SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

AIR5924

Issued 2004-02

Guidelines for the Integration of
Electronic Engine Control Systems with
Transport Category Aircraft Systems

INTRODUCTION

Modern digital electronic engine controls are capable of a much higher level of functional integration with aircraft systems than was possible with their primarily hydromechanical predecessors, and system designers have taken advantage of this increased capability. Electronic systems also result in a greater degree of physical integration with the aircraft, with increased dependence on aircraft wiring, remote (from the engine) mounted sensors and transducers and even control units located within the aircraft. While this is a major impetus for the publication of this report, the report also addresses many issues that apply to hydromechanical controls.

This report captures many years of hands-on experience in solving problems arising from powerplant control integration and provides a valuable source of lessons-learned from those endeavors.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) provides methodologies and approaches that have been used to install and integrate full-authority-digital-engine-control (FADEC) systems on transport category aircraft. Although the information provided is based on turbofan engines installed on large commercial transports, many of the issues raised are equally applicable to corporate, general aviation, regional and commuter aircraft, and to military installations, particularly when commercial aircraft are employed by military users.

The word "engine" is used to designate the aircraft propulsion system. The engine station designations used in this report are shown in Figure 1.

Most of the material concerns an Electronic Engine Control (EEC) with its associated software, and its functional integration with the aircraft. However, the report also addresses the physical environment associated with the EEC and its associated wiring and sensors.

Since most of today's transport category engines use dual-channel full-authority digital engine control (FADEC) systems, this is the configuration which is primarily addressed. A typical FADEC system configuration is shown in Figure 2. Special considerations that pertain to single-channel FADEC systems or limited authority "supervisory" control systems are also addressed.

1.1 Purpose:

This report provides guidance to engine/control designers and aircraft system designers on the issues associated with the installation and integration of engine control systems with aircraft systems. Future technologies employed may be different from those addressed in this report, but the basic concepts are the same. The readers must judge the importance of the concepts being addressed to the technology that they are employing in a new application. The examples used have satisfied the requirements in existence at the time of design/certification; they are not considered requirements.

1.2 Field of Application:

The field of application is aerospace, primarily the commercial transport aircraft and their engines certified under Title 14 of the Code of Federal Regulations (14 CFR), part 25, but it may also apply to commuter aircraft and their engines certified under part 23 and rotorcraft certified under parts 27 and 29, which are used for commercial transport service.

FREESTREAM, Pamp, Ptotal, TAT

P2.5, T2.5 (station 2.5)

PB (burner pressure)

Exhaust gas temp (EGT)

P2, T2 (station 2)

N1

N2

N3

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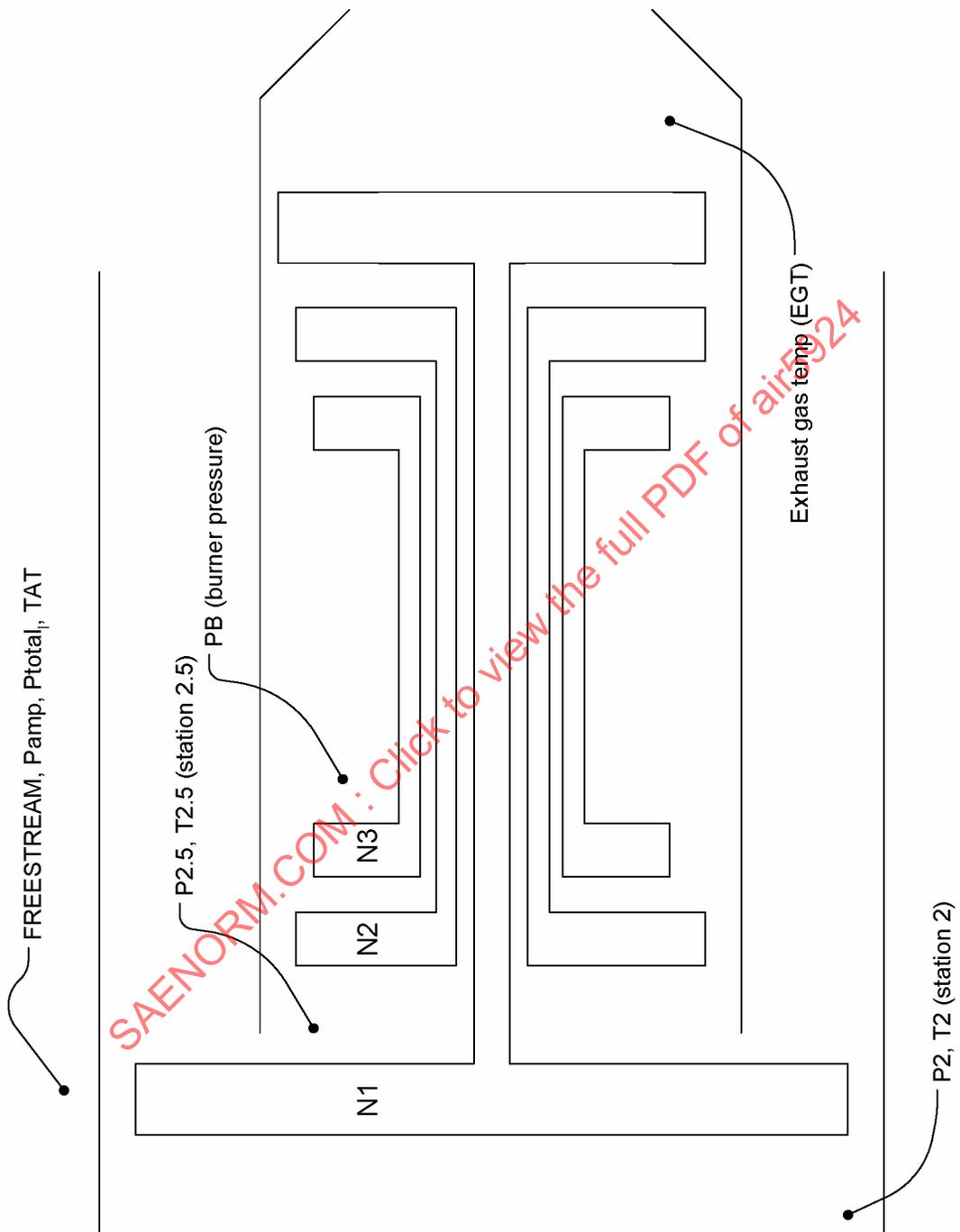
FIGURE 1 - Station Definitions Used Herein
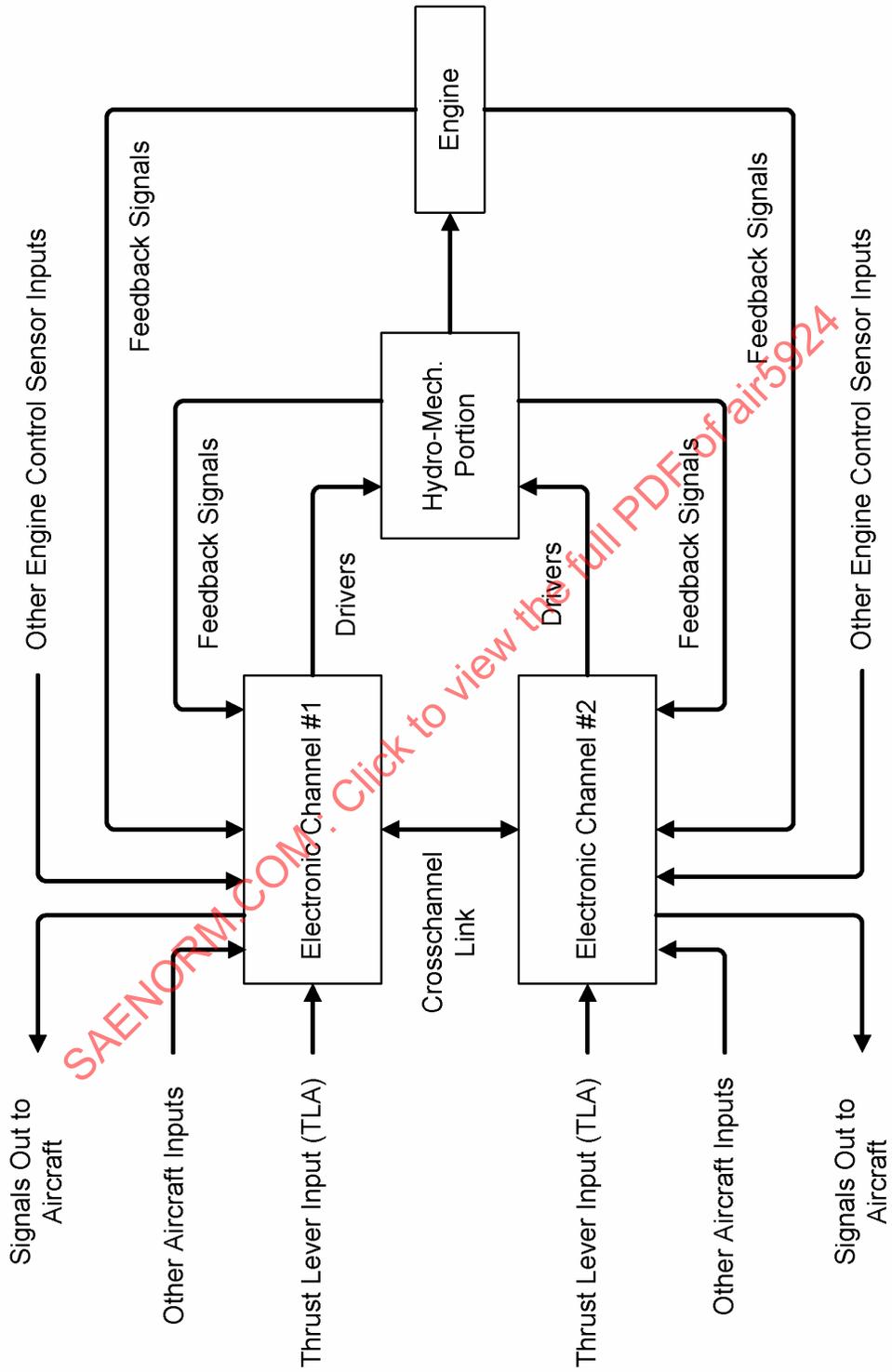
FIGURE 2 - Typical FADEC System

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this report to the extent specified herein. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 Federal Aviation Administration (FAA) Publications:

- 14 CFR Parts 23, 25, 27, 29, 33 and Advisory Circulars (ACs) available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591. A few of the ACs are:

  - AC 20-53A, Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning, issued April 12, 1985.

  - AC 20-88A, Guidelines on the Marking of Aircraft Powerplant Instruments (Displays), issued September 30, 1985.

  - AC 20-136, Protection of Aircraft Electrical/Electronic Systems against the Indirect Effects of Lightning, issued March 5, 1990.

  - AC 25-13, Reduced and Derated Takeoff Thrust (Power) Procedures, issued May 4, 1988.

  - AC 33.28-1, Compliance Criteria for 14 CFR §33.28, Aircraft Engines, Electrical and Electronic Control Systems, issued June 29, 2001.

- FAA Notice, N8110.71, Guidance for the Certification of Aircraft Operating in High Intensity Radiated Field (HIRF) Environments, issued April 1998.

- Transport Aircraft Directorate Policy Letters:

  - Policy Letter TAD 95-001, The Role of Maintenance Computers in Exposure Time Assumptions For Quantitative Safety Analyses, issued February 22, 1995.

  - Policy Letter TAD 00-113-1028, Availability of All-Engine Maximum Continuous Thrust (MCT), issued July 31, 2000.

- Engine and Propeller Directorate Policy Letter: ANE-1993-33.28TLD-R1, Policy for Time Limited Dispatch (TLD) of Engines Fitted with Full Authority Digital Engine Controls (FADEC) Systems, issued June 29, 2001.

2.1.2   Joint Aviation Authorities Publications:

Joint Aviation Requirements (JAR) 25, Joint Aviation Requirements-Engines (JAR-E), ACJs and AMJs.

2.1.3   Other Documents:

- SAE ARP5107, Guidelines for Time-Limited-Dispatch (TLD) Analysis for Electronic Engine Control Systems, issued June 1997.

- SAE ARPAS755C, Aircraft Propulsion System Performance Station Designation and Nomenclature, issued December 1997.

- RTCA DO-178B, Software Considerations in Airborne Systems and Equipment Certifications, issued December 1992, and ERRATA sheet issued March 1999.

- RTCA DO-160D, Environmental Conditions and Test Procedures for Airborne Equipment, issued July 1997.

- Goodrich Total Temperature Sensor Technical Report 5755, Rev. b, dated 1990

2.2   Acronyms and Symbols:

TABLE 1

	Meaning	Comments
ADC	Air-data Computer	
AGL	Above Ground Level	
AFM	Aircraft Flight Manual	
ATM	Assumed Temperature Method	
ATTCS	Automatic Take-off Thrust Control System	Also known as APR or ATR (Automatic Power or Thrust Reserve)
CMC	Central Maintenance Computer	
CMR	Certification Maintenance Requirement	
ECS	Environmental Control System	
EEC	Electronic Engine Control	This term may be used to describe just the basic electronic engine control unit
EICAS	Engine Indication and Cockpit Advisory System	System for displaying engine parameters and warnings to the flight crew. Also known as ECAM (Electronic Centralized Aircraft Monitoring)
EPR	Engine Pressure Ratio	
FADEC	Full-authority Digital Engine Control	This term is generally used to represent to whole engine control system, including wire harnesses, fuel metering unit, etc.
FOD	Foreign Object Damage	

GW	Gross Weight	
LADC	Left (side) ADC	
LOTC	Loss of Thrust Control	
MEL	Minimum Equipment List	
MMEL	Master Minimum Equipment List	
N1	Engine low-pressure shaft speed.	Usually also fan speed.
N2	Engine high-pressure shaft speed	Intermediate shaft speed in 3-shaft engines.
N3	Engine high-pressure shaft speed	3-shaft engines
OAT	Outside Air Temperature	
OEI	One Engine Inoperative	
$P_{ambient}$	Ambient (static) air pressure	Indication of altitude
PB	Burner Pressure	
Ps	Static air pressure	
P	Total air pressure	
P2	Engine intake total pressure	
Q	Dynamic Pressure	P minus Ps
RADC	Right (side) ADC	
TAT	Total Air Temperature	
Theta	T2/Tstd.	
TLA	Thrust Lever Angle	
TLD	Time Limited Dispatch	
TMC	Thrust Management Computer	
Tstd	Standard Day Temperature	
T2	Engine core intake total temperature	
V1	Takeoff decision speed	
V2	Second segment climb-out speed	
Vmca	Minimum control speed in-the-air	
Vmcg	Minimum control speed on-the-ground	
VR	Rotation speed	
Wf	Fuel Flow	
Wf/PB	Fuel Flow – Burner Pressure Ratio	

3. APPLICABILITY:

This information is primarily intended for FADEC-equipped engines certifying to FAA part 33 regulations and for the installation of those engines on aircraft certifying under part 25 regulations, commuter category aircraft certificated under part 23, and transport rotorcraft certificated under parts 27 and 29. In addition, many of the issues raised apply equally to corporate, general aviation, regional and commuter aircraft, and to military installations, particularly when commercial aircraft are employed by military users.

4. THRUST AND POWER CONTROL:

4.1 Control Modes:

4.1.1 Primary (or Rating) Mode - Steady State Control Functions: The engine control generally has several operating modes. During steady state operation, normal control is generally governed by either closed loop control on an idle control parameter or on the engine's power setting parameter when above idle. The control may operate on a limiter at high power, but operation on a limiter is usually the result of engine deterioration or an engine or control system malfunction. The thrust setting parameter in most large fan engines is either fan speed (N1) or engine pressure ratio (EPR).

In most modern FADEC systems, the normal mode of operation is generally a rating mode that implements a control that adjusts engine thrust automatically as a function of atmospheric flight conditions.   When operating in this mode, engine thrust goes from idle to maximum rated power, which is usually a function of altitude, airspeed, and ambient or total air temperature, as the thrust lever is advanced from the idle stop to the full forward stop. Figure 3 shows a typical thrust vs. thrust lever position schedule. (See 4.2.1.3 and 4.2.2.2 for a more detailed discussion of programmed thrust vs. thrust lever position.) Operation in the forward thrust regime generally requires consideration of what is referred to as good thrust setting sensitivity or capability. This is simply the slope of the thrust parameter (and thrust) as a function of thrust lever angle. Reasonable slopes need to be provided so that the flight crew can modulate thrust as necessary for aircraft handling and "set" a particular value of the thrust setting parameter accurately during various phases of flight. For example, high bypass ratio engines using N1 as the thrust setting parameter may require N1 to be set within 0.1% of a physical fan speed target when conducting a takeoff, and engines using EPR as the thrust setting parameter may require EPR to be set within 0.002 of the target during a takeoff.

Setting reverse thrust in the primary (or backup) modes does not generally require any significant reverse thrust modulation capability. Figure 3 shows that there is usually a reverse idle detent and full reverse thrust lever position. In the reverse idle detent the engine remains at idle thrust with the reverser fully deployed; in the full reverse thrust the engine operates at maximum rated reverse thrust. The slope of the line from reverse idle to maximum reverse can be quite steep, as the flight crew operating procedure is either to leave it at reverse idle or pull the thrust levers completely back to the maximum reverse stop.
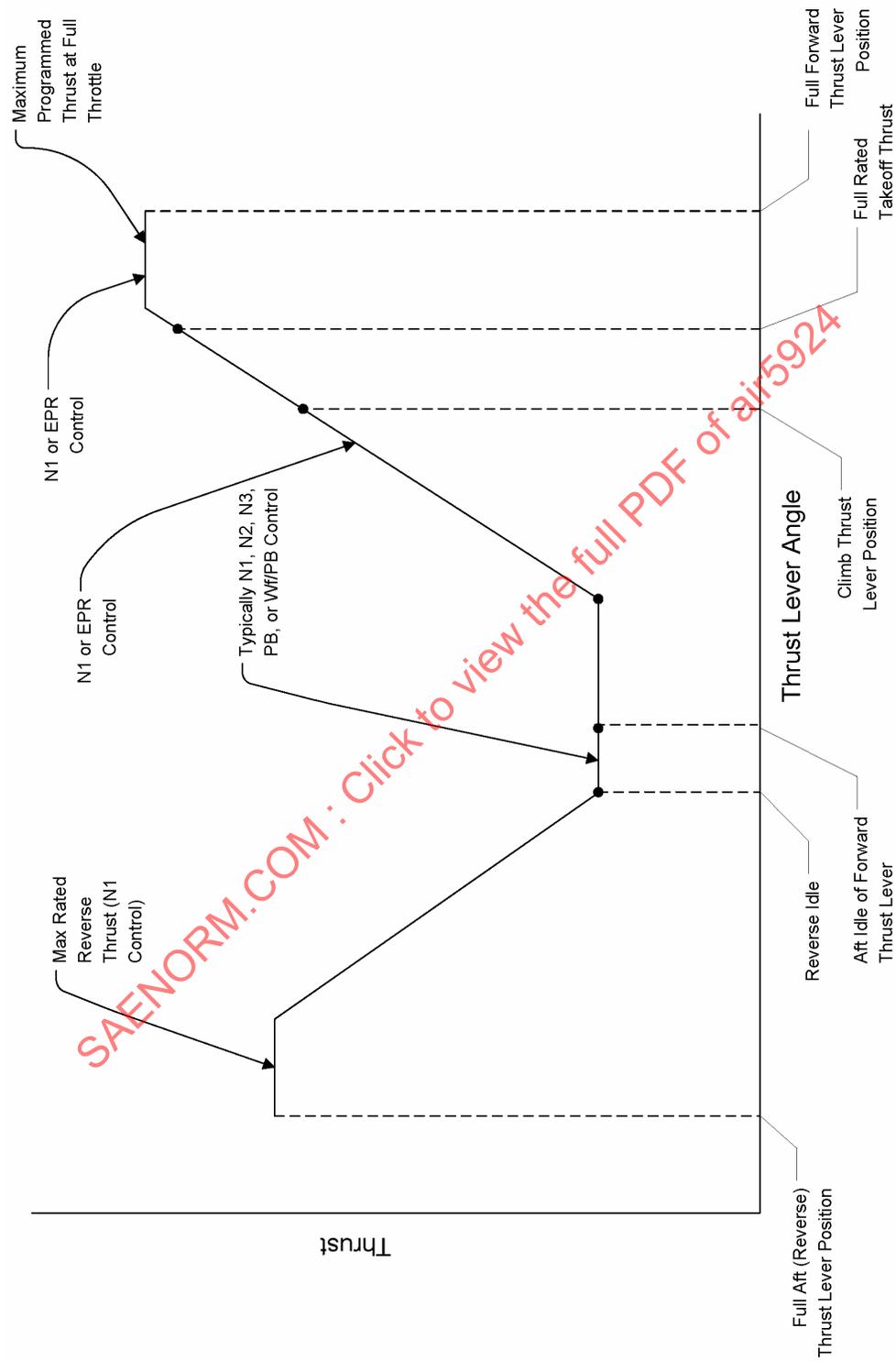
FIGURE 3 - Example of Thrust vs. Thrust Lever Angle

4.1.2   Backup, Alternate, or Reversionary Mode - Steady State Control Functions: This section describes the main backup mode.

Most modern FADEC systems have a backup, alternate, or reversionary operating mode that is usually a non-rated mode. As the thrust lever is advanced from idle to the full forward position in this mode, thrust goes from idle to some high level of thrust, which in many environmental conditions may be well above the engine's maximum rated thrust. The control may enter the non-rated mode as a result of a failure in the control that made the primary mode unusable, or simply because the flight crew commanded the mode via a cockpit-located, mode selection switch. There are applications in which the backup or alternate mode is a rating mode like the normal (or primary) mode. In these designs, rated thrust in the backup mode may or may not be equal to rated thrust in the primary mode. If takeoff rated thrust in this mode is less than that of the primary mode, a gross weight (GW) penalty would be applied to aircraft performance when dispatching in this mode.

In most large transport applications, the aircraft is fully dispatchable with the engine controls operating in the backup mode. Usually, all engines are required by approved operating procedure to be placed in the same mode at dispatch. This maintains thrust lever alignment as well as similar performance on all engines.

Modern FADEC systems have several "get-home" modes. These modes are used to keep the engine running after the control has suffered one or more significant component faults or failures. This report does not address these get-home modes in any detail. This report discusses the main backup mode because it is one of the more important items in understanding the integration of the control system into the aircraft. In addition, it is usually desirable to gain approval for dispatching the aircraft with all engines operating in the backup mode – even though there may be an associated GW penalty or operational restriction for these dispatches.

For engines that use EPR as the thrust setting parameter in the primary mode, the backup or alternate mode is usually a fan speed (N1) governing control. For engines that use N1 as the engine's power setting parameter, N1 is usually still used as the thrust setting parameter in the backup mode. If N1 is used in both the primary and backup modes as the power setting parameter, the backup mode is usually a simplified N1 scheduled function, such as a function in which the engine goes from idle to N1 redline as the forward thrust lever is advanced from idle to the full forward stop. (See 4.2.2 for a discussion of lapse rates in the primary and backup modes.)   It is good design practice to have the backup or alternate mode(s) independent of aircraft airspeed and Mach number information. Loss of the FADEC system's capability to calculate an airspeed signal, loss of or inability to use the ADC airspeed or Mach number signals, or loss of the capability to compute EPR for an EPR-rated engine are the predominant reasons for transitioning out of the primary mode and into the backup mode.

