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EVALUATION OF ADVANCED DISPLAYS FOR ENGINE MONITORING AND CONTROL

L. G. Summers

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TRANSPORT AIRCRAFT UNIT
Long Beach, Callifornia 90846

Contract NAS1-18028
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Space Administration

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FOREWORD

This study was Task Assignment 16, Engine Monitoring and Control System Display Study, which was part of the Advanced Transport Operating Systems Program sponsored by the National Aeronautics and Space Administration Langley Research Center under contract NAS1-18028. The NASA contract technical manager was Mr. Terry Abbott.

Special thanks go to the pilots who participated in this program. These pilots included the Air Lines Pilot Association (ALPA) pilots, the pilots from the Los Angles Federal Aviation Administration Certification Office, and the Douglas Aircraft engineering test pilot. Thanks go to the assistance of Mr. Bill Phaneuf of ALPA for recruiting the ALPA pilots.

Dr. Leland Summers of the Crew Systems Technology group was the principal investigator. He was ably assisted by Mr. John Zich of Crew Systems Technology, Captain Don Alexander of Flight Operations, Mr. Darrin Curry of Propulsion Subsystems Technology, and Mr. Pete Hammontre, Ms. Cathy Yan, Mr. Steve Roberts and Mr. John Schaefer of Crew Station Simulation Laboratory.

SUMMARY

The objective of the study was to assess the relative effectiveness of two advanced display concepts for monitoring engine performance for commercial transport aircraft. The concepts were the Engine Monitoring and Control System (E-MACS) display developed by NASA Langley and a display by exception design. Both of these concepts were based on the philosophy of providing information that is directly related to the pilot's task. Both concepts used a normalized thrust display. In addition, E-MACS used column deviation indicators, i.e., the difference between the actual parameter value and the value predicted by an engine model, for engine health monitoring; while the Display by Exception displayed the engine parameters if the automated system detected a difference between the actual and the predicted values.

An engineering cockpit simulator was used for the study and the two display concepts were compared with current generation engine displays. Twelve pilots participated in the evaluation. Nine pilots were recruited from the Air Lines Pilot Association (ALPA), two were federal Aviation Administration (FAA) certification pilots and one was a Douglas engineering test pilot. Each pilot flew from the left seat and the test conductor sat in the right seat and acted as the first officer. The test conductor would not initiate or inform the subject pilot of any engine related problems but he would respond to instructions from the subject pilot.

The experimental treatment conditions were the display concepts, the fault conditions and manual versus autothrottles. A repeated measures, fractional factorial experimental design was used. The pilots flew each display concept in a block of trials. A trial consisted of (1) engine start, (2) takeoff, (3) initial climb, and (4) transition to cruise. Each flight phase had two engine faults associated with it, resulting in a total of eight engine faults. One of the faults occurred within each trial and the pilots were required to recognize the fault and take corrective action. The pilots flew the simulator with manual controls, the flight director, and either manual or autothrottles. The objective performance measures were the number of detections, the detection time, the time to initiate the response, recognition errors, and primary flight task activity and performance. The subjective measures were perceived workload and pilot comments.

The results showed that the advanced display concepts had shorter detection and response times. There were no differences in any of the results between manual and autothrottles. There were no effects upon perceived workload or performance on the primary flight task. The majority of pilots preferred the advanced displays and thought they were operationally acceptable. Certification of these concepts depends on the validation of the engine model. Recommendations are made to improve both the E-MACS and the display by exception display formats.

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ABBREVIATIONS

AGL	Above Ground Level
ALPA	Air Lines Pilots Associatioon
ANOVA	Analysis of Variance
ASRS	Aviation Safety Reporting System
C	Centigrade
CRT	Cathode Ray Tube
DC	Direct Current
DBE	Display by Exception
EAD	Engine and Alert Display
ECU	Electronic Control Unit
EGT	Exhaust Gas Temperature
E-MACS	Engine Monitoring and Control System
EMADS	Engine Monitoring and Display System
EPR	Engine Pressure Ratio
FAA	Fedearal Aviation Administartion
FADEC	Full Authority Digital Engine Control
FMS	Flight Management System
KIAS	Knots Indicated Airspeed
N1	Low Pressure Compressor Rotation Speed
N2	High Pressure Compressor Rotation Speed
NASA	National Aeronautics and Space Administration
PFD	Primary flight Display
PPH	Pounds per Hour
SSD	System Status Display
TRA	Throttle Resolver Angle

INTRODUCTION

Current aircraft engine instruments provide data from individual sensors that are used to set engine thrust and monitor engine performance and health. Advances in technology have developed (1) fly-by-wire engine control systems where there is no longer a mechanical link between the throttle and the fuel lever angles and (2) electronic display media for the presentation of the engine parameters to the flight crew. However, these advances have not taken advantage of digital computation and the electronic display media to provide the flight crew with a direct readout of engine thrust or to assist them in monitoring the engine health and performing corrective action. These capabilities would lower the flight crew's workload and reduce the possibility of pilot error.

Past studies have developed potential engine control and monitoring displays that used digital processing technology. In 1979, Douglas Aircraft and General Electric developed a concept called an Engine Monitoring and Display System (EMADS) (Reference 1). This system was based on two concepts; (1) a continuous display for thrust monitoring and (2) display by exception, that is, the display of information when it is required, for engine health monitoring. More recently, the Engine Monitoring and Control System (E-MACS) was developed at NASA Langley Research Center (Reference 2). This system was developed on a design philosophy that was oriented toward providing information that is more directly related to the pilot's task than conventional engine instruments. The objective of the current study was to assess the technology readiness of advance display concepts including the E-MACS concept. The methodology was to compare the advance concepts with current generation engine displays. An emulation of the MD-11 tape instruments for GE engines were used for the comparison. These were used in combination with a simulation of General Electric CF6-80C2 engine with a Full Authority Digital Engine Control (FADEC) system.

FULL AUTHORITY DIGITAL ENGINE CONTROL (FADEC)

The FADEC system is a computer based electronic engine control system that provides engine control and information processing. It consists of an Electronic Control Unit (ECU), a hydra-mechanical unit, engine sensors and other subsystems. The FADEC system reduces the pilot's workload by continuously controlling engine thrust and increases flight safety by monitoring the engine sensors.

The ECU regulates fuel flow in order to maintain constant thrust at a given throttle position. Engine fuel flow is regulated to establish the N1 required. The ECU calculates thrust ratings based on inlet temperature, altitude and Mach number. Ratings are calculated for takeoff, maximum continuous and climb thrust; and a pseudo rating is calculated for idle. These ratings are modified appropriately to account for service bleed extraction, such as airpacks and anti-icing bleeds. After establishing the ratings, the desired N1, between idle and takeoff, is calculated based upon the throttle resolver angle (TRA). The schedules are established such that TRA is linear with thrust from idle to maximum power. Maximum available N1 is always attained at the normal forward stop and maximum climb is always attained at the same TRA setting. In addition, the engine control will override the N1 control loop and adjust the fuel valve to maintain engine operation within limits on the high or the low rotor speed or compressor discharge pressure.

In order to set thrust, the pilot only has to set the TRA to a position that results in lining up N1 from the ECU (the throttle position command) with the thrust limit reference from the Flight Management System. The engine control system will automatically accelerate or decelerate the engine so that the thrust limit will be maintained without the pilot continually monitoring the N1 display, despite any changes in the environment.

The ECU is a dual channel unit where both channels receive the same inputs, process the inputs, and produce separate outputs. Each channel operates independently of the other and is fully capable of maintaining all system functions. One channel is used in the active mode while the other is on standby. To enhance system reliability, a cross channel data link is used, which allows both channels to remain fully functional if an input to one channel fails. It is also used to compare data inputs. Therefore, if one channel fails, the other provides the required output.

The ECU is capable of regulating fuel flow in the event of an N1 or EPR sensor failure. With N1 regulated engines and an N1 failure, it will generate a modeled N1 based on N2. With EPR regulated engines and an EPR sensor failure, it will use N1 to regulate the engines.

BASELINE ENGINE DISPLAYS

The baesline engine instruments are conventional displays that are provided in either circular dial or vertical tape (fixed scale and moving column) formats. For the General Electric engines, percent N1 is the thrust setting parameter. It has a thrust limit indicator (<) whose position is provided by the flight management system (FMS) and a throttle position indicator (a rotated "T") which is provided by the Full Authority Digital Engine Control (FADEC).

The primary engine parameters are provided on an 8 by 8 inch CRT called the engine and alert display (EAD). The vertical tape format is shown in Figure 1. For the GE engines, N1, EGT, and N2 are displayed with both analog gauges and digits while fuel flow is displayed in digits. The displays are grouped by engine parameter. This allows comparison between engines that assists the crew in determining an out-of-tolerance parameter. The vertical tape format presents all the information in a row. The circular dial format allows the presentation of engines in columns and the parameters in rows. The engine oil parameters and vibration indicators are presented on the system status display (SSD) to the right of the EAD. This format is time shared with formats for the other aircraft systems.

The displays are color coded. The tapes or pointers and the digits are normally white on a black background. The limits are shown by amber or red tick marks. If a limit is exceeded, the tape and digits turn the appropriate color, depending on the limit exceeded.

The displays are used in combination with the warning and alerting system. If certain engine limits are exceeded, a caution or caution advisory alert occurs. The master caution light comes on and an alert message appears on the alert list of the EAD. If it is a caution alert, the alert message is in amber color and boxed indicating that immediate attention and subsequent action is required. If it is not boxed, it is a caution advisory and only immediate attention but no action is required. The only warning alert associated with the engines is an engine fire. The master warning light comes on, the fire bell sounds, a voice message "Engine _ Fire" occurs and the alert message ENG _ FIRE appears in red color and boxed on the EAD. This alert requires immediate crew attention and action.

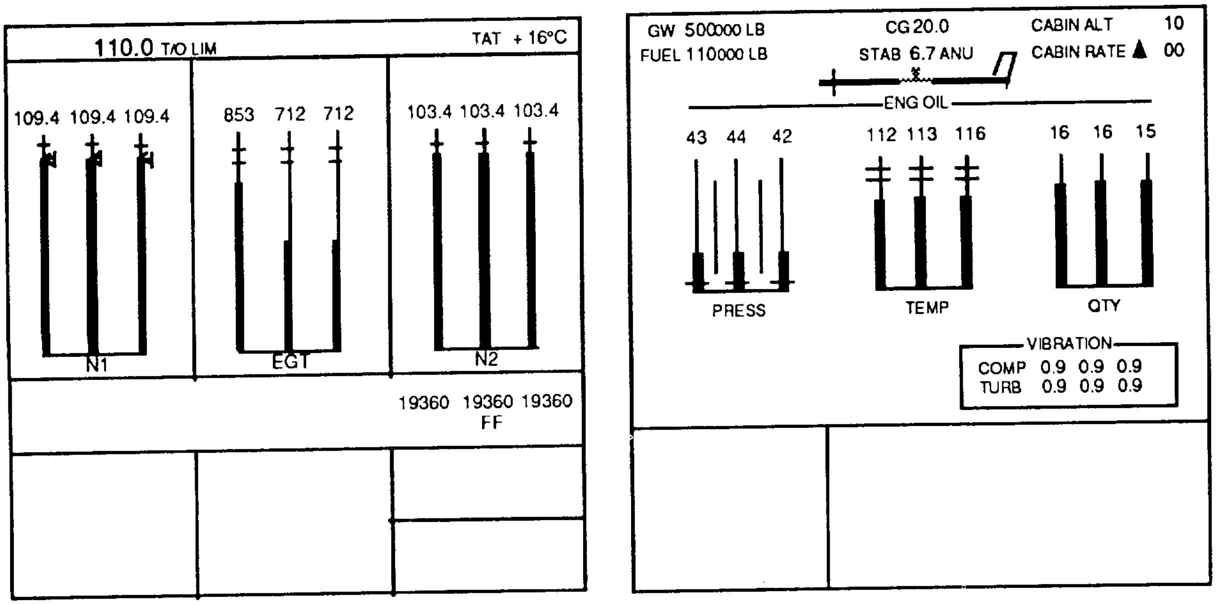

Figure 1. Baseline Engine and Alert Display and System Status Display

ENGINE MONITORING AND CONTROL SYSTEM (E-MACS) DISPLAY

E-MACS contains two display elements: (1) a primary thrust display for setting and monitoring engine thrust and (2) column deviation indicators for engine health monitoring. The general form of the display is vertical tapes (Figure 2). The thrust display is on the left and the column deviation indicators are grouped for each engine on the right.

The engine thrust display is based on an engine model of thrust[1]. The thrust tape is normalized against the maximum allowable thrust. The digital readout is in percent of normalized thrust. The maximum allowable thrust is defined as the thrust limit having the lesser value when the maximum takeoff thrust, the N1 redline, and the EGT redline limits are compared. The amber limit is based on the lesser thrust value when the maximum continuous thrust, the N1, EGT and N2 amber limits are compared. The display elements are similar to the N1 display on the Baseline and include the thrust limit and throttle position indicators. The advantages of this display are (1) the position of the indicators does not change providing a fixed visual reference, (2) the normalized maximum power is always corrected for current conditions (temperature, pressure, Mach and horsepower extraction) and (3) the takeoff setting is always a percent of the maximum allowable thrust.

The second display element is used for engine health monitoring and is based on a column deviation indicator. The indicator shows the difference between the actual and nominal values

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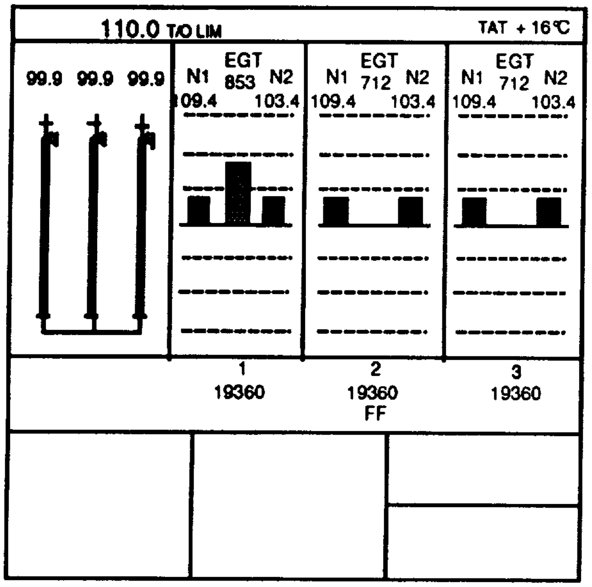
[1] The model was based on "E-MACS Implementation Notes" from T. S. Abbott, NASA Langley, VA.



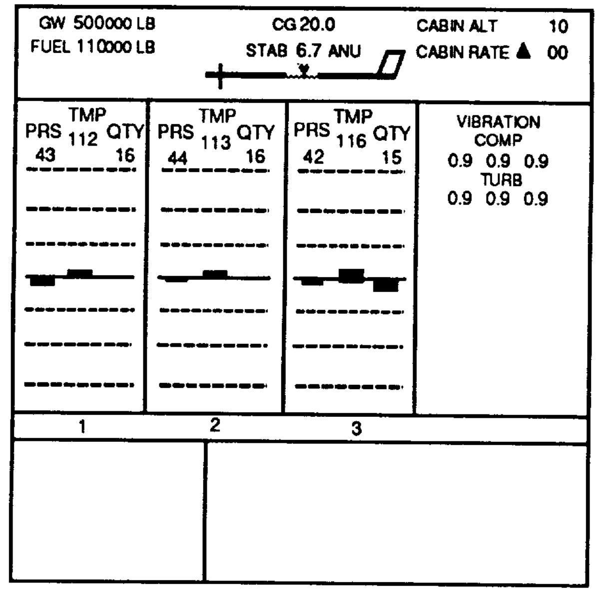


Figure 2. E-MACS Primary and Secondary Displays

for each engine parameter. The estimated value is based upon the engine model. The height of the column is the difference between the actual parameter value and the estimated value. The column is divided into normal operating range (within 10% of normal), an amber range (between 10 to 15%), and a red range (greater than 15%) for differences above and below the estimate. The column changes color depending upon which range it is in. Included in this concept is a limitation value that is integrated with the deviation value whenever a parameter approaches an operating limit. That is, a parameter may be the same as its estimated value but operating close to its amber limit. Then the column begins to transition into the caution range when it goes over the limit. With each column deviation indicator, a digital value is presented. The digital value is the same color as the column deviation indicator.

The display formats differed from the formats in Reference 2 in that the column deviation indicators were grouped per engine with the primary engine parameters on one page and the engine oil parameters on the secondary page. Reference 2 grouped the deviation indicators for each parameter. Grouping the deviation indicators by engine was thought to provide a more meaningful presentation for monitoring engine performance.

THE ALTERNATIVE DISPLAY CONCEPT

An alternative to the E-MACS concept was developed to provide automated monitoring using the same engine model as E-MACS. The design philosophy was to relieve the flight crew from continuously monitoring engine health. This function was allocated to the computer. When a deviation occurred, the automated monitoring would alert the crew to a potential problem and provide the crew with information to diagnose the problem and take corrective action. Normally, only the primary thrust display will be presented during the major portions of flight operations. However, the flight crew has the capability of calling up all the engine displays whenever they want to. When a deviation from the engine model occurs, all the parameters for that engine will be displayed. The parameters are shown in their original form similar to the Baseline parameter displays. However, the value estimated by the engine model is shown as a green tick mark on each parameter. The tape will turn amber for the parameter having more than a 10% deviation. This removes the flight crew from continuous monitoring of the engine displays but when there is a deviation it allows for quick detection of the engine and the parameter causing the problem. This concept has the potential for conserving display space in the cockpit which is always at a premium.

This concept, called Display by Exception (DBE) for convenience, is illustrated in Figure 3. The same thrust display that is used for E-MACS is used in this concept. However, room is added for N1, EGT, and N2 on the EAD that decreases the amount of display spacing. Fuel flow is left digital. The secondary engine display remains the same as the Baseline except the analog displays remain blank unless there is a problem with the engine. This concept will allow for the display of specific parameters during certain flight phases. For example, when the start switch is pulled, the displays for that engine appear, allowing the crew to know when to turn the fuel switch on and to monitor the start relative to the engine model (the green tick marks). When the start logic is satisfied and N1 reaches idle, the displays disappear.

