procedures to follow in carrying out engine performance tests. For example, the B767/PW4000 AMM [6] states that the performance test requires using the Engine Indicating and Crew Alerting System (EICAS) to display the relevant parametric data. Before the test is completed, it must be ascertained that the EICAS is fully functional. Accurate pressure measuring instruments are required for engine pressure ratio (EPR) measurement. To keep the power level and the time at high power to a minimum, the test is done at 1.4 EPR. The requirement of an alcohol thermometer for outside air temperature (OAT) measurement is observed in most manuals [3 through 8]. It is cautioned that a mercury thermometer should not be taken onboard in case of breakage and exposure to sensitive instrumentation. Onboard indicators should not be used for OAT or local pressure measurements. An accurate hot-film anemometer is required for performance testing of a previously untested engine [6].

4.4 SYMMETRIC POWER REQUIREMENTS.

Because of the high thrust levels of the high-bypass turbofans, a number of tests, including power checking, requires that at least two engines on the same aircraft are operated simultaneously, one on each wing in the same relative location (assuming two or four wing-mounted engines). This is done to reduce asymmetric loading of the airframe and landing gear. For example, for the CF6/A300 combination [4], if one engine is being operated at N1>85 percent, then the other engine must be run at N1> 65 percent. In many cases, asymmetric power limits may preclude takeoff power tests, but other power assurance tests are provided in AMMs that ensure that the engines will produce takeoff power when required.

Reference 5 explicitly cautions that two engines should not be operated on the same wing at the same time. For operation at high power, the aircraft brakes must be used along with parking brakes and wheel chocks to restrain the aircraft. In addition, some aircraft procedures require that the fuel tanks also contain significant quantities of fuel because of balance considerations during high-power testing. Reference 6 also requires that sufficient fuel be onboard so aircraft hydraulic heat exchangers are not damaged from overheating.

4.5 OTHER PRECAUTIONS AND PROCEDURES.

Among the other precautions for on-wing engine testing is the use of the anti-icing system. The manuals surveyed [3 through 8] state that performance testing should not be done if the anti-icing system needs to be used, which is typically the case when the OAT is 8°C or less, and rain, snow, or fog conditions exist. If testing is done with the anti-icing system in operation, such as may be the case for tests other than performance tests, then engine data should be obtained by moving the anti-ice switch to the OFF position for the last 30 seconds of each power setting being tested. Also, prior to testing in cold weather conditions, the engine inlet, inlet lip, fan, spinner, and fan exhaust duct must be checked to ensure that they are clear of snow and ice buildup. If the fan does not turn freely, the engine should be thawed with hot air before operating the engine.

6. Boeing, Aircraft Maintenance Manual, B-767/PW4000 Series Engines.

7. General Electric Aircraft Engine Group, Engine Manual, CF6-80A Series Engines.

8. Pratt & Whitney, Engine Maintenance Manual, JT9D.

9. Department of Labor Occupational Noise Exposure Standard (issued 7/l/85).

- Replacement engine test (untested engine)

  - No anti-icing
  - Equipment required: alcohol thermometer, hot-film anemometer, ground pneumatic chart.
  - Detailed engine test procedures are given.

CF6/747

- For on-wing operation of an engine, the inlet and outlet exhaust areas are given.

  - 18 feet in front of inlet
  - 1560 feet aft of tail

- Maximum wind/orientation similar to PW4000/747.

- May run engine on opposite wing to provide counter balance thrust. Also, cannot run more than two engines at a given time.

Detailed procedures for operating (not testing) engine are given.

CF6/A300-600

- Test reference table is given. It lists exactly what tests are required for a particular maintenance function.

- If one engine is being tested at N1>85%, then counter thrust compensation must be provided at least N1>65%.

- Wind direction restrictions allow for 5-knot tailwind unlike the CF6/B747 configuration.

- Power Assurance Test—"demonstrates the capability of the engine to produce required takeoff thrust within exhaust gas temperature and N2 limits."

- Acceleration check test procedures stated.

CF6

- Detailed listing of test parameters and the accuracy to which they should be measured. It is not clear whether these apply to installed, on-wing testing, or both.

JT9D

- Information given is for test cell testing only. List of tests:

  Pneumatic leak
  Engine motoring
  Leak test—idle, 80%N2
  Oil system static leak test
  Oil pressure test
  Engine vane and bleed control
  Fuel control trim
  Bleed valve trim
  Vibration survey
  Performance test
  Turbine case cooling
  EEC check

- Tests are designed to minimize engine running.

- Acceptance Test—to be performed after engine has been completely disassembled, repaired, and reassembled.