4.1.3 Controller Operation During Engine Transients: Control functions governing transient engine operation may be the same in both the primary and backup modes of controller operation. Fuel flow adjustments usually result from the difference between the command and actual values of the thrust setting parameter, controlling the rate of change of engine core speed or on a maximum (or minimum) allowed fuel flow schedule during the transient. Engine startup and acceleration to idle may also be the same in both the primary and backup modes, as are the auto-start and auto-relight functions (if provided). Avoid significant differences in engine operability when operating in the backup mode, as these differences can adversely affect flight crew workload.

4.1.4 Use of a Soft Reversionary Mode: As engine thrust (or power) as a function of thrust lever position is usually significantly different in the primary and backup modes, a significant thrust or power change on the engine would occur if the control were to transition suddenly from one mode to the other at a high power engine operating condition. Because significant thrust changes are undesirable, many system implementations use a soft reversionary mode to facilitate the transition from the primary mode to the backup mode. The soft reversionary mode provides a path by which the control can leave the primary mode <u>without</u> implementing a significant power change on the engine. The soft reversionary mode is a holding mode. That is, when a detected fault occurs that causes the control to not be able to maintain the primary mode, the control automatically enters the soft reversionary mode and remains there until flight crew action initiates full backup or alternate mode operation. Full thrust modulation (via thrust lever movement) should still be available in this soft reversionary mode. The soft reversionary mode is not intended to be a fixed thrust mode.

A soft reversionary mode is reasonably simple to implement. When the control has determined that it has a fault condition that cannot maintain the primary mode, it calculates the value of the backup parameter (e.g., N1 or N2) that the backup mode would command on the engine at the given thrust lever position and computes the difference between that calculated value and the actual N1 engine operating value at the time of the transfer. The control then locks this difference into the command schedule of N1 that the control would implement in the backup mode. Figure 4 illustrates this scenario. The backup mode with the locked-in trim is called the soft reversionary mode. It allows the engine to leave the primary mode with essentially no thrust change. The control then stays in this mode until the flight crew, through a distinct command signal to the control, commands the control to enter the complete backup mode. On receipt of this signal, the control sets the locked-in trim signal to zero. The flight crew should be trained to place the engine at an intermediate power condition before activating the backup control mode command. This will prevent the control from commanding what could be a large overboost power condition when the backup mode is commanded by the crew.
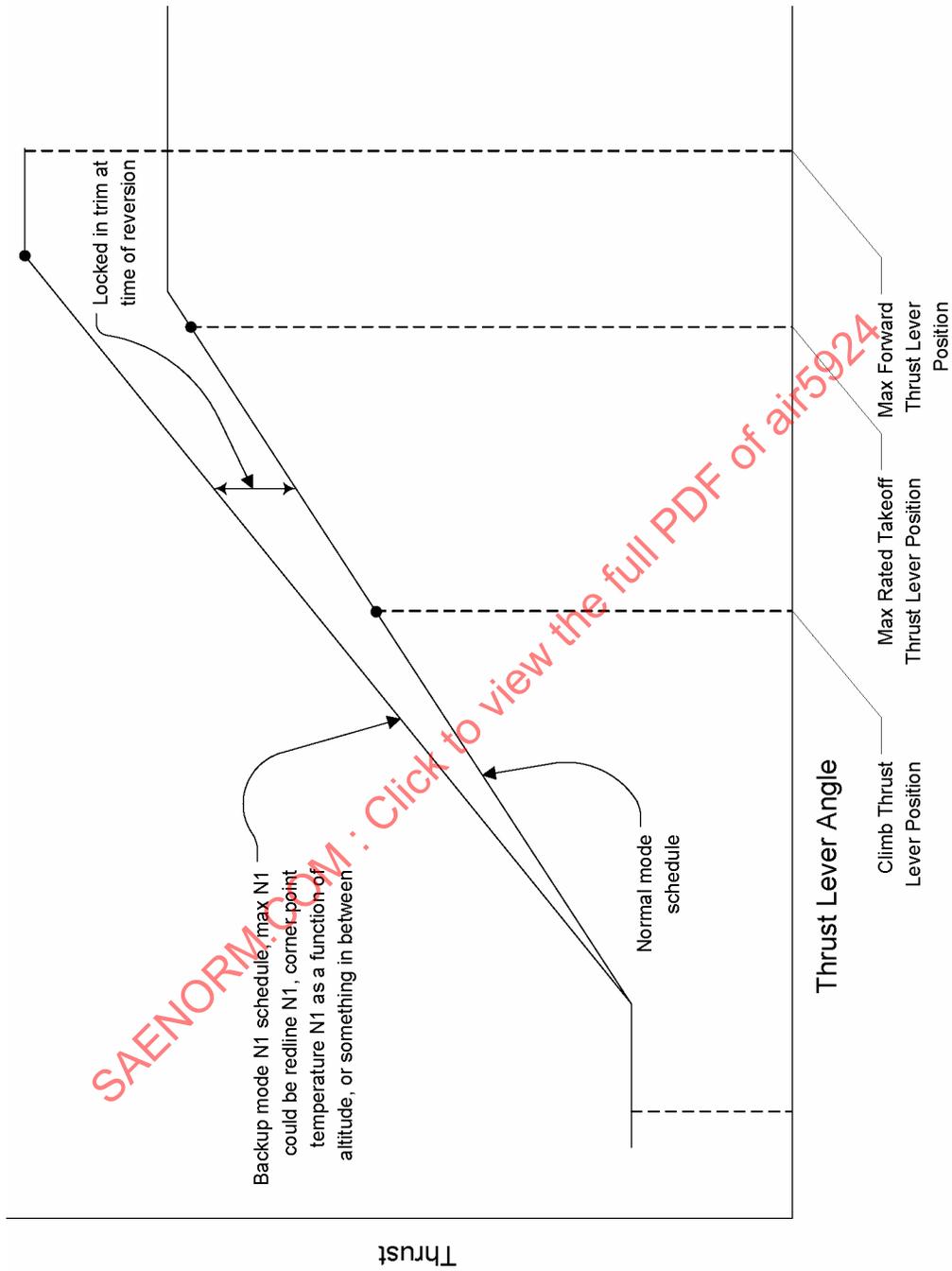
FIGURE 4 - Normal Mode Thrust Schedule as Compared with Typical Alternate
(or Backup) Mode Schedule for Forward Thrust

4.1.4   (Continued):

A question is often asked as to how well this transition works if it occurs during an engine transient. This has not proven any kind of significant difficulty. If the engine is at steady state during the transition, essentially no thrust change occurs; if the engine is in a transient, the flight crew is in the process of changing thrust due to a flight crew command, and if the locked-in value of trim is not the correct steady state one, this causes no significant difficulty, as the flight crew is expecting a power change.

Some implementations wash out the locked-in trim value of N1 as the thrust lever is moved from its position at the point of transfer. These implementations are slightly more complex, and since the flight crew should be trained to activate the backup mode when operating in the soft reversionary mode, this extra complexity may be unnecessary.

4.1.5   Primary or Backup Mode Activation and Switching Between Modes: Figure 5 shows suggested mode selection logic. In general, whatever the thrust lever position, the control should go directly to the backup mode when it receives the flight crew command to change modes. If the thrust lever is at the maximum forward position, a significant overboost may result. However, even though there may be a significant thrust increase, the control should prevent the engine from exceeding any rotational speed limitations. There has occasionally been considerable discussion of trying to incorporate some logic in the FADEC system to avoid this situation, but generally the instructors and flight test pilots have indicated that flight crews should know what they are doing when they activate cockpit switches, and that they should exercise the proper procedure of retarding power before initiating a mode change.

NOTE: If the flight crew activates a transfer from the backup mode to the primary, rating mode at a forward thrust lever position, engine thrust may significantly decrease. If this were to happen in the takeoff mode to multiple engines, the aircraft might experience a significant thrust loss. If it applies, address this in the following manner:

In the case in which the control does not have the necessary signals for the primary mode, the control should already be providing an indication of primary mode failure (see 6.1.3 below), and it will stay in the backup mode. Therefore, there will be no thrust change. If, however, the control has the signals available to enter the primary mode, it could do so. If this is considered too undesirable, the control can be configured to contain logic that would prevent the transfer. For example, the control can be configured to look at such signals as airspeed and engine power setting when a transfer command to primary mode is received, and if the engine is at high power and airspeed is low (that is, less than Mach 0.35 or 0.4), the control logic can be configured through software logic to reject the mode change command. If control logic is incorporated to do this, the control should not implement an automatic mode transfer to the primary mode when power is reduced or airspeed increases to a value above the decision threshold, because this would result in an unexpected thrust change. The control should require
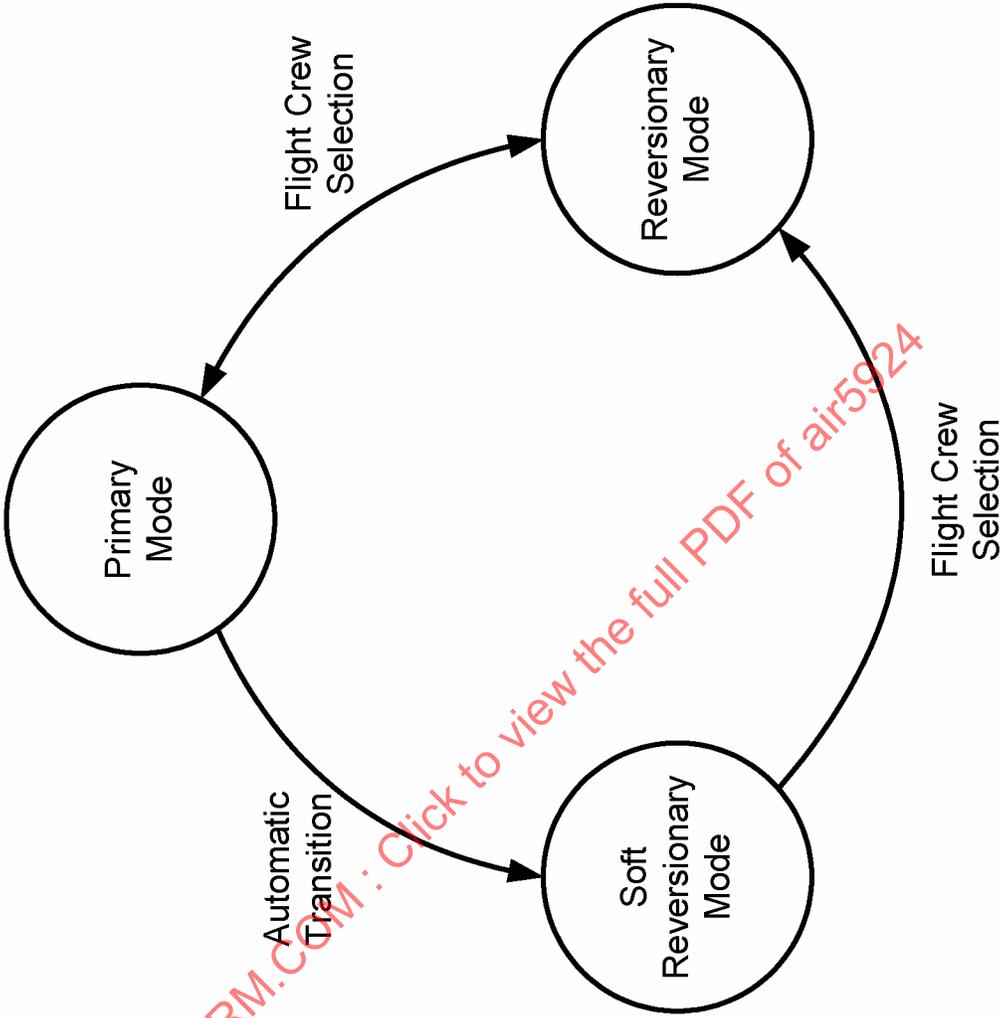
FIGURE 5 - Logic for Mode Selection

4.1.5   (Continued):

the mode command signal to go through a reset, so that the mode command signal returns to the original state and is then re-issued before the control accepts the signal. Each engine FADEC system should have a separate, independent mode command signal, and the flight deck indication of backup mode operation should remain until the command is reissued.

4.1.6   Initiation of the Primary/Backup Mode at Engine Start:

4.1.6.1   Establishing a Valid P2 Signal for Engines Using EPR as a Primary Mode Power Setting: After a successful engine start, the engine control needs to determine whether to operate in the primary, backup, or soft reversionary mode. This can be complex because it depends on the operational state of the aircraft's electrical power system at the time of engine start. The aircraft may be completely de-powered – with the exception of aircraft battery power – when the first engine is started, or the aircraft may be powered by a ground power source at engine start.

Control systems for engines using EPR as the primary thrust (or power) setting parameter will probably have their own control system dedicated total pressure probe. It is assumed that this is the case, and that the control system's dedicated total pressure probe, P2, is mounted inside the engine inlet and uses aircraft-provided electrical power to heat the probe and prevent probe icing. Assuming that the aircraft generators are not disengaged, and that the aircraft is not on ground power during the first engine start, the aircraft electrical system will power up when the first main generator comes on-line at approximately 5% below engine idle speed. Following this first engine start, aircraft power should be available for the engine control system's dedicated P2 probe. The aircraft may (1) switch probe heat on automatically, (2) supply power to the control system and let the FADEC system switch it on (this is the preferred system), or (3) have the flight crew activate engine probe heat via a cockpit-located probe heat switch (the least preferred configuration). If the aircraft is configured to power the probe automatically or supply power to the engine control system (so that the FADEC system can turn on probe heat), the sequence may take several seconds. So, the FADEC system should wait an appropriate time period after reaching idle (typically 12 seconds), to ensure that the electrical power transfer to the engine-driven generator has been completed, before determining whether probe heat has been activated. It is desirable that the control system have its own dedicated current sensor for establishing probe heat on/off status. If not configured this way, the FADEC system will have to receive an aircraft discrete for this function. Assume that probe heat will be confirmed within the wait period, and do not have the FADEC system send any abnormal indications during this wait period. It is normal to be sending a valid EPR signal during engine ground starts, even though probe heat may not be on during starting. If confirmation of probe heat on is not received within the wait period (after reaching idle), invalidate the EPR signal and have the FADEC system begin sending the primary mode fail flag and the backup mode active signal and initiate control operation in the backup mode.

4.1.6.1   (Continued):

If the control is in the backup mode and the P2 probe heat on discrete is received from the aircraft (or probe heat current is sensed by the FADEC system), the FADEC system should stay in the backup mode, continue to send out the backup mode active signal, and stop sending the primary mode fail signal.

4.1.6.2   Engines Using N1 as the Primary Power Setting Parameter:

4.1.6.2.1   FADEC Systems with a Dedicated P2 Probe (and also a $P_{ambient}$ Sensor): For those FADEC systems using N1 as the power setting parameter, and in which a dedicated P2 probe is provided, the activation of the primary, soft reversionary, or backup mode following the engine start is essentially the same as given in the above discussion for EPR-rated engines.

4.1.6.2.2   FADEC Systems Without a Dedicated P2 Probe (but with a $P_{ambient}$ Sensor): For those FADEC systems that do not have a dedicated P2 probe, the logic is similar to those with a probe. The FADEC system needs to receive valid total pressure signals from both ADCs, with at least one having probe heat on. The ADC total pressure signals should agree within approximately 2 to 3% of point. However, during ground operation at low forward speeds, the aircraft total pressure signals from the ADCs can vary quite a lot due to side-wind conditions, so the FADEC system should contain logic to accept a fairly large difference (such as 10% of point), for a reasonably long time (such as 15 seconds), before declaring a disagree between the aircraft's total pressure signals. Because of cross-wind difficulties, many of today's systems are configured not to cross-comparison of aircraft total pressure signals at low airspeeds.

If valid ADC total pressure signals are not received within an appropriate wait time after the engine reaches idle, with an indication that at least one of the ADC dedicated total pressure probes has probe heat on, the FADEC system should revert to the backup mode and transmit the primary mode fail and backup mode active signals. The wait time interval is normally selected to allow for electrical power system transfers during engine starting. The initialization times for the sources of ADC total pressure probe heat and the FADEC controller receiving an ADC total pressure signal with an indication that probe heat is on can be as long as 10 to 12 seconds. So have the control wait that long before declaring the ADC total pressure signals invalid and initiating the backup mode. Again, after initiating the backup mode of operation, the control should not change modes without receiving a flight crew command to do so. If an indication that probe heat is on is received after that backup mode has been initiated, the FADEC system should remain in the backup mode, but it can indicate that the primary mode is available (assuming that it has the other needed resources for primary mode operation) by ceasing the transmission of the primary mode fail signal.

4.2   Thrust Scheduling Logic:

4.2.1   Primary Mode: Engine Idle Control, Thrust Ratings, and Thrust Lapse Rates as a Function of Altitude, Air-speed and Temperature:

4.2.1.1   Engine Idle Control: Transport category aircraft usually use several engine idle control functions. Examples of these are as follows:

- An idle schedule established to allow operation on a minimum physical or corrected core speed. There may be different schedules for ground and in-flight operation.

- Minimum core speed or bleed air pressure schedules that allow the engine to deliver given levels of engine air bleed or maintain minimum acceptable bleed pressures. These schedules are generally at higher levels of core speed than the minimum allowed physical or corrected speed schedule, and there may be different schedules for normal bleed and the higher bleed airflows required when cowl and/or wing anti-ice are selected on. (When anti-ice bleed is on, the schedule may be established by an engine's requirement to maintain a given level of core speed, above that required for engine bleed during icing conditions.) The ability to govern the engine to maintain a minimum bleed pressure at idle can result in high idle thrust conditions that affect descent and glide slope capture capability. These conditions are generally caused when the bleed demand of the aircraft requires higher engine bleed pressures at idle, thus requiring higher idle thrust. The result is a negative impact on descent profile.

- A still higher idle speed schedule (sometimes called approach idle) established to allow the engine to achieve a given level of thrust within a specified number of seconds following a snap accel command. This idle speed is established by the aircraft's go-around thrust requirements. Approach idle in transport category aircraft is usually activated when the aircraft is configured for approach and landing. The approach and landing configuration has a higher associated drag, and thus, the descent profile is still maintained with the higher idle thrust.

- Flight idle schedule(s) (fan speed or EPR) intended to provide a controlled low level of thrust during descent or approach.

- Ground idle schedule(s) optimized for ground operations.

4.2.1.2   Engine Ratings: Takeoff, Climb, and Maximum Continuous Thrust (or Power) Ratings: For transport category aircraft, takeoff, climb, and maximum continuous thrust are generally established to achieve (1) good engine life (from the engine manufacturer's viewpoint), and (2) good aircraft performance (from the aircraft manufacturer's viewpoint). Those two viewpoints are, by their very nature, conflicting. For fixed-wing transports, maximum continuous thrust is generally less than takeoff thrust and is really only intended for use during one engine inoperative (OEI) conditions. However, it must always be available and nothing should prevent its use during all-engines operating conditions. The use of maximum continuous thrust usually has a significant effect on engine life. With the high levels of engine reliability being achieved with modern turbine engines, the need to use maximum continuous thrust is reasonably rare.

For transports, takeoff, climb, and maximum continuous thrust are generally functions of altitude, total air temperature, and airspeed (or Mach number).

4.2.1.3   Various Thrust (or Power) Scheduling as a Function of Thrust Lever Position:

4.2.1.3.1   TLA Selection of Thrust: It is recognized that at any given, fixed thrust lever position, thrust can change with changes in altitude, temperature, and airspeed. However, in this system implementation, the setting of a given value of the thrust setting parameter, either EPR or N1, must be achieved by moving the thrust lever. In other words, the system is not one in which the thrust lever is set to a given position, and when in that position, the FADEC system receives a command from some other aircraft avionics box as to the value of EPR or N1 to be implemented by the control. That type of system is discussed in 4.2.1.3.2.

The descriptions given below are for transports that use a thrust vs. thrust lever position schedule in which idle thrust, climb thrust, takeoff thrust, and maximum programmed thrust are obtained at specific thrust lever positions as the thrust lever is advanced from the idle stop to the full forward stop. Figure 6 shows a typical thrust vs. thrust lever position schedule for such a system. The thrust lever position for full takeoff power is usually the same as that for maximum continuous power when outside the takeoff envelope.

Maximum continuous thrust is less than takeoff thrust and generally higher than climb thrust. When operating in the takeoff envelope, maximum continuous thrust is achieved at a throttle position between climb and takeoff. When outside of the takeoff envelope, maximum continuous becomes the maximum power setting. At high altitudes, maximum continuous generally becomes equal to the climb power setting. Figure 6 shows an example of the various thrust vs. throttle position schedules at the different operating altitudes.

"Headroom" may be small when operating on aircraft data information, larger when operating on engine sensor information

Max Thrust Lever Travel

T.O. Power Position

Climb Power Position

Max Rated T.O. Power

Max Continuous Power

Max Climb Power

Thrust Lever Position

NOTES: (1) Max Con is maximum thrust schedule when operating above approved takeoff envelope.
(2) Max Climb is maximum thrust schedule at higher altitudes.

Thrust

FIGURE 6 - Altitude Dependent Thrust Schedules

4.2.1.3.1   (Continued):

The thrust commanded by the control just before achieving the full forward thrust lever stop (that is, about two to three degrees before the stop) is referred to as the maximum programmed thrust. This programmed thrust is above the engine's certified maximum rated thrust. The difference between this thrust and the engine's maximum certified thrust is generally called headroom. Headroom is used to ensure that with the worst-case stack of system sensor errors (that is, the errors associated with operation on engine sensors only), the control can always achieve the certified thrust rating for the condition. The purpose of headroom is to ensure that each and every installed engine is capable of delivering its rated thrust at the full forward thrust lever position. Typical values for headroom are 0.5 to 1.5% thrust above the maximum rating. Thrust from this thrust lever position to the stop can be flat (that is, no increase as the thrust lever moves forward from that position). The two to three degrees thrust lever travel allows for inaccuracy in the rigging of the thrust lever position transducer and the associated errors in thrust lever position measurement. The design intent is that the engine will always be able to achieve its maximum certificated thrust, and will not be limited due to normal tolerances in the thrust lever system. The maximum programmed thrust can be higher than 1.5% above the maximum certified thrust if desired. There are no certification requirements in this area as long as the flight crews are not trained to advance the thrust levers to the stop to achieve maximum rated thrust. Therefore, it is recommended that the flight crews be trained to set power to the target during normal operations, and only full throttle the engines during extreme situations, such as those resulting from wind shear.