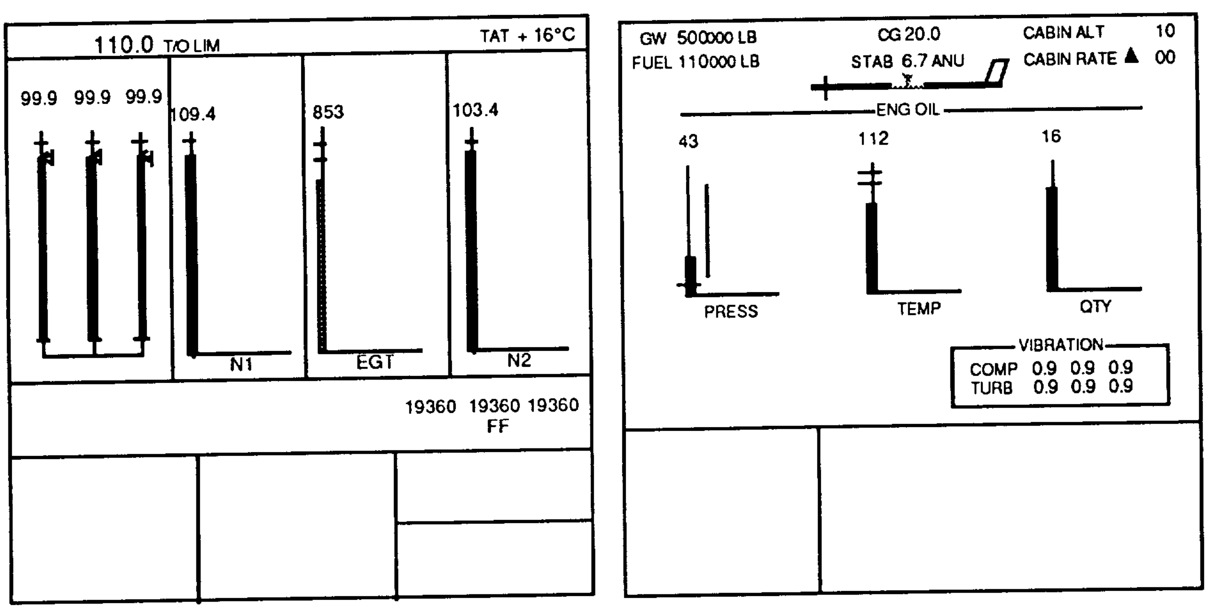


Figure 3 Primary and Secondary Engine Displays for Display by Exception Concept

The Display by Exception, E-MACS and the Baseline engine displays were implemented for this evaluation. The implementation included the following:

1) The thrust display for E-MACS and DBE were the same. The thrust display was modified from the one described in Reference 2. The maximum takeoff thrust rating was

used for the 100% normalized thrust and the amber and red limits were deleted. Thrust limit ratings are calculated performance of the engine that is guaranteed by the manufacturer. There are two certified ratings: (1) maximum takeoff thrust which is restricted to a 5 minute duration and (2) maximum continuous thrust. These thrust ratings are not associated with operating limits of the engines. Therefore, the amber and red limits were removed and the primary thrust display did not have a malfunction indication. In addition, the digital readout was in percent of normalize takeoff thrust instead of pounds of thrust.

2) The original E-MACS engine model used a third order polynomial, regression equation. The engine model used in this study for both E-MACS and DBE was the simulation model developed by MD-11 Propulsion Engineering.

3) The DBE concept left a gray line on each display where the engine parameter would normally be displayed. When there was an engine fault, this would assist the crew in determining which of the three engines was at fault. During engine start, all the parameters for the engine being started would appear when the start switch was pulled. They would blank out 5 seconds after the start logic was satisfied. For the experimental evaluation, the flight crews were not allowed to call up the displays when they wanted to. The displays would only appear when an engine parameter was out-of-tolerance.

4) A warning and alert system similar to the MD-11 one was used for all three concepts. All three concepts contained the same caution and caution advisory alerts. These would cause the master caution light to come on and an alert message to appear on the EAD. There were no aural warnings associated with these alerts. Most of the alerts had a checklist procedure. The alerts were inhibited between V1-20 KIAS and 400 feet AGL. In addition, if there was a 10% difference in N1 between any two engines on takeoff, an engine fail light illuminated on the glareshield.

METHOD

PILOTS

Twelve pilots participated in this study. Nine pilots were recruited by ALPA and were active line pilots from various airlines. Two pilots were from the FAA and one pilot was a Douglas engineering test pilot. Of the twelve, seven were currently qualified as captains, two others had served as captains on previous aircraft, and the remaining were first officers. One pilot had less than 500 hours in a transport category aircraft. Three pilots had between 1000 to 2500 hours experience in transport category aircraft and the remaining pilots had greater than 2500 hours of experience. Two pilots had experience in only twin engine aircraft. The remaining pilots had experience in three or four engine aircraft. One pilot had no experience with EFIS displays or with two-man flight crews. The remaining pilots had experience both with EFIS displays and two-man flight crews.

SIMULATOR

A fixed base, research and development simulator was used for this study. The cockpit emulated an MD-11 aircraft. It consisted of six across CRT displays, a hydraulically driven control wheel and column, functional secondary flight controls, back driven autothrottles, a glareshield flight control panel, and an outside visual scene. A photograph of the cockpit is shown in Figure 4. The CRT displays were 8 by 8 inch Xytron tubes, raster driven, and driven by Silicon Graphics computers. Four computers were used for the generation of the primary flight, the navigation, the engine and alert, and the system status displays. The left primary flight and navigation displays were duplicated on the right side.

The primary flight display (PFD) contained the basic "T" flight display formats, with the attitude display centered, airspeed on the left, altitude and vertical speed on the right and a partial compass rose at the bottom. The flight mode annunciator was located at the top of the display. The navigation display (ND) was a horizontal situation indicator or a compass rose display. The glareshield's flight control panel was functional and allowed speed, heading, altitude, and vertical speed select and hold functions, as well as autoflight and autothrottles engagement. A McFadden hydraulic force wheel and column system was provided on the left side of the cockpit. This unit allowed programmable forces to be computer controlled in both pitch and roll axes, in order to simulate the force loading of the MD-11. Rudder pedals and toe brakes were provided with passive springs. The throttles were servo driven with a DC torque motor. The dynamic characteristic of the autothrottles back drive were computer controlled. The throttle handles contained the autothrottles disconnect switch, the TOGA button, and reverse throttles. Active secondary flight controls included the flap/slat, spoiler, and longitudinal trim handles from a DC-10 pedestal. The out-of-the-window visual scene used a rear projection screen placed eight feet from the left seat pilot's eye position. The visual scene was generated by a Redifon Visual Flight Attachment consisting of a terrain board, a servo-driven, color television system, associated electronics and lighting.

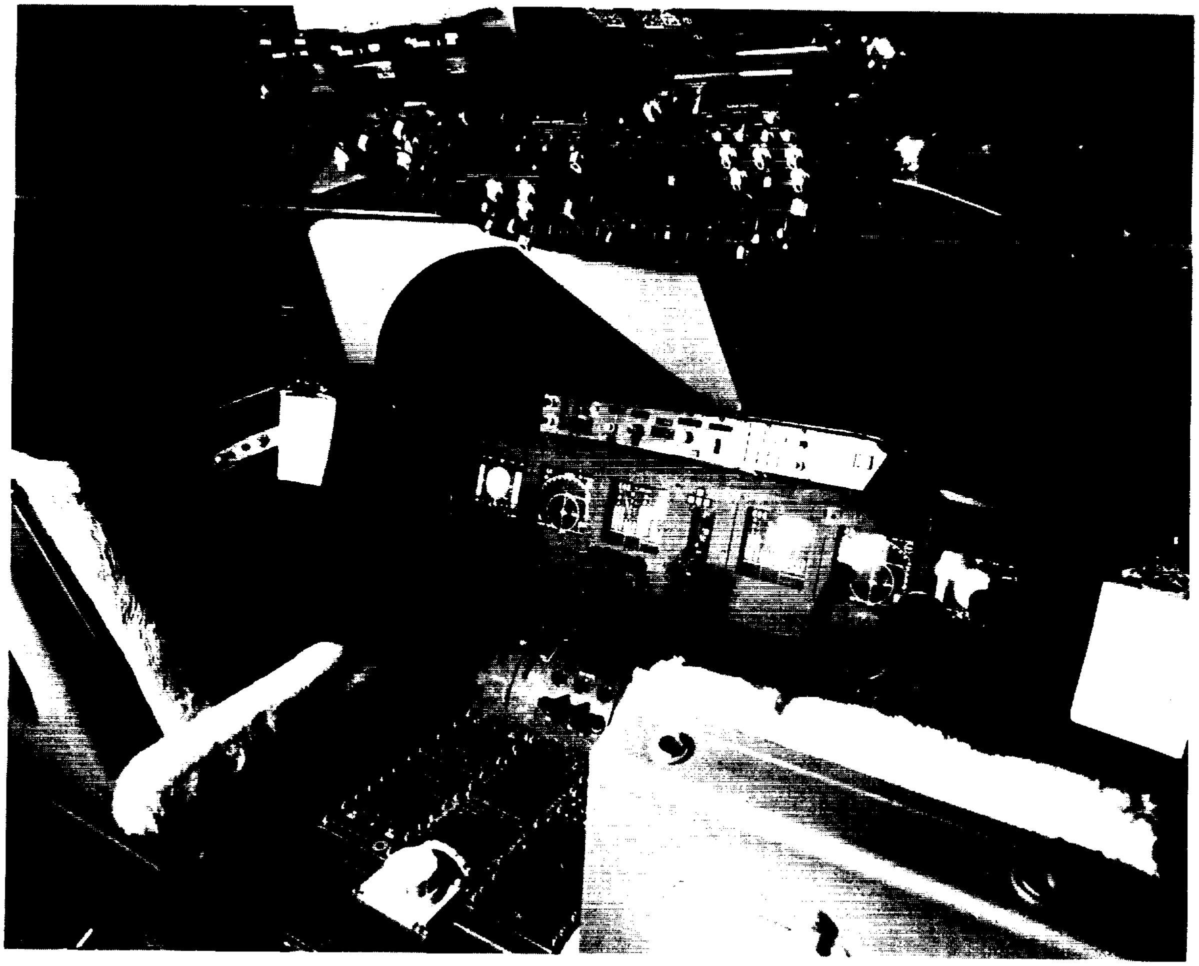


Figure 4. Fixed Base, Research and Development Simulator

A standardized, modular software system was used for the simulation. The modular components are shown in Figure 5. The airplane model was based on angle-of-attack equations. It was developed from original MD-11 wind tunnel data and refined by aerodynamic engineers. The engine model was based on the General Electric CF6-80C2 engines. It was a simplified non linear dynamic model. It provided estimated steady state and transient performance throughout the operating envelope. It was based on the thermodynamic engine cycle at a specific operating point and was defined by six independent engine variables. The basic functions of the FADEC system were duplicated in the fuel flow model. The engine model was entered three times to simulate each engine separately. The same model was used for the engine monitoring model for the advanced display concepts. The cockpit hardware was interfaced to the simulation by a flight deck software package. A separate software module was used (1) to modify the output of the engine model to simulate the engine faults, (2) to drive and generate the different display concepts, and (3) to provide the experimental control program. The computation iteration frequency was 20 hertz. The aircraft models were calculated by a DEC VAX 8650 computer and an Avalon A/P-34 processor installed in a Unibus environment of the computer to provide additional processing power for the engine model. The models were linked to the cockpit through a parallel bus to a LSI-11 computer. The graphics were provided by Silicon Graphics computers linked to the VAX by Ethernet. A data recording system allows the recording of any aircraft or test parameter in real time. The parameters were recorded in tabular format at 20 hertz.

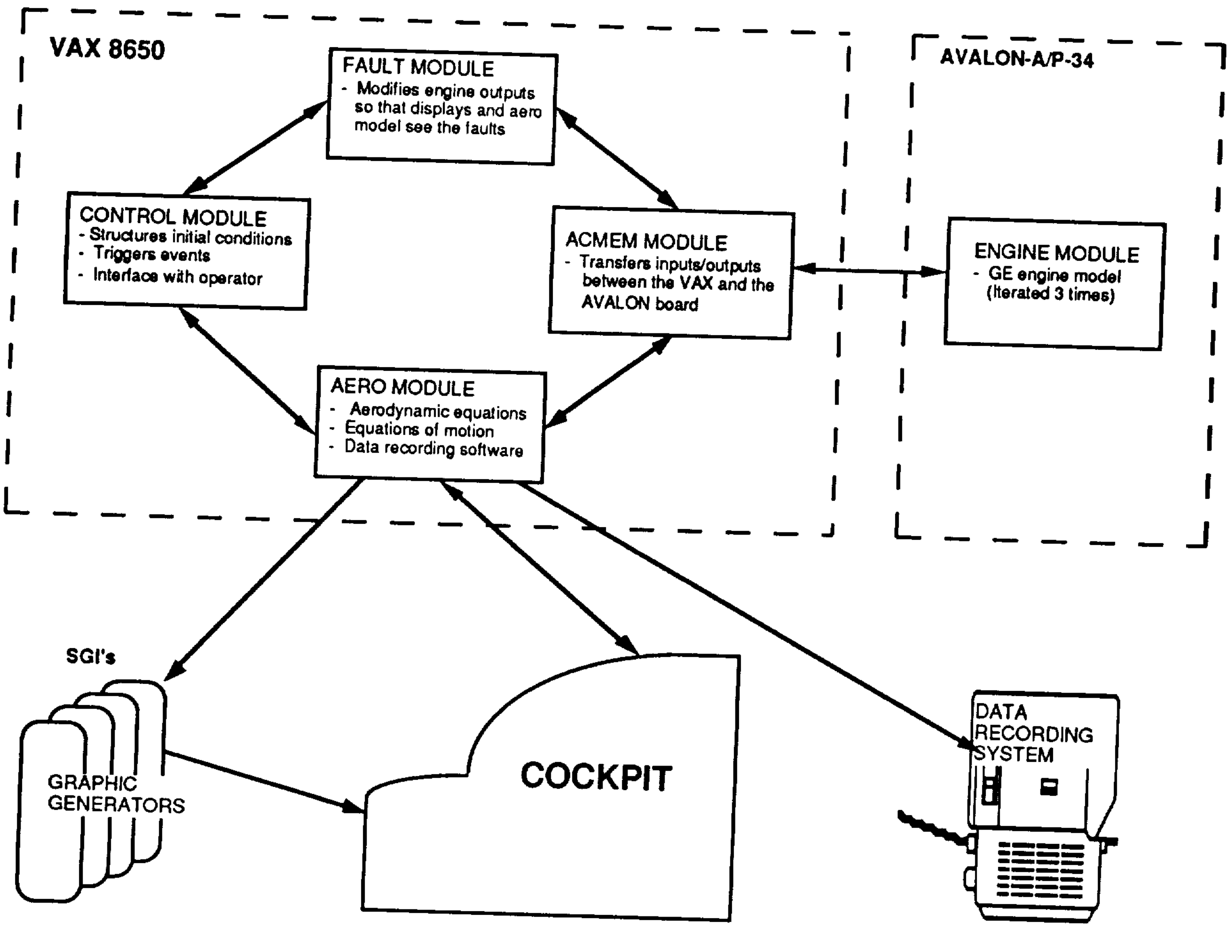


Figure 5. Block Diagram of the Simulation

EXPERIMENTAL DESIGN

The treatment conditions were the three display concepts, the throttle mode, and the fault conditions. The throttle mode was manual versus autothrottles. The fault conditions were the eight engine faults, where one fault occurred in each experimental trial. In addition, two lateral profiles were used where, after initial climb out, the pilots were given either a left or right turn.

The statistical design was a repeated measures, fractional factorial, block design. A pilot received each display condition in a block of trials. Within the block of trials, a pilot received all eight fault conditions, four repetitions of each throttle mode, and four repetitions of each lateral profile. They received a total of eight combinations out of 32 combinations of treatment conditions for each block of trials. An example of the trials that one pilot received is shown in Figure 6. This design allowed the evaluation of the main effects and some first order interactions but no second or third order interactions.

The order of presentation of all display concepts was counterbalanced across pilots to reduce order effects. The order of presentation of the eight faults within a display block was randomized. The faults only occurred on one of the two wing engines. The wing on which it occurred was balanced between the treatment conditions and the pilots. The throttle mode was equally divided among the eight fault conditions. (Except for the engine start faults that did not have a throttle mode.) The throttle mode versus fault condition was counterbalanced between pilots so that each combination occurred the same number of times. The experimental trials that each pilot received are presented in Appendix A.

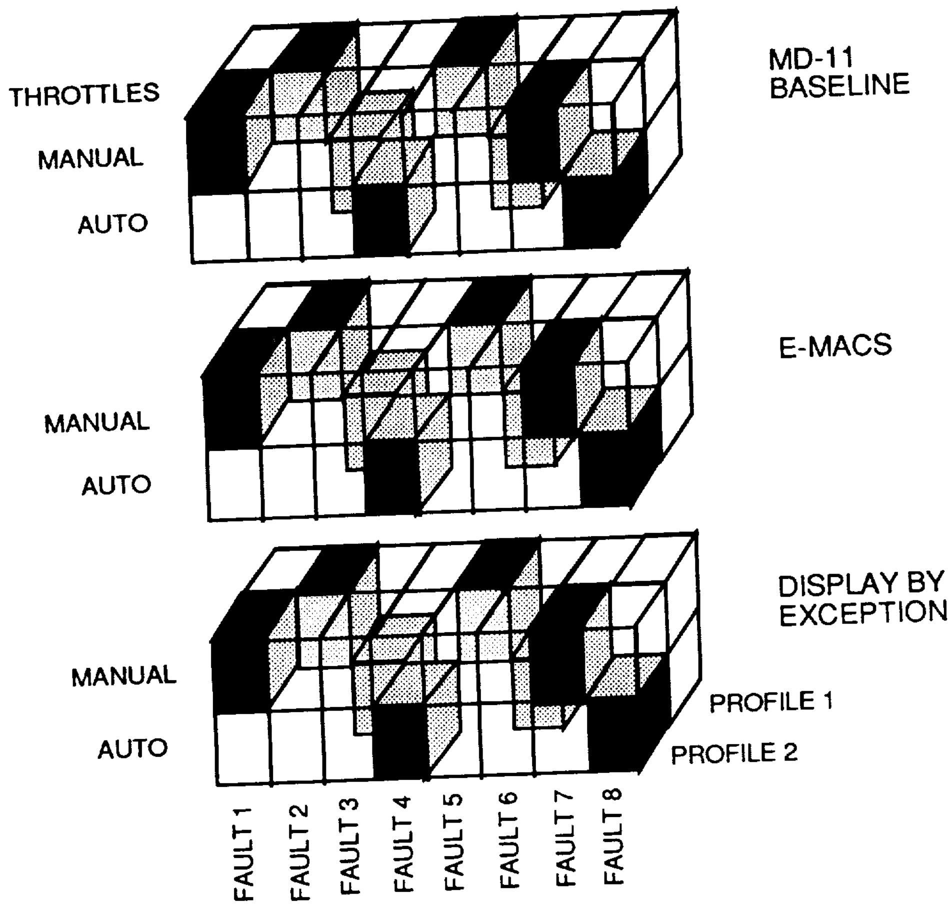


Figure 6. **The Experimental Trials One Pilot Received out of the Total Possible Combinations**

FLIGHT PROFILE

Each trial consisted of four phases: (1) engine start, (2) takeoff, (3) initial climb, and (4) transition to cruise. The departure runway was always Runway 36 and was located at sea level. The environmental conditions remained the same for every trial and were the standard atmospheric conditions, a 10 knot head wind, and visual flight rules. Initial climb was on the runway heading and climb speed was 250 knots. At 1500 feet, the pilot was commanded either to make an eastbound turn to 090 or a westbound turn to 270 and level off at 4000 feet. The transition to cruise started in level flight at 27,000 feet, on a heading of 360, and at Mach 0.78. The pilot climbed to 31,000 feet and accelerated to Mach 0.85.

ENGINE FAULTS

Both the Aviation Safety Report System (ASRS) and Douglas incident databases were searched for actual incidents on engine anomalies. Relevant incidents were reviewed and the summary reports were scanned for pertinent details. The reports were sorted by phase of flight and failure categories within each flight phase were tallied to determine the most likely candidates for the study. From this pool of data, two faults were selected for each of the four phases of flight. The details of each fault follow.