There are two ways to determine the value of the power setting parameter (to which the engine will be controlled) as the thrust lever moves from the climb power position toward idle:

a. Set up a low value of the same parameter as the climb power setting parameter at a forward idle thrust lever position (see Figure 7) and interpolate between this value of the climb power setting value for thrust lever positions between climb and idle. Select the idle control if the interpolated power setting would cause the engine to operate below the idle control setting.

b. Multiply the climb power setting value by a number less than unity and decrease the number as the thrust lever moves toward the idle stop (see Figure 8). Select the idle control function if the multiplier-determined power setting would cause the engine to operate below the idle control setting.
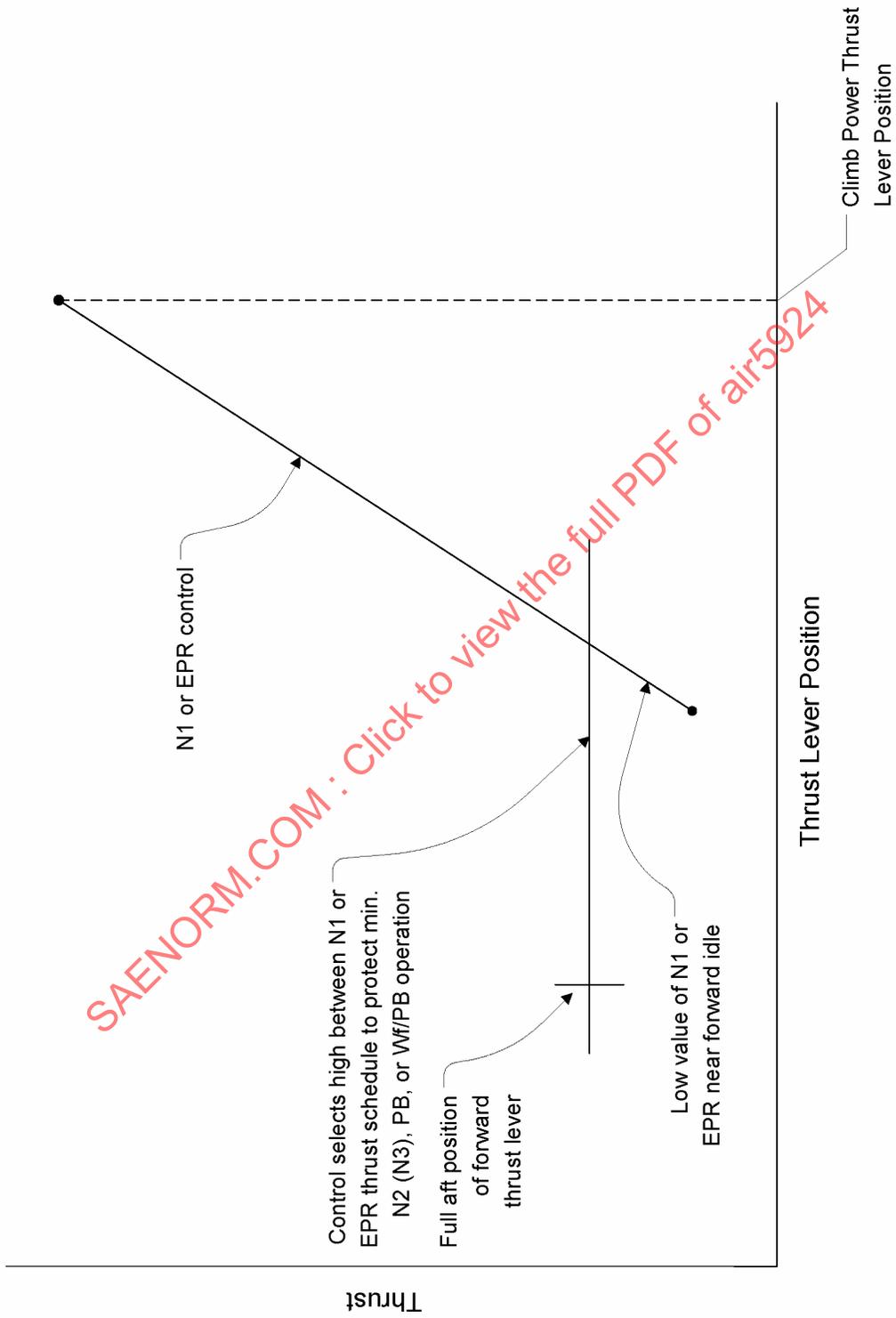
FIGURE 7 - Engine Idle Selection

Climb Power Thrust Lever Position

N1 or EPR control

Control selects high between N1 or EPR thrust schedule to protect min. N2 (N3), PB, or Wf/PB operation

Full aft position of forward thrust lever

Low value of N1 or EPR near forward idle

Thrust Lever Position

Thrust

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NOTE: Value from schedule is multiplied times max. rated climb EPR (or N1) to obtain commanded EPR or N1 when thrust lever is below climb position. Control selects idle function if control of EPR or N1 would cause engine to operate at too low of an N2, N3, or PB.

Aft Position of Forward Thrust Lever

Idle Control

Increasing Thrust Lever Position

Climb Thrust Lever

Multiplier Value

1.0

0.8

0.6

0.4

0.2

0.0

FIGURE 8 - Example of Multiplier Schedule

4.2.1.3.1   (Continued):

In many FADEC systems, the parameter being controlled when the engine is operating above idle is different than the parameter being controlled at idle. For example, engine N2 (or N3) or burner pressure may be the parameter being controlled at idle, and above idle the control parameter may be N1 or EPR. In these cases, the control transfers over to the idle control function if the controlled parameter when above idle, such as of N1 or EPR, would result in a value of the idle control parameter that is less than the idle function would allow. Either of the two approaches above can be constructed to provide a smooth transition between control parameters.

It is desirable to have the crossover from the normal EPR or N1 control to idle control occur at least two to three degrees above the thrust lever idle stop to ensure that the engine can achieve idle thrust. Flight crews typically squawk non-agreement between engine rotor speeds and other parameters during engine-idle descent conditions. Therefore, it is highly desirable that during normal flight descent conditions, all engines are operating on the same idle control when the thrust or power lever is at the idle position.

The thrust lever positions for the climb and takeoff power settings are usually determined so that thrust from idle to the maximum programmed power setting increases approximately linearly with thrust lever position.

4.2.1.3.2   Thrust Schedules with Flight Crew (Thrust) Mode Selection: A simple way of implementing thrust schedules with thrust lever position has been used in some of the smaller, transport category aircraft. Figure 9 shows the types of thrust schedules. Figure 10 shows the thrust mode select panel used to select a given schedule and the aisle stand layout in vertical and cross-section view. In this implementation, maximum rated thrust can be obtained from any thrust mode or schedule by advancing the thrust levers to the full forward stop.

The FADEC systems used in this implementation of thrust schedules share (i.e., cross-talk) information concerning which thrust schedule is being used between the different engine controls. If that information differs for a significant period of time between engine controls, all FADEC systems revert to the use of the maximum takeoff schedule.

4.2.1.3.3   Installations Using Thrust Lever Detents: Thrust lever quadrants with detents for each engine rating have also been used. For example, the crew selects the Takeoff, Maximum Continuous, or Climb thrust lever detent. Thrust tolerances are of interest in this type of system as well. A means of detecting failures, such as power setting splits, is incorporated.
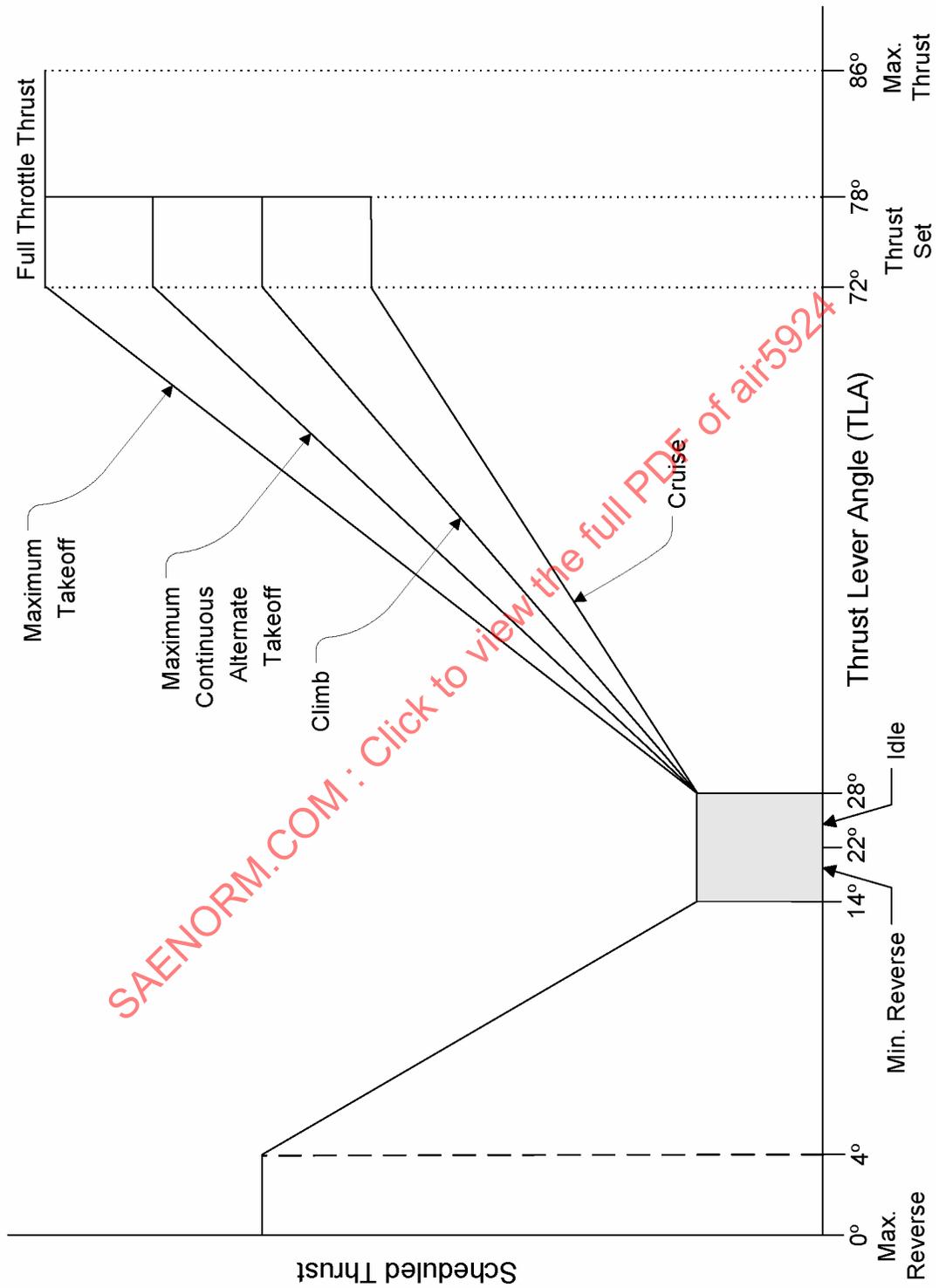
FIGURE 9 - Thrust Schedule Using Mode Selection Panel
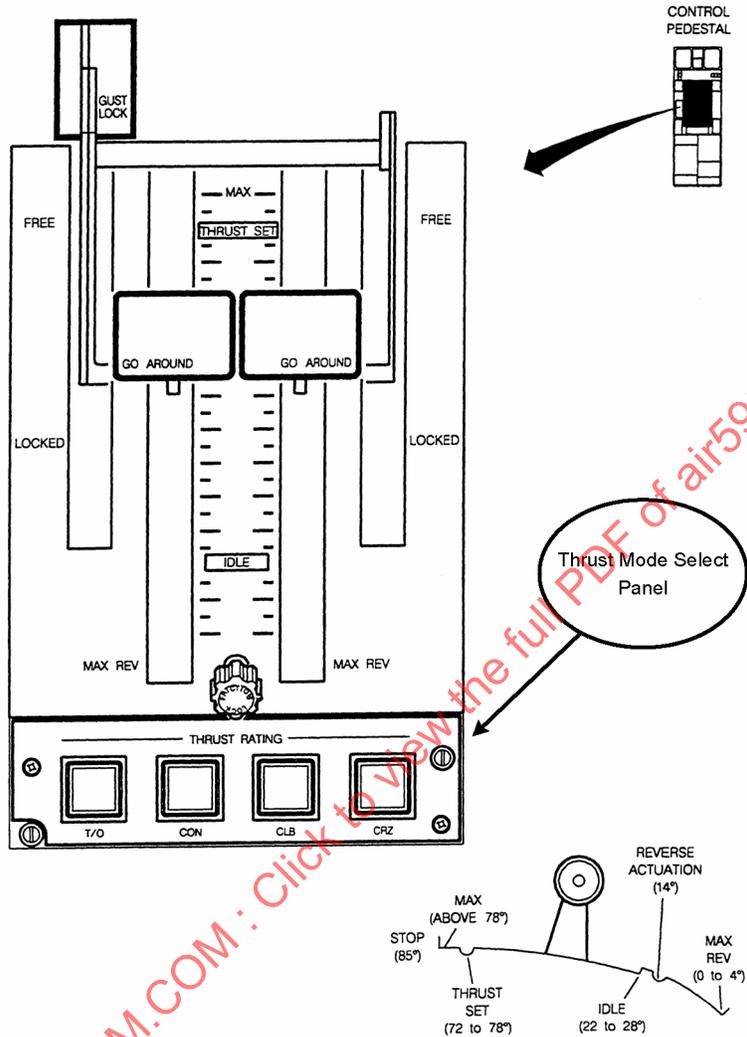
FIGURE 10 - Thrust Rating Selection Panel

4.2.1.4   Derated and Reduced Takeoff Thrust Operation: When not operating at the maximum permissible gross weight for the prevailing ambient temperature and altitude conditions, using a lower takeoff thrust provides a significant savings in engine life. Two basic methods implement a lower thrust setting for takeoff operation. These methods are defined in FAA Advisory Circular 25-13. One method is called Derated Thrust Operation, and the other is called Reduced Thrust Operation. The Reduced Thrust method is also known as the FLEX Takeoff or Assumed Temperature Method (ATM) of operation.

The characteristics of the methods are discussed below.

4.2.1.4.1   Derated Thrust Operation: Derate takeoffs have historically been performed throughout the jet transport era. Before the extensive use of onboard computers, a takeoff derate could be easily defined at dispatch, and a takeoff performed at less than full rating with well-defined performance limits. The inclusion of capable onboard performance computers has allowed the installation of pre-programmed derate values (usually identified as Derate 1, Derate 2, etc.) and allows onboard computation of the derate power settings, but the determination and use of derate thrust has, in concept, changed little over the years.

Similar to a full takeoff rating, a Derated Thrust Setting is an officially recognized (by the FAA) rating. This means that when this rating is used on an aircraft, there is a set of aircraft performance data in the aircraft's flight manual (AFM) for that rating, as if lower thrust engines were installed on the aircraft. This data would include the power setting data (that is, values of the thrust setting parameter) as a function of altitude and temperature and all the aircraft performance data that specifies the maximum gross weights for that thrust setting as a function of outside air temperature, takeoff flap setting, and runway length. This data also includes V-speeds, such as the minimum control speed on the ground (Vmcg), decision speed (V_1), rotation speed (V_R), the second segment climb-out speed (V_2), and the minimum control speed in the air (Vmca). It is important to note that these V-speeds (V_1, V_R, V_2) will be slightly different (higher, by virtue of the reduced thrust-to-weight (T/W) ratio) from those associated with use of the full takeoff thrust (or power) setting. The associated minimum control speeds (Vmcg and Vmca) may be significantly reduced. If the aircraft is loaded to the maximum gross weight allowed for the derated thrust setting, the aircraft would be performing a critical or performance-limited takeoff. This means that if the aircraft suffers an engine failure during the takeoff roll, the performance of the aircraft will just meet either the field length limits or the minimum engine-out climb gradients required by the regulations (depending on which parameter is limiting for a given takeoff situation.) Regular use of derated thrust settings would result in a higher percentage of performance-limited takeoffs than full thrust settings.

4.2.1.4.1   (Continued):

Although the flight crews could select the full takeoff rating following an engine loss, the FAA/JAA do not give performance credit for that thrust increase. With the possible exception of automatic takeoff thrust control system (ATTCS) operation (discussed in 4.2.1.7), the flight crew is not trained to change the thrust setting following an engine loss in the takeoff mode.

4.2.1.4.2   Reduced Thrust Operation: This method for using a lower takeoff power setting has existed nearly as long as the concept of derated thrust, but requires a somewhat more complex process to determine the allowable thrust setting for any given takeoff. The method only gained full acceptance with the advent of onboard performance computers, which allow more precise definition of the ambient parameters required for any given takeoff in which use of reduced thrust is desired. This method only requires one rating, the full takeoff rating, to be stored, and this one rating can be used to obtain a lower value of the power setting when the aircraft is operating at a lower-than-the-maximum-allowed-gross-weight at the prevailing ambient temperature and altitude conditions.

When discussing reduced thrust operations, one may often say that, "We're providing ATM (derated thrust) capability on the aircraft." Although everyone usually knows what the speaker means, we should stop using the word "derate" in that phraseology and replace it with "reduced thrust" to avoid confusing the two methods.

Reduced thrust operations are slightly different than derated thrust operation in that there are no new performance charts in the AFM for this type of operation; the same full takeoff performance charts are used. In reduced thrust operations, if the GW of the aircraft is less than the maximum GW allowed for the current outside air temperature (along with the other variables of flap position, runway length, etc.) then one enters the performance charts backwards, with the aircraft's GW and determines from the charts the appropriate value of the thrust setting parameter.

For reduced thrust operations, the V-speeds that must be used for that takeoff are the same as the V-speeds associated with those for the full takeoff power setting at the same temperature. Therefore, the V-speeds for the same thrust setting determined using a reduced thrust procedure will be lower than those used for a derated takeoff. Takeoff distances and takeoff profile (climb performance) will be similar to full rate performance at the same temperature. Depending on the associated performance limits, aircraft performance during a reduced thrust operation may have better field length and climb performance than a derated thrust operation at the same power setting. But a case-by-case comparison would be necessary to determine which method provides the greatest advantage for any given takeoff.

4.2.1.4.2   (Continued):

Another item that provides slightly more performance capability when performing a reduced thrust takeoff at the same power setting as the derated takeoff is the slight engine thrust differences due to the air density difference effects on engine thrust. In both cases the same power setting value is set at the beginning of the takeoff. However, in the reduced thrust takeoff, the day is actually colder than the day temperature for the limiting takeoff case, and therefore the air is slightly denser than it would be at the higher temperature, and the engine will make slightly more thrust with the denser air. This slightly higher thrust (at the same thrust setting) will give the reduced thrust operating aircraft a higher T/W and, therefore, slightly better performance.

4.2.1.4.3   Combinations of Derate and Reduced Thrust Operations: It is acceptable to combine both the derated and reduced thrust operating methods. When doing this, select the derated thrust level first. If the derated thrust level chosen allows a maximum GW that is greater than the GW to which the aircraft is loaded, an additional thrust reduction using an approved method, such as ATM as applied to the derated performance calculations, is allowed.

4.2.1.5   Engine Thrust Lapse Rates from the Basic Ratings Computations: In the following discussion, takeoff thrust set or setting applies to the value of the thrust setting parameter that is set during a takeoff. In a typical turbofan powered transport aircraft, this is the value of the thrust setting parameter that is set by the flight crew (or automatically by the autothrottle or flight management system), when the aircraft is between 60 and 80 knots during the takeoff-roll. Although not normally done, the takeoff thrust setting could be done statically. All transport aircraft typically use a call-out of thrust set by the non-flying pilot at or around 80 knots. There is no rule requiring this; it is just a typical operating procedure recommended by the transport aircraft manufacturers and used by virtually all operators.

The profile that the engine thrust follows after takeoff thrust set is usually referred to as the engine's takeoff thrust lapse rate. This lapse rate is important because it is used to compute the aircraft's takeoff performance. This lapse rate is how thrust changes with altitude and airspeed. When completing aircraft performance calculations, it is assumed that static or ambient air temperature follows the standard atmospheric profile and decreases 2 °C per thousand feet of altitude increase; therefore, by definition, the lapse rate is only a function of airspeed and altitude and not temperature. Note: the engine's actual thrust lapse rate may be a function of total air temperature (TAT) because the control may be using an actual real time selection of temperature to determine the thrust rating. (See 4.2.1.6.2 for more discussion on this subject.). Figure 11a illustrates this, showing the change in ambient temperature expected to occur during standard day operation, along with the

4.2.1.5 (Continued):

temperature lapse that may occur when climbing out into a cold or hot (i.e., temperature inversion) atmosphere. During the cold or hot day conditions, thrust will not be the same as the standard day climb out thrust if the engine control is using actual, real time sensed temperature. This is illustrated in Figure 11b. Section 4.2.1.5.2 discusses the impact of this.

As the engine control is scheduling thrust by controlling EPR or N1, the data in the control that determines how EPR or N1 varies with altitude and airspeed determines the takeoff thrust lapse rate.

4.2.1.5.1 Full and Reduced Takeoff Thrust Lapse Rates Without Lock and Lapse Logic: In most modern FADEC systems used today, the ratings for takeoff and climb are continuously calculated as a function of the FADEC system's selected values for the environmental parameters (that is, total temperature, altitude or barometric pressure, and Mach number or airspeed), and the control simply governs the engine to the value(s) computed. If the thrust lever is in the full takeoff position, the control varies the thrust setting parameter (for example, N1 or EPR) by modulating fuel flow and other variables as needed to follow the calculated value of takeoff thrust. If the thrust lever is in the climb position, the control governs the engine to the climb power setting calculation. If the thrust lever is between the takeoff and climb power positions, the control interpolates between those two power setting calculations. If the thrust lever is less than the climb power setting, which is common with reduced thrust takeoffs, the control simply governs the engine to some fraction of the climb power setting calculation.