Engine Start Faults

The two faults for engine start were a hot start and a hung start. For the hot start the engine parameters appeared normal until approximately 40 seconds after the fuel switch was turned on at which time N2 began to slow its rate of increase. EGT did not begin to decrease but continued to rise. By 60 seconds N2 had stabilized at 51% and EGT had reached the red line of 750 degrees C.

For the hung start, EGT slowed to half its normal rate about 10 seconds after the fuel flow switch was turned on. Fuel flow increased at its normal rate but began to fall after 10 seconds. N2 was at a lower than normal rate and leveled off after 50 seconds. At the same time, EGT and fuel flow leveled off. After 60 seconds into the start, N2 was 55%, EGT was 600 degrees C, and fuel flow was 1450 PPH. There were no alerts during the engine start phase. However, there was a non alert Abnormal Start checklist that the pilots were instructed to follow.

Takeoff Faults

The two faults were a low N1 during engine spool up and high EGT during the takeoff roll. When the throttles were advanced, N1 on the faulty engine stopped and leveled off at 93% while the two remaining engines increased normally to 110%. EGT, oil temperature, and N2 for the affected engine indicated operating conditions for an N1 of 93%. There was neither an alert nor a checklist procedure for this fault.

The high EGT fault occurred at about 40 Knots in the takeoff roll. At the start of takeoff roll, EGT was at its nominal value for the takeoff thrust setting. At 40 Knots it increased at a rate of 1.8 degrees per second. If the takeoff was continued, the redline was reached at about 300 feet AGL. A caution alert, ENGINE EGT HI, occurred when the amber limit was reached. There was no checklist procedure for this fault.

Initial Climb Faults

The faults that occurred during climb out were low oil pressure and a compressor stall. The low oil pressure occurred at an altitude of 1000 feet, as the aircraft began to accelerate to 250 KIAS. Prior to the fault, oil pressure was within its normal range. At 1000 feet it started to decrease at a rate of 10 psi per second. The caution alert ENG _ OIL PRES LO occurred when it reached the amber limit. The checklist procedure, ENG _ OIL PRES LO, was followed.

The compressor stall occurred at 3200 feet while at the climb thrust setting. N1 rapidly decreased at 18% per second. Due to the decline in air flow, EGT increased at 21 degrees per second and reached the amber limit in 5 to 6 seconds. N2 decreased at 12.8% per second and fuel flow was 16000 PPH and increased to 18000 PPH in 5 seconds when it tried to keep N1 on schedule. The first alert associated with this failure was a caution ENGINE EGT HI and it was followed by a caution ENGINE N2 LO. The checklist applied to this fault was the ENGINE FIRE or Severe Damage checklist.

Transition to Cruise Faults

The two faults that occurred within this flight phase were low oil quantity and high oil temperature. The low oil quantity fault started at 28,000 feet. At this time, the oil quantity started to decrease at 1 quart per minute. All other engine parameters remained the same. By the end of the flight, the oil quantity would have lost 10 quarts with 6 quarts remaining. There was no alert or checklist procedure associated with this fault.

The high oil temperature occurred at 29,000 feet. Oil temperature would be constant at 115-118 degrees C prior to the fault and started increasing at a rate of 3 degrees per second. A caution alert ENG _ TEMP HI occurred when it reached 160 degrees. There was a checklist procedure for this alert.

THROTTLE MODE

With the manual throttle mode the subject pilot was required to set and adjust the throttles to the takeoff and climb thrust limits using the N1 scales on the Baseline or the normalized thrust scales on E-MACS and DBE during takeoff roll and climb. When the pilot reached altitude, he was required to adjust the throttles to maintain constant speed and altitude. With autothrottles the subject pilot was required to advance the throttles to either 70% N1 or 80% normalized thrust and engage the autothrottle mode. Thereafter, he had to set and engage the speed select knob on the glareshield panel. The autothrottles automatically set thrust to the takeoff limit during the takeoff roll and to the climb thrust limit at 1500 feet AGL.

TEST PROCEDURE

Each pilot was sent a pre-briefing package several days prior to his participation. This package contained a description of the study objectives, the simulator including the display formats, and the test procedures. This package is presented in Appendix B. The evaluation took place over a two day period. The first day included an oral briefing, training trials, and the first block of trials. The second day included the second and third block of trials. The briefing included a description of display formats and the crew procedures. It was supplemented by a video tape of the display formats. The briefing was followed by a period of familiarization in the simulator and hands-on flying experience. This allowed the pilots to become familiar with the test conditions, checklists, configuration changes, speed reductions, and display formats prior to the actual data collection.

Once the familiarization training had been completed, the first experimental block began. A block of trials consisted of one trial without engine faults and eight trials with faults. The faults were presented in random order for each block of trials. At the completion of the block, the subject pilot was asked to fill out that portion of the questionnaire that pertained to the display format tested. The second and third block of trials were conducted in the same manner but on different display concepts. After the completion of all trials, the subject pilot completed an additional questionnaire on the comparison of the three display concepts.

The subject pilot sat in the left seat of the simulator and was the pilot flying. The test conductor sat in the right seat of the cockpit and acted as the pilot not flying. The test conductor would not inform the pilot of any problems and would only take actions upon command from the subject pilot. The subject pilot was provided with a pickle switch to be used when he detected an abnormal engine condition. This was used to measure the detection time. As a backup, the test conductor was provided with a switch that he would activate when he observed that the subject pilot had detected a problem. All trials were performed with manual flight control and the flight director providing flight path guidance.

All trials began with the starting of the engines. If this was completed, the pilot and test conductor would complete a pre-takeoff checklist and the aircraft would be placed in the takeoff position on the runway. The pilot would release the parking brake, set thrust, and takeoff. The test conductor would call out the V1 and rotation speeds and operate the secondary flight controls upon request from the subject pilot. The subject pilot would request the speed of 250 knots at 1000 feet AGL and the heading and altitude at 1500 feet. When the simulator reached 4000 feet and a speed of 250 knots, the simulator would be stopped and repositioned at the transition to cruise altitude. The simulator would be restarted, the subject pilot would request an altitude change to flight level 310 and when 31,000 feet was reached he would request a speed of Mach 0.85.

If the subject pilot detected an engine anomaly or fault during any phase of flight, he would push the pickle switch, request the abnormal procedure checklist and if there was a procedure, the test conductor would read the checklist items. If there was not a procedure, then the decision and action were left up to the subject pilot. After the procedures for the fault condition were completed and the aircraft was stabilized, the trial would be terminated. After completion of the trial, the test conductor would ask the subject pilot to give a workload rating using the modified Cooper-Harper rating scale.

PERFORMANCE MEASURES

The objective performance measures used in the study are listed in Table 1. The rms tracking errors were only collected when the simulated aircraft was airborne. The control activity was only collected for the takeoff and flight phases. Both the rms error and control activity were averaged for one minute of flight after the fault onset time.The subjective performance measures included the workload ratings and the responses to the questionnaire. The subject pilot was asked for a workload number after each trial. The modified Cooper-Harper workload rating scale developed by Wierwille and Casali (Reference 3) was used for the ratings. Three

Table 1
Objective Performance Measures

MEASURE	DEFINITION
DETECTION	
Missed Detections	Number of missed detections
Detection Time	Time from fault onset time until the (1) pilot pushed the radio transmit switch, (2) test conductor pushed the pickle switch, or (3) first recorded action
FAULT CORRECTION	
Recognition Errors	Number and type of errors made in response to the fault
Time to Initiate Action	Time from fault onset time until one of the following actions occurred: (1) brake pedals activated, (2) throttles returned to idle, or (3) fuel lever turned off
PRIMARY FLIGHT TASK	
RMS Tracking Error	Average longitudinal and lateral flight director rms deviations for one minute duration after the fault onset time
Control Activity	Sum of the (1) wheel, (2) column, (3) rudder pedals, (4) brake pedals, and (5) pitch trim counts for a one minute duration after fault onset time. Throttle counts are added for the manual throttle mode. A count is control movement greater than 2.5% of full control displacement.

types of questionnaires were used: (1) a rating of the specific display concept, (2) comments on the advance display concepts, and (3) a comparative rating of the three display concepts. The questionnaire forms are contained in Appendix C.

RESULTS

Contingency analyses were performed on (1) the number of detections, (2) the number of errors, (3) the pilot workload ratings, and (4) the pilot ratings of the display features, to determine if there was a relationship between these measures and the experimental treatment conditions. A X^2 statistical test was used to determine if these relationships were significant. A repeated measures, analysis of variance (ANOVA) statistical test was used to test for significant differences between the experimental conditions for detection time, time required to initiate action, the rms tracking error scores, and the control activity. The test scores averaged across pilots and the standard errors of the mean were calculated for the significant treatment conditions. The probability level of accepting significant differences between treatment conditions was 0.01 for the ANOVA tests and 0.05 for the X^2 tests.

DETECTION OF FAULTS

There were 10 undetected faults out of 96 trials with the Baseline. There were no undetected faults with the other two display concepts. This gave a X^2 value of 18.58 with 2 degrees of freedom that was significant at the 0.001 probability level.

All of the undetected faults occurred on the faults that did not have an associated alert. Of the faults that did not have an alert, (1) hot starts were always detected, (2) two out of 12 pilots were not able to detect the hung start, (3) three out of 12 pilots did not realize that there was an engine problem with the low N1 fault, and (4) five out of 12 pilots did not detect the loss of oil quantity prior to the completion of the trial. On the low N1 fault, one pilot aborted twice. After aborting a takeoff due to the yawing motion of the simulator, he tried it again before realizing there was an engine problem. Another pilot thought he caused the yaw motion and the third pilot thought it was a simulator problem. The undetected low oil quantity trials were not considered errors since no action was required of the pilot.

FAULT DETECTION TIME

Separate ANOVA tests were performed on detection time for (1) the display by fault, (2) the display by throttle, and (3) the order by fault treatment conditions. This was due to the partially replicated design of the experiment. A summary of the ANOVA tests for fault detection times is presented in Table 2[2]. The main effects of display and fault as well as the display by fault interaction were significant. The throttle mode or its interaction with display was not significant. Also, the order of presentation or its interaction with fault was not significant.

Figures 7 through 10 present the average detection times for the display by fault conditions. For the hot start, there were no significant differences. However, E-MACS did have a lower average detection time and less variance. For the hung start, both E-MACS and DBE had

[2] Since the detection times for the fault conditions were assumed to be significantly different apriori, the missing detection times were filled in by using the average score for the fault condition. This provided a conservative test for the other treatment conditions.

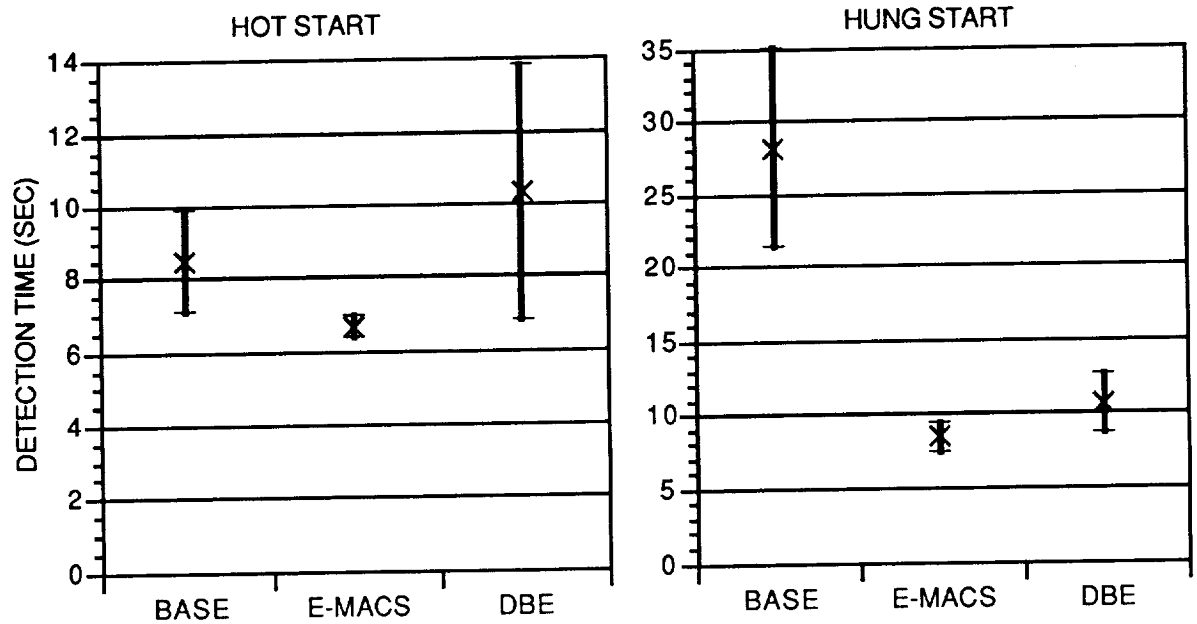
significantly lower detection times than the Baseline. For both takeoff faults, low N1 and high EGT, E-MACS and DBE had lower detection times. For the climb faults, low oil pressure and compressor stall, there were no significant differences between E-MACS and the baseline condition. The only significant difference was between DBE and the Baseline for low oil pressure. However, DBE had lower detection times and less variance than either E-MACS or the Baseline. For the transition to cruise faults, low oil quantity and high oil temperature, both E-MACS and DBE had lower detection times than the Baseline.

Table 2
ANOVA Tests for Detection Time

VARIABLE	DEGREES OF FREEDOM	F RATIO	PROBABILITY
Display	2,22	37.48	0.000
Fault	7,77	151.79	0.000
Display by Fault	14,154	11.69	0.000
Display	2,22	24.17	0.000
Throttle Mode	1,11	0.18	0.684
Display by Throttle mode	2,22	0.35	0.705
Order	2,22	0.31	0.737
Fault	7,77	151.94	0.000
Order by Fault	14,154	0.37	0.981

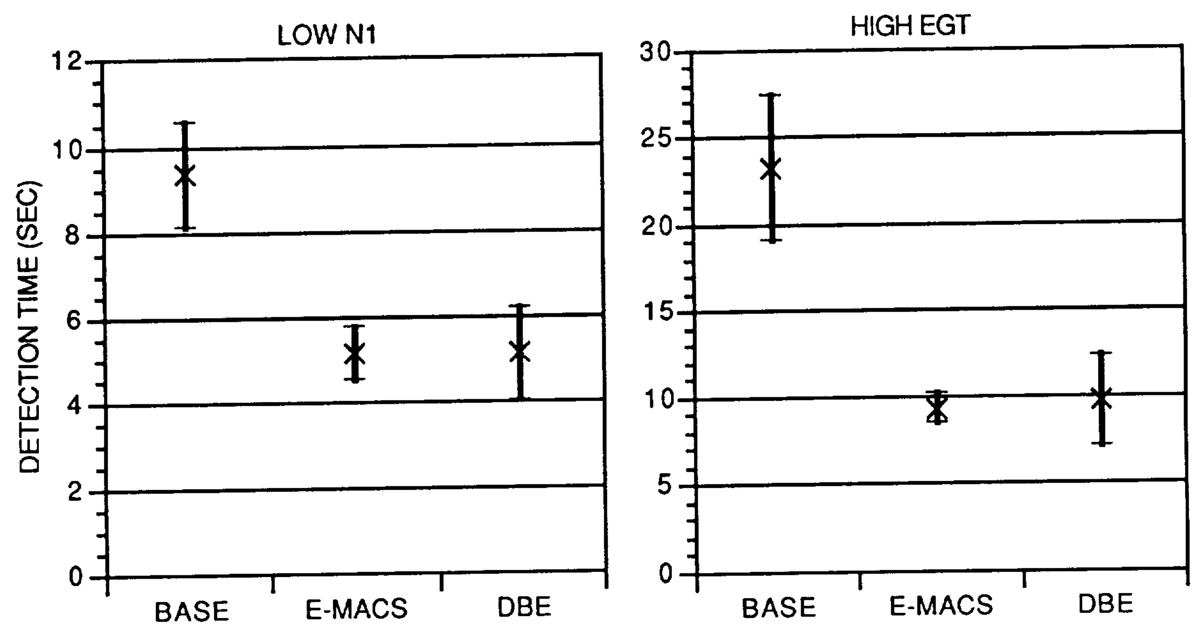
FAULT RECOGNITION ERRORS

Recognition errors occurred on each of the display concepts. There were five errors out of 96 trials on the Baseline, ten errors out of 96 trials on E-MACS, and six errors out of 96 trials on DBE. This produced a X^2 statistic of 5.266 with 2 degrees of freedom that had a probability level of 0.072 which was not considered significant. Table 3 identifies the type of recognition error for each display and fault condition. For the Baseline, the errors occurred on the hung start and the low N1 fault conditions. These errors were identified previously as missed detections. For the E-MACS concept, eight errors were due to misidentification of the engine, two errors were due to misidentification of the fault type, and in one error the pilot was unsure of the problem. For DBE, two errors were due to misidentification of the fault, one error was due to misidentification of the engine, two errors were due to the pilot being unsure of the problem and one error was due to the pilot performing the wrong action.



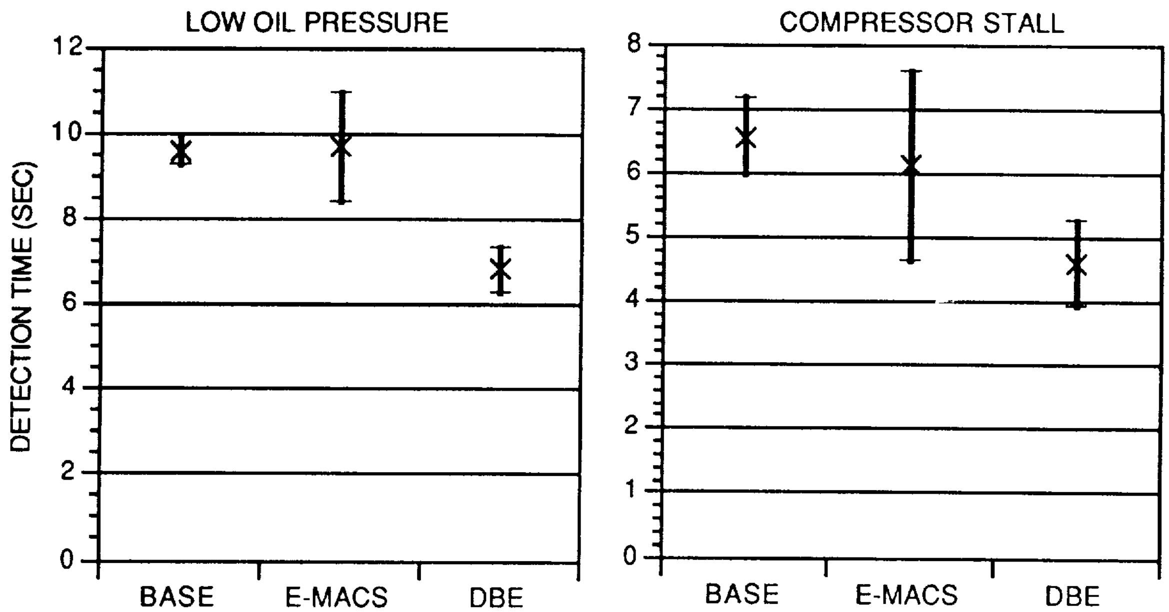
Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 7. Average Detection Times for Engine Start Faults



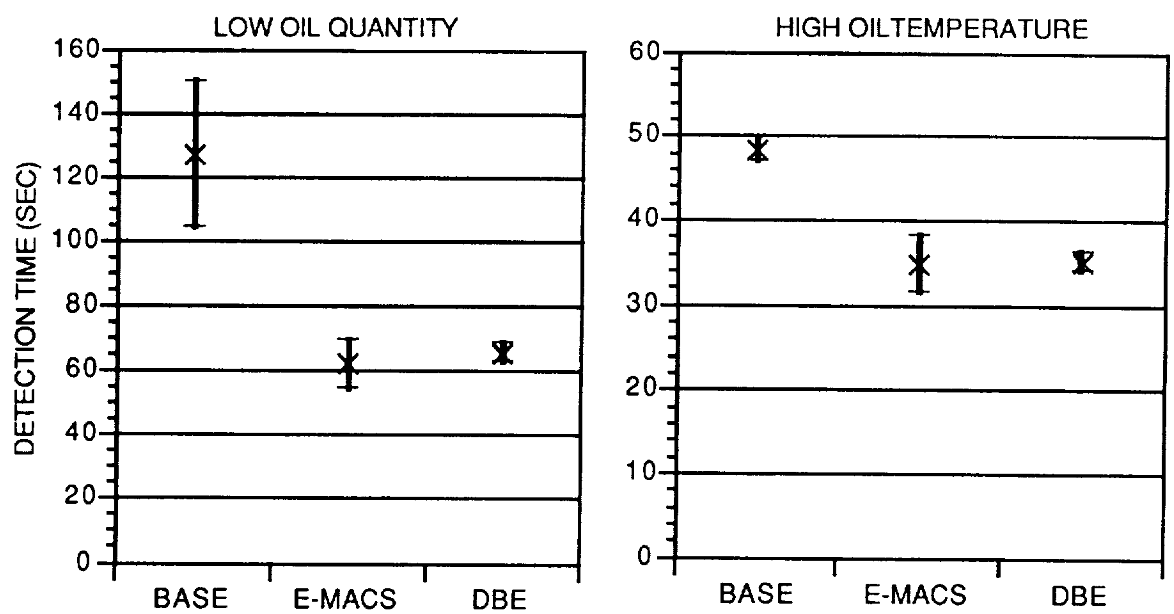
Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 8. Average Detection Times for Takeoff Faults



Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 9. Average Detection Times for Climb Faults



Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 10. Average Detection Times for Transition to Cruise Faults

Table 3
Fault Recognition Errors

FAULT	BASE	E-MACS	DBE
HOT START	-	-	-
HUNG START	Undetected (2)	Misidentified (2)	Unsure of problem (2)
LOW N1	Undetected (3)	-	Misidentified fault (2)
HIGH EGT	-	Shutdown wrong engine (2) Misidentified engine (1)	-
LOW OIL PRESSURE	-	Misidentified fault (1)	-
COMPRESSOR STALL	-	Thought all 3 engines were abnormal (1) Unsure of engine and problem (1)	Pulled back all 3 throttles (1)
LOW OIL QUANTITY	-	-	-
HIGH OIL TEMPERA-TURE	-	Shutdown wrong engine (1) Misidentified engine (1)	Shutdown wrong engine (1)

TIME REQUIRED TO INITIATE ACTION

The time required to initiate action was measured from the onset time of the fault until the pilot performed the first action. This action was either throttles to idle, brakes on (if nose wheel on ground), or fuel switch off. As before, three ANOVA's were performed: (1) display by fault, (2) display by throttle mode, and (3) order by fault. The results of the ANOVA tests are shown in Table 4[3] . As with detection time, the display, the fault, and the display by fault interaction were the only significant differences. Figures 11 through 14 show the average action times across pilots for the display by fault conditions. For the hot start, the DBE display had longer action times and there was more between pilot variability than with the other two displays. With the hung start, the action times were dependent upon the detection time. The responses to the low N1 condition were uniform across the display conditions. The usual response by the pilots was either to detect the low thrust setting while advancing the throttles, or to detect the yawing motion on brake release, and to reject the takeoff. Afterwards, the pilot would run up

[3]The times were not recorded for every data trial. In order to perform the ANOVA test, the average values per fault condition were used for the missing data.

the throttles with brakes on and check the engine displays. With the high EGT condition, the Baseline display had four high speed rejected takeoffs (approximately 130 knots). The other pilots did not detect the fault prior to rotation or waited until the aircraft was airborne. Then, they would climb to a safe altitude prior to taking any action. With both E-MACS and DBE, the pilot would detect the fault and reject the takeoff well below V1.

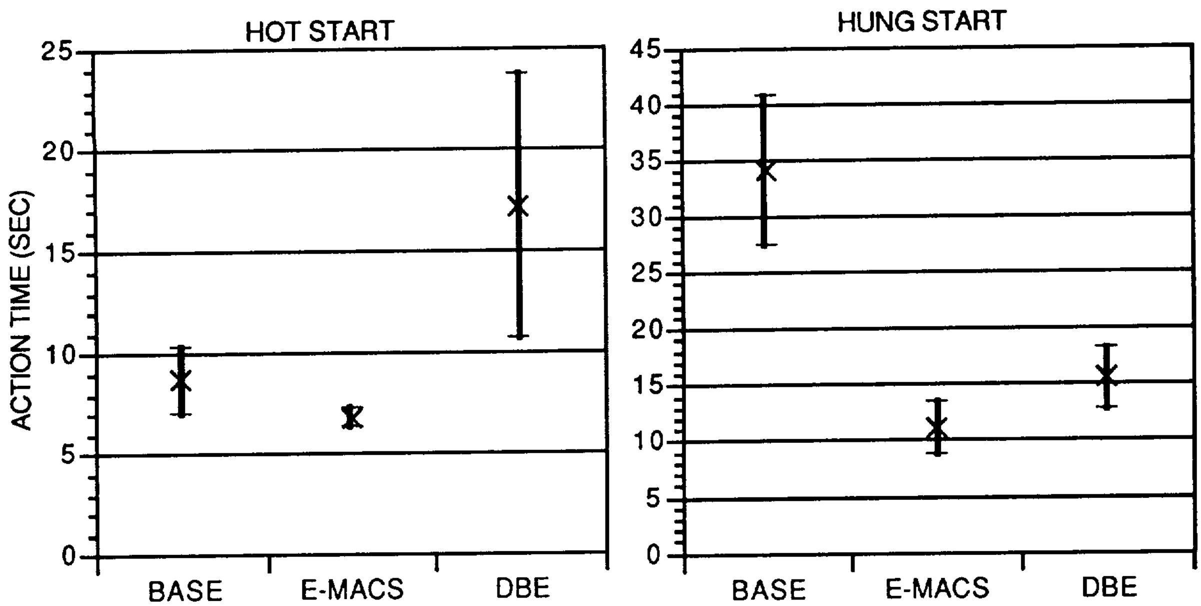
Table 4
ANOVA Tests for Action Time

VARIABLE	DEGREES OF FREEDOM	F RATIO	PROBABILITY
Display Fault Display by Fault	2,22 7,77 14,154	16.09 155.31 6.62	0.000 0.000 0.000
Display Throttle Mode Display by Throttle Mode	2,22 1,11 2,22	10.74 0.17 0.22	0.001 0.688 0.806
Order Fault Order by Fault	2,22 7,77 14,154	0.26 155.31 0.22	0.776 0.000 0.999

With the climb faults, low oil pressure and compressor stall, there were no significant differences between the display concepts. However, the action time and variability were higher with E-MACS than the other two display concepts. For the low oil quantity fault, the baseline had only one response and E-MACS had a lower action time than DBE. For the high oil temperature fault, there were no significant differences between the three display conditions.

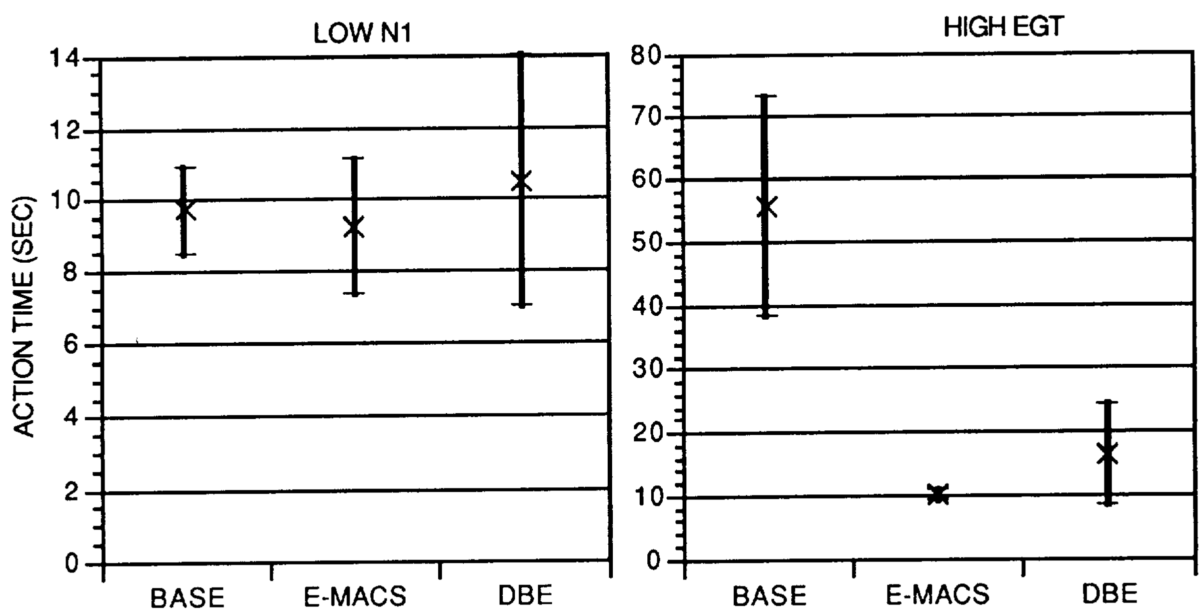
FLIGHT PERFORMANCE

The flight director's rms tracking error per unit time was recorded in both the pitch and roll axes for the climb and transition to cruise faults. There was no flight task during engine start and the flight director was not active until the simulator was airborne on takeoff. ANOVA tests were conducted on both the pitch and roll rms error scores. The summary of these tests is presented in Table 5. The results show that the display and throttles mode treatment conditions were not significant. There were significant differences in the pitch and roll rms error scores for the different fault conditions. Also, there was a significant interaction between order of presentation and fault condition. Further analyses showed no consistent trend between order of presentation and fault condition.



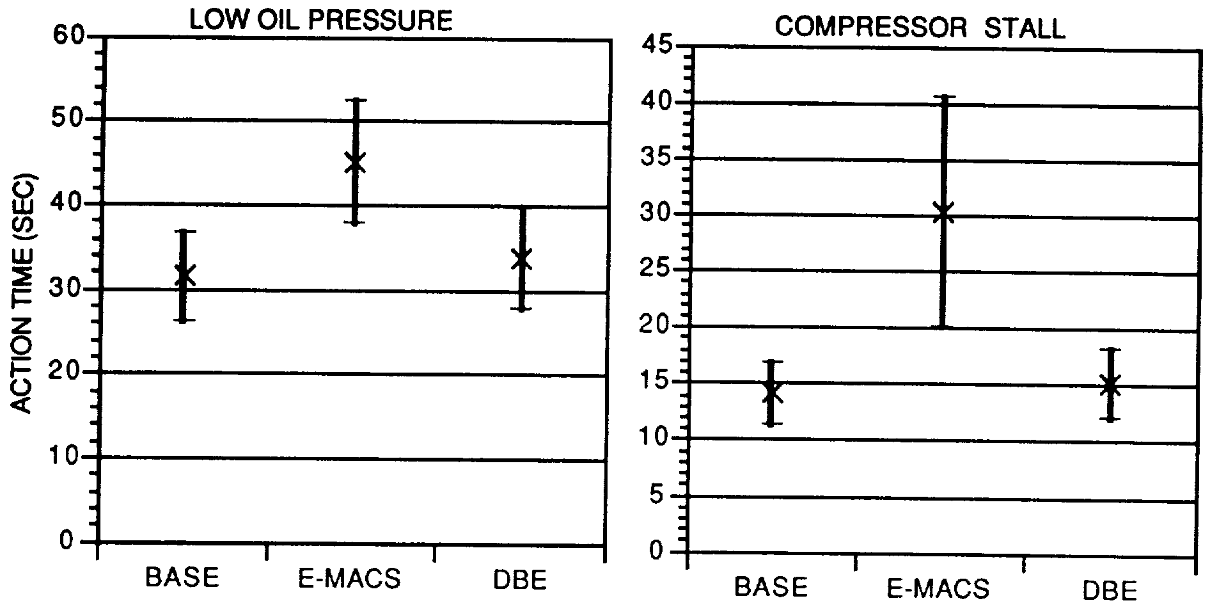
Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 11. Average Times to Initiate Action for the Engine Start Faults



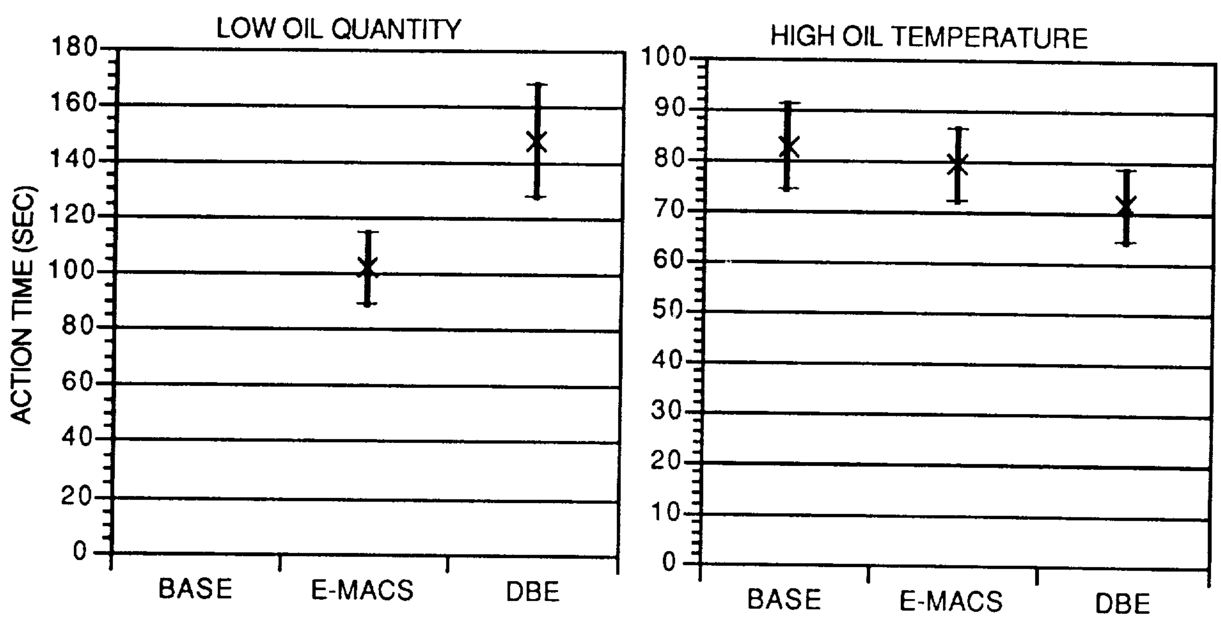
Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 12. Average Times to Initiate Action for Takeoff Faults



Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 13. Average Times to Initiate Action for Climb Faults



Note: Data point is average across pilots and bar is ± one standord error of the mean.

Figure 14. Average Times to Initiate Action for Transition to Cruise Faults

Table 5
ANOVA Tests for the RMS Error

VARIABLE	DEGREES OF FREEDOM	F RATIO	PROBABILITY
PITCH			
Display	2,22	0.28	0.761
Fault	3,33	12.29	0.000
Display by Fault	6,66	0.29	0.937
Display	2,22	0.28	0.761
Throttle Mode	1,11	1.00	0.339
Display by Throttle Mode	2,22	2.08	0.149
Order	2,22	0.63	0.544
Fault	3,33	12.28	0.000
Order by Fault	6,66	0.84	0.542
ROLL			
Display	2,22	2.54	0.102
Fault	3,33	9.83	0.000
Display by Fault	6,66	0.41	0.868
Display	2,22	2,54	0.102
Throttle Mode	1,11	2.33	0.155
Display by Throttle Mode	2,22	0.64	0.538
Order	2,22	1.60	0.225
Fault	3,33	9.83	0.000
Order by Fault	6,66	3.64	0.004

AMOUNT OF CONTROL ACTIVITY

Control movements were recorded for the takeoff, climb and transition to cruise flight phases. A summary of the ANOVA tests is presented in Table 6. The table shows that there were no significant differences in control activity for the different displays, throttle mode or trial order. Again, fault type was significant due to the amount of primary flight activity for the phase of flight.

Table 6
ANOVA Tests for Control Activity

VARIABLE	DEGREES OF FREEDOM	F RATIO	PROBABILITY
Display Fault Display by Fault	2,22 5,55 10,110	0.24 8.06 1.24	0.786 0.000 0.273
Display Throttle Mode Display by Throttle Mode	2,22 1,11 2,22	0.33 0.49 0.27	0.724 0.498 0.768
Order Fault Order by Fault	2,22 5,55 10,110	0.72 8.20 1.06	0.498 0.000 0.389

SUBJECTIVE WORKLOAD RATINGS

The modified Cooper-Harper workload ratings were analyzed with the X^2 statistical test for differences between the displays, fault type and throttle mode. The results are presented in Table 7[4]. Again, the only significant variable is the fault condition. The average workload ratings varied from 2.0 to 3.4.

Table 7
Contingency Analysis of the Workload Ratings

VARIABLE	X^2	DEGREES OF FREEDOM	PROBABILITY
Display	7.41	6	0.284
Throttle Mode	4.08	3	0.253
Fault Type	77.72	11	0.000

PILOT RATINGS OF THE DISPLAY CONCEPTS

The pilot ratings of the displays for ease, speed and accuracy of use were analyzed with the X^2 test for significant differences. The results are presented in Table 8. There were no significant

[4]Workload ratings greater than 4 were collapsed into a single cell in order to obtain a minimum expected value of 5 or greater for the X^2 test.

differences between the displays. (The only rating that was close to being significant was the speed of fault isolation.) In order to show the amount of separation between the display ratings, the average ratings are presented in Table 9. The only differences in average scores are (1) ease of reading out-of-tolerance conditions and (2) speed of fault isolation. In these cases, the pilots rated E-MACS and DBE as being easier and faster than the Baseline.