When operating at lower than maximum gross weights and performing takeoffs at thrust settings below the full takeoff thrust setting, the lapse rate that thrust follows after power set is still called the takeoff thrust lapse rate even though the engine is not operating at full takeoff power. This lower thrust setting lapse rate is just as important as the full takeoff thrust lapse rate because aircraft performance will be based on this lapse rate for the lower thrust takeoffs. Therefore, takeoff thrust lapse rates must be established for all full and lower takeoff thrust power settings. This is particularly important when performing reduced thrust takeoffs using the ATM method as described in 4.2.1.4.2 above. After thrust set, the control will be governing and lapsing thrust from a set point that is less than the full takeoff thrust setting value, but it is the same thrust setting value that would be set for full takeoff thrust on a hotter temperature day. Therefore, the difference in the thrust lapse rates when setting the same value of engine power during hot and cold day operating conditions must be understood to properly account for aircraft performance during reduced thrust takeoffs.
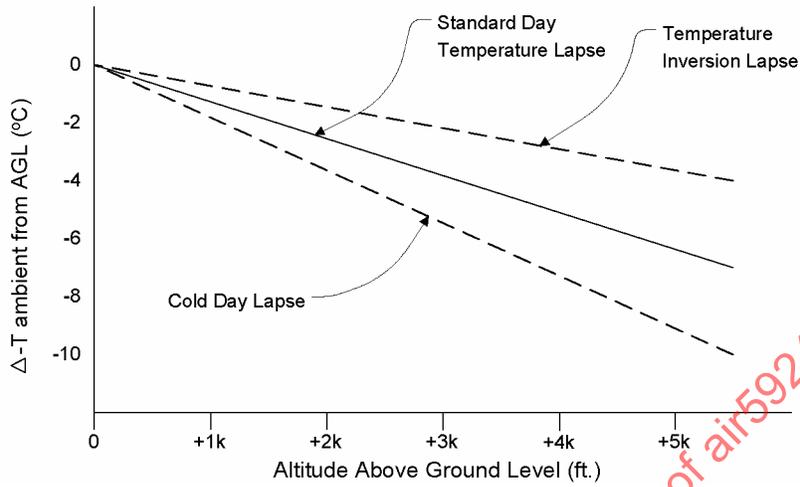
FIGURE 11a - Ambient Temperature Lapse from AGL
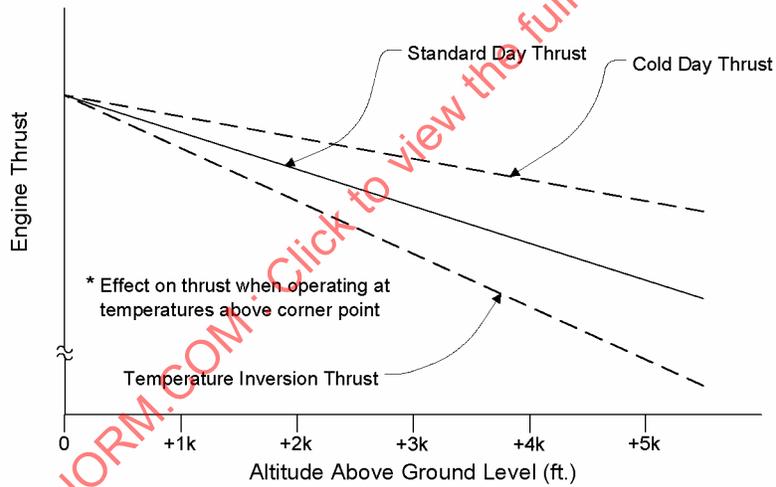
FIGURE 11b - Thrust* as a Function of Ambient Temperature &
Altitude Increase at Constant Mach Number

4.2.1.5.2 Takeoff Lapse Rates Using Lock and Lapse Logic: Due to the complexities involved with different takeoff thrust lapse rates at the same value of the power setting parameter on hot and cold days, it is beneficial to both engine life and aircraft performance calculations to define a specific engine lapse rate characteristic and construct that characteristic into the control system. The control logic that contains and implements this characteristic has been termed lock and lapse logic. Several engine manufacturers use lock and lapse logic for controlling the engine's thrust lapse during the takeoff. In this implementation, the control system locks in the pressure altitude and temperature information at approximately 65 knots and programs a given lapse rate as a function of the change in altitude, change in temperature, change in Mach number, and, in some implementations, the 65 knots set value of the thrust setting parameter, EPR, or corrected fan speed (that is, $N1/(Theta)^{0.5}$). These types of implementations are recommended because the lapse rate in thrust is always the same for a given altitude and a given initial value of thrust setting. This type of implementation does not require an extensive analysis to show that assumed temperature derated takeoffs have the same lapse rates.

The change in temperature can be either the change in static temperature or the change in total temperature. Since the control knows Mach number (and airspeed), the change in static temperature is easily computed. Using the change in freestream temperature allows the control to program a takeoff thrust schedule that maintains an approximately constant exhaust gas temperature (EGT) throughout the takeoff. However, when performing takeoffs into temperature inversions, the implementation that adjusts engine thrust during inversion conditions results in LESS thrust than the aircraft flight manual assumes. The manual assumes that outside air temperature (OAT) will decrease 2 C per 1000 feet of increase in elevation. If the actual static OAT does not do this (that is, if it decreases less than expected with increasing altitude), then the engine may be holding constant EGT, but the aircraft is getting less thrust than planned. If this is the case, many engine FADEC systems implement a lock and lapse logic that locks in the OAT at 65 knots and programs an assumed temperature lapse rate with altitude in which the static air temperature decreases at 2 C per 1000 feet of altitude and disregards the actual static air temperature change with altitude. The engines could go over EGT redline if the engines are close to redline at power set and the aircraft encounters a temperature inversion during climb-out, but the aircraft will be getting the planned thrust. If an engine fails during takeoff, getting the planned takeoff thrust from the remaining engines is more important than engine overtemperature conditions. In addition, when all engines are working properly, most takeoff conditions end around 400 feet AGL. The engines are then reduced to climb power, so the exposure to overtemperature conditions occurring during normal operations is small.

This latter approach of locking the altitude and OAT at 65 knots and programming engine thrust using an assumed 2 C static OAT decrease per 1000 feet of altitude is the recommended approach to implementing takeoff thrust lapse rates, because this is the thrust used for aircraft performance calculations.

4.2.1.5.3   Lapse Rates for Fan Speed Controlled Engines Without a Dedicated P2 Probe: As discussed above, engine controls systems that use fan speed as the power setting parameter may have a thrust rating definition in which the ratings are not significantly affected by Mach number or airspeed during low speed operating conditions. In this situation, it has been considered acceptable for the engine control not to incorporate a dedicated P2 probe and sensor into the FADEC system. If this is the approach pursued, the sole sources for Mach number (or airspeed) information will be the aircraft's ADCs. For obvious reasons, it is important that ADC failures do not cause the thrust of all engines to be significantly affected in the critical modes of operation. While all modes of operation are important, it is generally recognized that two of the critical modes are the takeoff and the engine out, maximum continuous thrust operating conditions.

For systems without a dedicated P2 probe and sensor, it is recommended that the engine control system have essentially no Mach number influence on the scheduled thrust rating when operating in the takeoff mode. One way to achieve this is to use lock and lapse logic for the takeoff. At 65 knots, the takeoff altitude and static air temperature are frozen. (At least one of the ADCs needs to be alive and transmitting data to implement this. If both are available, the one that indicates the higher airspeed should be used. If the two ADCs disagree, selecting the higher of the two airspeed signals may cause the control to lock-up sooner than it should, but this is generally conservative.) The lapse rate is programmed as a function of only two variables; the change in altitude and, if desired, the 65 knots set value of corrected fan speed. At constant altitude, this logic results in a given value of physical fan speed set at 65 knots and maintained at constant altitude, but as airspeed increases, total temperature increases and thus, corrected fan speed decreases with increasing airspeed. This decreasing corrected fan speed with increasing airspeed will tend to keep EGT constant, which is desirable. When using this logic, physical fan speed is usually programmed to change as altitude increases. The programmed change is normally implemented by adding a delta N1 as a function of delta altitude. This logic will essentially allow the takeoff thrust rating to be independent of any ADC airspeed errors or failures in the takeoff mode. If, after a suitable time period, no air data information is available from either air data computer to the engine control, the above lock and lapse logic cannot be implemented. In this case the control should indicate a primary mode fail condition and should enter the soft reversionary or backup mode, depending on thrust position and (possibly) air/ground information.

For all other modes, the average of the ADC Mach numbers can be used as long as the Mach numbers agree within 0.05 Mach (see 5.5.4).

4.2.1.6   Autothrottle/Autothrust Systems – Engine Control in Primary Mode:

4.2.1.6.1   Moving Thrust Lever Systems: For transports that use an autothrottle servo to move the thrust levers as the primary means of commanding a thrust change, the engine power ratings as a function of thrust lever position are usually implemented as discussed above. The autothrottle system may use a single servo to drive all thrust levers or separate servos for each thrust lever. Figure 12 depicts a simple autothrottle system schematic. In modern systems, the feedback from the thrust lever servo positioning system is generally used for servo limit protection and rate control, and the feedback from the FADEC system units are usually the EPRs or N1s that the FADEC systems are commanding of the engines. In a typical implementation, when the highest FADEC system EPR or N1 command achieves the value desired by the autothrottle computer, the autothrottle servo system stops driving the throttles. In those systems using a single servo motor to drive all thrust levers, the computer used to drive the thrust levers, which is referred to as the thrust management computer (TMC), may provide digital trim signals to the EECs to align the power setting parameters, to compensate for the rigging errors and slight thrust lever position differences, which would otherwise result in differences in the power settings between engines. In these systems, if the software in the TMC system is not developed with a software assurance level equivalent to DO-178B, level A, it is recommended that the servo system go to a hold mode at approximately 65 knots. This hold mode should be designed into the system to prevent an autothrottle servo system error from moving the thrust levers and commanding thrust changes on all engines after takeoff power set. The FADEC systems should latch any trim signals received from the TMC system at approximately 65 knots for the same reason. The flight crew must confirm that the engines are operating at the target power setting at an aircraft speed of approximately 80 knots. By having the autothrottle servo system go to the hold mode and the EECs latch any trim inputs at approximately 65 knots, the flight crew has time to adjust the power setting, as necessary, to achieve the target prior to reaching 80 knots. Eighty knots is typically used as the point above which the flight crew should not make further adjustments.

Systems using a separate autothrottle servo for each thrust should be designed to work in the same way as single servo systems. Multiple servo systems may or may not employ trim signals for each engine's FADEC system; this would depend on the accuracy of the servo system.
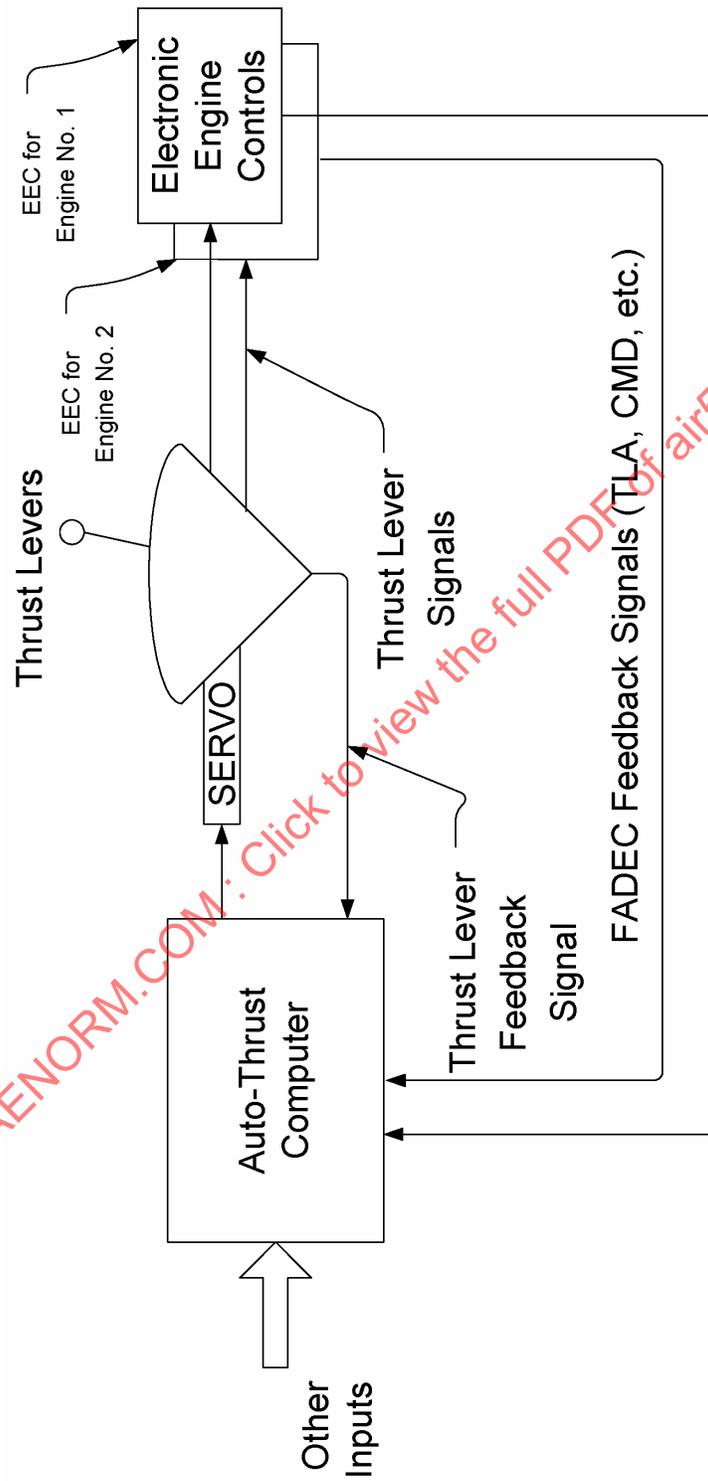
FIGURE 12 - Moving Thrust Lever Auto-Thrust System

4.2.1.6.2   Non-Moving Thrust Lever, Autothrottle/Autothrust Systems: Some autothrottle systems are configured not to use a servo to drive the thrust levers, but instead to use an electrical/electronic thrust management system input to the FADEC system(s) to modulate thrust. In these systems, the thrust levers are manually advanced by the flight crew to the appropriate detent position, and when the autothrust system is armed and active, the FADEC system accepts thrust commands from the thrust management computer. Figure 13 illustrates such a system. In these systems, it is recommended that the EECs lock the thrust command signal at 65 knots, and not accept any thrust command changes from the TMC until at least 400 feet AGL is reached. Section 4.2.1.7. discusses aircraft incorporating Automatic Takeoff Thrust Control Systems (ATTCS) or Automatic Power Reserve (APR) systems.

4.2.1.7   Automatic Power Reserve (APR) or ATTCS Systems: Many of today's small and medium-sized transport aircraft employ APR systems, which are also known as ATTCS. These are systems that are designed to sense an engine failure when operating in the takeoff or go-around modes of flight and command a thrust increase on the remaining engines. The current FAA rule applying to such systems is given in Appendix I of 14 CFR Part 25. A revised rule, which is a harmonized effort toward achieving commonality in FAA, JAA, and Transport Canada requirements for these types of systems, has been drafted and will be available for public comment in the future. The revised rule would allow new APR systems to implement thrust increases greater than 11%, but would limit credit in takeoff and go-around performance to be not greater than 11%. For example, assume that an APR (or ATTCS) takeoff is being performed at a reduced thrust (from maximum APR thrust) of 25%. If an engine fails, the remaining engines may increase to the maximum APR thrust, but the credit to aircraft performance will be limited to that associated with an 11% thrust increase. The airplane performance credit refers to the aircraft GW for engine out performance, which in this case would be limited to that associated with only an 11% thrust increase on the remaining engines.

The original discussions and regulation material on APR systems refer to full APR takeoff thrust as 100% thrust, and normal takeoff thrust was limited to being not less than 90% of that full thrust value during APR operation. This is a thrust decrease of 10% from maximum thrust. The newly harmonized material uses the wording of an 11% increase from the normal takeoff thrust setting. The 11% increase in the new wording and the 10% decrease in the original wording refer to the same increment.

The limiting of aircraft performance credit to that associated with an 11% thrust increase, in both the past and newly proposed regulatory material, was established by the FAA so that, "the all-engine performance is not significantly degraded and that a minimum level of performance is available if an engine and ATTCS failure occur simultaneously."
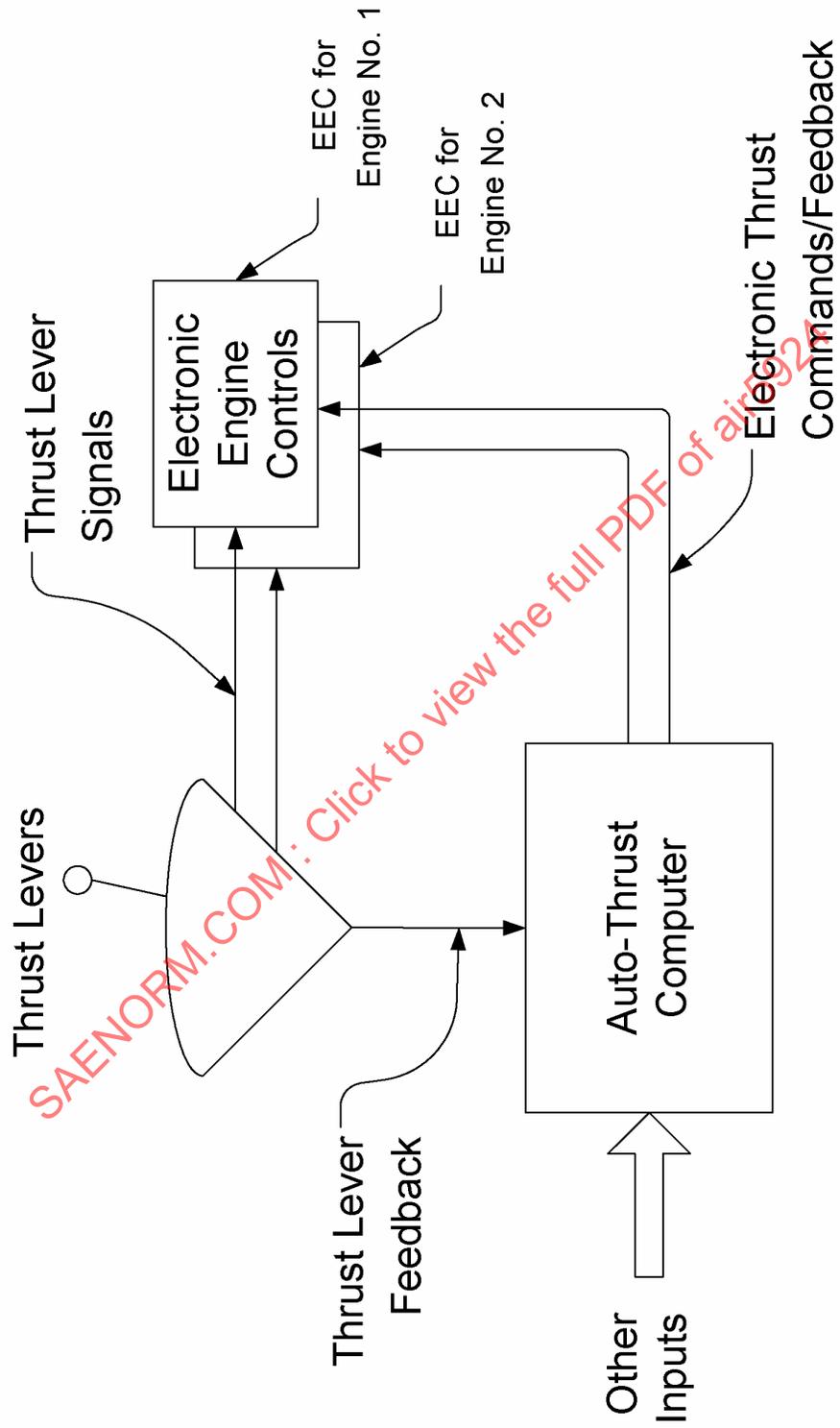
FIGURE 13 - Non-Moving Thrust Lever Auto-Thrust System

4.2.1.7   (Continued):

The introduction of FADEC systems allowed APR functionality to be completely contained in the FADEC system. Aircraft interfaces are generally limited to an APR on/off selection switch and displays of APR functionality. The new designs incorporate multiple data paths between the engine control systems. Engine information in these data paths is used by each engine control to determine whether another engine has failed. If it has, then the control system(s) on the non-failed engine(s) calls for a thrust increase. The probability of having a failed engine, in combination with the probability that the remaining engines will not increase in thrust due to a control system malfunction, has to be extremely improbable (that is, the failure rate for this combination of failures has to be less than 10^{-9} events/flight hour).

An additional certification requirement when implementing APR systems concerns the engine displays. The requirement is for the flight crew(s) to be able to determine that the engine is capable of achieving the APR thrust setting without exceeding any engine limits when they set the lower takeoff thrust. (This requirement is not clearly specified in the current Part 25, Appendix I, requirements; the newly harmonized, proposed revision to the rule contains this requirement.) In general, past applicants have met this requirement by providing two redlines on the appropriate engine displays. The lower redline is not really a redline, it is a reference value. This indicates to the flight crews that if normal (that is, reduced) takeoff or go-around thrust can be set with the engine operating below the reference redline, then full APR thrust can be achieved without the engine exceeding its real redline. Some new aircraft/FADEC system designs are not using the dual redline approach. In these systems, an aircraft avionics unit or the FADEC system incorporates a suitable alert to notify the crew if the engine does not have adequate margin(s) to get to APR thrust without exceeding an engine operating limit. This implementation is considered an improvement as compared to the dual redline display approach.

4.2.1.8   Two Basic Thrust vs. Thrust Lever Position System (FAA) Requirements: There are two basic thrust vs. thrust lever position system requirements that, although well known, have caused some difficulty in some installations.

4.2.1.8.1 Requirement for Monotonic Relationship of Thrust with Thrust Lever Position: The first is the requirement that thrust must monotonically increase with forward thrust lever motion. Flats (that is, thrust remaining unchanged with thrust lever movement) are acceptable. This requirement has been overlooked in some cases, when large reduced takeoff thrust operations are employed. This omission has occurred when the thrust lever system uses a fixed position for climb rated power as well as takeoff power. In these systems, the thrust level is placed in the takeoff position for all takeoff, including all derated and reduced thrust takeoff operations. It is easy to implement a derate and/or reduced thrust condition when power being used for that takeoff is less than normal climb power. Therefore, climb power must be lowered on those takeoffs as well, because otherwise thrust can actually increase when the thrust level is retarded from the takeoff position to the climb position. This would not meet FAA regulatory requirements. Most designers recognize this requirement, but there have been cases in which this has been overlooked. The simplest solution is to have the control do a select low between the computed takeoff thrust setting value and the climb thrust setting value when computing the climb power setting.

4.2.1.8.2 Requirement for Maximum Continuous Thrust Setting Capability with All Engines Operating: An FAA requirement, expressed in the Transport Aircraft Directorate Policy Letter 00-113-1028, dated July 31, 2000, is that the capability must exist for setting maximum continuous power on all engines at all flight conditions (see 4.2.1.2). Some designers believe that the capability for setting maximum continuous power is only required during engine inoperative conditions. This has been a problem in past thrust control systems in which ATTCS is used full time. Figures 14a and 14b illustrate how thrust scheduling has been implemented in some past aircraft. The particular thrust schedule being used by the flight crew is selected by a mode control panel in the cockpit. The Figure 14a schedules are available for selection during all-engine operative conditions, and the system automatically switches to the schedules shown in Figure 14b when an engine inoperative condition is sensed from engine data. In these systems, the normal takeoff thrust setting is usually 10% below full takeoff (APR) thrust and in many instances is below the maximum continuous thrust setting.

Note that the flight crew cannot set maximum continuous thrust on the engines during an all-engine-operative condition if the system is designed as shown in Figure 14a, because the maximum continuous power setting is on the step from normal takeoff power to full APR power. It is not possible to set maximum continuous thrust in such a configuration.