Table 8
Contingency Analysis of the Display Format Ratings

TOPIC	X^2	DEGREES OF FREEDOM	PROBABILITY
Ease of reading and interpreting engine power.	5.12	8	0.744
Speed of setting engine power.	7.42	6	0.284
Accuracy of setting engine power.	1.15	6	0.979
Ease of reading of engine health.	12.51	8	0.130
Ease of reading out-of-tolerance conditions.	8.00	8	0.433
Speed of isolating engine faults.	14.03	8	0.081

Table 9
Display Format Ratings Averaged across Pilots

TOPIC	BASE	E-MACS	DBE
Ease of reading and interpreting engine power.	3.61	3.92	3.75
Speed of setting engine power.	3.83	3.67	3.92
Accuracy of setting engine power.	3.42	3.50	3.67
Ease of reading of engine health.	3.17	2.67	3.08
Ease of reading out-of-tolerance conditions.	3.08	3.42	4.00
Speed of isolating engine faults.	3.08	3.42	3.92

PILOT COMPARISONS BETWEEN THE DISPLAY CONCEPTS

The results for the pilot comparisons between the display concepts are shown in Table 10 as the percent of pilots favoring one concept over another. If the pilot rated any of two displays as being equal, a half point rating was given to each of the displays. If he rated all three as being equal, a third of a point was given to each display. Even though the two thrust displays were the same, more pilots rated the DBE thrust display as being easier to read and faster to set power than the E-MACS. The same number of pilots selected the Baseline and the DBE display for being the easiest to read and the fastest to set engine power. Most pilots selected the MD-11 thrust display, N1, over the other two displays for the accuracy of power setting. Most pilots selected DBE as being (1) the easiest to read and interpret engine health, (2) the easiest to detect out of tolerance conditions and (3) the fastest to isolate engine faults. However, more pilots selected E-MACS over the Baseline for the same three comparisons. When asked which display concept is easiest to use overall, 60% of the pilots selected DBE, 33% selected the Baseline, and 8% selected E-MACS.

Table 10
Percent of Pilots Favoring One Display Concept over the Other Two.
Number in parenthesis is the number of pilots selecting that concept.

TOPIC	BASE	E-MACS	DBE
Easiest to read and interpret engine power.	47.2 (5.7)	18.1 (2.2)	34.7 (4.1)
Fastest to set engine power.	33.3 (4)	25.0 (3)	41.7 (5)
Most accurate for setting engine power.	58.4 (7)	20.8 (2.5)	20.8 (2.5)
Easiest to read and interpret engine health.	41.7 (5)	16.6 (2)	41.7 (5)
Easiest to detect out-of-tolerance conditions.	16.7 (1)	25.0 (3)	66.7 (8)
Fastest to isolate engine fault.	12.5 (1.5)	29.2 (3.5)	58.3 (7)
Overall easiest to use.	33.3 (4)	8.3 (1)	58.3 (7)

PILOT COMMENTS

The pilot comments are grouped in positive, negative and modifications they would like to see on the thrust display, the E-MACS monitoring display and the DBE monitoring display. The acceptability and the certification issues of both the E-MACS and the DBE were grouped separately. The results are listed in Table 11 and presented below.

Thrust Display

Seven out of 12 pilots thought that thrust was easy to set and adjust to the thrust limit. One pilot liked the concept of thrust scaled as percent. One pilot thought the vertical tapes were easy to read and set thrust by. Three of the 12 pilots did not like the normalized thrust scale. Of the pilots who did not like it, one said there was no absolute value of thrust such as EPR or N1 and that a person must always think in terms of percent of

Table 11
Pilot Comments on the Advance Display Concepts.
Number in parenthesis is the number of pilots making that comment.

QUESTION	COMMENTS
Thrust Display	
Positive	Thrust is easy to set and adjust to the thrust limit. (7) Liked the concept of thrust scaled in percent. (1) Vertical display is easy to read and set thrust by. (1)
Negative	No absolute value of thrust such as EPR or N1. You must always think in terms of percent of maximum takeoff thrust. (1) Percent readout of thrust is not friendly. (1) Not sure I like thrust scale, although it does have advantages. (1)
Modifications	Have caret representing the thrust direction when speed is in the thrust mode. (1)
E-MACS	
Positive	Faults are easy to detect when there is more than a 10% deviation. (8) Bars and the color change of the bars are helpful. (2) Like the idea of providing information to the crew when engine parameters are different from the predicted value. (1) Excellent concept. (1)
Negative	The grouping of parameters for each engine causes confusion. (8) The amber and red lines make the display too busy. (8) Disliked all the red lines on the display (1) Disliked the extra red line (1) When the deviation was below the predicted value and the bar turned red, it caused confusion. This was especially true for the hung start. (3) There are no indications as to what the values are until the engine is out of nominal range. You must refer to the digital values. (2) You have to refer to the digital values during engine start. (2) Display is awkward for determining status. There is no flow to scan. (1) The display parameters are too close together. (1) Do not like horizontal displays as opposed to over and under. (1) Would prefer actual parameters instead of a microprocessor monitoring them for me. (1) Did not like any of the features. (1)
Modifications	Group the column deviations per parameter instead of per engine. (6) Remove red and amber lines when not in use. 5) Expand the normal and caution range. (2) Display the actual analog values. (2) Do not use red for low EGT. (1) Do something about the start display. (1)

Table 11 Continued

QUESTION	COMMENTS
E-MACS	
Modifications	Turn the primary thrust indicator the same color as the column deviation indicator for that particular engine. (1) More exposure to this display concept would enhance recognition and interpretation. (1)
Operational Acceptance	
Positive	It is easier to read than current displays. (3) More training is required. (2) If certification issues can be resolved. (1)
Negative	Due to grouping of the parameters by engine. (1) Unless modifications are made. (1) In actual use the columns would be varying above and below the nominal that would be disturbing and tells the pilot nothing. (1)
Certification Issues	Arrangement of engine parameters. (4) The specification of the engine model. (3) No certification issues. (2) The starting display. (1) Red limit lines on the display. (1) Pilot out of the monitoring loop. (1) Difficult to interpret. (1) Spacing of the parameters. (1) Not certifiable. (1)
DBE	
Positive	Quick indication of the problems. (8) Easy to scan the indications that only display the malfunctions. (4) Color gives a quick indication of the problem. (3) Display is easier to use because there is less to monitor. (2) Would be easy to use during periods of both high and low workloads. (1) During engine start, the target values make the analysis easy. (1) Potential to time share display with other functions. (1)
Negative	Pilot is out of the monitoring loop. (4) Cannot see trends prior to a 10% deviation. (3) Difficult to interpret problems. (3) Cannot compare to other engines. (2) Difficult to ascertain which engine. (1) Display is blanking prior to engine stabilizing during the start cycle. (1) Didn't like not being able to call up the displays. (1) If engine goes back within limits, displays will become blank. (1)

Table 11 Continued

QUESTION	COMMENTS
DBE	
Negative	Parameters are grouped too close together. (1) Didn't like concept. (1)
Modifications	Provide the capability for the pilot to select. (3) Extend the start presentations until the engines are stabilized. (2) Add aural cues. (2) Would be nice if they were blank unless there was a 10% difference from the other engines. (1) Add digital values like in E-MACS. (1) Move fuel flow below each engine. (1) Use a flashing indicator for the engine having the problem. (1) Would like to see the checklist procedures like the Airbus. (1)
Operational Acceptance	
Positive	Need assurance the alerts exist when the automatic monitoring system limits are reached. (1)
Negative	Want full time access to the displays. (3) Not comfortable being out of the monitoring loop. (1) No opportunity to troubleshoot or analyze. (1)
Certification Issues	Validity of engine model. (6) Total trust in monitoring computer. (3) Not providing trend or rate of change information. (2) No problem if parameters stay up during engine start and pilot has capability to call up the parameters. (2) Reliability and redundancy of monitoring system. (1) Engine wear and environmental variations in engine model. (1) Situation awareness, monitoring integration, parameter thresholds and alerts. (1) Closely grouped parameters. (1)
Additional Comments	
Positive	Powerful or outstanding concept. (2) Color aspect is vital. (1)
Negative	Prefer to monitor all parameters at all times. (1) False warnings may cause delays and flight canceling. (1) Maintenance would be high. (1) Maybe it would be better having words describe the problem. (1)

maximum takeoff thrust. Another said the percent readout was unfriendly, and the third said he was not sure he liked the normalized thrust scale but that it did have some advantages.

Only one pilot suggested modifying the thrust display. This modification would be to have the thrust limit caret represent the throttle position that the flight control computer commands when speed is in the thrust mode. This would assist the pilot in the manual throttle mode as the flight director does during manual flight.

E-MACS Monitoring Displays

Eight of the 12 pilots thought that faults were easy to detect when there was more than a 10% deviation. Two of the 12 pilots thought that the color change of the bars was helpful. One pilot liked the idea of providing information to the crew when the engine parameters differed from their predicted value. One pilot thought it was an excellent idea. Eight of the 12 pilots thought that grouping the display parameters per engine caused confusion. In addition, eight pilots thought the amber and red limit lines made the display too busy. One of the eight disliked the red lines and another just disliked the second red line. Three of the 12 pilots thought that, when the parameter value was less than the predicted value and the column turned red, it caused confusion. This was especially true with the hung start condition. Three of the 12 pilots thought the column deviation indicators were difficult to interpret and they had to refer to the digital values to interpret the problem. Two of the 12 pilots did not like the fact that there was no indication of the parameter values when they were within normal range and they had to refer to the digital readouts. Two other pilots made the same remark for the engine start condition. Individual pilots made the following comments: (1) the display is awkward and it is hard to determine status, (2) the display parameters are too close together, (3) one pilot did not like to scan the horizontal displays as opposed to over and under, (4) one preferred the actual parameters instead of the output of a microprocessor and (5) one did not like any of the features.

Six of the 12 recommended grouping the column deviations by parameter instead of by engine. Five of the 12 suggested removing the red and amber lines when not in use. Two recommended expanding the normal and caution range and two wanted the actual analog values displayed. Individual pilots recommended that (1) red should not be used to indicate low EGT on the column deviation indicator, (2) something should be done about the start display, (3) the primary thrust indicator should turn the same color as the column deviation indicator for a particular engine, and (4) more exposure would enhance recognition and interpretation.

Display by Exception

Eight of the 12 pilots thought that this concept gave a quick indication of the problem. Four liked the concept of displaying all the parameters for one engine. Three thought that the parameter with the color change was a quick way of isolating the problem. Two said it was easier to use because there was less to monitor. Individual pilots made the comments that (1) it would be useful during periods of both high and low workloads, (2) during engine start, the target values make it easy to analyzed, and (3) there is potential to time share the display with other functions.

Four of the 12 pilots did not like being out of the monitoring loop. Three said unless there was more than a ten percent deviation, you could not see trends. Three thought it was difficult to interpret problems and one of the three thought it was difficult to ascertain which engine had the problem. Two pilots did not like the idea that you couldn't compare the engine with the other two engines. Individual pilots did not like (1) that the displays blanked prior to the engines stabilizing during the start, (2) that they could not call up the displays, (3) that the parameters were grouped too close together, and (4) the overall concept.

Three pilots suggested that the pilot be given the ability to select the engine display. Two suggested that the start presentation be extended until the engines are stabilized. Two suggested that aural cues be added to the presentation. Individual pilots suggested (1) it would be nice if they remained blank unless there was a 10% difference from the other two engines, (2) have full time digital values like in E-MACS, (3) use a flashing indicator for the engine having the problem, (4) move the fuel flow values below each engine, and (5) add checklist procedures like the Airbus aircraft.

Operational Acceptance of the Advanced Displays

The responses to the question of operational acceptance of E-MACS and DBE are shown in Table 12. Seven pilots said E-MACS was operationally acceptable and eight said DBE was operationally acceptable. Of the seven pilots who said that E-MACS would be operationally acceptable, four gave a qualified answer: two of the four said that more training is required, one said if the certification issues can be resolved, and one said if modifications are made. One of the eight pilots gave a qualified yes response for the DBE. This was that assurance is needed that alerts exist when the engine limits are reached.

Table 12
Percent of Pilots Responding to Question of Operational Acceptance of the Advance Display Concepts.
Number in parenthesis is the number of pilots selecting that option.

DISPLAY	YES	NO	NON-COMMITTAL
E-MACS	58.3 (7)	33.3 (4)	8.3 (1)
DBE	66.7 (8)	25 (3)	8.3 (1)

Of the four pilots who responded that E-MACS was not operationally acceptable, one said it was due to grouping of the parameters and one said it was because the columns would be varying above and below the normal which was disturbing and not telling the pilot anything. The three pilots who said that DBE was not operationally acceptable said they wanted full time displays. One said he was not comfortable being out of the monitoring loop, and one said there was no opportunity to troubleshoot or analyze the problem.

Certification Issues of the Advanced Display Concepts

When asked what the certification issues are with the E-MACS concept, two pilots said there were no issues and one said it was not certifiable. Four pilots said certification would depend on the arrangement of the engine parameters and three pilots said it would depend on the validity of the engine model. Individual pilots made the following comments about certification: (1) the starting display, (2) the red limit lines, (3) the pilot is out of the monitoring loop, (4) the difficulty in interpretation, and (5) the spacing of the parameters. When asked about the DBE concept, six pilots said it would be the validity of the engine model. Of the six, one pilot said it would be the reliability and redundancy of the monitoring system and one said it would be the variations in the model due to engine wear and the environment. Three pilots said it would require placing total trust in the monitoring computer and two said it would be necessary to provide trend and rate of change information. One pilot said it would depend on the situation awareness, the parameter thresholds, and the alerts. Another pilot said it would depend upon the spacing of the parameters on the display.

DISCUSSION

NORMALIZED THRUST DISPLAY

One of the advantages of the normalized thrust display is that the flight crew is not required to look up thrust limits based upon the ambient conditions. This study did not evaluate this feature since it was only a part task simulation and the pilots were not required to determine the thrust limits. However, the requirement for flight crews to use look up tables for thrust limit setting is disappearing due to thrust rating computers in current transport aircraft such as the one incorporated in the MD-11's Flight Management System and FADEC's.

In this study, the only differences between the normalized thrust and the N1 scales were the linearity of the scale. The other features were the same, i.e., the thrust limit caret, throttle position indicator, and the thrust tape. As a result, the pilots did not show a clear preference for the normalized thrust scale over the N1 scale. The fact is that the FADEC system compensates for the inadequacies of thrust displays with mechanical engine control.

Only two pilots did not like the normalized thrust scale. This may have been due to the lack of experience with the normalized thrust. One pilot said it did not give an absolute value of thrust but neither does EPR or N1. The other pilot said it was not user friendly but there is no difference in user friendliness between the normalized thrust scale, EPR, or N1.

This study used the maximum takeoff thrust as the normalizing value and not the lessor limit of the maximum takeoff thrust, the N1 redline limit, or the EGT redline limit. The normalized thrust scale eliminated the amber and red line limits that were used in the NASA study (Reference 2). This made a clear distinction between the thrust rating limits and performance limits due to N1, EGT or N2 redline limits. However, having the thrust tape turn the appropriate color when a limit is exceeded should be considered as an option for either one of the advanced concepts. This would eliminate some of the confusion over which engine is causing the problem.

ENGINE HEALTH MONITORING

The primary benefit of the advanced display concepts is their ability to alert the crew to engine problems. This includes the more awareness of the problem, shorter detection times and more timely responses to the problem than the Baseline. For most of the faults, there did not appear to be any differences in detection times between E-MACS and DBE. Also, there was no difference in perceived workload, the amount of control activity or the precision in performing the primary flight task between any of the display formats.

When the pilots rated the formats individually, there were no significant differences between their ratings. This indicates that they thought all the formats were acceptable. When they were asked to compare the formats for being the easiest to detect out-of-tolerance conditions and the easiest for fault isolation, they preferred (1) E-MACS over the Baseline and (2) DBE over

E-MACS. These comparison ratings agree with the average detection time comparison between the advanced concepts and the Baseline but not between the two advanced concepts.

Even though the advanced display concepts contributed to the timely response to the faults, the principal problem with them was the recognition and interpretation of the problem. Factors that may have contributed to the fault recognition problems in this study include (1) the within group experimental design, (2) the E-MACS column deviation indicators being grouped by engine instead of parameter, and (3) the extensive training of the pilots on conventional instrumentation as compared to the advanced concepts. Some of these factors may be eliminated by (1) using a between group design where one group of pilots is exposed to only one display concept, (2) for the E-MACS concept, grouping the column deviation indicators by parameter, and (3) providing more training to the pilots who received the E-MACS and the DBE concepts.

Another factor affecting the E-MACS display is that the column deviation indicators present a normalized scale and it was difficult for the pilots to identify the problem or recognize trend information without observing the numeric values. This factor led to a lower rating of E-MACS for the ease of reading engine health. However, one observation by the test conductor who had more exposure to the fault conditions was that trend information could be recognized with the column deviation indicators after sufficient practice.

During engine start, the pilot is required to monitor the rise of oil pressure, N2, and N1 prior to turning the fuel switch on. This could only be perform by the pilots monitoring the digital values on the E-MACS concept which is more difficult than monitoring an analog scale. Some pilots commented on this problem and thought that faults were difficult to interpret with the column deviation indicators. For example, on the hung start fault, the column deviation indicator goes below normal and turns red in color. Two of the pilots misinterpreted this condition as being a hot start. Again, this may have been due to the lack of experience on the advanced display concepts. With DBE it may be necessary to continuously display some engine parameters during certain phases of flight. During engine start, all the parameters for one engine were displayed until the start cycle had been completed for the engine. It may also be necessary to monitor EGT during takeoff with the DBE concept instead of depending upon the 10% deviation. Two pilots commented that they normally monitor EGT during takeoff especially if the engine is operating nears its EGT limit.

The green tick mark on the DBE displays (the expected value based on the engine model) made it easy for the pilots to compare the actual engine performance with the engine model. This should have made it easier to recognize the faults. However, two pilots were unsure of the problem with the hung start. This may have been due to the pilot's lack of exposure to hung starts since two pilots failed to even detect the hung start with the Baseline.

OPERATIONAL ACCEPTANCE OF THE ADVANCED DISPLAYS

Two-thirds of the pilots thought that either of the advanced display concepts were operationally acceptable. Some of these pilots recognized that humans lack the same vigilance as a monitoring system and it is better to leave the monitoring to automated systems. The pilot's role should be determining the response to the problem based on the information presented.

A third of the pilots did not like the automated monitoring but preferred to do their own monitoring. The reasons given are (1) that they do not trust the automated system, (2) they do not feel as if they are in control of the aircraft, and (3) when a problem does occur, it takes longer to recognize it and respond. The third reason is inconsistent with the findings of the objective performance data.

Most pilots preferred the Display by Exception over the E-MACS concept. This was primarily due to (1) not as much information to monitor, (2) the lack of red and amber lines on the display, and (3) the grouping of the displays by parameter instead of by engine. If the red and amber lines were eliminated and the displays were grouped by parameter, the preferences may have been equal between the two concepts.

CERTIFICATION ISSUES

The pilots including the FAA certification pilots gave a number of issues to be resolved. The major issue is the validity of the engine model and its capability to adapt to environmental conditions and engine wear. The monitoring model in the current study did adapt to environmental conditions but did not change with engine wear. Either an aging model that changes the parameter values, or an adaptive model that monitors the actual engine parameters and adjusts itself as the engine ages will be required. System reliability can be solved by redundant monitoring systems that will provide 10^{-9} probability of failure. The display formats can be redesigned to provide adequate spacing and remove the objectionable features such as red and amber lines and grouping the parameters by engine. The requirement to provide the continuous display of all the engine parameters does not appear to be a major problem and if required, digital numbers are adequate.