A simple solution is to provide a ramp up from the normal takeoff rating to the maximum takeoff rating and make the slope acceptable for setting power at a point along the slope.
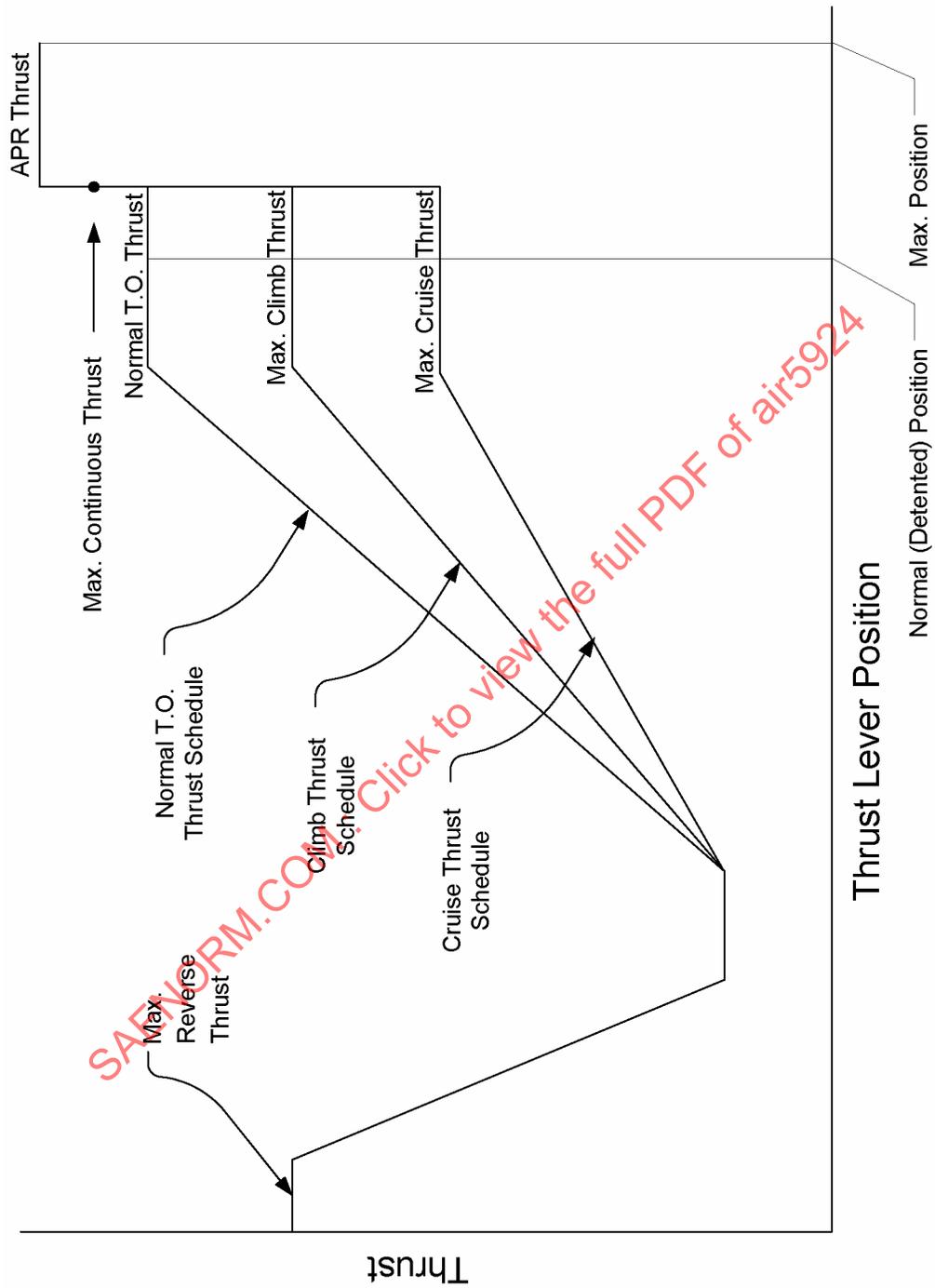
FIGURE 14a - All Engines Operating, Available Thrust
Schedules (cannot set maximum continuous thrust)
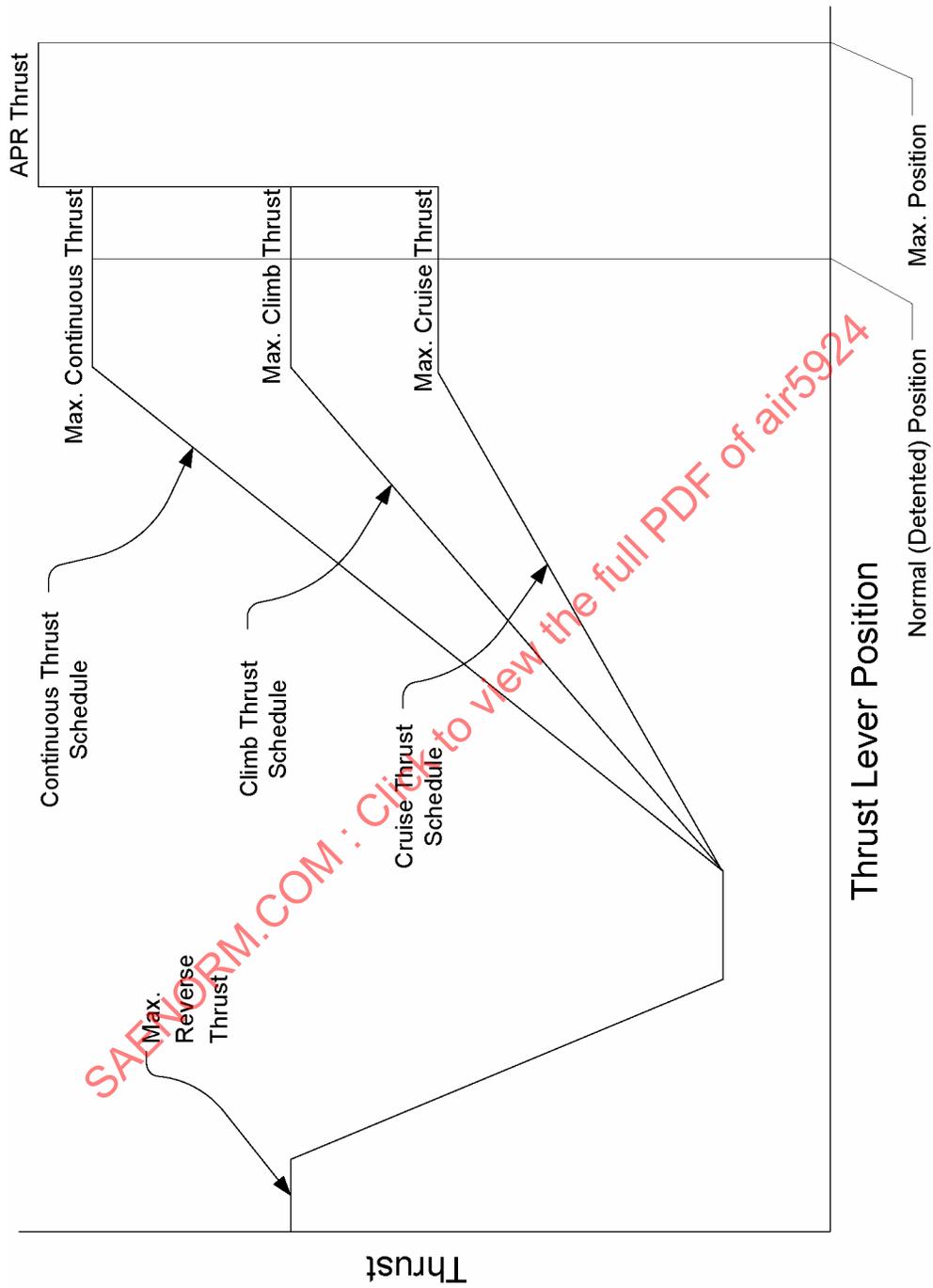
FIGURE 14b - One Engine Inoperative, Available Thrust Schedules
(system automatically reconfigures when it senses OEI)

4.2.1.8.2   (Continued):

Another approach would be to have a cockpit-located, maximum continuous selection switch that changes the selectable thrust schedules from Figures 14a to 14b when the switch is activated. This allows the flight crew to select the Figure 14b schedules and set maximum continuous power on all engines whenever that thrust setting is desired.

4.2.2   Engine Ratings and Thrust Lapse Rates in the Backup (or Alternate) Mode:

4.2.2.1   Idle Control: Idle control is generally the same in both the primary and backup modes; the functions that might typically be incorporated into idle control are discussed in 4.2.1.1. These functions can be the same because their implementation generally only involves the use of altitude and total temperature information, and the control system normally has this information available in all dispatchable modes. If this is the case, the control is usually considered non-dispatchable if its own sensors supplying this information are inoperative.

4.2.2.2   Thrust vs. Thrust Lever Position - Non-Rating Modes: For turbofan engines that use EPR as the primary thrust setting parameter, control in the backup mode is normally that of governing fan speed. Therefore, thrust in the backup mode is determined by the programmed schedule of N1 as a function of thrust lever position. Air speed or Mach number information may not be available to the control. Indeed, this may be the reason that the control is in the backup mode. In this mode, the control is usually programmed to schedule fan speed from some fraction of the full thrust value of N1, up to the full thrust value of N1, as the thrust lever is advanced from idle to the full forward stop. The full thrust value of N1 can be a function of altitude and, if desired, total temperature. As in the case of control in the primary mode, the multiplier fraction used when the thrust lever is at idle needs to be small enough that the control will select the idle function as the thrust is reduced to idle.

4.2.2.3   Backup Mode Lapse Rates - A Simple Approach: As the backup mode does not usually implement a rating type of control function, there is no need to lock-up aircraft discretes, such as those associated with customer bleed, at 65 knots.   Changes in these discretes generally have no effect on the controller's N1 setting, and without airspeed, the controller cannot use a lock and lapse logic routine to implement a given lapse rate. Therefore, the lapse rate is quite simple. If the scheduled value of N1 is only a function of thrust lever position and altitude, the control will hold a constant fan speed at constant altitude. (Increasing airspeed (at constant altitude) while holding physical fan speed constant causes corrected fan speed to decrease. This tends to hold EGT constant during the takeoff.) The lapse rate of thrust with airspeed and altitude is readily calculable and must be compared with that of the full up rating mode. If the lapse rate is not equal to or better than the full- up mode, a gross weight penalty will probably be necessary for takeoffs in this mode. If the ATM derated takeoffs (see 4.2.1.4.1) are allowed in the backup mode, the lapse rates for these types of takeoff also must be compared with those of the full-up mode.

4.2.2.3   (Continued):

The full thrust scheduled value of N1 may be a function of total temperature as well as altitude. This makes the calculations of the lapse rates much more complex because it adds another variable, but the principal remains the same. The lapse rates in the backup mode, at all altitudes and temperatures, must be compared with those of the primary, or full-up mode, and the appropriate aircraft performance adjustments must be made. Any performance adjustments must be contained in the aircraft's master minimum equipment list (MMEL), because the MMEL will be the reference used to allow dispatch in the backup or alternate mode.

4.2.2.4   Backup Mode Lapse Rates - Autothrottle/Autothrust Operation: If the autothrottle moves the thrust levers to achieve a target thrust (for example, N1), the operation of the autothrottle is essentially the same in the backup mode as the primary mode. Again, the autothrust or autothrottle computer should go to a hold mode at 65 knots to ensure that a fault in that system does not inadvertently move the thrust lever(s) after power set.

The non-moving autothrottle system or autothrust system is not so simple. The FADEC system still knows what thrust position allows the autothrust function to be activated, but since the EECs cannot lock at 65 knots (because they might not have airspeed), it is recommended that the fixed thrust lever, autothrust system not be used when performing takeoffs with the EECs in the alternate mode. The difference between this and the moving autothrottle system is that in the case of the moving thrust system, the flight crew can see inadvertent thrust movement after thrust set. In the non-moving thrust autothrust system, the flight crew would have to diagnose an inadvertent thrust change from the engine displays. This could be difficult to do in a timely manner. If it is agreed that this is the case, the engine control can be programmed to ignore autothrust inputs during ground operation in the backup mode. If this approach is taken, a time delay on the air/ground transitions should be used to inhibit autothrust operation until an adequate altitude is achieved. This will prevent an erroneous autothrust command from affecting all engines at lift-off.

4.2.3   Automatic Shutdown or Low Thrust/Power Modes: This report does not intend to fully address all control, thrust, or power modes; however, there are two modes that usually receive considerable discussion because these modes implement a significant thrust or power deduction on the engine.

4.2.3.1 Reverser not Stowed (Response Mode): As thrust in the opposite direction of that commanded by the thrust lever can be extremely detrimental to aircraft performance, many FADEC systems are programmed to rapidly go to idle thrust or power if a confirmed not-stowed or deployed thrust reverser position signal is sensed or received by the control and the aircraft is in-flight. Most FADEC systems have their own, dedicated reverser position signals. There usually is not much discussion as to how fast fuel flow should be reduced to idle. In many engine control systems, decelerations to idle can be quite slow at altitude. The required response time should be established by coordination with the installer/aircraft manufacturer. A rapid decel may be required, and although the engine may experience a decel surge and/or flameout in such a situation, the rapid engine response may be necessary to maintain aircraft safety.

4.2.3.2 Thrust Higher than Commanded and Not Decreasing: Recent emphasis has been placed on failure conditions in engine control systems in which thrust or power can be higher than commanded and not decreasing. Such conditions can lead to a hazardous or potentially catastrophic failure condition at the aircraft level. Such a situation occurred on a twin engine, wing-mounted aircraft during ground operation. In this case, an engine control system failure caused thrust to go above takeoff thrust during the takeoff roll. The control did not respond to a throttle command to reduce thrust (on both engines), and the aircraft departed the side of the runway. Although there were no fatalities, an ensuing fire resulted in a complete hull loss.

Although the failure mode could be addressed at the aircraft level through an aircraft system that shuts down the non-responding engine, the installers/aircraft manufacturers will probably want/require the engine manufacturers to provide protection for the engine control system single failures that could lead to such a condition. If the condition is a result of multiple failures, the combination of those multiple failures will have to be shown to be suitably small.

4.3 Auxiliary Functions:

The FADEC installation may have a number of auxiliary functions. Examples are: pitch control, synchronization, load sharing, and engine condition monitoring. The implementation and integrity of these functions should be consistent with the safety and hazard analyses for the engine and aircraft.

5.   USE OF SENSORS, AIRCRAFT SIGNALS, AND DATA:

5.1   Engine Control System Signals and the Use of Aircraft Signals:

The functional requirements for the use of aircraft signals by FADEC systems are quite different if the signals are dedicated to one engine only or are common to more than one engine. For those signals dedicated to an individual engine, such as the engine's thrust lever input signal, it is acceptable to allow a failure in the signal(s) to cause a significant (for example, greater than 10%) engine power loss. The regulatory requirements for the control system operation with regard to power losses are provided in 14 CFR § 33.28, JAR E-50, and the associated advisory material. If aircraft signals used by the control can affect more than one engine, the allowable power or thrust change may be much more restricted.

5.2   Signals Dedicated to an Individual Engine:

Signals dedicated to an individual engine include analog (continuous variable), discrete (on/off), or digital (numerical) signals.

5.2.1   Thrust Lever Signals and Thrust Reverser Position Signals: Many current FADECs use dedicated analog-type signals from the aircraft for some of the FADEC system interface functions. Traditionally, two such signals have been the thrust lever position signal and the thrust reverser position signal. If these signals are changed to digital-type signals in the future – assuming that a digital-type position sensor is used – is not particularly important here. The primary intent of this paragraph is to indicate that these signals are dedicated to a specific engine and that a failure of these signals cannot directly affect the operation of any other engine(s). Therefore, these signals are allowed to have a relatively large effect on engine thrust when they fail. Currently, the engine control is not required to take a specific action when these signals are lost. Some engine controls are programmed to maintain the engine's current thrust setting, and some engine controls are programmed to run the engine to flight idle or a fixed value of thrust when the signals are lost. Refer to 4.2.3.2.

There is a special situation. In many installations, the transducer used for the thrust lever angle or position may be set up to operate between certain limits. If a signal outside of those limits is received by the control, the control may be programmed to assume that the sensor is failed. In the case of the thrust lever position transducer, consideration of the following condition is recommended:

5.2.1   (Continued):

Many FADEC systems are programmed to command maximum (or a defined amount greater than 100%) rated thrust on the engine if the thrust lever is placed in the full forward position. When the full thrust signal is programmed to request a thrust greater than normal, maximum takeoff thrust, the full thrust position will not be used during the normal takeoff conditions. If the engine control is programmed to implement an idle thrust command when the thrust lever position signal is lost or out-of-range, consider the possibility that the thrust lever position transducer may have been mis-rigged during maintenance activities so that it may rotate to an out-of-range signal condition when the thrust lever is positioned full forward. This condition may not be noted by the flight crew during everyday operations, as most takeoffs are at less than maximum takeoff thrust conditions. Such a situation could cause an engine to go to idle when the flight crew is asking for maximum thrust. There are at least two approaches to addressing this issue. The first is to design the thrust lever rigging mechanism to have limited authority, so that the thrust lever transducer cannot be rigged to give an out-of-range condition. In a derivative application, it may not be possible to limit the rigging authority. In these cases, a second approach may be used with a redundant channel FADEC system implementation. Assuming a dual channel system, as an example, if the two thrust lever signals are valid and agree; and if both indicate that the thrust lever signal is out of range, the last in-range value can be held to prevent the engine from going idle. The first approach is the preferred approach.

5.2.2   Cowl and Wing Anti-Ice Signal Sources: In many installations, wing anti-ice bleed is selected during the pre-flight procedures, but the wing anti-ice valve does not actually open until liftoff, because the engine air bleed temperatures are too hot for the wing ducting with no airflow over the wing. This may be the case for engine cowl anti-ice bleed as well. In these situations, it is recommended that the signal of those bleeds should come directly from the cockpit switch and not the valve controlling the bleed. This will allow the correct thrust setting to be set by the flight crew during the takeoff roll; although EGT will increase when the valve opens and bleed air is extracted from the engine, the proper engine thrust will be maintained.

Several modern aircraft now employ automatic ice detection systems that activate the engine's anti-ice bleed air system if ice buildup is detected. In these systems, the cockpit switch for cowl and wing anti-ice may have an AUTO position, and the switch may normally be left in that position. If this is the case and the FADEC system knows that the switch is in the auto position, the FADEC system should assume the engine air bleed is being supplied, or will be required to be supplied at liftoff, if TAT is below 10 C, for example. If TAT is below 10 C, the engine maximum thrust ratings should be reset accordingly.

5.2.3 Air/Ground Signals: The air/ground transition signal can come from several sources. It may come from nose wheel compression or squat switches, main gear compression or squat switches (these are sometimes called weight-on-wheels discretes), main gear tilt switches, or other suitable sensors. In general, the transition to the air mode should not cause any significant thrust change on the engine. Knowledge of the air/ground transition is used in several functions. These include air data selection logic, thrust reverser logic, and several other logic functions. It should also be noted that air/ground transition discretes have not proven to be very reliable in some applications, so care should be exercised when using this discrete. For critical functions it is important to ensure that this signal is logically combined with other independent indicators to establish a signal of the required integrity.

5.2.4 Other Dedicated Signals: Dedicated discrete signals may be used for functions such as engine air bleed on/off signals, air bleed high/low selection signals, high idle/low idle enable signals, and others. These signals generally have a limited power or thrust impact on the engine. For these signals it is recommended that the loss of the signal result in the control implementing a fail-safe condition. The fail-safe condition may be dependent on a specific aircraft system and/or configuration. For example, loss or lack of the air/ground signal may cause the control to limit idle thrust on the engine to a high idle setting. (This is generally considered fail-safe because go-around performance for the aircraft is usually based on engine acceleration capabilities, which are usually performed from the high idle setting. Thus, failing to high idle protects in-flight aircraft performance. This condition may not be evident to the flight crew in flight, but it would be during ground operation. If dispatch with the engine(s) operating at the high idle setting is permitted, the condition and appropriate performance penalties should be contained in the aircraft's master minimum equipment list (MMEL), because stopping distance would be impacted during a rejected take-off (RTO) event.)

The discrete signals are usually dedicated to a specific engine with dedicated switches, sensors, and wiring, so that no single or common failure could cause an incorrect signal to be sent to more than one engine's FADEC system.

These same aircraft signals could be received by the FADEC system in digital form. These signals would function like the dedicated signals. For these signals to be dedicated and independent for each engine, different computers would have to receive input signals from independent sensors and send the information to a specific FADEC system. The question always arises as to whether this separation of engine signals can be achieved in a configuration in which an aircraft computer interfaces with all engines through the same digital data bus, but a data bus in which there are separately identified words for each engine. This is considered acceptable. A question for this situation is the software and hardware integrity of the computer sending out those independent engine signals and the authority level given those signals. If those levels are acceptable, these signals can be considered engine-dedicated signals as well. See 5.3.2 for additional discussion of this subject.

5.2.5 A Potential Difficulty with Aircraft Discrete Data Words: FADEC system designers should be aware of a potential difficulty when using aircraft avionics (ARINC 429) discrete data words. This problem can and has occurred in several installations in which the aircraft discrete data words contain aircraft status information that originates from multiple sub-systems (for example, bleed management computers, brake control units, etc). Most aircraft have central systems or concentrator units that receive the data from these subsystems, then repackage some or all of the data that comes in on numerous labels into a few bit packed ARINC 429 discrete words.

The problem is how to indicate the validity of data from multiple line replaceable units (LRU) in the two bit ARINC Sign Status Matrix (SSM=Fail/Warn or Normal) of the ARINC word being sent to the FADEC. In some implementations, the SSM for the discrete words being sent to the FADECs was not set to Fail/Warn when some of the data being sent from the subsystem to the aircraft concentrator unit was set to Fail/Warn. Thus, the FADEC would believe that the data received from the aircraft concentrator unit was valid (that is, good) when some of the subsystem data sent to the integrating unit was invalid. This could lead to the FADEC using default or erroneous aircraft data. Depending on the overall engine/aircraft ARINC architecture, this could be a common mode problem. The FADEC designers should be aware of this potential difficulty and work with the installer to get a detailed understanding of aircraft data sent to the FADECs. In future systems this type of difficulty must be considered during the development of the protocol for the data bus.

5.3 Aircraft Signals Common to Multiple Engines:

5.3.1 Aircraft Air Data Signals: Most current transport aircraft have two air data computers; some have a third computer, which is generally used as a hot spare. The more common configuration has two air data computers. One, commonly called the left ADC, generally feeds information to the captain's display, and the other, the right ADC, feeds information to the co-pilot's displays. This is the configuration used for the air data selection logic discussed in this section. When two air data computers are used, the left ADC output bus is normally connected to channel A of all engine FADEC systems, and the right ADC is normally connected to channel B of all systems. Channel A and B of each FADEC system cross-talk the data, so each FADEC system channel has both sets of information.

Most FADEC controllers receive aircraft ADC information and use it in the computation of engine ratings, such as one engine inoperative, takeoff, maximum continuous, climb, and go-around ratings. Engine ratings are a function of pressure altitude, freestream static or total air temperature, and Mach number or airspeed, but air data is also used in other logic functions as well. The use of ADC information by all EECs allows the engine controls to compute the same values for the engine ratings, and therefore, the thrust lever alignment across the engines is usually very good (at the same power setting). The concern is that use of the same data by multiple engines could affect multiple

5.3.1   (Continued):

engines if the data is faulty. To address this concern, independent engine sensors may be used to validate ADC information; if the engine sensors differ significantly from aircraft ADC information, the engine control normally reverts to its own sensors' values.

Air data may also be used in other logic functions, such as detecting faults in engine mounted sensors. The concern is the same as with the rating calculations in that the improper use of the aircraft air data information could invalidate the same sensor on multiple engines. This is an important consideration because the aircraft air data sensors may be affected differently than the equivalent sensors on the engine. As an example, aircraft mounted ADC sensors can be affected by angle-of-attack changes, while the engine inlet tends to straighten the airflow and reduces this effect.

Another important consideration for the use of air data by the engines is to ensure that the ratings computed by the engines and other aircraft LRU agree when all systems are normal. Due to the differences in tolerances and in the location of the sensors measuring the local air data information, the engines and the rating computer on the aircraft will calculate slightly different ratings. In the days of analog displays this was not much of an issue, as the individual systems calculated values that were close to each other, and the differences were smaller than the analog display resolution. With the advent of digital cockpit displays, in which ratings are shown to the resolution of two or three digits past the decimal, small differences become more obvious. It is possible that if the engines and thrust rating computer all used their own sensors, the individual sources would calculate rating values in which the differences would be greater than the thrust setting accuracy requirements. This raises the issue of which displayed numeric value is correct. The use of common, validated air data results in all the calculations being equal, thus eliminating this issue.

5.3.2   Other Aircraft Signals: In multi-engined aircraft, many of the signals sent to the FADEC system are signals that are common to more than one engine. If properly handled, this is quite acceptable, whether they are analog, discrete, or digital signals.

Many configurations in a digital system have digital signals that are dedicated to a FADEC system in a given engine location by virtue of location information in the digital word. The initial consideration may be that dedicated digital signals can be handled in the same manner as dedicated analog signals. However, in many (probably most) cases, the dedicated digital signals come from a common source. This might be a common computer and/or a common sensor. Examples of dedicated digital signals are power or thrust trim signals or engine air bleed demand signals that are sent by a thrust management computer to all engine control systems on a common digital data bus. Although these signals may be on the same data bus, the signals are dedicated to particular engine locations by virtue of an engine position code or some other means that may be embedded within the signal. Thus, each FADEC system is intended to read its own signals and ignore the others.

5.3.2   (Continued):

Signals of this type may be dedicated to each engine; however, failure modes in the sending computer could alter all signals, thereby affecting the control of more than one engine. Because of this, it is recommended that for fixed wing, multi-engined aircraft, the engine control allow only a limited authority for these signals. The recommended limit is approximately ±5% thrust in the takeoff mode, and larger values when outside the takeoff mode. Like the latching logic discussed in 4.2.1.5.2 and 4.2.1.6 above, all of the dedicated digital signals that come from a common source or computer, as well as those that affect thrust, should be latched at approximately 65 knots in the takeoff mode.

5.4   Air Data Sensor Considerations:

5.4.1   Aircraft Sensors: The following discussion provides information on some typical aircraft air data sensor configurations.

5.4.1.1   Air Data Ambient Pressure Probe and Probe Heat Configurations: Barometric altitude, as determined from the sensed value of ambient static pressure, is an important parameter to aircraft and engine performance and operations. The sensors used in most aircraft air data systems are quite accurate (0.25% of full scale or better). The normal static pressure inputs to the air data computers are from manifolded static ports on either side of the aircraft. A typical configuration is shown in Figure 15a. The manifolding is done to minimize the effects of aircraft yaw and angle-of-attack. The static ports may or may not be heated. A typical static port pickup is shown in Figure 15b. The static ports may also be located on the side of the aircraft's total pressure (pitot) probes. In these configurations, they are normally manifolded as well. Two sets of manifolds and pick-up ports enable the ADCs to receive independent manifolded static pressures signals. Some aircraft may provide a third source of ambient pressure. It may be only one port with the pneumatic signal feeding directly to a standby display. This display may provide an electrical signal output available to other users. If it does, it is an excellent source of an independent pressure altitude signal.

The static pressure ports are sometimes heated; not from a concern that the ports will ice-up in-flight, but to address the concern of condensation, which could cause water to flow down the body of the aircraft during overnight (static) conditions, accumulate in the pickup port(s) and freeze. In these situations, heat is used to de-ice the static port(s) after aircraft power up. If the static pressure pickup port locations are on the sides of the aircraft's total pressure probes, it is important to check that probe heat is on before using the static pressure value. In these cases if probe heat is not on, the front of the total pressure probe may ice-up, and the airflow around the static pressure ports may be disturbed. If the airflow is disturbed, there will be an error in the static pressure measurement.

FIGURE 15a - Typical Cross-Manifolded Body Static
Pressure Sensing Configuration

FIGURE 15b - Typical Body or Nacelle
Static Pressure Sensing Port

5.4.1.2   Air Data Total Temperature Probes and Sensors: Like the pressure altitude signal, TAT is an important parameter in setting the engine's thrust or power rating at a given flight condition.

Many aircraft have a single total temperature probe. In this case, the probe generally has two independent resistive elements, which are used to sense the total temperature and to supply the two air data computers with electrically independent signals. Since the signals come from a single probe, the two sensors are subject to common probe failures. Any foreign-object-damage (FOD) or probe contamination could cause both resistive elements in a single sensor to agree, but be incorrect. Some aircraft use separate probes for the two independent aircraft TAT signals. This, obviously, is a preferred situation when it comes to selecting a total temperature signal because it eliminates any immediate concern about common probe failures or malfunctions.

There are generally two types of TAT probes. Those that are aspirated, as shown in Figure 16, in which airflow from the aircraft's environmental system (ECS) is discharged from the aft end of the probe, causing freestream airflow to pass through the probe during static conditions, and those that are not aspirated. Aspirated probes, if not clogged from FOD, yield a reasonably accurate total temperature signal during static conditions. Probes that are not aspirated can be (depending on their location) significantly affected by solar radiation and should not be used during ground operation as the source of OAT used to establish the takeoff power setting. Figure 17 illustrates a typical non-aspirated TAT probe.

Whether aspirated or not, total temperature probes are usually **not** heated on the ground. The application of probe heat would cause a significant error in the sensed temperature. For aspirated probes, the aspiration is not strong enough to overpower the errors caused by heater power at static conditions. Total temperature probe heat is usually applied when the aircraft transitions to the air mode. Most air data computers will output a TAT signal that contains an indication of probe heat status: on or off.

Even with probe heat on, there have been reports that the aircraft's total temperature probe has iced-up temporarily in flight. Note, however, that for a well designed probe, the total percentage of these occurrences vs. total flight hours is quite small and only happens in very specific regions of the inter-tropic convergence zone. When it does occur, it is temporary with durations of minutes, not hours. Simply applying more probe heat has not proven successful. Too much heat affects signal accuracy during high altitude (low air density) and low speed conditions. Obviously, too little heat allows the probe to ice during heavy, but more ordinary icing conditions. Other than these peculiar icing conditions, the aircraft's TAT probes have proven to work quite well. When the probe ices, the signal tends to drift toward 0 deg. C, because the aft exit of the probe becomes restricted and an ice/water mixture tends to accumulate around the sensor(s). (See the reference listed in section 2.1.3 from Goodrich on total temperature probes for more detailed information.)

When redundancy for the aircraft's total temperature signal is desired - and this is always a good thing - separate aircraft total temperature probes should be used.
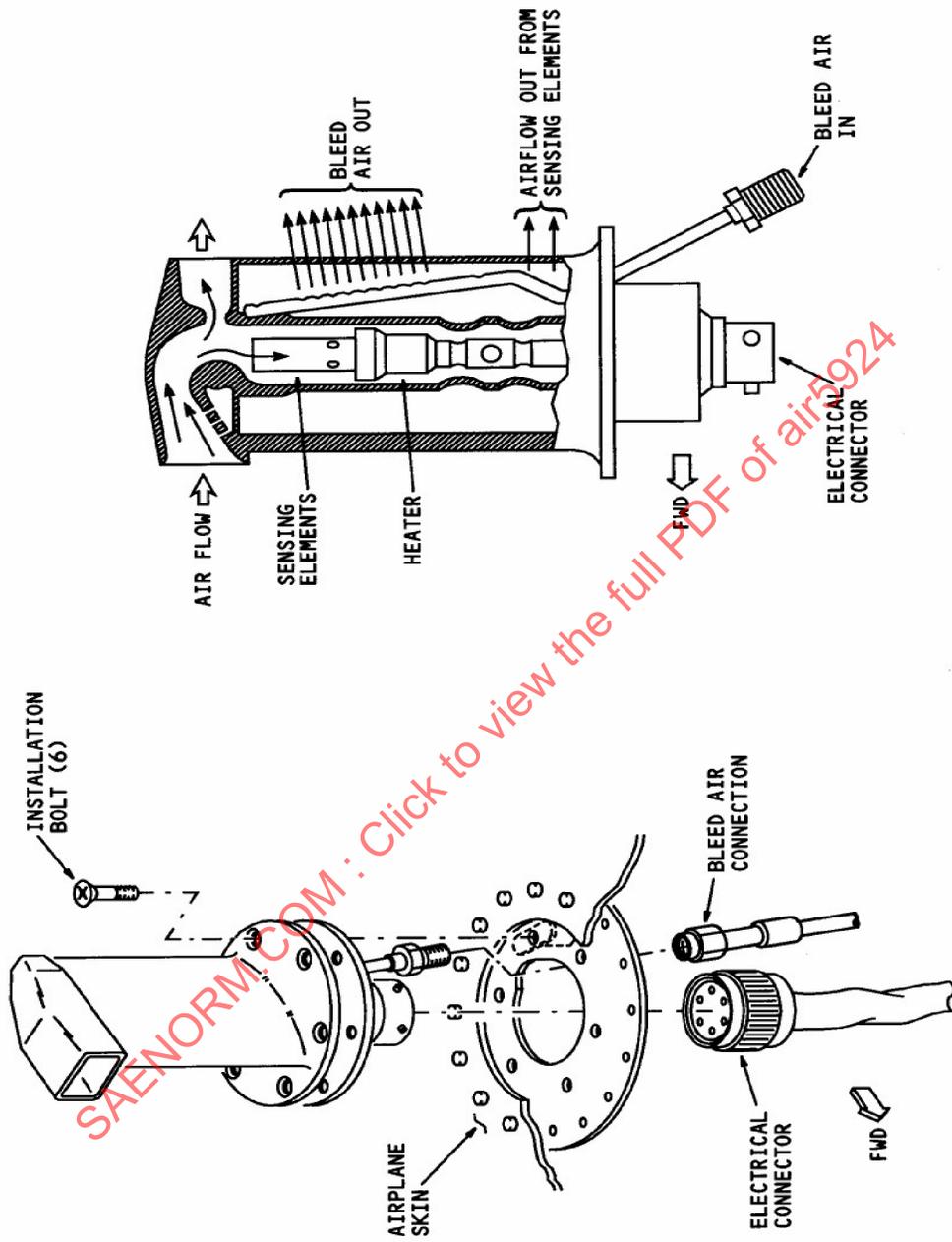
FIGURE 16 - Total Air Temperature Probe
(Courtesy of Rosemount Aerospace Inc. The external
shape of the TAT probe in the figure is a registered
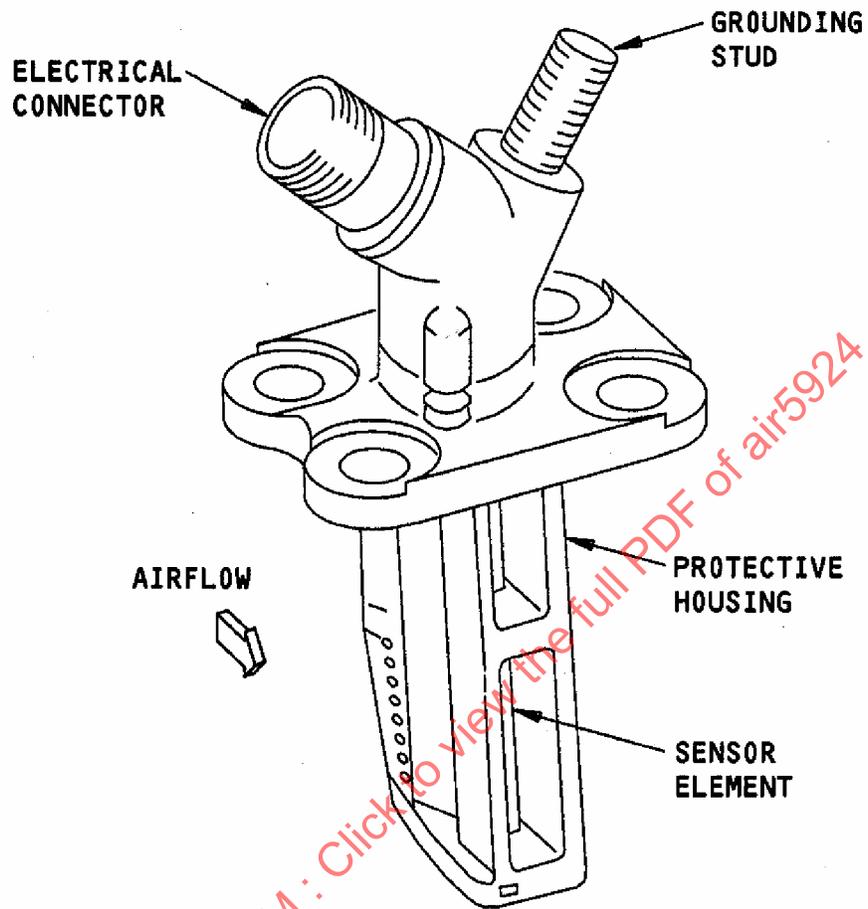trademark of Rosemount Aerospace Inc.)

FIGURE 17 - Non-Aspirated TAT Probe
(Courtesy of Rosemount Aerospace Inc. The external
shape of the TAT probe in the figure is a registered
trademark of Rosemount Aerospace Inc.)

5.4.1.3   Air Data Total Pressure Signals: The aircraft's total pressure sensor signal, in combination with the aircraft's static pressure signal, is used to compute the aircraft's airspeed or Mach number. The total pressure signals are generally obtained from two separate total pressure probes. The two probes feed independent pressure signals to the two separate air data computers. Modern aircraft total pressure probes are usually de-iced electrically. A low heat wattage is generally used during ground operation, and the probes transition to a high heat setting in-flight. Low heat is used during ground operation to achieve improved probe heater life. The total pressure signal transmitted from the ADCs usually includes a heat on indication. That signal may or may not indicate low or high heat operation. If the total pressure signal has two heat settings, and if the signal is to be used by the engine control to determine airspeed or Mach number, it is important to ascertain if the probe is on high heat in-flight. A probe on low heat can ice-up in heavy ice or moisture conditions in-flight. Since many aircraft may not have probe heat activated on the aircraft's total pressure probes when operating on external ground power, or the aircraft may not even be electrically powered when the first engine is started, a suitable waiting period should be used before the FADEC system attempts to validate and use the aircraft's total pressure signal. The waiting period can be similar to that used for validating engine P2, as discussed in 4.1.6.1 above.

In some applications, aircraft total pressure probe heat is turned on by the flight crew after engine start. In this type of system there has been a tendency to delay turning on the probe heat until the aircraft takes the active runway as a means to extend heater life. To prevent nuisance indications, consider delaying the heat check until engine power is set above levels required for taxi. Yet do not make the delay so long that detection of probe heat off occurs during the take-off roll, which could cause a potential for a RTO.

Some ADCs may not put total pressure on the ADC's digital output bus. These systems may provide dynamic pressure, Q, which is (P – Ps). During ground operating conditions, the measured total pressure may be less than the measured static pressure Ps during cross- and tail-wind conditions. Since Q is not allowed to be negative, Q may be broadcast as zero or as an invalid signal during these conditions. Assuming probe heat is present, a fairly long period, such as 30 seconds to a minute, should elapse before air data Q is declared to be unavailable, to allow transient environmental conditions to subside (assuming that Q is set to invalid during these conditions). If the FADEC system does not receive a valid Q signal after this time, air data Q should be declared to be unavailable. If the FADEC system receives a good Q signal during this countdown period, the timer should be reset. If the engine control does not have its own P2 probe, the engine manufacturer should request the installer to have total pressure output as a separate, individual signal on the ADC's output bus. This, or having Q be a valid signal of zero when measured P is less than measured Ps, will improve the robustness of the FADEC system's primary mode.

5.4.1.4   Air Data Airspeed and Mach Number Signals: Aircraft airspeed is very important to aircraft operations. Air data airspeed signals are generally available at airspeeds above 30 knots. Mach number usually does not become active until it exceeds approximately 0.10 to 0.15. The aircraft's airspeed (or Mach number) generally has a smaller effect on the engine's thrust or power rating than altitude or temperature, but is still quite important from thrust lapse rate considerations as discussed in 4.2.1.5).

5.4.2   Engine Sensor and Probe Configurations (For Determining Aircraft Air Data):

5.4.2.1   Engine Static Pressure Probe Configurations:

5.4.2.1.1   Internal Fan Case Pressure Measurements: Since ambient pressure has a reasonably strong influence on the engine's thrust or power rating, the engine control is assumed to have its own dedicated ambient pressure signal. Most FADEC systems are fan case mounted. If the fan case has a solid aft bulkhead or adequate ventilation to prevent pressure build up, so that the fan case pressures are isolated or adequately relieved from any increased pressures coming from the fan exit system and the thrust reverser system, then a simple opening on the side of the FADEC system feeding an inner cowl pressure signal to an internal FADEC system pressure sensor has proven adequate. A correction factor as a function of airspeed and altitude may be needed. Internal fan cowl pressures - in a fan case with a solid aft bulkhead - have not needed a correction for engine power setting, but it is always a possibility that should not be overlooked. A fan case located duct burst will obviously affect the FADEC system sensed static pressure.

5.4.2.1.2   External Engine Cowl Pressure Pickups: When a cascade-type reverser design is used and the fan case does not have a solid aft bulkhead, but uses seals to isolate the fan case compartment from the thrust reverser and fan exit nozzle system, it is recommended that the engine ambient pressure pickups for wing-mounted engines are located on the engine fan cowls in a manner similar to the way static ports are placed on the aircraft (that is, ports on either side of the nacelle). A picture of cowl-mounted static pressure pickups is shown in Figure 15b. For aircraft aft fuselage-mounted engines, the static pickups may be located on the aircraft body. Useful locations may be determined from wind-tunnel testing and validated during flight testing. These static pressure locations may require a correction factor, which is usually defined as a $\Delta P/P_{(sensed)}$, in which ΔP is $P_{(true\ ambient)} - P_{(sensed)}$. $\Delta P/P_{(sensed)}$ is usually defined as a function of Mach number. A correction with aircraft angle-of-attack may also be necessary, but this should be avoided, if possible, because aircraft angle-of-attack information is not always available. Small adjustments of the static port locations around the cowl will generally yield locations that are reasonably insensitive to angle-of-attack. The sensed pressure will probably be slightly sensitive to the pressure increase that occurs under the aircraft surfaces as the aircraft rotates and lifts off, but this increase has not been found to present significant difficulty.

5.4.2.2   Engine Total Temperature Configurations: Total or static freestream air temperature is also important to determining the engine power or thrust rating, and it is recommended that the engine control have its own dedicated total temperature sensor. The probe, which usually contains two sensors when two FADEC system channels are provided, is normally located in the engine intake. Typically, two types of probes have been used. The first type is a hooded probe, much like the aircraft's total temperature probe. If desired, this type of probe can be combined with a total pressure probe, so that one probe serves both purposes. The hooded type of TAT probe, whether combined with a total pressure probe or not, needs to be de-iced. In modern FADEC systems, this is usually done with electrical power.

If the total temperature probe does not incorporate the combined function of sensing total pressure, a vane type total temperature probe may be used. This type of probe does not incorporate a hood. It has a turning vane that directs the airflow against a resistive temperature element, like the probe shown in Figure 17. Figure 18 shows a typical combined T2/P2 probe.

Locating a TAT sensor aft of the fan is not recommended. There have been numerous attempts to locate a total temperature sensor there, in case a sensor ahead of the fan breaks off and damages the fan. When a sensor has been located behind the fan, a temperature rise correction term as a function of fan speed has been used to attempt to correct the sensor reading to freestream conditions. This is always difficult. Trying to compensate the fan temperature rise during engine transients and heavy moisture conditions has generally not been very accurate.

5.4.2.3   Engine Total Pressure Probes: Engines using EPR as their thrust setting parameter should have their own total pressure (P2) probe. In these cases, the total pressure probe is usually combined with the total temperature probe and mounted in the engine inlet. The location chosen for the probe is important. Thrust will be established on a Pexhaust (exhaust nozzle exit pressure measurement)/P2 parameter setting. If the inlet's airflow separates at high airflow or high angle of attack conditions, the sensed value of P2 will be lower than it should be. (This can be controlled somewhat by not allowing P2 to be less than Ps, the static pressure. Note: P2 should not be invalidated when this happens, unless P2 is out-of-range low. It can be set equal to Ps during these conditions.) Thus, the selected location for the P2 probe should be investigated to determine the recovery of the sensed P2. A P2 probe may yield a low pressure value due to inlet separation effects. This can happen at high inlet airflows during low airspeed conditions. Therefore, the sensed value of P2 may need a correction at such conditions. If a correction is needed, it is usually a function of aircraft Mach number and engine power setting. The inlet should be reasonably clean from 60 knots and up and should not experience any significant airflow separation with aircraft angle-of-attack (within the aircraft's operating envelope).
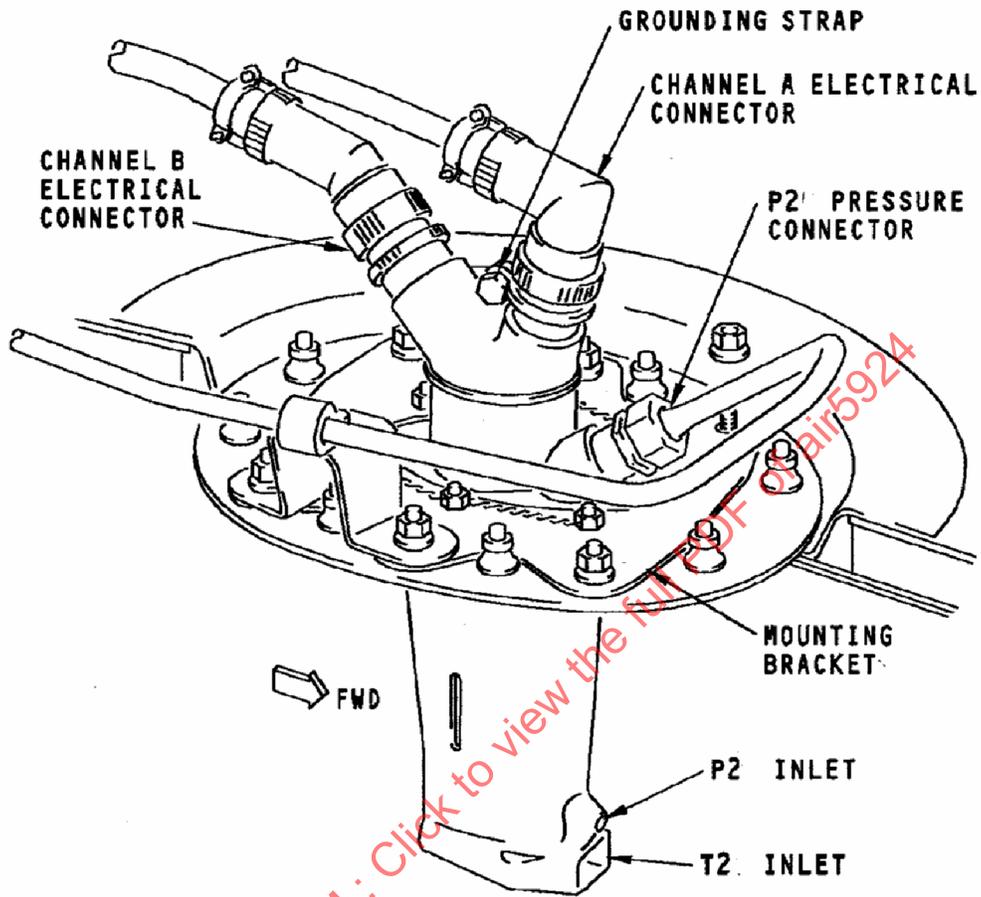
FIGURE 18 - Engine Inlet Mounted PT2/TT2 Probe
(Courtesy of Rosemount Aerospace Inc. The external
shape of the PT2/TT2 probe in the figure is a registered
trademark of Rosemount Aerospace Inc.)