RECOMMENDATIONS

As a result of this evaluation, the following recommendations are made for E-MACS and advanced engine displays:

1) An engine model that provides the parameter values of a normal engine should be developed. This model should reflect the changes in parameter values that occur with engine aging as well as atmospheric pressure, temperature, MACH number and horsepower extraction. It should reflect the operation of the engine over its life span and between overhauls. The goal is to come up with a model that will meet FAA certification requirements.

2) The following recommendations are made for the E-MACS display concept:

   a) The column deviation indicators should be grouped by parameter instead of by engine. This will make them compatible with the pilot's previous training and other engine tape displays.

   b) The red and amber lines should be eliminated on the E-MACS display. Tick marks should be used in place of these lines to show the range limits. The upper red line or mark should be eliminated.

   c) The red region of the column deviation indicators should be eliminated except when a parameter exceeds a red limit. For the General Electric engines red limits exist for high N1, high EGT, high N2, low oil pressure, and high and low oil temperature. Except for these regions, the column deviation indicators should only have an amber region when there is a 10% deviation.

   d) Expansion of the normal region of the column deviation indicators should be considered so that pilots can detect a deviation prior to it reaching the 10% level.

   e) More spacing between the displays will be required for ease of reading and interpretation. This will be a certification requirement.

4) The following modifications are recommended for the Display by Exception concept:

   a) Display formats should be developed that conserve the amount of display real estate in use at one time. For example, display (1) the normalized thrust scale on the EAD, (2) N1, EGT, N2 and Fuel Flow on one page of the SSD and (3) the engine oil parameters on the second page.

   b) The parameters that are likely to be monitored continuously by the flight crew should be determined for each phase of flight. The display formats should be modified to incorporate these parameters. An example is the display of N1, EGT, N2, fuel flow and oil pressure during engine start.

c) More spacing between the displays will be required for ease of reading and interpretation. This will be a certification requirement.

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APPENDIX A
TRIAL SCHEDULE FOR THE PILOTS

The following table shows the trial conditions each of the pilots recieved for their eight trials on each of the display formats. The sequence of the four characters in each cell are (1) the fault, (2) the throttle mode, (3) the failed engine, and (4) the flight profile. The legend for these characters is presented below the table.

		FAULT-THROTTLE-ENGINE-PROFILE CONDITION PER TRIAL							
PILOT	CONCEPT	1	2	3	4	5	6	7	8
1	MD-11 E-MACS D-B-E	7-A-R-1 1-M-R-2 4-M-L-1	3-A-R-2 8-M-L-1 1-M-R-2	6-M-L-2 4-M-L-1 2-M-L-1	1-M-R-2 5-A-R-2 7-A-R-1	4-M-L-1 7-A-R-1 8-M-L-1	2-M-L-1 3-A-R-2 3-A-R-2	5-A-R-2 6-M-L-2 5-A-R-2	8-M-L-1 2-M-L-1 6-M-L-2
2	D-B-E MD-11 E-MACS	1-M-L-2 7-M-L-1 5-M-L-2	7-M-L-1 8-A-R-1 6-A-R-2	3-M-L-2 2-M-R-1 3-M-L-2	2-M-R-1 5-M-L-2 7-M-L-1	4-A-R-1 3-M-L-2 1-M-L-2	8-A-R-1 4-A-R-1 4-A-R-1	6-A-R-2 6-A-R-2 2-M-R-1	5-M-L-2 1-M-L-2 8-A-R-1
3	E-MACS D-B-E MD-11	7-A-R-1 6-M-L-2 8-M-L-1	8-M-L-1 8-M-L-1 5-A-R-2	6-M-L-2 4-M-L-1 2-M-L-1	5-A-R-2 5-A-R-2 4-M-L-1	3-A-R-2 7-A-R-1 3-A-R-2	1-M-R-2 1-M-R-2 6-M-L-2	4-M-L-1 3-A-R-2 7-A-R-1	2-M-L-1 2-M-L-1 1-M-R-2
4	MD-11 D-B-E EMACS	4-A-L-2 3-M-R-1 8-A-L-2	7-M-R-2 2-M-L-2 7-M-R-2	1-M-R-1 6-A-L-1 3-M-R-1	5-M-R-1 4-A-L-2 4-A-L-2	2-M-L-2 1-M-R-1 1-M-R-1	3-M-R-1 8-A-L-2 2-M-L-2	6-A-L-1 5-M-R-1 5-M-R-1	8-A-L-2 7-M-R-2 6-A-L-1
5	D-B-E EMACS MD-11	1-M-L-1 7-A-L-2 6-M-R-1	5-A-L-1 2-M-R-2 8-M-R-2	8-M-R-2 8-M-R-2 7-A-L-2	3-A-L-1 3-A-L-1 1-M-L-1	4-M-R-2 1-M-L-1 5-A-L-1	6-M-R-1 6-M-R-1 4-M-R-2	7-A-L-2 5-A-L-1 3-A-L-1	2-M-R-2 4-M-R-2 2-M-R-2
6	E-MACS MD-11 D-B-E	2-M-L-2 1-M-R-1 8-A-L-2	7-M-R-2 4-A-L-2 6-A-L-1	5-M-R-1 3-M-R-1 3-M-R-1	6-A-L-1 7-M-R-2 7-M-R-2	3-M-R-1 8-A-L-2 5-M-R-1	4-A-L-2 2-M-L-2 2-M-L-2	8-A-L-2 6-A-L-1 4-A-L-2	1-M-R-1 5-M-R-1 1-M-R-1
7	MD-11 E-MACS D-B-E	3-M-L-2 5-M-L-2 1-M-L-2	2-M-R-1 8-A-R-1 6-A-R-2	6-A-R-2 6-A-R-2 4-A-R-1	5-M-L-2 1-M-L-2 3-M-L-2	8-A-R-1 2-M-R-1 2-M-R-1	7-M-L-1 7-M-L-1 7-M-L-1	4-A-R-1 4-A-R-1 5-M-L-2	1-M-L-2 3-M-L-2 8-A-R-1
8	D-B-E MD-11 E-MACS	3-A-R-2 2-M-L-1 5-A-R-2	1-M-R-2 6-M-L-2 7-A-R-1	8-M-L-1 1-M-R-2 6-M-L-2	6-M-L-2 5-A-R-2 1-M-R-2	4-M-L-1 8-M-L-1 3-A-R-2	5-A-R-2 7-A-R-1 8-M-L-1	7-A-R-1 3-A-R-2 2-M-L-1	2-M-L-1 4-M-L-1 4-M-L-1
9	E-MACS D-B-E MD-11	7-M-L-1 8-A-R-1 4-A-R-1	8-A-R-1 2-M-R-1 3-M-L-2	2-M-R-1 3-M-L-2 8-A-R-1	1-M-L-2 1-M-L-2 1-M-L-2	5-M-L-2 6-A-R-2 7-M-L-1	4-A-R-1 7-M-L-1 2-M-R-1	3-M-L-2 5-M-L-2 5-M-L-2	6-A-R-2 4-A-R-1 6-A-R-2
10	MD-11 D-B-E E-MACS	8-M-R-2 1-M-L-1 7-A-L-2	6-M-R-1 7-A-L-2 1-M-L-1	1-M-L-1 5-A-L-1 4-M-R-2	4-M-R-2 2-M-R-2 8-M-R-2	5-A-L-1 3-A-L-1 6-M-R-1	7-A-L-2 6-M-R-1 3-A-L-1	2-M-R-2 8-M-R-2 2-M-R-2	3-A-L-1 4-M-R-2 5-A-L-1
11	D-B-E E-MACS MD-11	4-A-L-2 8-A-L-2 3-M-R-1	7-M-R-2 3-M-R-1 7-M-R-2	3-M-R-1 6-A-L-1 2-M-L-2	5-M-R-1 2-M-L-2 1-M-R-1	6-A-L-1 1-M-R-1 8-A-L-2	8-A-L-2 4-A-L-2 4-A-L-2	2-M-L-2 7-M-R-2 6-A-L-1	1-M-R-1 5-M-R-1 5-M-R-1
12	E-MACS MD-11 D-B-E	4-M-R-2 1-M-L-1 8-M-R-2	8-M-R-2 5-A-L-1 7-A-L-2	6-M-R-1 2-M-R-2 6-M-R-1	7-A-L-2 3-A-L-1 3-A-L-1	2-M-R-2 7-A-L-2 1-M-L-1	5-A-L-1 8-M-R-2 2-M-R-2	1-M-L-1 6-M-R-1 5-A-L-1	3-A-L-1 4-M-R-2 4-M-R-2

LEGEND		
Faults:	Start: 1 = Hot Start 2 = Hung Start	Climb: 5 = Low Oil Press 6 = Compressor Stall
	Takeoff: 3 = Low N1 4 = Hi Eng EGT	Transition: 7 = Lo Oil Quantity 8 = Hi Oil Temp
Throttle:	A = Automatic	M = Manual
Engine:	L = #1	R = #3
Profile:	1 = Westbound	2 = Eastbound

A-2

APPENDIX B
PILOT BRIEFING MATERIAL

OBJECTIVE

The objective of the study is to assess the relative effectiveness of the Engine Monitoring and Control System (E-MACS) and an alternate concept against the current engine displays which is referred to as the Baseline. The display concepts differ in terms of their engine monitoring capability and the information that they display.

TEST DESCRIPTION

An engineering cockpit simulator will be used for this study and four flight phases will be analyzed: (1) engine start, (2) takeoff, (3) initial climb and (4) transition from climb to cruise. These four will be combined to represent one complete trial. Eight trials will be repeated with each of the three display concepts for a total of 24 trials per pilot. Two different takeoff and climb lateral profiles will be flown by each pilot and the flights will be performed under both manual and autothrottles.

Each subject pilot will fly from the left seat and will be paired with a Douglas experimenter pilot who will sit in the right seat and perform the usual first officer functions. The experimenter pilot will not initiate or inform the subject pilot of any engine related functions or actions but will respond to instructions from the subject pilot. Air traffic control (ATC) functions will be performed by the Douglas experimenter who will be located at a control console behind the subject pilot.

Engine faults may be associated with an experimental trial and may occur during any of the flight phases. The subject pilot is required to recognize and take corrective action until the situation is stabilized, Once the simulator is stabilized, the trial will be terminated.

Objective measures of performance, such as response times to detect anomalies, response accuracy, tracking error and amount of control activity, will be recorded during each trial. Subjective measures will include pilot comments and workload ratings. Workload estimates will be obtained after each trial by means of a modified Cooper-Harper rating scale. After the completion of each block of eight trials with a display concept, a questionnaire will be administered to elicit pilot opinion regarding the particular concept. After all three blocks of eight trials are completed, a post test questionnaire will be administered to elicit pilot opinion on the relative merit of the three display concepts. An additional questionnaire will then be administered to obtain suggestions for improvements to the E-MACS concept and the alternative display concept that was developed as part of this study.

SIMULATOR DESCRIPTION

The simulator is a wide body, engineering development, fixed base simulator. It is configured as a MD-11 flight deck with six across, 8 by 8 inch CRT displays. An experimenter's station is located behind the left pilot's seat. The simulator is driven by alpha based full flight envelope equations and GE engine models. Wheel and column force loading are dynamically programmed by a McFadden controller that is available on the left side only. The rudder pedals and brakes are functional. The pedestal has operative flight controls, back driven autothrottles, fuel and engine start switches.

The glareshield panel emulates the MD-11 flight control panel. The speed/Mach select, heading/track select, altitude select and vertical speed/flight path angle select windows and knobs are operable. Rotation of the controls will pre-select values in the windows and on the flight displays. Pulling the knob will select the pre-selected value. Pushing the knobs will hold the current value that the simulator is at. The autoflight system including the autothrottles is engaged by the autoflight switch on the glare shield. The autopilot is disconnected by the switch on the control wheel. The throttle levers contain autothrottles disconnect and TOGA switches and reverse thrust levers. The out-of-the-window visual scene uses a rear projection screen that is eight feet from the left pilot's eye point. The visual image is generated by a Redifon visual flight attachment consisting of a terrain board with a 10,500 foot runway, a servo driven color TV camera, associated electronics and lighting. The visual scene is capable of producing night and reduced visibility conditions.

Electronic Instrumentation System

The flight displays are the primary flight display (PFD), the navigation display (ND), the engine and alert display (EAD) and the system status display (SSD). Normally the ND and the SSD have more than one format. However, for this evaluation the ND will have a compass rose or horizontal situation indicator format and the SSD will have the secondary engine display format. The primary and secondary engine formats on the EAD and SSD will have three alternative formats that are three of the experimental test conditions. These are (1) the Baseline tape instruments, (2) the E-MACS display concept, and (3) the alternate concept or the display by exception concept. The various formats are described.

Primary Flight Display

The primary flight display (PFD) combines the function of the basic "T" and the flight mode annunciator. Figure B-1 shows the PFD format during initial climb. The airspeed tape consists of a vertical moving scale with indices 10 knots apart and labeled at intervals of 20 knots. The precision airspeed is shown in a box at the center of the tape. When the aircraft Mach number goes above 0.47, the aircraft Mach will be displayed digitally to the right of the airspeed index. The selected airspeed is shown as a filled bow tie overlying the tape and will mesh with the pointer of the digital airspeed box when it is on speed. If it is off the scale, it will be parked at the top of the scale if it is above the scale and at the bottom of the scale if it is below the scale. When it is off scale, a digital readout of the selected speed will be next to the bow tie. The pre-selected speed will be shown as an unfilled bow tie. Speed bugs are shown as dashed letters at the edge of the tape. These bugs are V1 for takeoff decision speed, VR for rotation speed, V2 for takeoff safety speed, FR for flap retract speed and SR for slat retract speed. The stick shaker speed is indicated by the end of a wide red checker bar column extending from the low end of the tape. V min is indicated by a narrow amber column extending from the stick shaker speed to a horizontal line at V min. The airspeed trend is indicated by a green column extending from the index at the center of the tape. The end of the column corresponds with the speed to be achieved in 10 seconds. The trend column does not appear until the trend becomes larger than 5 knots and is removed when it is less than 2 knots.

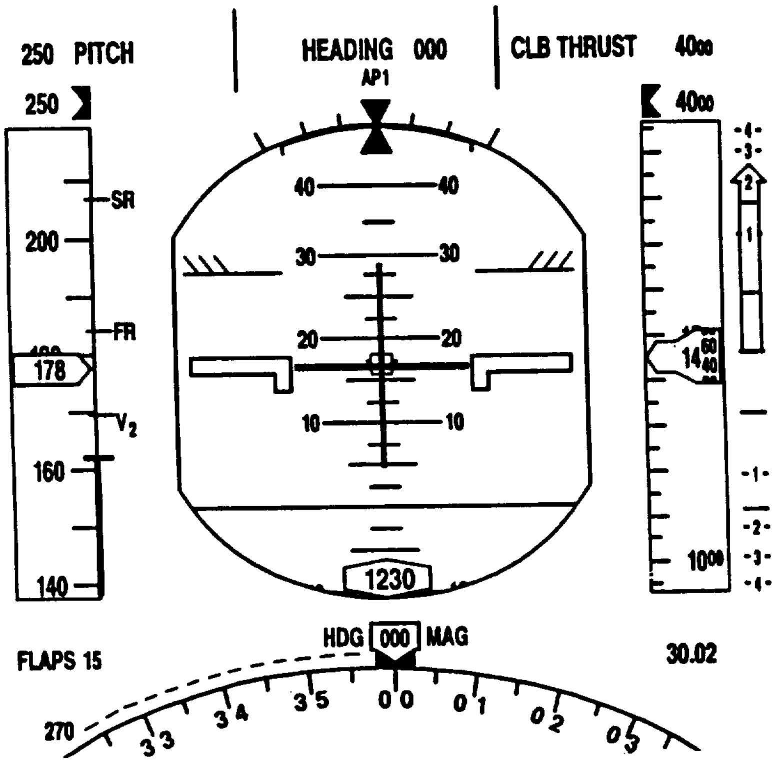

Figure B-1. Primary Flight Display

The altitude tape consists of a moving vertical scale and a digital readout. The tape has tick marks at 100 foot intervals. The altimeter setting is in inches of mercury and the referenced barometric setting is shown below the tape. An amber wedge is displayed starting at the right side of the tape at 200 foot's radio altitude and ending on the left side at 0 foot's radio altitude. The tape is black below 0 foot's radio altitude. The selected altitude is shown as a filled bow tie overlying the tape and will mesh with the pointer of the digital altitude box when it is on altitude. If it is off the scale, it will be parked at the top of the scale if it is above the scale and at the bottom of the scale if it is below the scale. When it is off the scale, a digital readout of the selected altitude will be next to the bow tie. The pre-selected altitude will be shown as an unfilled bow tie.

The vertical speed indicator is a fixed scale display containing a wide, outlined pointer that points to the current vertical speed. The pointer is not displayed until the vertical speed is greater than 100 feet per minute and disappears when there is less than 50 feet per minute. If the vertical speed exceeds g 4000 minute the current vertical speed is shown by two digits at either the top for positive or the bottom for negative vertical speeds.

The attitude director indicator includes the pitch bar, the flight director, the aircraft reference symbol, a pitch limit indicator, a digital radio altitude indicator and roll indices. The pitch limit indicator is a broken horizontal line with feathers on each end and is normally cyan. The angle between the horizontal bar of the indicator and the aircraft reference symbol is the angle of attack remaining until stick shaker is reached. The radio altitude indicator will be centered on the aircraft reference symbol at 0 feet and will start to move down with increasing altitude. At 500 feet it will park at the bottom of the attitude indicator and remain there until 2500 feet at which time it will disappear. The roll pointer is a solid triangle moving along the top of the attitude indicator and indicates 0 degrees of bank when dead center. Short tick marks indicate 10 and 20 degrees of roll, large tick marks indicate 30 and 60 degrees of roll and triangular outlines indicate 45 degrees of roll. The slip/skid indicator is a solid trapezoid attached to the bottom of the roll pointer. For 0 slip, the trapezoid is aligned with the pointer and will move parallel with the horizon line in the direction of rudder correction.

A digital heading indicator is shown below the attitude indicator and above a partial compass rose scale. A drift angle pointer is a green diamond moving on the inside of the scale. The selected heading is indicated by a filled white bow tie moving along the outside of the scale. It is connected by a white dotted arc to the heading index to show the direction of the turn. When the selected heading is off the scale, the value is displayed digitally at the edge of the scale. The pre-selected heading is an unfilled bow tie.

To the left of the heading scale is the flaps/slats configuration. When the flaps are deployed, the message "FLAPS ##" is displayed in white where ## is the flap position. When the flaps are in transit, the display shows the set flap position followed by an arrow indicating the direction of flap motion. The slats configuration is shown below the flaps display. If slats are deployed it show "SLATS" and while the slats are in transit, "SLATS" is displayed followed by an arrow showing the direction of travel.