5.4.2.3 (Continued):

Engines using N1 as the thrust setting parameter do not have to have a P2 probe. These engine controls would only use a P2 signal for the purposes of computing airspeed or Mach number, and if that signal has a reasonably small effect on the takeoff rating, the complication of having a P2 probe, along with its de-icing heater installation, is not considered worth the benefit of having a separate, engine dedicated airspeed signal. If a P2 probe is not provided with the engine, the ADCs will be the only sources of airspeed information for the EECs, and in this case, the control logic used in the EECs when the airspeed values differ should choose the airspeed signal that ensures thrust or default to a safe schedule, as discussed in 4.1.6.2.2.

5.4.2.4 Probe Heat Considerations: P2, Combined T2/P2, and Simple T2 Probes:

5.4.2.4.1 P2 and Combined P2/T2 Probes: Since probe heat usually requires considerable power (for example, 300 to 500 watts), probe heat is generally supplied by the aircraft. Combined P2/T2 probes (see Figure 18) generally require more anti-icing heat than P2 probes due to their increased surface area. It is recommended that heater power be turned on and off by the FADEC system during engine starting, at 2 or 3% N2 (or N3) below the engine's lowest idle speed or as a function of N1. The engine-mounted aircraft electrical generators may or may not be on-line by the time that N2 (or N3) is reached. A current sensor should be used to confirm heater power. This sensor could be aircraft-supplied, in which case a discrete signal indicating heater operation should be supplied to the FADEC system, or the sensor could be contained in the FADEC system's electronics unit itself. In either case, wait an appropriate period before performing the check on probe heat. This is similar to the discussion of validation engine P2 that is given in 4.1.6.1. If heater power is not confirmed after an appropriate wait period, it is recommended that for those engines using EPR as a thrust setting parameter, EPR be set to invalid and the control revert to an alternate mode. If heater power comes back after an extended outage period, it is acceptable to re-set EPR to valid if it is known that the probe will de-ice when power is reapplied; however, if the probe is iced, it may take a significant period of time for the probe to de-ice and start working properly, and this delay should be taken into account. The control should NOT automatically revert back to the EPR mode. (See 4.1.6.1.)

Concerning the T2 portion of combined P2/T2 probes: If the electrical heater circuit fails, the probe will most likely read total temperature, but the time constant of the probe becomes considerably longer in icing conditions. Therefore, if the heater circuit fails and the sensed total temperature is below 10 C, the engine control temperature selection logic must account for the significant increase in time delay that the sensor may have. (The FADEC system will not know if the probe is operating in icing conditions, or just cold clear air conditions when TAT is below 10 C.) If probe heat returns after being inoperative for a significant period of time (and a long time constant is being used because T2 has been below 10 °C for some time), approximately 2 to 5 minutes must elapse before changing from the use of a

5.4.2.4.1   (Continued):

long time constant to a short time constant, or other special logic that may be used to account for probe icing, so that the probe has a chance to de-ice. After loss of heat during icing conditions, the re-application of heat while still in icing conditions can be problematic. It must be proven that the probe will de-ice when heat is restored in icing conditions. Then the transient effects of re-establishment of heat must be accommodated. Depending on the probe design and the nature of the ice build-up, it is possible that the air trapped in the probe around the sense element will initially heat up and yield an erroneous temperature. The logic used to allow re-use of the T2 signal when heat is re-applied needs to properly account for these types of transient responses.

5.4.2.4.2   Simple T2 Probes: The simple T2 vane type of probe in many installations is recessed into an indented area, which acts as a separator for some of the water/ice that may be flowing into the inlet. These types of probes do ice up, but in many installations, no de-icing system is included. When operating in icing conditions, the probe time constant will be longer for this type of probe, as well.

5.5   FADEC System Air Data Selection Logic:

The air data selection logic should comply with the requirements of 14 CFR §33.28, as detailed in AC 33.28-1. In general, the regulation states that errors or faults in aircraft signals used by the EECs should not result in a thrust change - due to undetected faults - of greater than 3% when operating in the takeoff envelope. Outside the takeoff envelope, greater undetected thrust changes have been accepted.

The following logic is an approach to meeting the requirements of §33.28, but it is not the only method or logic that can be used. However, it has been shown to meet the requirements in previous applications. This section also provides guidance on an approach that can be used to evaluate a selection logic even though a specific manufacturer's implementation might differ in detail.

The objective here is to use air data signals - when they are correct - to determine the engine thrust ratings, so that all the thrust levers align throughout the operating envelope. The objective is NOT to replace engine information with air data information. It is also not acceptable to have a failure or malfunction in aircraft air data signals cause an unacceptable (see AC 33.28-1) change in power or thrust on any or all engines.

5.5.1　Ambient Pressure Selection Logic: Since the aircraft's pressure altitude signals from the left (L) and right (R) ADCs of transport aircraft are independent, the FADEC system selection of pressure altitude is generally straightforward.

Today's FADEC systems are configured with either one or two dedicated $P_{ambient}$ signals. Those FADEC systems with two sensors generally use either the one closest to the average of the ADC signals or an average of the two engine dedicated signals (if they are in reasonable agreement) to complete the logic described below.

It is acceptable to select the aircraft's ambient pressure (or pressure altitude) signal if the signal agrees with the engine's ambient pressure signal(s) - after the engine signal(s) have been corrected for position error. A detail to be considered is the system response when the tolerance between the ADC signals and the engine sensor is exceeded. The simplest approach is to make a step change to the engine sensor value as the difference between the ADC value and the engine sensor value exceeds the acceptable tolerance band. This approach results in a step change in thrust. As a response to a failure this is a generally acceptable response. However, if the step change is a result of aircraft maneuvers causing transient exceedences of the tolerance band, then the step change may not be acceptable.

The following describes a way of implementing a smooth transition between ADC data and engine data. This smooth transition logic is used in the discussion of the total temperature and total pressure selection logic, as well.

The design intent is to use ADC information whenever it agrees with engine sensor information. Therefore, the control is allowed to use ADC $P_{ambient}$(s) if they are within a given ΔP of the engine control system's ambient pressure signal. ΔP should be chosen so that a faulty aircraft $P_{ambient}$ signal will not cause a thrust change of more than 3% on all engines when operating in the takeoff envelope. (The ±3% thrust change requirements usually results in a ΔP of approximately 0.3 psid.) The selection priority of which air data ambient pressure signal to use (left ADC or right ADC) is usually given to the one that is closest to the engine's $P_{ambient}$ signal, but if the left ADC $P_{ambient}$ is within the ΔP criterion, give this ADC value preference so that all engines will compute maximum rated thrust using the same parameter(s). (If the left ADC $P_{ambient}$ is not within ΔP of the engine's but the right ADC is, use the right ADC's $P_{ambient}$.) Once the aircraft's closest $P_{ambient}$ signal becomes farther than the chosen ΔP away from the engine's signal, the engine needs to begin moving over to its own signal. To avoid a step change, this can be accomplished with a linear interpolation between the aircraft signal and the engine signal over an interval from ΔP to $2*\Delta P$, so that the engine is operating on its own signal when the difference between the aircraft and engine signals is double the chosen ΔP starting value. At this point, stay on the engine signal unless the difference becomes less than the double ΔP threshold. If the difference becomes less than the double ΔP threshold, start interpolating again. If the signal difference becomes less than ΔP, select the ADC's $P_{ambient}$ signal. This logic is referred to as smooth transition or fairing logic and is illustrated in Figure 19. This same logic can be used for total temperature selection and total pressure selection as well.

NOTE: When the ADC parameter value is incorrect, the maximum error will occur when the absolute value of the difference is Δ. Choose Δ so that the effect on engine thrust is $\leq 3\%$ Fn when operating in the takeoff envelope.

diff. = (eng. Control sensed - ADC value of parameter)

Interpolate between ADC value and engine sensed value when in this range.

Use engine sensed value when diff. > 2Δ

Use ADC value of parameter when - $\Delta \leq$ diff. $\leq \Delta$

Interpolate between ADC value and engine sensed value when in this range.

Use engine sensed value when diff. < -2Δ
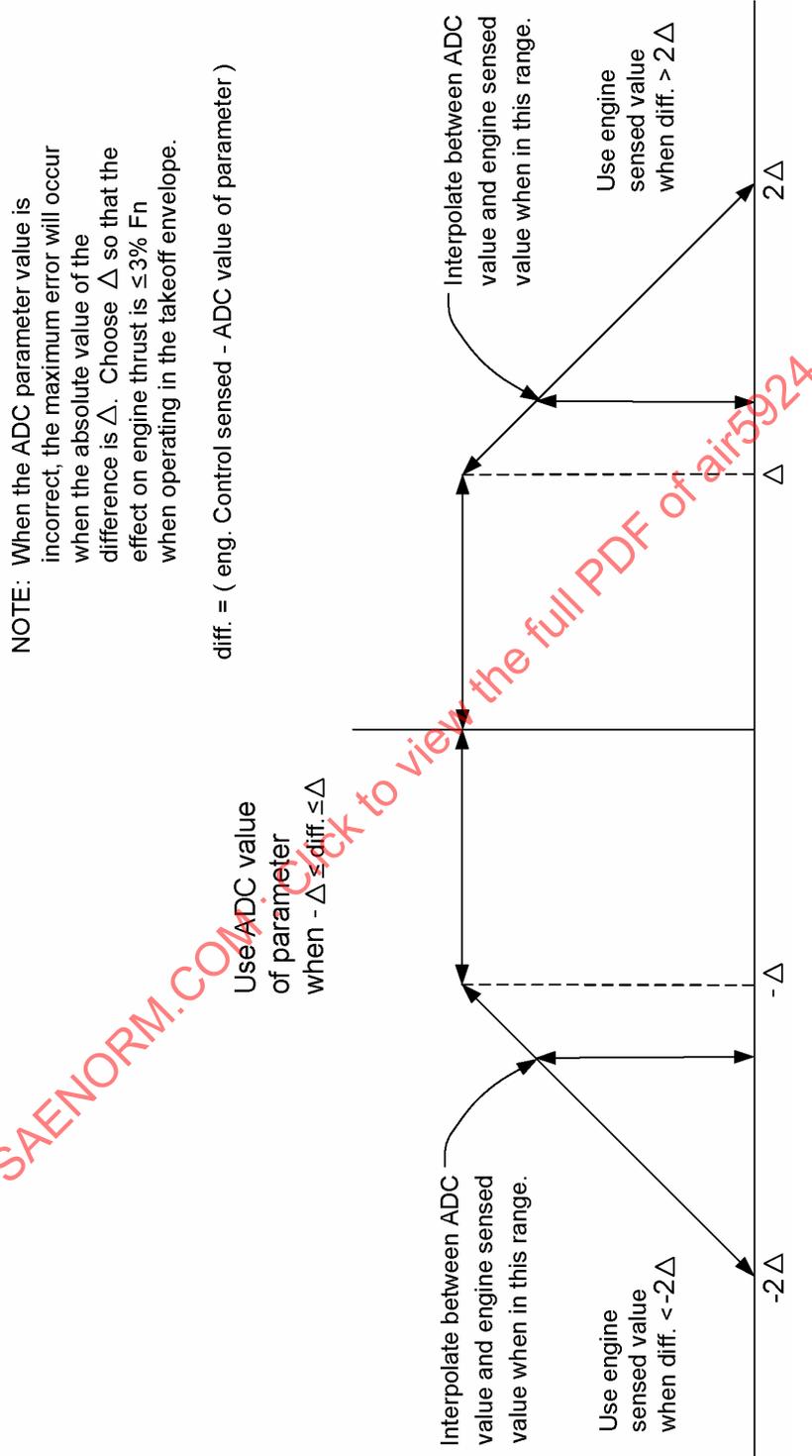
2Δ

Δ

$-\Delta$

-2Δ

FIGURE 19 - Typical FADEC Selection Logic for Static Pressure, Total Temperature, and Total Pressure Information

5.5.1 (Continued):

If the engine's ambient pressure signal suddenly goes out of range and the aircraft's ambient pressure signal is available and valid, use it for get home purposes. A valid FADEC system dedicated pressure signal is required for dispatch.

The following selection logic can be used to assess the health of the engine's remaining (that is, remaining if it started with two sensors and one has failed, or if the FADEC system only has one sensor) $P_{ambient}$ signal:

If the FADEC system has access to two aircraft ADC ambient pressure signals and

a. If the two aircraft ADC signals agree within approximately 0.1 psia, or so, and if necessary, at least one of their probe heats is on; and

b. If the engine's remaining $P_{ambient}$ signal differs from both of the ADC signals by more than $2*\Delta P$ psid or greater, then:

c. Declare the engine's $P_{ambient}$ signal failed for the remainder of the flight and use the aircraft's ADC ambient pressure signal to get home. Latch an engine $P_{ambient}$ fail message. Declare the control to be in a non-dispatchable configuration, and after having locked out the engine's $P_{ambient}$ signal, don't use it again in that flight.

If the two aircraft ADC $P_{ambients}$ do not agree within ΔP psia, various schemes may be used to determine what $P_{ambient}$ signal the engine control should use. Some examples are:

a. If the engine control has two dedicated $P_{ambient}$ sensors and those sensor values agree, use the average of the two engine sensor $P_{ambient}$ values as the selected $P_{ambient}$.

b. If only one engine $P_{ambient}$ sensor value is available and it agrees with one of the ADC's $P_{ambients}$ within ΔP, use that ADC $P_{ambient}$ as the selected signal.

c. If only one engine $P_{ambient}$ sensor value is available, and that signal and the two ADC signals all differ by more $2*\Delta P$, then either select the engine $P_{ambient}$ signal or go to a default value.

The above logic works well for determining engine $P_{ambient}$ sensor soft shifts and other malfunctions when the two ADC $P_{ambient}$ values agree and are correct, but there have been situations in which this logic may not work so well. These situations occur when the two aircraft ADC values agree and are wrong. Such situations have occurred during maintenance when the static ports were taped over, and the tape was not removed before returning the aircraft to service. If the above logic is used during such a situation, it is possible for all engines to end up operating on incorrect ADC values of $P_{ambient}$.

5.5.1   (Continued):

A solution to this might be to have the other engine(s) $P_{ambient}$ signal(s) available to all engine controls. This would appear to offer a significant benefit for fault isolation, detection and accommodation. If this were the case, the engine control system could revert to their own $P_{ambient}$ signals if the other engine $P_{ambient(s)}$ agree and differ from the ADC $P_{ambients}$. It is possible in this situation to have improper maintenance done to all engines at essentially the same time, which results in the engine $P_{ambients}$ agreeing, but being incorrect. The only mitigating factor in this scenario may be that to prevent common engine maintenance problems from occurring, the operators are continually encouraged to work on only one engine at a time between revenue flights.

There is one configuration logic that is often used to obtain engine-to-engine separation, and it has not appeared to offer any significant advantage to FADEC system or aircraft operation. This logic has been used on twin engine aircraft and is as follows: When the left and right $P_{ambients}$ disagree by a certain amount, have the left engine FADEC system only compare itself with the left ADC $P_{ambient}$, and the right engine FADEC system only compare itself with the right ADC $P_{ambient}$. While this achieves engine-to-engine separation, it immediately results in a configuration in which one engine FADEC system is selecting and using ADC information (because the engine and aircraft $P_{ambient}$ agree), but the other engine reverts to its own sensor values (because it disagrees with the aircraft $P_{ambient}$). Sometimes this results in thrust stagger and an associated flight crew squawk. Therefore, when the two ADC values disagree with each other, have the engine control use the one that's closest to its own value. This will keep both (all) engines operating on the correct ADC $P_{ambient}$ throughout the flight, and since the pilot's and co-pilot's altitude information will not agree in that flight, the ADC system will receive the required maintenance before the next flight.

Finally, when the engine control is not configured to receive information from the other engine(s) $P_{ambient(s)}$, and all three $P_{ambients}$ for one engine control system - the two ADC $P_{ambients}$ and the remaining engine $P_{ambient}$ - differ considerably and the engine's signal is in range, use the engine signal. This will maintain engine-to-engine separation.

A single FADEC system $P_{ambient}$ sensor has been considered acceptable because of the redundancy of independent aircraft altitude sensors. Due to this, some engine manufacturers have requested that the engine be allowed to operate full time on the aircraft's sensors and that any need for an engine static pressure sensor be deleted. However, even with aircraft designs in which electrical power is considered critical, conditions of total power loss for significant periods of time are expected to occur. That is why many fly-by-wire aircraft have dedicated power sources - engine located - to maintain power to those critical flight control functions. Therefore, it is considered inappropriate - at this time - to let a signal of such importance as pressure altitude be supplied by the aircraft systems for all engines. If it could be shown that the engine operates satisfactorily and meets all of its FAA Part 33 requirements without pressure altitude information, it would, of course, be a different matter. Obviously, if other sensors internal to the engine could supply the needed information, that would also be considered acceptable.

5.5.1 (Continued):

NOTE: The engine $P_{ambient}$ signal should be frozen following touch-down on the landing. The $P_{ambient}$ signal can become quite erratic during thrust reverser operation, and the selection logic will not work well.

5.5.2 Total Temperature Selection Logic: The total temperature selection logic is quite similar to the ambient pressure selection logic, but there are differences in the fault detection logic when only one TAT aircraft probe with two temperature sensors is used.

For aircraft systems with two separate aircraft mounted probes, the selection logic is essentially the same: Use ADC TAT if it agrees with engine T2 within approximately ΔT deg. deg. C (see Figure 19). The ΔT meets the ±3% thrust change requirement in the takeoff envelope generally around 3 C. Again, as with $P_{ambient}$, the LADC should be given preference, but the RADC TAT should be used if it is the only signal meeting the ΔT criterion. If neither ADC is within ΔT of engine T2, use the one that is closest to the engine and begin fairing to the engine sensor's value of T2 over an interval from ΔT to $2*\Delta T$, so that the engine is selecting its own T2 value when the difference between the closest ADC TAT and the engine's T2 is equal to or greater than $2*\Delta T$. This fairing logic is similar to that used for the $P_{ambient}$ selection, as discussed above.

When there are two separate aircraft probes, the failure detection logic is essentially the same as the $P_{ambient}$ failure logic given above; however, for the total temperature signal, the use of the selection logic is dependent on knowing when the aircraft's TAT signals can be used. Generally, the engine's T2 signals have a higher degree of accuracy if the engine is running. When mounted inside the engine inlet, the probe benefits greatly from inlet airflow, and even if the aircraft TAT probe is aspirated during ground operation, it can have significant heating errors from solar radiation. Therefore, in most applications, the following total temperature logic is only used in flight. Since the engine probe is generally equal to or better than the aircraft TAT probes, the malfunctioning condition that the logic is attempting to detect is a partially plugged engine T2 probe.

The logic is as follows:

If the FADEC system has access to two independent aircraft ADC TAT signals, and the aircraft is operating in a regime in which it is known that the aircraft TAT signals should be good, and

a. If the two aircraft signals agree within approximately ΔT C, and at least one of their probe heats is on, and

b. If the engine's T2 signal(s) differ from both of the ADCs by more than $2*\Delta T$, for a significant period of time, then

5.5.2   (Continued):

c. Declare the engine's T2 signals failed for the remainder of the flight and use the aircraft's ADC TAT signals to get home. Latch an engine T2 message. Declare the control to be in a non-dispatchable configuration, and after having locked out the engine's T2 signal, don't use it again in that flight.

If the two aircraft ADC TAT signals do not agree within ΔT C, various schemes can be used to determine what total temperature signal the engine control should use. Some examples are:

a. If the engine control has two separate, dedicated T2 probes and sensors and those sensor values agree, use the average of the engine sensor T2s as the selected TAT value.

b. If only one engine T2 probe with two sensors is used, and the two engine sensor values agree, but those values and both of the ADC TAT values all disagree by more than $2*\Delta T$, then either select the engine T2 signal or go to a default value.

When a single aircraft probe with two separate sensors for the two ADCs is used, aircraft TAT should probably not be used unless the engine's T2 sensors (there are usually two in the same engine probe) are both confirmed as failed. In single aircraft TAT probe configurations, the aircraft TAT signals are **NOT** independent. It is just as likely for the aircraft's TAT probe to be partially plugged as the engine's T2 probe. If both engine sensors are definitely confirmed as failed, use the average of the aircraft TAT if both are valid. Use the valid one if one is invalid, or use a default values as appropriate. This is another configuration in which having each engine's T2 signals be available to all engines would appear to offer a significant benefit for fault isolation, detection and accommodation. The benefit is that of being able to construct a more robust detection logic for determining faulty engine T2 signals.

Concerning default values: Use the corner point day temperature as a function of altitude for the ratings or transition to an alternate non-rating mode. Use a conservative T2 default with altitude that tends to close down the stator vanes, or place other variable geometry in a position that favors improved engine stability - even if the engine cannot make full thrust because it would hit an N2 or N3 redline limiter - with the altered geometry in place. If involved, use a conservative value of T2 for the engine's accel and decel fuel flow limits.

If the control uses T2 for rating determination only, and other internal engine sensor information is used to set the variable geometry and fuel limiting schedules (and any other important items), the control could be considered dispatchable with the engine's T2 sensors failed. If this is the case, it is assumed that the control would go to a non-rating mode when both T2 signals are considered failed, and the control does not have to send a no dispatch message to the aircraft. There should be a provision to put all other engines in the same mode so that the thrust levers align during power settings, even if the aircraft is equipped with separate autothrottle servos for each thrust lever.