Flight Mode Annunciator (FMA)

The flight mode annunciator indicates the selected control mode and the commanded state of the aircraft. The speed data is positioned above the airspeed tape, the roll data is positioned over the attitude indicator, and the altitude data is position over the altitude tape. For this evaluation all indications will be in white. The speed window will show the selected speed and either "PITCH" if speed is being controlled by pitch and the throttles are being controlled by the thrust limit or "THRUST" if speed is being controlled by the throttles. The roll window will show "TAKEOFF" during the takeoff roll, the selected heading and the "HEADING" mode, or the selected track and the "TRACK" mode. The altitude window will show the vertical profile mode such as the thrust limit (T/O THRUST, CLB THRUST, or MCT THRUST), the throttles clamped (T/O CLAMP), or altitude hold (HOLD). If altitude hold is selected, the hold altitude will appear in the window to the right of the mode. Autopilot and autothrottles off indications are shown by a box around the affected modes. The box is in white and labeled "AP OFF" or "ATS OFF". If speed is being controlled by pitch, the ATS OFF box will be around the altitude window and AP OFF will be around the speed and roll windows. If speed is being controlled by thrust, the ATS off box will be around the speed window and AP OFF will be around the roll and altitude windows.

Navigation Display

The navigation display will be a horizontal situation indicator format (VOR mode) as shown in Figure B-2. The current heading is digitally displayed in boxed white characters at the top center of the display. The compass rose is a 4 inch circle with the aircraft reference symbol in the center. The diameter represents one half of the selected weather radar range. Small tick marks are placed every 5 degree's interval and larger marks are placed every 10 degree interval. The large tick marks are labeled at 30 degree intervals. The tape is oriented with the current aircraft heading at the top of the scale and is shown as a V which is aligned with the digital readout at the top of the display. The selected heading is a filled bow tie shaped bug on the outside of the compass rose. A dotted white arc connecting the selected heading with the current heading indicates the direction of the turn. An unfilled bow tie bug indicates the pre-selected heading. A green diamond pointer on the inside of the scale indicates the drift angle.

The selected course is displayed by a magenta arrow that is centered on the compass rose indicating the selected bearing. The course deviation indicator is shown as a laterally moving center section to the selected course pointer. The arrow point on the course deviation indicator indicates the to/from direction. Four white circles arranged in a line perpendicular to the course deviation indicator serve as a scale for the lateral deviation. The source identifier and the distance to go is identified in a box to the left of the compass rose.

There are two bearing pointer displays on the compass rose. Bearing pointer 1 is a single cyan arrow and bearing pointer 2 is a double green arrow. The bearing pointer sources are displayed at the bottom of the display. Bearing pointer 1 is on the left hand side and consists of the respective arrow, the identifier, the bearing in degrees and the distance to the station. Bearing pointer 2 is on the right hand side and contains the same information.

At the top left of the display is the ground speed and below it is the true airspeed. A wind vector is shown below these readouts with an arrow showing the direction of the wind relative to the aircraft and the velocity readout. At the top right is a chronograph providing elapsed time in minutes and seconds. It is reset and activated by the push-button switch on the lighting panel. Pushing the switch again will stop the clock and the elapsed time will remain until it is reset.

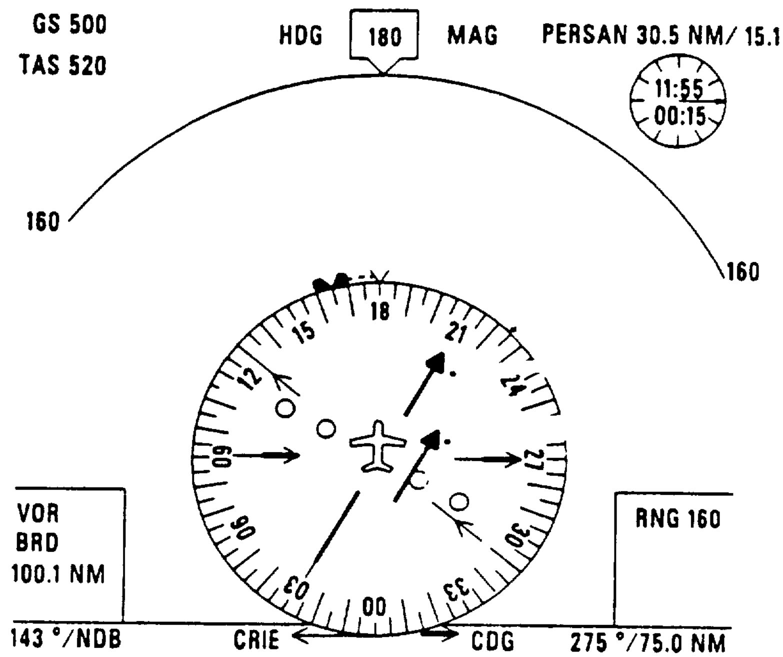

Figure B-2. The Navigation Display

Primary and Secondary Engine Displays

There will be three different formats of the engine displays for you to evaluate. As stated above, one format is the baseline tape instruments for the General Electric engines. A second is called the Engine Monitoring and Control System (E-MACS) display that was developed by NASA Langely. The third is an alternative concept that was developed as part of this study and referred to as the Display by Exception concept. These concepts are described below.

Baseline Engine Instrumentation

The baseline displays are shown in Figure B-3. The primary display has three tapes N1, EGT, and N2. Fuel flow is shown as a digital readout. The tape displays show the current values as white thermometers and the digital values are at the top of the tapes. The tapes will turn amber or red if the limits are exceeded. The N1 display is the primary thrust setting parameter. Throttle position is indicated by a white T riding along the scale. The thrust limit is indicated by a white V. The thrust limit digital value and the thrust mode is shown at the top of the display.

The total air temperature is shown with white digits to the right of it. When the throttle is set to the computed thrust rating, the T will just fit inside the V. The N1 red line is shown as a short red line crossing the scale. If N1 exceeds the red line for any flight leg, the exceeded value will be shown as small amber digits above the current value. This will be reset on each trial. The reverser status is shown above the current value. It is blank for the stowed position, amber U/L (unlocked) for in transit and green REV for fully deployed.

The EGT tape has both an amber and red line limits. If the amber line is exceeded for more than 5 minutes, the tape and digits turn amber. If the red line is exceeded, the tape turns red and the maximum exceeded value is shown in small amber digits above the current value. In the engine start mode, an additional red line limit will appear for engine start. The N2 display has a red line limit. In the start mode, a cyan line appears crossing the scale to indicate the N2 at which the fuel switch should be turned on. Fuel flow is shown in pounds per hour. The value is filtered and the last digit is shown as a 0. When the fuel valve is closed, a FUEL OFF message appears for the appropriate engine.

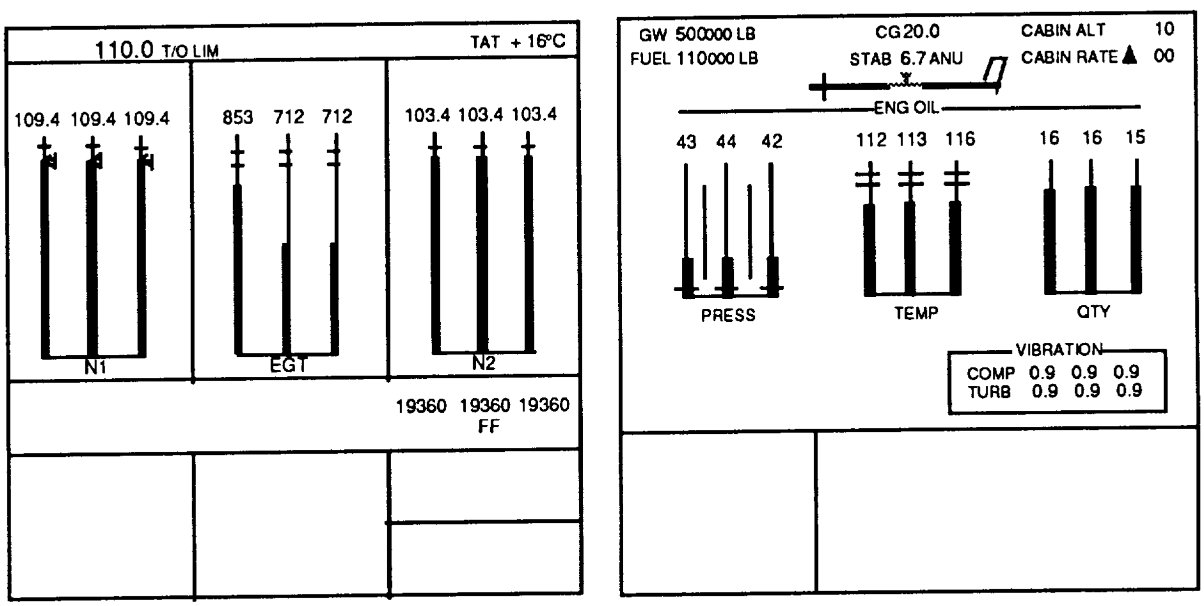

Figure B-3. Baseline Tape Instruments for the General Electric Engines

The secondary engine format contains tape gauges for engine oil pressure, temperature and quantity. It has digital readouts for engine vibration monitoring, APU monitoring, gross weight, fuel weight, center of gravity location, stabilizer position, cabin altitude and cabin altitude rate. The oil pressure tapes have a green line between the tapes that show the normal operating range and the digital value at the top of the tape. The units are in pounds per square inch (psi). If the normally white tapes move outside the green band, the tapes and digital values turn amber. If they move below the red line, they turn red. The temperature tapes have low and high amber lines and a high end red line. The digital values are in degrees centigrade. If the tapes exceed these limits, they will turn the appropriate color. The oil quantity tapes are in quarts. The oil quantity tapes have a cyan line that indicates the initial oil quantity when the engine reaches minimum idle speed on the ground. This serves as a reference for oil quantity consumption. If the quantity drops below 4 quarts, the tape and digits turn amber. The compressor and turbine engine vibration levels are shown in white. If they exceed the limits, the digits will turn amber.

The APU parameters will not be displayed during the simulation based on the assumption that the APU will not be running. The weights, center of gravity, and stabilizer position will remain constant during the simulation. The cabin altitude and rate will change as a function of altitude.

Engine Monitoring and Control System (E-MACS) Display

The E-MACS concept was developed at NASA Langley and is based on a design process that provides information that is appropriate to the task of the user. This resulted in two display elements for the engine information: (1) a primary thrust display and (2) a system monitoring display.

The display formats are shown in Figure B-4. The primary thrust display is normalized engine thrust. The metric is percent of engine thrust relative to the maximum attainable thrust at the current flight condition. At takeoff it is equivalent to the takeoff thrust limit. Since the parameter is thrust, there is no correction for air temperature, pressure altitude, Mach number or bleed air. The scale is from -10% to 110%. The current value is shown digitally above the tape. Both the tape and current digital value are normally white unless a N1, EGT, N2 red line limit or a EGT amber line limit has been exceeded. Once one of these limits is exceeded, the tape turns the appropriate color. Throttle position is indicated by a white T riding along the scale. The thrust limit is indicated by a white V. The thrust limit digital value and the thrust mode is shown at the top of the display. If the thrust value exceeds the red line for any flight leg, the exceeded value will be shown as small amber digits above the current value. This will be reset on each trial. The reverser status is shown above the current value. It is blank for the stowed position, amber U/L (unlocked) for in transit and green REV for fully deployed. The other major display elements that are grouped for each engine are column deviation indicators. N1, EGT, and N2 are shown on the primary engine display and the oil parameters are shown on the secondary engine display. These indicators show the difference between the actual value and an estimated value for each engine parameter. The estimated value is based upon a model of a normal engine and varies as a function of throttle lever position, air temperature,

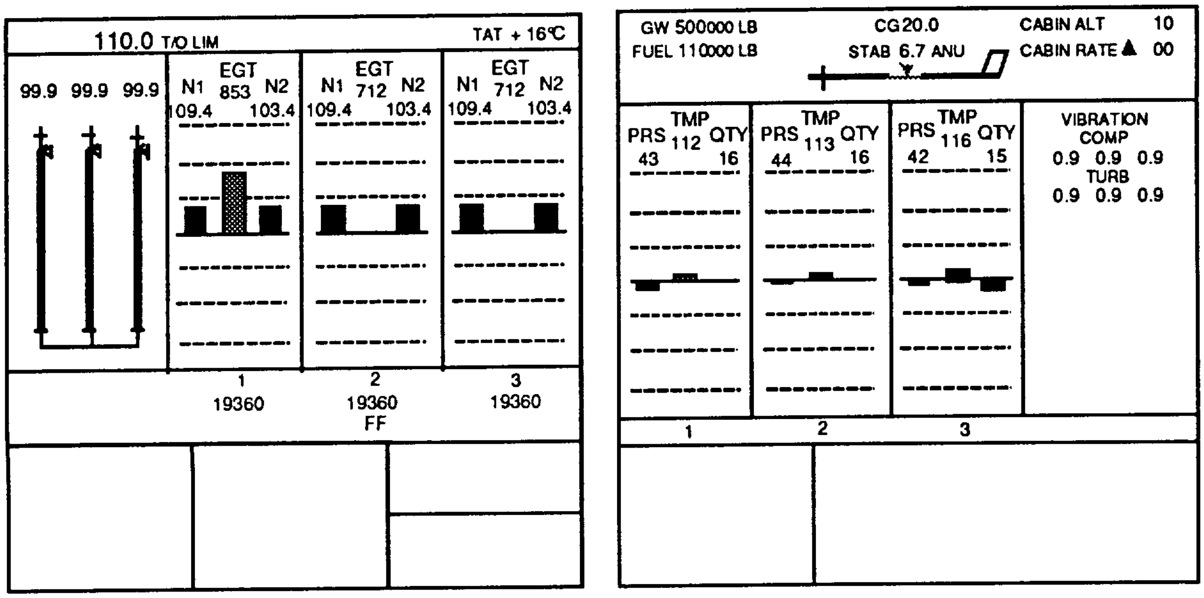

Figure B-4. E-MACS Displays for the General Electric Engines

altitude pressure, Mach number and bleed air. The indicators are divided into normal, caution, and warning ranges for differences both above and below the estimated value. The ranges are 0 to 10% for normal, 10% to 15% for caution, and greater than 15% for warning. In addition, the conventional limitations for a parameter are merged with the deviations as they approach a limit. For example,

if the caution limit is a 12% deviation, the parameter will begin to transition into a caution at a 10% deviation and be in the caution area at a 12% deviation. Above the column deviation indicator is the actual digital value. Both the column and digital value will be white if it is in the normal range, change to amber if in the caution range and change to red if it is in the warning range. As before, if a red line is exceeded, the maximum value will be shown above the column identifier until the end of the trial.

Display by Exception Concept

If there are no out-of-tolerance conditions or deviations from the normal conditions, the only engine parameter that is displayed is the normalized thrust value. The normalized thrust indicator is the same as the one described for the E-MACS display concept except it does not change color if a N1, EGT, or N2 limit is exceeded. The other engine parameters are compared to a normal engine model as in E-MACS and if a 10% deviation or a limit is exceeded, then all the parameters for that engine will appear automatically. The tapes for these

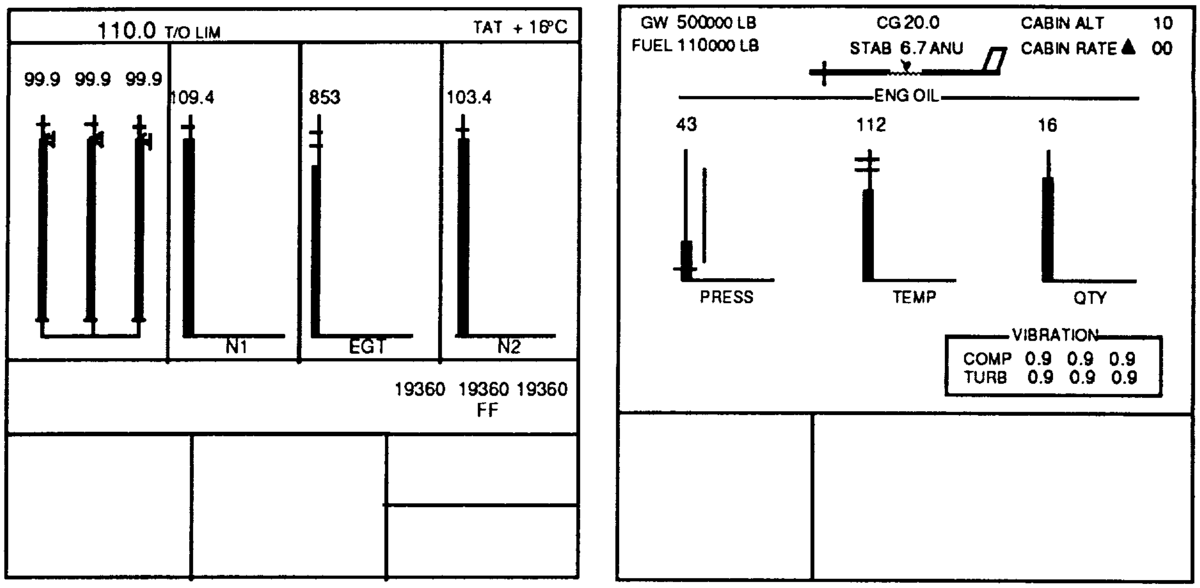

Figure B-5. Display by Exception Formats for the General Electric Engines

parameters will be the same as the baseline tapes. This is illustrated in Figure B-5 where a 10% deviation in N1 has occurred. The color of the tapes will be

white except for the tape with the deviation that will be amber or red. In addition a green tick mark will be added to the tapes to indicate the values estimated by the engine model. (Note: Normally the pilot would have the ability to call up all other engine parameters at any time. (This feature is inhibited for the evaluation.)

Warning and Alerting System

The alerting system consists of the Master Warning and Caution (MW/MC) lights on the glare shield and the Engine and Alert Display. The alerts are categorized into four levels: level 3 -- warning, level 2 -- caution, level 1 -- caution advisory and level 0 -- status. For this evaluation, only level 2 and 1 alerts will occur. Both level 2 and 1 alerts are inhibited on takeoff from V1 -20 knots until a 400 feet in altitude. The alerts are presented in three columns in the lower third of the EAD. Each column allows up to 17 characters for each alert annunciation. The first two columns may contain up to 6 alerts and the last column 4 alerts. The alerts are listed according to priority level and chronologically with the highest level at the top of the list and the latest at the top of the within level list.

The level 2 alerts require immediate crew awareness and possible crew action. They are characterized by: (1) the amber master caution light illuminates and (2) a boxed amber alert annunciation appears on the EAD. Upon pushing the master caution light, the light is extinguished but the alert will remain on the alert list until the problem is resolved. The level 2 alerts have crew procedures that are contained in the quick reference handbook and the flight operations manual. Level 1 alerts require crew awareness but do not require crew action. They are characterized by: (1) the amber master caution light illuminates and (2) an amber alert annunciation appears on the EAD.

TEST PROCEDURES

The evaluation will take place over a two day period. The first day will begin with an oral briefing that will cover the same topic areas found in this package but in more depth. This briefing will pay particular attention to the flight, navigation and engine monitoring display formats and the crew procedures. The oral briefing will be supplemented by a color video tape that will show each of the display formats under dynamic flight conditions and will include a narration that explains the features of the various displays as they change state.

This briefing will be followed by a period of familiarization in the simulator, consisting of both verbal instruction and hands-on flying experience. This will allow the pilots to become familiar with the test conditions prior to the data collection. Once the familiarization training has been completed, the first of three experimental sessions will begin. Each session will consist of eight trials with one of the three engine monitoring display concepts. The schedule calls for one session to be completed on the first day of the evaluation, with the remaining two to be completed on the second day. Prior to the resumption of testing on the second day, a short period of time will be allowed for the pilots to re-familiarize themselves with the simulation and to ask any questions that may have occurred to them after the end of the first day.

The subject pilot will sit in the left seat and will be the pilot flying the simulator. An experimenter pilot will sit in the right seat and will respond to commands given by the subject pilot. The experimenter pilot will not take any action without direction from the subject pilot or inform him of a problem. A pickle switch will be provided on the control wheel for the subject pilot to respond after he has detected a problem during flight. This will allow measurement of his detection time. All trials will be manual flown with the flight director. Crew procedures will include setting the speed, heading and altitude knobs on the glare shield. The subject pilot can perform these procedures himself or direct the experimenter pilot to perform them. When flying with manual throttles, the subject pilot will be required to manipulate the throttle levers to maintain or modify aircraft speed and to balance individual engine thrust. When flying with autothrottles engaged, the subject pilot will not have to manipulate the throttles but just monitor the thrust setting.

Each trial will begin by the subject pilot starting the engines. If either a hot or hung start occur, the subject pilot should shut down the engine. Once the engine is shut down, the trial will be terminated.

If no problems occur during engine start, the simulator will be placed into hold and advanced to the takeoff position. The pilots will go through the pre-takeoff checklist and inform the experimenter that they are ready to start. The experimenter will start the simulator. The subject pilot will request the experimenter pilot to call out the speeds. The subject pilot will advance the throttles to takeoff thrust limit and steer the aircraft. If a fault is detected prior to

V1, the subject pilot should hit the pickle switch and initiate a rejected takeoff. After completion of the rejected takeoff, the trial will be terminated. Otherwise, the subject pilot should continue to rotate the aircraft at VR and when a positive rate of climb is established, he should command gear up. If he detects a fault after V1, he should hit the pickle switch and continue to climb to 400 feet. At that point he should take corrective action. If the fault results in engine failure, he should initiate the engine failure takeoff procedures.

If no fault occurs, the pilot will continue the climb scenario, set the climb airspeed, request the experimenter pilot to retract the flaps and slats at the appropriate speeds and continue the climb and lateral maneuvers until the level off altitude is reached. If a fault occurs during the climb, the subject pilot will hit the pickle switch and take appropriate action. If this action includes shut down of the engine, he should command the experimenter pilot to request a return to the departure airport.

If no fault occurs during this phase, the simulator will be placed into hold and repositioned at the transition altitude to cruise, e. g., at FL 270 feet and leveling off at FL 300. The experimenter will restart the trial and if a fault occurs, the subject pilot will hit the pickle switch and take appropriate action. Otherwise the subject pilot will go through the transition to cruise.

Once a trial is completed, the subject pilot will be asked to provide a workload rating of the preceding trial using a modified Cooper-Harper rating scale (see Figure B-6). The simulation will be reset and the next trial will begin. Engine problems will appear on a random basis. After eight trials have been completed with a particular engine monitoring display concept, the session will be ended. At this point, the subject pilot will be asked to complete a questionnaire relating to the display concept that he has just experienced.

Each of the two remaining experimental sessions will include eight trials as above but a different engine monitoring display concept will be evaluated each time. At the conclusion of the third session, an additional questionnaire will allow the pilots to compare the three display concepts and another will allow them to offer detailed recommendations for improvements to these concepts. Table B-1 show the time schedule of the evaluation.

CREW PROCEDURES

The crew procedures are divided into three flight phases: (1) engine start, (2) takeoff and climb and (3) transition to cruise. The experimenter will inform you when each of these phases begins.

Engine Start

The engine start sequence order is engine 3, 1, and 2. Refer to Table B-2 for the procedures. If an abnormal condition occurs during the engine start, refer to the Abnormal Start in the Non Alert Abnormal Procedures (Figure B-7).

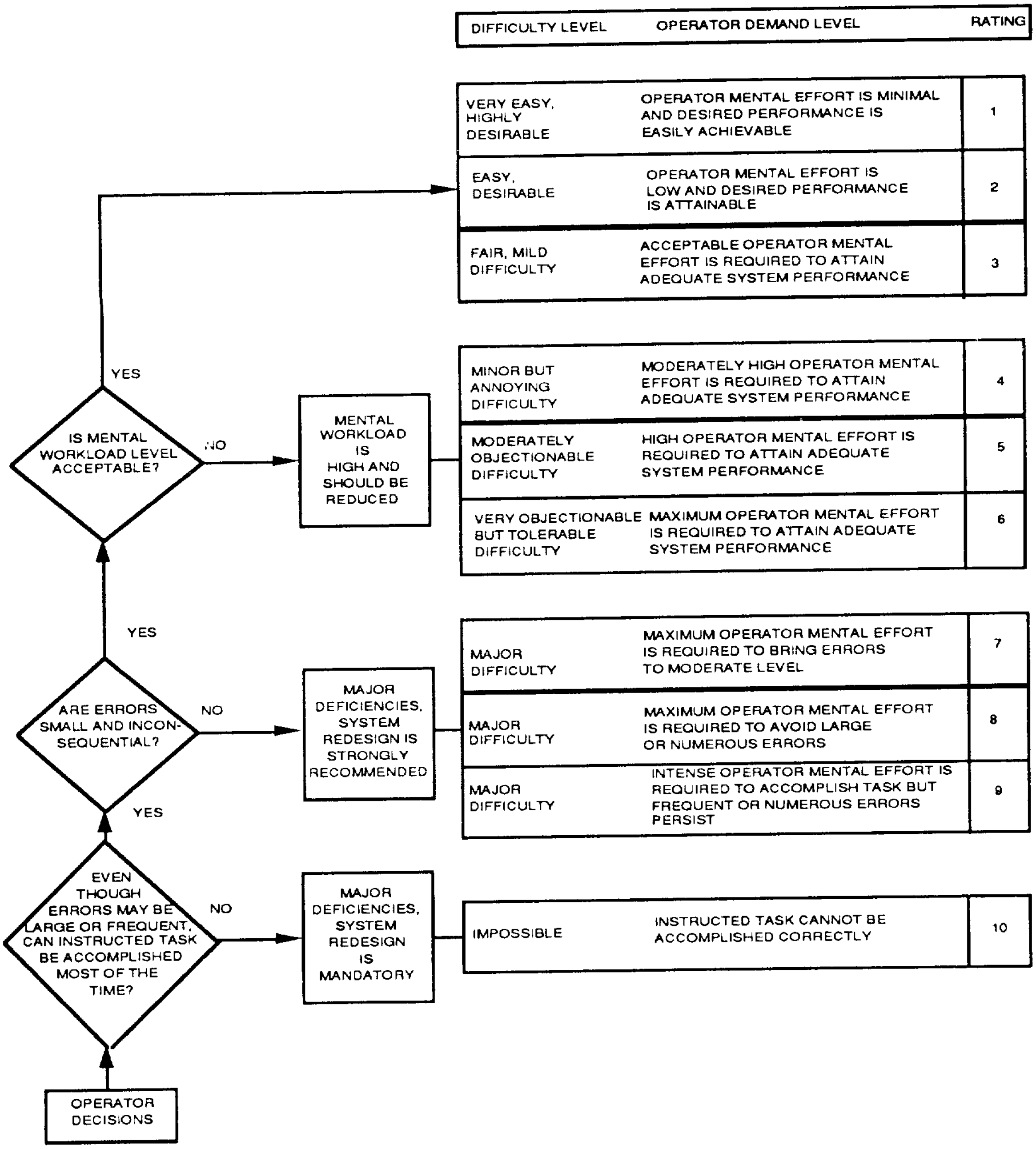

Figure B-6. Modified Cooper-Harper Workload Rating Scale

Takeoff and Initial Climb

1) Set the takeoff flap setting and verify on the PFD.

2) Confirm the proper V speeds are selected and set. Pre-select speed of 250 knots for the initial climb speed and 4,000 feet for the level off altitude.

Table B-1. Daily Schedule

	TIME	ACTIVITY
DAY 1	1000 - 1200	Briefing
	1200 - 1300	Lunch
	1300 - 1400	Simulator familiarization and practice
	1400 - 1530	Experimental session 1
	1530 - 1600	Debriefing
DAY 2	1300 - 1330	Simulator practice
	1330 - 1500	Experimental session 2
	1500 - 1530	Debriefing
	1530 - 1600	Break
	1600 - 1730	Experimental session 3
	1730 - 1800	Debriefing

3) Perform the takeoff and departure briefing including emergency procedures.

4) Review the EAD for any alerts.

5) Perform the Before Takeoff checklist (Refer to Figure B-8.)

6) Inform the experimenter that you are ready to takeoff.

7) Refer to Table B-3 for the takeoff and climb procedures.

8) If an engine failure occurs prior to V1, perform a rejected takeoff, i. e. simultaneously retard throttles, deploy spoilers, and apply full brakes. Apply reverse thrust and maintain braking until a safe stop is assured. If directional control becomes a problem, reduce reverse thrust to reverse idle detent to regain directional control.

9) If an engine failure occurs after V1, maintain directional control and continue the takeoff. At VR, rotate at approximately 2.5 degrees per second to attain V2 at 35 feet AGL. Use rudder to maintain directional control with wing's level and adjust

Table B-2. Engine Start Procedure

CONDITION	SUBJECT PILOT	EXPERIMENTER PILOT
Engine start switch on	Pull the number 3 ENG START switch and observe the switch light illuminates indicating the start valve is open.	
Fuel switch on	At 15% N2 move the number 3 FUEL switch to ON and call "FUEL ON".	Start clock.
	Observe fuel flow gage indicates normal fuel flow and EGT indicates a rise within 25 seconds.	
EGT rises	Call "EGT" when gage shows a rise.	Stop clock.
	Check for normal EGT rise and peak EGT does not exceed engine start limits.	
	Observe ENG START switch poops in and switch light extinguishes. N2 and N1 indications stabilize at ground idle RPM, EGT and ENGINE OIL PRESS gages indicate the normal range.	

pitch to maintain V2. At 1000 feet, select V3 or 225 KIAS on the speed knob and pull. Select 2,500 on the

altitude knob and pull which will enable maximum continuous thrust. At flap retraction speed, retract flaps. At slat retraction speed, retract slats. At V3, follow pitch guidance to continue climb to 2,500 feet. After the aircraft is stabilized, perform the appropriate checklists.

10) If a level 2 engine alert occurs, refer to the Engine Abnormal Procedures (Figure B-9).

Transition to Cruise

1) Pre-select the cruise altitude to 30,000 feet and the cruise speed to 0.830 Mach.

2) Inform the experimenter that you are ready to start.

ABNORMAL START

(Hot Start, Hung Start, No Start)

FUEL Switch . ... OFF

Motor engine with starter for 30 seconds. If starter not engaged, do not re-engage until N2 has stopped decreasing.

Determine type of abnormal start.

HOT START

Record maximum EGT and elapsed time EGT was above 750 deg C.

END

HUNG START/NO START

END

ENGINE SHUTDOWN IN FLIGHT

Throttle... IDLE

NOTE: Conditions permitting, operate engine at idle for 3 minutes prior to shutdown.

FUEL Switch .... OFF

END

Figure B-7. Non Alert Abnormal Procedures

BEFORE TAKEOFF

1. FLAPS ....FLAPS 21 P/FO
2. Takeoff Data............CONFIRM/SET P/FO
3. EAD ....CKD FO
4. Flight Control Panel............AS RQD P

AFTER TAKEOFF

1. GEAR/Lights ....UP/LTS OFF PNF
2. FLAPS/SLATS..................... UP/RET PNF
3. EAD .... CKD PF

Figure B-8 Normal Checklist

Table B-3. Takeoff and Climb Procedure

CONDITION	SUBJECT PILOT	EXPERIMENTER PILOT
Cleared for takeoff	Align aircraft on runway and proceed with takeoff procedure.	
Power advance	If autothrottles, set throttles to approximately 79% N1. Verify symmetrical thrust and call "ENGAGE AUTOFLIGHT". Observe autothrottles advance to T/O thrust, verify "T/O THRUST" appears in FMA and keep hands on throttles till past V1. If manual throttles, set throttles to T/O thrust, verify symmetrical thrust, verify "T/O THRUST" appears on FMA and keep hand on throttles till past V1.	On command, select AUTO- FLIGHT on FCP. Set clock. Set clock.
80 KIAS	Verify airspeed and "T/O CLAMP" appears on FMA.	Call out "80 KNOTS".
V1 speed	Verify airspeed at V1 and place both hands on the control wheel.	Call out "V1".
VR speed	Rotate at 2.5 degrees per second to attain V2 + 10 knots at 35 feet AGL with three engines or V2 with two engines.	Call out "VR".
Positive rate of climb	Call "GEAR UP", continue to accelerate and maintain V2 + 10 knots.	Retract gear.
1000 feet of altitude	Select 250 knots and pull speed knob. Select 4000 and pull altitude knob. Verify "CLIMB THRUST" appears on FMA and follow flight director commands.	
Flap retraction speed	At flap retraction speed call "FLAPS UP".	Raise flap/slat handle to 0/EXT and monitor flap position.
Slat retraction speed	At slat retraction speed, call "SLATS RETRACT".	Move flap/slat handle to 0/RET.
Reach climb speed	Verify and follow flight director command to maintain speed. Check EAD for messages	Begin "After Takeoff Checklist".

3) Follow the procedures listed in Table B-4.

4) If a fault occurs, follow the appropriate Abnormal Procedures (Figure B-9).

ENGINE __ FIRE

or

SEVERE DAMAGE

Throttle ....IDLE

When engine at idle,

"ENG FIRE" ALERT REMAINS DISPLAYED OR SEVERE DAMAGE SUSPECTED

NO

FUEL Switch ....OFF
ENG FIRE Handle/Agent .. DOWN & DISCH/CHECK

After 30 seconds,

"ENG FIRE" ALERT REMAINS DISPLAYED

NO

Remaining Agent, If Available ....DISCH

Land at nearest sutiable airport

END

Operate engine at idle.
Land at nearest suitable airport

END

ENG __ OIL PRES LO

or

ENGINE OIL PRESSURE BELOW REDLINE

INDICATOR PRESSURE BELOW RELINE AND "ENG OIL PRES LO" ALERT DISPLAYED

NO

Shut down affected engine. Refer to Abnormal Non-Alert Procedure - ENGINE SHUTDOWN IN FLIGHT.

END

Associated Oil Quantity,
Temperature and Pressure .. .. .MONITOR

ENGINE N2 LO

Observe engine parameters on EAD/SD.

THREE ENGINES INOPERATIVE

NO

Refer to Emergency Non-Alert Procedure - ALL ENGINE FLAMEOUT.

END

TWO ENGINES INOPERATIVE

NO

Refer to Emergency Non-Alert Procedure - TWO ENGINES INOPERATIVE.

END

Refer to Abnormal Non-Alert Procedure - ENGINE SHUTDOWN IN FLIGHT.

END

ENG __ OIL TEMP HI

Throttle . . . . ADJUST

NOTE: Advancing throttle results in increased fuel flow and may decrease oil temperature.

Record maximum temperature reading in maintenance log.

NOTE: Operation in caution range is permissible for 15 minutes. Operation above redline is not permitted.

OIL TEMPERATURE WITHIN LIMITS

NO

Continue engine operation. Monitor oil temperature.

END

Shut down engine. Refer to Abnormal Non-Alert Procedure - ENGINE SHUTDOWN IN FLIGHT.

END

Figure B-9 Abnormal Alert Procedures

Table B-4. Transition to Cruise Procedure

CONDITION	SUBJECT PILOT	EXPERIMENTER PILOT
FL 270	Select 30000 and pull altitude knob. Verify "CLB THRUST" in FMA and follow flight director command	
FL 300	Verify and follow flight director pitch over command and "ALTITUDE HOLD" appears on FMA. Select MACH .83 and pull speed knob. Verify that cruise speed is captured and ".830 THRUST" appears on FMA.	

APPENDIX C
PILOT QUESTIONNAIRES

Subject____________________

Format____________________

Date____________________

FORMAT EVALUATION QUESTIONNAIRE A

Instructions: Rate the specified format on the basis of the trials you have just completed during this study. Circle your response:

1. How would you rate the **ease** with which engine power indications can be read and interpreted?

   excellent very good good fair poor

2. How would you rate the **speed** with which engine power can be set?

   excellent very good good fair poor

3. How would you rate the **accuracy** with which engine power can be set?

   excellent very good good fair poor

4. How would you rate the **ease** with which engine health indications can be read and interpreted?

   excellent very good good fair poor

5. How would you rate the **ease** with which engine out-of tolerance conditions can be read and interpreted?

   excellent very good good fair poor

6. How would you rate the **speed** with which engine problems can be fault isolated?

   excellent very good good fair poor

Subject____________________

Date______________________

FORMAT EVALUATION QUESTIONNAIRE B

Instructions: Compare the three concepts on the basis of the trials you have just completed during this study. Circle your response:

1. Which display concept allowed the **easiest** reading and interpretation of engine power indications?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

2. Which display concept allowed the **fastest** engine power setting?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

3. Which display concept allowed the **most accurate** engine power setting?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

4. Which display concept allowed the **easiest** reading and interpretation of engine health?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

5. Which display concept allowed the **easiest** detection of engine out-of-tolerance conditions?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

6. Which display concept allowed the **fastest** engine fault isolation?

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

7. Overall, which display concept was the **easiest** to use? .

   BASELINE   E-MACS   DISPLAY BY EXCEPTION

Additional Comments:

Subject____________________

Date_____________________

FORMAT EVALUATION QUESTIONNAIRE C

Instructions: Please provide detailed comments about each of the following display concepts.

EMACS

1 In general, what did you find to be negative or positive aspects of this display concept?

2. What features of the engine thrust display did you particularly like? What did you dislike?

3. What features of the engine parameter monitoring display did you particularly like? What did you dislike?

4. What specific modifications would you suggest which might enhance this display concept?

5. Is this display concept operationally acceptable? Please explain your response.

6. What do you believe are the certification issues with this display concept?

DISPLAY BY EXCEPTION

1. In general, what did you find to be negative or positive aspects of this display concept?

2. What features of the engine thrust display did you particularly like? What did you dislike?

3. What features of the engine parameter monitoring display did you particularly like? What did you dislike?

4. What specific modifications would you suggest which might enhance this display concept?

5. Is this display concept operationally acceptable? Please explain your response.

6. What do you believe are the certification issues with this display concept?

Additional Comments:

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13. ABSTRACT (Maximum 200 words)

The objective of the study was to assess the relative effectiveness of two advanced display concepts for monitoring engine performance for commercial transport aircraft. The concepts were the Engine Monitoring and Control System (EMACS) display developed by NASA Langley and a display by exception design. Both of these concepts were based on the philosophy of providing information that is directly related to the pilot's task. Both concepts used a normalized thrust display. In addition, EMACS used column deviation indicators; i.e., the difference between the actual parameter value and the value predicted by an engine model, for engine health monitoring; while the Display by Exception displayed the engine parameters if the automated system detected a difference between the actual and the predicted values.

The results showed that the advanced display concepts had shorter detection and response times. There were no differences in any of the results between manual and autothrottles. There were no effects upon perceived workload or performance on the primary flight task. The majority of pilots preferred the advanced displays and thought they were operationally acceptable. Certification of these concepts depends on the validation of the engine model. Recommendations are made to improve both the EMACS and the display by exception display formats.

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