5.5.2   (Continued):

Many inlet located temperature sensors indicate erroneous TAT when the engine is in reverse thrust during ground operations. One solution that could be considered is to freeze the engine's TAT value when reverse thrust is commanded on the ground.

5.5.3   Total Pressure Selection Logic: For an EPR controlled engine, it should be acceptable to use the selected total pressure signal, whether it is the engine control's dedicated signal or the air data total pressure signal, in the calculation, display, and control of EPR.

If the FADEC system has a total pressure probe - with one or two pressure sensors located within the FADEC system - the selection logic for the FADEC system total pressure signal is quite similar to that for ambient pressure and total temperature. Again, the agreement between the aircraft's total pressure signals and engine's P2 signal should be established so that the effect on all engines from faulty aircraft total pressure signals meets the ±3% criterion in the takeoff envelope.

In setting up FADEC system logic to detect engine P2 system faults, experience has shown that any tolerance test between air data total pressure and engine P2 should NOT be done when operating below a Mach number of approximately 0.2. The aircraft's signal can be quite erratic during ground operations and cross-wind conditions, and in previous FADEC system applications that have used tolerance checks between ADC total pressures and engine P2s to validate the FADEC system's signal, there have been numerous reports of false engine P2 fail messages latched by the FADEC system during ground operations. In flight, ADC total pressure is normally quite accurate. However, caution should be used before declaring the engine's P2 failed if it falls out of tolerance with aircraft P2. Several incidents have occurred in which the aircraft has been dispatched with the aircraft's total pressure probes inadvertently left capped by maintenance or with probe heat not selected on by the flight crew. In these cases, had the engine controls been set-up to select ADC total pressure when the two ADC total pressures agree and the engine's P2 differs, all engines would have reverted to the use of aircraft total pressure. This would have aggravated the situation. Therefore, it is important to make sure that probe heat is on the aircraft probes, and even if the two aircraft ADC total pressure signals agree, and they differ significantly from the engine's P2 signal, it is recommended that the engine control either: (1) follow its own P2 signal; or (2) set a fault flag on its own signal and transition to the soft reversionary mode. If the engine control's P2 signal is faulty, the flight crew will note it in the first of these options via different values (between the engines) in the other engine parameters. In the second option, the flight crew will note the mode transition and place the control on the hard reversionary mode. This mode is generally independent of freestream total pressure. As with the engine's $P_{ambient}$ and T2 signals, it would appear to be beneficial to all FADEC systems to have each engine's P2 signals be available to all other engines for fault isolation, detection, and accommodation. This would allow a more robust detection of faulty or malfunctioning engine P2 signals to be constructed.

5.5.4   Airspeed and Mach Number Selection Logic: Airspeed (or Mach number) generally has a small impact on engine ratings in the takeoff envelope. It can be significant at higher speed conditions, such as at Mach 0.6 and above, but these are generally considered to be higher altitude conditions. For engines that incorporate a P2 probe, the calculation of airspeed from the FADEC system's selected static and total pressure signals is straightforward.

For engines that do not have a P2 probe, compare the two ADC Mach number signals and, if they agree within 0.05 Mach, use the average. When in flight, make sure that at least one of the aircraft total pressure probes has high heat on and allow sufficient time after the ground/air transition of the aircraft's weight-on-wheels (WOW) or air/ground transition detection system to apply high power to the aircraft's total pressure probes before checking for the high heat signal. If high heat does not come on, it is suggested that the control default to a conservative Mach number schedule as a function of altitude. For large turbine engine aircraft, a suggested schedule is Mach 0.2 from 2000 feet altitude to 1500 feet above the highest altitude certified for takeoff. This protects go-around performance. From 1500 feet above the highest certified takeoff altitude, the default Mach number schedule should reflect the engine-out, max-continuous-power, drift-down-speed-schedule for the intended aircraft. Obviously, this ensures that the engines will deliver maximum continuous thrust or power during engine out conditions. This portion of the schedule only has to go to the highest obstacle clearance altitude along the intended flight path. For aircraft flying over mountainous regions, this can be as high as 21,000 feet. From that altitude, the schedule can fare over to the normal Mach number cruise schedule as a function of altitude. If the Mach numbers differ by more than 0.05 for several seconds, for example 10 seconds or more, hold the last good average value while the clock is running, and then transition to the default schedule. The control should latch that condition and not shift back to using ADC Mach number, even if the ADC Mach numbers were to then agree within 0.05. Doing this could cause the thrust of all engines to abruptly go up or down during the transition. In general practice, the Mach number values from the two ADC should never differ by more than 0.05 during normal operation.

5.5.4.1.1   Thrust Management Computer (TMC) Selection of TAT: As many aircraft have a common TAT probe with two elements, both elements will agree, but be incorrect if the probe becomes blocked due to icing or FOD. Indeed, many TMCs do not even cross-compare the two TAT values from the left and right ADCs to see if they disagree. They simply use the left ADC TAT and, if it becomes invalid, which may be based on a gross failure such as the signal going out of range, they switch to using the right ADC TAT. As a result, there have been several reported incidents of incorrect TAT signals causing incorrect engine rating information to be displayed to the flight crew. Based on this experience, it is strongly recommended that the aircraft's TMC compare multiple sources of TAT before selecting a valid TAT for use in the calculation of engine ratings.

5.5.4.1.1   (Continued):

If the two ADC TAT signals agree within ΔT of each other (for example, approximately 3 °C), but they differ significantly from the engine T2 signals and the engine T2's agree with each other, the aircraft TAT probe is probably partially plugged. This is a situation that can occur more frequently on an aircraft that is configured to use one probe. If the single aircraft probe is partially plugged, the two TAT signals will probably be higher than true TAT, but they may not be out-of-range. If the aircraft computer computing thrust uses this signal, the calculated thrust rating will probably be lower than it should be.

Aircraft that are not equipped with an aspirated TAT probe are not usually set up to have the TMC use the engine's T2 probe for TAT information to determine the takeoff power setting. In these aircraft, the flight crew has to either look up the rating in a power setting chart based on altitude, tower OAT, gross weight, runway length, and flap setting, or manually input a TAT to the TMC, so the TMC can look up the rating. Because of these situations and other conditions, it is recommended to program the EECs to be able to achieve at least 0.5 to 1.5% more than the full takeoff rated thrust at the full forward thrust position. (See 4.2.1.3.) During manual operations, the flight crew (during pre-flight) may input a reported tower TAT that is correct at the time, but because of the time lag involved, it is colder than actual runway conditions when the actual takeoff commences. If the engine cannot achieve the target set by the flight crew, the crew may elect to abort the takeoff. A little headroom provided by the FADEC system addresses this concern. Aborted takeoffs caused by small temperature differences during hot day operating conditions should be avoided.

Future aircraft thrust management systems may use the FADEC system to compute the ratings. This will eliminate some of the differences in the computation of the rating in today's systems. However, as some of those calculations may have to be completed before engine start, the aircraft systems will probably have to send TAT information to the control to obtain the calculated information (because the engine's T2 signal is probably not valid when the engine is not running). Therefore, the same situation as that described in the paragraph above could occur.

6.   INSTRUMENTATION AND FLIGHT-CREW INTERFACES:

6.1   Aircraft Located Engine Displays and Switches:

It is not the intent of this report to describe all of the propulsion displays provided or used in an aircraft. The general display requirements are given in the appropriate sections of the CFR, such as §§23.1305 and 25.1305. The intent is to mention a few displays in which standardization would be helpful and some indicators that are needed and not specified in §§23.1305 and 25.1305.

Figure 20 illustrates a typical propulsion system flight deck display.

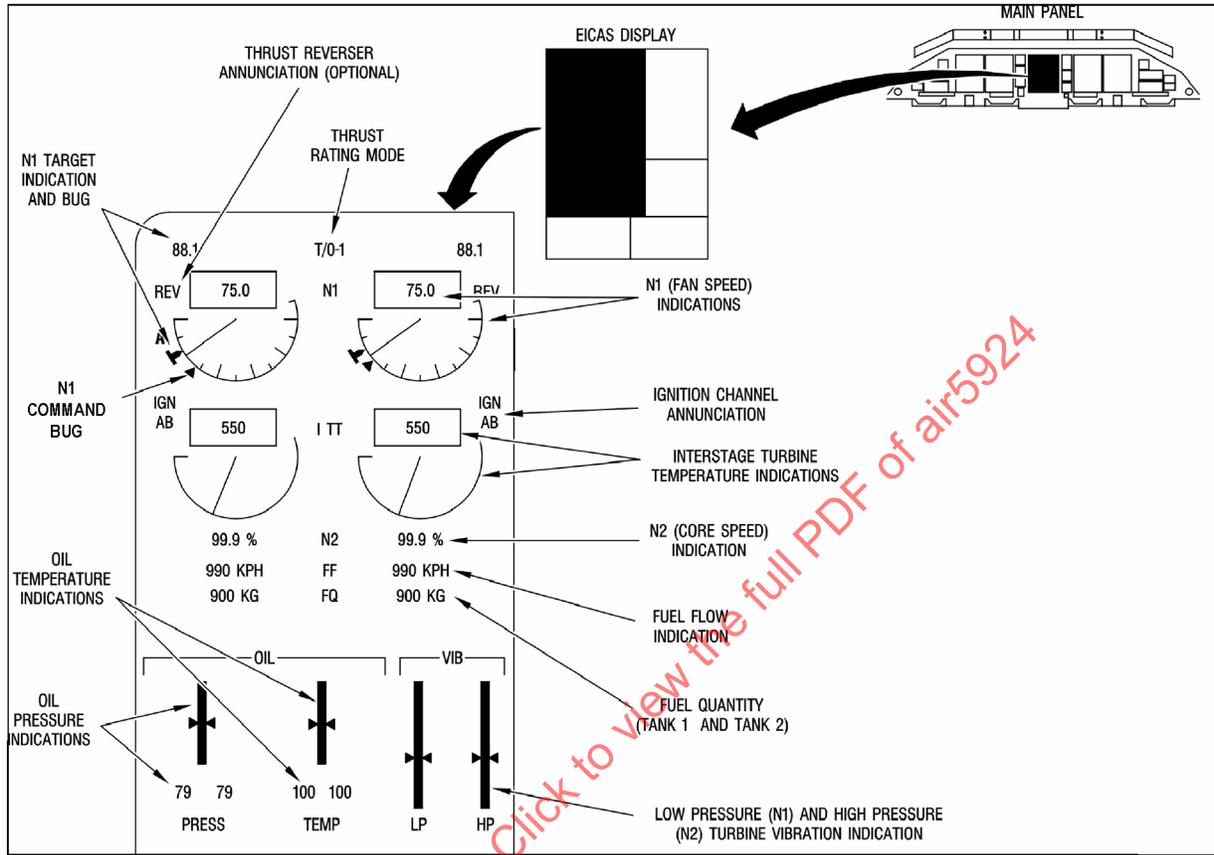FIGURE 20 - Typical Presentation of Powerplant Data

6.1.1 Thrust Setting Parameter Display - Primary Mode of Operation: There are several different configurations for the display of thrust setting parameter. Whether the display is a circular or a vertical tape type of display, it is desirable for the display to show the following information:

a. The actual value of the parameter;

b. The control system (instantaneous) commanded value of the parameter;

c. The value that the FADEC system would command if the thrust or power lever were advanced to the maximum forward position;

d. The target value for the parameter as determined by a thrust, flight management computer, or FADEC system; and

e. Any redline or maximum certified limit that is required to be observed by the flight crew, such as a rotor speed redline.

Figure 21 depicts a typical thrust setting display showing this information. The control system commanded value of the parameter is quite helpful to the flight crews because it moves with thrust lever position and shows the value being commanded of the engine when it reaches steady state operation. The maximum value to which the engine would operate, shown in Figure 21 as the max bar at the top of the display, is also informative. If, due to some malfunction, the max bar is the target bug, which is provided by the thrust or flight management computer, the flight crew would know that something is wrong, because the display is indicating that the engine control is not capable of achieving the target value at the full forward thrust lever position. The flight crew would not initiate a takeoff under such conditions. Note that the max bar does not represent the parameter value for maximum rated engine thrust at that flight condition. It merely represents the parameter value commanded at full thrust lever position. This should always be greater than the maximum rated thrust value. (See 3.2.4.2.3 for more discussion on thrust vs. thrust or power lever position.)

At steady state conditions, the commanded value of the thrust setting parameter should be equal to the actual value. A standing difference between the two would indicate abnormal control system or engine operation. For example, as the fuel pump deteriorates, the pump may not be able to deliver the fuel flow needed to achieve the commanded value of the thrust setting parameter. Such a situation would be squawked by the flight crew and investigated and corrected by maintenance.

If it is considered that the maximum rated value of thrust is more important than the value to which the engine would run at full thrust, let the max bar be driven by the TMC and let the circular arc showing the outline of the display stop at the maximum value the engine control would command at full thrust. This is shown in Figure 21. This display format is fine, but it becomes a bit more difficult to determine if the engine is capable of achieving the target thrust at full thrust lever position, because the ending of the circular arc is not as apparent as the max bar.

A "standing" command sector shows a shortfall condition.

Max Bar

Command Sector:
Area
Between
Lines is
Generally
Shaded

Actual Value

Target Bug

Command
Indicator

Actual
Indicator

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FIGURE 21 - Typical FADEC Engine Thrust Display

6.1.1 (Continued):

Since the control is generally designed not to govern the engine to EPR at idle, logic is usually added to the displayed EPR (or N1) command signal to eliminate the disagreement between the command and actual values of EPR (or N1) at idle condition. Simple logic, such as the following, has proven to be adequate.

IF (EPRcmd.GT.1.15)   EPRcmd-display = EPRcmd
IF[(EPRcmd.LE.1.15).and.(EPRactual.GT.1.15)]   EPRcmd-display = 1.15
IF[(EPRcmd.LE.1.15).and.(EPRactual.LE.1.15)]   EPRcmd-display = EPRactual

The above logic assumes that the engine is capable of being close loop EPR controlled at EPRs above 1.15 at all flight conditions. If not, use a threshold value that is. The threshold value can be a function of altitude and Mach number if desired.

For an N1 rated and controlled engine, which operates on N2 or some other parameter, such as a minimum bleed delivery pressure at idle, the logic for the display might be:

IF (N1cmd.GT.40%)   N1cmd-display = N1cmd
IF[(N1cmd.LE.40%).and.(N1actual.GT.40%)]   N1cmd-display = 40%
IF[(N1cmd.LE.40%).and.(N1actual.LE.40%)]   N1cmd-display = N1actual

The above, of course, assumes that the engine will always be in N1 control at N1 rotor speeds above 40% physical speed. If not, the logic needs to contain a number at which the engine is under N1 control.

6.1.2 Thrust Setting Parameter Display - Backup Mode of Operation: The thrust setting display in the backup mode can be very similar in function to that shown in the primary mode. If the primary mode uses EPR as the power setting parameter, the backup mode will probably be fan speed, N1. In past applications, the EPR display for the primary mode of control had a max bar at the full scale position of the display that represented the FADEC system full thrust commanded value for EPR. When the control reverts to the soft reversion mode, or the pilot selects the backup mode, the EPR display blanks and shows no information, and the N1 display becomes the power setting display. This display has the same indicators on it as the primary display, but in this case, the display also shows the redline value of N1. Also, it was felt that using the max bar to show the maximum value to which the engine would be controlled at full thrust would not be especially useful, because generally, this value was too far above the maximum rating to be of much value. Therefore, although the max bar on the EPR display in the primary mode represents the full thrust value of FADEC system commanded EPR, in the backup mode, the max bar on the N1 display is driven by the aircraft's TMC and shows the N1 for the maximum rated value of thrust at that flight condition.

6.1.2   (Continued):

Changing the meaning of the max bar from one mode of engine control to another is not considered to be good practice, even though the display parameter changes from EPR to N1 when the control reverts to the backup mode. For N1 controlled engines, the thrust setting display would be N1 for both modes. If it is desired to have the max bar represent the maximum certified thrust value (at that flight condition) in the backup mode, it is recommended that max bar have this same meaning in the primary mode, and that the end of the circular arc represent the maximum value of N1 commanded by the FADEC system at full thrust lever position.

6.1.3   Primary Mode Fail and Backup Mode Active Indications, and Backup Mode Command Switches: There generally is no indication that the control is operating in the primary mode. It is assumed that when operating normally, the control is in the primary mode and no special indication of that is needed. It is recommended that the aircraft have a distinct primary mode fail indication to notify the flight crew of a FADEC system primary mode failure, and that a separate indicator is used to show that the control is in the backup mode. One method to accomplish this goal is to use two indicator lights, as described below:

- If both indicators are off, the control is in the primary mode.

- If the primary mode fail indicator is on and the backup mode active is off, the control is in the soft reversionary mode and is indicating that it is not capable of primary mode operation.

- If the primary mode fail indicator is off and the backup mode active is on, the control is in the backup mode, but the FADEC system believes that it is has the necessary resources to operate in the primary mode.

- If both indicators are on, the control is in the backup mode. It also shows that the control is indicating that it is not capable of operating in the primary mode.

These displays can be driven solely by the FADEC system or not, depending on what the aircraft manufacturer wants displayed when the aircraft is electrically powered but the engines are not running, and what the aircraft manufacturer wants displayed during in-flight shutdowns, with the fuel switch on and off.

It is recommended that there is a separate switch - one for each engine - that when activated, commands the control to enter the backup mode. De-selecting the switch commands the control, if the resources are available, to leave the backup mode and re-enter the primary mode. Experience indicates that these switches should **not** be located near the fuel on/off switches from a human factors standpoint, to prevent inadvertent engine shutdown.

6.2   Display of Information Concerning FADEC System Faults and Dispatch:

There have been several examples of the in-flight display of information concerning FADEC system fault conditions and dispatchability, which have caused some difficulties for flight crews. A rather severe example, which has occurred in service, was the showing of a FADEC system channel fail message when a channel was not using aircraft air data information because it disagreed with the channel's own sensor inputs. In this case, the aircraft in question had some difficulties with aircraft air data and both channels on a twin-engine aircraft reverted to operating on their own sensors. This caused failure messages for all four channels to be shown to the flight crews, virtually simultaneously. In some of these examples, the flight crew believed that all engine controls had failed, and they diverted the flight and landed at the nearest suitable airport.

Cases such as these have raised the important issue of what messages should be shown to the flight crews, and when should they be shown. In general:

- DO show messages to the flight crew when they need the information to understand abnormal FADEC system operation and the effects on engine operation, and may need to take action.

- DO NOT show messages concerning minor failures, when system operation is essentially unchanged and there is nothing for the flight crew to do. A brief listing of some of the messages that are acceptable, and those that are not, along with the expected effect on engine operation, the crew action, and when it is recommended that the message be inhibited, is given below.

The following examples are based on lessons learned and have been considered useful. They are meant to be generalizations and the recommendations may not apply to a specific installation. Note that the acceptability of any of the following messages must be dependent on and consistent with the flight deck display philosophy being used on the aircraft.

- E1(2,3,4) CONTROL FAIL

  Show the engine control fail message **only when absolutely necessary** (for example, cannot control fuel flow or variable geometry).

  - Effect on Engine: Engine Thrust/ Power Modulation may not be possible. Engine may operate erratically. Engine will probably shutdown.

  - Crew Action: Monitor engine operation, secure engine if required.

  - Inhibit: Takeoff (V1 - x kts. to 400 feet AGL)

6.2   (Continued):

- E1(2,3,4) RPM LIMIT (or, just LIMITER)

  Engine is at steady state power and operating on an RPM (or other) limiter.

  - Effect on Engine: Engine is not making commanded thrust.

  - Crew Action: None needed. This just provides crew awareness.

  - Inhibit: Takeoff (V1 – x kts. to 400 feet AGL).

- E1(2,3,4) SUB-IDLE

  Engine operating below the selected idle

  - Effect on Engine: Engine operating below the selected idle and the control cannot recover the engine.

  - Crew Action: Shut down the engine and restart.

  - Inhibit: Takeoff (V1 - x kts. to 400 feet AGL)

- E1(2,3,4) NO DISPATCH

  Control is in a no dispatch configuration. Refer to 7.1.

- Effect on Engine: Generally none.

- Crew Action: None.

- Inhibits: In-flight & on-ground at speeds above V1.

  (Showing this message in-flight may only distract the flight crew.)

6.2   (Continued):

- E1(2,3,4) SHORT DISPATCH

   Control is in a short term (allowable, but time-limited) dispatch configuration. Refer to 7.1.

   - Effect on Engine: Generally none.

   - Crew Action: None.

   - Inhibits: In-flight & on-ground at speeds above V1.

      (Showing this message in-flight may only distract the flight crew.)

- E1(2,3,4) IDLE

   Control is holding engine thrust to idle, probably because the reverser is not stowed or all thrust lever position information has been lost.

   Message may not be needed if an "E1(2,3,4) REV UNSTOW" message is incorporated and TLA FAIL is used.

   - Effect on Engine: Thrust modulation not possible.

   - Crew Action: Usually Information only, secure engine as necessary.

   - Inhibits: Maybe takeoff (V1 - x kts. to 400 feet AGL).

- E1(2,3,4) AUTO-START OFF

   Autostart has been selected off.

   - Effect on Engine: None, control will not turn on fuel at pre-programmed N2. Fuel flow will begin when selected on. Control may not monitor EGT during start.

   - Crew Action: Turn on fuel at appropriate core speed, monitor engine starting.

   - Inhibited: Inflight (if control has auto ignition in-flight) and on-ground at engine core speeds above idle - x percent.

6.2   (Continued):

- E1(2,3,4) CONTROL MODE

  Control is operating in the backup or alternate control mode.

  - Effect on Engine: Usually none.

  - Crew Action: Awareness, engine may be over-boosted at full thrust lever position.

  - Inhibits: Takeoff (V1 - x kts. to 400 feet AGL) and Landing (less than 200 feet AGL to x sec. after WOW).

- E1(2,3,4) THRUST (or LOW N1 or LOW EPR)

  Many installers are showing a thrust-related message to the flight crews if the engine does not achieve the commanded value of the thrust setting parameter.

  - Effect on Engine: Engine is not achieving commanded value of thrust.

  - Crew Action: Generally none. Usually, there is nothing the crew can do (except abort a Takeoff).

  - Inhibits: Takeoff (V1 –x kts to 400 feet).

- E1(2,3,4) FADEC OVERTEMP

  FADEC detected internal temperatures above allowed temperature.

  - Effect on Engine: Abnormal engine operation may occur.

  - Crew Action: Turn off bleed and/or anti-ice system, depending on the possible source of heat that may be affecting the FADEC. Perform an engine shutdown in case of abnormal engine operation.

  - Inhibits: Takeoff (V1 –x kts. to 400 feet).

  This is an often discussed message, and there are many pros and cons to such a message. Currently, the few installations that show these types of messages have experienced a higher than normal number of aborted takeoffs, caused by the inappropriate showing of the message when the condition was really minor. This does not mean that such a message might not be valuable to the flight crew in other flight conditions. In general, the data seems to show that when to show this type of message needs more development work and a better validation of the value of the message.